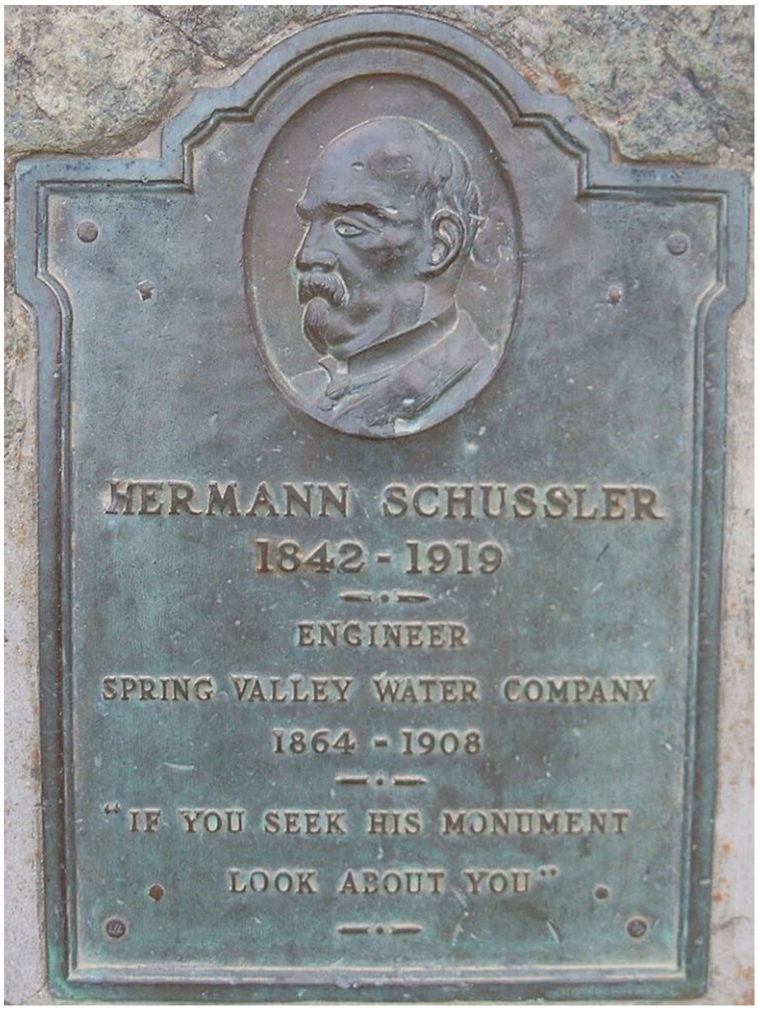
History of the Water Works of San Francisco: Its Performance in the 1906 Earthquake and Aftermath



John M. Eidinger and N. Timothy Hall

Revision 2
August 2024

Table of Contents

TABLE OF CONTENTS **2**

ABSTRACT **5**

INTRODUCTORY REMARKS **13**

0.1 PREFACE BY JOHN EIDINGER 13
0.2 PREFACE BY TIM HALL 28
0.3 PREFACE BY ALEX TANG 32
0.4 ABOUT THE AUTHORS 33

1.0 INTRODUCTION **39**

1.1 CAST OF CHARACTERS 42
1.2 THE FUTURE 55
1.3 UNITS AND ABBREVIATIONS 57
1.4 COPYRIGHT, CREATIVE COMMONS 60
1.5 ACKNOWLEDGEMENTS 61
1.6 REVISION HISTORY 61

2.0 THE SAN FRANCISCO WATER SYSTEM **63**

2.1 THE DEVELOPMENT OF THE WATER SYSTEM 1776-1930 63
2.1.1 Water Supply for the Original Settlement 63
2.1.2 Salt Water and Potable Water and Cisterns, 1850 to 1857 66
2.1.3 The San Francisco City Water Works, 1858 to 1862 70
2.1.4 The Olympic Salt Water Company, 1892 - 1894 78
2.1.5 The Spring Valley Water Works, 1858 to 1930 83
2.2 WHAT SHOULD BE WATER RATES AND THE BIRTH OF HETCH HETCHY 94
2.3 THE SVWC SYSTEM AND FIRES 99
2.4 THE SVWC SYSTEM AT THE TIME OF THE 1906 EARTHQUAKE 100
2.5 THE SVWC AFTER THE 1906 EARTHQUAKE 111
2.6 THE PRESS 113

3.0 THE SEISMIC HAZARDS IN THE EARTHQUAKE **116**

3.1 GROUND MOTIONS IN 1906 EARTHQUAKE 116
3.2 LIQUEFACTION HAZARDS 119
3.3 FAULT OFFSET HAZARDS 130

4.0 DAMAGE TO THE SVWC WATER SYSTEM IN THE 1906 EARTHQUAKE **142**

4.1 PILARCITOS CONDUIT 151
4.1.1 Site 1. Collapse at Large Frawley Canyon 169
4.1.2 Site 2. Collapse near Small Frawley Canyon, FX-1 174
4.1.3 Site 3. Collapse of Pipe South of FX-1 179
4.1.4 Site 4. Fence 1 Offset 183
4.1.5 Site 5. FX-2 185
4.1.6 Site 6. FX-3 186
4.1.7 Site 7. FX-3 South 192
4.1.8 Site 8. FX-4 195
4.1.9 Site 9. Adjacent to Pipe FX-4. Fence 2 (Lawson's Fence "C") 202
4.1.10 Site 10. San Andreas Dam Outlet Works 207
4.1.11 Site 11. San Andreas Dam and Road Across Crest 215
4.1.12 Site 12. San Andreas Dam Wastewater Tunnel and Locks Creek Flume near San Andreas Dam 226
4.1.13 Site 13. Fence 3 244
4.1.14 Site 14. FX-5 248
4.1.15 Site 15. Lawson Fence "A" or Schussler Site "N" 256

4.1.16 Site 16. Schussler Site N' ... *263*
4.1.17 Site 17. FX-6. 44" Locks Creek Pipe ... *265*
4.1.18 Site 18. FX-7 Abandoned Stone Dam / Locks Creek 37.5" Pipe ... *272*
4.1.19 Site 19. Old Hayward Dam, Lower Crystal Springs Reservoir ... *276*
4.1.20 Site 20. Tunnel Between Lower and Upper Crystal Springs Reservoirs ... *277*
4.1.21 Site 21. Highway 92, Causeway Across Upper Crystal Springs Dam ... *280*
4.2 SAN ANDREAS CONDUIT ... 284
4.3 CRYSTAL SPRINGS CONDUIT ... 294
4.4 ALAMEDA CONDUIT ... 314
4.5 LAKE MERCED ... 328
4.6 LOCKS CREEK SYSTEM ... 331
4.7 OTHER DAMAGE ... 341

5.0 WHAT WENT RIGHT? WHAT WENT WRONG? ... 343

6.0 OUTCOMES OF THE 1906 EARTHQUAKE ... 349

6.1 DID WATER UTILITIES LEARN MUCH ABOUT SEISMIC DESIGN? ... 350

7.0 FIRE FOLLOWING EARTHQUAKE ... 356

7.1 FIRE AREA ... 356
7.2 FIRE IGNITIONS ... 361
7.3 FIRE SPREAD ... 371
7.3.1 Fire Spread During Period 1: Wednesday April 18 5:13 am until 6 pm. ... *374*
7.3.2 Fire Spread During Period 2: Wednesday April 18, 6 pm until Thursday noon April 19. ... *375*
7.3.3 Fire Spread During Period 3: Thursday noon April 19 through Midnight ... *376*
7.3.4 Fire Spread During Period 4: Friday April 20 early hours through Friday night ... *377*
7.3.5 Saturday April 21 ... *377*
7.4 FIRE OUTCOMES ... 377
7.5 FIRE DEPARTMENT RESPONSE ... 403
7.6 FIRES OUTSIDE OF SAN FRANCISCO ... 406
7.7 THE VALENCIA STREET SITUATION ... 407

8.0 AWSS ... 418

8.1 ADDRESSING FUTURE FIRES ... 420
8.2 AWSS SALT WATER PIPE SYSTEM DESIGN OF 1903-1904 ... 425
8.3 AWSS SALT WATER PIPE SYSTEM DESIGN OF 1907-1912 ... 427
8.4 SALT WATER PIPE SYSTEM PERFORMANCE IN 1989 EARTHQUAKE ... 442

9.0 THE HETCH HETCHY WATER SUPPLY ... 452

9.1 THE HETCH HETCHY SYSTEM DESIGN, 1867 - 1910 ... 452
9.2 THE HETCH HETCHY SYSTEM DESIGN, 1912 ... 461
9.3 COMPARISON OF THE PLANS, 1902-1912 ... 477
9.4 COST OF THE PLANS ... 479
9.5 HETCH HETCHY, 1934 - 2023 ... 487
9.6 CALAVERAS DAM ... 491

10.0 CONCLUSIONS ... 494

10.1 SUMMARY OF SAN ANDREAS FAULT SLIP PARAMETERS IN THE VICINITY OF THE SAN ANDREAS DAM IN 1906 ... 494
10.2 SUMMARY OF SVWC WATER SYSTEM PERFORMANCE ... 499
10.3 FIRE AND CONFLAGRATION ... 506
10.4 AFTERMATH ... 506
10.5 AFTER THOUGHTS ... 507

11.0 REFERENCES ... 510

APPENDIX A. EARTHQUAKE OF OCTOBER 1868 ... 516

INDEX 521

Abstract

The M_w 7.8[1] earthquake, along the northern San Andreas fault of April 18, 1906, remains the costliest and deadliest in U.S. history. The City of San Francisco bore the brunt of the earthquake: about 80% of its assessed value of $500,000,000 ($1906) was lost by the ensuing fire conflagration. For the past 117 years, the City of San Francisco and various researchers have suggested that much of the blame for the fire could be traced to the damage of the Spring Valley Water Company (SVWC) water system. There can be no dispute that the failure to deliver water to fires soon after the earthquake allowed the initial fires to spread.

Beginning in the late 1860s, the City of San Francisco threatened to condemn the SVWC and threatened to build a parallel water system to compete with SVWC. Numerous lawsuits between SVWC and the City followed. It took more than 60 years to ultimately resolved these lawsuits, when in 1930 the City purchased SVWC's properties and infrastructure that served San Francisco.

In the early 1890s, SVWC planned critical two new infrastructure projects. The first project included a new 16 to 20 million gallon reservoir and pipeline to provide reliable fire flows along Market Street should pipes in the Mission Creek / Sullivan Marsh area break. The second project included a 400 to 500 million gallons reservoir and to assure a multi-week supply of water to San Francisco should the transmission pipes from the Peninsula lakes fail. The San Francisco Board of Supervisors rejected both projects.

Between 1900 and 1905, The City reduced payments to SVWC for fire service by about 80%. This starved SVWC for funds to construct new pipes and hydrants, and construction largely stopped.

As a result of the 1906 earthquake, the City built its own parallel AWSS (the Auxiliary Water Supply System) in 1912, costing $600,000. The City also voted $45,000,000 to build its own Hetch Hetchy water system (authorized by Congress in 1907) with the intent to capture and store water in a new reservoir in Yosemite National Park and to deliver that water to end user customers in San Francisco via a new aqueduct and a newly-built grid of water distribution pipes along every city street in San Francisco. First water from the Hetch Hetchy system was delivered into the Crystal Springs reservoir in 1934; the new water distribution grid was never built.

There are several key questions.

[1] M_w is the modern abbreviation to indicate moment magnitude, the modern magnitude scale of choice for large earthquakes. But, to simplify, except here, the report uses M. Older reports and papers sometimes assigned magnitudes up to 8.3 for this event, sometimes using different magnitude scales. More commonly today, it is assigned moment magnitude 7.8 or 7.9. Without belaboring the point, we adopt M = 7.8 for this report.

- Question 1. Why did the 1906 earthquake fail SVWC water transmission supply pipes at 49 locations?

- Question 2. Why did the water distribution system break at 299 locations and fail to deliver water to hydrants? How many fires ignited, and why did some of them spread?

- Question 3. A parallel AWSS was built in 1912, designed and built to be earthquake resistant. When it was finally put to the test in the 1989 Loma Prieta earthquake, it did not deliver water to a major fire. Given the seismic weaknesses of the AWSS, should it be abandoned or seismically upgraded?

- Question 4. There was animosity between the privately-held monopoly (SVWC) and the public (the City of San Francisco, represented by its Mayor and Board of Supervisors). This was stoked by the journalism of the fourth Estate (the newspapers). Did these conflicts contribute to the fire conflagration triggered by the 1906 earthquake?

In this report, we attempt to answer all four questions.

Question 1. Transmission Pipes

- The water transmission pipes in 1906 delivered water to San Francisco from four sources: Pilarcitos, San Andreas, Crystal Springs and Alameda. The pipelines from all four sources were damaged. The Pilarcitos pipe failed at every location where it zig-zagged over the San Andreas fault, at some elevated wood trestles, and many other locations. The San Andreas pipe failed at one location atop a wood trestle. The Crystal Springs pipe failed at multiple locations, including long lengths where it was supported on wood trestles across marshes adjacent to the San Francisco Bay margins (modern day liquefaction zones). The Alameda pipe had modest damage at a few locations.

- We present the available evidence, including old (generally pre-1907) photos of many of the pipe failure locations. We discuss and provide commentary of these failures, coupled with modern understanding of the level of ground motions the pipes were exposed to at the various fault crossing locations, as well as the seismic withstand capacity of the pipes. Every pipe that crossed the San Andreas fault, broke.

- The thin-walled riveted wrought iron 30-inch diameter Pilarcitos pipe could not sustain the imposed fault offset without loss of the pressure boundary. The pipe failed at all 5 locations where it was exposed to as little as ~7 feet to as much as ~12 feet of right lateral offset. The pipe also failed at 2 locations where it was supported on wood trestle bridges that collapsed. The thin-walled pipe failed at 24 (or more) locations where it was exposed to moderate to strong inertial shaking.

- The thicker-walled riveted wrought iron 30-inch diameter Pilarcitos pipe did not fail at any location where it was exposed to moderate to strong inertial shaking, including several locations where it was on wood trestles. Also, none of the wood-flume portions of the Pilarcitos conduit failed where they were exposed to moderate to strong inertial shaking.

- Excluding the fault offset locations, the rate of failure of thin-walled wrought iron riveted pipe (D/t > 250) was about 10 times higher than the rate of failure for thicker-walled (D/t < 150) wrought iron riveted pipe.

- In 1894, the SVWC planned on building a new 400 to 500 million gallon reservoir in San Francisco. The intent of this reservoir was to be able to supply San Francisco with 2 to 3 weeks of high quality water should there be failures in the transmission pipes. SVWC purchased the Industrial site to build this reservoir. The City declined to allow SVWC to pass on the cost of this reservoir to customers. As a result, the reservoir was never built.

- The majority of the pipe failures were due to a failure to factor in seismic design principles. First, the common practice (even to this day) of designing transverse girth joints for only half the load as longitudinal seam joints, for continuous steel (or wrought iron) pipes, is absolutely wrong for pipes that need to have ductile response in earthquakes. Second, the practice of placing pipes atop wood trestles without suitable seismic lateral restraint, led to the failure of the above ground Crystal Springs pipeline. Third, axial slip joints placed irregularly along long reaches of continuous pipe, will tend to open / close several inches under strong ground shaking.

Question 2. Distribution Pipes and the Fire

- At least 70% of the 299 cast iron and wrought iron distribution pipe failures in San Francisco occurred in liquefaction zones. Using 2024 terminology, the bulk of these failures occurred where the pipes traversed the Mission Creek, Sullivan Marsh and the backfill areas of the second sea wall for the Port area. The cast iron and wrought iron pipes were considered the best available types of pipes when they were installed, prior to 1906; unlike other west coast communities of the era, no wooden pipes were used.

- Both SVWC (owner of the water pipes) and the City (owner of the sewer pipes) were aware of the ongoing soil settlement problems in the liquefaction zones. Annual surveys of ongoing soil movements were taken. The water company had resorted to placing pipes through these unstable areas on buried planks, in a (futile) attempt to "even out" the differential settlements.

- In the 1890s, SVWC proposed to build a new 16 to 20 million gallon reservoir at the head of Market Street, and a new large diameter pipeline down Market Street, studded with hydrants, to prevent any fire from the South of Market Street area to encroach into the central business district north of Market Street. The City refused to allow SVWC to build this reservoir.

- SVWC and the City had been in dispute over fire service for many years prior to the 1906 earthquake. Prior to 1899, the City required that SVWC provide water for fire service for free, which SVWC did; but with the proviso that the diameter of the water pipes was sized mostly to deliver sufficient water to paying customers. Recognizing that the water grid had many areas with pipes too small (some were 3-inch or 4-inch diameter) to provide high fire flows, SVWC and the City agreed that the City would pay a monthly rent for fire hydrants, and then SVWC set out to build large diameter pipes to deliver higher flow rates. However, with the election of a new Mayor Phelan in 1899, who campaigned on putting SVWC out of business, the City quickly moved to severely reduce these monthly fire hydrant payments by about 80%; SVWC responded by effectively stopping construction of new large diameter pipes.

- At the time of the 1906 earthquake, the City distribution system was operated in three main pressure zones: Lake Honda (grade line[2] 365 feet), College (grade line 255 feet), and University Mound (grade line 160 feet). This reflected the hilly topography of the City. Water pipes to the two lower zones broke in the earthquake, preventing re-supply. Most fire ignitions in the upper zone were quickly controlled / extinguished. Within minutes (south of Market area) or a couple of hours (north of Market area), fires that started in the lower two zones had no water available; most of these fire ignitions spread.

- The fires burned for 3 days. During most of this time, winds were light, and the rate of spread was generally slow. At the time of the earthquake, there were some 70 cisterns in the streets; water from 3 of these was used to help contain the spread in a couple of locations; but mostly, the small amount of water in these cisterns was insufficient to deal with large fires. Dynamiting buildings during the 3 days was done with the intent to create fire breaks; mostly, this was ineffective, and perhaps in some locations ignited more fires. Fire department (and in some locations, citizen support) was in constant use throughout the 3 days of the fires. The spread and ultimate control of the fires was largely governed by the wind speed and direction: the spread of fire was stopped when there was availability of water. On the west, the fire was stopped when it burned close to areas that were being supplied with water in the Lake Honda Zone (along the west sides of Van Ness and Dolores). On the east, the fire was stopped by water from tug boats / fire boats along the waterfront (nearly all of the wharves were saved from fire). On the south, the fire was stopped by pumping water out of Mission Inlet (Islais Creek). Overall, where there was continuous supply of water from hydrants or

[2] The "grade line", refers to the maximum elevation of water in the zone, assuming the in-zone reservoir is full. The water pressure at any given point is in proportion to the grade line less the local elevation at that point, less pressure losses as water flows through the pipes.

other sources, the fire department was very effective in stopping the fire from spreading.

Question 3. The AWSS

- Within a few years after the earthquake, the City designed and built a parallel AWSS water pipeline system. The intent was that this system would normally have sweet water available from a 10 MG reservoir at Twin peaks at its highest elevation, and supplemented by two 0.5 MG tanks at middle elevations; and in case sweet water was unavailable, from two salt water pump stations that could draft from the Bay. The pipeline grid (generally 12-inch to 18-inch diameter) covered much of the areas burned in 1906, but was not installed on every street. The largest diameter pipes, 18-inches, were located to avoid zones that liquefied in 1906. However, many 12-inch pipes traversed the very same areas that liquefied and had PGDs in the 1906 earthquake. Additional cisterns were also built. All pipes were heavy wall cast iron, nominally rated for 300 psi internal pressure. Where these pipes traversed known liquefaction zones, they included restrained joints. The original AWSS cost was $5,750,000 ($1909).

- The AWSS was put to a real test in the 1989 Loma Prieta earthquake. A large fire started in the Marina District, an area that had ground settlements of a few inches due to liquefaction. Although an AWSS hydrant was located adjacent to this large fire, no water was available from this hydrant to fight the fire for almost 3 hours. The reason there was no water is that the 12-inch cast iron pipes in the area that liquefied, as well as the hydrant laterals, suffered a few breaks and leaks; this de-pressurized the system, preventing water from reaching the hydrant where it was most needed. Fire department procedures were not fast enough to rapidly (within minutes) identify these leaks / breaks and valve them out; it took nearly 3 hours to do so. The large Marina fire was ultimately controlled by relaying water using above ground hose, initially from a nearby pond and later from the San Francisco Bay; but this took over an hour to deploy. Fortunately, at the time of the earthquake, there was no wind, so this fire did not spread very much.

- The City has recognized the seismic deficiencies in the AWSS, and has recently (2019-2021) proposed a $6 billion program over 25 years to seismically upgrade the AWSS. The authors point out that a more cost effective program would be to selectively seismically upgrade the potable water system for $180,000,000 over 10 years, and once that is done, then abandon the old AWSS pipe system and re-purpose it to non-potable recycled water usage.

Question 4. Hetch Hetchy

- The initial bond to build Hetch Hetchy was for $45,000,000 ($1909), to build a water transmission system able to initially deliver 60 MGD from three reservoirs in and near Yosemite National Park to San Francisco; plus a brand new parallel potable distribution water pipe grid to deliver that water to customers in San Francisco. Water demand in San Francisco in 1912 was about 35 to 40 MGD; with ultimate demand in a century forecast to be no more than 100 MGD. Water rights for the Hetch Hetchy system were 400 MGD, with the excess water to be used for future population growth in San Francisco, and remaining water sold to neighboring cities like Oakland, Berkeley, Alameda and other Bay Area communities yet to be built.

- Congress passed the Raker Act in 1913, which allowed San Francisco to build a dam across the Tuolumne River in Yosemite National Park. There was much controversy about flooding the Hetch Hetchy Valley for providing a domestic water supply for San Francisco. Most notably, John Muir was dead set against it; believing that the new reservoir would be cycled and nearly emptied annually, leaving an ugly mess of debris along the shorelines each fall. Ultimately, Congress approved this work, with San Francisco sharing the water rights from this watershed of somewhat more than 2,000 MGD with two other water irrigation districts (Modesto Irrigation District, MID, and Turlock Irrigation District, TID). Based on Freeman's design of the Hetch Hetchy system in 1912, San Francisco was to get 400 MGD after the two irrigation districts were to get a combined 1,600 MGD. These three stakeholders also agreed that excess power developed from the system, not used for public purposes in San Francisco, would be available at cost to MID and TID.

- To help sell this project to the citizens of San Francisco, various promises were made, including claims in various newspapers and politicians like [sic] "water will be pure and free (or at least a lot cheaper than SVWC water)"; "SVWC's system provides limited supply with putrid water"; "SVWC monopolists cannot be trusted" and other such political hyperbole. The bonds were voted upon in 1909, and passed by a margin of 6-to-1.

- The City was not all that satisfied with the original designs for Hetch Hetchy that were developed by the City's own City Engineers, Mr. Grunsky (1900-1902) and later Mr. Marsden (1908-1911). In 1912, the City hired John Freeman to re-design the system. John Freeman, an independent consultant from Boston and a civil engineering graduate from the Massachusetts Institute of Technology, got to work. He abandoned the prior Hetch Hetchy concepts that included a series of open canals and a large pump station, and redesigned it to be an essentially closed system comprised of tunnels and pipelines, and that would deliver the water to San Francisco entirely by gravity flow. Freeman estimated that his design would cost $38,898,000, about the same as the original design, if one excluded the (extra expense) of a parallel city distribution pipe grid. Freeman's 1912 re-design and his report helped convince Congress to pass the Raker Act in 1913.

- In 1914, the City hired Mr. O'Shaughnessy to oversee the construction of Hetch Hetchy. And so he did, from 1914 through 1933. The actual construction varied a bit from Freeman's 1912 design, but retained the key elements of being an enclosed system in tunnels (rated to flow 400 MGD by gravity, or 500 MGD with supplemental pumping) and pipes.

- The initial construction of Hetch Hetchy did not go as planned. The initial cost estimate of $38,898,000 soon ballooned to about $105 million. Eighty-nine workers lost their lives building the system. Ultimately, the plan to build a parallel set of water pipes in San Francisco was abandoned entirely. Costs were so high and construction so difficult, that in 1923 the City and SVWC got together to jointly use BDPL 1[3] to deliver SVWC water from SVWC's Alameda watershed to Crystal Springs reservoir. At one point, SVWC loaned money to the City so that City workers could continue construction, as the City had run out of funds.

- The original plan of selling excess water to Oakland, Berkeley and Alameda (by 1913, then having a population of about 250,000, or about two-thirds that of San Francisco) was turned down by those communities; instead those communities built their own entirely independent mountain water supply from the Mokelumne River, with first deliveries to Oakland in 1929. The Mokelumne water supply was designed to ultimately deliver 330 MGD.

- In the 21st century, the SFPUC has further upgraded the Hetch Hetchy system, at a cost of $4.6 billion. These upgrades were to improve operating reliability and seismic capability. One of the goals of the upgraded Hetch Hetchy system is to reliably deliver winter day water demands to most wholesale customers, within 24 hours after a large earthquake.

- In the 21st century, there remain some stakeholders who advocate restoring Hetch Hetchy Valley to its pre-development status. Today (2024), some 2.6 million people rely on this water supply for all or part of their daily water usage. While the quantity of water supply in the watershed would remain the same, the loss of storage would result in lower annual safe yields; and accessing this same water from a point downstream of Yosemite National Park will negate the benefits afforded by the granitic geology in the Park, and the water quality would not be "so pure" as was promised to the Citizens in 1912. Replacement water storage, treatment and various pipeline and tunnel reconfigurations, and / or loss of hydroelectric power capability would be costly, probably costing $10 billion or perhaps much more to maintain a similar (but not as pure or reliable) water supply system. The authors do not dispute that the original Hetch Hetchy Valley with cliffs and waterfalls over 1,500 feet high was beautiful; but today's Hetch Hetchy Valley, with a reservoir some 300 feet deep, is also quite beautiful; the cliffs and waterfalls are still some 1,200 feet high; and the lack of millions of annual visitors (like in nearby Yosemite Valley) is a blessing for those seeking a wilderness

[3] BDPL 1 is the modern abbreviation for Bay Division Pipeline No. 1. This pipe is the last leg of the Hetch Hetchy Aqueduct, and moves water from Fremont to Crystal Springs reservoir. Chapter 9 of this report describes the Hetch Hetchy system in detail.

experience. The authors would like to think, that if John Muir were alive today, he might be reasonably pleased with the result.

- The SFPUC water customers in the 21st century know that the Hetch Hetchy system water is certainly not free, and it certainly is not cheap. The 1913-era water rights of 400 MGD average flow has never been fully used, with the current Hetch Hetchy system hydraulically limited to about 330 MGD. In California, historic water rights can be impaired if one does not constructively use the water. Up to now, a key virtue of Hetch Hetchy water is its extremely high quality source water; but this is now threatened by the California State Water Resources Control Board that is considering new rules to allow water utilities to recycle toilet water to tap water.

- The future of the Hetch Hetchy and the San Francisco water systems remains to be told. We hope this report shines a bright light on the first 170+ years of these water systems. Those who do not remember the past are condemned to repeat it[4].

[4] George Santayana *in* The Life of Reason, 1905.

Introductory Remarks

0.1 Preface by John Eidinger

This book documents the water system lifeline performance in the Great 1906 San Francisco M 7.8 earthquake.

Figure 0-1 shows a photo of the Earthquake Investigation Team en-route to examine the San Andreas fault and the damaged Pilarcitos water pipeline at "Site 9" (see Section 4.1.9 for details of what happened at that site). The black splotch in the center of the photo and a few other dark splotches in the top right are artificial as the old photo was creased; hand-drawn arrows have been added to highlight certain features; "Fence C" is discussed in Section 4.1.8.

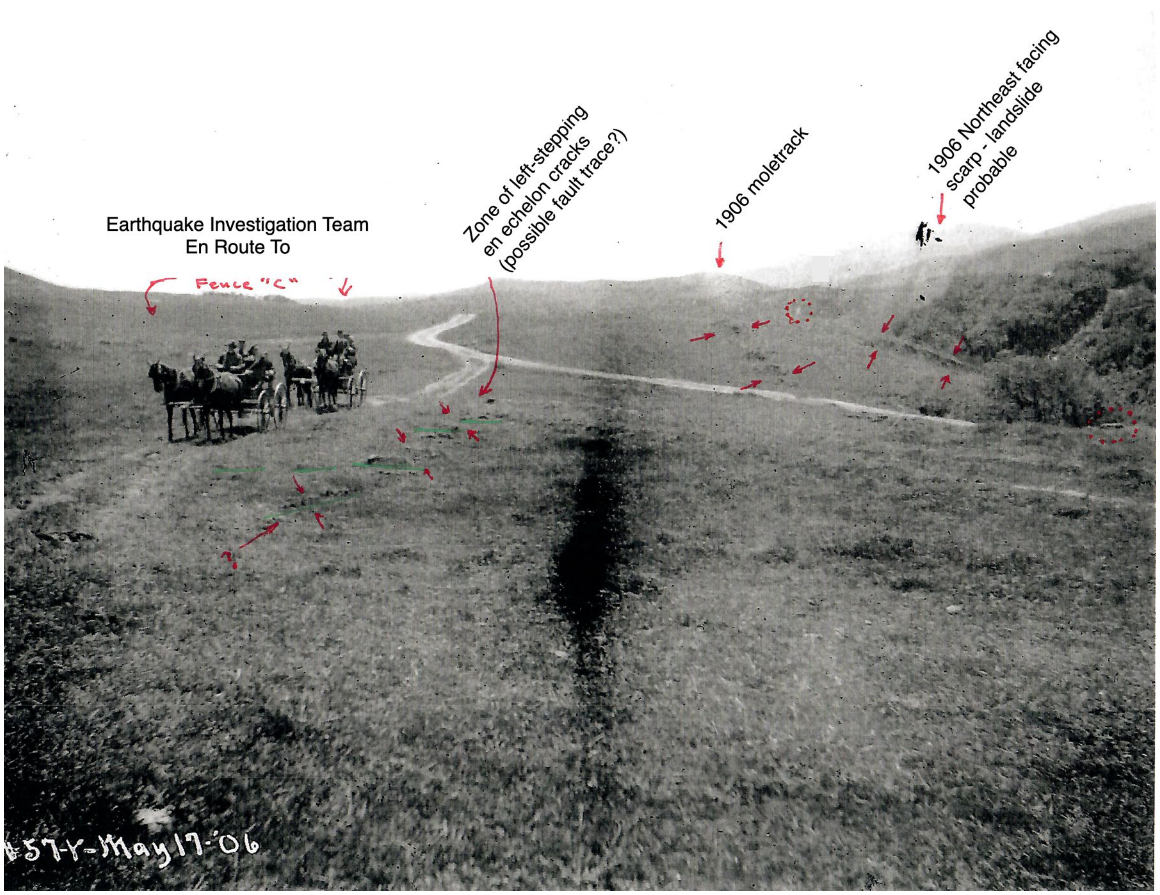


Figure 0-1. Earthquake Investigation Team (photo: Schussler 1906)

Who is in this photo? We are fairly certain today that it includes Victor Elmo Perry (then Assistant to the City Superintendent of the SVWC, and he was directed to support this investigation by Hermann Schussler, then Chief Engineer of the Spring Valley Water Company), Professor of Geology A. C. Lawson (U. C. Berkeley), Dr. Reed (head of U.S. Coast and Geodetic Survey, who came from Washington DC to inspect the damage), and

Professor J. C. Branner (Stanford University). The photo was taken on May 17, 1906, 29 days after the earthquake of April 18, 1906.

Although we presently don't know the details, organizing this investigation must have required a lot of logistics. We can only guess that Lawson, Reed and Branner expressed interest in doing an investigation of the fault in the vicinity of the San Andreas reservoir; that they contacted the Spring Valley Water Company for help in getting access; that "the boss" Schussler, amidst all his post-earthquake restoration efforts, took the time, effort and cost to accommodate these folks by directing Mr. Perry to provide access and support the effort.

On May 17, 1906, this field trip was a day-long affair. The team began the day near the Crystal Springs Reservoir, and headed north. They stopped at a variety of locations along the way, including many of Sites 1 through 21 that are documented in this report. They brought cameras on tripods. They brought lunch for themselves and the horses. They traveled over 12 miles by horse and wagon.

What was the outcome of this one-day investigation?

- Schussler took it upon himself to publish a report (Schussler, 1906). It is John Eidinger's opinion that this report remains the world's greatest post-earthquake investigation of a water system, possibly ever.

- Lawson wrote and edited a massive report on the 1906 earthquake (Lawson 1908). It is Tim Hall's opinion that this report was (for its time) the world's greatest post-earthquake investigation. The elastic rebound theory of faulting was presented in this report.

- While Schussler published the 1906 report under his name, we have Mr. Perry to thank for many of the actual photos that are reproduced in this volume.

There were many other investigators who examined this earthquake, covering the damage to the building stock in San Francisco, the ensuing fire conflagration, and many other aspects of the earthquake.

The factual evidence documented in Schussler's and Lawson's (and other's) reports led to some major changes to the water system for San Francisco, the Bay Area, and a larger portion of the Central Valley near Fresno and Merced:

- First, SVWC had to repair its water system and get the City re-supplied with water. After the earthquake, the Pilarcitos pipeline was excavated and re-laid, re-named the Baden-Merced pipeline. Lake Honda, the first major reservoir to ever supply water to San Francisco, was reconfigured and was re-supplied with water from San Andreas reservoir, via the newly-re-laid Baden-Merced pipeline, and a new pump station. SVWC sustained on the order of $620,000 in repair costs to its water system (equivalent to about $60,000,000 in $2024).[5]

- Second, The City of San Francisco decided to build a parallel water system to fight fires. They developed the design in 1907, raised the funds by 1908, and built the Auxiliary Water Supply System (AWSS) system in 1909-1912. The cost was $5,750,000, equivalent to about $600,000,000 ($2024).

- Third, in 1930, the SVWC sold its water system to the City for $40,000,000 (about $2.5 billion in $2024).

- Fourth, the City pushed its efforts forward to build the Hetch Hetchy water system, to replace (as originally envisioned) or to augment (as actually built) the SVWC water system. The designs for this system were started in 1875, with on-and-off updates through 1901. Between 1901 and 1905, the Federal government repeatedly refused to allow the Hetch Hetchy reservoir site to be flooded. With the great earthquake and fire of 1906, the Federal government relented, and in 1907, gave provisional approval to build the system. The City approved $45,000,000 (equivalent today of $4.5 billion) in 1909, on a vote of 6-to-1 in favor. The Hetch Hetchy design was refined in 1912. Negotiations over water rights from the Tuolumne River were conducted in 1912-1913, and were agreed to between the City of San Francisco and the Turlock and Modesto Irrigation Districts (TID and MID). In 1913, Congress passed the Raker Act, which forever granted to San Francisco the rights to build and operate the Hetch Hetchy system, subject to meeting the agreed-upon water rights of TID and MID. Construction began in 1916, with the dam forming Hetch Hetchy reservoir in Yosemite National Park completed in 1923. First water delivery of this mountain water to the Crystal Springs reservoir occurred in 1934. The cost to build the initial Hetch Hetchy system (including tunnels capable of gravity flow at 400 MGD, and pipes able to flow at 120 MGD) was $105 million or about $8 billion in $2024. The present day system has subsequently been upgraded as water demands have increased, and can now deliver peak flows of about 330 MGD by gravity. With future additional pipes, flows can be further upgraded to deliver the full water rights of 400 MGD by gravity; or over 500 MGD with pumping.

- Fifth, the Hetch Hetchy Valley inside Yosemite National Park was flooded and forever changed. Naturalist and first Sierra Club President John Muir was horrified by this prospect and he fought against the development of Hetch Hetchy as a water supply. Muir protested that the cycling of the reservoir with the flood

[5] Throughout this report, we discuss costs. Dollars in $2023 are a lot different than dollars in $1906. Inflation, measured by the Consumer Price Index, shows that $1 (1906) is about $37 ($2023). The cost to install one mile of 6-to-12 inch pipe in 1906 was about $17,000; in 2023, this cost has increased to about $2,500,000 to $3,000,000; more than 100 times as expensive. In this report, we use a multiplier of 100 to "inflate" 1906-era costs for water infrastructure to "about" equivalent 2023-era costs for similar infrastructure.

> of water in the spring, and then the draining of the reservoir in the fall, would result in a valley, by late fall, that would be strewn with debris and destruction. Muir died in 1913, and never saw what was actually built. But, in 1912 Mr. John Freeman, the last great engineer to design the Hetch Hetchy water system, may have listened… for what was finally built now shows a beautiful alpine lake that on a windless day, mirrors the over one thousand-foot-tall granite cliffs surrounding the valley and magnifies the beauty of the place. In some ways, the Hetch Hetchy valley's remoteness and type of beauty that mountain men go to see, was saved by the development of the water system. Today, unlike nearby Yosemite Valley, there are no hotels, gas stations, convenience stores, roads or millions of annual visitors in the Hetch Hetchy valley.
>
> No, humanity should never go back to the age when reliable water supply for farming and domestic needs was scarce. It is the duty of today's managers of the Hetch Hetchy water system to maintain the beauty of the valley while providing water for the benefit and prosperity of the millions of people in the Greater San Francisco Bay Area and the Central Valley.

We look back today (2024) at the Earthquake Investigation Team in their horse-drawn wagons of May 17, 1906. Did they know that their investigation was going to result in tens of billions ($2024) being spent on water systems? Did they know that they would change humanity's understanding of earthquakes forever? Well, possibly the unknown and unheralded graduate student in the back of the wagon might have imagined this….

It takes a great deal of time, effort and (usually some modest) cost to investigate an earthquake. Who paid Lawson, Reed and Branner (and their graduate students) and who fed these horses? These costs are "small potatoes", and men and women of vision know that. On the face of it, the cost to pay the wranglers and to feed the horses was possibly $10 for that day in 1906. Without this seeming pittance, the horses would not work. But far more important, it was Schussler who agreed to let the Professors and other researchers do this investigation. We cannot be sure today, but the evidence suggests that Schussler "pulled no punches" and was of the mindset: what we find, we will publish, and we will let the world know about our successes and our failures.

So, in this report, Hall and I collect in one volume much of the information as we can about the impact on the water system from the 1906 earthquake. We provide our observations and our opinions. We pull no punches. Everyone mentioned in this report, we think did the same: they did their best to meet the needs of their day. But, as time marches on, and we learn new ideas, we learn that somethings work and somethings are do not work.

If the reader sees something in this report that appears to criticize, the reader is told that we mean no disrespect. When we see failures in the past, we should learn from them, and make progress for the future. If the reader is searching for failures, then this report should suffice, for there were mistakes made leading up to the earthquake, hundreds of failures in the 1906 earthquake, a great fire caused by the loss of water supply, the subsequent construction of a parallel water system that again failed in 1989 earthquake, the construction of the great Hetch Hetchy water supply system, and the demise of the SVWC company in 1930. All these things we will discuss. We hope that this will help future generations to make informed decisions about how to design, construct and maintain water systems that are earthquake resilient.

And, lest the reader think that the authors know everything… we don't. There are undoubtedly errors and misinterpretations in this book. Perhaps a hundred years from now, these will be obvious. But, this is what we understand today, and we hope this report provides some enlightenment.

Unlike our past earthquake investigations, the authors cannot see for ourselves the direct evidence, or interview the various lifeline utility operators to find out what happened in 1906. Instead, we have written this report as a way to document the history, relying on the documentation created by the historical utilities and investigators. To do this, we have reflected upon our experience working with present day utility owners (including the San Francisco Public Utilities Commission, Pacific Gas and Electric, East Bay Municipal Utility District, and more than 30 other utility operators in the greater San Francisco Bay Area); we have reviewed the historical record from 1849 through 1930; and we have applied modern (21st century) seismic analysis techniques to try to interpret what happened, and why it happened.

Other modern-day researchers have written about various aspects of the 1906 earthquake, This book is not based on their work. Instead, the authors have independently assessed what happened and why, and we have tried to avoid being influenced by their findings. Even so, much of the source data used by other researchers and used in this book are the same, including the reports by Schussler (1906, 1909), Lawson (1908), NFBU (1905), Reed (1906), USGS (1907), Derleth (1907), ASCE (1907).

In reviewing all these reports dating back to 1909 or earlier, it dawned on us that pretty much all these early 20th century researchers came to the following somewhat simplified conclusion: water pipes cannot be reliably designed across earthquake faults or through liquefaction zones, and remain operational immediately after earthquakes. Well, that can't be right! In this book, we examine the evidence as to what happened to the Spring Valley Water Company's water system (built from 1862 to 1905) that served San Francisco during the 1906 earthquake, and the subsequent construction of the piped auxiliary salt water system for San Francisco (1907 to 1913) and then the Hetch Hetchy Aqueduct supply system (1913 to 1930). All three water systems were designed and constructed before modern techniques were developed to allow engineers to quantify the level of ground motions in earthquakes, or to install pipes through fault crossing zones and liquefaction zones that can reliably sustain permanent ground deformations (PGDs). Today (2024), it is not uncommon to design and construct pipes that cross faults and go through liquefaction zones; and the evidence from recent earthquakes shows that these pipes have performed as intended. Since 1990, $ billions have been spent to seismically upgrade various portions of these three water systems; as of early 2024, more work yet remains to be done.

Our Questions

In the two years of research it took us to write this report, we came up with a number of questions:

- Question 1. Why did Mr. Schussler zig-zag the Pilarcitos pipes 5 times over the San Andreas fault? Our research shows that the 1906-era water system was generally not designed for earthquakes. The water system, at the time of the 1906 earthquake, had been constructed starting in about 1860, with continual expansion through 1906. There is no evidence that Mr. Schussler, nor for that matter, any other civil engineer of the time, knew of the existence of the San Andreas fault trace that zig-zagged beneath the Pilarcitos pipe alignment when it was built in 1868. Derleth (1907) reported that Schussler was aware of the 1868 earthquake on the Hayward fault, and factored that into his decision to make the batter of the inner (wet) face one in four for the Lower Crystal Springs dam; this dam was practically unaffected by the 1906 earthquake.

- Question 2. Why did all four of the water transmission pipes that delivered water to San Francisco, fail at one or more locations? Our research shows that Mr. Schussler did design these pipes for water pressure, for water thrust loads, for external soil loading, for thermal expansion, and for corrosion. But Mr. Schussler knew nothing about PGA, PGV or PGDs[6], and the designs did not consider these loads.

    - Schussler designed the pipes with a factor of safety of at least 2 against internal pressure. This is the same factor of safety used in modern water pipeline design. All pipes were dipped in asphaltem (a tar-like substance), to coat it inside and outside to limit the effects of corrosion. A large number of standpipes were installed along the pipe alignments to limit the maximum possible hydrostatic water pressures, so as to keep the pipe wall as thin (and as economical) as practical. A double line of rivets were used to create longitudinal seam joints; and a single line to form girth joints. In the southern portion of the Pilarcitos pipeline, this resulted in a low pressure (under 70 psi internal pressure) very thin wall pipe, with D/t ratio on the order of 288. In 1904, the pipeline had already failed due to corrosion-related effects. Today (2024), we know that this 1868-vintage design is entirely unsatisfactory for placing steel pipes across active faults: modern design would require D/t ratios of 90 or lower (meaning wall thickness had to be at least 3 times thicker) and girth joints as strong as the pipe itself, and a corrosion protection system that should last at least 40 years, and preferably 100 or more years.

[6] PGA = Peak Ground Acceleration. PGV = Peak Ground Velocity. PGD = Permanent Ground Deformation. These are the modern way to quantify earthquake ground motions. Chapter 3 describes these seismic hazards in more detail.

- Question 3. Did Schussler try to work around the weaknesses in the transmission and distribution pipes? The evidence shows that Mr. Schussler was keenly aware that the four transmission pipes each had weaknesses. In the 1890s, he proposed construction of two major facilities in San Francisco: The Industrial Reservoir, and the Market Street Reservoir; and by 1900, SVWC was being paid by the City to build larger diameter pipes for fire flows through a monthly "hydrant" fee. But, the City undermined all these efforts:

    - The Industrial Reservoir. This reservoir was to be located in San Francisco (site "9" in Figure 2-27). SVWC bought the property. The plan was to construct a large reservoir (400 to 500 MG), to be filled with water via either the Pilarcitos pipeline or the San Andreas pipeline. This reservoir would store enough water to supply all of San Francisco for 2 to 3 weeks (assuming water demand of about 30 to 35 MGD), should there be disruptions in the supply system. The City, however, refused to allow SVWC to build that reservoir.

    - The Market Street Reservoir. This reservoir was to be built on Market Street. The reservoir would hold 16 to 20 MG (site "8" in Figure 2-27). From this reservoir, a large pipeline would be laid down Market Street, studded with hydrants, and be able to provide very high flows for fire-fighting purposes. The idea was to preclude fires from the South of Market Street area from encroaching upon the high value business district on and north of Market Street. The City, however, refused to allow SVWC to build that reservoir; instead the Board of Supervisors re-zoned the site for commercial purposes, in part to allow the continued urban growth of San Francisco, which necessarily would result in increased tax assessments to fill the City coffers.

    - SVWC proposed to build parallel 10" to 24" pipes along city streets to provide high fire flows to hydrants. In the late 1890s, SVWC and the City agreed to do this, with the proviso that the City would pay a monthly fee for hydrants; this money was to be spent on the new large diameter pipes. From 1895 to 1900, some of these extra parallel large diameter pipes were built. But then came the election of Mayor Phelan in 1900 and a new Board of Supervisors; they advocated for putting SVWC out of business. Under the direction of the Board of Supervisors, fire hydrant fee payments to SVWC were reduced by 80%. In response, construction of these parallel large diameter pipes and hydrants was severely curtailed between 1900 and 1905.

    - These financial and political decisions, seen by the authors in hindsight as armchair quarterbacks, were short sighted, and significantly contributed to the subsequent fire conflagration triggered by the 1906 earthquake that destroyed 80% of San Francisco.

- Question 4. Why did the water distribution system fail in San Francisco at nearly 300 locations, resulting in loss of water supply to fight fires? Nearly all the water pipes were made of heavy cast iron pipes, then considered the best pipe product in the world. Our research shows that the bulk of the failures (70% or more) occurred where the pipes traversed major liquefaction zones, and thus were subject to PGDs. It is now well established that cast iron pipes cannot sustain PGDs. Prior to the 1906 earthquakes, both the water company (Spring Valley Water Company, SVWC) and the City (who built the sewers) were well aware of the problem of laying pipes through marshy areas and filled land along the San Francisco Bay. As mentioned above, the evidence shows that by the early 1890s, Mr. Schussler wanted to build a new Market Street reservoir and pipeline system studded with hydrants, that would avoid the liquefaction zones, and thus provide vast quantities of water to fight any fire and prevent fires in the South of Market area to spread into the high value central business district. But, in 1894, the City refused to allow SVWC to build that reservoir and pipeline system.

- Question 5. Why did 80% of the City burn after the 1906 earthquake? This is a complex question, but the bulk of the answer is that the main water pipes in the burn area were broken and could not be re-supplied from the transmission system. Still, there were, at the time of the earthquake, dozens of cisterns (underground water tanks) all over the area that burned. These cisterns proved ineffective in stopping the spread of the fires.

- Question 6. What were the two major outcomes of the 1906 conflagration with respect to the water system?

  - First, a parallel Auxiliary Water Supply System (AWSS) was built, owned by the San Francisco Fire Department, able to provide at hydrants very high flows of either sweet water (by gravity flow from reservoirs in the hills) or salt water (by pumped flow from the Bay). This cost $5.75 million, with construction starting in 1908 and the system working by 1912. This system was eventually put to the test in the 1989 Loma Prieta earthquake: but because a few of its pipes broke, and no water was available via the piped system to suppress the large fire in the Marina District that ignited. Fortunately, there was zero wind at the time of the 1989 Loma Prieta earthquake, else a general conflagration may have ensued.

  - Second, in 1907, the City voted (6 to 1) to fund a bond to build the Hetch Hetchy system. This bond was for $45,000,000, to build reservoirs in Yosemite National Park, and an aqueduct to bring that water at a rate of 60 MGD to San Francisco, and to build a brand new city water distribution system. Between 1908 and 1912, a series of studies were done to refine the initial design from a pumped system at 60 MGD to a gravity system capable of 400 MGD, and to negotiate the water rights with two irrigation districts who already were using the water from this same watershed in

> Yosemite National Park. After a series of initial setbacks (including President Teddy Roosevelt vetoing the use of the Hetch Hetchy Valley in Yosemite National Park), the U.S. Congress approved the Raker Act in 1913 and President Woodrow Wilson signed it into law. "I have signed this bill because it seemed to serve the pressing public needs of the region better than they could be served in any other way, and yet did not impair the usefulness of materially detract from the beauty of the public domain," Wilson said. Construction began in earnest in 1916, and first waters from Hetch Hetchy were delivered to the Crystal Springs reservoir in 1934. By that time, the initial cost had ballooned to $105 million, not including an additional $40 million spent in 1930 to purchase the SVWC transmission and distribution systems serving San Francisco.

Underlying these questions was a pervasive political problem. The SVWC and the City were at odds with each other. In the late 1850s and early 1860s, the City was a small but growing community, and could not afford, along with all its other obligations, to build a water system. So, the City granted several franchises to private companies to build a water system. A few small and poorly-capitalized companies initially took these franchises, but most failed. By 1862, SVWC emerged as the winner, taking over the other franchises, and operated the water system as a monopoly. To pay for this water system, the City would set water rates that amounted to about a 5% return on total capital invested in the water system. By 1867, the City politicians regretted this situation, and began formal efforts to design and build a separate and parallel water system, with the intent of putting SVWC out of business. Over the following 63 years, the City and SVWC were at nearly constant odds with each other, with the City threatening condemnation of the water system, refusing payment for water supplied, and regularly suing SVWC in California State courts. SVWC responded in two fashions: by responsibly planning out new sources of supply and expanding the water system to meet the current and future needs of the City through 1950 (targeting a supply of 100 MGD by 1950); and also by countersuing the City in Federal courts. Several times over the decades, the City tried to purchase SVWC, but always by offering less money than SVWC offered to sell. For decades, no agreement was reached (a few times, the offer / sell prices were within 10% of each other, yet the parties could not close the deal). It took until 1930 for the City to eventually buy SVWC, at a cost of $40,000,000.

It would be fair to say that there was a lot of mis-trust between the City and SVWC. In considering the history of this conflict, the winners of this mistrust were the lawyers on both sides who argued in the Courts; the Newspapers that reported and sensationalized the issues and thus sold more copy; and the Authors of this report. Why have the Authors benefited? With all the lawsuits, and various documents to support each side's point of view, we have a rather thorough public historical record of the issues. But lest the reader think this is all frivolous, the Authors point out that the real losers were the citizens and insurers of San Francisco; and the magnitude of their loss dwarfs all. Everyone was horrified by the magnitude of the destruction of the 1906 earthquake and ensuing fire.

The Present Day and Future Hetch Hetchy, AWSS and City Distribution Systems

The Hetch Hetchy system brings potable water from Yosemite National Park and adjacent Stanislaus National Forest to San Francisco. This system is owned by the Citizens of San Francisco. From 1867 to 1930, politicians and those with vested interests used this system as a cudgel to try to put SVWC out of business. Its early design called for deliveries of 60 MGD to San Francisco, including the Hetch Hetchy, Cherry Lake and Lake Eleanor reservoirs, tunnels, canals and pipelines to bring water to San Francisco and entirely bypassing the SVWC water system, and an entirely new distribution system (some 400 miles of pipe) to deliver water to end users. By 1912 the design had evolved, calling for ultimate delivery of up to 400 MGD to San Francisco and surrounding communities, with initial construction able to deliver 200 to 240 MGD (50 MGD to San Francisco, 50 MGD to fill Crystal Springs Reservoir, and the remainder MGD to be sold to other cities (like Oakland and San Jose). By 1934, the initial Hetch Hetchy system was built and began delivery of water from Yosemite National Park into Crystal Springs Reservoir, costing $105 million. In the nearly 90 years since 1934, the initial Hetch Hetchy system has been upgraded by adding more pipelines, adding more reservoirs (San Antonio, Calaveras, Cherry Lake, Lake Eleanor), adding two water treatment plants, and incorporating the original SVWC Pilarcitos, San Andreas and Crystal Springs reservoirs. Today (2024), the modern Hetch Hetchy system can deliver somewhat over 300 MGD to the Greater San Francisco Bay area, delivering potable water to San Francisco (about 86 MGD) and the remaining water sold wholesale to about 29 other water companies around the San Francisco Bay. Over the past two decades, about $4.6 billion has been invested to increase the reliability of the Hetch Hetchy system, including seismic upgrades of some of the original pre-1906 SVWC pipes. Today (2024), the Hetch Hetchy system delivers about two-fifths of the total water demand for over 7.5 million people in the nine counties and 101 cities of the greater San Francisco Bay Area.

In 2019, the Civil Grand Jury of San Francisco issued a report that recognizes the seismic weaknesses of the AWSS, and potential for future fires. The report calls upon the City to seismically upgrade the old AWSS system. In 1913, the AWSS had some 77 miles of pipe, and through various expansions in 1916 and later, by 2009, had some 135 miles of pipe, and runs under about 10% of the City's streets (a higher ratio in the central business district). The SFPUC, the agency with current management of the AWSS, is considering a $6 billion seismic upgrade program for the AWSS. The AWSS is not connected to the City's portable water distribution system.

The City Distribution system presently has about 1,200 miles of water pipe. These pipes run under essentially every city street, and have fire hydrants placed about every 500 feet or so. Essentially ***none*** of this pipe has been designed to resist earthquakes.

Today, San Francisco is the only city in the United States with two parallel buried pipe water systems for fighting fires. The reason to have two systems is historic and stems, in part, from the animosity between the City and SVWC. Does it make economic sense to seismically upgrade the AWSS for $6 billion? A more economic and ultimately a more robust approach would be to replace about 50 miles of the weakest pipes in the City distribution system with new seismic resistant pipes, costing about $180,000,000 over the next decade; and then, slowly over the following 90 years or so, as part of the normal replacement cycle, replace all the old pipe with new seismic resistant pipe. In this way, in ten years' time, the City will be nearly seismic-proof with regards to delivering water for fighting fires after earthquakes; and in a century, the job will be complete.

In the meantime, the clock is ticking. Large earthquakes on the San Andreas fault can occur nearly any time, but best estimates suggest a return period between very large events on the order of 150 to 200 years[7]. The last large San Andreas event along the Peninsula was in 1906. If the City adopts the Author's recommendations, the bulk of the seismic risk from fire conflagrations due a loss of water supply can be eliminated by 2035 or so.

It is now 118 years since the last big one in 1906.

The clock is ticking.

A Quick Review of Selected Bay Area Lifelines, 2024 Status

Today, in 2024, the City of San Francisco owns and operates two parallel water systems: the potable water system and the non-potable AWSS:

- The potable system includes some 260 miles of transmission pipelines bringing water from the Sierra snowpack and local Bay Area storage reservoirs, to the City as well as some 29 other municipal water agencies encircling the San Francisco Bay Area; as well as some 1,200 miles of pipelines and fire hydrants that deliver drinking water to every customer in San Francisco, as well as fire hydrants for firefighting.

- The AWSS system includes some 135 miles of pipelines in San Francisco that can deliver water from three sweet-water (but non-potable) reservoirs in San Francisco, or two pump stations that can inject salt water into these pipes in an emergency. The AWSS pipelines are located under about a tenth of all city streets. The AWSS has its own fire hydrants.

- From 2000 to 2020, the City of San Francisco has made considerable progress in seismic upgrade of the potable water transmission system, spending about $4.6 billion in that effort. While not "seismic-proof", the modern transmission system (as of 2024) is a lot more reliable than it was in 1999. After spending the $4.6 billion (or so), the system has been upgraded to meet a goal of delivering winter day potable water flows to 90% (or more) of its wholesale customers, with 95%

[7] For the San Andreas fault, based on paleoseismic investigations, Hall estimates long term slip at the Filoli estate is Woodside at ~17 mm / year. If the expected average large slip in a future earthquake is ~ 10 feet (or ~ 3,000 mm), then the average recurrence interval is ~ 3,000 / 17 = 177 years (or so) (say 150 to 200 years).

(or more) reliability, within 24 hours after major earthquakes on the San Andreas, Hayward or Calaveras faults.

- This 24-hour proviso is critical. It allows that there is some possibility that the modern transmission system will not deliver any water in the first 24 hours after a major earthquake. From a fire-fighting perspective, ready access to usable quantities of water for fire flows is needed ideally within a few minutes of fire ignition. So, the reader should understand that this $4.6 billion investment has not eliminated the potential for another Great Fire.

- This leaves the City of San Francisco, as well as the 29 other water agencies that draw water from the SFPUC's water transmission system, to rely on their own water distribution systems to provide the reliable water flows to be used to control fire ignitions that are likely to occur within the first minutes to day (or so) after major earthquakes. Today (2024) we now know how to design and construct water distribution systems that will suffer nearly zero damage after major earthquakes. The problem is that the bulk of both water systems in San Francisco (the potable distribution and the AWSS systems), as well as the water distribution systems of the 29 member agencies, were all built with non-seismic components. Most of the 29 member agencies, as well as San Francisco, have taken steps from 1980 to 2024 to seismically harden water tanks and pump stations: a good first start. But, around the Bay Area, there remain more than 8,000 miles of vintage buried distribution water pipes (vintage cast iron, asbestos cement, plastic, ductile iron, steel, all without seismic design provisions) that remain prone to fail in future large earthquakes. Today, there are new materials and styles of construction that allow buried water pipes to survive nearly any level of ground shaking or ground deformation without damage. A wholesale effort to replace all the seismically-weak vintage water pipes with new seismic-resistant water pipes would easily cost, on average, $2 to $3 million per mile of pipe. What does this mean? It means that to complete the effort to seismically harden all the water systems around the Bay Area will cost about $2 to $3 million / mile times 8,000 miles = $16 to $24 billion.

- Some progress is being made. The largest water system utility in the San Francisco Bay area (by miles of water pipe) is the East Bay Municipal Utilities District (EBMUD), serving 22 cities in the East Bay, and having about 4,000 miles of distribution water pipes. Up to about 2010, EBMUD was replacing about 5 miles of water pipe per year, meaning an 800 year replacement cycle; clearly, non-sustainable in the long term, as many water pipes tend to wear out (leak excessively) after 50 to 200 years of service. Enlightened managers and engineers at EBMUD have convinced its Board of Directors (and ultimately its customers) to increase water rates to allow up to 40 miles of pipe to be replaced per year.

- Some other water agencies around the Bay Area are also experimenting with installing new water pipes using seismic resistant design, such as for example, the City of Palo Alto, where some new water pipes are fusion bonded HDPE.

- The City of San Francisco presently has two parallel water systems: the potable water system (some 1,200 miles of pipe, including some vintage SVWC-era pipe) and the AWSS "salt water" system (some 135 miles of pipe, including a lot of 1909-1916 vintage cast iron pipe). The SFPUC is presently contemplating a $6 billion seismic upgraded program for the AWSS to be completed by the year 2046; but this is not yet funded. The authors recommend an early replacement of some 50 miles of the potable water system, costing about $180,000,000, could quickly (say over 5 years if 10 miles of pipe were replaced per year) improve the reliability for fire flows in the most seismically-weak areas in San Francisco. Over a 50-year to 100-year time cycle, all of the distribution potable water pipe can be replaced with new seismic-resistant pipe. A seismic-resilient potable water system should suffice, and once enough pipe in that system is upgraded, the parallel non-potable AWSS water system can be retired, and thus saving the citizens from paying twice.

There was plenty of destruction to other lifelines that existed in 1906, including electric power and gas:

- Electric power. Today, Pacific Gas and Electric is the primary electric system operator for San Francisco. In 1906, there were a variety of coal-powered local power plants that produced electricity, and 4 competing electric power providers. Today, there are no more coal (or any other thermal) power plants in the County of San Francisco, and the bulk of all power for San Francisco is imported via long transmission lines. Today, all new high voltage equipment is installed to modern seismic standards; and in over 20+ recent earthquakes, essentially no such equipment has failed. In the past two decades, hundreds of millions of dollars have been spent to installed new seismic-resistant high voltage transmission service San Francisco. But, there still remain a variety of seismic weaknesses, notably for buried transmission lines that traverse liquefaction zones, and a plethora of weaknesses in the low voltage distribution grid.

- Natural gas. Today, Pacific Gas and Electric is the only natural gas (methane) system provider for San Francisco. In 1906, there was over 400 miles of cast iron pipe that distributed manufactured gas (then made from coal) to customers for heating, cooking and lighting, as well as street lighting. In 1906, these gas-system cast iron pipes broke at many locations. Two gas plants suffered heavy damage due to ground shaking or PGDs. Today, PG&E has replaced 100% of cast iron pipes with either butt welded steel transmission or medium density polyethylene distribution pipes; both kinds are highly seismic resistant. Today, all natural gas to San Francisco is imported from distant locations; there are no gas wells or gas storage facilities remaining in the City of San Francisco.

One cannot have a full discussion about the 1906 earthquake without at least mentioning the failures of the general building stock. In this book, only limited reference to the general building stock is provided: many other researchers have examined the poor performance of unreinforced masonry (brick) buildings, so-so-performance of wooden buildings in liquefaction zones, etc. One section of this report examines what happened on Valencia Street: a location where liquefaction resulted in building collapse with major loss of life, and water pipeline failures that contributed to the ensuing fire and conflagration.

How to Design Water Pipes for Earthquakes?

What is the basis for our modern-day approach to designing water pipes for earthquakes? In this report, we re-examine the evidence of the extremely poor performance of the water pipes in the 1906 earthquake. All of the major water pipes that crossed the San Andreas fault failed. There were a large number of pipe failures in areas that sustained liquefaction. And there were a significant number of pipes that failed, apparently, due to strong ground shaking.

Our present approach to design water, oil and gas pipes across active earthquake faults generally calls for the following approach:

- Establish the total PGD that the pipe must accommodate, the azimuth of the PGD (generally along the strike of the fault), and the sense of faulting (right lateral, left lateral, normal, reverse or some combination).

- Define a narrow zone for primary fault offset PGD. Design the pipe there for 85% to 100% of the total PGD, assumed to be applied as a "knife edge".

- Define a wider zone for secondary fault offset PGD. Design the pipe there for 0% to 15% of the total PGD, also assumed to be applied as a "knife edge".

- Define additional zones for sympathetic fault offset PGD. These additional zones can be nearby (within 5 km) fault features (whether active or of unknown activity) that might slip "sympathetically" with the primary offset. The amount of PGD to be applied for these sympathetic zones is taken as 10% to 20% of the total PGD. A 20% value can be assumed if the feature is within 1 km of the main fault. Almost all sympathetic fault offset occurs within 2 to 5 km of the main fault.

Forecasting all of the above parameters in future earthquakes means having to deal with uncertainty. The modern approach is to quantify these uncertainties, and then design the pipe for the worst case.

Modern codes often use probabilistic "Return Period" for designing for earthquakes, like 475, 975 or 2,475 years. ALA (2005) describes how to apply return periods for design of water pipes, factoring in the importance of the water pipe, and the redundancy of the network. Often, a "scenario" based approach might be best for evaluating existing or designing new pipes, where multiple performance goals should be met, like:

- Given a local San Andreas M 7.8 earthquake, ensure that disinfected potable water can be delivered to 95% of end-user customers within 24 hours of the earthquake.

- Given a San Andreas M 7.8 earthquake, ensure that water can be delivered to at least one fire hydrant within 1,000 feet of nearly all likely fire ignition sites, within 5 minutes of the earthquake.

If these two goals can be met, the job is mostly done. See ALA (2001) for approaches to evaluate existing water systems for earthquakes. See ALA (2005) for a thorough description of performance goals, and methods to design water pipes for earthquakes.

John M. Eidinger

July 2024

0.2 Preface by Tim Hall

Introduction

Over the last three decades, John Eidinger and I have been involved with investigating and designing water pipes where they cross several active earthquake faults in the San Francisco Bay Area, including the Calaveras, Hayward, Serra and San Andreas faults. My area of expertise includes the study of faults: finding exactly where they are located, how much they might have moved in the past, how much they are likely to move in the future, and how often we might expect these earthquakes to recur. John's area of expertise includes the evaluation and design of pipes to accommodate earthquake induced-ground movements due both to severe ground shaking and active surface fault slip, and ultimately to survive and continue functioning.

Over the course of many projects, we have jointly come to recognize that modern pipeline designs for crossing active faults and other unstable ground conditions requires both experience and some give-and-take. A modern balanced design requires that the surface fault offset hazard be quantified: where exactly is the fault located; how much is the future fault offset likely to be; what is the fault's slip geometry; will the fault offset occur over a narrow or wide zone; and what is the likely return period between future earthquakes on the fault. Also of importance in the design of fault crossings is the necessity for well documented soil properties: how stiff/soft are the native soils, what is their susceptibility to settlement and/or liquefaction, are they suitable for pipe bedding and backfill, and how corrosive are they likely to be? All these factors must be accommodated in developing the pipeline design, selecting the pipe material, wall thickness and segment connections. Underlying this entire process is, of course, to do all this earthquake hazard mitigation in a cost-effective manner.

In developing the information for this report, I have assessed the San Andreas fault hazards over a 12-mile-long reach of the fault on the San Francisco Peninsula near the San Andreas and Crystal Springs reservoirs. In the 1906 earthquake, the Pilarcitos pipeline was destroyed where it zigzagged over the fault at five locations; the Locks Creek pipeline failed at a sixth fault crossing. I have reviewed the available evidence from 1906, and coupled with subsequent paleoseismic investigations, and I have summarized in this report the earthquake effects and the amount of fault offset at 21 different locations where there were various Spring Valley Water Company water facilities.

Geologic Research Strategy and Data Resources

This report centers on the early development of San Francisco's municipal water supply system and how critical pipeline failures caused by the San Andreas fault enabled the conflagration caused by 1906 earthquake to destroy a major part of the city. The geologic component of the story addresses three key elements: water storage dams located in San Mateo County, the four conduits that delivered potable water into the city beginning in the 1860s, and the distribution pipes in the city; Hermann Schussler, Chief Engineer for the Spring Valley Water Company (SVWC) who designed and constructed most of the city's initial water storage, transmission and distribution systems; and the characteristics of the seismically active San Andreas fault, a major Earth structure, which stretches almost the entire length of California from Mexico to Oregon. This is the story of the effects the great earthquake of 1906 had on certain vital components of San Francisco’s water storage, transmission and distribution systems and how the SVWC and the City responded to the disaster. The geologic study herein focuses on the multiple earthquake-induced failures of the southern Pilarcitos pipeline and what these failures have taught us about both the seismic performance of riveted wrought iron pipe and the scale of the hazardous fault slip and ground shaking characteristics of the then recently discovered San Andreas fault.

The great San Francisco earthquake of April 18, 1906, provided a brutal test for the then privately owned SVWC system that was designed to provide a secure and stable supply of potable water to this burgeoning metropolis, which happens to be surrounded on three sides by salt water. Beginning in the mid-1860s, the Company’s Chief Engineer, Hermann Schussler, directed the construction of a system of dams, pipelines, tunnels, and flumes on the San Francisco Peninsula to collect, store and ultimately deliver local Peninsula water for distribution to the city of San Francisco. Local watersheds like Pilarcitos Creek were dammed and water collected and transported downslope to a topographically well-suited valley for the storage of large quantities of water that was located not far from the southern boundary of San Francisco. As the City grew, SVWC expanded into Alameda County and by the time of the 1906 earthquake, about a third of the City's water supply was coming from Alameda County.

It has been both fascinating and a challenge to assess the interaction between the active surface displacements and the strong ground shaking along the San Andreas fault that severely impacted the SVWC supply system's ability to provide the water necessary for San Francisco in 1906. We, the authors, are like armchair quarterbacks, who have been deeply involved in the endeavor to promote development of well-engineered facilities that will secure and protect both the City’s water transmission and distribution systems. We were not available in 1906 to make the original post-earthquake observations and measurements and so have had to depended primarily on the data and observations that others have gathered to explain the causes for many of the hundreds of water system failures that were triggered by the great earthquake. We have carefully assessed sketches, maps, field notes and photographs from professional engineers and scientists that were made available soon after the earthquake. Of particular interest, and included herein, are historical photographs, many heretofore unpublished, that record the impact of 1906 surface faulting and ground shaking on SVWC's water transmission system.

There are several historical resources we have used to compile the impact the 1906 earthquake had on the SVWC's water system for San Francisco and to assess the reasons for the substantial number of locations where the system failed. One of our principal goals has been to understand how the 1906 event impacted the Pilarcitos pipeline, especially its southern reach, one of SVWC's earliest water transmission conduits (initially built as a flume in 1862, then upgraded as a pipe in 1868) that brought water from the northern San Francisco Peninsula to the City itself. First in line resource document is the 78-page folio that the SVWC's Chief Engineer, Hermann Schussler, published on July 23, 1906, just 96 days after the disastrous quake. This was a remarkable accomplishment. This folio (Schussler, 1906) (1) expertly documents the breakdown of the system from both surface faulting and from structural failures caused by severe ground shaking, and (2) describes the timely efforts that were made by the water company to restore the system. Schussler and his staff took many of the photographs we have subsequently used to understand both the appearance and behavior of the San Andreas fault, and witness both the performance and subsequent restoration of the water company's transmission and distribution systems in response to the earthquake. In 1930, the SVWC water system was purchased by the city of San Francisco and is now administered by the San Francisco Public Utilities Commission (SFPUC). Their assistance and files have been an invaluable resource for our research.

A second valuable resource published in 1907 is the book entitled *The California Earthquake of 1906,* which consists of eight articles edited by David Starr Jordan, President of Stanford University. Jordan provides an insightful overview of the earthquake, which is accompanied by geological assessments of the San Andreas fault (then referred to as the Portola-Tomales fault by Stanford Geology Professor John Casper Branner and geology student Stephen Taber). Also included are reports by geologists Harold W. Fairbanks of Berkeley, Grove Karl Gilbert, one of the most prominent geologists of the USGS (who referred to the causative fault as the San Andreas), and Berkeley Structural Engineering Professor Charles Derleth, Jr. We found the article by Professor Derleth (1907) particularly valuable for he spent considerable effort documenting, measuring and evaluating the impact of the 1906 earthquake on SVWC's facilities, especially the Pilarcitos pipeline and their storage reservoirs on the San Francisco Peninsula.

Our principal focus in this report has been to understand how the 1906 event impacted the Pilarcitos conduit, the first of SVWC's water transmission systems to bring water from the northern San Francisco Peninsula to the City itself. By "conduit", it is meant the combination of tunnels, flumes, trestles and pipeline. All damage occurred on pipeline segments of the conduit. The pipeline broke in 31 places in 1906. After assessing the damage to many structural facilities up and down the San Andreas fault along the 1906 trace in northern California, which included a focused evaluation of the SVWC system's performance for San Francisco's potable water supply, Berkeley professor Charles Derleth (1907) concluded: *“The Pilarcitos conduit must be abandoned.”* We found Derleth’s observations and measurements he made where the Pilarcitos pipeline crossed the San Andreas fault five times to be particularly instructive. Schussler concurred with Derleth’s assessment: a 7-mile long reach of the pipe was quickly excavated and by 1907, was reinstalled at a different location. But the question remains as to why did Schussler install the Pilarcitos pipe along the fault and manage to cross it five times? Did he not know about the existence of the fault and its destructive capabilities? In the pages that follow, we will visit each of these crossings and see what can be learned of engineering significance about both the fault and the performance of the pipe.

The third and most valuable resource for study of the San Andreas fault and the 1906 earthquake is the massive report compiled and edited by Berkeley Geology Professor, Andrew Cowper Lawson, for the State Earthquake Investigation Commission that was published by the Carnegie Institution of Washington in 1908. For many years this was the most comprehensive study of an earthquake ever published. It ended the debate whether earthquakes cause faults or faults cause earthquakes via putting forth the "elastic rebound theory" wherein tectonic forces cause the rocks to bend and store increasing amounts of elastic strain energy until the rocks break and "snap" into new positions along a fault releasing the stored energy as seismic waves. Lawson was the first geologist to identify the causative fault before the 1906 event on the San Francisco Peninsula and name it (Lawson, 1895) for *San Andres Lake*, a name chosen by Gaspar de Portola in 1769 for a sag pond in this prominent linear fault valley on the San Francisco Peninsula. At the time of the earthquake, the fault was also known by other names, but the Lawson (1908) report traced it far into northern and southern California, firmly cementing the name San Andreas fault into our culture.

In more recent times, detailed research and geologic mapping by U.S. Geological Survey geologist, Earl Pampeyan (1975, 1981 and 1983), added to our understanding of the Peninsula Segment of the Northern San Andreas fault and the impact of the 1906 earthquake on San Francisco's water supply system. In addition, published research papers by Hall (1984) and Hall, Wright and Clahan (1999) have enhanced the authors' understanding of inevitable future activity of the Peninsula Segment of the Northern San Andreas Fault that will undoubtedly impact the future performance of San Francisco's and the region's water supply system. Hall (1984) summarizes the results of an investigation for the SFPUC to assess the likely future seismic performance of San Andreas Dam that Schussler built *across* the 1906 San Andreas fault trace. Hall, Wright and Clahan (1999) assesses buried stream channels in the fault valley south of Crystal Springs Reservoir on the Filoli Estate that have been displaced by fault slip and radiocarbon dated them to establish a time-averaged rate of fault slip, which has enabled the potential timing of near future 1906-type earthquakes to be estimated.

Additionally, we found the book *"The Top of the Peninsula"* by Marianne Babal (1990), a detailed history of Sweeny Ridge and development of the Peninsula watershed lands, to be a very useful guide. It provides a well-ordered chronology of the construction activities of the Spring Valley Water Company during the administration of its Chief Engineer, Hermann Schussler.

N. Timothy Hall

December 2023

0.3 Preface by Alex Tang

Mr. Eidinger and I have been involved with investigating and reporting on the earthquake performance of lifelines for nearly three decades. Our first joint investigation was the Great Hanshin-Awaji M 6.9 earthquake of 1995, commonly known as the Kobe earthquake. Since then, we have jointly investigated and written reports on lifeline performance of many high magnitude earthquakes, including Kocaeli Turkey 1999 M 7.4, Chi-Chi Taiwan 1999 M 7.6, Atico Peru 2001 M 8.4, Sichuan China 2008 M 8.0, Concepcion Chile 2010 M 8.8, Christchurch New Zealand 2010 and 2011 M 7.1, 6.5, 6.0, Tohoku Japan 2011 M 9.0, Lushan China 2013 M 6.5, Napa 2014 M 6.0, Kumamoto Japan 2016 M 7.0, Puebla Mexico 2017 M 7.1, and Hokkaido Japan 2018 M 6.8.

In researching and writing reports about earthquake lifeline performance, we were extremely lucky to have cooperation of the affected lifeline owners who were willing to allow us access to their facilities, resources, and sharing of perishable information. The support of lifeline owners, as well as the local lifeline earthquake engineers / researchers is key to developing a large knowledge base of lessons learned on earthquake lifeline performance. We have jointly published more than 20 books and papers that describe our field investigations.

In this book, Mr. Eidinger has endeavored to write an assessment to the performance of the water system serving San Francisco in the 1906 earthquake. Dr. Hall describes the fault offset patterns at 21 sites. Yet, they were not there in 1906 to perform a field investigation. This is very tricky, as they cannot interview the people who designed, managed and repaired the water system; or independently measure the fault offset.

I am confident that the authors have done a lot of search and research of the materials and records archived in deep cellars of libraries to establish their findings and opinions about what happened, and why, from this earthquake. The knowledge they have from modern investigations forms a foundation for their conclusions. This report is not the first one on the 1906 earthquake, but it is the first one that delves so deeply into the performance of the water system performance.

This book also provides a third eye view of this historic event. There is much to be learned about what went right, and what went wrong.

Alex K. Tang

August 2023

0.4 About the Authors

Over the past 30 years, Tim Hall and John Eidinger have collaborated on a variety of projects, on the evaluation and design of water pipes across various earthquake faults and liquefaction zones. Today, there are recently-constructed large diameter water transmission pipes that cross the San Andreas, Serra, Hayward and Calaveras faults, and both Tim and John have had a hand in the process of getting these pipes built.

Figures 0-2 and 0-3 are photos of John Eidinger and Tim Hall. These photos were taken in February 2006, while Tim and John were inside the Bay Division Pipeline No. 3 (part of the Hetch Hetchy Aqueduct) where it crosses the Hayward fault, in Fremont, California. The authors were examining the deformations in this pipe, to see how the pipe had accommodated 54 years of accumulated fault creep (1952 through 2006). Subsequently, the San Francisco Public Utilities Commission removed this pipe, and by 2014 had replaced it with a new seismically-designed pipe, capable to sustain up to 6.5 feet of knife-edge fault offset, concurrently with ground accelerations corresponding to a 975-year return period earthquake (with Peak Ground Acceleration of 1.05g). The "ring" around Tim Hall is a slip joint within the pipe, right at the Hayward fault. The rock hammer that John is holding is in fact Tim Hall's; John borrowed the hammer; Tim has this hammer to this day.

Figure 0-2. John Eidinger (Photo 2006, inside 78-inch diameter BDPL 3)

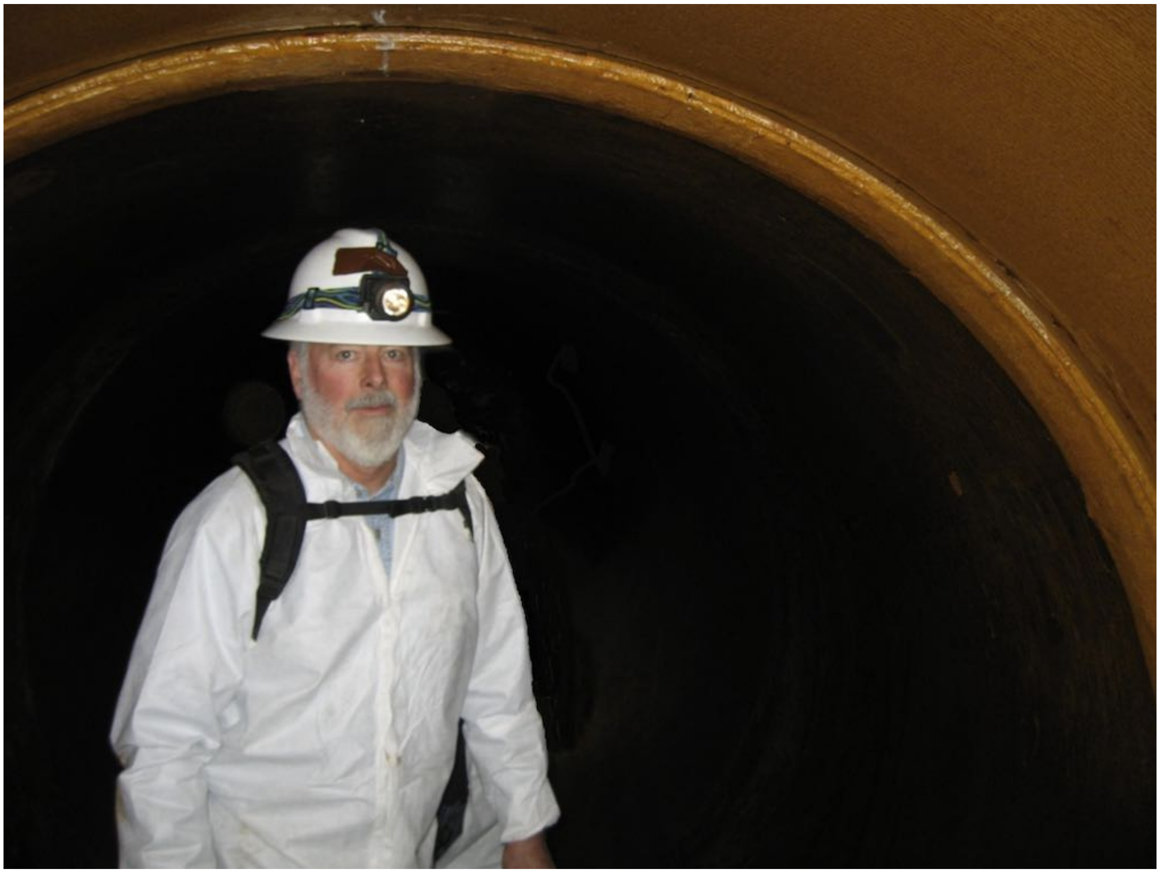


Figure 0-3. Tim Hall (Photo 2006, inside 78-inch diameter BDPL 3)

Tim Hall

Dr. Hall grew up a country boy in the Ramapo Mountains of southern New York State. He attended Hamilton College, a small upstate liberal arts institution, and graduated in 1961 with a Bachelor's degree in geology. His initial goal was to become a civil engineer, but after reading a roommate's geology text, changed his career path to the earth sciences, a very happy decision for him.

Summer geology field camp in Wyoming convinced him to pursue graduate studies in the west where tectonic processes, like volcanic eruptions and seismic activity, were ongoing and exciting. He attended U.C. Berkeley to continue his education and chose a research project to piece together the geologic history of a geologically young coastal basin that was filled with shallow marine and shoreline deposits named the Merced Formation. These deposits formed the landslide-prone sea cliffs south of San Francisco in the community of Daly City. Here he realized that many thousands of years of slip along the San Andreas fault had created the basin into which this formation was deposited. He saw the place where several feet of slip in the 1906 earthquake had occurred and where severe ground shaking had triggered large landslides in the coastal cliffs made of poorly consolidated Merced sediments. He also became very aware that homes were being built where the cliffs had failed in 1906 and built across the surface trace of this very active fault. It was obvious that the developers had not considered the life-threatening consequences for the residents of these homes from inevitable future seismic activity. He did not agree with the warning: *caveat emptor*, but decided that his was the responsibility to educate the public about active geologic processes, their hazards, and their mitigation.

After graduating from Berkeley with a Masters Degree, he joined the faculty at Foothill College in Los Altos Hills where he taught geology for more that two decades. While there he and his students designed and built educational "earthquake trails" on parklands at Point Reyes National Seashore, Palo Alto and San Juan Bautista. While at Foothill College he spent a sabbatical year mapping the faults in Santa Cruz County, which included the San Andreas fault, site of the Loma Prieta earthquake in 1989. Joining with other geologic faculty at DeAnza College, he investigated active California faults including the San Andreas, Hayward, Calaveras, White Wolf and Pleito faults with research funds provided by the U.S. Geological Survey's National Earthquake Hazards Research Program (NEHRP).

One of his favorite areas for training students in the art of field mapping was the San Andreas fault zone located along San Francisco’s San Andreas and Crystal Springs reservoirs in San Mateo County. Ironically, his familiarity with the fault in this area led to his participation in an assessment of the seismic stability of San Andreas Dam mandated by California’s Division of Dams (DSOD). In 1980 he assisted the engineers of Earth Sciences Associates of Palo Alto in performing this investigation. The results of this analysis have played a major role in this book about the stability and vulnerability San Francisco’s water supply system. It was here along the east side of San Andreas Reservoir that the Pilarcitos pipeline, a major supplier of the City’s potable water, was torn apart in 1906 in several places where it crossed the San Andreas fault.

At the time of this investigation, he had become a doctoral student at Stanford University while retaining his teaching position at Foothill College. Although his studies there took several years to complete, he researched and wrote a dissertation on the history and properties of the Pleito fault, a thrust which forms the northern boundary of the Transverse Ranges, a large crustal structure that has been squeezed up where the San Andreas fault makes a large bend to the west separating the Los Angeles area from the southern San Joaquin Valley. While at Stanford, he developed and taught a course focused on geologic hazards and served as advisor for another doctoral candidate, now Dr. Tina Niemi, a professor at the University of Missouri, Kansas City. Together, they performed extensive research for the U.S. Geological Survey on the recent number and timing of prior earthquakes on the San Andreas fault north of San Francisco in Marin County where the maximum fault slip of sixteen feet was recorded in 1906.

After earning his doctorate in 1984, he subsequently joined Earth Sciences Associates, and for several years thereafter led the field investigation of both onshore and offshore faults with the potential to adversely impact Pacific Gas and Electric Company’s Diablo Canyon Nuclear Power Plant near San Luis Obispo. When that multiple year investigation was completed, he joined Geomatrix Consultants in San Francisco and became this firm’s Principal Engineering Geologist. Here he worked for various clients on a variety of engineering projects including conventional and nuclear power plants, dams, roads and bridges, potable and waste water treatment facilities, canals and levees, tunnels, and pipelines.

It was on projects related to the design, construction, and seismic remediation of water facilities, especially pipelines, that Tim Hall of Geomatrix and John Eidinger of G&E Engineering formed a successful team. Their collaborative efforts for major California clients like Pacific Gas and Electric Company (PG&E), East Bay Municipal Utility District (EBMUD) and San Francisco Public Utilities Commission (SFPUC) yielded many successfully completed projects and satisfied clients. This book on the history of San Francisco's water supply system, its performance in the 1906 earthquake, and the steps necessary to protect this essential lifeline from inevitable future seismic events is an outgrowth of our years of successful collaboration and commitment to public safety.

May 2024

John Eidinger

Mr. Eidinger grew up in Montreal, Canada. At age 17, he left Canada and started his college education at MIT in Cambridge Massachusetts, where he earned a Bachelor of Science in Civil Engineering in 1975. He then went to U. C. Berkeley, where he was a Teaching Assistant in the Structural Engineering and Structural Mechanics program. He was supposed to "teach" classes he never took as an undergraduate at MIT, so he had to study hard to be one class ahead of the students. A year later, he became a Research Assistant for Professor James Kelly, and spent two years testing base isolation systems on the shake table at the Richmond Field Station.

Upon graduation with a Masters of Engineering degree in 1978, he joined EDS Nuclear, where he spent 12 years doing earthquake engineering for nuclear power plants. While working at EDS, John continued his education during "evening programs" and earned two more degrees from U. C. Berkeley: a Master of Science in 1982 and a Master of Business Administration in 1984.

In 1991, he founded a consulting firm, G&E Engineering Systems Inc., where he has practiced earthquake engineering for lifelines. Over the past 34 years he has worked for many water, power, gas, wastewater and transportation lifeline operators.

John has worked with Tim Hall on a variety of projects. G&E and Geomatrix teamed up to provide services for a number of clients. One project consisted of evaluating and then replacing two pipelines that crossed the Hayward fault. One task was to dig a trench across the fault. Tim showed John what had been found in the trench: a bone from a camel that roamed the area some 5,000 to 10,000 years ago. That cemented a friendship that has lasted more than three decades.

When people ask John what he does, he occasionally tells them "I chase earthquakes". After big earthquakes, John often travels to the affected area, whether in the United States, Japan, China, New Zealand, Turkey, India, Peru, Chile or other parts of the world.

John meets with utility operators to find out "what worked well" and "what broke". In this way, one learns from our collective mistakes.

Over the years, John has written or co-authored 4 books on the earthquake design of water systems, fire following earthquake, and has published more than 100 papers on seismic performance of lifelines.

The genesis for writing this book came about when John learned that the Civil Grand Jury of San Francisco had issued a finding in 1999 that the City of San Francisco should spend billions of dollars to seismically upgrade its auxiliary water supply system (AWSS, often called the salt water system). His curiosity piqued, John studied the history of the salt water system, and how it was originally conceived. This led to documenting the history of the three water systems described in this report, namely:

- The private Spring Valley Water Company's water system that performed poorly in the 1906 earthquake, and that was eventually purchased by the City of San Francisco in 1930;

- The subsequent outcry for an auxiliary "salt water" high pressure water system to augment the SVWC system for fighting future fires; and

- Finally the new Hetch Hetchy water supply system. To bring in new supply from Yosemite National Park.

This led John to examine the politics of building and funding and owning these three water systems. Prior to the 1906 earthquake, the SVWC water system had some known weaknesses, and SVWC had made various attempts to strengthen that system in the 15 years prior to the 1906 earthquake. But politics and cost resulted in "business as usual" and key water system upgrades never got built prior to the 1906 earthquake.

There are several topics that are addressed in this report: the seismic weaknesses of the 1906-era water system; the number of fire ignitions and subsequent fire spread; and the various pre-1906 and post-1906 efforts to upgrade the resiliency of the water system. From 1991 to the present time, Mr. Eidinger has addressed these topics for over 100 water utilities in high seismic hazard zones in the United States; in part, these current-era efforts have been based on the lessons learned (or not learned) from the 1906 earthquake.

Hopefully the reader will gain appreciation as to the water system in place before the 1906 earthquake, and what was done in the aftermath up to 1930, including building the auxiliary salt water system and the Hetch Hetchy system. By 1990, it was recognized that all three of these pre-1930 water systems remained seismically vulnerable. Between 1991 and 2024, a few billion dollars have been spent to strengthen these systems. Future earthquakes will still find remaining weaknesses in these present day water systems. More can be done. The author hopes that the reader will find insight in this report, and that wise choices will be made that continue the development of seismic improvement of these water systems.

August 2024

1.0 Introduction

SVWC built a water system from 1862 to 1905 that well served San Francisco. By the time of the 1906 earthquake, the transmission system included 3 impoundment reservoirs, 76 miles of transmission pipes, 11 bored tunnels, 50 wood or steel trestles, 6 wood flumes; and the City distribution system included 9 local reservoirs and 432 miles of pipe. There was no explicit seismic design for the water system.

The system was originally designed to deliver water for potable and domestic use. San Francisco had a long history of fires, and the water system also had many fire hydrants. The water system was very capable of delivering fire flows for day-to-day fires, with about 6,800 fires being controlled without any substantial fire conflagrations for the 15 year period prior to the 1906 earthquake. Distribution pipes were sized for day-to-day usage, and on streets where water demand was modest, 3-inch and 4-inch diameter pipes sufficed. Today (2023), pipes with diameter under 6-inches are not typically sufficient to deliver fire flows of 1,000 gallons per minute (gpm) or more. Prior to the 1906 earthquake, the City and SVWC discussed the need for larger diameter pipes for fire flows; when money was available, SVWC built those pipes; but the City often denied permits to build new reservoirs and pipelines, or reduced payments to SVWC; the net result was that two key reservoirs and large diameter pipelines that SVWC had planned to build, did not exist at the time of the 1906 earthquake.

The April 18, 1906, earthquake occurred at 5:13 am local time. The earthquake resulted in fault offset, liquefaction and strong ground shaking hazards that damaged the water transmission system at 49 locations with 91 broken pipe segments, and the water distribution system with 299 breaks in cast iron and wrought iron pipes. At least 70% of the 299 breaks in the City distribution system were in areas where the ground liquefied (Eidinger 2023). All primary distribution pipes delivering water from the transmission pipes to San Francisco's South of Market and Central Business District areas were broken. All transmission pipes delivering water to terminal reservoirs in San Francisco were broken.

Multiple fire ignitions occurred within a few minutes of the earthquake, primarily in the South of Market area. There was essentially no water at hydrants available to immediately control these fires. The winds were light at the time of the earthquake (about 2 mph), and the initial fires spread slowly to involve most of the South of Market area, and spread westerly to involve the upper Mission area. On April 19, the winds shifted to blow about 10 to 15 mph from the west / southwest, and the fires spread into the Central Business District, the Western Addition, and Chinatown. The spread of the fires stopped at Telegraph Hill on April 20. A heavy rain on April 21 brought the fires practically under control.

The water transmission system consisted of 4 conduits that normally delivered water to 3 terminal reservoirs in San Francisco. In 1906, the normal flow into the City was about 29 million gallons per day. The earthquake broke all 4 conduits.

The 30-inch Pilarcitos conduit broke at 31 locations with about 60 broken segments. This conduit consisted of 30-inch low pressure, thin-walled wrought iron pipe (D/t > 250), 30-inch medium pressure wrought iron pipe, 3 tunnels, 2 flumes and 11 trestle-supported pipes over drainages. All failures were in the low pressure 30-inch pipe. The pipe broke at all of its 5 fault crossing locations, as well as at 2 trestles over drainages, as well as at 24 other locations. At these 24 other locations, a combination of high levels of ground shaking, earthquake-induced hydrodynamic pressures, and accumulated corrosion led to the failure of the thin-walled pipe.

The 44-inch Crystal Springs conduit broke at 10 locations, with about 22 broken pipe segments. The most significant damage was the failure of about 2,850 feet of wood trestles that traversed through three liquefaction zones, requiring extensive repair of the wood trestles; the pipe was thrown off the trestle across Colma Creek, with the pipe suffering damage to its expansion joints.

The 44-inch, 37-inch, 30-inch San Andreas conduit broke at 1 location with 2 broken pipe segments at an expansion joint atop a wood trestle across Colma Creek.

The 36-inch to 54-inch Alameda pipe broke (or leaked) at 7 locations.

This paper includes photographs of the 1906-vintage wrought iron riveted pipe that have not been seen in over a century. This style of pipe construction suffered a very high rate of damage. Almost none of this 1906-era pipe is presently in use as part of the modern water transmission system that serves San Francisco.

Fragility models were used to forecast the damage to the 1906 transmission system. These models reasonably predict the damage to the transmission system due to fault offset, liquefaction and ground shaking hazards. Eidinger and Hall (2023b) describe the fragility models, including comparison to those in ALA (2001). An important finding is that low pressure thin-walled wrought iron riveted pipe (D/t > 250) is nearly 10 times more vulnerable than medium pressure wrought iron riveted pipe (D/t on the order of 125 to 150).

The actual observed fault offset (primary plus secondary) along the pipes varied from as low as 6.3 feet to as high as 12 feet, with an average of 10.3 feet: these values are low for a M 7.8 earthquake. How much fault offset should essential water pipes across the Peninsula segment of the San Andreas fault be designed for? By "primary", we mean the zone subject to significant sharp right lateral offsets, typically over a zone width of 10 to 20 feet or so. By "secondary", we mean the zones either side of the primary offset zone, where secondary slips and distortions may occur. Outside the primary and secondary fault offset zones, there was additional warping of the ground surface; this warping is not thought to have been a contributor to pipeline damage in the 1906 earthquake. Table 3-3 in this report presents the statistics for the measured fault offset from the 1906 earthquake.

The primary cause of the disastrous fires was the 299 breaks in the distribution system, which prevented water getting to hydrants in the fire zone. The failure the transmission conduits at 49 locations with about 91 pipe breaks was not a direct factor leading to the conflagration. Had there been modern earthquake-resistant pipes used in the 1906-era distribution system, there would have been ample water available to control the initial fire ignitions. As of 2023, the water transmission system serving San Francisco has had a variety of seismic upgrades, but the local water distribution system serving San Francisco still remains extremely vulnerable.

In response to the great 1906 fire conflagration, two new water systems were built:

- First, the AWSS system was funded in 1909 and constructed by 1913. The concept was to use a parallel set of pipes to deliver either sweet water or salt water to high pressure hydrants. The initial system cost $6,000,000 to build.

- Second, the Hetch Hetchy system was approved by the Raker Act (1913) and the Hetch Hetchy Valley in Yosemite National Park was flooded in 1923. First water from Hetch Hetchy reservoir reached Crystal Springs reservoir in 1934. The initial system cost $105 million to build.

The architects of these water systems, built from 1862 to 1930, included Hermann Schussler, Carl Grunsky, Marsden Manson, John Freemen and Michael O'Shaughnessy. They got a great many things right. But they were not clairvoyant about earthquakes. Much of what they built contained a variety of earthquake vulnerabilities.

Our present pique is simple: we presently have water systems serving the various communities around the San Francisco Bay area that were constructed over the past century. These systems remain vulnerable to earthquakes. Efforts over the past three decades have been undertaken to seismically harden a portion of our present-day water system infrastructure…. But much work remains to be done to complete the job.

1.1 Cast of Characters

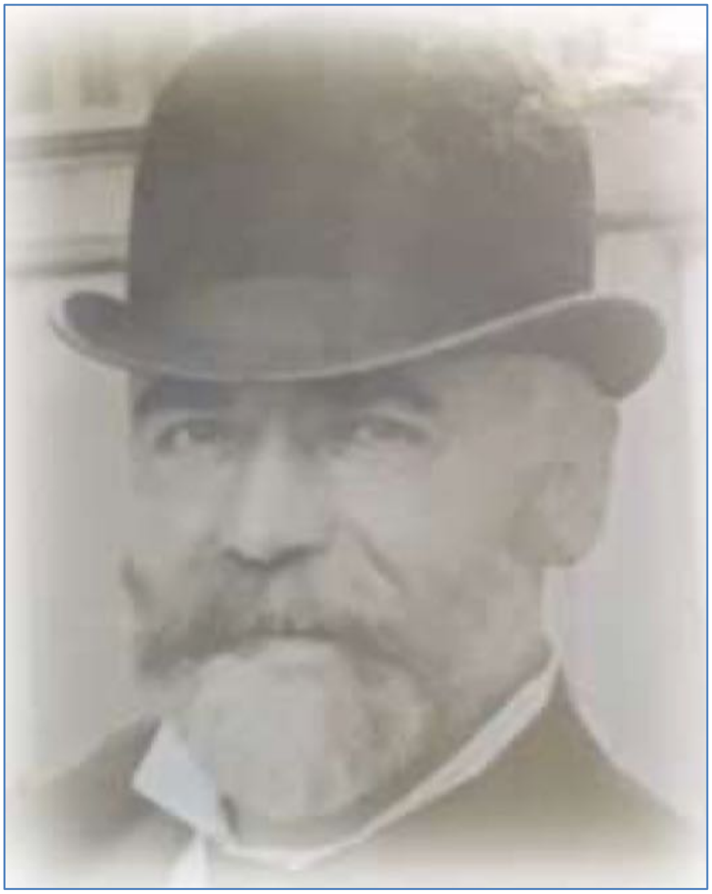
A number of people are important in the development of the San Francisco water system, the damage that occurred in the 1906 earthquake and resulting conflagration, and the subsequent development of the Hetch Hetchy water system and the AWSS.

The earthquake occurred on April 18, 1906. By mid-May 1906, the SVWC had compiled a thorough evaluation of what happened to its water system, and Hermann Schussler published an excellent report by summer 1906. For the remainder of 1906 and much of 1907, scientists and engineers from the two large local universities, U. C. Berkeley and Stanford, documented the earthquake and examined the issue of the San Andreas fault.

The following notable people are often quoted or referenced in this report.

The Architect of the SVWC Water System

Hermann Schussler (1842 – 1919). Hermann Schussler was born in Germany and studied civil engineering in Zurich. He emigrated to California in 1864. In 1864 he was hired by the Spring Valley Water Works, as part of their initial efforts to expand the Pilarcitos Reservoir. He quickly rose in the company, and by 1868, was the chief architect for constructing the new San Andreas dam. By the 1870s, he became the Chief Engineer of the Spring Valley Water Works, and was the chief architect for the lower Crystal Springs dam. By 1900, he was the primary witness of the Spring Valley Water Company in their many lawsuits against the City of San Francisco, arguing over the question of rates (revenues) to be paid to SVWC. Mr. Schussler retired from SVWC in 1908. Between 1906 and 1913, he issued many reports about the capability of the SVWC to deliver water up to over 200 MGD to San Francisco and other communities (all of which were eventually built); wrote critiques of San Francisco's c. 1900 design concept of the Hetch Hetchy system (his critiques were eventually adopted into the final design of the Hetch Hetchy system by John Freeman in 1912). Mr. Schussler was so well respected that a variety of other California and Nevada communities hired him as consultant to lay out their water systems: notably, he designed the Marquette Lake (source water at 8,000 feet) water system that delivered water to Virginia City (6,000 feet) through a pipeline that traversed Washoe Valley, using a 12-inch diameter riveted steel pipe that had to sustain a water pressure of 3,000 feet (nearly 1,300 psi). He laid out and constructed more than half of all the larger diameter steel (or wrought iron) pipe in the entire United States over the period from 1865 to 1890. In 1949, the American Society of Civil Engineers posthumously erected a bronze plaque in honor of Mr. Schussler, located near the Water Temple at Crystal Springs Reservoir, which is inscribed: "If you seek his monument, *look about you*" (cover photo of this report).



Hermann F. A. Schussler, c. 1890 (from Louise Schussler Scrapbook, San Francisco History Center, San Francisco Public Library)

Anthony Chabot (1813 – 1888). Chabot was born in St. Hyacinthe Quebec, Canada. He moved to California in 1849. Amongst his earliest efforts, he developed approaches to hydraulic mining for gold in the foothills of the Sierras. In 1856, he abandoned the mining business and went to San Francisco, where he teamed up with Mr. Beasley to construct San Francisco's first water system, bringing water from Lobos Creek to San Francisco. He later founded the Contra Costa Water Company in 1866, which developed into the primary water system serving Oakland. San Leandro Reservoir (since renamed Lake Chabot) was built in 1870, and was built as a primary water supply for Oakland; although no longer in service as a water supply, as of 2024 connections remain that the water in Lake Chabot could be introduced into the EBMUD water system in case of dire emergency. In 1883, he donated funds and a telescope to build an observatory in Oakland; over the years, this observatory has moved and expanded to present-day Chabot Space and Science Center.

Anthony Chabot c. 1883 (Oakland Public Library)

Documenting the 1906 Earthquake

In addition to Schussler's, efforts, the following people were key in documenting the 1906 earthquake.

Charles Derleth Jr. (1874-1956). Charles Derleth was Emeritus Dean of the College of Engineering, U. C. Berkeley. He was born on October 2, 1874, in New York City. He received his Bachelor of Science degree at the City College of New York in 1894 and his degree of Civil Engineer at Columbia University in 1896. In 1903 he accepted appointment as Associate Professor of Civil Engineering at the University of California, Berkeley. During his career, he was Chief Engineer for the Carquinez Bridge in 1927, Consulting Engineer for the Golden Gate Bridge and the San Francisco – Oakland Bay Bridge, and the Posey Tube in Alameda.

Andrew Cowper Lawson (1861-1952). Lawson was a Scots-born Canadian. He was the first person to identify and name the San Andreas fault in 1895. In 1890 he accepted a position at U. C. Berkeley. He was the editor and co-author of the 1908 report on the 1906 San Francisco earthquake, which later became known as the "Lawson Report".

Harry Oscar Wood (1879-1958). Wood was a seismologist. He was an instructor of geology and seismology at U. C. Berkeley from 1904 through 1912. In 1908, he developed a map of potentially active faults in Northern California. Some of his early efforts were to document the 1906 earthquake, under the direction of Professor Lawson. Later, he went on to develop the Wood-Anderson seismometer and the modern Modified Mercalli Intensity scale.

The Architects of the Hetch Hetchy System

No discussion of the events of the 1906 earthquake on the water system would be complete without recognizing the architects of what was eventually to become to the modern Hetch Hetchy system.

T. R. Scowden (1815 – 1881). Theodore R. Scowden was a civil engineer who designed water systems, including Cincinnati Ohio, Cleveland Ohio, Dubuque Iowa, and Newport Kentucky between 1844 and 1872. He wrote a report on the water supply for San Francisco in 1875.

C. E. Grunsky (1855 – 1934). Carl Ewald Grunsky was a geologist and civil engineer. He became City Engineer for the City of San Francisco (1900-1904).

From 1900 to 1901, Mayor Phelan directed Grunsky to study 14 possible water sources, including: Spring Valley Water Works; San Joaquin River; Lake Tahoe; Clear Lake and Cache Creek; Yuba River; Stanislaus River; Feather River; Mokelumne River; American River; Tuolumne River; Sacramento River; Bay Shore gravels; Eel River; and the Bay Cities Water Company (predecessor to EBMUD).

From 1900 to 1906, Grunsky appraised the valuation of the SVWC system, from which the Board of Supervisors set the water rates.

Carl Grunsky

Grunsky's initial plan for Hetch Hetchy was to develop a system able to deliver 60 MGD to San Francisco via a series of tunnels, canals, pipes and a pump station. In 1912, Freeman re-designed the system as a closed system (gravity flow, no canals), and by the time that O'Shaughnessy oversaw the initial construction, the design was to construct the system able to eventually reliably deliver 400 MGD to San Francisco and 1,600 MGD to the Turlock and Modesto Irrigation Districts.

Marsden Manson (1850 – 1931). Manson succeeded Grunsky as City Engineer. Manson received his PhD in Engineering from U. C. Berkeley in 1893. He served as Consulting Engineer to the City from 1901-1907 and served as City Engineer through 1912. From 1908 - 1911, he modified Grunsky's earlier Hetch Hetchy design to accommodate feedback from Congress. Manson also developed the design of the AWSS in 1908.

John Ripley Freeman (1855 – 1932). BS, 1876, Massachusetts Institute of Technology. He served as a consultant of water power, river control, water supply and allied problems of hydraulic engineering. He also worked in the area of fire protection and studied the role of design and construction in relation to earthquakes. He was elected a member of the MIT Corporation and served until his death in 1932.

John Ripley Freeman

Freeman was retained by the City of San Francisco in 1912 to re-design the Hetch Hetchy system. It is under his leadership that the final configuration of the system was set, radically increasing the 1901 design by Grunsky for a target flow rate of 60 MGD as a pumped system with canals, to 400 MGD by gravity flow from the Hetch Hetchy reservoir in Yosemite to Crystal Springs reservoir along the Peninsula. In 1912, Freeman issued a report with several illustrations of the to-be-flooded Hetch Hetchy Valley as a pristine mountain lake, and these images helped overcome John Muir's scathing description of the to-be flooded valley. Freeman's report helped eventually get the U.S. Congress to vote for the Raker Act in 1913. Without Freeman's efforts, the Hetch Hetchy system would probably never have been authorized by Congress.

Freeman's 1912-vintage design allowed that the high quality soft water from Hetch Hetchy and future Eleanor / Cherry reservoirs would be naturally used preferentially over water stored in other then-existing (Crystal Springs, San Andreas, Pilarcitos) and future (Calaveras and San Antonio) reservoirs.

Freeman was also retained by the SVWC in 1912 to design the Calaveras Reservoir to a flow line of 783 feet, at which level it would contain 46 billion gallons. The concept was that this reservoir would form a buffer should the aqueduct from Hetch Hetchy be compromised by water shortage or other accident / calamity. In 1912, the combined water demand by San Francisco and Oakland and adjacent communities was about 50 to 65 MGD, so should the Hetch Hetchy system be cut off by calamity, the local storage reservoirs could support the entire region for over a year (less time as water demand continued to grow). But for multiple year droughts, as commonly observed from 1850 to

1912, the large storage capacities of Hetch Hetchy, Eleanor and Cherry reservoirs were needed.

Mr. Freeman relied on advice from Schussler to help re-design the Hetch Hetchy Aqueduct. Schussler had been critical of Grunsky's design, pointing out hydraulic flow limitations. Freeman's design, resting atop the efforts of Grunsky, Manson and Schussler, have stood the test of time.

In 1914, Mr. Freeman reported that a storage volume of 190 billion gallons (about 590,000 acre-feet) was needed to dependably supply 400 MGD to the City, during a series of lowest rainfall years ever (then) yet known. This could be achieved by building reservoirs at Hetch Hetchy (117 billion gallons, 361,000 acre-feet), Eleanor (9 billion gallons, 28,000 acre-feet) and Cherry (87 billion gallons, 270,000 acre-feet).

Michael M. O'Shaughnessy (1864 – 1934). O'Shaughnessy was appointed City Engineer in 1913, succeeding Manson. During his tenure, he was Chief Engineer for the initial construction of the Hetch Hetchy Dam and Aqueduct through 1934.

In the photo of O'Shaughnessy below, the map shows "San Francisco's 420,000 Acre Water Shed", most of which is within the Yosemite National Park boundary. This map does not tell the whole story, as the majority of the water rights here belong to TID and MID.

The original bond issue for Hetch Hetchy, approved by the San Francisco voters in November 1909, was for $45 million (the vote carried by six to one); that bond issue promised the reservoirs in Yosemite, various tunnels and pipelines to bring that water (at a rate of 60 MGD) to the San Francisco, and an entire parallel distribution system in the City to deliver that water to end users.

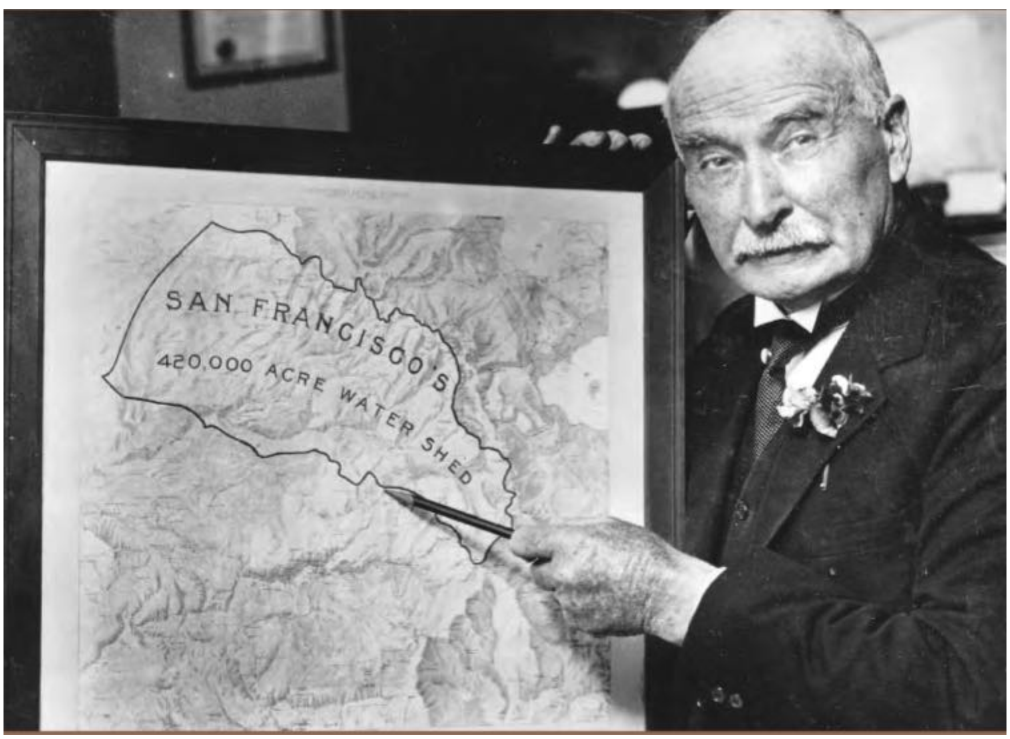
In the same election of November 1909, the voters of San Francisco turned down an additional bond for $35,000,000 to purchase the properties of SVWC serving San Francisco. On December 31, 1913, the City of San Francisco filed suit to condemn the properties of the Spring Valley Water Company. A year before, tentative negotiations had been broken off, with SVWC asking $37.5 million, and the City offering $37 million. It took until 1930 before the parties agreed, and in 1930 the City bought the SVWC properties serving San Francisco for about $40 million.

Construction of the Hetch Hetchy system started in 1914. Construction of O'Shaughnessy Dam started in 1919 and the dam was completed in 1923. The Bay Division Pipeline (BDPL 1 and Pulgas Tunnel) were built in 1923, beginning in Fremont and ending at Crystal Springs Reservoir. All the necessary connecting tunnels between O'Shaughnessy Dam and BDPL 1 were not completed for another decade, and in the interim, SVWC water was diverted from Sunol to enter BDPL 1. In 1934, the first Hetch Hetchy water was actually delivered to Crystal Springs reservoir; at a cost of $105.1 million (see Table 9-4 for cost breakdown); and without any parallel city distribution water system. The

City's eventually cost to have its own city-owned municipal water system, adding the Hetch Hetchy supply to SVWC's supply, and the city distribution system, was about $145 million, or about 322% of what was promised to the voters in the 1909 bond election.

In 1916, O'Shaughnessy stated: "with the inclusion of the conditions in the Raker Bill, which guarantees to TID and MID their developed water rights, thus there is no longer any serious opposition of the Hetch Hetchy project from any faction in San Francisco or the San Joaquin Valley, except from some irreconcilable agitators".

He continues: "[AWSS] system, acknowledged by all experts to the best in the world, containing 72 miles of mains, covering all the principal business and residence districts, and reduce the [fire] insurance rates annually by $1,250,000. Cost: $5,750,000." Author's note: this AWSS system failed to deliver water to a large fire triggered by the 1989 Loma Prieta earthquake. By "all experts" in the world, it appears he excluded Mr. Schussler, who advocated that the cast iron water pipelines should not be laid through liquefaction zones; whereas Grunsky, Marsden and O'Shaughnessy deemed this obvious shortcoming, even in 1909, to be suitable. Earthquakes do not care a whit about politician's pontifications, and the 1989 Loma Prieta earthquake proved the 1909-vintage (and later expanded) AWSS to be unreliable for its intended purpose. See Section 8 of this report for further discussion of the AWSS.



Michael M. O'Shaughnessy

O'Shaughnessy summarized the potential water yield from SVWC supplies. SVWC (and others) estimated that supply to be on the order of 220 to 250 MGD; whereas City-retained consultants estimated that supply to be the on the order of 110 MGD. 1915-era demand was about 40 MGD, so there was no dispute that SVWC could reliably develop its properties to supply the foreseeable water demand for the future (or perhaps through 1950). That said, the addition of Hetch Hetchy would greatly expand the total water supply. Recall that in 1916, while the $45,000,000 bond issue had been approved, but the debate as to whether (or not) to build Hetch Hetchy was still ongoing by various parties. Recall that O'Shaughnessy was appointed City Engineer in 1913, and he had vested interest (like many engineers) to build, build, build; and also to satisfy the in-power political class of the time, who continued to maintain their opposition to privately-held SVWC.

O'Shaughnessy in 1916 stated: "… San Francisco and Oakland are both "in the same boat" as regards to water supply; both need immediate extensions, both are suffering from the exploitation of private speculative corporations." Any fair reading of O'Shaughnessy's rhetoric must conclude that he was fully on the side of San Francisco's politicians, some of whom harbored contempt for the traditional American free enterprise ideal. Was O'Shaughnessy a Progressive - Socialist – Marxist? Or simply beholden to toe the line of his paymaster? Today, one might call O'Shaughnessy a "Crony Capitalist", whereas he demands that only the all-powerful State can be trusted to build and operate a water system, no matter what the cost, all the while handsomely being paid for his efforts[8].

O'Shaughnessy goes on to use the independent cost analysis by the Board of the U.S. Army Engineers: "the project proposed by the City of San Francisco, known as the Hetch Hetchy Project, is about $20,000,000 cheaper than any other feasible project for furnishing an adequate supply". (Ref. Hetch Hetchy Valley: Report of the Advisory Board of the Army Engineers to the Secretary of Interior," February 19, 1913). Time would prove the Army's cost forecast to be greatly underestimated.

O'Shaughnessy wrote of Grunsky's (ASCE, 1916) criticism of the Hetch Hetchy project: "Mr. Grunsky speaks of extraordinary expenditures and lack of study. He neglects to mention that if there were any extraordinary expenditures, he was a beneficiary thereof… possibly Mr. Grunsky's professional pride is hurt… this, together with the fact that Mr. Grunsky's original plans were radically changed, undoubtedly inspires much of his criticism".

The Politicians

Politicians are public figures. They campaign. They have opinions. They make promises. If elected, they try to make things happen. This book can be considered an Op Ed, as the Authors try to expose the underlying issues that led to the damage of the water system in 1906, that then led to the great conflagration. As an Op Ed piece, the Authors place at least some of the blame on Politicians, including Mr. Phelan and the San Francisco Board of Supervisors. The story is complex, but there can be no dispute that in the decades leading up the 1906 earthquake and fire, there was major controversy between the

[8] O'Shaughnessy was paid $15,000 per year as City Engineer in 1913 (equivalent to over $500,000 per year in $2023).

Politicians of San Francisco and the Spring Valley Water Company. Essentially, the Politicians wanted a public-owned water system, whereas the SVWC was a privately-owned system. This devolved into classic "socialist versus capitalist" arguments. The press was firmly on the side of municipal ownership.

But earthquakes don’t care at all as to anybody's political viewpoint or which form of societal organization is geared to best creating the greatest innovation and the greatest wealth and the greatest good for all.

There can be no dispute that in the decades leading up to the 1906 earthquake, the factions were fighting amongst themselves. The numerous lawsuits between the parties (SVWC and the City of San Francisco) in State and Federal court are a matter of public record. There can be no dispute that all this energy focused on lawsuits led to a "less than ideal" water system in place on the eve of the 1906 earthquake.

In retrospect, the argument of whether water rates should allow for profit to stock holders of a private company, pales in comparison to the loss of 80% of the City of San Francisco in the great conflagration after the 1906 earthquake. It is worse than that: the City of San Francisco was blessed with having Mr. Schussler as Chief Engineer of the water system. Had the City allowed Mr. Schussler to mobilize SVWC and build all the infrastructure he wanted in the 1890s, it is quite likely that the initial fire ignitions in the 1906 earthquake would have been quickly controlled with plenty of water, and with no subsequent conflagration.

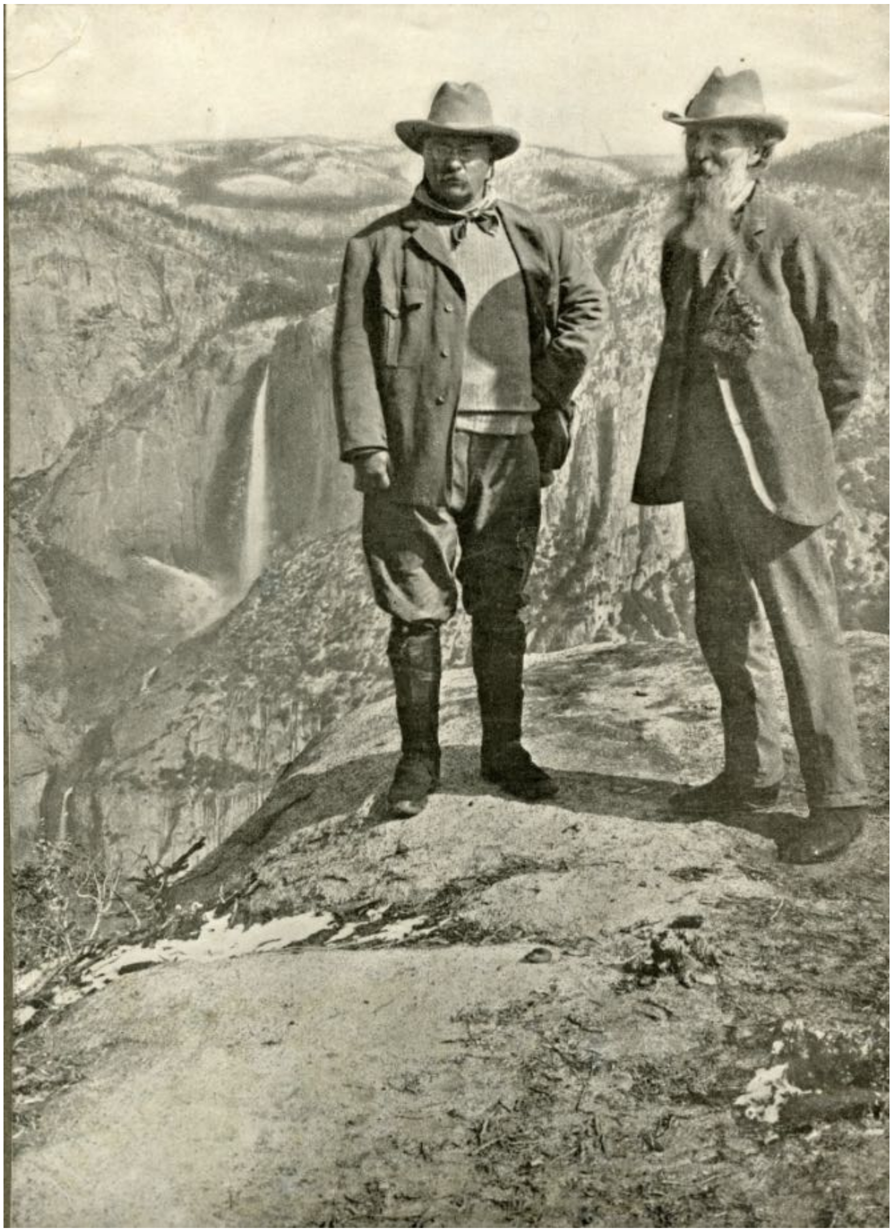
Wait, it gets worse. After the 1906 earthquake, everyone (Schussler and the Politicians) realized that having cast iron or wrought iron pipes traverse zones of liquefaction, was a really poor design. Both Schussler and the Politicians proposed to build a parallel water system. Of course, the Politicians refused to allow Schussler to build it; so the City built it themselves, calling it the AWSS, and having the SFWD to maintain and operate it. Well, the AWSS as actually designed committed the very same errors: it laid many pipes through known liquefaction zones; opposite to the advice proffered by Schussler's competing design. With the SFWD in charge, the AWSS was initially put into service in 1909, and has been expanded regularly over the decades. Then, the 1989 Loma Prieta earthquake occured. The pipes of the AWSS broke in liquefaction zones, and for hours, no water was available from AWSS hydrants to control the major fire in the Marina District. Only with the good fortune of zero wind at the time of the 1989 Loma Prieta earthquake, did the initial fire not spread into a major conflagration.

James D. Phelan (1861 – 1930). Served as Mayor of San Francisco 1897 – 1902. He promoted the Chinese exclusion act of 1882. As Mayor, he advocated for the municipal ownership of the water system for San Francisco. Later, Phelan was elected as U.S. Senator, advocating for Japanese exclusion and for keeping California "white". In 1912, he helped push through California's discriminatory alien land law in 1913. Today (2023), Phelan is often remembered for his racist views against the Chinese and Japanese. To understand the policies that led up to the great fire conflagration of 1906, it is Phelan's and the Board of Supervisors' efforts to create the Hetch Hetchy system, reduce water rates for the Spring Valley Water Company, and their efforts to put Spring Valley Water Company effectively out of business by building a parallel water system, were all contributing factors. Phelan was the head of the political establishment that set water rates. From 1900 up to the time of the 1906 earthquake, the political apparatus of San Francisco was squeezing the water rates. In the 1890s, the City turned down SVWC's proposals to build new in-city reservoirs for the purpose of supply the city uninterrupted with water, should the supply pipes break; and to supply high flows of water for firefighting along Market Street.

James D. Phelan

John Muir (1838 – 1914). Any discussion about the Hetch Hetchy system would be remiss without some review of what John Muir had to say (Naturalist, first President of the Sierra Club).

The photo below shows Mr. Roosevelt (United States President, 1901 – 1909) and Mr. Muir at Glacier Point, overlooking Yosemite Falls. The photo was taken in 1903.



President Theodore Roosevelt (left) and John Muir (right) (Credit: Underwood and Underwood)

Muir wrote (The Yosemite, 1912): "*Should Hetch Hetchy be submerged for a reservoir, as proposed, not only would it be utterly destroyed, but the sublime canyon way to the heart of the High Sierra would be hopelessly blocked and the great camping ground, as the watershed of a city drinking system, virtually would be closed to the public. So far as I have learned, few of all the thousands who have seen [Yosemite] park and seek rest and peace in it are in favor of this outrageous scheme.*"

Muir goes on to write: "*Sad to say, this most precious and sublime feature of the Yosemite National Park, one of the greatest of all our natural resources for the uplifting joy and peace and health of the people, is in danger of being dammed and made into a reservoir to help supply San Francisco with water and light, thus flooding it from wall to* *wall and burying its gardens and groves one or two hundred feet deep. This grossly destructive commercial scheme has long been planned and urged (though water as pure and abundant can be got from outside of the people's park, in a dozen different places), because of the comparative cheapness of the dam and of the territory which it is sought to divert from the great uses to which it was dedicated in the Act of 1890 establishing the Yosemite National Park.*"

Muir goes on to write: "*That anyone would try to destroy such a place [Hetch Hetchy Valley] seems incredible; but sad experience shows that there are people good enough and bad enough for anything. The proponents of the dam scheme bring forward a lot of bad arguments to prove that the only righteous thing to do with the people's parks is to destroy them bit by bit as they are able. Their arguments are curiously like those of the devil, devised for the destruction of the first garden*".

To be sure, Muir was not 100% supported by other members of the Sierra Club. Further, Muir stated that "*the resulting Hetch Hetchy reservoir would be cycled annually, being full only for a month or two in the spring; and then gradually drained, exposing slimy sides of the basin with the gathered drift and waste, death and decay*". For nearly a century that the Hetch Hetchy reservoir has been in existence, the reservoir has rarely been so cycled as Muir had predicted, and in fact is a clear mountain lake with a beauty of its own. The author has hiked around the lake, and observed that the beauty of the Hetch Hetchy Valley is remarkable, and its environs lightly trampled, and in many ways superior to that of the tourist-developed and heavily visited Yosemite Valley.

The issue was decided in December 1913, when President Woodrow Wilson signed the Raker Bill into law, authorizing the construction of the (yet to be named) O'Shaughnessy Dam across the Tuolumne River and the other aspects of the Hetch Hetchy system.

An open question remains, as of 2024, whether O'Shaughnessy Dam should be removed, and thus to allow the Hetch Hetchy Valley to restore itself (over some extended period of time) to its original pre-development state. Certainly there would be a financial cost to remove the dam. To assure a reliable water supply for both domestic purposes for the City of San Francisco and 29 other Cities around San Francisco Bay, as well as the irrigation needs of TID and MID, the loss of reservoir storage would either have to be replaced with equivalent storage someplace downstream (also at additional cost, with lower water quality, and with likely reduced seismic safety); and the downstream reduced water quality would necessarily require additional filtration and treatment for domestic purposes. The costs of such an effort would be high (certainly many $billions in 2024 dollars), while the benefits of a restored Hetch Hetchy Valley being ultimately subjective: creating a highly touristy and commercialized Hetch Hetchy Valley in a manner similar to nearby Yosemite Valley is not a "positive benefit" even to most nature lovers.

1.2 The Future

This book focuses on the history of the San Francisco water system, from 1849 to the time of the 1906 earthquake, and the post-earthquake decisions about changes to the water system. There are many lessons to be learned.

But, what about the future? Are the present-day water systems around the San Francisco Bay area "*seismic proof*"? The answer is "*no*".

Today (2024), there are about 60 water systems that serve water to the ~8,000,000 people in the 9 county greater San Francisco Bay Area. The three largest systems are EBMUD (serving about 1.4 million people), the SFPUC (serving about 2.4 million people) and the Santa Clara Valley Water District (serving about 1 million people). There are dozens of other water systems serving communities of 50,000 to 100,000 people. There is sometimes overlap between water systems, and some communities can obtain water from multiple sources via different water systems.

Between 1990 and 2024, there have been a few billion dollars spent investing in seismic upgrades of the various water systems around the San Francisco Bay Area. This is a good start. But the job is not nearly done. Today (2024), there remain over 20,000 miles of water pipes in the Bay area that are made of seismically-weak materials (cast iron, asbestos cement, etc.). Many of these pipes traverse zones prone to liquefaction or landslide; there are hundreds of water pipes that crisscross over active faults (notably the Hayward fault). A single future earthquake on the active Hayward fault has been forecasted by EBMUD to potentially result in many thousands of water pipe repairs. Other active faults in the Bay Area abound, including the San Andreas, Rodgers Creek and Calaveras faults; as well as many lesser (but locally still quite hazardous) faults.

Today (2024), there are new modern styles of water pipes that are practically earthquake-resistant. These include ductile iron pipe with chained joints (commonly used in Japan); high density polyethylene pipe; and butt-welded heavy wall steel pipe. But, less than 0.1% of all water pipes in the San Francisco Bay area presently use these types of seismic-resistant pipes.

Today (2024), it commonly costs about $2,000,000 to $3,000,000 to install one mile of water pipe (commonly 6-inch to 12-inch diameter). Replacing the first 5,000 miles of old pipe with these new seismic resistant pipes will go a long way to reducing the potential of loss of water supply after any likely large magnitude earthquake in the Bay Area. This means that an additional $12.5 billion dollars (in $2024) remain to be invested before the bulk of the earthquake vulnerability of our water systems is mitigated.

Most of the 60-odd water systems in the Bay Area are public-owned; a few are privately owned. Whether public or private, the seismic issues remain the same, and future earthquakes will not "give a damn" as to the style of ownership. Present-day engineers now know how to build seismic-resistant water systems. Nominally, it will be up to the Boards of Supervisors, Boards of Districts, City Councils and Private Owners to decide where and how much to spend on seismic upgrade, and how this will affect water rates. But ultimately, it will be the water customer, who pays all the bills, who is the final decision maker.

Collectively, we hope our communities can strive to build better water systems, to help protect our communities from fire conflagration, deliver potable water for all our uses, and all done in a cost effective manner.

Respectfully submitted,

the Authors,

Tim Hall and John Eidinger, August, 2024 (Revision 2)

1.3 Units and Abbreviations

This report makes use of common English and SI units. No attempt has been made to convert historical units to SI units. Abbreviations and units are as follows.

All pipe diameters are quoted as nominal diameters. For example, a "30-inch" pipe has nominal diameter of 30 inches, but actual inside diameter (to the inside of the wetted surface) and outside diameter (to the outside of the pipe in contact with soil) can vary from the nominal diameter, commonly by as much as 1/2 inch.

1 acre-foot = 325,851 gallons (U.S. measure)

1 cubic foot per second (cfs) = 448.843 gallons per minute (gpm)

1 inch = 25.4 mm = 2.54 cm. 12 inches = 1 foot

1 foot = 1 ft = 0.3048 meters

1 gallon (U.S. measure) = 3.7854 liters

1 kip = 1,000 pounds

1 ksi = 1 kip per square inch

1 mile = 1.609 kilometers (km)

1 pound = 4.48 Newtons.

1 psf = Pounds per square foot = 47.8803 Newtons / square meter

Throughout this report, we mention elevations, like overflow levels of reservoirs, grade lines, pipe inverts, etc. The reader is cautioned that these are not presented using the modern NAVD 1988 vertical datum; but rather using the vertical datum of the era. Over time, vertical datums have changed. The differences between these vertical datums and modern NAVD 1988 might range from a foot to as much as 12 feet, depending on location.

AD	Average Displacement across the fault
ADD	Average Day Demand (MGD)
ALA	American Lifelines Alliance
AWSS	Auxiliary Water Supply System
BDPL	Bay Division Pipeline
CI	Cast Iron pipe with push-on joints
CIB	Cast Iron pipe with belled joints
CS	Crystal Springs
D	Pipe diameter (inches)
EBMUD	East Bay Municipal Utilities District
FEMA	Federal Emergency Management Agency
Fy	Yield stress of steel or wrought iron (psi)
Fu	Tensile stress of steel or wrought iron (psi)
gpm	gallons per minute
kV	kiloVolt
kW	kilowatt
LADWP	Los Angeles Department of Water and Power
M	Moment magnitude (same as M_w)
MD	Maximum Displacement across the fault
MG	Million Gallons
MGD	Million gallons per day
MID	Modesto Irrigation District
MIT	Massachusetts Institute of Technology
MLWC	Mountain Lake Water Company
mph	Miles per hour
MVA	MegaVolt Ampere
MW	MegaWatt
NAVD	North American Vertical Datum on 1988
NFBU	National Board of Fire Underwriters
NGA	Next Generation of Attenuation models (ground motion models)

PGD	Permanent ground deformation (inches, cm)
PG&E	Pacific Gas and Electric
PGV	Peak ground velocity (inches / second or cm / second)
psf	pounds per square foot
PRCI	Pipeline Research Council International
R, R_w	Response Modification Coefficients, as described by building codes like (UBC 1979 - 1997, R_w), IBC (2000 - 2021, R). Radius, inches.
SFCWW	San Francisco City Water Works
SFG&E	San Francisco Gas and Electric (predecessor to PG&E)
SFFD	San Francisco Fire Department
SFWD	San Francisco Water Department
SFPUC	San Francisco Public Utilities Commission
SVWC	Spring Valley Water Company (earlier named Spring Valley Water Works)
t	Pipe wall thickness (inches)
TID	Turlock Irrigation District
UBC	Uniform Building Code
UC	University of California
V	Seismic Base Shear (kips)
Vs30	Shear wave speed in the top 30 meters of the subsurface (meters / sec)
W	Weight, used for seismic design as described by building codes like UBC (1979 - 1997), IBC (2000 - 2021)
WI	Wrought Iron pipe

1.4 Copyright, Creative Commons

1.5 Acknowledgements

This report includes a number of vintage maps and photos and details (pre-1930). Each photo is attributed to the original author, many being derived from Mr. Herrmann Schussler's book (1906). Some images were taken by the SVWC between 1904 to 1907 and became the property of the City of San Francisco upon its purchase of the SVWC in 1930; these images are used with permission by the City of San Francisco.

In 2022, The City of San Francisco provided the authors copies of various pre-1930 photos and drawings of the SVWC water system. Many thanks are given to the support by Mike Housh, the SFPUC's historian and archivist; and Ms. Annie Li, Ms. Stacie Feng, Mr. Calvin Hue of the SFPUC for locating and providing various historic documents and drawings.

For all these old (pre-1930) maps and photos, the authors thank and give credit to the original creators. Copyright has expired on these pre-1930 images. In any case, the use of such material is considered "Fair Use", and is presented for purposes including criticism, comment, news reporting, scholarship and / or research.

Photo captions include source information. Some captions are denoted with "HS50", meaning that the image is the same as provided by Hermann Schussler which he numbered "50" in his 1906 report; we suspect that Mr. Schussler did not actually take these photos, and instead a SVWC staff person did. Many of Schussler's images reproduced in this report are made from the original 1906-era plates, to provide the most detail.

Unless otherwise indicated, aerial photographs and drawings are presented with north "up".

Many thanks are given to the various libraries who have collected these old photos and made them available.

Photos, drawings and maps that are presented without attribution are original documents prepared by the authors. These are covered by copyright and creative commons provisions in Section 1.4.

1.6 Revision History

Revision D. Working draft, issued to SFPUC for comment. October 2023.

Revision 0. Initial public release. December 2023.

Revision 1. May 2024. Added "About the Authors" Section 0.4. Updated Sections 4.1.8, 4.1.10, 4.1.11 and 4.1.12.

Revision 2. August 2024. Additional descriptions of Locks Creek Aqueduct, Section 4.6. New Table 4.6-1. Updated Figures 2-26, 4.6-1. Various editorial updates.

2.0 The San Francisco Water System

2.1 The Development of the Water System 1776-1930

2.1.1 Water Supply for the Original Settlement

San Francisco was founded on June 29, 1776, when colonists from Spain established the Presidio of San Francisco and Mission San Francisco de Asis a few miles away. Yerba Buena was the original name of the settlement. Figures 2-1 and 2-2 show sketches, dating from 1847-1848, of what is now the area around Montgomery Street and Market Street, c. 1848, with Yerba Buena Island in the Bay, and Mount Diablo (highest peak) in the distance.

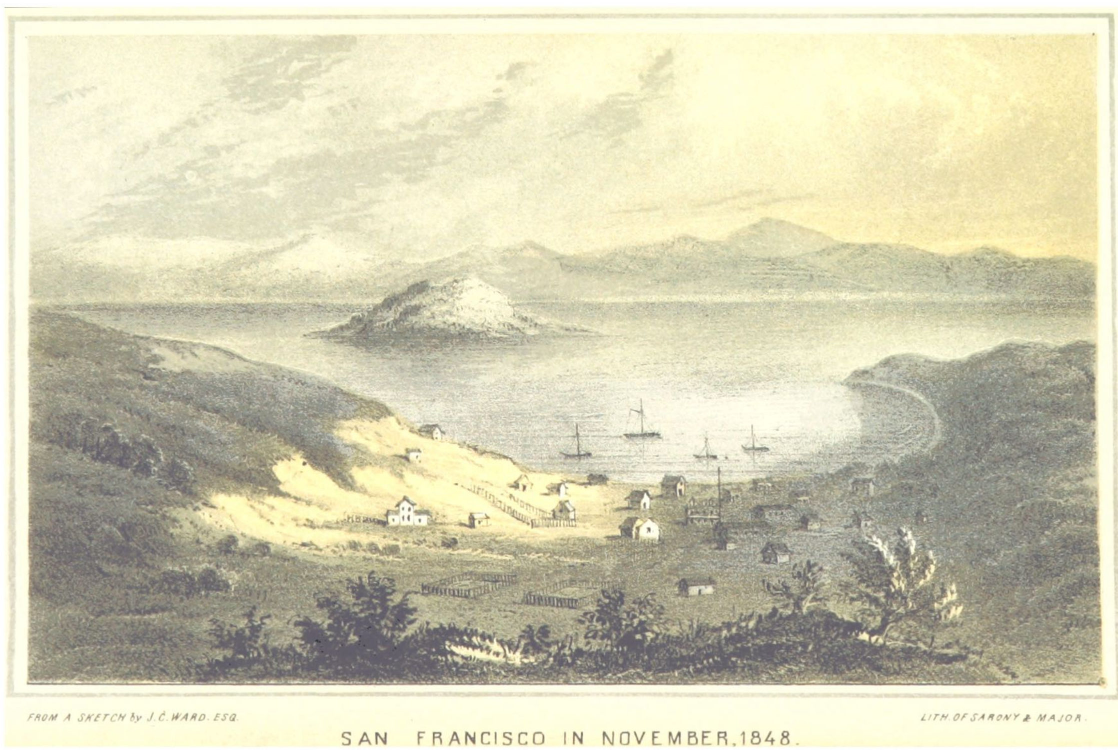


Figure 2-1. Sketch of San Francisco in November 1848
(J. C. Ward)

Figure 2-2. View of San Francisco in 1846-47, Before the Discovery of Gold (Library of Congress)

The sketch in Figure 2-2 was commissioned by General Vallejo. Highlighted features include:

- Middle Foreground. Montgomery Street forms the shoreline. Other named streets are Kearny Street, Clay Street and Washington Street. On July 9, 1846, Captain Montgomery of the sloop of war Portsmouth (ship denoted "A") raised the American flag in the plaza (Kearny and Clay) and seized the region for the United States.

- Right Foreground. An inlet of the Bay water is shown heading westwardly towards present-day Jackson Street.

- Left Background (#33). Twin Peaks.

- Middle Background (#34). Lone Mountain (present-day named Nob Hill).

- Right Background. Russian Hill. The trail drawn as a winding diagonal goes to Mission Dolores (not shown in this sketch).

Early settlers in San Francisco used springs and wells for their water supply; water was also delivered from Sausalito via water boat. In 1852, the Daily Alta reported:

- "*Artesian wells are becoming quite numerous in San Francisco, and these promise to do away with the host of water carts in our City. The first such well was, we believe, on Montgomery Street, before the May fire of 1851. Since then, many others have been dug up, and good clear pure water has become quite plentiful. During the past few days a well has been dug on Sansome Street, between Pine and California streets, and fine water obtained at a depth of 140 feet. ... the humblest cottage can in a short time afford a leaden pipe to carry the pure sparkling water*." Of course, time would show that these wells were no long term solution for the burgeoning population of more than a few thousand, as there is not a sufficient aquifer under San Francisco to support more than a few thousands of people. Further, as the population increased, there were more pollutants, and the limited available ground water basin became unpotable.

Between 1849 and 1851, six great fires occurred in San Francisco. These fires were summarized by the Hartford Agent (The Adjuster, 1913):

- December 24, 1849. When the fire came, it spread like a pestilence and completely consumed the most flourishing portion of the city. So rapidly spread the flames, that they defied all control – water, labor, powder, everything was powerless to stay them. More than a million dollars thus burned to ashes.

- May 4, 1850. The city had revived, and prosperity smiled on her streets. The ignition of this fire was close to the December 24, 1849 fire. Within a few hours, the fire swept away three entire blocks, destroying an estimated 4 million dollars. Within 10 days of the fire, reconstruction was underway and more than half the burnt district was covered with new buildings.

- June 14, 1850. The fire ravaged more than the two previous fires combined. Losses were estimated at 5 million dollars. Reconstruction started to use brick and masonry buildings, although being more expensive than wood frame, were thought to be more fire resilient.

- September 17, 1850, 4 am. About 175 buildings destroyed. But, still, the destruction was less than the three prior fires. The appearance of this conflagration disappeared quickly, with "*gold dust flowing like a river*".

- May 4, 1851, evening. In 9 hours, 20 blocks were consumed by fire, then being the bulk of the city. Many lives were lost in the fire. Within 10 days, some 300 buildings were in a fair state of reconstruction.

- June 22, 1851. Nearly 15 blocks were consumed by fire. There was little doubt that the fire was caused by arson. Property loss was estimated at 4 million dollars.

2.1.2 Salt Water and Potable Water and Cisterns, 1850 to 1857

Parts of early San Francisco were destroyed by fires several times in the early 1850s.

From the available historical record, it appears that in 1850, the City entered negotiations to have private enterprises construct two water systems for the growing population. This culminated on June 11, 1851, when the City council formally granted two water supply franchises: a salt water system and a potable water system:

- Conrad K. Hotaling was to build a salt-water fire protection system that would use a steam engine to pump water from the San Francisco Bay into a reservoir at Green and Montgomery streets (atop Telegraph Hill), capable of holding 2 million gallons of water. Water from that reservoir would then be distributed by underground pipe to the business district. Mr. Hotaling's salt water system was never built.

- Azro D. Merrifield was granted a franchise by the City to build a potable water system. This system was to be built by 1852. Mr. Merrifield subsequently transferred his franchise to the Mountain Lake Water Company (MLWC), which was incorporated on August 14, 1851. The Mountain Lake Water Company planned to take source water from Mountain Lake and deliver it about 3 miles eastward to San Francisco. As specified by the City's permit, this new water system was to include a 1 million gallon reservoir at elevation at least 100 feet above sea level, with pipes able to carry a flow rate of at least 700 gpm. Efforts were made to construct this system, and there were several extensions in time requested to complete the effort, through 1858 (this is further described below). Ultimately, this enterprise was unsuccessful.

In parallel, the City undertook to construct cisterns in the built-up area, to be filled with water from a spring on Sacramento Street delivered by underground pipes, waters from the Bay at high tide, or flows from sewers…. Certainly not potable.

The Board of Assistant Aldermen (predecessor to present-day San Francisco Board of Supervisors), by the Committee on Fire and Water, presented an ordinance for the creation of a Fire Department. The ordinance reads, in part: "What have become of the immense water projects, which, after weeks of hard work, were finally sanctioned by the Common Council last spring? Neither the plan of Mr. Merrifield or Mr. Hotaling have at yet been put in operation, and not even a commencement has been made. With the exception of the pipes laid from the Sacramento Street spring, no attempt has been made for the protection of the city from fire, and in case another [fire] should break out, we shall be as badly prepared for it as ever before, in fact, we shall be in a worse condition, as the water, which might have been obtained from the bay in the vicinity of Montgomery street, has been encroached upon by building, and where three months since the tide flowed, earth has been filled in, and large and easily combustible buildings erected. Greater danger may be anticipated from a fire should another one occur, than ever before, from the fact that the shipping in the harbor would be placed in closer connection with the fire. Wharves and buildings have extended until they have reached nearly to the ship channel, and houses and ships are now strangely mingled together. After our city has been so many times destroyed by fire, and we have been obliged to look on powerless, without being able to move a hand toward the suppression of the raging element, it is high time that some decisive action should be taken to prevent the recurrence of such disastrous results in the future. One plan by which the cisterns, certainly, could be kept continually full during the rainy season at least, would be to connect the sewers from certain streets into the cisterns in their vicinities. This would at least be economizing the water, and turning the rain into a source of protection, at the same time that it is so annoying in other ways."[9]

On August 21, 1851, the "Plaza Water Works" was put into service. This water system was fed by a spring at Sacramento Street, then into a small local reservoir, and then by pipe downhill to fill a cistern in the Plaza (now Portsmouth Square, Kearny at Clay Streets). The water quality was described as "*a rich yellow color, unlike the usual pale appearance of water*"[10]. It was described as being able to fill the cistern in 3 or 4 days, with water being conveyed by pipe from the spring; and branch pipes were envisioned to be used to fill other cisterns that were being developed. The Daily Alta newspaper stated "*This is about the best thing the City authorities have ever done*".

Figure 2-3 shows the proposed layout of Merrifield's proposed water system. (Note: Mountain Lake Water Company never completed the system). Source water was the Mountain Lake (in the Presidio). Two alternate aqueduct routes were envisioned: a northern route and the Pacific Street route. The Pacific Street route would have a reservoir near Broadway and Octavia (never built). Note the shorelines at North Beach, and the filled-in areas east of Montgomery Street and south to Rincon Point, and the shoreline of Mission Bay. Many of these areas were filled in by 1906, and played an important role in the pipeline damage and subsequent fire in the 1906 earthquake.

[9] Daily Alta California, September 18, 1851.

[10] Daily Alta California, August 22, 1851.

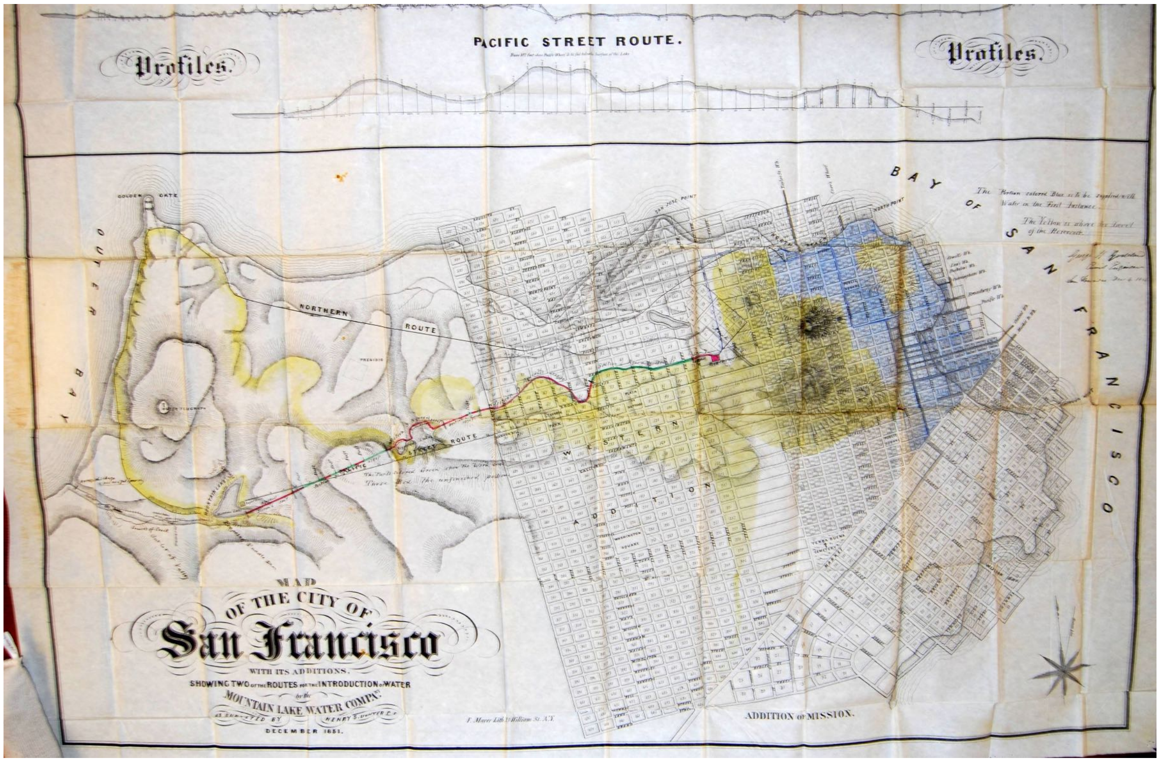


Figure 2-3. Mountain Lake Water System (December 1851) (Huntington Library)

The Daily Alta of June 15, 1852, reported that the work on the Mountain Lake Water Company water system to date was: "*to no purpose. For a year the undertaking has lain dormant, because it was found impossible to induce the public to invest their money in the enterprise*". The City Aldermen took up a request by the Mountain Lake Water Company for a revised franchise, to give a two year extension until January 1, 1855, to construct the system, and also to give a 20 year exclusive license to operate the system. The City Aldermen also considered not giving MLWC the revised franchise, and instead taking upon itself the cost and ownership of the water enterprise: to which, the City Aldermen stated: "*We are opposed to monopolies in theory and practice, and such is undoubtedly the feeling of the community. … There are then two alternatives – either undertake the work as a city improvement, or grant the MLWC such special rights as will enable it to prosecute the enterprise. To the first proposition, with our already large debt, no one would assent, [though] such a decision would save us from possible contingencies of oppression by a soulless corporation*". … [for the second proposition]… "*the health of the City may become impaired, she may be devastated by fire, and thus lose infinitely more*". The City ultimately decided to give MLWC one more year to complete the works (to January 1, 1854) and set water rates by a Board of Commissioners (3 commissioners appointed by the City, 2 commissioners appointed by MLWC).

The Daily Alta of January 4, 1854, reported that the works of the MLWC were halted for want of funds.

In June, 1854, the City passed a resolution (No. 418) to investigate the affairs of the Mountain Lake Water Company, and report whether it would be expedient to accept a surrender of their privileges at a cost to be determined; and to develop a plan for the city to construct its own water system.

The Daily Alta of June 20, 1854, reported that the works of the MLWC were halted for want of funds. MLWC set forth their inability to proceed with the work, and asked that the City grant such aid or relief as may be necessary as needed to continue the work; alternately, MLWC would surrender the in-progress works to the City on equitable consideration. MLWC contended that they were unable to raise sufficient funds by the selling of stock.

The Daily Alta of March 20, 1856, reported that per the recently adopted City Ordinance 896: MLWC had 18 months (to September 1857) to complete its works and begin flow of water to the City; failing that, MLWC would be in default of its franchise, and the City would have the right to purchase the works at a fair valuation.

By late 1857, the water works not having been completed by MLWC, the City proceeded to condemn the franchise: the Board of Supervisors passed a resolution declaring MLWC's privileges at an end. By 1862, the Mountain Lake Water Company was out of business, lacking financing to complete the works.

By 1854, the City Alderman approved the construction of several cisterns, commonly with 30,000 gallon capacity, and constructed with brick. These were owned by the City Fire Department. Two dozen Cisterns were approved for construction in 1854, see Table 2-1. The locations reflect the bulk of high value business district of the City, and exclude most of the residential areas. At the time these cisterns were approved, there was essentially no piped water system in the City, and no fire hydrants. By the time of the 1906 fire, there were piped water systems and hydrants; but liquefaction (see Section 3 for a description of liquefaction hazards) failed the cast iron pipeline system in several key places, leaving most of the business district without piped water. The efficacy of these cisterns, of which about 23 were thought to be in place and mostly operational (full) at the time of the 1906 earthquake, was either nil, or at best, extremely limited, in controlling the conflagration; the available historical record suggests at best that the water from one cistern was useful in controlling a nearby fire; the water at another cistern was not particularly useful, and possibly the water at all of the remaining cisterns were either not used or not particularly useful. At the time of the 1906 earthquake, there might have been about 700,000 to 800,000 gallons total storage in all the cisterns (assuming all were full and not leaking). Given that once the fire spread, useful fire flows to control the fire at multiple fronts would have been in the range of 10,000 gpm x 24 hours = 346 million gallons, it is clear that the limited capacity of cisterns would be particularly useful only if the fire department could arrive at the fire site, and lay perhaps 2 handlines at 200 gpm via a pumper truck from the cistern, and initiate water onto the fire within 5 to 10 minutes of ignition, and to control and essentially douse the fire within 60 to 75 minutes or so; which could usually be the case assuming light winds and rapid response.

Cistern Location	Cistern Location
Pacific and Powell	Mission and Ridley
Powell and Jackson	First and Folsom
Powell and Green	Second and Folsom
Powell and Filbert	Post and Kearny
Powell and Jackson	Union and Dupont
Powell and Clay	Stevenson and Ecker
Powell and Bush	Montgomery and Vallejo
Bush and Dupont	Minna between First and Second Sts.
Sacramento Street (repair the 1851 cistern)	Sutter and Stockton
Sacramento and Montgomery	Stockton and California
Battery and Pine	Broadway and Kearny
California and Sansome	Broadway and Mason
Sansome and Bush	Clay and Taylor
Center and Dolores (60,000 gallons)	Sacramento and Dupont
Center and Mission	Washington and Powell

Table 2-1. Cisterns Approved, 1854

2.1.3 The San Francisco City Water Works, 1858 to 1862

With the demise of the MLWC, two new private water companies were formed to develop a water supply for San Francisco. One was the San Francisco City Water Works [sometimes called the "Bensley" company], and the other the Spring Valley Water Works.

The legislature in Sacramento passed a law in 1858 to encourage private capital to embark on constructing water works for municipalities in California. This law provided a maximum rate of interest of about 24 percent per year. The underlying concept was that the entire capital cost of the water works should be recovered in about 5 years' time, and then the water system revenue was to be about 5% of installed assets per year. The key points were that cities (including San Francisco) were cash-short and could not afford the capital cost to construct their own water works; and in order to attract sufficient money to construct a capital-intensive water works, private enterprise was going to have to get guarantees that they would be able to recover the large up front capital cost, and then have sufficient funds to operate on an annual basis.

Mr. Bensley (and associates) claimed that he owned the Mountain Lake property, and not MLWC. There were court cases, and the Bensley et al claims were upheld. Bensley formed the San Francisco City Water Works company (SFCWW). The City of San Francisco de-facto cancelled their prior charter with MLWC, and entered into a new charter with SFCWW. The new charter, summarized below, reflects what was actually built.

On August 28, 1859, the City Board of Supervisors passed Order 172, etc. with regards to granting the San Francisco City Water Works the franchise to deliver Lobos Creek water to San Francisco. This was confirmed by the Statutes of California, 1858, Ch 95. The grant required that the San Francisco City Water Works was to provide water to the City through a system that would include a diversion dam at the mouth of Lobos Creek; an aqueduct of sufficient capacity to move all of the water of said stream along the north shore of the Bay to near the foot of Van Ness Avenue in North Beach area; to there-build a reservoir with at least 50,000 gallon capacity; and a pump station at North Beach to a 6 MG reservoir not less than 130 feet above grade, and a 2 MG reservoir not less than 250 feet above grade; that the reservoirs shall be connected by iron pipes capable of discharging 2 MGD (1,400 gpm); the design of the pipes to withstand 400 feet of head; capacity of which as per the Croton Water Works of New York; and a 16" main from the reservoir to Market Street by August 6, 1860, and to distribute at least 0.2 MGD. Also, a marble fountain is to be erected in the Plaza (Portsmouth Square), costing $2,000 to $2,500 at SFCWW's sole expense, with water flowing on Sundays, and that water could then be repurposed.

The San Francisco City Water Works was incorporated on June 14, 1857 by John Bensley, Alexis Waldemar Von Schmidt, and Anthony Chabot. Von Schmidt later went on to develop a plan to use Lake Tahoe water as a source supply for San Francisco, and was a founder of the Spring Valley Water Works (see Section 2.1.4). Chabot later went on to found the Contra Costa Water System for Oakland, California (later incorporated into EBMUD); the present-day Chabot Observatory in the Oakland Hills is also part of his legacy.

On September 15, 1858, the SFCWW delivered water into the City from Lobos Creek near Mountain Lake, via a flume. Figures 2-4 to 2-9 show the SFCWW's water supply system that was actually constructed. The Sacramento Daily Union described it as thus: "*The Bensley Water Works, consisting of a wooden flume, winding around the tortuosities of the beach, here placed upon trestles, there running a trench, and again pouring through short tunnels, where rocky points run out*." Highlighted are Mountain Lake and Lobos Creek (in the Military Reserve now called the Presidio), the Lobos Flume (from Lobos Creek to Black Point pump station) and the pipes from Black Point Pump Station to the lower (Francisco Street) and upper (Lombard Street) reservoirs on Russian Hill. This water system was completed and in service by 1860. This source water system was the first major potable water system to serve the central business district area of San Francisco, and was able to deliver on the order of 2 MGD. The supply system (dashed blue line in Figure 2-4) consisted mostly of wooden flumes, with a tunnel under the hill near Fort Point. The flume delivered water to the Black Point pump station (with two 200 horsepower pumps), which in turn would deliver water to the two aforementioned reservoirs via 10-inch and 12-inch mains. Not shown in Figure 2-4 is the pipe network that took water from the two reservoirs to end user customers.

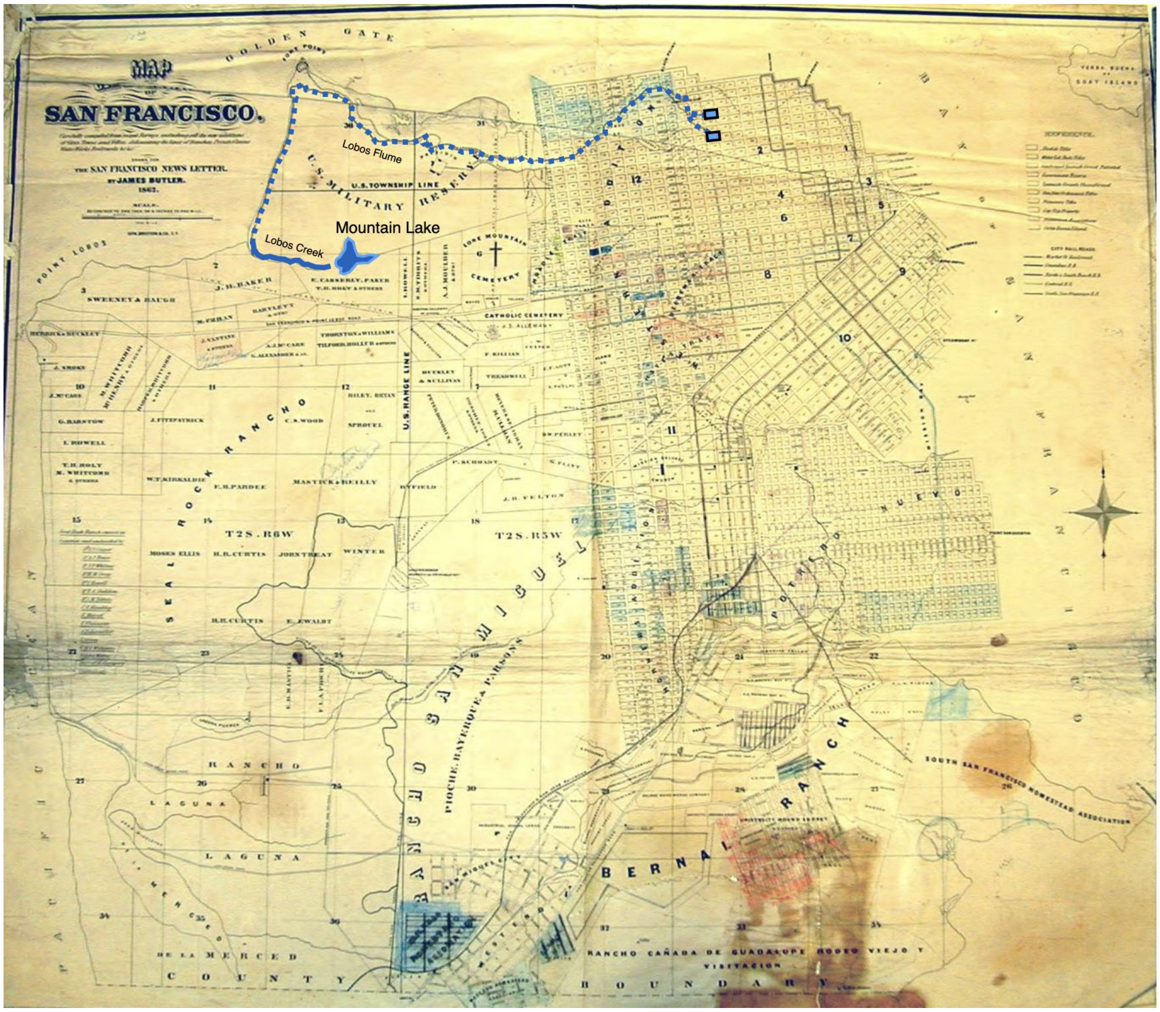


Figure 2-4. Map of San Francisco, 1862 (James Butler, Huntington Library), Showing the SFCWW Water Supply System from Lobos Creek

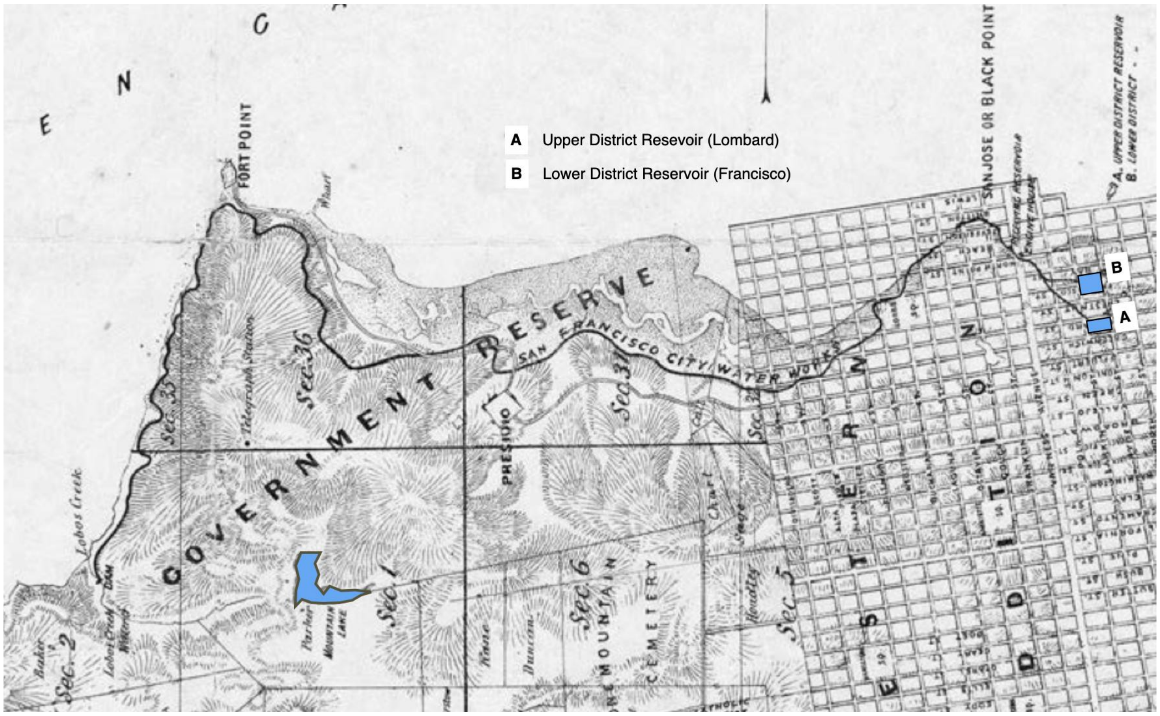


Figure 2-5. Map of San Francisco, 1858, showing the SFCWW Water Supply System from Lobos Creek. Mountain Lake and Terminal Reservoirs Highlighted in Blue.

Figure 2-6 shows hikers atop the wooden flume, near Baker Beach, c. 1882.

Figure 2-6. Hikers Atop Lobos Flume, Near Baker Beach, 1882 (Photo: John Martini, WNP Collection, wnp4.1462)

Figure 2-7 shows the Lobos Flume along Baker Beach. The Fort Point Military citadel is seen in the top right of the photo, guarding the entrance to San Francisco Bay, via the Golden Gate. It would be several decades before the namesake Golden Gate Bridge would be constructed.

Figure 2-7. Lobos Flume Near Baker Beach (Photo: Bancroft Library, U. C. Berkeley)

Figure 2-8 shows the flume just south of Fort Point, before it turned eastward through a tunnel.

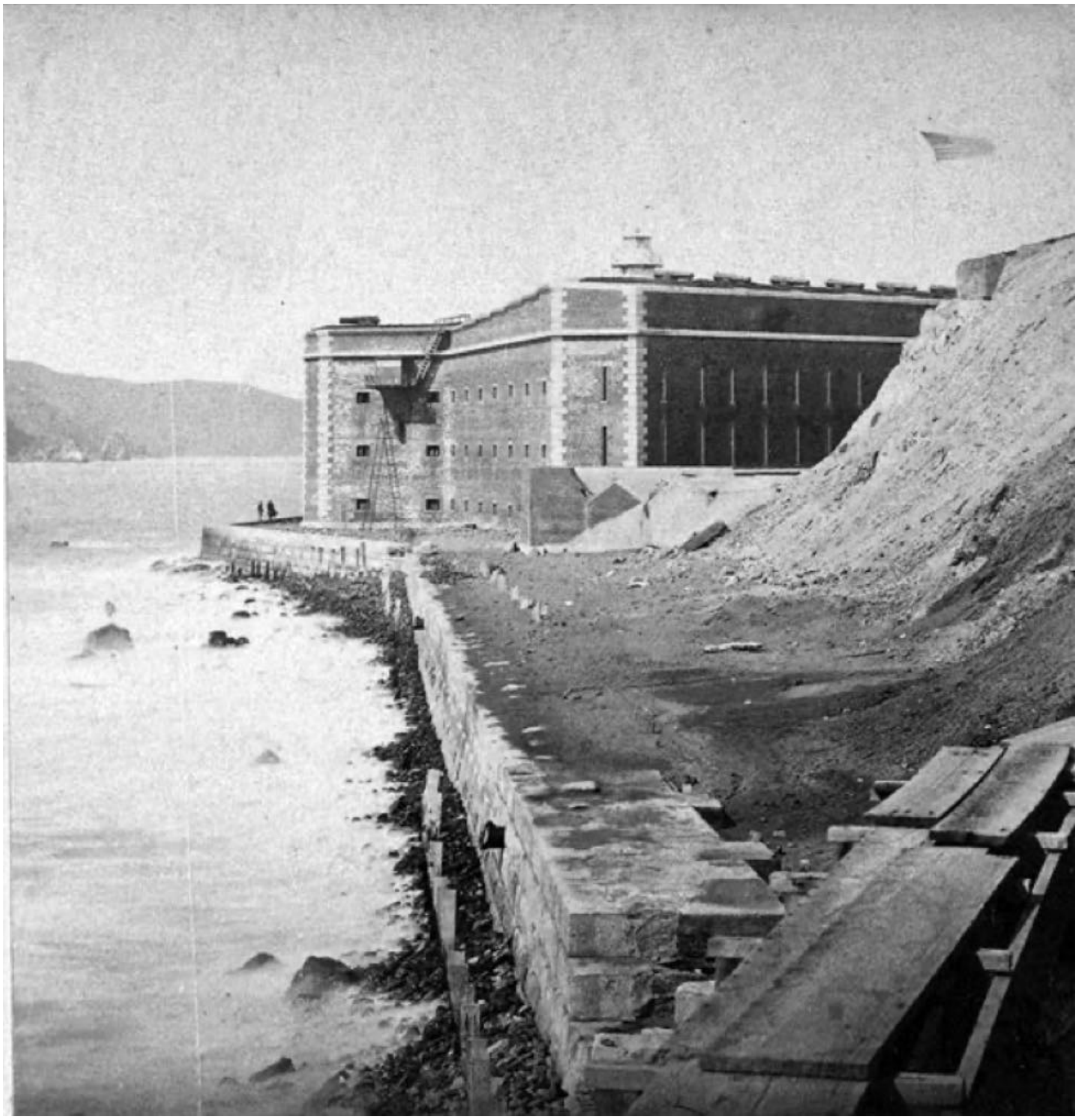


Figure 2-8. Lobos Flume at Fort Point (Photo: Carleton Watkins, 1866)

SFCWW's offices were at 805 Montgomery Street near Jackson Street. Their supply was 2,000,000 gallons daily. They advertised to ships, at the foot of Sansome and Pine Streets, the sale of water at $5 per ton or $0.02 per gallon[11]. A water pipeline distribution grid was constructed into the ever-growing city. This pipeline grid was built using cast iron pipes, generally 3- to 4-inch diameter in residential streets, and 8-inch diameter in

[11] Weekly Alta California, Volume 1, Number 36, September 1849.

larger commercial streets. This initial water system was focused on delivering water for sanitary and consumption purposes.

Figure 2-9 shows a remnant of the Lobos Creek flume, circa 1900, by which time the flume had been taken out of service. The reason that the flume was taken out of service relates to the degraded water quality of the source water in the Government Reserve (Mountain Lake, Lobos Creek), and possibly, in part, by the competing local demand by the Army for water in the Presidio. Within the Presidio, the Army ultimately constructed their own 2 MG reservoir just to the north of Mountain Lake, with source water from local springs. The Army constructed their own water distribution pipes, cast iron pipe in the 1800s and through the middle 20th century, and asbestos cement pipe more recently. A water treatment plant was eventually built in the Presidio, able to treat up to 2 MG from Lobos Creek; this treatment plant was upgraded (including seismic renovations) in the mid 1980s. The water system in the Presidio was run more-or-less independent of the City of San Francisco water system from 1900 to 1994. After 1994, the National Park Service operates this water system (water treatment plant, pipes, the 2 MG reservoir and related facilities) in the Presidio. Today (2024), the water system in the Presidio continues to be largely separate and disconnected from the water system serving the rest of the City of San Francisco.

Figure 2-9. Remnant of Lobos Creek / Black Point Flume (c. 1900). Alcatraz Island in the background. (Photo credit: SFPUC)

The Francisco Street reservoir was built in 1859. See Figure 2-10. It was the first large reservoir in the City of San Francisco. When originally built, it had a storage capacity of about 6.5 million gallons. In 1859, water was delivered via the wooden Lobos flume and pumped up hill to the reservoir via the Black Point pump station. With the eventual abandonment of the Lobos flume, this reservoir was filled with water coming from SVWC's San Andreas reservoir via the San Andreas conduit and via a 22-inch pipe from the College Hill reservoir. Once the Crystal Springs reservoir and conduit were constructed, the Francisco Street reservoir was filled with water by gravity flow from Crystal Springs reservoir via the University Mound reservoir.

By 1957, the Francisco Street reservoir had fallen into disuse, and remained empty for decades. Since 1957, various groups considered re-use of the land for housing. By 2022, this reservoir site had been redeveloped to store about 500,000 gallons of treated stormwater, in an underground basin, with a park atop the basin; the water is used to operate 6 toilets. Presently (2024) the basin is not part of the modern potable water system and does not provide water to fire hydrants.

Figure 2-10. Francisco Reservoir, 1904. (Credit SF Library)

The Black Point pump station, Figure 2-11, was originally built c. 1858. Source water was the Lobos flume, delivered at a grade line just a few feet above the tide level. The pump station (smaller building with two stacks) boosted this water into the Francisco Street and the Lombard Street reservoirs. The larger building (center left of photo) was the San Francisco Woolen Mills.

By the time of the 1906 earthquake, the pump station had been reconfigured to be able to take source water from either the College or University Mound pressure zones or the Francisco Street reservoir, and pump it up to the Lombard Street reservoir or Clay Street tank; further, water from the higher elevation zones could be regulated downhill into the lower zones. At the time of the 1906 earthquake, under normal day-to-day operation, pumping at the Black Point pump station was not normally needed.

The Black Point pump station consisted of engines that were purchased second hand from an old wrecked steamer in Oregon. The engines were low pressure, connected to four ordinary piston pumps, capable of delivering the water either to the Lombard Street or Francisco Street reservoirs.

Figure 2-11. Black Point Pump Station and Lobos Flume, c. 1864. (Credit: GGNRA Archives)

With the construction of the AWSS from 1909-1912, the Black Point pump station was again reconfigured, being entirely disconnected from the potable water system and re-purposed to pump salt water from San Francisco Bay into the AWSS. Presently (2024), this pump station is called AWSS Pump Station No. 2.

2.1.4 The Olympic Salt Water Company, 1892 - 1894

The following is adopted from an article by Arnold Woods (2021), the Western Neighborhoods Project, and information from the newspapers of 1893.

The San Francisco Olympic Club was established in 1860. The club was geared to foster health via gymnastics. In the 1800s, membership included Mark Twain, William Randolph Hearst and many other notables.

In the early 1890s, the club decided to construct an indoor salt water swimming pool. The facility was located on Post Street between Mason and Taylor. The pool opened in 1893.

Figure 2-12 shows the layout of the salt water system. The reservoir and pools were filled with salt water from the Pacific Ocean. While salt water from the Bay was nearer, the water from the Bay was considered to be too polluted. The route for the pipe system began near Point Lobos, where an intake pipe and pump station were constructed; the pipeline went east along Point Lobos Avenue and filled a 3 million gallon reservoir in the Laurel Heights area. From there, water would flow by gravity to the swimming pool on Post Street, and the pipeline would continue all the way to the Bay to discharge. The intake, pump station, reservoir and pipeline were owned by the Olympic Salt Water Company, which was incorporated in 1892, capitalized with $350,000. The pump station cost $10,300. The pumps were designed to pump 3 million gallons per day, with the amount not delivered to bath houses, residences, tanks or fire hydrants, to be wasted into San Francisco Bay.

Figure 2-13 shows the salt water intake pipe on the pier that extended 650 feet into the Pacific Ocean. Suction was available only during high tide. The pier was known locally as either the Lurline Pier or the Olympic Pier.

The pipeline was to deliver 200,000 gallons of salt water to the Olympic Club each day. The pipeline was completed in 1894. The pipeline was cast iron. The 3 million gallon reservoir (elevation 266 feet) was completed soon thereafter. First salt water deliveries to the Olympic Club pool on Post Street were on April 17, 1894.

A second bath house, called Lurline Baths (Figure 2-15), opened in 1895. Another bathhouse opened in Folsom between 4th and 5th. There were many other salt water customers, including other bathhouses, hotels, clubs and the Steinhart Aquarium. Only a few of these other customers are shown in Figure 2-12.

Figure 2-12 shows a map of the Olympic Salt Water System. Solid green lines show where the cast iron mains are known to have been laid; dashed lines where speculated. The base map is dated late April, 1906, prepared by the US Army, to highlight locations where the army set up relief camps after the earthquake. The heavy red line shows the final extent of the fire of April 18 to 20, 1906. Also noted in this map is the SVWC Market Street reservoir: more of this in another section. The total length of cast iron pipe was about 6 miles. There are no reports of any damage to the salt water system in the 1906 earthquake, and in fact, water was drawn from at least one salt water hydrant during the fire. Schussler's map of location of damage to SVWC's city distribution system water mains in the 1906 earthquake shows no known water pipe damage on Post Street or 3rd Streets. There were reportedly hydrants every block along the pipeline's alignment.

By the time of the 1906 earthquake, the salt water system had been in use for about 12 years, and some build-up of tuberculation on the inside of the pipes would likely have occurred. The gravity flow from the reservoir at 266 feet, via a 12" main over a distance of 3 miles, assuming mildly tuberculated mains (say C = 100), would have been able to deliver a flow rate of about 2,000 gpm, right in the vicinity of the main fires along Market Street and the South of Market area. The 3 MG reservoir would thus have been able to supply water to the fire area for about 25 hours. Yet, the water from this salt water system was insufficient to control the initial fires in the 3rd Street area during the first day, April 18, of the earthquake. Once the initial fire ignitions spread more than a few hundred feet away from 3rd Street, the salt water pipe and its hydrants would have been of no practical use for fighting the 1906 conflagration.

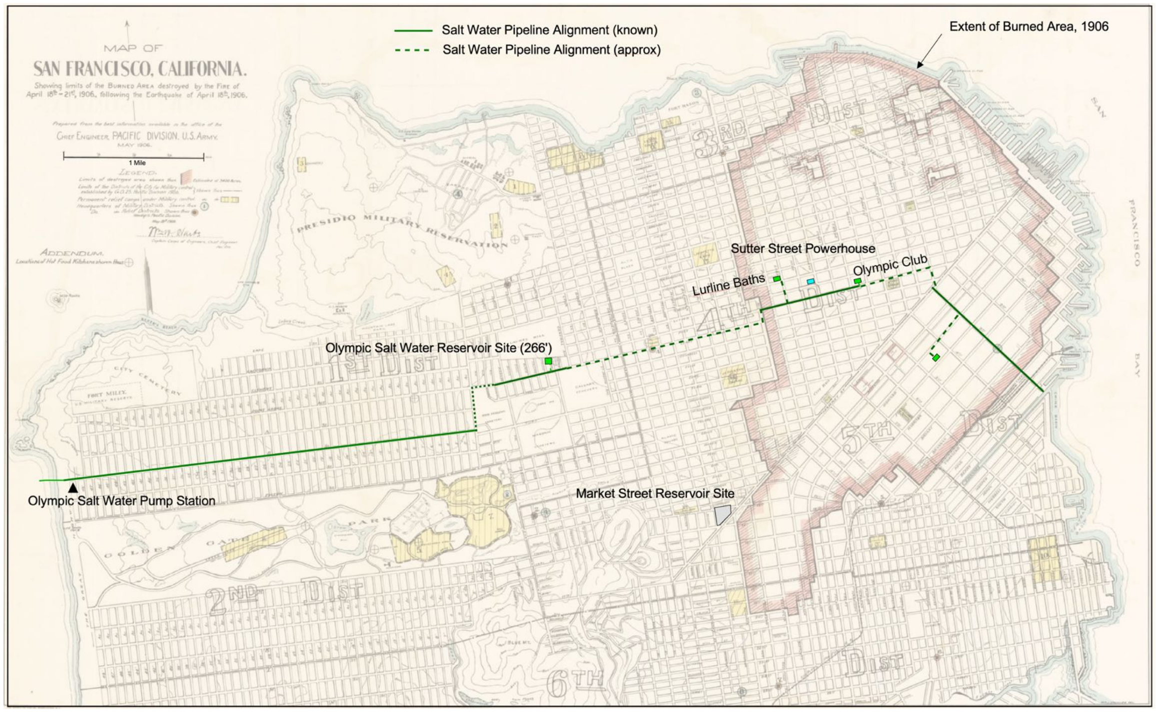


Figure 2-12. Map of the Olympic Salt Water System

Figure 2-13. Salt Water Intake Pipe (Bancroft Library)

Figures 2-14, 2-15 show the salt water pump station at Ocean Beach, c. 1895. The pump station is the structure with the tall stack, near the center of the photo. Sutro Heights is atop the cliff in the left foreground. Note the extensive sand dunes in the background, the area that would later be developed as the Sunset District.

Figure 2-14. Cliff Road and Bathing Beach; Stack and Salt Water Lurline Pump Station in Center (c. 1895, W. C. Billington, photographer)

Figure 2-15. Cliff Road and Bathing Beach; Stack and Salt Water Lurline Pump Station on Right (c. 1890 California Alta)

Figure 2-16 shows the Lurline bath house. This was a large structure, and by some accounts, the "strongest building" in San Francisco.

Figure 2-16. Lurline Bath House (c.1920, Marilyn Blaisdal Collection)

Figure 2-17. Collapsed street on 4th Avenue between Anza and Balboa on March 18, 1930. (Horace Chaffee, SF Department of Public Works book A2488). Salt Water pipe runs perpendicular to the trench caused by erosion from the broken 12" pipe. It took 2 hours to isolate the leaking pipe.

The Laurel Hill salt water reservoir was located near Euclid and Masonic, consisting of a large basin and some settling tanks. Ground elevation was about 266 feet above sea level. The salt water pipe was 12", 14" and 16" diameter; coated with asphaltum and paraffin for external corrosion protection.

The pipe ended at the foot of 3rd Street, where wasted water would be discharged into the Bay. Total length of pipe was about 6 miles. At the Pacific Ocean Beach location, a sand separator was included.

Mr. Adolph Sutro objected to the construction salt water system. He objected to a "smoking pump house at the beautiful location in front of the sea shore at Sutro Heights". He later stated "The applicants for this franchise are after a monopoly such as the Spring Valley Water Company possesses. What the applicants desire is to fatten "*this*", patting his pocket to express his meaning.[12] The backstory was that the land for the reservoir and pump station was originally offered by Mr. Sutro, but the Olympic Salt Water Company eventually purchased other land. The claims about the beauty of Ocean Beach being marred: well, that is in the eye of the beholder, and probably so. The San Francisco Board of Supervisors were apparently not convinced by Mr. Sutro's arguments, so the franchise was approved, and the salt water system was constructed. As part of the franchise, the salt water company agreed to pay 2% of its earnings to the City, the salt water could be used free of charge anytime to flush the City's sewers, and the salt water could be used free of charge to fight fires.

By 1904, the salt water system had 28 fire hydrants on its salt water pipeline system.

The 1906 earthquake destroyed the Olympic Club and the Lurline Baths structures.

The Lurline Bath house was rebuilt after the 1906 earthquake, and closed permanently in 1936.

By 1955, there were only 6 customers on the salt water pipeline: the Olympic Club, the Steinhart Aquarium, a business at Playland (amusement Park at the Ocean Beach), two other small bathhouses, and occasionally, the San Francisco Fire Department.

The salt water pipeline was abandoned in the mid-1960s. In March 1967, the Lurline Pier was torn down. The pump station was demolished along with Playland in 1972.

2.1.5 The Spring Valley Water Works, 1858 to 1930

By act of the California legislature on April 23, 1858, the Spring Valley Water Works (incorporated June 19, 1858) was authorized to lay down water pipes in the public streets of San Francisco. The company was under the guidance of Colonel Von Schmidt. The name later changed to Spring Valley Water Company, SVWC, which is used throughout this report. The original Spring Valley Water Works offices were at the southeast corner of Montgomery and Jackson Streets.

SVWC first delivered water from Islais Creek (Mission Creek, Dolores Creek, etc.) into San Francisco on April 4, 1861, filling a new reservoir on Potrero Hill.

[12] San Francisco Examiner, January 28 1893.

By 1860-1861, it became clear that the demand for water by the growing City would soon outstrip the available supply from Islais Creek (Von Schmidt's company) and the Lobos Creek (Bensley's company) systems. SVWC purchased five or six hundred acres of land around Pilarcitos Creek, built a small dam across that creek, and constructed the original Pilarcitos conduit that delivered that about 2 MGD to Laguna Honda. Much of the original 1862-viintage Pilarcitos conduit was wooden flume (Figure 2-18), on a grade of about 7 feet per mile (slope 0.0013), two feet wide and 16 inches deep. Portions of this flume ran along a similar alignment as the later-constructed 1868-vintage riveted wrought iron Pilarcitos pipeline. With the 1862-vintage flume, and a few tunnels and pipes, the first water from Pilarcitos reservoir was delivered to Laguna Honda in 1862. Most of this original flume was removed and replaced with a 30-inch riveted wrought iron pipe in 1868, except the 5,320-foot-long Ocean Avenue flume, which was upsized in 1868. From Laguna Honda, two 12-inch cast iron pipes were laid down Haight Street to Market and Buchanan Streets to deliver water to the original Market Street reservoir. Critically, the Market Street reservoir was subsequently destroyed by the cutting through of Ridley Street, at the direction of the San Francisco Board of Supervisors in 1894; this was a critical error and in part led to the fire conflagration of 1906.

Figure 2-18. Pilarcitos Flume 1913. Looking north, near Ocean Avenue (Credit SF Library, dpwbook6 dpw 1590)

Laguna Honda (Figure 2-19) was originally planned to have a capacity of 100,000,000 gallons (it was actually constructed with about 30,000,000 gallon capacity). Spring Valley also built the Islais reservoir (corner of Brannan and 16th Streets), capacity 500,000 gallons.

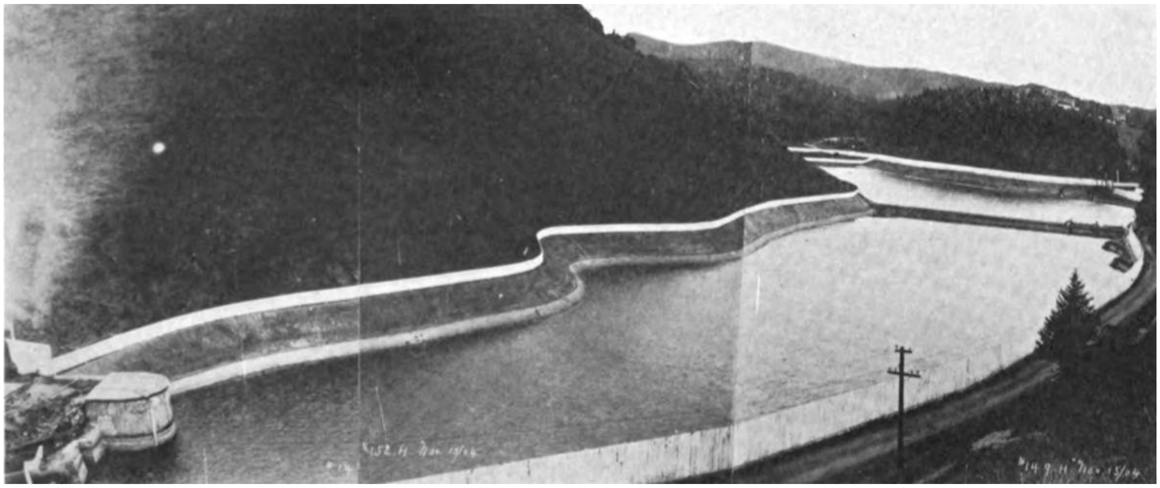


Figure 2-19. Laguna Honda (Schussler 1909)

With the ever growing water demand, and with the hiring of Mr. Schussler in 1864, the company surveyed the watersheds around Pilarcitos Creek, and identified that it could produce substantially more water than the original 2 MGD from the original small dam. The company bought about 4 to 5 square miles of land, and then constructed the second Pilarcitos Dam, with a clay core, impounding a reservoir of nearly 600,000,000 gallon capacity. This dam later was enlarged (Figures 2-20, 2-21) to impound a reservoir of about 1,050,000,000 gallon capacity. With the enlarged dam, a new (c. 1868) Pilarcitos pipeline was laid, using about 64,000 feet of 30-inch wrought iron pipe, upsized flumes, and three of the original tunnels. The new 1868-vintage Pilarcitos conduit could deliver an increased flow of up to 10 MGD to Laguna Honda. This "new" (c. 1868) Pilarcitos pipeline is the pipeline that suffered so much damage in the 1906 earthquake, and will be discussed in detail in Section 4.1.

Figure 2-20. Pilarcitos Dam Under Construction, 1867-68 (SVWC, 1867)

Figure 2-21. Pilarcitos Reservoir (Aerial image courtesy Google, April 2010)

In the construction of the Pilarcitos pipeline, Schussler noted that the San Andreas Valley could be dammed, with the potential to store about 6,000,000,000 gallons of water. The company, through agents, proceeded to buy up that land, gaining an additional 4 to 5 square miles of watershed. The construction of the San Andreas Dam commenced in 1868, an earthen dam with a clay core, 700 feet long at its crest, and 95 feet high (Figure 2-22). Unrecognized at the time of initial construction, the main trace of the San Andreas fault runs through the native materials near the eastern end of the dam (foreground in Figure 2-22, further discussed in Section 4.1.11). In the 1906 earthquake, there was at least 7 feet of right lateral offset at this location. Schussler reported (1909) that the dam bent into an "S" shape, but remained perfectly water tight (see Sections 4.1.11 Site 11, 4.1.12. Site 12, for more information).

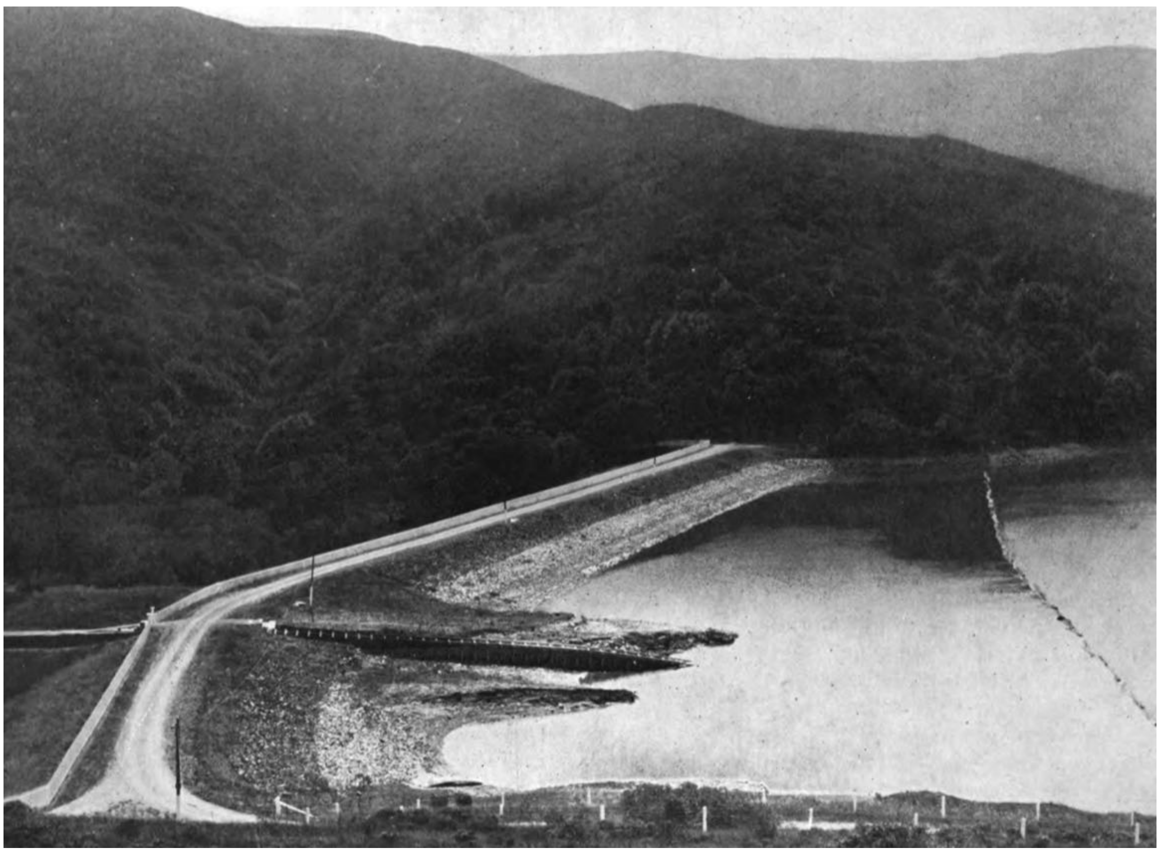


Figure 2-22. San Andreas Dam, Looking West (Photo: SVWC c. 1900)

With the ever increasing demand for water, the next reservoirs constructed were the Upper and Lower Crystal Springs reservoirs. The Upper reservoir was formed by building an earthen dam in 1877 that impounded water from local creeks. The Lower reservoir was formed by building a concrete dam (sometimes called the Lower Dam or Crystal Springs Dam) between 1887 to 1890. For the Lower Dam, Schussler decided that a stone masonry or concrete dam was more suitable than an earthen dam; lacking a suitable nearby quarry for large stones, he opted for concrete. By the time of the 1906 earthquake, the Lower Dam had an overflow height of 289 feet. With the construction of the Lower Dam, the water heights of the basins (Upper and Lower) were equalized and floated together, with a combined impoundment capacity of 19 billion gallons when filled to elevation 289 feet. The Upper Dam was eventually increased in height to form the Highway 35 causeway. The long term plan was to eventually increase the height of the Lower Dam to elevation 323 feet, to eventually impound 33 billion gallons; the most recent renovation of the Lower Dam was completed in 2012, resulting in an increased storage capacity of 22.5 billion gallons.

Table 2-2 lists the population and water demand (average daily demand over a year) for San Francisco from 1848 to 2021. Once the gold rush began in 1849, San Francisco's population quickly grew from about 1,000 people (1848) to nearly 25,000 people by December 1849. By 1860, with the discovery of the Comstock silver deposit near Virginia City, Nevada, the City's population had increased to nearly 57,000 people. the expansion of the SVWC water system from 1860s to 1930 was driven by the increasing population and its increased demand for water.

Table 2-2 summarizes the population and water demands in San Francisco from 1848 to 2023.

Year	San Francisco Population	Water Demand, MGD	Water Demand per capita, gallons / day	Comment (Supply source, approximate capacity in MGD)
1848	1,000			
1849	25,000			Gold Rush Begins
1852	34,776			
1860	56,802			Comstock Silver Rush
1862				Lobos flume (2 MGD)
1864				Pilarcitos flume (2 MGD)
1865	110,000	2.36	21.5	
1868				Pilarcitos 30" pipe replaces flume (10 MGD)
1870	149,473	6.04	40.4	San Andreas 30" pipe (6 MGD)
1875	190,000	11.68	61.5	
1877		11.94		Upper Crystal Springs 44" pipe (8 MGD)
1880	233,959	12.67	54.2	
1885	265,000	17.05	64.3	
1888				Alameda 36" (10 MGD)
1890	298,997	20.43	68.3	Lower Crystal Springs 44" pipe (10 MGD)
1895	330,000	19.90	60.3	
1897		23.70		Water demand per Fire Engineering, April 8, 1898. 40,189 service connections, an increase of 834 over 1896

Year	San Francisco Population	Water Demand, MGD	Water Demand per capita, gallons / day	Comment (Supply source, approximate capacity in MGD)
1898		23.98		Second outlet Bald Hill Tunnel. San Andreas pipe upsized to 44"-37" (9 MGD).
1899		25.14		Water demand per Hering, 1903
1900	342,782	26.47	74.3	12,000 people living in San Mateo County
1901		26.71		
1902		29.53		Alameda 54" (15 MGD)
1905	455,000* 400,000**	34.89* 29**		*SVWC (1909) estimate **NFBU (1905) estimate
1906	375,000		80	Estimate
1910	416,912	40.0		
1911		37.5 - 39.0		
1913		41.5		
1920		55		Estimate
1923				60" BDPL 1 first delivery of Sunol water to Crystal Springs (up to 50 MGD)
1930	634,394	72		City of San Francisco purchases the SVWC water system serving San Francisco, at a cost of $39,962,606.51
1933				66" BDPL 2 delivers Hetch Hetchy water to CS (55 MGD)
1940	634,536	90		Estimate
1950	775,357	110		Forecast (1909)
1960	740,316			
1970	715,674		100	
1980	678,974			
1990	723,959			
2000	777,340			
2010	805,519			
2020	873,965	86	98	
2021	815,201			Covid Exodus
2022	808,437			
2024	2,300,000	230 (Complete system)	100	Portions of BDPL 1, 2 retired and replaced by new 72" BDPL 5. System capacity 330 MGD.

Table 2-2. San Francisco Population and Water Demand (US Census, SVWC, SFPUC data)

In Table 2-2, the population data listed at decades is based on the US Census Bureau; the population data for other years is based on SVWC estimates; the Average Daily Demand for water is based on SVWC data. The rapid growth of water demand between 1900 and 1905 (25.47 MGD to 34.9 MGD) is thought to be accurate, and SVWC might have forecast the population by using the water demand data and assigning a constant 74.3 gallons / capita / day using the year 1900 data. At the time of the 1906 earthquake, supply capacity to the three terminal reservoirs was:

- Lake Honda. 10 MGD.
- College Hill. 9 MGD.
- University Mound. 25 MGD (10 from Crystal Springs, 15 from Alameda)

Over time, from 1933 to 2024, the SFPUC has added many wholesale customers along the Hetch Hetchy system. Today (2024), the system delivers up to about 80 MGD to San Francisco, and up to about 250 MGD to 27 wholesale customers along the modern BDPL 1, 2, 3, 4 and 5 pipelines. Today (2024), the system has a gravity flow capacity to deliver about 330 MGD, and an average day demand of about 230 MGD.

Figure 2-23 shows the (2006) facilities of the modern reservoirs and facilities in the Peninsula.

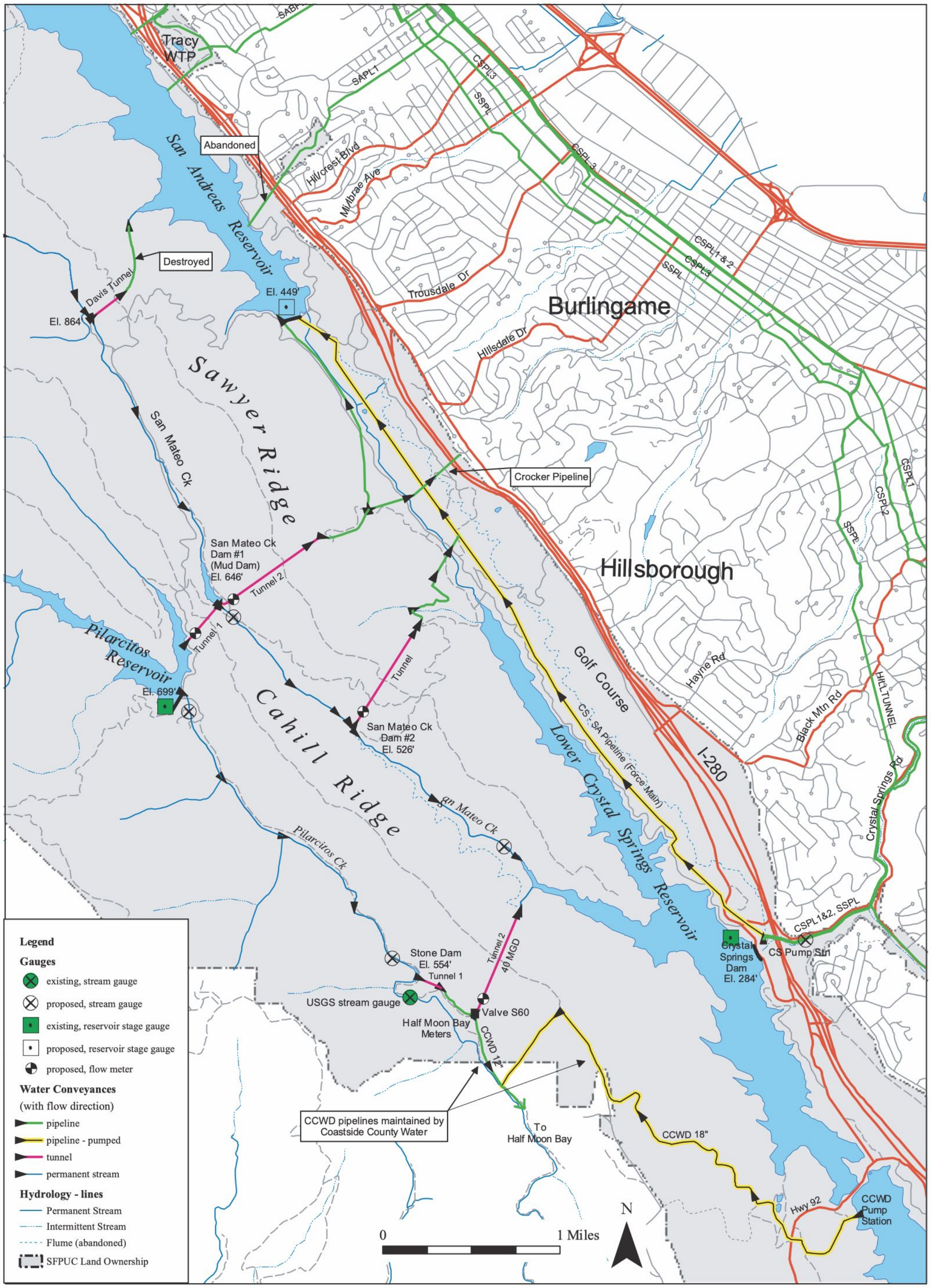


Figure 2-23. Pilarcitos Facilities (Based on Hand Drawn Map of J. Chester, SFPUC, 2006)

Figure 2-24 shows a map of the Pilarcitos water system from 1875. At that time, the lower Crystal Springs reservoir had not yet been built, and portions of the 1875-vintage Locks Creek Flume, which traversed the northern reach of lower Crystal Springs Reservoir, were ultimately removed by 1890. In Figure 2-24, the San Andreas Creek flows from the San Andreas Dam and to join with San Mateo Creek. The "proposed dam" site is where the Lower Crystal Springs Dam would be eventually constructed.

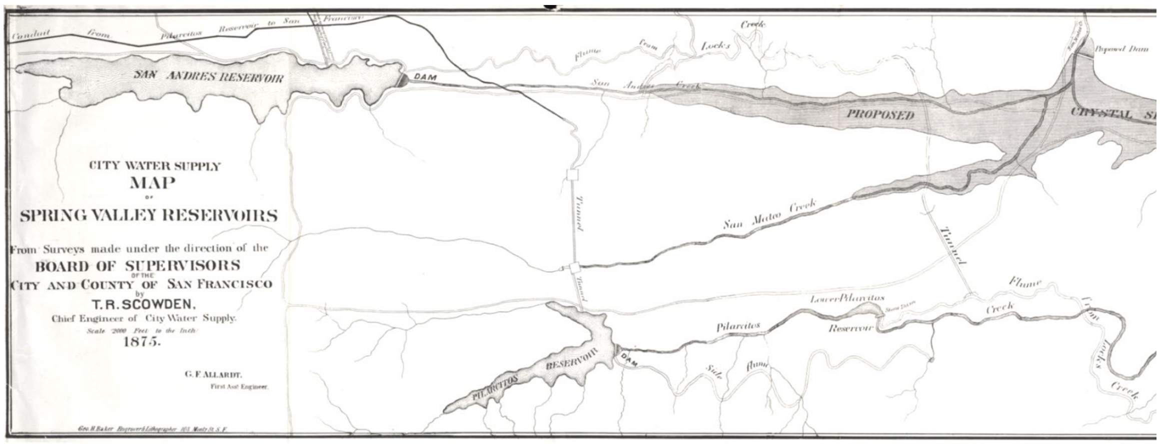


Figure 2-24. SVWC Peninsula Water System, 1875. (Map by T. R. Scowden, 1875)

The total reliable supply from Pilarcitos, San Andreas and Crystal Springs reservoirs with their watersheds was about 19 MGD. By the 1870s, it was apparent that the continued growth of San Francisco would require almost 100 MGD by 1950. So, SVWC bought lands around Alameda Creek and surrounding watersheds in Alameda County, south of Sunol (Figure 2-25). The initial waterworks in Alameda County relied on creek run off to an area of gravel beds near Sunol, from which a flume, tunnel and pipeline system was soon built by 1888 to deliver an additional 10 MGD to San Francisco. This watershed area, upon full development including Calaveras Reservoir, Del Valle Reservoir, San Antonio Reservoir, and local wells, coupled with the Peninsula reservoirs, could eventually supply about 220 MGD, more than two times the supply that the City of San Francisco's water demand could ever reach at city build out (then thought to be about 100 MGD by 1950, but in practice, about 80 MGD as of 2024). Chapter 9 of this report, "Hetch Hetchy", delves into the details, and how it came to be that the Hetch Hetchy system with source water from the Tuolumne River was eventually developed. Historically, the development of the Alameda system was as follows:

- By 1888, water from the gravel beds in Sunol was delivered into a tunnel and flume through Niles Canyon, then along a 36-inch pipe to the Dumbarton Bay Crossing, then on 16,000 feet of wood pile-supported pipe through the shoreline areas of the Bay, then in twin 16-inch diameter pipes through two submarine sections under the Bay, then boosted at the Ravenswood pump station, then by 36-inch pipe to Belmont where there was a standpipe to control the head / surges, then by 36-inch pipeline to connect to the 44-inch Crystal Springs pipeline.

- By 1902, an increasing flow rate was developed by adding twin 22-inch submarine pipes under the Bay, and adding a parallel 54-inch pipe along the Peninsula to supply the pump station at Millbrae.

- By 1909, SVWC had purchased some 30,000 to 35,000 acres (47 to 55 square miles) of lands and water rights in the vicinity of the Alameda Creek watershed area, with lands reaching from Mount Hamilton in the south, all the way to Livermore in the east and Mount Diablo in the north, with nearly 600 square miles of watershed.

- In 1913, construct the initial Calaveras Dam. The initial dam had a slope failure in 1918, and was replaced in 1925. The 1925-vintage dam was replaced by a new dam in 2019. The original Dam formed a reservoir filled by run-off from Alameda Creek and other tributaries. Once the Hetch Hetchy system was constructed, the reservoir was filled, in part, with excess flows from water coming from the Sierra via the Hetch Hetchy aqueduct.

- The Alameda conduit was upgraded after the construction of the initial Calaveras Dam, by converting the original Niles Canyon wood flumes to reinforced concrete, as well as enlarging the flume's cross sectional area through Niles Canyon.

- By 1923, the first BDPL 1 60-inch riveted pipe (part of the Hetch Hetchy system) was constructed between Fremont and the Upper Crystal Springs Reservoir. However, the upstream portions of the Hetch Hetchy system would not yet be complete for another decade. In the interval between 1923 and 1932, SVWC water from Sunol was put into the BDPL 1 pipe, via a transfer pipe between the western terminus of Niles Canyon flume and the eastern terminus of BDPL 1. During this time period, both the 36-inch Alameda pipeline and the 60-inch BDPL 1 pipeline were in service.

- In 1930, SVWC sold most of its assets to the City of San Francisco for $40 million. This included the watersheds for the three reservoirs along the Peninsula, portions of the Alameda watersheds (notably Alameda Creek and lands for Calaveras and San Antonio reservoirs).

- SVWC did not sell to the City of San Francisco its water rights and lands for Del Valle and Coyote reservoirs or the aquifers in the Livermore Valley. These lands and water rights were eventually developed into water supplies by the California Department of Water Resources (Del Valle Reservoir, part of the South Bay Aqueduct, 1950s); Santa Clara Valley Water (Coyote Reservoir and Anderson Reservoir); Zone 7 (Pleasanton ground water); CalWater (Livermore ground water); etc.

- By 1933, the 66" BDPL 2 pipe was completed, and the Irvington Tunnel of the Hetch Hetchy system was put into service. With the twin BDPL 1 and BDPL 2 pipes in service, the original 36" Alameda pipeline was made more-or-less redundant, and was taken out of service. The original 54" Alameda pipeline (built 1902) was renamed Crystal Springs pipeline No. 2, and remains in service in 2024.

2.2 What Should Be Water Rates and the Birth of Hetch Hetchy

From the earliest development of piped water systems for San Francisco in the 1860s, there was an ever-present tension: should a private water system (SVWC) have a monopoly for delivering water to San Francisco, or should a publicly-owned water system deliver water to San Francisco?

- In the 1850s and early 1860s, the answer was clear: The nascent City could not afford to build its own water system, and thus it had to turn to private companies and private capital.

- In 1867, the San Francisco Board of Supervisors created the "San Francisco Water Company", incorporated July 22, 1867. The purpose of this entity was to investigate sources of water that could supplement and/or replace the SVWC water system. A series of surveys were conducted to prepare concepts and cost estimates to deliver water from sources such as Pescadero Creek, Clear Lake and Lake Tahoe. A series of consultants were retained to investigate the issues (1872 to 1875).

- In 1868, the larger San Andreas reservoir had yet to be built. A drought led to a water shortage for the rapidly growing city. The City announced that people should drill taps into the SVWC pipes and obtain water for free. SVWC threatened to shut off water to the City. The belligerence and distrust which boiled over in 1868 led to many lawsuits between the City and SVWC for the following 6 decades.

- By the 1890s, the City had grown substantially and was wealthy enough to invest significant capital in a water system.

- By 1900, the rapid growth of the city led to ever-increasing demand for water, and there were open questions as to whether the new supplies being developed by SVWC were sufficient either in terms of quantity or quality.

In 1895, a great fire occurred south of Market street, after which the City asked SVWC to extend its large diameter water pipes. To which SVWC replied: "*Our water pipes are sized large enough to supply our customers – that is private customers, who furnish fully 90% of our revenue. If you (City) want us to increase the size of our pipes, and thereby give you a fire service at the same time, and if you will contribute towards it by giving us* *a better rate on hydrants, we will put in larger pipes for fire purposes*" (Schussler 1909). With the understanding that the revenue per hydrant would increase from $2.50 per month to $5.00 per month permanently, SVWC went ahead at once and spent in a few years very large sums of money to increase the size of pipes, commonly by installing new 12-inch or 16-inch pipes parallel to existing 6-inch or 8-inch pipes. By 1898, the City paid about $245,000 for the fire hydrant fees for the year.

Then came the debacle with the new regime (Phelan) and the new City Charter of 1900. Phelan was elected mayor in 1897 and served until 1902. Under the new regime, SVWC reported that "*the City paid whatever they felt like paying*", with payments having a rapid decline after the year 1900.

Between 1895 and 1900, SVWC had spent about $2,000,000 to increase its pipe system, for which extra investment it was paying interest of (about) $90,000 per year, atop of the initial capital cost. But the parties in control (the Board of Supervisors) cut the annual payment from about $226,000 in 1900 to $161,000 in 1902, to $93,000 in 1904, to $65,000 in 1906. SVWC, faced with loss of funding, was compelled to decrease its extension of larger mains for fire purposes. Then came the April 18, 1906 earthquake and fire.

Prior to the new City Charter, SVWC had purchased the Industrial reservoir site, 42 acres, sized for a 400- to 500-million gallon reservoir with overflow elevation of 310 feet (site 9 in Figure 2-27). This was contingent on the City continuing to pay the increased hydrant fees. But, while the Board of Supervisors prior to 1900 was willing to do so, that was not the case for the newly elected Progressives of the Phelan administration in 1900. With the newly elected Progressives in charge of water rates, Schussler reported (1909): "*we had to live hand to mouth and practically stopped all work*". The Industrial reservoir was never built.

Similarly, SVWC wished to rebuild an older 2 MG Market Street reservoir (site 8 in Figure 2-27) as a much enlarged 16 to 20 MG reservoir on an elevated rocky knoll, from which a large independent fire main would be built along Market Street, to and through the main business district, studded with hydrants. In 1865, a 2 MG reservoir stood at that location (Figure 2-12). The City answered by ordering a new Ridley Street be constructed through the reservoir site, not only destroying the original reservoir, but also putting a quietus on the SVWC plan for building a large fire protection reservoir there in the heart of the city. Further, SVWC was ordered to pay an assessment of $60,000 for cutting the street through, thus permanently destroying this unique reservoir property (Schussler 1909).

To be understood is that under the new City Charter, the City was willing to set water rates to be based on 5% of SVWC's assessed value for delivering water to customers. This required the establishment of the assessed value. The City directed its City Engineer, Mr. Grunsky, to compute this value.

- The City Engineer valued the SVWC at $24,667,000.
- In 1901, SVWC spent about an additional $1,000,000 for improvements. The Board of Supervisors reduced the City Engineer's value to $22,940,000.
- In 1902, the City Engineer valued the SVWC at $24,466,000. In 1902, SVWC spent about an additional $700,000 for improvements. The Board of Supervisors reduced the City Engineer's value to $23,914,000.
- In 1903, the City Engineer valued the SVWC at $28,024,000. In 1903 SVWC spent an additional $500,000 in improvements. The Board of Supervisors reduced the City Engineer's value to $24,124,000.
- Then came another so-called expert, and the City valued SVWC at $24,673,000 in 1904. In 1904 SVWC spent an additional $540,000 in improvements. The Board of Supervisors reduced the City Engineer's value to $23,121,000.
- In 1905, the City valued SVWC at $25,000,000.
- Between 1905 and 1909, SVWC spent an additional $1,000,000 on improvements, and the City valued SVWC at $24,404,000 in 1909.

Schussler reports in 1909: "*Under these circumstances, no sane man or corporation was willing to invest more money for betterments, in an enterprise that, although vital to the City's existence and growth, was so unjustly and unfairly treated by the city authorities*".

By 1909, SVWC was contending with an uncertain future. Should the City of San Francisco eventually build the Hetch Hetchy system, capable of supply an average day flow of 400 MGD, then SVWC could be left "*holding the bag*" on a lot of land and water supply, while losing their primary customers. Schussler noted in 1909 that SVWC was considering selling water to other cities, notably the then populated areas from Niles northwards all the way to Berkeley. That East Bay population base, in 1909, was about 80,000 people (perhaps a quarter that of San Francisco), and was already supplied with water. The SVWC had already purchased land and water rights that could be developed to about 220 MGD, meaning they could support an eventual population of around 2 to 2.5 million people. Today (2024), the San Francisco Bay Area population exceeds 7.5 million people, with total potable water demand on the order of 600 MGD. But, in 1909, the owners of all this land and water rights and infrastructure were worried about who they would sell water to in the short term, so that they could remain in business, pay the interest on their bonds, and make a reasonable return on their equity. The ongoing threats by the City of San Francisco to condemn the SVWC lands and put SVWC out of business were an ongoing concern. To anyone with a neutral point of view, it was financially irrational (why have parallel water pipes down every street?) for the City of San Francisco to threaten to build parallel water pipes throughout their city, in order to deliver Hetch Hetchy water directly to end user customers. Suffice it to say, these issues bore hugely on the minds of SVWC and the burgeoning Hetch Hetchy developers, as to how new water supply infrastructure should be developed to meet the ever increasing demand for water. Recall that the entire water demand in 1909, for the entire San Francisco Bay Area, was perhaps 50 MGD, and much new infrastructure was going to have to be developed to meet the present-day demand of about 600 MGD.

In understanding some of the motivations of the SVWC, one needs to look into the way SVWC was to be paid for delivering water to San Francisco. The law of 1858 allowed for a sliding scale of revenue, geared to initially allow the rapid pay-back of initial capital expenditures over a time period of about 5 years (ergo rates of about 24% of assets over the first few years), then reduction to about 6% of assets, on a long term ongoing basis. At that time, the common rate of interest on bonds was about 4.5% for low risk ventures, and the 6% rate was set high enough to allow the water company to borrow money to build new infrastructure, while also having enough revenue for day-to-day operations. Schussler reports that between 1858 and about 1880, the City and SVWC fairly cooperated and the water rates were reasonable to allow SVWC to continually buy more lands and construct more reservoirs and pipelines to meet the ever-growing demand for water.

In 1880 a new Constitution was passed in California, and that Constitution changed the manner in which water rates would be set, giving total power to the San Francisco Board of Supervisors. That said, Schussler reports that the San Francisco Mayors and Supervisors from 1880 and 1900 were fair minded, and allowed a return of 6% on assets.

In 1900, as outlined above, the "troubles" began in earnest. The City of San Francisco passed a new Charter. The Charter included a clause stating that the City should have its own municipal water supply. The Charter provided that the City Engineer should be appointed, and this City Engineer, would work under the Board of Public Works. This Board was under the direction of the San Francisco Board of Supervisors. The Board of Supervisors directed the City Engineer to calculate a value of the SVWC. Schussler reported that his valuation, having spent a lifetime constructing the system, was between $40 and $50 million. Schussler reports that when he submitted this valuation, the City Engineer and Board "laughed at me". Schussler based his valuation on what the entire works was worth, including its potential for future necessary increases in water supply for an ever growing population. The City Engineer stated that only the cost of the present water system should be valued, and that none of the water system (lands, water rights) should be included until such time that they were put into actual use for delivering water. This led the City Engineer / Board of Supervisors to value the water system at around $21 to $25 million (this valuation varied yearly between 1901 and 1905, as described above).

Assuming everyone involved was fair minded and honest, the difference in valuations presented an intractable problem. The City's point of view was like: let us buy a factory that can produce 100,000 cars per year, but only pay half that amount, as presently the factory only produces 50,000 cars per year. From the owner's point of view, they have invested in a larger factory with capacity for expansion. Clearly, something is amiss, and there would never be a sale if the buyer and seller have such different expectations.

The corruption in this scheme should be evident. While C.E. Grunsky (the City Engineer from 1900-1905 and one of the original architects of the Hetch Hetchy system) was denying that the value of SVWC's vast capability for expansion to 200+ MGD supply should be included in the purchase price, at the very same time Grunsky was promoting constructing a Hetch Hetchy system capable of delivering 60 MGD, quickly revised upwards to 400 MGD, at a time when the water demand in San Francisco was about 30 to 35 MGD.

Mayor Phelan ran for office with a key element of his platform to "put SVWC out of business". Most of the Board of Supervisors were on board with this. There were also private businessman who stated that should the City purchase water rights from the Sierra, the local water system serving the City would make a good foundation for an overall system, and that the City should purchase the SVWC system. Schussler pointed out, that "*when you want to buy a thing, it takes two people – buyer and seller*". Apparently, the City wanted to low-ball the price to pay for the water system, and SVWC was not especially anxious to sell. Between 1900 and 1905, there was increasing unfairness in the interpretation of water rates, with the City de-facto squeezing SVWC's revenues to below that needed to operate and upgrade a reliable water system and be able to pay its bonds and provide a fair rate of return to shareholders. In 1909, Schussler reported that "*SVWC's people gradually got worn and tired out, so that several directors gave it up as a hopeless task*". By "*it*", Schussler is not clear, but is interpreted to mean: selling SVWC to the City at a fair price, continued investment by SVWC in the water system, etc.

SVWC's response from 1900 to 1905 was natural: they substantially cut back on new construction, thus lowering their annual costs. Today (2024), a fair interpretation of this state of affairs was that the water company was being starved of funds, investments were curtailed, and new reservoirs and pipes within the City of San Francisco were not built. This is much the same argument as rent control: Initially, the renters "save" by not having seemingly ever-increasing rents charged by landlords; and landlords respond over time by reducing the amount spent on maintenance; and landowners respond by not building new buildings. In the long term, this leads to a deteriorating building stock, and a limitation on new supply of building stock. Should demand for buildings increase, the price skyrockets on new construction. Today, the price of housing is extremely high in San Francisco, and the root of this high price stems primarily by the restrictions on construction of new supply.

Well, the laws of supply and demand still operated much the same in 1900. As the San Francisco Board of Supervisors squeezed down the revenue to SVWC, SVWC responded by building less. The upshot was that in the 1906 earthquake, the critical water infrastructure that could and should have been built to provide reliable and high fire flows along Market Street, ***had not been built***. The lack of this infrastructure was a main contributing factor to inability of the fire department to rapidly control the initial fire ignitions, and led to the nearly complete demise of the majority of San Francisco. This is the editorial opinion of the authors, and some may politically disagree, as is their wont. But there can be no doubt, by any fair interpretation of the facts, that in 1905, the downtown and south of Market street areas of San Francisco were extraordinarily vulnerable to a total loss of water supply in earthquakes.

After the 1906 earthquake exposed the weaknesses of the SVWC water pipes in the liquefaction zones, there was an outcry to build a parallel "salt water" system. Schussler proposed to design and built it. The San Francisco Board of Supervisors wanted to build it, but not by SVWC; instead, the City's own Fire Department would build, maintain and operate it. Bonds were raised in 1907, and the system designed and constructed between 1909-1912. Incredibly, that brand new 1912-vintage salt water system remained entirely vulnerable to the same earthquake effects as the SVWC 1905-water system. In other words, the new pipeline system of the AWSS of 1909-1912, was nearly a total waste of money for its intended purpose: to reliably provide substantial fire flows after earthquakes. This was observed to be true in the 1989 Loma Prieta earthquake, when pipe failures in the AWSS caused the system to de-pressurize, and the pipe system did not provide any water to suppress the Marina fire for the first 3 hours after the earthquake. Fortunately, there was no wind at the time of the 1989 Loma Prieta earthquake, and the initial Marina fire did not spread; but had it been windy, like 20 mph breezes so common in October, much of the City could have burned down again. Chapter 8 of this report examines the AWSS in more detail.

2.3 The SVWC System and Fires

There was no explicit seismic design for the original SVWC water pipeline system. The system was capable of delivering fire flows for day-to-day fires, with nearly 6,800 fires controlled without any material fire conflagrations for the 15 year period prior to the earthquake, see Table 2-3. There were no major conflagrations, which confirms that the SVWC water system, leading up to 1906, was adequate for both domestic service and fire service, at least under non-earthquake conditions.

Year	Total number of fires	Total fire losses ($1905)	Average loss per fire ($1905)
1891-1899 (avg per year)	631	1,023,769	1,620
1900	1056	525,412	498
1901	1182	661,461	560
1902	1212	691,225	570
1903	1342	1,602,157	1,239
1904	1356	791,340	584

Table 2-3. San Francisco Fire Losses, 1891 – 1904 (NFBU, 1905)

While the dollar values in Table 2-3 seem small by today's standard, the reader should understand that the rate of inflation from 1906 to 2024 would increase the values by a factor of 37; if one also accounts that modern (2024) construction is to a higher standard than that in 1906, then the rate of increase should be about 100 times. Thus, the average fire loss of $584 for 1905 is akin to an average loss of about $584,000 in 2024.

2.4 The SVWC System at the time of the 1906 Earthquake

Figures 2-25 through 2-28 show the regional and San Francisco distribution water system at the time of the 1906 earthquake.

Up to the time of the 1906 earthquake, there were six sources of water for San Francisco (year built, name):

1858 Lobos Creek. A flume (with tunnel segments) was built to deliver about 2 MGD from Lobos Creek to the Black Point (near Fort Mason) pump station, which delivered water to the Francisco Street and Lombard Street reservoirs. From these two reservoirs, water was delivered by gravity flow via cast iron pipes to downtown San Francisco. The demand for water in the growing City quickly outgrew the 2 MGD capacity, and there were also water quality issues. By the time of the 1906 earthquake, this source of water had been entirely abandoned. Section 2.1.3 describes this system in more detail.

1862-1868 Pilarcitos System. The initial 1862-vintage Pilarcitos system was a 32-mile long conduit, mostly built using wooden flume, that took water from a small dam in Pilarcitos Creek and delivered water to Laguna Honda. With the ever increasing water demand in the City, and with the constant need to maintain wooden flumes, by 1865 a new larger dam had been constructed along with a second tunnel that considerably shortened the total length of the conduit. Most of the original wooden flumes were replaced and by 1868, the new Pilarcitos conduit included 13 miles of 30-inch wrought iron riveted pipe. At the time of the 1906 earthquake, the Pilarcitos conduit brought water from Pilarcitos Reservoir (elevation 669 feet) to Laguna Honda (elevation 365 feet). Water from Laguna Honda served the upper elevations of San Francisco, generally 160 feet or higher, and generally west of Van Ness. After the southern portion of the Pilarcitos conduit failed in the earthquake, Laguna Honda was resupplied with water from Lake Merced, beginning 16 hours after the earthquake. The conflagration did not materially encroach into the areas supplied from Laguna Honda. Section 4.1 describes this system in more detail.

1870 San Andreas System. This 44-37-30-inch WI pipe brought water from San Andreas Reservoir (445 feet in 1906, 449 feet in 1928) to College Hill reservoir (252 feet). Section 4.2 describes this system in more detail.

1880 Crystal Springs System. This 44-inch WI pipe brought water from Crystal Springs Reservoir (288 feet) to University Mound Reservoir (160 feet). Section 4.3 describes this system in more detail.

1888 - 1902. Alameda System. A 36-inch wrought iron riveted pipe brought water from the Niles Aqueduct to a point where the pipe originally joined the 44-inch Crystal Springs pipeline. In 1902, this system was extended: the Sunol Aqueduct was built, the 36-inch pipe was continued with a 54-inch wrought iron riveted pipe to the Millbrae pump station, and two additional submarine crossings of Newark Slough and Dumbarton Strait were installed. Depending on water demands, pump stations at Ravenswood (if supplied from the Niles Aqueduct), Burlingame and Millbrae were used to boost pressure in the Alameda system so that water from the Alameda watershed could eventually reach University Mound or College Hill Reservoirs. Section 4.4 describes this system in more detail.

1862-2023. Lake Merced. Lake Merced is a natural fresh water lake located in southwest San Francisco. Ever since the 1850s, this lake was contemplated as being a potential source of fresh water for San Francisco. As soon as pipelines were laid near Lake Merced, beginning with the original Pilarcitos pipeline, connections to Lake Merced were built to allow Lake Merced water to flow to San Francisco. Lake Merced has an overflow elevation of about 26 feet above sea level, so access to this water required a pump station. The original pump station built was at the northwest end of the lake; this pump station was abandoned by the 1880s. A newer (and larger) pump station was subsequently built at the southeast end of the lake, and this pump station, with updates, remains in service to this date (2024). These pump stations were originally constructed to pump water into Lake Honda via the Pilarcitos pipeline. By the time of the 1906 earthquake, the newer pump station could pump water into either the Pilarcitos pipeline (to Lake Honda) or the San Andreas pipeline (to College Reservoir).

However, the water quality in Lake Merced was never ideal. Frequent winter storms would result in runoff of low quality water into the Lake. Algae and marine mammals degraded water quality. Various efforts in the 19th century were made to divert storm water from entering the Lake and mitigate the water quality issues; but none were entirely successful.

Therefore, at the time of the 1906 earthquake, under normal day-to-day operations, water from Lake Merced was never introduced into the SVWC system. However, given the disaster of the 1906 earthquake and the failure of all the upstream transmission pipes (Pilarcitos, San Andreas and Crystal Springs), the pumps at Lake Merced were turned on 8 hours after the earthquake, and water from Lake Merced was pumped into Lake Honda (via the undamaged northern portion of the Pilarcitos pipeline) and to College Hill Reservoir (via an intertie to the San Andreas pipeline). During and immediately after the earthquake, Lake Honda was never emptied and the upper pressure zones of San Francisco never entirely lost water service.

After the 1906 earthquake, the southern part of the Pilarcitos pipeline was abandoned. Soon thereafter, this abandoned pipe was dug up and relaid, and called the Baden-Merced pipeline; it was normally fed via the San Andreas pipeline, and at its northern end, delivered water into the new Central pump station, capable to pump 8 MGD from the Baden-Merced pipeline into the northern Pilarcitos pipeline, and thus to fill Lake Honda.

To this day (2024), the SFWD / SFPUC continue to maintain the pump station at Lake Merced, for the expressed purpose of using Lake Merced as an emergency source of water for San Francisco; even recognizing that water quality from Lake Merced remains inadequate for purposes of day-to-day consumption. Section 4.5 describes the Lake Merced water supply in more detail.

Figure 2-25 below shows the four main water transmission supply conduits (color coded) to San Francisco at the time of the 1906 earthquake. This figure also shows the modern (2024) interpretation of the location of the major earthquake faults in the region, including (from west to east) the San Gregorio, San Andreas, Serra, Monta Vista, Hayward and Calaveras faults. These four conduits terminated at the three major terminal reservoirs in San Francisco, namely the Laguna Honda, College Hill and University Mound reservoirs. In the east bay area near Sunol, the Calaveras and San Antonio reservoirs are shown, although these reservoirs had not yet been constructed at the time of the 1906 earthquake. The area in green represents the majority of the urbanized zone of San Francisco at the time of the 1906 earthquake.

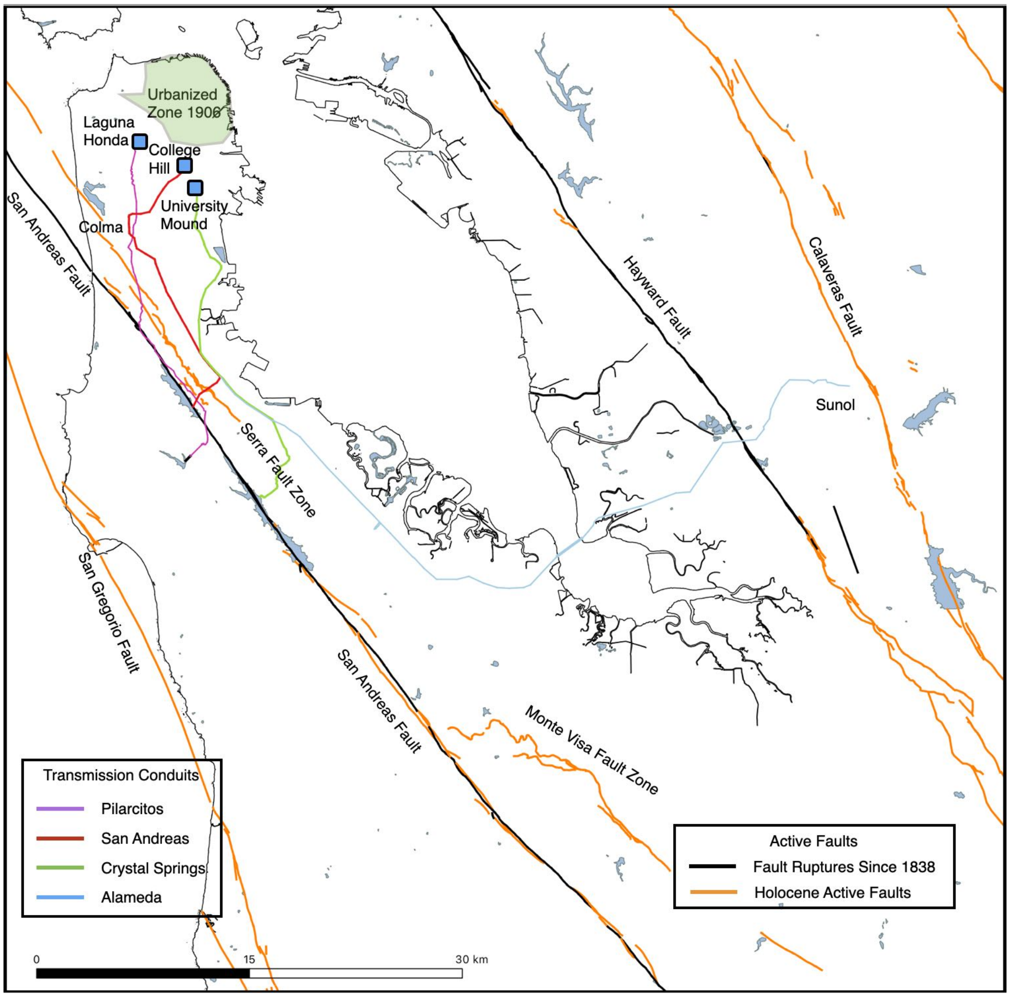


Figure 2-25. SVWC Regional Water Supply System, 1906

Figure 2-26 below shows the four main water transmission supply conduits (color coded, same as in Figure 2-25) to San Francisco at the time of the 1906 earthquake. This figure also shows the raw water flumes that delivered water from several creeks into Pilarcitos and San Andreas Reservoirs, as they existed at the time of the 1906 earthquake. All the 1906-era terminal reservoirs and tanks within the urbanized area of San Francisco are shown. The thin black lines represent the major transmission pipes within the City of San Francisco (see Figure 2-27 for further detail).

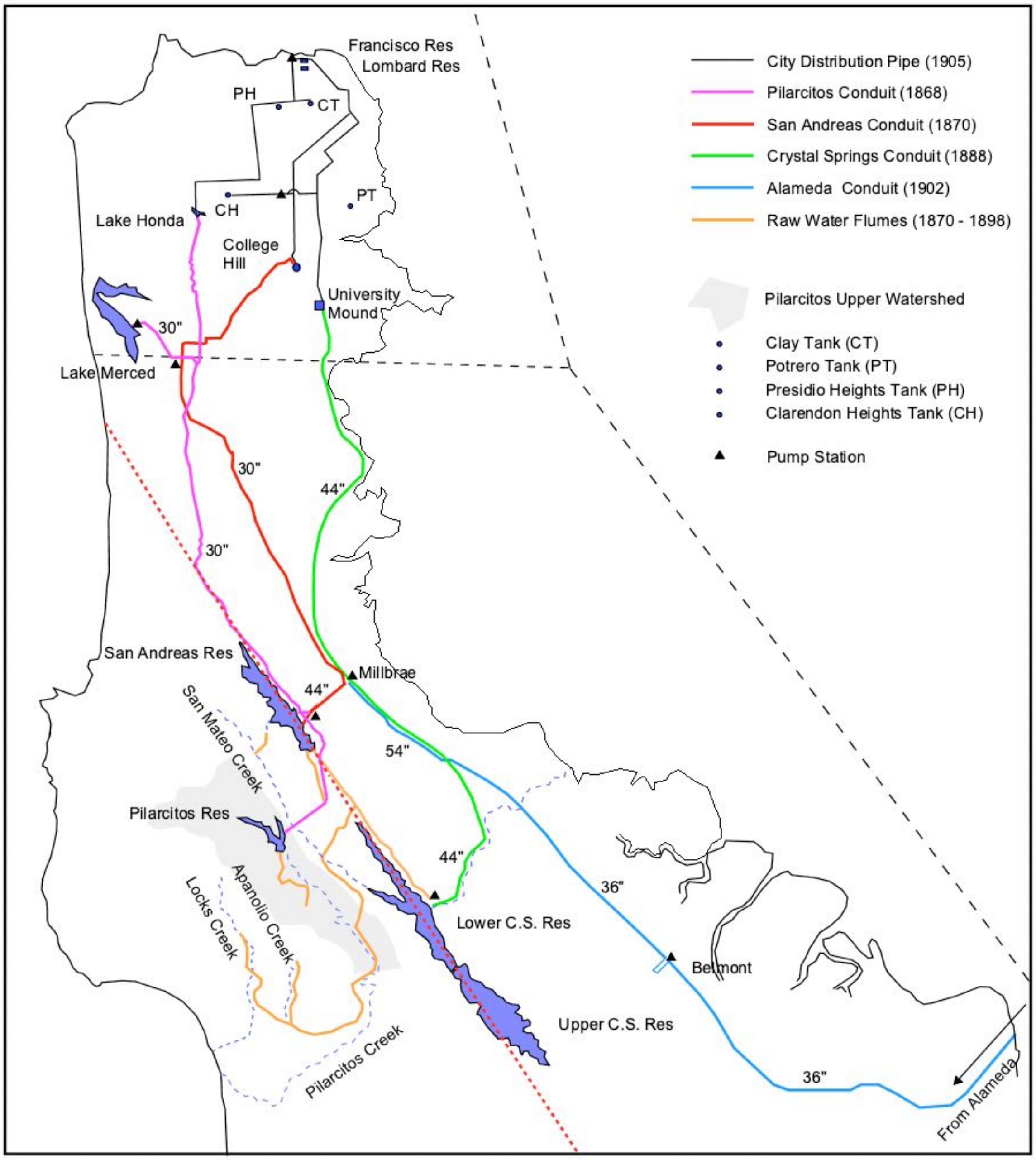


Figure 2-26. SVWC Peninsula Water Supply System, 1906

Figure 2-27 shows the main pipelines in the City system, as of 1894. Figure 2-27 also shows the Market Street (No. 8) and Industrial (No 9) reservoir sites. By the early 1890s, Mr. Hermann Schussler, the Chief Engineer of the SVWC, intended for them to be constructed as part of a much-improved fire-fighting water system, along with large diameter pipes that would avoid the liquefaction zones of Mission Creek and Sullivan Marsh areas. In 1893, the San Francisco Board of Supervisors turned down SVWC's request to build these reservoirs. Critically, reservoirs No. 8 and 9, along with pipes along Market Street studded with hydrants, could have prevented the conflagration that destroyed most of San Francisco in the 1906 earthquake.

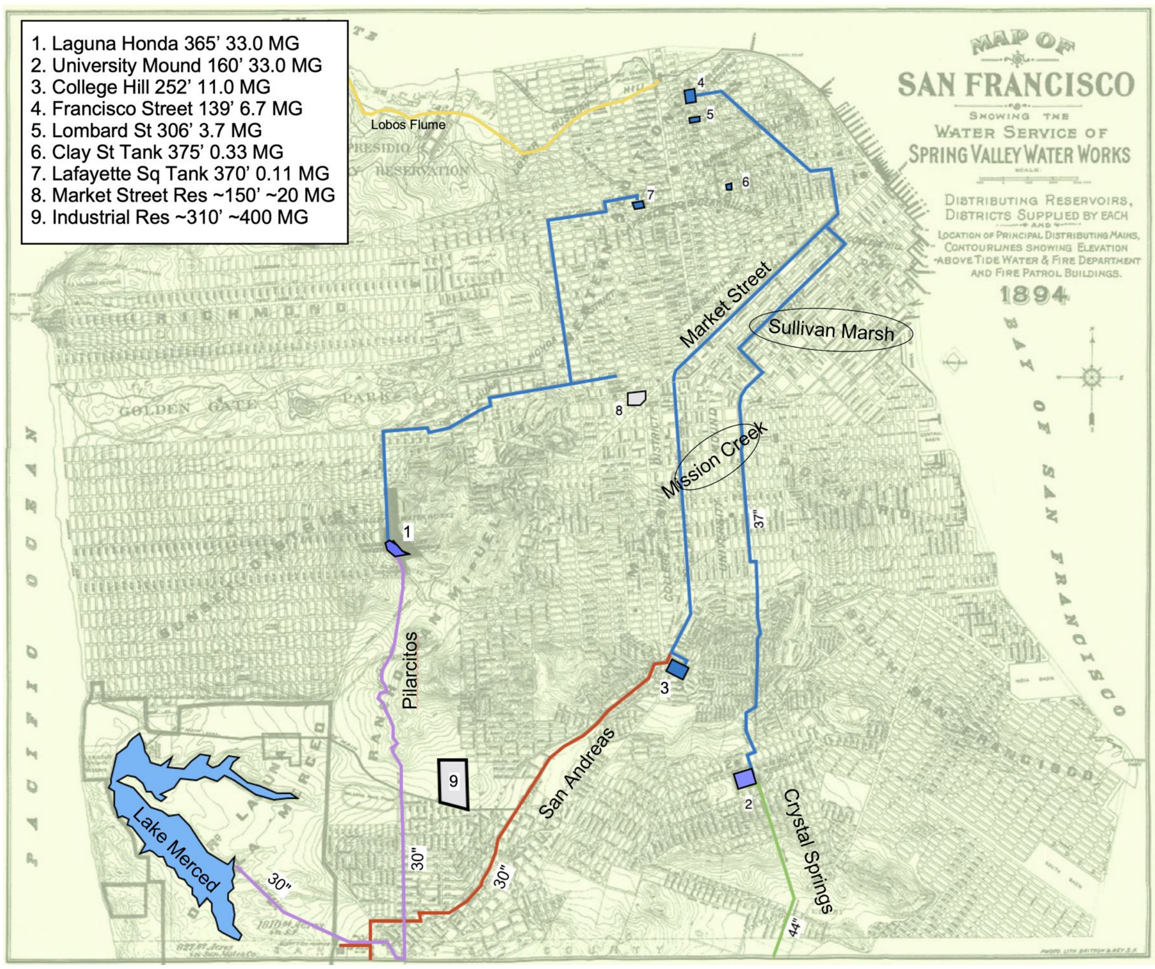


Figure 2-27. SVWC Water System – Main Pipes of the Distribution System – 1894

Figure 2-28 shows the water distribution system serving San Francisco, as it existed just prior to the 1906 earthquake. At the south side of the City were three terminal reservoirs: Laguna Honda, College Hill and University Mound. Water from reservoirs along the Peninsula and Alameda County was delivered to these three terminal reservoirs by the four transmission conduits. In 1906, Average Day Demand (ADD) was about 29 MGD. Prior to the 1906 earthquake, water supply capability was 10 MGD via Laguna Honda, 9 MGD via College Hill Reservoir, and 25 MGD via University Mound reservoir. The red dots show the location of where 299 distribution system water pipes broke in the 1906 earthquake. The major liquefaction areas in the 1906 earthquake were in the Sullivan Marsh and Mission Creek zones, schematically highlighted in Figure 2-27 by the two ovals; these same areas are shown in Figure 2-28 by the diagonal hatched areas.

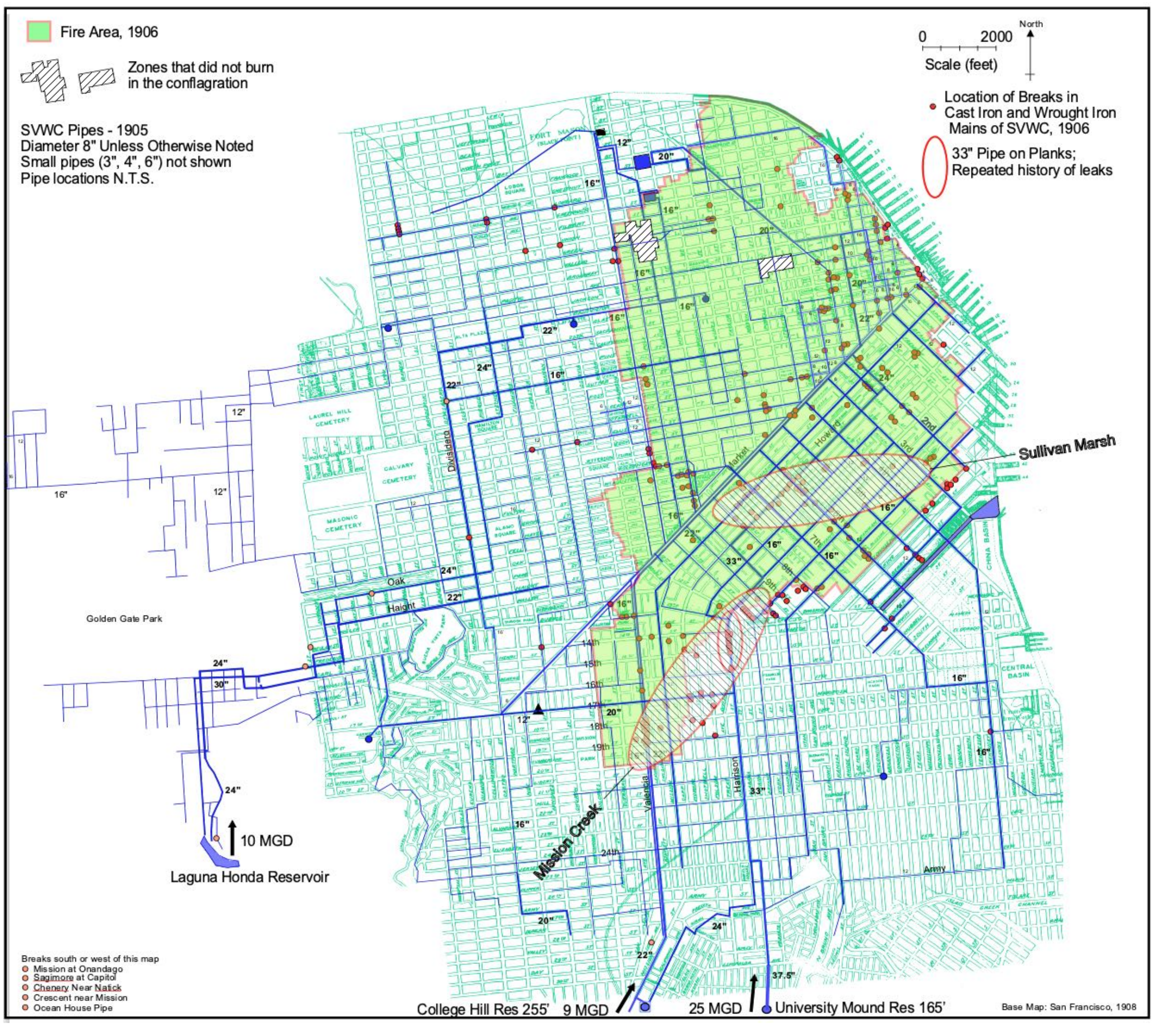


Figure 2-28. 1906 Water Pipe Breaks (Dots) in City Mains (Blue Lines) and Ultimate Fire Area (Green)

Not shown in Figure 2-28 are the planned Market Street and Industrial reservoirs (Locations 8 and 9 respectively in Figure 2-27). By the early-1890s, the SVWC intended for them to be constructed to be part of an improved fire-fighting water system, along with large diameter pipes avoiding the liquefaction zones of Mission Creek and the South of Market Street areas. In June 1893, the Board of Supervisors turned down SVWC's urgent request to build these reservoirs. In our judgement, water from these planned reservoirs, along with pipes along Market Street studded with hydrants, could have saved most of San Francisco from the ensuing conflagration.

At the time of the 1906 earthquake, the regional supply system consisted of 4 conduits, see Tables 2-4 and 2-5. By "conduit", is meant a combination of buried pipe, pipe on wooden trestle, wooden flumes and brick-lined tunnels.

Conduit	Pipe Diameter (Inch) and Type	Bored Tunnels	Trestles	Flumes
Pilarcitos	44, 30 WI; 22 CI	3	11	2
San Andreas	44, 37, 36, 30 WI	1	18	0
Crystal Springs	44 WI	2	19	0
Alameda	36, 54 WI; 16 CIB; 22 CIB	5	2	4
Total		11	50	6

Table 2-4. Regional Water Supply System Conduits

Conduit	Pipe Length (feet)	Tunnel Length (feet)	Trestle Length (feet)	Flume Length (feet)	Submarine Length (feet)
Pilarcitos (see Table 4-3 for further breakdown)	69,053	7,741	761	7,365	0
San Andreas	70,434	2,820	1,769	0	0
Crystal Springs	87,524	2,145	8,538	0	0
Alameda	158,316	14,741	16,454	11,370	28,896
Total	385,327	27,447	27,522	18,735	28,896

Table 2-5. Regional Water Supply System Lengths

Not included in Tables 2-4 and 2-5 are the flumes of the Locks Creek system, further described in Section 4.6. At least 5 segments of these flumes collapsed in the 1906 earthquake, many more segments suffered minor leaks.

At the time of the 1906 earthquake, the City distribution system consisted of 430 miles of pipe, Table 2-6.

Nominal Pipe Diameter (Inches)	Cast Iron Length (Miles)	Wrought Iron Length (Miles)	Total Distribution (Miles)
3	24.91		24.91
4	69.37		69.37
6	108.15		108.15
8	126.47		126.47
10	1.88		1.88
12	48.20		48.20
13		0.16	0.16
16	23.88		23.88
20	4.14		4.14
22	4.45	4.82	9.27
24	6.60		6.60
30	0.85	2.40	3.25
33		0.48	0.48
37		2.32	2.32
44		1.37	1.37
Total	418.90	11.55	430.45

Table 2-6. Length of Pipe in City Distribution System (1905, Miles)

Figures 2-29 and 2-30 show hydraulic profiles of the 1906-vintage regional water transmission system. The overflow for the San Andreas Reservoir is shown as 445 feet; the dam was later raised in 1928 and today (2024) the overflow elevation is 449 feet.

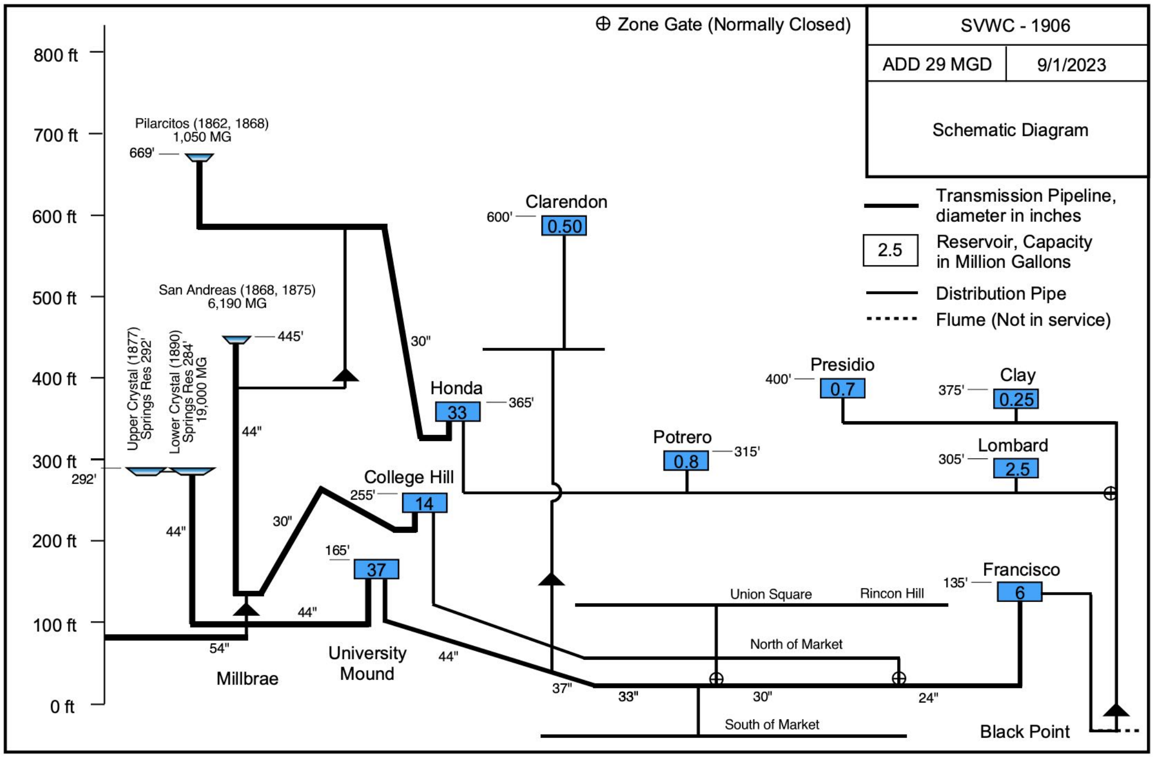


Figure 2-29. Hydraulic Profile, Peninsula System (1906)

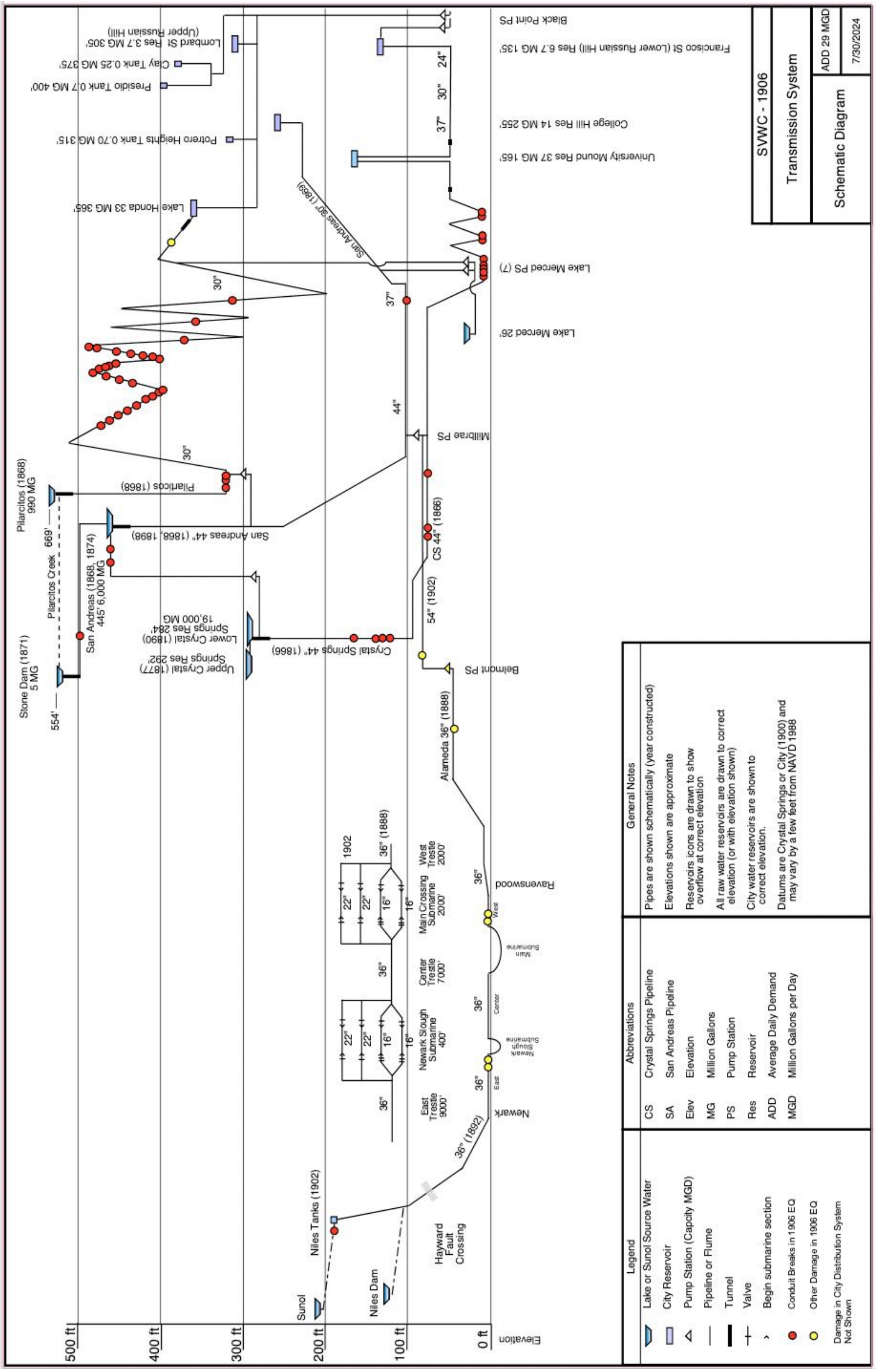


Figure 2-30. Hydraulic Profile, Regional System, with Transmission System Damage (1906)

The SVWC water system had a number of pump stations at the time of the 1906 earthquake:

- Belmont. Original built 1898, with two pumps originally each 5.5 MGD; expanded with three additional pumps in 1902, each 4 MGD, all with a lift of about 320 feet.

- Millbrae. Built 1899. Source water is either Crystal Springs 44" pipe or Alameda 54" pipe, or both (grade line about 190 feet), to the San Andreas pipeline (grade line about 372 feet). Two pumps, each 8 MGD with a lift of about 182 feet.

- Crystal Springs. Located just below Lower Crystal Springs Dam. Occasional or emergency use to pump water from Crystal Springs Reservoir into San Andreas Reservoir via a force main, flume and tunnel. Four pumps, each 3 MGD and a lift of about 250 feet.

- Ocean View. Can pump water from the Lake Merced force main to the aerator atop Daly Hill, thence into the Pilarcitos pipeline. Single pump, 2 MGD with lift of about 175 feet.

- Pilarcitos. Built 1897. Located at the outlet of Bald Hill Tunnel. Used for occasional service to pump San Andreas water into the Pilarcitos pipeline, in case of accident to the upper Pilarcitos conduit. Three pumps, capacity 4 MGD with a lift of about 225 feet. After the 1906 earthquake, this pump station was removed, and components reused for the Precita Valley pump station.

- Lake Merced. The amount of water pumped from Lake Merced into the water system was (years beginning July 1, in billions of gallons): 1898: 1.546; 1899: 1.349; 1900: 0.187; 1901: 1.246; 1902: 1.269. Over this 5 year time frame, the average daily supply from Lake Merced was about 3 MGD. 2 pumps. Can supply 3.5 MGD with lift of about 460 feet; either into the San Andreas pipeline or the Pilarcitos pipeline; or can boost water from San Andreas pipeline into the Pilarcitos pipeline, by way of an aerator atop Daly Hill.

- Black Point. Source water from University Mound zone, pumps it into the Clay Street Tank, Presidio Heights Tank with surplus into the Lake Honda pressure zone. Two pumps, one being 2.75 MGD, the other 3.25 MGD capacity.

- Clarendon Heights. Takes suction from the University Mound zone (normally), pumps to Clarendon Heights Tank.

- Precita Valley pump station. Built after 1906 earthquake. Can pump water from University Mount 44" pipe to Lake Honda pressure zone, 4.5 MGD.

- The Ravenswood pump station (1888) was not in use at the time of the 1906 earthquake.

2.5 The SVWC After the 1906 Earthquake

The City of San Francisco was devastated by the 1906 earthquake. Some 80% of all buildings were burnt in the ensuing conflagration.

However, such was the economic vitality of the City, that nearly the entire City was rebuilt within 2 years. Insurance certainly helped provide finds for rebuilding.

The SVWC reported that they suffered about $620,000 of cost ($1909) to make repairs to their water system. Today, that would translate to $23,000,000 to $60,000,000 ($2024), depending if one uses inflation indices (the lower amount) or the modern way to repair and install pipe (the higher amount). After the earthquake, a judge ruled that SVWC could not recover through water rates, the cost for repairs to the water system; a ruling that would not likely pass master in 2024.

There are historic reports that suggest that some 10,000 people were involved with repairing the water system after the 1906 earthquake; but we find that doubtful, as SVWC then employed about 500 people. This included a work force of 140 men employed in the City and County of San Francisco, including those engaged in laying new water pipes; and an additional 71 men at supply works in San Mateo and Alameda counties.

As of July 1, 1912, the SVWC water system included:

- 453.4 miles of mains, of which 442.2 miles were cast iron and 11.2 miles were wrought iron. This is about 5% more pipe than was installed in 1905. The City was continuing to grow.

- 98 miles was 4 inch diameter or smaller; the remainder 6 inch diameter or larger. This is about the same as in 1905. These small diameter pipes may have been adequate for providing day-to-day flows, but remained too small to provide much above 200 to 500 gpm (or so) in terms of fire flows. This, in part, reflects that SVWC was not being reimbursed for providing high flow rates for fire flows, as well as the fact that the City had independently built its own AWSS, which, if undamaged, could provide high fire flows.

- Average water demand in 1911 was 37.5 MGD, of which: 14.8 MGD was in the Low (University Mound pressure zone), 5.3 MGD was in the middle (College Hill pressure zone), and 17.5 MD was in the High and Hill pressure zones (principally Lake Honda pressure zone). This was about 10% more than the water demand at the time of the 1906 earthquake (see Table 2-2), confirming that the City was once again rebuilt, and once again growing.

- There were 59,500 service connections in San Francisco. These were mostly metered. The length of service lateral pipes is not included in the above tabulation.

- There were 8 pumping plants in place in 1911. These were unchanged from those in service at the time of the 1906 earthquake, except:

  - A temporary pump station (Precita, Figure 9-12) was put in place in 1907 to pump from University Mound to Lake Honda pressure zone. This was needed to get water flowing around the heavily damaged Mission Creek and Sullivan Marsh liquefaction zones.

  - The Pilarcitos pump station was abandoned after 1906 earthquake.

- By 1911, there were 9 city reservoirs (no change from earlier years). These are shown in Figures 2-26 and 9-9.

2.6 The Press

The 4th estate (also called The Press) was not much of a friend to the Spring Valley Water Company. For decades the Press was at odds with SVWC. The core issues were:

- SVWC was a privately-held company monopoly. The Press wanted a publicly-held monopoly.

- SVWC had the charter to supply water to the City. The Press, reflecting public interest, wanted low water rates. At the same time, the Press lambasted SVWC for not spending enough money. The inconsistency of these two positions should be obvious. Absence of malice, the Press can publish with impunity whatever inconsistencies, falsehoods or fabrications it wants.

Expansion of the SVWC system to meet the rapidly growing water demands around 1876 (see Table 2-2) placed high capital requirements on the company. Keeping up with water demand was highlighted in the press: "*It is whispered in the air that Spring Valley has taken the alarm since the meagerness of their resources has been so thoroughly ventilated by the press… It would be wise to remember that [Spring Valley's] mains are neither large enough, nor in sufficient good condition to furnish the city any better than with the present inadequate supply… The supposition is also gaining strength that the financial affairs of Spring Valley are not in a condition to permit them to remedy the evil were they so inclined… it is observable that in cases of absolute necessity, as recently in the case of repairs on Market street, that the new pipes laid down are made of sheet-iron… if they continue to make repairs in this shabby style, it will only be necessary for the committee having these affairs in charge, to examine the streets to realize the stupendous swindle in the price which Spring Valley asks. Even with its best foot foremost, 14 millions is rather a big figure to ask for two big puddles in the San Mateo hills, and a city full of tin pipes*."[13]

Figure 2-31 shows an editorial cartoon published by The Call (November 11, 1908) on the eve of the election to vote for initial funding of Hetch Hetchy (see Section 9). The San Francisco Call reported on the issues about raising funds for Hetch Hetchy. The term "*Collected Under Injunction*" refers to the judge who sided with SVWC against the San Francisco Board of Supervisors, about setting rates high enough to sustain the water system, had higher rates been allowed to be collected while the multi-year lawsuits pended their way to resolution. The Federal courts eventually found that the San Francisco Board of Supervisors had not allowed sufficient water rates to be collected.

[13] Daily Alta California, Volume 28, Number 9406, January 6, 1876.

For The Call's Index of the news of today see Page 3, Column 1

THE CALL

"THE High School Girls' Page," it might be called—the new page for misses which, with its splendidly written articles and clever illustrations, has already become one of the strongest features of The Sunday Call. See it next Sunday.

VOLUME CIV.—NO. 164. SAN FRANCISCO, WEDNESDAY, NOVEMBER 11, 1908. PRICE FIVE CENTS.

Look at Your Water Bill—and Vote for Hetch Hetchy

The Words "Collected Under Injunction" Tell the Story

Figure 2-31. San Francisco Call Front Page, November 11 1908 (credit: SF Call)

The Call further editorializes:

- "*You know that Spring Valley's supply is inadequate*."
- "*You know that Spring Valley never sold you pure water.*"
- "*You know that the last official analysis of Spring Valley water shows that its use is, at best, dangerous.*"
- "*You know that Spring Valley's defective plant was responsible for the most disastrous fire in the history of the modern world.*"
- "*You know that Spring Valley has filled your hospitals and your cemeteries.*"
- "*You know that Spring Valley has multiplied your insurance rate by two and by three.*"
- "*You know that further multiplication of those rates is at hand.*"

- "*You know it [SVWC] has defied your laws and finally abrogated them.*"

- "*You know that the yeggman*[14] *is your master now – governing you by injunction.*"

The election was November 12, 1908. The vote was 6 to 1 in favor of a $600,000 bond issue to obtain land and water rights for the Hetch Hetchy and Lake Eleanor watersheds. This was the first voted bond money needed for the construction of Hetch Hetchy; there were to be multiple later votes to cover the $45 million to build the initial Hetch Hetchy and a parallel potable water system in San Francisco (the latter never built), and eventually for the ultimate $105 million cost. Chapter 9 describes the design and costs of the Hetch Hetchy system in more detail. On November 13, 1908, the day after the election, the SF Call editorializes:

- "*By a vote of 6 to 1 at the special election yesterday, the people of San Francisco proclaimed that they want Hetch Hetchy and that they have had enough of Spring Valley's chicanery, bulldozing and more or less legal extortion.*"

- "*Yesterday gave the people their first chance for an authoritative expression of their will concerning the Hetch Hetchy plan and concerning the water monopoly that has had every San Franciscan by the throat for forty years.*"

- "*Now if Spring Valley were not as stupid as it is greedy – for its corporate head were not as fat as its corporate purse – it would profit by this lesson and get out of the people's way and try no further to block the road to Hetch Hetchy. But Spring Valley has no more sense than it has conscience – no more brains for understanding than bowels for compassion. … And in the end – the early end – Spring Valley's ramshackle ditchwater plant will be acquired by the city for what it is worth, and not a penny more.*"

- "*A long and irretraceable step has been taken toward Hetch Hetchy. Spring Valley can never take from the city the fruit of yesterday's victory – not with all its lying and lawyering and enjoining. Cheap water, pure water, water that you can drink without boiling, shall soon flow from the faucets of San Francisco – water from the snow fed Hetch Hetchy. Spring Valley is on its way into ancient history of this city, adding thereto one of its least pleasant chapters. San Francisco is on her way to ownership of such a water supply as will insure and enlarge her municipal greatness.*"

- "*Well done, San Francisco!*"

Well, that is a mouthful.

[14] Yeggman (slang): a person who breaks open safes, a burglar, a yegg.

3.0 The Seismic Hazards in the Earthquake

3.1 Ground Motions in 1906 Earthquake

Figure 3-1 shows a map created in 1907 that shows the extent of surface fault rupture in the 1906 earthquake.

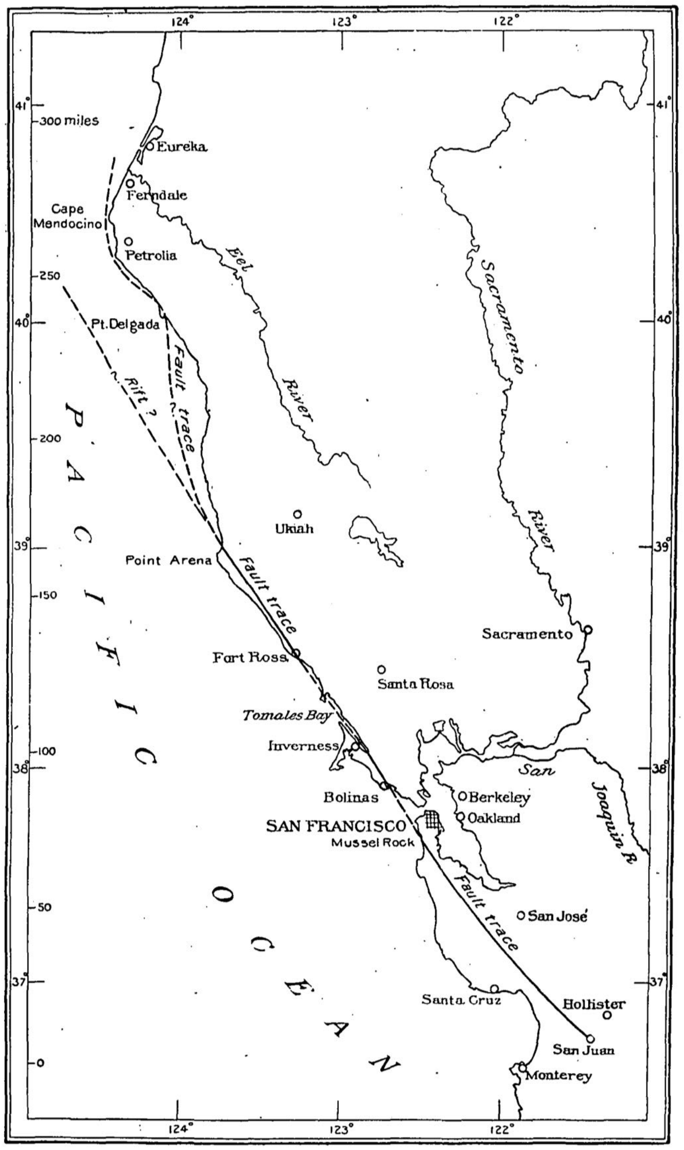


Figure 3-1. Map of Observed Surface Rupture (solid line) (after USGS, 1907)

In modern parlance, it is most common to use Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) and corresponding response spectra to evaluate or design new buildings, structures and lifeline infrastructure like buried pipes. Table 3-1 shows the estimated PGA and PGV ground motions at select locations for the 1906 event. The PGA and PGV motions were computed assuming a M 7.8 event, strike slip, and are the horizontal geometric mean values. These motions were computed using an average of four NGA13 ground motion relationships (Bozorgnia, 2014), with assumed Vs30 values representative of the general locales listed. To estimate the maximum of two horizontal direction motions, increase the values in Table 3-1 by about 18%.

Location	PGA g	PGA + 1s g	PGV cm/sec	PGV +1s cm/sec
San Francisco Cliff House	0.44	0.74	68	126
San Francisco City Hall	0.30	0.52	47	88
San Francisco Ferry Building	0.29	0.47	53	97
Oakland Downtown	0.22	0.41	35	65
Berkeley Shattuck Downtown	0.20	0.33	23	55
Stanford University	0.39	0.61	71	132
Palo Alto Downtown	0.37	0.58	67	122

Table 3-1. Estimated Ground Motions for 1906 Earthquake (PGA, PGV)

The then-built-up downtown San Francisco would have experienced ground motions in the range of those listed for City Hall (reasonably firm soils) or the Ferry Building (somewhat softer soils), or PGA about 0.30g and PGV about 50 cm/sec. The columns listed as "+1s" are the 84^{th} percentile ground motions (median plus one sigma). About $1/6^{th}$ of the building inventory in downtown San Francisco would have experienced ground motions of about PGA = 0.52g and PGV = 88 cm/sec (or higher). Similarly, about $1/6^{th}$ of the building inventory in downtown San Francisco would have experienced ground motions of about PGA = 0.18g and PGV = 27 cm/sec (or lower).

The ground motion data listed in Table 3-1 for San Francisco Cliff House, closest to the San Andreas fault rupture, are representative for the few buildings located along the Pacific Coastline or the nearby Presidio, on stiff soils.

The ground motion data listed for Oakland downtown are representative for the buildings on non-liquefied Merritt Sand Formation, being the bulk of the modern downtown area of Oakland.

The ground motion data listed for Berkeley Shattuck Downtown are representative for the buildings in downtown Berkeley along or near Shattuck Avenue, and are representative of the motions felt at the U. C. Berkeley campus for locations with stiff soils.

The ground motion data listed for Stanford University are representative for the buildings in the main Quad of the campus, on medium stiff soil. The damage to unreinforced masonry structures at the Stanford campus was especially severe.

The ground motion data listed for Palo Alto Downtown are representative for the buildings in downtown Palo Alto, on medium stiff soil. Similar or slightly lower ground motions would have been experienced for other small communities that had been developed by 1906 along the Peninsula, including Brisbane, Belmont, San Mateo, Redwood City, City of Santa Clara, City of San Jose, located along El Camino Real.

The highest ground motions would have been felt with 1 km (or so) either side of the San Andreas fault. At the time of the 1906 earthquake, however, there were few buildings located along or near the fault line. Some notable important water-system structures in this close-in zone were the Crystal Springs Dams, the San Andreas Dam, the Pilarcitos Dam, the Stone Dam, and the Pilarcitos pipeline trestles. All the dams fared well (despite intense ground shaking as well as fault offset). A trestle supporting the Pilarcitos pipeline failed due to inertial shaking. The Pilarcitos pipeline also failed due to fault offset at 5 locations. The brick-lined outlet works from the San Andreas Reservoir was considerably damaged due to fault offset. A brick-lined waste tunnel from San Andreas reservoir collapsed where it crossed the fault. All this damage from the earthquake will be described in more detail in Section 4.1.

3.2 Liquefaction Hazards

Understanding the damage to water pipes in the 1906 earthquake cannot be done without an understanding of the underlying liquefaction hazards.

Figure 3-2 shows one of the oldest maps of San Francisco, dated January 15, 1851. Highlighted are the original shoreline (heavy black line), Mission Creek, and unnamed creeks (thin blue lines) in the Sullivan Marsh area.

Figure 3-2. San Francisco Shorelines (Survey Map of San Francisco, dated January 15, 1851)

Figure 3-3 is a map of San Francisco, showing the historical evolution of various shorelines.

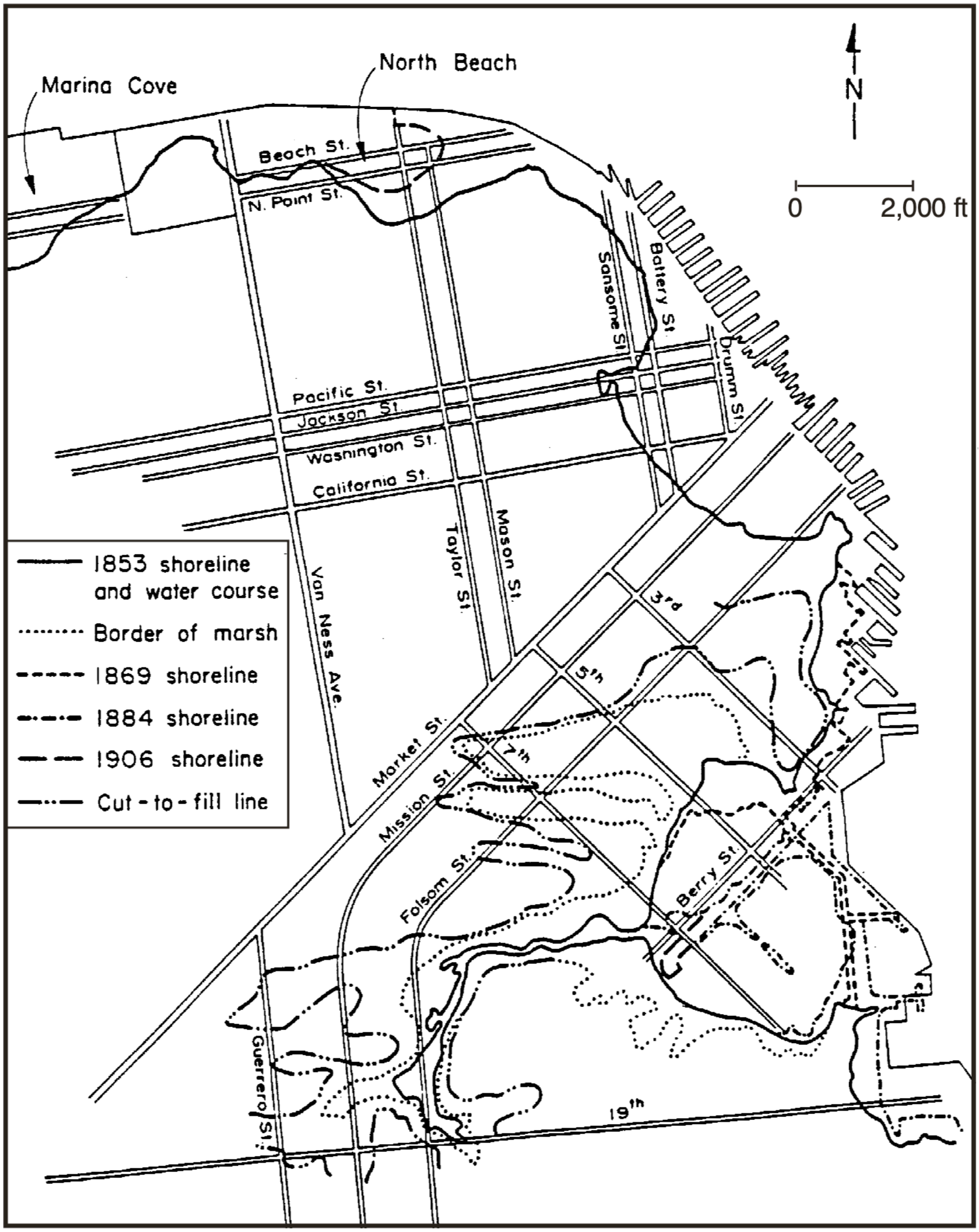


Figure 3-3. San Francisco Shorelines, 1853-1906 (after Olmstead et al 1977, Roth and Kavazanjian, 1984, Hovland and Daragh, 1981).

Portions of the South of Market Area are built on top of a former marsh. Areas outside the "cut to fill" line (Figure 3-3) are located outside the original marsh or shoreline areas. A large portion of the South of Market Area is within an old marsh area, then called the Sullivan Marsh.

The area shown in Figures 3-2 and 3-3 along Berry St. was originally called Mission Bay. There were two major valley feeders to Mission Bay, one going southwest (called Mission Valley), and one going northwest (called Sullivan's Marsh). Mission Creek and Sullivan's Marsh underly several key water pipelines, see Figure 2-28. Sullivan’s Marsh has been described as "*subterranean lakes, forty to eighty feet deep, crusted with a ten-foot layer of peat strong enough to bear the weight of a small house...*" (Brown et al, 1932).

Sullivan marsh was filled mainly with sand from nearby sand dunes (Roth and Kavazanjian, 1984), which often settled as much as 6 feet overnight, displacing the mud and causing it to heave (Brown et al, 1932). Filling of the marsh occurred in the 1850s and 1860s, and by 1869, filling had been completed in Sullivan’s Marsh (Olmstead et al, 1977).

This report does not delve into the details of how to predict liquefaction. The interested reader can read the excellent book on this topic by Idriss and Boulanger (2008).

A record of the estimated PGDs that occurred in the 1906 earthquake has been compiled by O'Rourke et al (1992), see Figures 3-4a, b. These PGDs were estimated based on available photographic evidence from the 1906 earthquake.

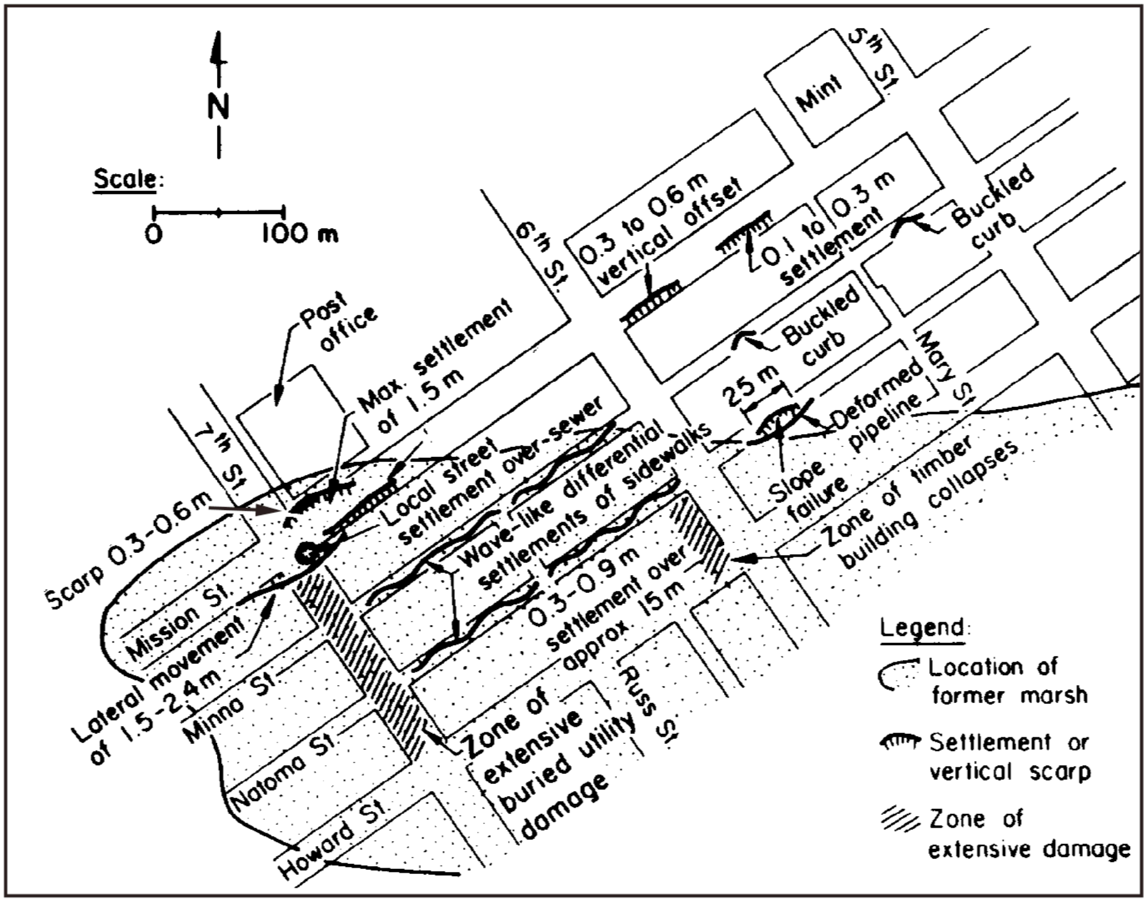


Figure 3-4a. Detailed map of 1906 Earthquake-Induced PGDs (Sullivan Marsh Area) (O'Rourke 1992)

Lateral spreads of up to 8 feet were recorded along the length of 7th Street, with ground moving from northwest to southeast. 1 to 2 foot settlements occurred sporadically over the entire lengths of Minna and Natoma streets. Probable lateral spreads on 6th Street between Natoma and Howard led to collapse of timber structures.

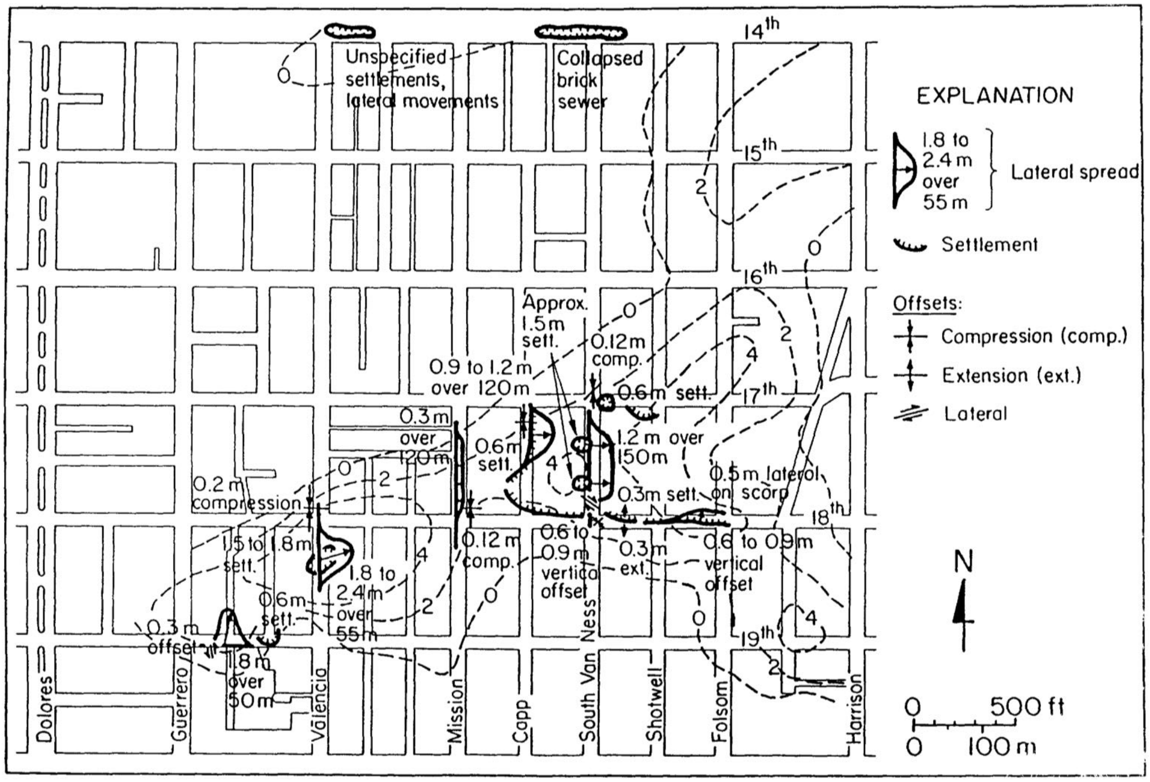


Figure 3-4b. Detailed map of 1906 Earthquake-Induced PGDs (Mission Creek Area). Dashed lines show depth of fill in 2 meter contours. (O'Rourke 1992)

Figure 3-4b shows that PGDs along Valencia Street were on the order of 1.5 to 1.8 meters (settlement) and 1.8 to 2.4 meters of lateral spread. In the 1906 earthquake, these PGDs led to major damage to water pipelines where they traversed the filled areas of the former Mission Creekand its lagoonal waters. See Section 7.7 for further details of the pipe damage along Valencia Street and the collapse of the Valencia Hotel.

Figure 3-5 shows the location of a pre-1849 spring that fed the Old Arroyo Dolores Creek, that merged with Arroyo Dolores (along present-day 18th Street) to feed what was then called Laguna Dolores, or sometimes called Mission Creek, that eventually feds into modern Islais Creek. It was the liquefiable materials deposited by these creeks that resulted in major ground failures along Valencia Street between 18th and 19th Streets in the 1906 earthquake: see Section 7.7 for details.

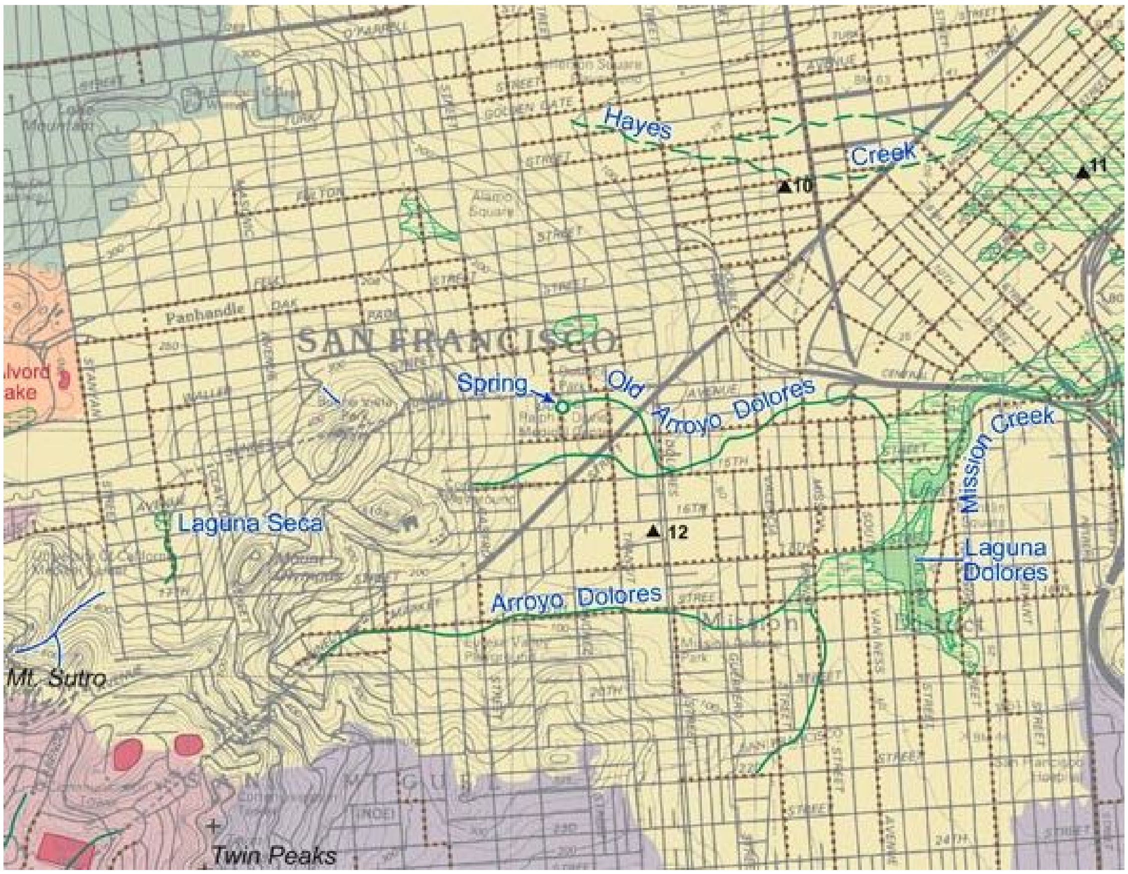


Figure 3-5. SF Watershed Creeks, c. 1849 (Oakland Museum of California)

Figure 3-6 shows the historical development of the Marina District in San Francisco.

The area now called the Marina District was originally called Marina Cove. In 1881, there was a meandering tidal slough west of Scott Street that extended westward into the Presidio. North of this was a broad area of beach sand, including an area of dunes then called Strawberry Island. The Fillmore Street wharf was built in 1863, was 400 feet long, extending north of Bay Street. The fill west of the SFG&E Gas Plant was placed around 1869. In 1882, the triangular area bounded by Bay, Buchannan and Fillmore Streets was filled. In 1891, SFG&E built a pier extending 1,000 feet north of Bay Street. By 1894, a sea wall had been built, now being the northeast boundary of the Marina Green; this seawall formed the northeast edge of the hydraulic fill placed around 1912 in preparation for the 1915 Panama-Pacific International Exposition.

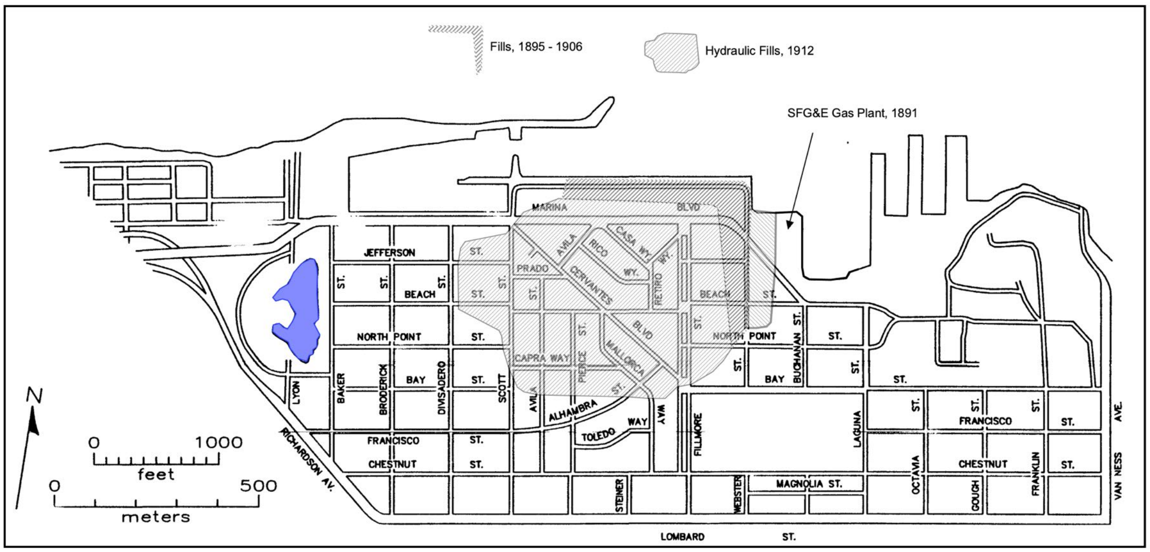


Figure 3-6. Marina District (After Bonilla, 1990).

How much debris, if any, from the 1906 earthquake was incorporated into the fills in the Marina District is unknown, but was probably a significant amount.

In 1912, large hydraulic fills were placed in both the central part of the Marina District, and in the adjacent parts of the Presidio. Smaller hydraulic fills were placed through 1917, as part of the restoration of the site after the Exposition.

In the 1906 earthquake, there were very few buildings in the area. There was damage to the SFG&E gas works, where settlements on the order of 1 to 2 feet occurred. The Baker Street sewer north of North Point failed. Lawson (1908) reports that frail wood frame buildings in the area were thrown out of vertical.

Figures 3-7 through 3-10 show the Pilarcitos Conduit alignment, along with modern interpretation of the location of the San Andreas fault (red line), as well as the nearby Serra fault zone (orange and other thin lines), and a modern interpretation of liquefaction susceptibility (adapted from Witter, 2006).

Some of the more spectacular damage to the Pilarcitos pipeline occurred at the 5 fault crossings (FX1 through FX5), and at the trestle crossing over Large Frawley Canyon. Section 4.1 of this report describes this damage in detail. Schussler (1906) reported there were at least 31 total failure locations, all of them occurring between FX-5 (in the south) and Colma (in the north). There were no failures north of Colma all the way to Lake Honda, as well as outlet Tunnels 1 and 2 from Pilarcitos Reservoir, and the flume between Tunnels 1 and 2. This is perhaps surprising. Here are some open questions:

- Was there damage to the 30-inch Pilarcitos pipe where the pipe crossed the surface traces of the Serra fault? It is conceivable that in the 1906 earthquake that there "might" (or might not) have been some sympathetic offset along the Serra fault, possibly in the range of 2 to 12 inches. None was recorded by Lawson (1908). The San Andreas pipeline crossed a mapped splay of the Serra fault, but it was not damaged there in 1906. The Authors tentatively suggest that there was no (or very little) sympathetic movement of the Serra fault in the 1906 event.

- Was there damage to the 30-inch Pilarcitos pipe where it traversed various drainages? (mapped as having low liquefaction susceptibility in these figures).

- Why was there no damage to the wood flume sections (between Tunnels 1 and 2 Figure 3-7, as well as south of Lake Honda, Figure 3-10).

- These questions will be explored in some detail in Section 4.1.

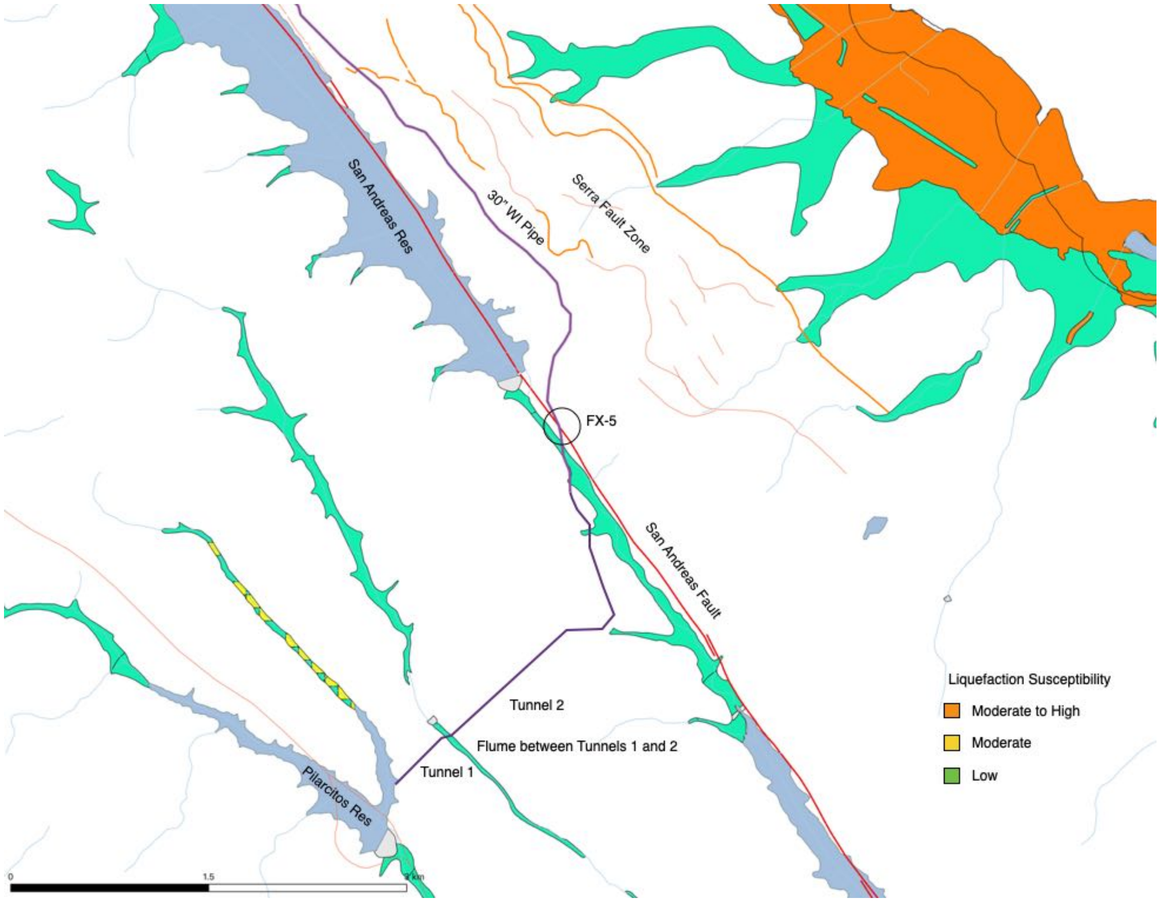


Figure 3-7. The Pilarcitos Conduit Near San Andreas Reservoir (Full scale 3 km)

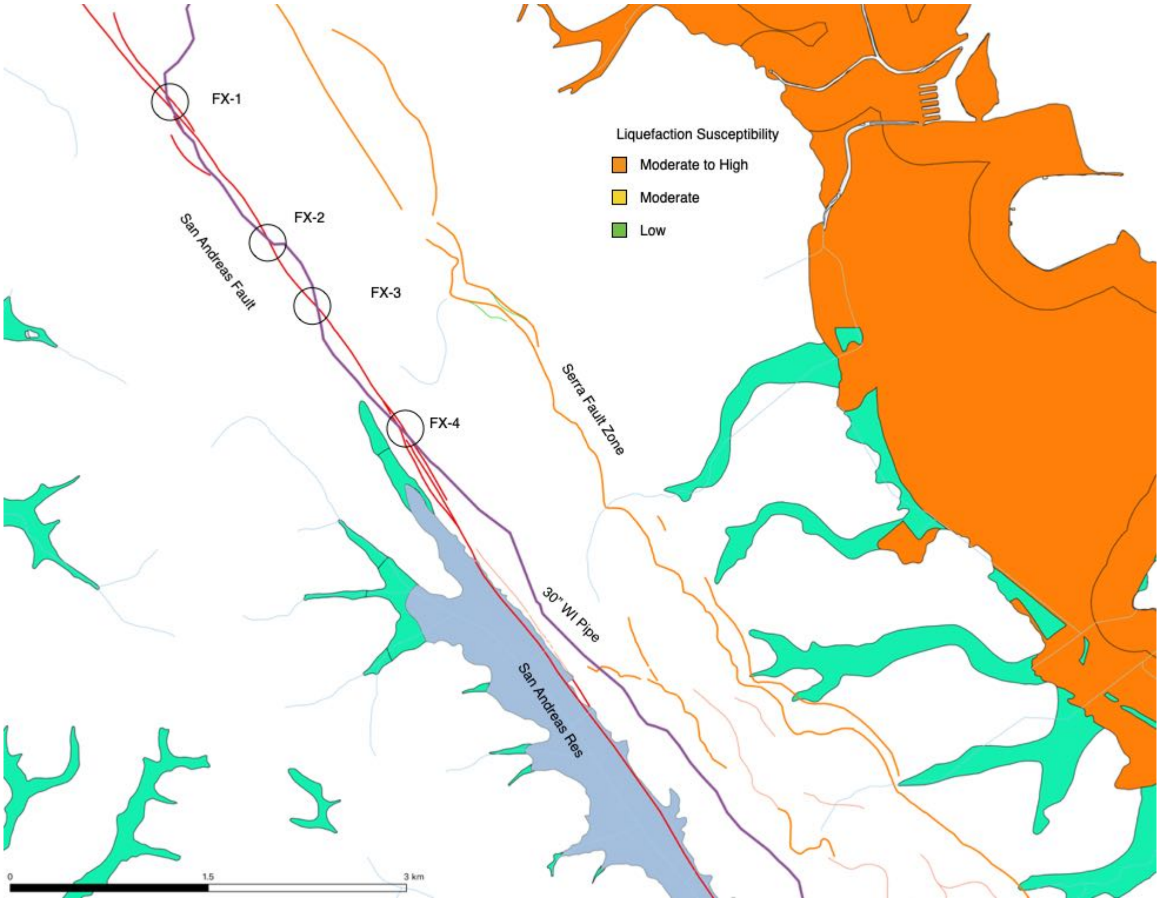


Figure 3-8. The Pilarcitos Conduit North of San Andreas Reservoir (Full Scale 3 km)

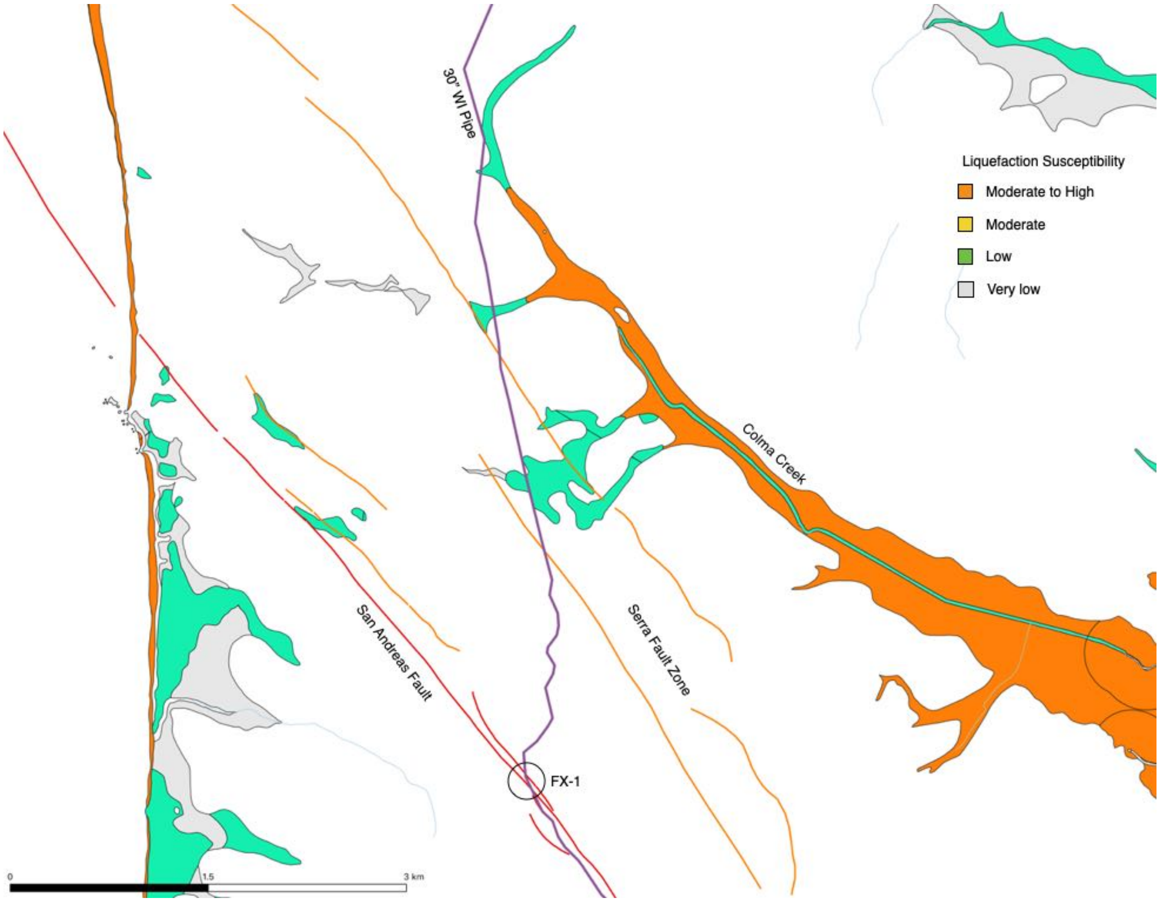


Figure 3-9. The Pilarcitos Conduit Through Colma (Full Scale 3 km)

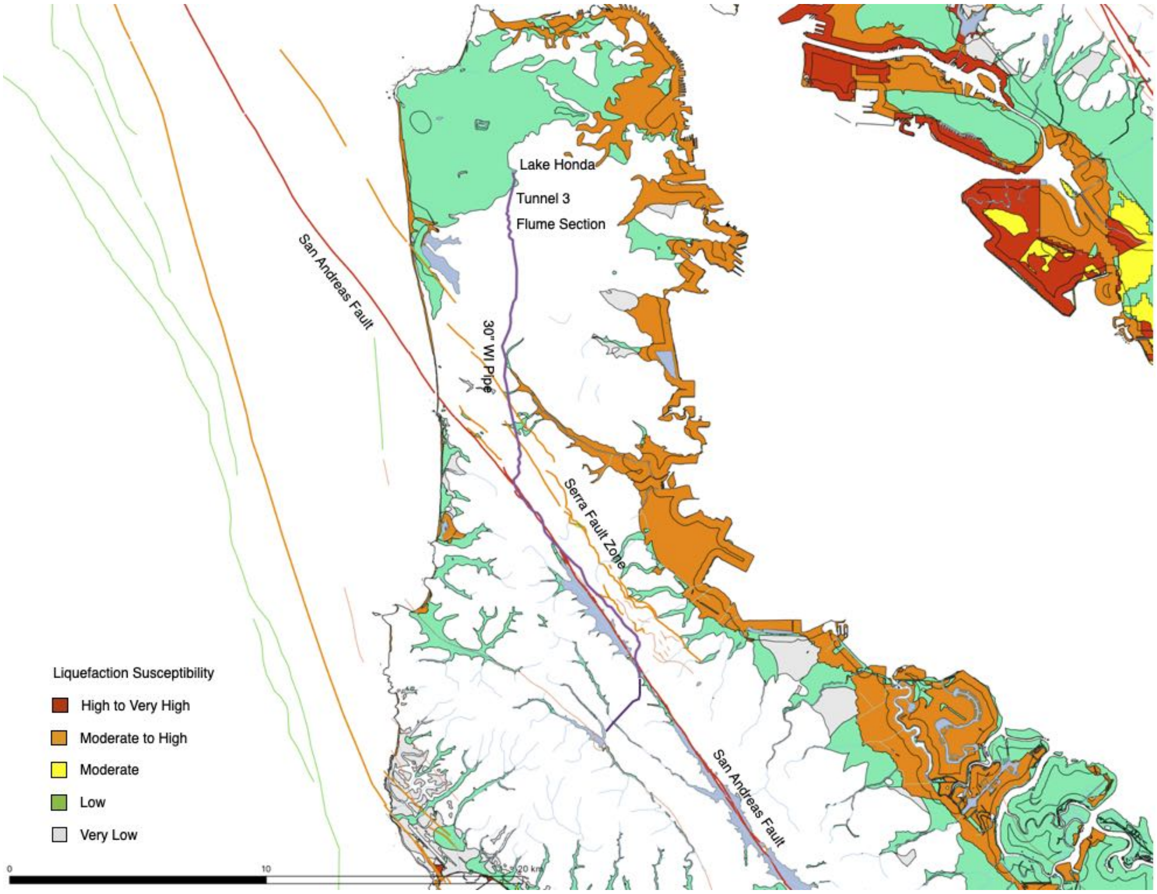


Figure 3-10. The Pilarcitos Conduit, San Andreas Reservoir to Lake Honda (full Scale 20 km)

3.3 Fault Offset Hazards

Figure 3-11 shows a topographic relief map of the San Francisco Peninsula. The four pipelines are the SVWC supply conduits as of 1906. The elevations are NAVD 1988. The map shows the present day (2024) coastline. The black line shows the location of observed surface fault offset in the 1906 earthquake. The white dashed line highlights the area of the fault that is examined in more detail in this report in Section 4.1.

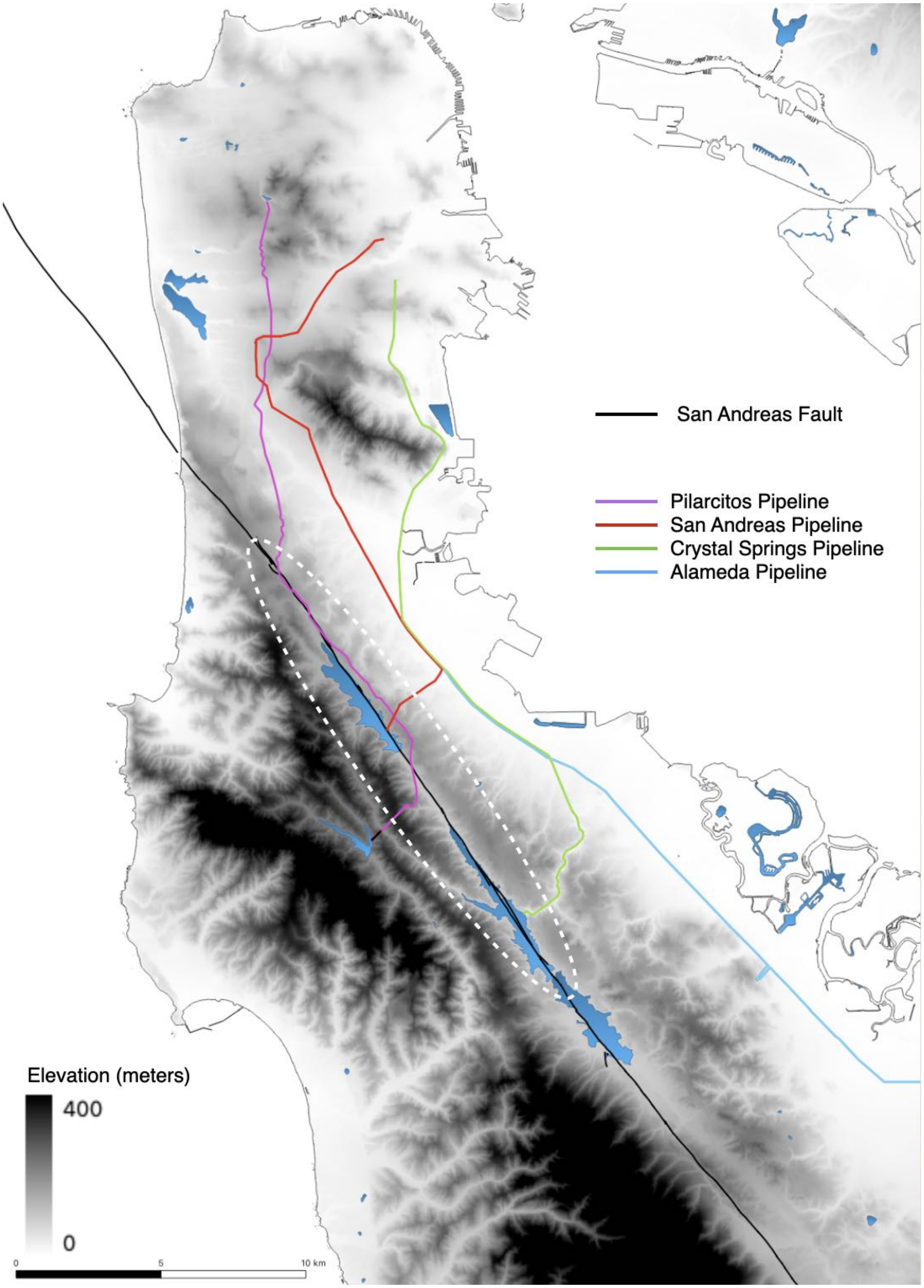


Figure 3-11. San Andreas Fault Rupture and 1906 SVWC Transmission Pipes

Table 3-2 documents the observed fault offsets around San Andreas Reservoir as observed and measured in the 1906 earthquake. The data in Table 3-2 are based on fault slip reported by Schussler (1906), Lawson (1908), Bonilla (1954), ESA (1980), Pampeyan (1983), coupled with the interpretations in this report that are provided in Section 4.1. See Pampeyan (1983) for further description of the offsets in and around Crystal Springs Reservoir (last 3 entries in Table 3-2). Section 4.1 describes the fault offset at each of the 21 sites in more detail. The following summarizes two of the main fault offset parameters (amount of offset and width of zone over which that offset is applied) commonly used for design of buried pipes through fault crossing zones (see Table 3-3 and Sections 4.1 for further details at each of the 21 locations)..

- Primary offset. The magnitude of concentrated strain recorded by the fences, pipes, and dams, for only the main (primary) offset trace varied in amount of right slip from about 6 to 9 feet and averaged 7.5 feet.

- Secondary offset. At some sites, one or two subsidiary (secondary) traces were also observed and those varied in right slip from under 2 feet to about 3.4 feet. Combined, the concentrated slip (primary and secondary) across the fault zone ranged from 6.3 to 12 feet.

- Total offset. Total slip across the zone of active faulting included both discrete offsets, especially the main trace and perhaps one or more subsidiary traces, plus ground warping. Maximum offset at any site, including observed primary offset, secondary trace offset and nearby ground warping was about 13 to as much as 17 feet. Ground warping effects are not very concentrated, and do not pose much risk to modern buried pipes that are designed to accommodate up to 1 foot of offset at any location.

- Width of primary fault offset zone. Photographs and field observations indicate that the width of the main trace by itself (primary offset zone) typically varied from ~2.5 to 10 feet.

- Width of secondary offset zones. At some (but not all) locations, there was secondary offset: these parallel fractures occurred primarily on the east side of the primary fault zone, but sometimes occurred on the west side of the primary offset zone. Where present, the width of these secondary offset zones ranged from ~30 to 250 feet.

- The width of zone of deformation (discrete primary and secondary right lateral displacements plus ground warping) varied from 120 feet to over 2,220 feet. The great discrepancy in these values, in addition to tectonics, might be explained at least partially, by the length and "original straightness" of the subject fence that was surveyed. The component of ground warping that is included in these summaries is generally not of significant concern for buried pipeline performance, especially to the extent that modern pipes are designed to accommodate up to 1 foot of offset at any location.

- For a more complete description of the fault's "mole track" expression across the surface near San Andreas Reservoir, the reader is advised to read the field observations of R. Anderson in Lawson (1908, p. 93-94).

Professor Derleth of U. C. Berkeley (1907) reported that in May 1906, he walked down the Pilarcitos pipeline between the north end of San Andreas Reservoir and the large Frawley Canyon, a distance of about 3 miles, and observed 19 locations where the 30-inch pipe was ruptured, always by separation at the girth riveted joints[15]. Derleth also noted that there may have also been additional unrecognized failures to still-buried portions of the pipe. Derleth describes that pipe wall thickness as t = 3/16 inches (based on the above-ground pipe at the Frawley Canyon crossing); but review of plans and profiles and historical pipe purchase data indicates the wall thickness for the low pressure portion of the 30" buried Pilarcitos pipe was 12 gage (t = 0.104 inches).

[15] See Section 4.1 for detailed descriptions of the pipe failures.

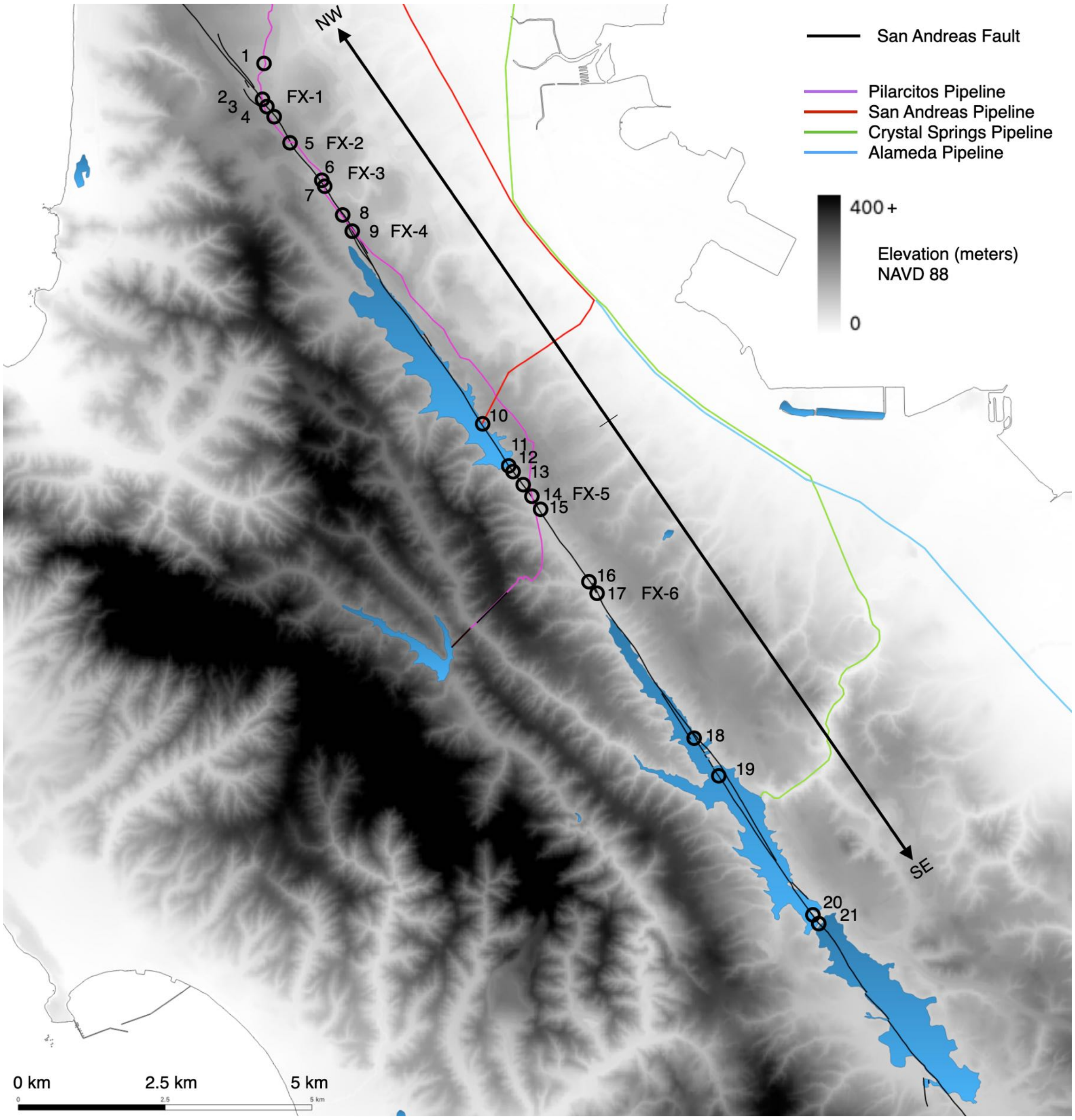


Figure 3-12. Location of Fault Offset / Other Pipe Damage Descriptions in the San Andreas Valley

Table 3-2 lists a summary of fault crossings (FX), and Water Supply Facilities, including the Pilarcitos Pipeline (PP) wrought iron and cast iron and Locks Creek wrought iron pipes near San Andreas Dam, as affected by the 1906 earthquake. Sections 4.1.1 through 4.1.21 provide further details and photos at each of the 21 locations.

In Table 3-2, the distances from San Andreas Dam are computed as the straight line distance from the road at the crest of the dam at the southeast end of San Andreas reservoir, to the indicated locations in Figure 3-12. In Figure 3-12, the alignment of the Pilarcitos pipeline is based on Scowden's 1875 survey (Figure 2-24). A number of location approximations are involved. The reader should interpret the distances in Table 3-2 are no more accurate than ±0.2 km.

These data, although somewhat sparse, suggest a couple of tentative hypotheses. First, the tectonic strain or signal transmitted through earthen embankments appears to attenuate when compared to more brittle but rigid materials like masonry structures. Second, it looks on average as if the threshold amount of strain that might have to accumulate in the current seismic cycle across the main trace of the San Andreas Fault prior to the next large magnitude earthquake is about 9 to 10 feet for the Peninsula segment. If this is the case *and* if the annual slip rate assessment of 17 +/- 4 mm/year from the trenching investigation at the nearby Filoli Estate is reasonable (Hall and others, 1999), then it might take only about another few tens of years of waiting. (This assumes, of course, that tectonic interactions among the multiple interacting faults that form the San Andreas Fault System in central California, which stretches from the San Francisco shoreline to the east side of the Sierra Nevada at Reno, generate earthquakes with the regularity of Newtonian clockwork.) Then we will know, once again, where the active San Andreas trace lies buried beneath the highly developed suburban areas that stretch from the northern end of San Andreas Reservoir to Mussel Rock on the Pacific coast. This post-1906 development will provide "fault finders" with hundreds of man-made strain gauges (roads, curbs, sidewalks, fences, walls, buried utilities, above ground occupied structures, etc.) that will record where the fault traces are located and just how much slip they have experienced. Serious damage to occupied above ground structures that straddle the fault cannot be ruled out: such damage can lead to potential life safety issues (injury and fatality to occupants or passersby).

No	Feature (NW to SE)	Km to Dam	1906 Fault Slip (feet). Total; Primary + Secondary Measured as right lateral slip	PP / Other Effects
1	PP @ Large Frawley Cyn	8.1 NW	Does not cross fault	PP trestle collapse
2	FX-1 PP @ Small Frawley Canyon	7.6 NW	8' right slip	PP trestle collapse. PP/fault 20°. PP telescoped 7.25', offset ~20"
3	PP 660' south of FX-1S	7.3 NW		PP buckled, possible vacuum
4	Fence 1	7.1 NW	8'-9' total 3 traces: W to E: 6', 2', 1'	
5	FX-2	6.8 NW	No data	PP WI failed
6	FX-3	6.15 NW	7.9 feet 2 traces @ 50 feet	PP WI failed
7	FX-3S 100' S of San Bruno Ck	6.12 NW	> 6.3 feet 2? traces	PP WI failed
8	FX-4	5.1 NW	7.9'; 6', 2.9'	PP WI failed
9	FX-4, Fence 2 Lawson Fence C	4.8 NW	9.5' total 2 traces: W 2.5', E 6.9', 160' between traces	PP WI failed
10	San Andreas Outlet Works	1.0 NW	8.25' in Bald Hill brick tunnel	
11	S.A. Dam road across crest	0	7' across embankment	
12	S.A. Dam Wastewater Tunnel	0.1 SE	9.57' in brick tunnel	
13	Fence 3, Lawson Fence B	0.5 SE	10.4' (8.9', 1.2' of drag)	
14	FX-5	0.7 SE	8.3' 2 traces: 6.7', 1.6', 100' between traces	PP CI pipe failure
15	Fence 4, Lawson Fence A	0.9 SE	12' 2 traces 9' (east trace incl 1' warp) 2' (west trace)	
16	Fence 5	2.3 SE	9' 30' wide zone of concentrated shear	
17	FX-6	2.49 SE	11.6'	Locks Creek 44" WI pipe failure
18	Old Locks Creek pipeline FX-7	5.47 SE	9'	Locks Creek 37.5" WI pipe failure exposed in 1924
19	Hayward Dam (submerged)	6.18 SE	7'+	Pre-1877 embankment
20	Upper CS Outlet Tunnel	9.3 SE	8.8' on brick outlet tunnel	Tunnel failed
21	Upper CS Dam, Road, Fence 6	9.4 SE	8'-9'	Highway 92 causeway

Table 3-2. Fault Offsets in the San Andreas Valley (See Section 4.1.X for further details at each site)

Table 3-3 provides statistics of the measured fault offsets.

Column [1] represents the total right lateral offset (primary + secondary) through the fault offset zone. Depending on location, this could have been all applied at the "primary" offset zone (knife edge, typically less than 10 feet wide), or some applied at the primary trace combined with some applied at one or more secondary traces.

Column [2] represents the total right lateral offset across the primary offset trace, at sites that exhibited 2 or more offset zones.

Column [3] represents the total right lateral offset across the secondary offset trace(s), at sites that exhibited 2 or more offset zones.

Column [4] represents the total width of primary + secondary traces, for zones that showed two or more offset zones.

Parameter	Total PGD Primary + Secondary. [1]	Primary Trace PGD. (locations with multiple traces). [2]	Secondary Trace PGD. (locations with multiple traces). [3]	Secondary Zone Width [4]
N Observations	17	8	8	9
Maximum, ft	12	9	3	250
Minimum, ft	6.3	6	1.2	30
Average, ft	8.86	7.19	2.35	139
Sigma, ft	1.51	1.16	0.68	90
Ratio Maximum / Average	1.35	1.25	1.28	1.80
Average + 1 Sigma, ft	10.37	8.35	3.03	229

Table 3-3. Fault Offset Statistics

How does the observed fault offsets compare with the worldwide database of fault offsets compiled and assessed by Donald Wells and Kevin Coppersmith (1994)? Assuming a M 7.8 strike slip event, using the worldwide database, the median Average Displacement (AD) across the fault would be 16.4 feet and the median Maximum Displacement (MD) across the fault would be 24.8 feet. Allowing for uncertainty between events, the AD and MD (84th percentile not to exceed) would be 21.8 feet and 34.9 feet, respectively.

However, as noted in Table 3-3, actual observed concentrated fault offset in the 1906 event, near the San Andreas Reservoir, at 17 observations locations, ranged from 6.3 feet to 12 feet, average 8.86 feet. The observed values in the 1906 earthquake, along the

Peninsula (Sites 1 through 21) is substantially lower than would be predicted using the worldwide dataset.

This raises the question whether the Peninsula segment of the San Andreas fault is somehow constrained to experience smaller offsets than would be expected considering the worldwide data for similar magnitude strike-slip earthquakes that rupture ~ 300 miles of fault.

How Much Offset Should Pipes be Designed to Accommodate Across Active Faults?

Water Pipes. In ALA (2005), the recommended approach to design new water pipes across active faults is to first assign the moment magnitude suitable for design, and then compute the AD, then increase the AD value to reflect the pipe's importance, and then design the pipe for various load cases (primary and secondary faulting) to acceptable strain levels. More specifically:

Step 1. Compute $Log_{10}(AD) = -6.32 + 0.90M$ (strike slip fault, AD in meters, M in moment magnitude). See ALA (2005) for recommendations for selecting M. If the style of fault offset is unknown (strike slip, normal or reverse), $Log_{10}(MD) = -5.46 + 0.82M$ (unknown style of offset, MD in meters, M in moment magnitude).

Step 2. Increase (or decrease) AD based on the pipe's Function Class (Table 3-4). Pipe Function Class I is reserved for pipes that are allowed to fail in earthquakes, and generally supposes that the repairs can be done in a week or so without material impact to end users. See the description below for the approach to consider if there are redundant pipelines. See Wells and Coppersmith (1994) for additional ways to compute AD or MD. Once AD or MD is established, compute the offset movements relative to the direction of the strike of the faults and the pipe's orientation.

Pipe Function Class	Design Movement	Probability of Exceedance in 50 years	Return Period (years)	Comment
I	0	100%	Undefined	Pipes not needed for post-earthquake system performance, response or recovery. Restoration time of weeks (or longer) acceptable
II	AD	10%	475	Normal and ordinary pipeline use
III	1.5 * AD	5%	975	Critical pipes serving large number of customers
IV	2.3 * AD	2%	2,475	Essential pipes serving large number of people, intended to remain functional and operational following a design earthquake

Table 3-4. Water Pipe Function Class

Approach for Redundancy.

- Water Pipe function Class III pipes may be designed as Pipe function Class II if there is 1 redundant pipe serving the same function.

- Water Pipe function Class IV pipes may be designed as Pipe function Class III if there is 1 redundant pipe serving the same function.

- Water Pipe function Class IV pipes may be designed as Pipe function Class II if there are 2 redundant pipes serving the same function.

- All redundant pipes need to be seismically designed.

Natural gas and liquid petroleum pipes. PRCI (2004) follows a somewhat similar approach as ALA (2005). For natural gas transmission pipes, if they are ranked Class 3 or 4, (going through urban or dense urban areas), then they are designed for:

- Gas (and flammable / explosive liquid petroleum). Class IV. MD

- Gas (and flammable / explosive liquid petroleum). Class III. 2/3 * MD

- Liquid petroleum in environmentally sensitive areas. 2/3 * MD

- Other natural gas or liquid petroleum pipes other than those above. AD

ALA (2005) provides direction as to how to address the uncertainty in the fault offset location (see Figure 3-13). Primary offset can occur anywhere in Zone A, and Secondary offset can occur in Zones B. Depending on the importance of the pipe and access to the site, and budgetary constraints, the width of Zones A and B can be established by geohazard professionals, possibly using trenches.

The Authors suggest design for at least 2 load cases:

- Case 1. Total PGD (Column [1] in Table 3-3) is applied as a knife edge across the pipe (equivalent to the worst case of scenarios 1, 2 or 3 in Figure 3-13).

- Case 2. Total PGD is divided into Primary PGD (Column [2] in Table 3-3) and Secondary PGD (Column [3] in Table 3-3). For the 1906 earthquake in the area investigated in this report, the width of Zone B ranged from 30 feet to 250 feet.

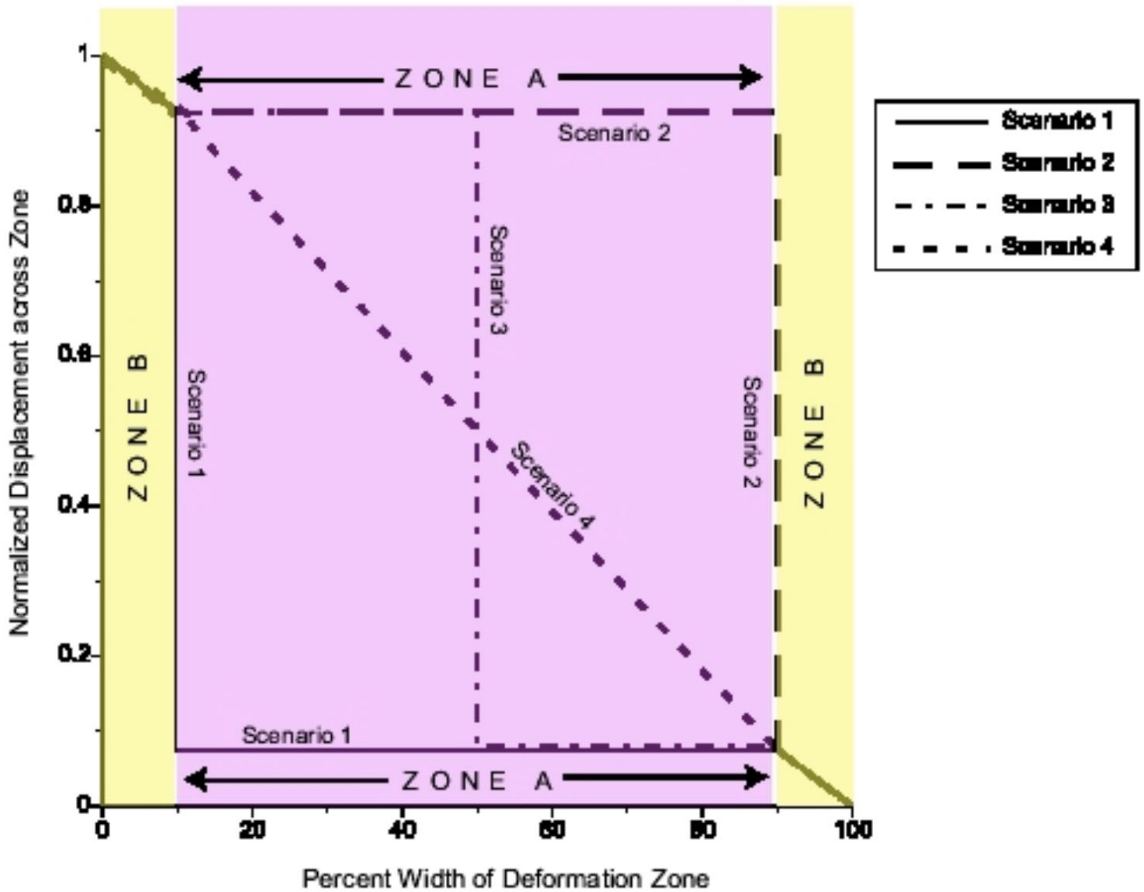


Figure 3-13. Fault Offset Location

ALA (2005) suggests design for the worst case of four load cases (scenarios). In all these scenarios, 15% of total PGD is applied in Zone B and 85% in Zone A.

- In the 1906 earthquake, for sites that did show 2 (or more) offset traces, the amount of PGD in the secondary zones averaged 25% of that in the primary zone.
- In the 1906 earthquake, about half the sites showed 100% of the PGD in the primary offset zone.

A fair question to ask is:

- For the 17 sites along the Peninsula, the AD was 8.86 feet, but the corresponding AD from Wells – Coppersmith (1994) is 16.8 feet. Why such a big difference?
- Recall that in this report, we are examining only about 18 km of fault rupture in the Peninsula over a 500 km long total fault rupture in 1906. The maximum PGD anywhere along the fault was measured at more than 20 feet[16]. Donald Wells

[16] A maximum of 16 feet of right lateral offset was documented at several locations in Marin County; a maximum of 20 feet of right lateral offset was reported where Sir Francis Drake Blvd

(personal communication, 2023) pointed out that much of the 1906 surface rupture was under the Pacific Ocean, where there were no offset observations for displacement; and possibly, along the Peninsula segment, the moment release was lower.

- If one assumes M 7, then AD = 3.13 feet and MD = 3.72 feet.

- If one assumes M 7.5, then AD = 8.83 feet and MD = 12.19 feet. This matches the observed 1906 offsets along the Peninsula segment quite closely.

- A speculative argument is that the Peninsula segment of the San Andreas fault is limited to about AD = 8.9 feet / MD = 12 feet.

Modern Design Considerations for Fault Offset

From the engineer's practical point of view, the observed average 7.19 feet of primary offset over a narrow zone (Table 3-3) is insufficient for design of modern-day water pipelines (or tunnels) exposed to the San Andreas fault along the Peninsula. A more reasonable approach might be to design for either 10.37 feet of "knife-edge" right lateral offset (load case 1, average plus one sigma) or 8.35 feet of "knife edge" offset plus 3.03 feet of distributed secondary offset at perhaps 130 feet either side of the knife edge offset (Load Case 2). These are based on the average plus one sigma offsets from Table 3-3.

If one adopts ALA (2005), and assuming the water pipe is classified as critical, then the PGD would be 1.5 x AD. If AD is 16.8 feet, then the design PGD is 25.2 feet presuming a M 7.8 event. This seems extreme, given the historic evidence in this area, and a maximum of about 20 feet observed anywhere along the fault in 1906.

Similarly, for inertial loading design, using the median inertial motion for a site adjacent to a M 7.8± event (about PGA = 0.7g) is insufficient for design of new critical or essential infrastructure. Today (2024), we would adopt taking the 84th percentile inertial motion for a M 7.8 event (say about PGA = 1.1g with corresponding spectra) and design to have limited damage and continued function (sustaining a minor leak at most) of any pipeline that delivers water for firefighting (or arguably regular consumption) purposes. On the other hand, for a pipeline that takes raw water from Crystal Springs Reservoir for purpose of re-filling San Andreas Reservoir, major (but repairable within 30 days) damage it tolerable, as the loss of ability to refill San Andreas reservoir would have de-facto zero impact on any downstream fire flows or potable water consumption; such a pipe would be classified as Class I (Table 3-4) and thus have no requirement for fault offset design.

---

crossed the fault south of Tomales Bay. But, the larger number (20 feet) might have been the consequence of lurching of soft bay muds at Tomales Bay.

4.0 Damage to the SVWC Water System in the 1906 Earthquake

Table 4-1 lists the damage to the Water Transmission System in the 1906 earthquake. In this table, a pipe break "segment" is the equivalent number of equivalent 10-foot long segments that would have to be replaced or re-layed in order to put the pipe back in service.

About 2,850 feet of the Crystal Springs 44-inch pipe fell off its support trestles at the San Bruno Marsh. Once the trestles were repaired, the pipe was simply replaced atop the wood trestle, and about 14 damaged slip joints repaired, while other girth joints showed no distress. The "~22" pipe break segments listed includes these 14 locations, as well as 8 other locations (4 between Crystal Springs reservoir outlet and the San Bruno Marsh, and 4 more locations where the pipe crossed two additional marshes).

Conduit	Pipe Breaks at Fault Offset Locations	Collapsed Trestles / Flumes	Total Pipe Break Locations	Total Pipe Break Segments	Time to Restore Water Service
Pilarcitos	5	2 trestles collapsed 1 flume minor damage	31+	~60	16 hours
San Andreas	0	0	1	2	62 hours
Crystal Springs	0	3	~10	~22	28 days
Alameda	0	1 rock fall impact	7	7	< 1 day
Locks Creek System	2	5 collapsed segments, plus others with minor damage	3	6	< 2 months
Total	7	11	52	97	

Table 4-1. Supply System Damage in the 1906 Earthquake

In Table 4-1 the term "break" or "collapse" is used to denote a loss of the pressure boundary, requiring the pipe to be shut down. The term "minor damage" is used where we have documented reports that some damage occurred, and was quickly repaired.

In addition to the damage to water conduits in Table 4-1, SVWC suffered other damage or had other emergency actions:

- The 5-story Class "A" fire-rated office building owned by SVWC at the southeast corner of Geary and Stockton suffered damage due to inertial shaking, and then was gutted by the fire that consumed the building on April 19 / 20. After the fire, all that was left of this building was a bare steel skeleton, the entire contents except the floors having been burned out. After the fire, the company immediately built a 1 story temporary frame building near Webster Street and Duboce Avenue in San Francisco.

- One of the pumps at the Belmont pump station failed.

- One of the pumps at the Lake Merced pump station had a broken steam gate. This was replaced and the pumps were in action by 3:00 pm April 18, furnishing 3 MGD out of Lake Merced to the Lake Honda reservoir. It was this water that had much to do to stopping the spreading fire at Van Ness Avenue north of Golden Gate Avenue.

- The Clarendon Heights tank and pump station (17^{th} and Pond Streets) had no significant damage. This pump station source supply was either the University Mound Zone (connected to the 44" pipe at Harrison and 17^{th} streets) or College Hill Zone (connected to the 22" pipe on Valencia and 17^{th} Streets). Both these zones suffered a great amount of damage, so the Clarendon Heights Zone could not be re-supplied. Once the break on the San Andreas 37" pipe at Baden was repaired (within a day of the earthquake), the 22" pipe to the Clarendon Heights pump station was re-pressurized, and water was again available to the Clarendon Heights Zone.

- As soon as the Crystal Springs 44" pipe was repaired (about a month after the earthquake), a temporary pump station was built in Garfield Park at 26^{th} Street in order to pump water from the Crystal Springs Zone into the Lake Honda Zone. This pump station was erected using parts from the Pilarcitos pump station that was abandoned after the 1906 earthquake. This was needed to supplement water into the Lake Honda Zone, which had lost its main source of supply (Pilarcitos pipeline) and which was being supplied on an emergency basis via the San Andreas pipeline and Lake Merced. Later, this pump station, known as the Precita Valley pumps, was moved to a permanent location at 26th Street and Treat Avenue.

- A very small pressure zone was served by the Forest Hill Tank (overflow elevation about 700 feet). This zone was served by a small pump station located adjacent to the Lake Honda Reservoir. Owing to the prompt starting of the Lake Merced pumps (about 3:00 pm on April 18), Lake Honda never was emptied, and this small zone never lost supply.

- There was slight damage at College Hill Reservoir near Park Avenue and Mission Street: a few boards were disrupted at the aerator. This did not prevent the reservoir from functioning.

- The University Mound Reservoir at University Avenue and Bacon Street was in good order, even though no water was being delivered to it.

- The Sutro Forest flume (part of the Pilarcitos conduit just south of Lake Honda) was in very good order once a few small leaks were repaired on April 18.

- By April 20, all city reservoirs were empty except for Lake Honda, which was being resupplied from Lake Merced. No water was able to reach the Black Point pump station, owing to the great amount of damage in the Lower zone pipe network in the City.

- Some 18,200 service laterals were damaged in some fashion. The fire damaged or destroyed some 18,200 structures, and essentially all these service laterals suffered damage (pipe breaks either inside or outside the meter). It is common that earthquakes would damage some service laterals, but with the fire, it is not possible now to discern the number of laterals damaged due to the earthquake (shaking, liquefaction, etc.) or fire. It is presumed that the vast majority of the damaged service laterals were due to the fire that led to widespread building collapses; these collapses would invariably result in an "open" pipe either inside the building or outside the building along the buried service lateral. Fallen bricks from collapsed buildings due to inertial shaking could also impact the ground above the service lateral, and damage the lateral beneath. For any of these cases, the service lateral pipe would have to be capped (closing the valve in the street where possible, or capping the pipe more commonly).

- After the earthquake, as repairs were made to the hundreds of broken cast iron pipes in the City in the burned zone, it would have been best to re-pressurize the system on a block-by-block basis. The historic record indicates that the Mayor intervened with this orderly restoration of the water system, as the Mayor demanded that SVWC keep valves open so that some customers could have access to some water sooner. But this type of restoration process was not best overall, as it continued to spill water through broken pipes, continued to prevent normal water pressure to be restored, and allowed more air into the pipes. Schussler noted that by following the Mayor's directive, this prevented the early re-filling of University Mound and College reservoirs, as all water delivered was quickly lost through the broken downstream pipes. Even so, the overall restoration of the water distribution system in San Francisco took many months, requiring a large crew of workmen shutting off broken service laterals at the curb or at the main before the main could be re-pressurized. It was often necessary to dig down through 2 to 3 feet or rubble to reach the street pavement and another 2.5 or 3 feet to reach the main and service line connection in order to shut off the service. The total manpower needed to isolate and repair all the 18,200 ± service line connections was likely larger than the manpower needed to make repairs to the 299 ± distribution mains.

- After the earthquake, for a period of about three months, it was customary at remining occupied houses to move stoves out to the curb, and cooking was done in the street. This procedure was followed until all chimneys had been repaired and inspected, to be safe for wood or coal fires as were commonly used in 1906. This precaution was done to limit the potential for additional fire ignitions.

Table 4-1 excludes unreported damage that did not require repair in order to restore water service in the system.

The quantities values in Table 4-1 are primarily based on Schussler's account of the 1906 earthquake (1906, 1909). Some water system damage descriptions are supplemented by Lawson's (1908) and Perry's accounts (1956).

Table 4-2 shows the number of repairs made to distribution pipes within the City distribution system, as a function of pipe diameter and the amount of PGD at each repair location. Schussler (1906, 1909) reported that there were a total of 299 repairs made to the distribution system, and provided mapped locations for 258 of these repairs. The mapped total of 258 repairs is 41 fewer than the actual total 299 repairs; the location of 5 of these 41 repairs is known to be in locations with no PGD (locations listed in lower left of Figure 2-28); the location for the remaining repairs is uncertain.

There were 12 repairs for the 37" WI pipe, subjected to about a foot of PGD. There were 2.32 miles of 37" WI pipe, mostly laid through Mission Creek liquefaction zone. It would be incorrect to assigned an overall fragility repair rate for 37" WI pipe being much worse than for the 44" WI pipe that was located just north of the University Mound reservoir; as long as one understands that the 44" pipe was not subject to PGDs, whereas the 37" pipe was.

The first column in Table 4-2 shows the amount of PGD (liquefaction); columns 2-7 show the number of pipe repairs, by pipe diameter, and the right most column shows the total repairs. All told, about 92 pipe repairs occurred at locations with no observed PGDs.

PGD, Inch	Pipe Diam, Inch 3 to 10	Pipe Diam, Inch 12	Pipe Diam, Inch 16	Pipe Diam, Inch 22	Pipe Diam, Inch 33	Pipe Diam, Inch 37-44	Total Pipe Repairs All
0	74	7	8	2	1	0	92
1	10	2	0	0	0	0	12
2	47	1	4	0	0	0	52
3	12	0	0	0	0	0	12
4	12	3	0	0	0	0	15
5	2	0	0	0	0	0	2
6	11	0	2	0	1	0	14
8	4	0	0	0	0	0	4
10	2	0	0	0	0	0	2
12	6	8	0	0	4	12	28
16	0	0	0	0	2	0	2
18	0	1	0	0	0	0	1
20	0	0	0	0	2	0	2
24	0	2	4	4	0	0	10
36+	0	2	4	4	0	0	10
Total	180	26	22	10	10	12	258

Table 4-2. City Distribution Pipe Damage from the 1906 Earthquake

Along Valencia Street, near the collapse of the Valencia Hotel, the College Hill 22" (east side of street) and 16" (west side of street) mains had failed, and by midday April 18, were observed to be spilling water down to the 18th Street cesspools (See Section 7.7 for more discussion on the pipe damage on Valencia Street). At 24th and Harrison Streets, a crew was closing the gate valve on the 44" pipe coming from the University Mound reservoir, made necessary by a break in the 44" pipe about 100 feet south of 14th Street.

Table 4-2 excludes repairs of service laterals. Essentially every service lateral (about 18,200) in the burned area of San Francisco required some type of repair over the following two years, as part of the reconstruction of the original buildings. There is no historical data available to determine the extent of damage to service laterals due to inertial or liquefaction-related phenomena, although there certainly would have been some.

Figures 4-1 and 4-2 show maps of the damage to SVWC's transmission pipeline system in the 1906 earthquake. See Figures 3-12, 4-9 for more detail of locations of damage along the Pilarcitos pipeline.

In 1909, as part of court proceedings between SVWC and the City of San Francisco over the setting of water rates, SVWC claimed a total repair cost of some $620,000 ($1909). The court filings available do not show a breakdown of this cost. Over several years and multiple demands and complaints about rates, the Court ruled favorably for SVWC. However, in the matter of whether (or not) the rate payer should be responsible for paying the cost of earthquake-related repairs, the Court ruled against SVWC, stating (paraphrased) that "*SVWC should alone bear that cost as the damage reflected insufficient original quality*". In modern understanding, such a ruling would likely to have been appealed and overturned: nothing the Authors have been able to uncover would suggest that SVWC built anything that did not meet the prevailing standard of care at the time; and most independent observers (such as Derleth in 1907) were on record that while the regular building stock failed at a very high rate, SVWC's nearby pump stations and facilities survived with almost no damage, reflecting a very high quality of construction. Further, SVWC used exclusively cast iron pipe (pipes 24" diameter and under) or wrought iron pipe (pipes 30" diameter and over), and avoided using lower cost (and generally weaker with shorter life expectancy) wooden pipes as was the common practice for other west coast water utilities of the era.

The common cost to install a mile of 8" diameter pipe in 1906 was about $12,000 ($1906). Available records suggest that Mr. Schussler earned $3,000 per year as Chief Engineer. A common annual wage in 1906 was $1,650 for a surgeon, $1,200 for a lawyer, $920 for a plumber, $425 for a bartender. If one allows that the $620,000 cost was split between about 2/3 for materiel (new pipe, new concrete, street paving, excavation equipment, feeding horses, etc.) and 1/3 for human labor, and allowing an average annual wage of $1,000 per SVWC worker, then the repair effort was about $206,600 / $1,000 = 207 man-years, or about 414,000 manhours (we use the term "manhours" to reflect work both by men and women).

Allow an average of 40 manhours to make each of 299 repairs in the City Distribution system, or 11,960 manhours. Allow a crew of 16 man 20 days to repair the Crystal Springs pipeline through the marsh zones, or 3,200 manhours. Allow 3,500 manhours to make other repairs to the transmission system. Allow a crew of 16 men 4 weeks to remove and temporarily store the Pilarcitos pipe, or 2,600 manhours. Allow a crew of 16 men 3 months to build the Baden-Merced pipeline (with the relocated Pilarcitos pipe), or about 12,000 manhours. and perhaps another 2,000 manhours to build the new Central pump station. The Precita pump station (see Figure 9-12) and related pipe might have required another 3,000 manhours to build. Another 2,000 manhours would have been needed to make repairs to the San Andreas Outlet Tunnel works, and repair the Stone Dam Flume (Locks Creek Flume).

This totals (11,960 + 3,200 + 3,500 + 2,600 + 12,000 + 2,000 + 3,000) field repair hours, or 38,260 manhours. Say an additional 50% (or so) number manhours for in-office and logistics work, then the repair effort is about 60,000 manhours, or about 30 man-years, or a direct labor cost of about $30,000.

This leaves the largest effort (perhaps 354,000 manhours) for making repairs / reconnections to the 18,200 buildings / customers in San Francisco. Most of these buildings were reconstructed between July 1906 and the end of 1908. This averages about 18,200 connections / 30 months = 607 connections per month. To do this, SVWC would need to install about 607 connections / 25 days / month = 24 connections per day over 2.5 years (assuming a 6 day work week). Today (2024), it commonly takes a 4-man crew to install one service lateral connection in half a day, or sometimes a full day (about 16 to 32 manhours per connection). This means that the average connection work took about 354,000 manhours / 18,200 = 19.5 manhours per connection, more-or-less in line with modern efforts.

While we presently do not have sufficient 1906-1908 accounting data to be more precise as to where the labor effort went during the repair and restoration process, the above computations strongly suggest that the bulk of the labor (perhaps 80% or more) of repairing the water system went to the re-build of service line connections, with the remaining 20% going to repairing the most dramatic damage to the supply system pipelines and the city distribution pipes. This 80% / 20% split of labor is an estimate, and if the assumed materiel costs for new lumber, pipe and equipment (2/3 of total) are off, then so will be this split.

In modern times (2024), most U.S. public water utilities would be reimbursed some 90% (or so) of their earthquake-caused repair costs from FEMA. But 1906 was a different era, and FEMA did not exist, the Federal Government reimbursed not a penny to SVWC. The animosity between SVWC and the City of San Francisco over water rates, the fire conflagration, and construction of a new Hetch Hetchy system with intent to put SVWC out of business, etc., were all factors that hopefully no modern-era water utility, whether privately-owned or publicly-owned, will have to ever face in future earthquakes.

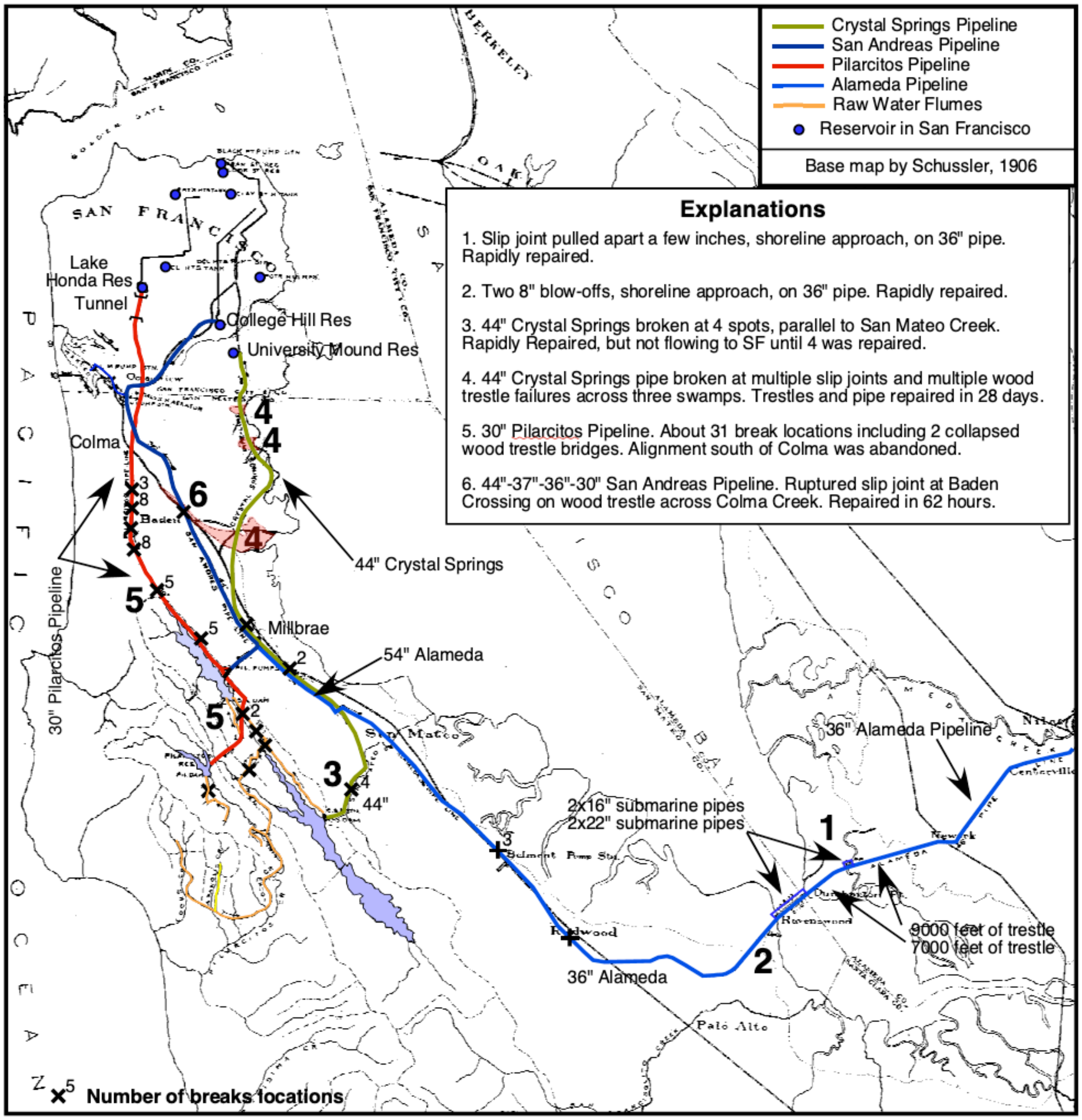


Figure 4-1. Damage to the Transmission Pipelines Serving San Francisco, 1906

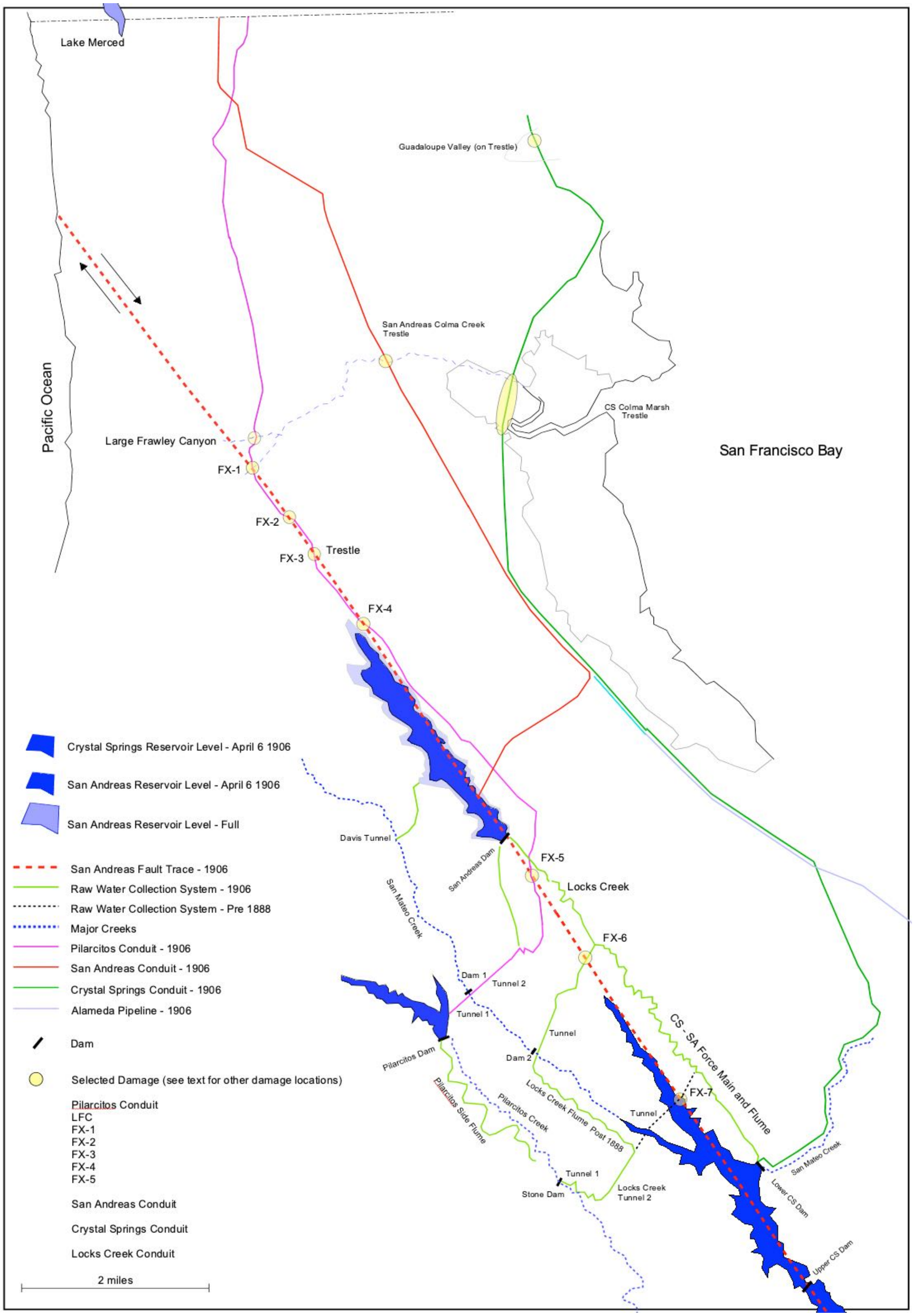


Figure 4-2. Location of Selected Pipeline Damage in the 1906 Earthquake

4.1 Pilarcitos Conduit

Figure 4-3 shows a piece of the Pilarcitos pipeline where it failed in July 1904 (about 20 months before the earthquake). The location of this failure was along the hillside east of San Andreas Reservoir, near station 167 (Stations per Table 4-5), at the north end of the reservoir. The girth riveted joint (with all rivets missing) is seen on top of the pipe segment. The torn edges were along the longitudinal direction of the pipe, with the two torn edges originally connected to each other.

This pipe segment failure mode was due to an excess of internal pressure that overcame the corrosion-weakened pipe. The water pressure at this location was about 40 to 50 psi, suggesting that the pipe wall thickness at the time of failure had thinned so as to be on the order of 0.025 inches or so. This is much thinner than the original installed wall thickness of 0.104 inches. At the time of failure, the pipe has been in the ground for about 39 years. This suggests a wall-thinning process of about (0.104 – 0.025 inches) / 39 years = 0.002 inches per year. A not uncommon approximation of wall thinning in corrosive soils is on the order of 1 mil per year (0.001 inches per year).

Figure 4-3. Failure of Pilarcitos 30" Low Pressure Pipe (WI-thin), July 28, 1904 (Photo: SVWC 1904)

Pipes. To understand the damage to the pipes, one needs to understand the design of the pipes during the time period from 1850 to 1902. Review of some 200 SVWC design drawings and hundreds of photographs that pre-date the 1906 earthquake suggest that Mr. Schussler's design process was as follows:

- Select wrought iron as the common material for all pipes 30-inch diameter and larger. Cast iron pipe was then generally available only up to 24-inch diameter. The WI material was commonly Fu = 50,000 psi, Fy = 30,000 psi, (see Section 1.3 for description of engineering terms) and with good ductility.

- Dip all the WI pipe into asphaltum for corrosion protection. Schussler built a pipe dipping facility in Millbrae for this purpose. There were no sacrificial anodes or impressed current used for corrosion control. There were no interior cement mortar linings used for erosion protection of the inside of the pipe. There was no water chemistry control (such as the addition of alum) to keep the pH of the pipe slightly basic (7.5 or so). Between 1901 and 1904, there were five failures along the 30-inch Pilarcitos pipeline (see Table 4-5 for locations); Figure 4-3 indicates one such failure was due to corrosion of the thin-walled pipe.

- In zones known to have hot (corrosive) soils, put the pipe above ground and support the pipe on wood trestles. The wood trestles commonly used redwood piles, and Douglas Fir or various species of pine for above ground portions. On trestles, the pipe was enclosed in wood to protect the pipe from salts in the air.

- Where a pipe traversed creeks, support the pipe atop a short wooden trestle over the creek. Figure 4-4 shows one such installation, constructed in 1907, supporting the "new" Baden-Merced 30-inch pipeline, built using a portion of the same Pilarcitos pipe that was dug up after the 1906 earthquake. (See Figure 9-8 for schematic location of the Baden-Merced 30" pipe). Trestle spans were commonly 12 to 16 feet. At each creek crossing, a blow off (commonly an 8-inch pipe with a gate valve) was included to allow draining of the pipe for maintenance purposes. It was not until 1923 that burying large pipe under creeks become a common practice.

- Standpipes were included along the pipe to control maximum hydrostatic pressures. Standpipes were commonly 12-inch diameter pipes, standing vertically to the desired overflow elevation. External wood towers for lateral load resistance were provided if the standpipe was much over 10 feet high. For very tall standpipes (over 30 feet high), supplemental guy wires were used to provide additional lateral resistance. Lateral loads on the standpipes were set at about 30 psf, a common practice of the time for high winds loads; there is no evidence that the standpipes were explicitly designed for seismic loads. No standpipe was reported damaged in the 1906 earthquake.

- Longitudinal joints were made with two offset rows of rivets, generally made in the shop. There is no evidence that any longitudinal joints were broken in the 1906 earthquake.

- Girth joints were made with one row of rivets. For the Pilarcitos pipeline, these were commonly 0.5-inch diameter rivets. In the 1906 earthquake, many girth joints failed, at locations subject to PGDs due to fault offset, as well as at locations with high inertial shaking coupled with hydrodynamic loading. The strength of the girth joints was set to be "at-least" one half (possibly as much as 70%) that of longitudinal joints. This design assured that at locations where the pipe would sustain axial (longitudinal) elastically-computed stresses much over yield, the girth joint rivets would break, resulting in a pipe break, which appears to have happened at about 24 places along the 30-inch Pilarcitos pipeline where the pipe had t = 0.104", with D/t ~ 288. There were no girth joint failures along the Pilarcitos pipeline north of Colma, where D/t < 150, and PGVs were in the range of 40 to 70 cm/sec.

- It appears that Mr. Schussler used the thinnest WI pipe that would be reliable under normal service: none of the WI transmission pipes used t > 0.25 inches, and most pipe, where exposed to operating pressures of 100 to 150 psi, were t = 0.14 to 0.19 inches thick. Practically, all the pipes were sized to limit hoop stress to about 10,000 psi under maximum hydrostatic conditions. The low pressure Pilarcitos pipe south of Colma, where hydrostatic pressures were less than 70 psi, suffered a great amount of damage; this was the thinnest-walled pipe in the entire water transmission system. Available records suggest it was purchased as t = 0.104-inch-thick wrought iron pipe.

Pipes on Trestles. Of the 46 reaches of pipe supported on wooden trestles (Table 2-3), 6 reaches of pipe failed, 5 trestles failed, due to inertial overload on the combined pipe / trestle system. The failure of 3 trestles along the Crystal Springs pipe may have been made more severe by the effects of deep soft soil / amplified motion / liquefaction. 41 wood trestles that supported pipes of various lengths survived without need for any immediate major repairs.

The Pilarcitos 30-inch WI pipe (thin wall) pipe collapsed at two trestle locations with the pipe broken and laying at the bottom of the canyons and the two wooden trestles collapsed or with major damage (Locations 1 and 2 in Figure 3-12). The San Andreas 37-inch WI pipe broke atop one trestle, where an expansion joint pulled open, requiring repair to 2 pipe segments. The Crystal Springs 44-inch WI pipe broke at three trestles across San Bruno (Colma), Guadalupe and Visitacion Valley marshes: at these locations, the 44-inch WI pipe was thrown sideways up to 5 feet, and broken open at multiple expansion joint locations. The abandoned 37.5-inch Stone Dam (Locks Creek) pipe on an old trestle that traversed under the flooded Crystal Springs Reservoir (Site 18) failed.

The original design of the Pilarcitos, Crystal Springs and San Andreas pipes on trestles provided for gravity support and thermal expansion. The pipe was commonly installed resting on transverse wood stringers, supported only at the pipe's invert, and with the pipe free to slide sideways a small amount under seismic inertial as well as thermal expansion loads. Restrained slip joints were placed about every 500 feet (or so), to allow for thermal growth / contraction of the pipe, or for maintenance of nearby gate valves. During the earthquake, these pipes were relatively free to slide sideways, and the slip joints tried to open / close several inches due to inertial shaking and strain incompatibility with the adjacent buried pipe segments. For the San Andreas pipe at the Baden trestle crossing, the slip joint tried to open a few inches, and the restraining cables were put into such high tension that they ripped out their anchors on adjacent pipe segments. For the Crystal Springs pipe through the marshes, the pipe moved sideways 4 to 5 feet and fell off the trestle; at one location for 800 feet; except at the slip joint locations, the pipe was almost uninjured; once the trestle was repaired, the uninjured pipe was replaced atop the repaired wooden trestle. Due to the short length of the Pilarcitos trestle collapses (Sites 1 and 2, both under 60 feet) and based on the available photographs of the failed pipes at these locations, there does not appear to have been any pipe expansion joints atop those trestles.

The most common span between supports on trestles was 14 feet. Under dead weight (weight of steel pipe and water within), this resulted in a maximum dead weight bending stress in the pipe of about 2,900 psi (for thin-wall 30" Pilarcitos pipe) or 1,600 psi (for heavy-wall 44" Crystal Springs pipe). These stresses are well below the nominal yield strength of the wrought iron pipe of 30,000 psi, a clearly safe level. If the girth joints on these pipes were as strong as the main barrel of the pipe, then the maximum dead-weight span before reaching yield would be 45 feet (for thin-wall 30" Pilarcitos pipe) or 61 feet (for heavy-wall 44" Crystal Springs pipe). If the girth joints on these pipes were half as strong as the main barrel of the pipe, then the maximum dead-weight span before reaching yield would be 32 feet (for thin-wall 30" Pilarcitos pipe) or 43 feet (for heavy-wall 44" Crystal Springs pipe).

The Alameda pipeline was supported on trestles along the shorelines of San Francisco Bay. Here, the pipe-trestle connection design was different than for the older Pilarcitos, San Andreas and Crystal Springs pipelines. For the 36" Alameda pipeline, the pipe rested atop a wood cradle (carved from a 12x12 to match the outside diameter of the pipe), and this cradle rested atop the pier cap (another 12x12). The cradle was free to slide atop the pier cap. Nonlinear seismic analyses of this type of pipe / cradle support (Eidinger et al, 2006) shows that this arrangement can sustain very high ground motions without damage to the pipe, in part due to the high friction / damping offered by the sliding support arrangement. So successful was the 36" Alameda pipe atop these sliding supports in the 1906 earthquake, that the parallel 1923-vintage and 1934-vintage BDPL 1 and 2 pipes were built in the same manner: these pipes were not damaged in the 1989 Loma Prieta earthquake.

Flumes. At the time of the 1906 earthquake, the Pilarcitos Conduit included three wood flumes:

- Flume and sand box between Tunnels 1 and 2, crossing San Mateo Creek. This was about 300 feet long. See Figures 4-6 and 4-7 for location and details.
- Flume downstream of Tunnel 2. See Figure 4-7 for location.

- Flume south of Lake Honda. See Figure 4-7 for location, Figure 2-18 for photo. This flume suffered some damage, which was repaired on the same day of the earthquake, April 18, 1906.

At the downstream end of the 44" pipe just past Tunnel 2, the Pilarcitos conduit had a bifurcation, where water could go to Lake Honda or into the Pilarcitos waste flume. By "waste", it is meant that water from Pilarcitos Reservoir that could not be used at Lake Honda was "wasted" into San Andreas Reservoir. This waste flume included three reaches of wood flume, totaling 4,976 feet in length. See Figure 4-8 for details.

1906 Earthquake Performance

Schussler (1906) provides an excellent treatment of the damage to the various pipelines and other SVWC facilities, including more than 50 photos of the damage. Lawson (1908) wrote extensively about the geological aspects of the earthquake. Perry (1956) provided a summary of his observations of water facilities based on his personal inspection done on April 19, 1906.

By 9 pm on April 18 (16 hours after the earthquake), SVWC isolated the heavily damaged southern reach of the Pilarcitos pipe (south of Colma), turned on the pumps at Lake Merced, and pumped at a rate of 6 to 7 MGD from Lake Merced through the undamaged Pilarcitos pipeline to Laguna Honda. This water, plus the 31 MG in Laguna Honda at the time of the earthquake, kept the Laguna Honda pressure zone in service throughout the three days of the fire. There were no fire conflagrations in the Laguna Honda pressure zone.

Figure 4-4. Construction of the Baden-Merced 30-inch Pipe at Creek Crossing (using former Pilarcitos Pipe segments) (SVWC 1907)

Heavy damage in the City distribution pipes and high demand for fire flows resulted in heavy outflows from the three main terminal reservoirs. The following reservoir levels are based on data provided in Schussler (1906); the flows are based on an understanding of where water was available to fight fires as described in Section 7.

- Laguna Honda. At the time of the earthquake, the reservoir was full at 31 MG. 24 hours later, it was at 13.7 MG. 48 hours later, was at 8.5 MG. 72 hours later, was at 5.4 MG. 96 hours later, was at 1.5 MG. 6 hours after the earthquake, new water from Lake Merced was being pumped into Laguna Honda at a rate of 6 - 7 MGD. Water being used from various hydrants for fire flows along Dolores, Van Ness and other locations were possibly in the range of 4,000 gpm.

- College Hill. At the time of the earthquake, the reservoir was full at 11.4 MG. The breaks of the 22" and 16" pipes along Valencia Street between 18^{th} and 19^{th} Streets (See Section 7.7), rapidly drew down the reservoir, and it was emptied in a few hours. New water from San Andreas Reservoir at a rate of a few MGD started around 9 pm April 20 (62 hours after the earthquake, gradually increasing to 8 MGD soon thereafter). However, there were many downstream broken pipes as well as broken service line connections, and much of this new water was wasted to ground; but some might have been used to control the spread of the fire in the upper Mission District around 20^{th} street, late on April 20 and during April 21. It would take several days before College Hill Reservoir began to fill again.

- University Mound. At the time of the earthquake, the reservoir was full at 30 MG. With the failure of the 44" Crystal Springs pipeline, it could not be re-supplied until 4 weeks later. 24 hours after the earthquake, it was at 12.2 MG; the bulk of the 18 MG drawdown in the first 24 hours would have been spilled to ground, where the 37" pipe broke along Harrison Street. 48 hours after the earthquake, it was at 6.5 MG. 72 hours after the earthquake, it was at 5.6 MG. 96 hours after the earthquake, it was at 5.2 MG. This reservoir level record suggests that SVWC was successful in isolating the pipe break along Harrison Street "about" 12 hours (or so) after the earthquake. Cross connections (opening zone gates) between the College Hill and University zones would have been able to provide water to the low elevation downtown areas (without pipe breaks) beginning a few days after the earthquake.

Figure 4-5. 30-inch Pilarcitos Pipe Preparation of a Riveted Girth Joint (SVWC 1907)

After the 1906 earthquake, the southern reach of the Pilarcitos pipeline was abandoned, and much of the pipe was excavated in later 1906 and 1907 and then re-used to build portions of the Baden-Merced pipe constructed in 1907. Figure 4-4 shows the 30-inch pipe atop a trestle at a creek crossing: the 15 wooden "steeples" are to support wood planking (not yet placed) to enclose the pipe against effects of external corrosion. The 30" pipe rests directly on horizontally-laid 4x12s. The 4x12s are supported by two 8x12 stringers, laid along the alignment of the pipe. The 8x12 stringers are supported on a 4x12 resting directly atop a concrete pier; or by the wood framing of the bridge structure.

The reader will quickly surmise that this 1907-vintage trestle design, while perhaps more robust than in pre-1906 trestles, is still deficient with regards to earthquake loads. With half-strength girth-riveted joints, the pipe reaches its elastic limit at applied 1g force at about a 32 foot span. The pipe rests on 4x12s[17], and the only lateral restrain is offered by pipe-on 4x12 wood friction (trivial) or the lateral resistance offered by the toe-nailed wood encasement structure. If such a pipe bridge were exposed to horizontal PGA ~0.4g, the amplified spectral motions on the pipe would be about 1g, and a pipe failure might be initiated, even if the bridge survives. Recognize that even after the lessons learned from the 1906 earthquake, structural engineers were designing important structures for V = 0.1W, such as the San Francisco Oakland Bay Bridge (designed in the early 1930s). Does the wooden post-and-beam bridge structure deserve R_w = 6 (like suggested by some building codes like the UBC)? (See Section 1.3 for description of engineering terms). We

[17] Lumber dimensions are described in inches.

think not, as the joinery detailing is not robust enough to mobilize the full strength of the lumber, nor providing high energy hysteretic damping under repeated nonlinear load cycles. For modern installation in a high seismic hazard location, the pipe on this short span (under 60 feet) might use heavy wall full penetration butt welded steel pipe for its entire length, including (or, perhaps double lap welded), extending some length into the soil. For longer span bridges, the pipe would require expansion joints, meaning that there would have to be intermediate pipe supports that resist the loads into the bridge, and the bridge must also be designed to sustain the seismic loads.

Figure 4-5 shows the common buried pipe installation in the sandstone of the Merced Formation (note the person inside the pipe). The de-facto seismic design concept of these pipes was that should they fail, the terminal storage in reservoirs at San Francisco would ideally be sufficient to continuously meet demand while repairs are made. But, as described elsewhere in this report, the large Industrial reservoir (400 - 500 MG capacity) was never built, and the large amount of damage in the 1906 distribution system resulted in draining College and University Mound reservoirs.

There were commonly 80 rivets for each girth joint on the Pilarcitos 30" pipe. Allowing D = 30-inch and t = 0.104-inch, Area (pipe) = 9.80 square inches. Allowing Fy = 30 ksi, and Fu = 50 ksi, the longitudinal yield / tensile strength of the pipe = 277 kips / 490 kips. Allowing that the single shear strength of the rivets would be set at no more than half the yield strength of the pipe, the rivet yield strength would be about 139 kips. At an internal hydrostatic pressure of 50 psi, the axial force on the girth rivet joint would be 3.6 ksi (longitudinal stress) * 9.80 (pipe axial area) = 35.3 kips. For a buried pipe at PGV = 90 cm/sec, the imposed pipe stress due to earthquake ground strain might be about 6.6 ksi. The earthquake-induced hydrodynamic longitudinal stress might be about 4.3 ksi. The total longitudinal pipe stress might be 3.6 + 6.6 + 4.3 ksi = 14.5 ksi, or total load on the rivets about 142 kips. This exceeds the nominal rivet yield strength of about 139 kips. If there is any corrosion over time, the pipe barrel / rivet strength would be lower. The "true" stress in the rivets would be higher, as the double lap of the riveted joint would impose some bending, and the additional bending stresses are not included in these stress computations. The net result is that some pipe failures due to inertial and hydrodynamic loading would be expected, likely concentrated at the girth joint rivets, and also where there had been pipe wall thinning due to corrosion. Thus, high tension or compression in the pipe will fail the girth joint before the main pipe has reached yield. This is not a ductile seismic design.

Table 4-3 lists the various segments of the Pilarcitos Conduit that were in place at the time of the 1906 earthquake (or, as noted, subsequently updated). The lengths and attributes of the Pilarcitos Conduit are based on a combination of surveys that are shown in Figure 4-7 (dated 1901-02) and Figure 4-8 (dated 1905). Flume lengths listed include the length of weir boxes, which were typically placed at the downstream end of each flume, in part to allow sand to settle out, and in part for measuring flow volumes over weirs.

Segment	Length (feet)	Description
1	1,495	Brick-lined Tunnel 1, 42 x 54 inches
2	298	Wooden flume, 36 x 60 inches (2023: 30" pipe)
3	3,426	Brick-lined Tunnel 2, 42 x 54 inches
4	730	44-inch wrought iron pipe, t=3/16"
5	2,135	Wooden flume, 30 x 60 inches and 22" pipe (branch, waste to San Andreas Res)
6	67,383	30-inch wrought iron pipe
7	5,230	Wooden flume, 16 x 42 inch
8	940	30-inch wrought iron pipe
9	2,820	Brick-lined Tunnel 3, 36 x 52 inches
	84,457 feet 16 miles	

Table 4-3. Pilarcitos Conduit (1870)

Figure 4-6 shows Segments 1, 2, 3, 4 (Table 4-3) that are located in the upper Pilarcitos watershed area (using 2006-vintage naming). Abbreviations: cu yd = cubic yards; Bd = Board; ft = feet.

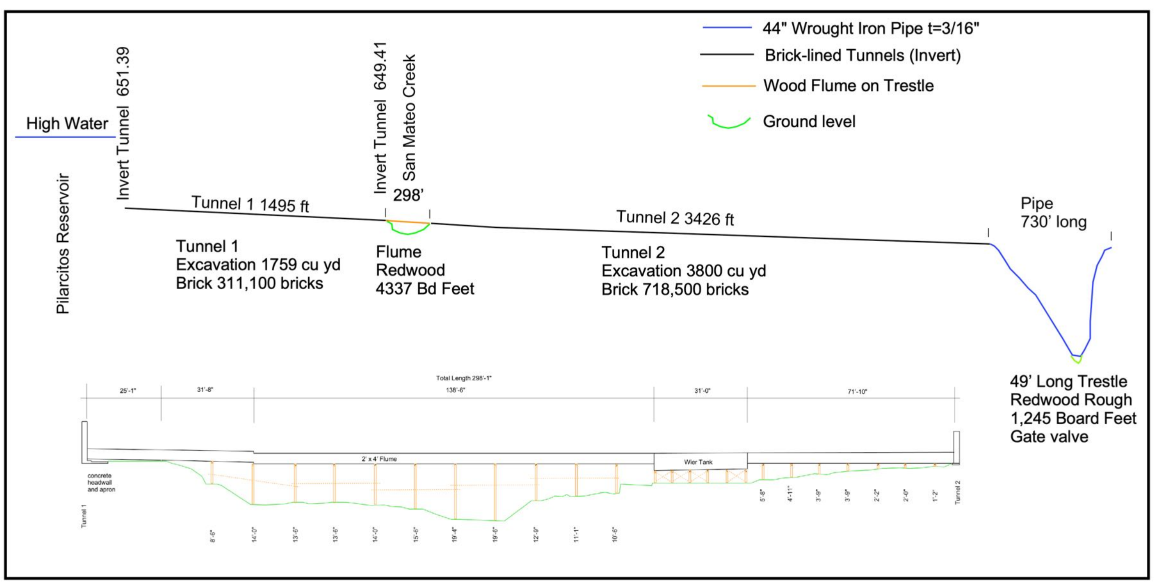


Figure 4-6. Pilarcitos Conduit: Tunnels 1 and 2, Flume Between Tunnels 1 and 2, 44" Pipe

The following describes the various segments of the facilities in the Pilarcitos watershed area:

- Pilarcitos Dam (elevation 669').

- Pilarcitos Tunnel 1. This is a 1,495-foot long brick-lined tunnel, 3'-6" x 54" (61" to the top) in cross section, and is the primary outlet from Pilarcitos reservoir. At the upstream end, there were two 2'x3' slide gates to control water from the reservoir from entering the tunnel. Tunnel 1 passes under Cahill Ridge, and exits just to the west of San Mateo Creek. Presently (2023) a 36" pipe takes water from Tunnel 1 to Tunnel 2; at the time of the 1906 earthquake, a 298-foot-long wooden flume supported on wood trestles connected Tunnels 1 and 2. See details in Figure 4-6.

- Pilarcitos Tunnel 2. This is a 3,426-foot long brick-lined tunnel, 42" x 54" (61" to the top) in cross section. In 1906, Tunnel 2 took water from Tunnel 1 via a 298-foot long wooden flume between Tunnels 1 and 2 (now a 36" pipe). In 1906, at the eastern exit of Tunnel 2, water could be diverted to fill into San Andreas Reservoir, or go into the Pilarcitos pipeline. Figure 4-8 shows the details of the diversion to San Andreas Reservoir.

- Davis Tunnel (elevation 864'). This tunnel diverts water from the upper reaches of San Mateo Creek into San Andreas Reservoir. At the tunnel exit was a flume. This flume was destroyed by fire in the 1880s, rebuilt, then abandoned. At the present time, there is a wooden slide gate at the upstream end of Davis Tunnel, and water is discharged from the downstream end into a 36" pipe, which discharges into the San Andreas Reservoir.

- San Mateo Creek Dam 1 (elevation 646'). This provided a diversion that could be used to send water into Tunnel 2 to fill San Andreas Reservoir. There is presently (2024) a 36" pipe controlled by stop logs that takes water from San Mateo Creek and puts it into the 36" pipe between Tunnels 1 and 2.

- San Mateo Creek Dam 2 (elevation 526') and Tunnel. This is a diversion and tunnel / pipe system to take water and deliver it to either Crystal Springs Reservoir or San Andreas Reservoir. The water is diverted from the creek into a 30" pipe, then enters San Mateo Tunnel No. 2 (48" x 54"), then enters a 44" pipe that presently (2024) connects to the 60" Crystal Springs-to-San Andreas force main pipeline.

- Stone Dam (elevation 554') and Stone Dam Tunnel 1 and Stone Dam Tunnel 2. Stone Dam was constructed by SVWC in 1871. It was constructed with rubble masonry, granite blocks quarried below the dam site, and topped with brick, laid herring bone fashion. It is a thin arch dam. Its small reservoir has capacity of 5 million gallons (15.4 acre-feet). This is a diversion and tunnel / pipe system (sometimes called the Stone Dam Aqueduct) to take water diverted at Stone Dam and deliver it to Crystal Springs Reservoir. This tunnel as well as Stone Dam, were constructed after the Pilarcitos dam and diversion, once it was recognized that the runoff from the downstream Pilarcitos Creek was substantial enough to warrant the cost to construct facilities to collect that water. Tunnel 1 is 4'-6" x 4'-9". Tunnel 2 is 3'-6" x 4'-4". There is presently (2024) a 30" pipe between Tunnel 1 and Tunnel 2; but originally this was a flume. Discharge from Tunnel 2 is presently (2024) directly into Lower Crystal Springs Reservoir but originally fed into the Locks Creek flume and fed into San Andreas Reservoir.

- Crystal Springs-to-San Andreas Pipeline (Force Main). This pipeline serves to take water pumped via the Crystal Springs pump station into the San Andreas Reservoir.

- Crystal Springs Dam (elevation 284'). This is the dam that holds back San Mateo Creek and forms the Lower Crystal Springs Reservoir.

- Crocker Pipeline. This pipe is a remnant to an agreement between the SVWC and the Crocker Estate Company dated to May 24, 1884. It allowed water from Pilarcitos Reservoir (669') to flow by gravity to the top elevation of Burlingame (elevation 624± feet) near the modern location of Skyview Drive and Kip Lane. Presently (2024), there is no connection to the modern Burlingame water system from the Crocker pipeline.

Figure 4-7 shows the profile of the Pilarcitos Conduit. This is based on 1901-era SVWC data. The top left of the profile is shown in more detail in Figure 4-6.

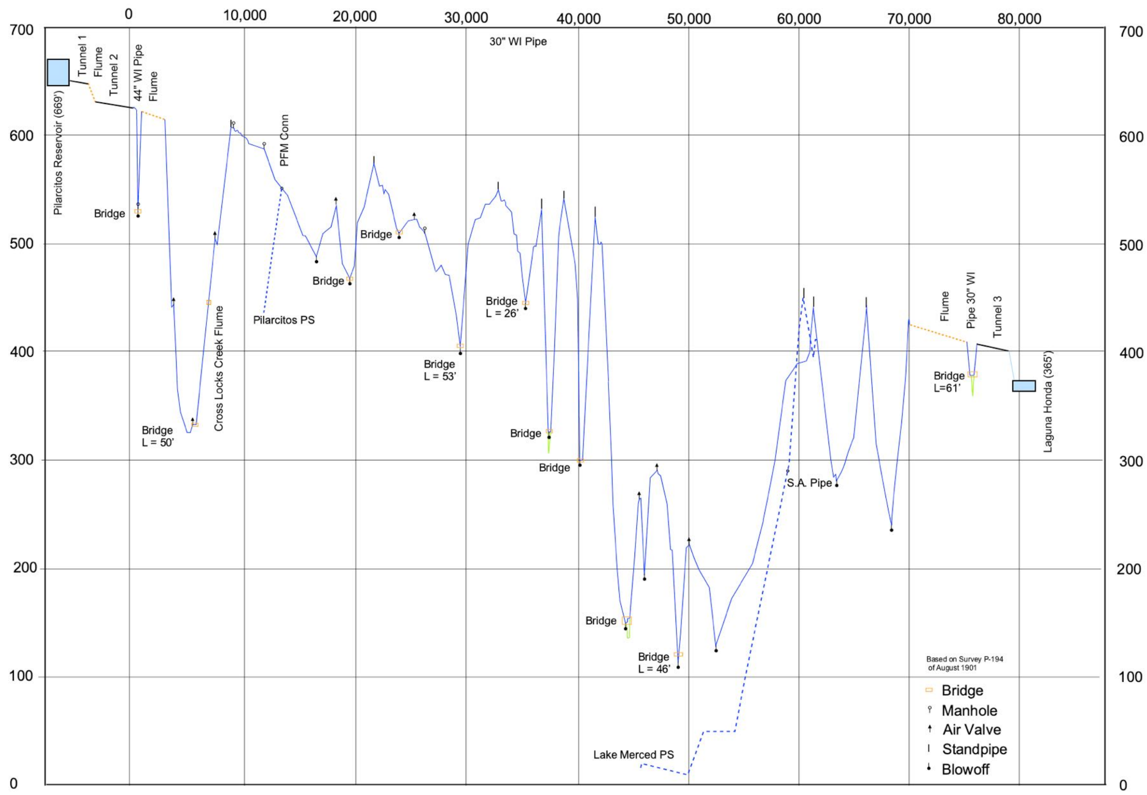


Figure 4-7. Pilarcitos Conduit Profile (Adapted from drawings P-189, P-194, 1901-1902)

At the eastern end of the second flume (station ~30 in Figure 4-7), there was a bifurcation in the conduit. Figure 4-8 shows the branch that took surplus waste water to San Andreas Reservoir. Using older terminology, so-called "waste water" refers to the water from Pilarcitos that could not be used in the Pilarcitos pipeline going to Lake Honda, so the water was "wasted" into San Andreas Reservoir; the term has nothing to do with sewage.

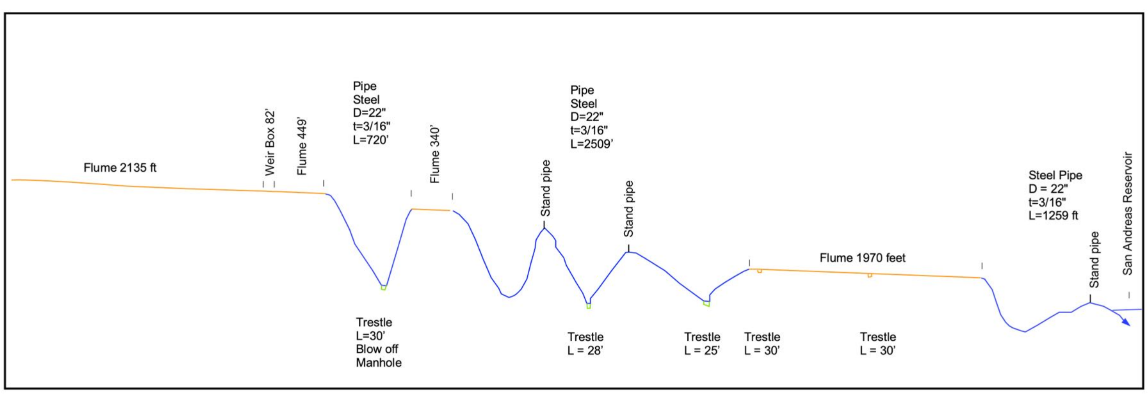


Figure 4-8. Pilarcitos Waste Water Conduit to San Andreas Reservoir (1905)

The following facilities were in place at the time of the 1906 earthquake:

- Pilarcitos Force Main. This is indicated schematically in Figures 2-29, 2-30 and geographically in Figure 2-26. This 1,250-foot long pipe began at the Pilarcitos pump station located at the eastern exit of the San Andreas Bald Hill outlet tunnel, and took water from San Andreas Reservoir and pumped it into the Pilarcitos pipeline. This pump station was built 1898, as part of a reliability upgrade. This pump station, while not used often, had the purpose of delivering water into Lake Honda should there be an issue that would require draining Pilarcitos Reservoir or some other adverse water quality event at Pilarcitos Reservoir. This pump station and pipeline were abandoned after the 1906 earthquake.

- The Locks Creek flume system collected water from Locks Creek, Apanolio and other nearby creeks to the southwest of Pilarcitos Reservoir, and diverted it to fill San Andreas Reservoir (prior to 1906). A few sections of these wooden flumes were destroyed by the 1906 earthquake. Figures 2-26, 4-1, 4-2, 4.6-1, 4.6-2 show the locations of the 1870-1906 era Locks Creek Flumes.

- There are 11 bridges shown in Figure 4-7. Short wooden bridges were constructed at the bottom of most canyons. The Pilarcitos pipe was supported atop the bridge. A blow off was commonly placed either before or after the end of the bridge, to allow draining the pipe into the creek below. There were also short bridges across small drainages that are otherwise not shown in Figure 4-7. Most bridges were 25 to 61 feet long, with maximum heights above the ground below of about 30 feet.

- The elevations shown in these Figures are based on either High Tide, Crystal Springs or Lake Honda datums for the 1880-1900 era. These vertical datums differ by a few feet from modern NAVD 1988 vertical control datum.

Along the east shore of San Andreas Reservoir, and immediately to the north of San Andreas Reservoir (from about station 9,000 feet to 43,000 feet in Figure 4-9) the 30" pipe had thin wall, t=0.104" (D/t = 288). For about 6.5 miles, the arrangement of standpipes and ground elevation of the pipe limited the maximum static head on the pipe to about 200 feet. Assuming a maximum static grade line of 200 feet, the hoop stress would be (200 feet)/2.31 * 15" / 0.104" = 12,500 psi. If the Fy of the wrought iron was about 28,000 psi, this suggests a factor of safety of 2.25. The common burial depth was 3 to 4 feet. It was coated with asphaltum.

Figure 4-9 shows the approximate locations of the pipe breaks. There are 31 reported pipe break locations, as reported by Schussler (1906). Schussler also reported "*between these breaks, there are no doubt many more*". To aide in interpretation, each red dot is assigned a number (1 through 31). Some dots represent 1 break; some dots represent multiple breaks (the red dot numbering in Figure 4-9 differs from the site numbering in Figure 3-12). The locations of FX-1 through FX-4 and small and large Frawley Canyons are highlighted by arrows (actual geographic locations should not be scaled from this drawing).

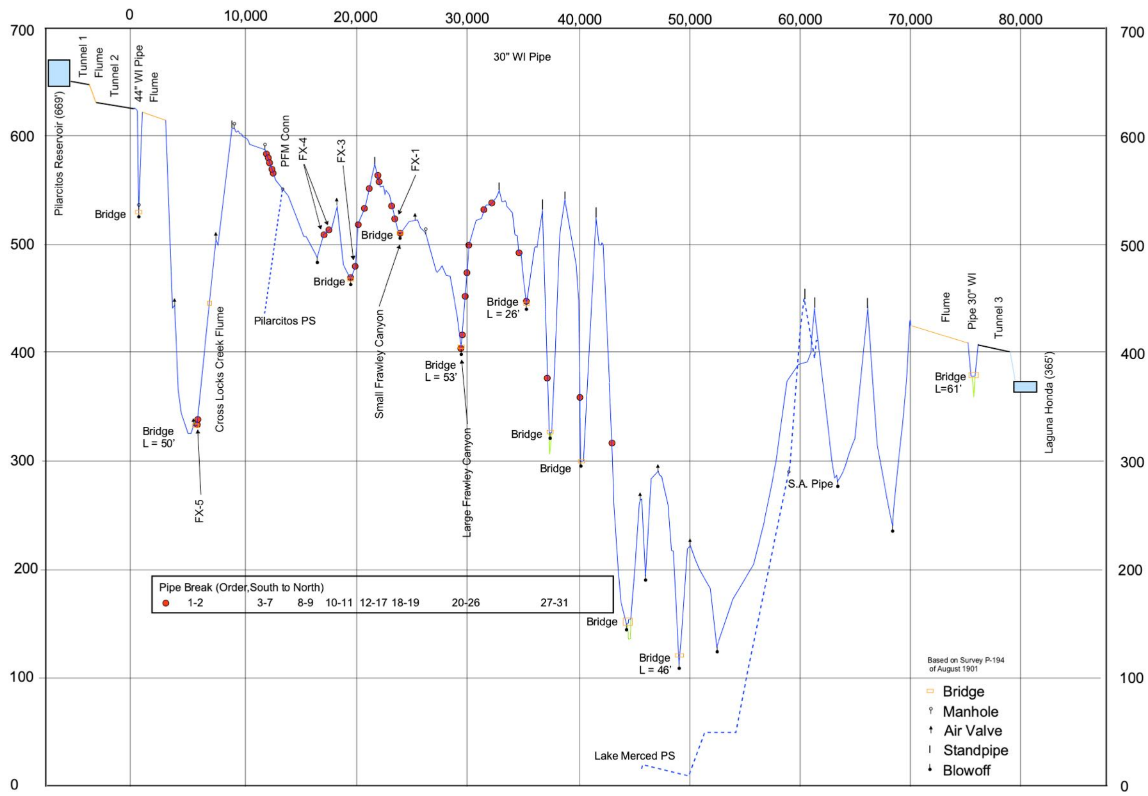


Figure 4-9. Pilarcitos Conduit Profile and Earthquake Breaks (Location of Breaks (Red Dots) after Schussler 1906)

Today, we have no photographic evidence of the damage at most of the locations: dots 3-7, 12-17, 21-31. The rate of damage (breaks / km) tapers off as the pipe heads further away from the San Andreas fault (somewhat lower shaking) and at lower elevations (thicker wall and stronger girth joints).

In its lowest elevation reaches, the 30" pipe is at elevation about 120 feet. The maximum static head would be 625' - 120' = 505', or 219 psi (if standpipes are closed) or about 180 psi if the standpipe at station 42,000 feet is open. To maintain a suitable hydrostatic factor of safety, the wall thickness, t, would have been commonly 1/4", 5/16", 3/8" or 7/16" at the very lowest elevations. Along with the increased wall t at these lower elevations, the riveted girth joints would have been made stronger than those at the upper elevations. In the elastic range, these stronger girth joints are a possible reason as to why there were few pipe failures where elevations were below 400 feet; none at elevations below 300 feet. Also, the pipe at station > 43,000 feet is moving progressively further away from the San Andreas fault, so the level of ground shaking is also diminishing, which is another reason for the lack of damage north of Colma.

North of Colma, at Station 690, the ground elevation is about 420 feet, and a flume is used, then a short inverted siphon, then the water enters the Tunnel 3, exiting at about 400 feet, then over a weir into Lake Honda.

Dot	Location	Station (Fig 4-9, Nearest feature)	FX Slip Sense **C**omp. **T**ens.	Bridge	Est. Top of Pipe Elev (ft)	Photos (this report)
1 2	FX-5	54+87 AV 57+39 BO 59+50 (est)	C	L=50' 58+00 to 58+50	333	4.1.15-1 4.1.15-2 4.1.15-3 4.1.15-4 4.1.15-5
3		118+58			585	
4		120+16			582	
5		120+95			576	
6		123+32			570	
7		125+30			565	
8	FX-4 main trace	164+65 BO 165+62 Fence 170+75	T		509	4.1.8-1 4.1.8-2 4.1.8-3 4.1.8-4 4.1.8-5
9	FX-4 west trace				514	4.1.8-6 4.1.8-7
10		196+68 BO		Yes	468	4.1.7-1 4.1.7-2 4.1.7-3
11	FX-3	198+72 MH	C		481	4.1.6-1 4.1.6-2 4.1.6-3 4.1.6-4 4.1.6-5
	FX-2		T			
12		201+19			519	
13		206+72			535	
14		211+07			554	
15		218+58			575	
16		219+37			558	
17		231+62			536	
18	FX-1 (S)	236+85 MH	C		513.3	4.1.3-1 4.1.3-2 4.1.3-3
19	FX-1	238+41		Yes	508.43	4.1.2-1 4.1.2-2 4.1.2-3

Dot	Location	Station (Fig 4-9, Nearest feature)	FX Slip Sense **C**omp. **T**ens.	Bridge	Est. Top of Pipe Elev (ft)	Photos (this report)
20	Large Frawley Canyon	295+34 BO		L=53'	404	4.1.1-1 4.1.1-2 4.1.1-3
21		296			417	
22		296+44			454	
23		300+00			475	
24		301+56			500	
25		315+56			534	
26		322+18			540	
27		346+30			493	
28		352+75		L=26'	446	
29		371+21			378	
30		401+00			359	
31		430+84			318	

Table 4-4. Location of Pipe Breaks on Pilarcitos Pipe

Abbreviations for Table 4-4: C = fault slip places pipe into net compression. T = fault slip places pipe into net tension. L = length. BO = Blow Off. MH = Man Hole. AV = Air Valve.

Station	Description
	298 foot-long bridge over San Mateo Creek between Tunnels 1 and 2
5	49 foot-long bridge supporting 44" WI pipe
58	50 foot-long bridge over San Andreas Creek, 24" CI pipe. FX-5.
118+68	Centerline road to Millbrae
135+53	Pilarcitos Force Main connection
167	Leak, July 1904.
179+50	Leak, 17 feet new pipe, re-lay 500 feet, 7 bends
198	Leak, re-lay 500 feet, pre-1906
200	Leak, new bends
295+05	53 foot-long bridge Large Frawley Canyon. Site 1. See Section 4.1.
360+50	Leak (big) July 1901, re-lay 450 feet
369	Small slides at right of line
374+85	102 foot-long bridge
403+95	~200 foot-long bridge
410	Small slides
448+50	~ 200 foot-long bridge
472 est	San Andreas Pipeline connection
489+37	Lead slip joint
493	46 foot-long bridge
552+25	Connections & meters at Colma
563+10	Lead joint
577+25	San Andreas pipeline crosses Pilarcitos pipeline
760+96	61 foot-long bridge over creek. Creek bed at 358 feet
764+63	Begin 2,820 foot-long brick tunnel. Tunnel invert 405.22 feet.
792+83	End brick tunnel. Grade 12 feet per mile. Invert 398.23 feet. Lake Honda

Table 4-5. Pilarcitos Pipeline. Elevations Crystal Springs base.
City base = Crystal Springs base less 4.45 feet.

The following portions of the Pilarcitos pipe were removed after the 1906 earthquake through 1907 (stations approximate). The remainder of the pipe was removed by 1913, Figure 4-10.

- 2,023 feet 25+87 to 46+00. Incudes all Pilarcitos pipe from end of Tunnel 2, through FX-5.

- 4,100 feet 46+00 to 87+00 Includes FX-5, portions of 30" WI, 24" CI and 22" CI pipe

- 167+00. Site of June 1904 leak

- 480 feet 177+00 to 181+80 (includes 500- long section with 7 bands that was re-laid due to pre-1906 failure)

- 820 feet 198+00 to 206+20 (includes 600-foot long section with 11 bands that was re-laid due to pre-1906 failure)
- 1,200 feet 287+00 to 299+00 (includes failure at Large Frawley Canyon in 1906, FX-1)
- 500 feet 359+500 to 364+50 (includes 450' long section that was re-laid after a big leak in 1901)
- 1,300 feet 370+00 to 383+00
- 1,800 feet 395+00 to 413+00
- 3,830 feet 433+70 to 472+00
- 4,280 feet 472+90 to 515+70
- 430 feet 520+50 to 524+80
- 1,700 feet 539+72 to 556+72
- 1,940 feet 560+20 to 579+60

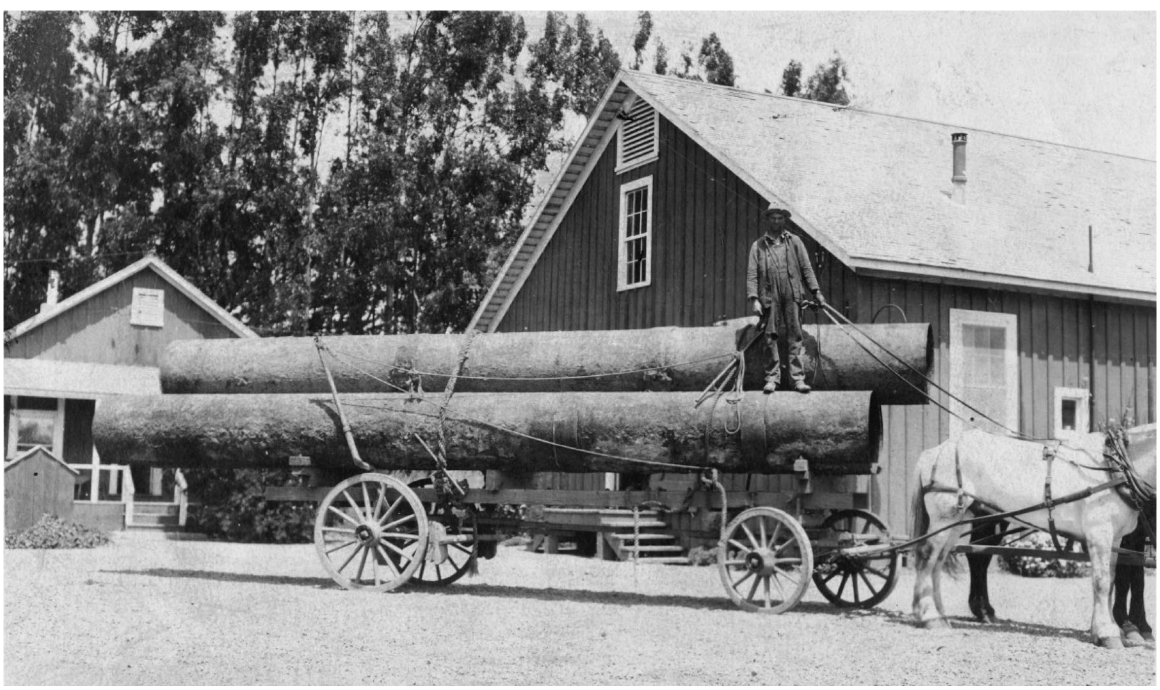


Figure 4-10. Portion of Pilarcitos Pipeline taken up. (Photo: SVWC, May 1913)

4.1.1 Site 1. Collapse at Large Frawley Canyon

At this location, the 30-inch pipe was supported on a wood trestle, crossing a canyon (then called Large Frawley Canyon, more recently as Knowles Gulch). Today (2024), the drainage here corresponds to modern-day Sneath Lane; the area has been substantially regraded, and the 1906-era terrain has been greatly altered: drainages placed into buried pipes, gullies filled, many suburban single-family homes constructed.

The site is located about ¼ miles east of the main fault.

The historic profile of the pipe (Figure 4-9) shows that the pipe at this location was supported on a bridge that was 53 feet long. The photos shown in this section show two lengths of pipe, each about 25 feet long; this confirms the 53-foot length.

Derleth (1907) described the wood trestle at Site 1 as being about 100 feet long, with a maximum height over the canyon of about 25 feet. We suspect that Derleth mis-judged the length of the trestle.

Figure 4.1.1-1 shows the pipe alignment from the south edge of the canyon, looking northwards. The wooden trestle collapsed in its entirety.

Figure 4.1.1-1. Large Frawley Canyon. Destruction of heavy bridge and 30-inch Pilarcitos pipe over Large Frawley Canyon. The pipe was torn in three locations and thrown sideways over 50 feet to the east into the canyon below. View looking northerly. (Photo: Schussler 1906, HS8)

Figure 4.1.1-2 shows the pipe lying at the bottom of the canyon. The pipe has a manhole atop it. Wood planking near the pipe was for a box around the pipe (non-structural) that was Schussler's approach to try to limit external corrosion for above ground pipes.

Figure 4.1.1-2 shows two segments of pipe that are lying in the gulley, rotated nearly 90° from their original alignment, and about 60 feet from the original alignment.

The left side of Figure 4.1.1-2 shows a complete failure through the girth riveted joint where the pipe enters the ground at the northern abutment.

Figure 4.1.1-2. Large Frawley Canyon. View downstream, looking easterly. Pipe on left side is original Pilarcitos pipe at the north edge of the canyon. (Photo: Schussler 1906, HS9)

Figure 4.1.1-3 shows the debris from the failed trestle.

Figure 4.1.1-3. Large Frawley Canyon. View downstream, looking easterly Shows debris of the bridge that has been thrown 40' to 50' to the east. (Photo: Schussler 1906, HS10)

In the gulley can be observed two sections of pipe. Several 12x12 pieces of lumber show steel "dogs": a ¾" diameter steel bar, L-shaped, about 12" long and 3" wide; these steel bars were used to form connections between heavy lumber.

Today (2024), we were unable to locate drawings of the original 1868-1870-vintage wooden bridge across Frawley Canyon. It is conceivable that this bridge was originally constructed in 1862 as part of the original Pilarcitos flume, but available Pilarcitos plans suggest that the flume was perhaps about 100 feet (or so) to the west (left of Figure 4.1.1-1) of this location. Pilarcitos pipeline drawings called for a 53-foot long bridge at this location, which is inconsistent with Derleth's estimated measurement of 100-feet.

That said, the available photographic evidence suggests that the bridge was constructed in a manner somewhat similar to the bridge shown in Figure 4-4, excepting that timber (~1868) was used instead of the concrete headwalls and piers that were used in 1907. Main support timbers would have been two 12x12s, at each of two locations. A braced frame system (two diagonals and a horizontal beam, all in compression and dead load, like in Figure 4-4) of 12x12s could have been used to form the main span over the drainage. 8x12s and 4x8s would form the beams and stringers that support the pipe. 1x8 sheathing and 4x4 posts would form the "encasement" around the pipe (entirely non-structural, and just for limiting exposure to foggy salty air). Main connections of the 12x12s were formed to be entirely in compression (for dead loads), coupled with ¼" steel spikes between the members.

Unlike the 1907-era bridge in Figure 4-4, the ~1868 bridge would have had very little seismic lateral (transverse to the direction of the pipe) load-carrying capacity. This style of post-and-beam construction, with weak connections, is now understood to be seismically weak. The pipe would have been nearly free to slide sideways under inertial loads. High vertical motions would have placed some of the main 12x12 members into temporary tension, and with extremely small capacity of the joinery to take tension or bending loads, inertial overload was likely, leading to complete collapse of the bridge structure.

There is no evidence that the pipe had any expansion joints over this 53-foot long bridge. The pipe had limited bending capacity and could not sustain inertial loading (likely well over 1.5g sideways at the first mode of the pipe) over a 53-foot long span. Highest bending moments would be at the two ends of the pipe (and both failed there) and at the middle of the pipe (and apparently the pipe failed there too).

The damaged timbers suggest the trestle was supported by two 12x12 wood posts near either headwall. No foundations can be seen in the debris field near the bottom of the canyon that would suggest any additional piers. This would make the main span of the trestle about 40 feet long, likely as long as feasible without middle supports. The damaged 12x12 posts have steel spikes, suggesting that the horizontal members were lightly connected to the posts.

Derleth (1907) describes the debris field as having heavy timbers, some showing signs of decay.

We researched the presently-available drawings for the Pilarcitos pipeline. Many of SVWC records were lost when their headquarters building was damaged and then burned in the great conflagration fire, but duplicates of some critical company records were kept in Millbrae, and thus were saved. Even so, no drawings for the wood trestle across Large Frawley Canyon were found.

4.1.2 Site 2. Collapse near Small Frawley Canyon, FX-1

At the Small Frawley Canyon, the pipe telescoped (got shorter) as the sense of the right lateral slip of the fault placed the pipe into compression. Figures 4.1.2-1, 4.1.2-2 and 4.1.2-3 show the pipe.

Schussler (1906) and Lawson (1908) differ in their interpretation of the location and action at Site 2. According to Schussler, this location corresponds to FX-1, the northernmost crossing of the Pilarcitos pipeline over the San Andreas fault. However, Schussler's sketches showed that about 550 feet south of Small Frawley Canyon, the pipe turned to a more easterly, and began to head northeasterly from the fault. Lawson describes FX-1 as where the pipe crosses the primary trace of the San Andreas fault at an angle of about 20°.

The pipe here has telescoped into itself by about 7.25 feet, and is offset sideways by about 15 inches (about half a pipe diameter). This is consistent with right lateral primary offset of about 8 feet.

The light-colored lineament at the top of Figure 4.1.2-1 (about 25-30 feet from the exposed pipe) suggests some type of right lateral secondary shearing fault movement.

Figure 4.1.2-1. Small Frawley Canyon. Failure of Pilarcitos 30 inch pipe. Pipe is telescoped and thrown sideways on bridge over Small Frawley Canyon. View looking south. (Photo: Schussler 1906, HS5)

Figure 4.1.2-2 shows the same location, but with a wider view of the environs. In the central part of this photo, the active fault trace is marked by a north-trending, left stepping en echelon ground cracks. This suggests that the major telescoping / shearing offset of the pipe is located very close to, or right at the fault offset.

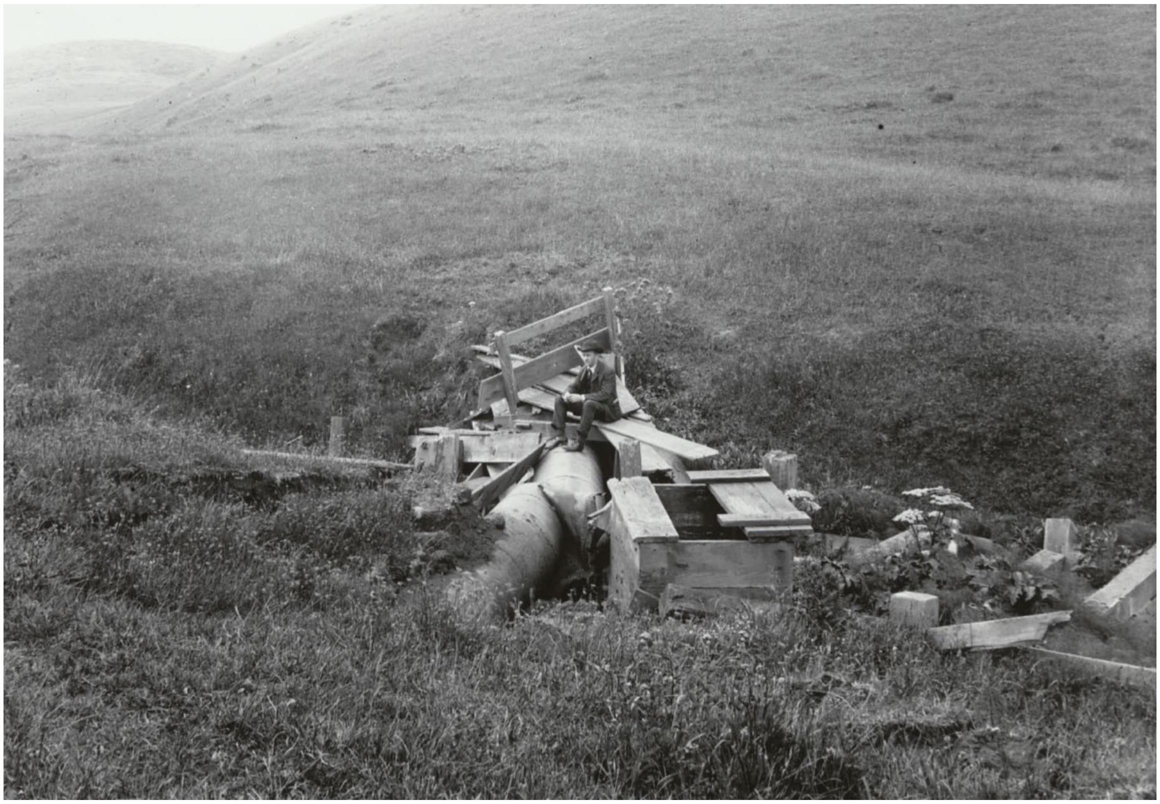


Figure 4.1.2-2. Failure of Pilarcitos 30 inch pipeline. Pipe telescoped and was thrown sideways off the wooden bridge crossing Small Frawley Canyon. View looking northeasterly. (Photo: Harry O. Wood, 1906)

Figure 4.1.2-3 shows a closer version of that seen in Figure 4.1.2-2.

Figure 4.1.2-3. Failure of Pilarcitos 30 inch pipe. Pipe telescoped and was thrown sideways off the wooden bridge crossing Small Frawley Canyon. View looking north. (Photo: Schussler 1906)

There was a 8" blow off with gate valve in the wooden box shown on the right side of Figures 4.1.2-2 and 4.1.2-3. Derleth (1907) reports that the blow off was thrown 10 feet away from the pipe, confirming that the blow off pipe traversed the primary fault.

[Author's note: Plate 56 in ASCE (1907) is a photo of the same damage but it appears that the photo was printed from a negative that was reversed as evidenced by the "left lateral" sense of offset of the pipe.]

What were the forces that led to this failure?

- There was major right lateral surface fault offset at this location. The compression induced by about 8 feet of right lateral primary fault offset into the pipe is the primary contributor to the failure. The minor right lateral shearing just a few tens of feet south of this location could also contribute to placing the pipe into compression.

- The high level shaking (likely PGA >> 0.5g) could have led to an inertial failure of the wooden bridge that supported the pipe over the small canyon; but the short length of pipe and bridge suggests this was a secondary factor to the failure.

- Possibly, minor slope failures either side of the small canyon could have put the pipe into some compression.

Given all these factors, the available evidence suggests that right lateral offset put high compressive forces into the pipe, which led to buckling of the pipe in its unrestrained state on the short bridge.

A modern constructed pipe across such a short drainage would commonly be buried well below the creek / canyon bottom, possibly encased in concrete to protect it from scour / erosion that might occur over the years at the drainage. By placing the pipe above ground and near a fault crossing that places the pipe into net compression, the designer needs to be careful that the pipe is able to easily resist the compression induced by fault offset, and the pipe should be designed to have no more than modest yielding where it is in above ground condition and subject to large compression. In modern parlance, the compressive strain allowable to prevent local buckling (about 1.76 t / D) is *not* applicable to above ground pipes, and should be used only for buried conditions or where there is no chance of large scale lateral buckling once yielding has occurred in the pipe.

4.1.3 Site 3. Collapse of Pipe South of FX-1

At Site 3, the pipe collapsed in on itself, Figures 4.1.3-1, 4.1.3-2, 4.1.3-3.

Figure 4.1.3-1. Failure of Pilarcitos 30 inch pipeline about 220 yards south of FX-1. Pipe is collapsed on itself. Looking southerly. (Photo: Schussler 1906, HS-4)

Figure 4.1.3-2. Failure of Pilarcitos 30 inch pipeline about 220 yards south of FX-1. Pipe is collapsed on itself. Looking southerly. (Photo: Schussler 1906)

Figure 4.1.3-3. Vacuum Failure of Pilarcitos 30 inch pipeline; same location as 4.1.3-1. South of the failure at FX-1, Small Frawley Canyon (Photo RLH)

Site 3 is about 660 feet south of the FX-1 / Small Frawley Canyon. Figures 4.1.3-1, -2, -3 show the pipe, looking southward. At this location the pipe is D = 30", t = 0.104".

At Site 3, the buried pipe is descending a steep slope, and the pipe completely collapsed for a distance of several yards. Lawson (1908) suggested the observed collapse may have been due to the establishment of a partial vacuum within the pipe, or the propulsion of the water induced by the shock.

Possibly the break at Site 2 (FX-1 / Small Frawley Canyon) may have allowed rapid release of water, leading to possible decompression of the water pressure, which resulted in the buckling collapse inward of the pipe seen in Figures 4.1.3-1, 4.1.3-2. The direction of fault rupture was first at Site 2 (FX-1), then propagating towards the south, so the initial break of the pipe might have been at FX-1 location, followed a few seconds later by a vacuum-related collapse at Site 3. Other possible explanations are that high lateral earth pressures ovalized the pipe sufficiently (see the crush near the top of the photos), that the pipe "snapped-through" downwards; the girth joint near the top of the photos tore open, possibly leading to a partial loss of vertical load carrying capability. In any case, failures of this type have not often been seen at fault crossing locations in other earthquakes, although a liquefaction-induced failure of a very thin walled large diameter pipe was reported in the 1994 Northridge earthquake near the Los Angeles Department of Water and Power water treatment plant.

The D/t ratio of the pipeline at this location was 30" / 0.104" = 288, much higher than the maximum of 90 recommended by ALA (2005), or preferable ~50 in fault crossing locations if one wants to achieve good compressive strain capability.

Schussler writes in his report (1906) that the pipe was t = 0.1875" at this location (t=3/16"); However, original purchase specifications suggests that the pipe was t = 0.104" for its low pressure portion (including this location) and shows that the pipe was t = 0.1875" at its more northerly locations (north of Colma). Today (2023), we can no longer confirm the true pipe wall thickness at every location as the pipe no longer exists; but it is possible that where exposed above ground atop bridges, Schussler went with the thicker pipe (0.1875") to provide some extra margin for corrosion effects from the often salty fog conditions in this area.

The authors note that the location of Sites 2 and 3 and the primary offset location for FX-1 are inconsistently described by Schussler (1906) and Lawson (1908). Reviewing available pipeline drawings, we adopt Lawson's interpretation. Thus, the pipe damage at Site 3 is *not* due to fault offset, and we concur that the observed damage was most likely due to rapid decompression of the thin-walled pipe that led to its collapse.

4.1.4 Site 4. Fence 1 Offset

At Site 4, the San Andreas fault offset a fence, Figures 4.1.4-1, 4.1.4-2. In this report, we call this fence "1".

Although this fence presently (2023) no longer exists, it did exist until the middle of the last century when land south of San Francisco, including the San Andreas fault zone, was being developed for housing. Locating structures for human habitation across active faults was not curtailed in this area until the Alquist-Priolo Earthquake Fault Zone Studies Act was passed by the California legislature in response to the destructive San Fernando earthquake of 1971. Aerial photos flown in 1946 clearly show this fence line and its position with respect to roads and other natural and cultural features in the vicinity the fault. Even though private land along the fault north of San Andreas Lake and SFPUC watershed land was graded and tectonic landscape features like sag ponds, fault scarps, deflected stream channels and other tectonic features indicative of active faulting were destroyed, historical photographs have made it possible to reconstruct the approximate location of such features and observe the nature and number of the 1906 fault surface offset traces.

Photographs showing this fence line and vicinity were taken by the team documenting the effects of the 1906 earthquake that were ultimately published by the Carnegie Institution in 1908 under the direction of Berkeley Geology Professor Andrew Lawson. Figure 4.1.4-1 shows that this fence was offset by three active fault strands with estimated displacements of about 6 feet, 2 feet and <1 foot that diminished up the hillside to the east. Figure 4.1.4-2, taken in 1956 by Manuel Bonilla of the U.S. Geological Survey (a mentor of one of the authors), shows more of the regional setting of the fence prior to development in the early 1960s and warping of the fence on either side of the active faulting. Readers interested in the development of this area are referred to Prentice, C.S. and others, (2006, p. 187-92), for more before-and after development pictures of this area.

Lawson (1908, p. 94) reports that the fence trended N68°E, nearly perpendicular to the N35°W-trending main fault and that the fence was offset 5.75 to 6 feet at the primary offset location (the span of the man’s arms shown in Figure 4.1.4-1). The fence warping was recorded as extending 200 feet to the west of the fault and 45 feet to the east, and was reported as responsible for a total of 13 feet of right lateral shift across the fault. Reid (1910, v. II, p.35-6) acknowledged that this interpretation probably did not represent the true tectonic movements, in part because the original configuration of the fence (the reference strain gauge) was unknown. From an engineering perspective, minor ground warping over a substantial distance is not usually considered to pose a severe hazard to well-built structures, and need not necessarily be explicitly factored into the design of seismic-resistant buried pipelines.

This fence is one of the sites within the northern part of the Pilarcitos pipeline-San Andreas fault study area whose location is well known today. This fence does not appear in any of the historic photographs of sites (Schussler 1906, USGS 1907 or Lawson 1908) in relation to where the Pilarcitos pipeline is known to have failed in 1906. We suspect that the Pilarcitos pipeline lies buried within the linear swale that lies just west of the offset fence shown in Figure 4.1.4-2. The Pilarcitos pipeline did fail at over 20 locations where the pipe was parallel (but not crossing) the fault, likely reflecting ongoing corrosion, hydrodynamic water pressure pulses as well as ground strain related to high ground velocities.

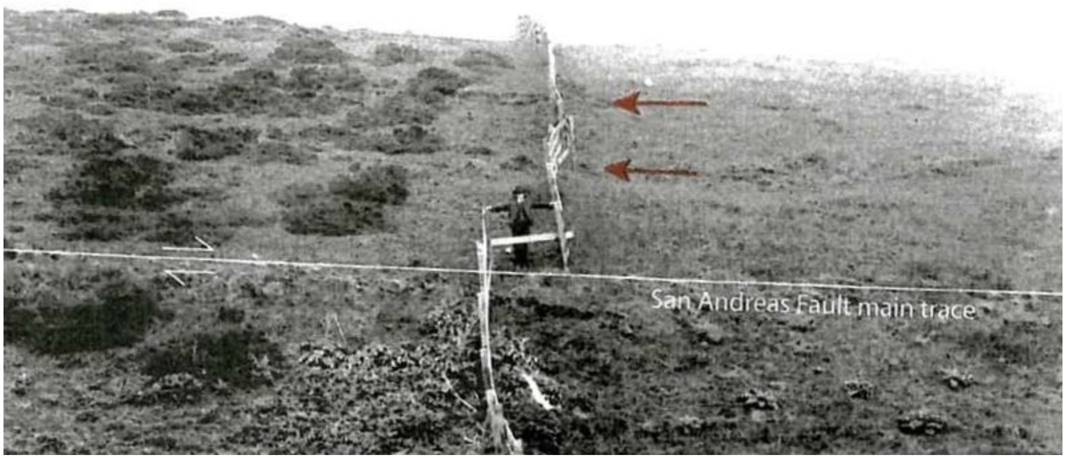


Figure 4.1.4-1. Offset of Fence, looking east, (Photo: Bancroft Library, U. C. Berkeley)

Figure 4.1.4-2. Offset of Fence. The change of vegetation from 1906 to 1956 reflects changes in land use / grazing conditions over time. (Photo: Bonilla 1956)

4.1.5 Site 5. FX-2

Moving to the southeast along the trace of the San Andreas fault from Small Frawley Canyon and Site 4 / Fence "1", Schussler's sketch Map No. 13 shows that the Pilarcitos pipeline crosses the fault from the west about 0.9 mile from FX-1 and makes a loop about 0.2 mile long before recrossing the fault at FX-3. At the FX-2 crossing, the pipe should have experienced tension and been pulled apart; at FX-3, the pipe would have been compressed by fault slip as described for Site 6 below.

For reasons unknown, none of the 1906 investigators provided photos of the FX-2 crossing or documented in text what, if anything, the 1906 event did to the Pilarcitos pipe there. Presently, we cannot interpret this "photographic silence" on the part of the investigators (Schussler 1906, Lawson 1908) that the pipe did not fail at this location. Schussler did indicate that there was pipe damage at (or near) FX-2, as suggested in the profile Figure 4-9 (6 red dots between FX-1 and FX-3). Apparently, there presently are no photos to visually document the damage of the pipeline at FX-2. We will probably never know.

4.1.6 Site 6. FX-3

FX-3 is located about a mile northwest of the upper end of San Andreas Lake. Here, the San Andreas fault intersected the pipe placing it into compression.

At FX-3, the fault offset furrow covered a considerable width. The pipe was broken at 3 locations over a length of 100 feet (one red dot is placed at FX-3 in the profile shown in Figure 4-9).

At one place, the pipe was telescoped by 17 inches, at another place and the farthest north, by 41 inches. Combined with Site 7 (also affected by the FX-3 fault offset), the pipe telescoped 58 inches. The minimum amount of right lateral offset along the strike of the fault at FX-3 was about 9.5 feet

Photos 4.1.6-1, -2 are taken nearly from the same vantage point, and possibly on the same day (May 17, 1906), but judging from the shadows, taken a few hours apart. Photo 4.1.6-3 is dated May 15, 1906.

Figure 4.1.6-1. FX-3. View North. South end telescoped 21". The north end moved 17" west and telescoped 41". (Photo: Derleth 1907. See Also Schussler 1906 HS2 for similar photo)

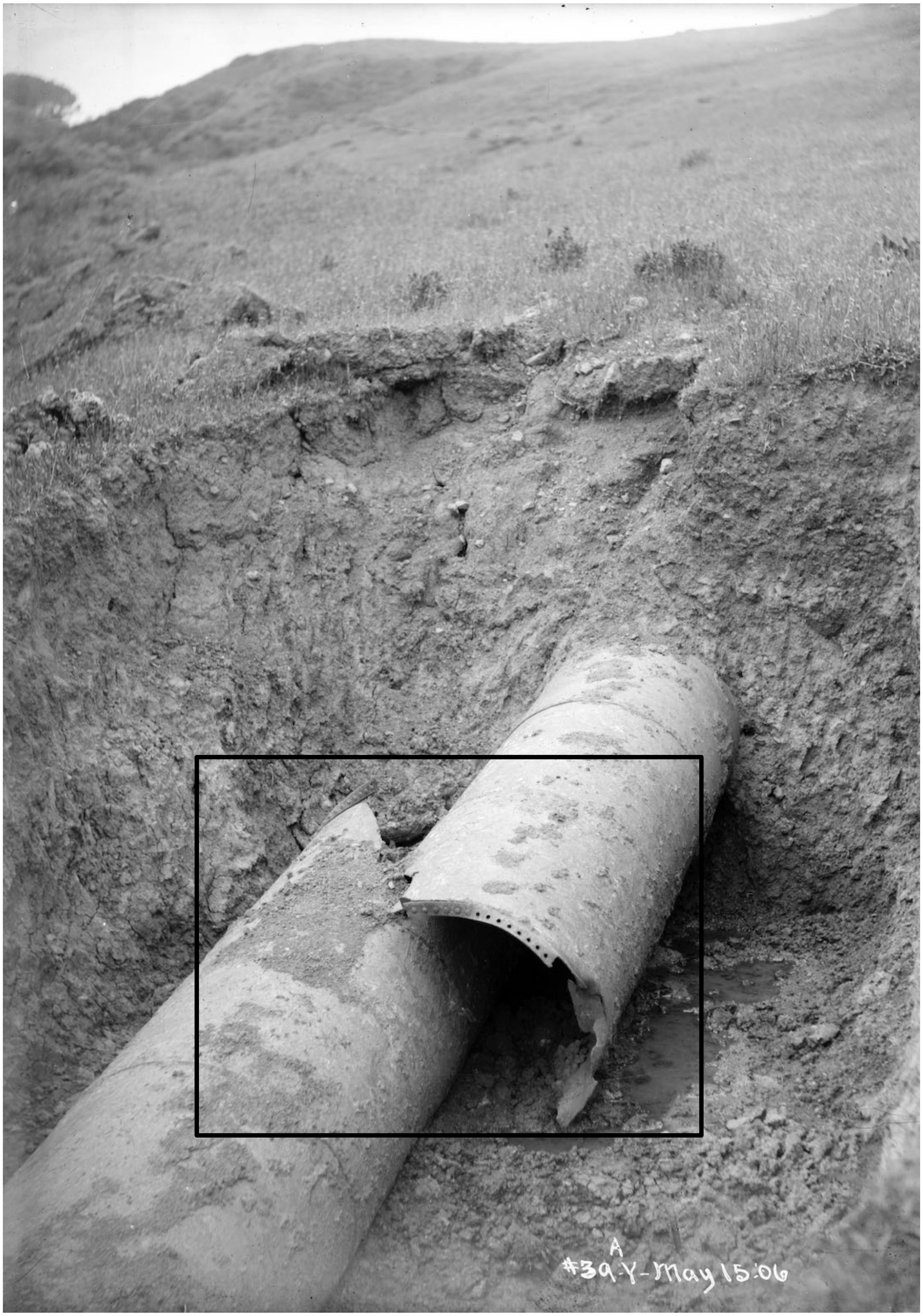


Figure 4.1.6-2. Detail of north end of fault crossing 3. (Photo: Schussler HS6). See Figure 4.1.6-3 for closeup of rivets.

Figure 4.1.6-3. Closeup of Figure 4.1.6-2 showing rivets. (Photo Schussler HS6)

The girth riveted joint is clearly seen in Figure 4.1.6-2, 4.1.6-3. In the foreground of the closeup (Figure 4.1.6-3), 8 rivets are missing, 6 rivet heads remain. In the background is the continuation of the riveted joint. The neat fold in the steel adjacent to the rivets suggests that the inch (or so) at the end of the pipe has been specially prepared to accept rivets, in a manner that might (?) allow overlap of the pipe in the riveted girth connection zone. The visual evidence suggests that the riveted girth joint is much weaker than the main barrel of the pipe. The hole spacing suggest about 80 rivets around the girth joint; circumference about 95 inches. This suggest center-to-center rivet spacing about 1.19 inches, and rivet hole about 0.5 inches. This suggests a rivet cross sectional area of about 0.2 square inches. Allowing Fu = 50 ksi, and 80 rivets, the single shear ultimate strength of the joint is 80 rivets * 0.2 sq in * 50 ksi * 1/1.73 = 462 kips. Allowing D = 30" and t = 0.1875", Area (pipe) = 17.78 sq inches. Allowing Fu = 50 ksi, the nominal tensile or compressive strength of the pipe = 889 kips. Nowhere along the length of pipe is there any evidence of pipe wrinkling, which should initiate at about compressive strain 0.175t/R (or so), considering the eccentricity of the lap girth joint (about compressive strain 0.6t/R if the adjacent pipes are perfectly concentric, which they are not).

Assuming t = 0.104", R=15", then idealized local wrinkling should occur at elastically computed compressive stress = 29,000 ksi * .6 (.104)/15 = -120 ksi, and initiating near a girth joint at elastically computed compressive stress = 29,000 ksi * 0.175 * 0.104 / 15 = -35 ksi. As the girth joint will rupture at about half the stress of the main pipe, or perhaps no more than about -15 ksi to -20 ksi in the main barrel of the pipe, one might expect the compressive failure mode to sometimes be exhibited as local wrinkling. But, local wrinkling was not exhibited at this or any other site.

The "fold" at the base of the girth rivet line (sharp fold seen in the figure above) gives a clue as to the failure mode. At this offset location, the rivets are being loaded in single shear by net compression in the pipe. The overall eccentricity of the ends of adjacent pipe segments introduces some bending into the pipe. For a rivet to reach yield in single shear, a bending moment of 0.36 kip-inch is applied to the base width (2*pi*R/80) of the steel fold. Assuming Fy = 30 ksi, under pure local bending, the steel fold yields at about 0.06 kip-inches. In other words, the girth joint folds (as observed) at about 1/6th the yield level of the rivet. At other locations, the rivet joint fails in tension, and we do not see the fold. Once folding is initiated, the rivet is loaded in high shear and bending, and many of the rivets break off.

Thus, it is clear that high compression in the pipe induces bending at the girth joint due to eccentricities, and this bending fails the girth joint fold well before the rivets break in direct shear and well before main pipe has initiated wrinkling. In other words, this is not a ductile seismic design.

Figure 4.1.6-4 shows the pipe at FX-3.

Figure 4.1.6-4. Crossing FX-3. Failure of Pilarcitos 30 inch pipe. (Photo: Lawson 1908)

Figure 4.1.6-5 highlights the "mole track" of the fault rupture. The two blue arrows point at a vertical boundary between soils of different colors: this marks the major active trace of the San Andreas fault.

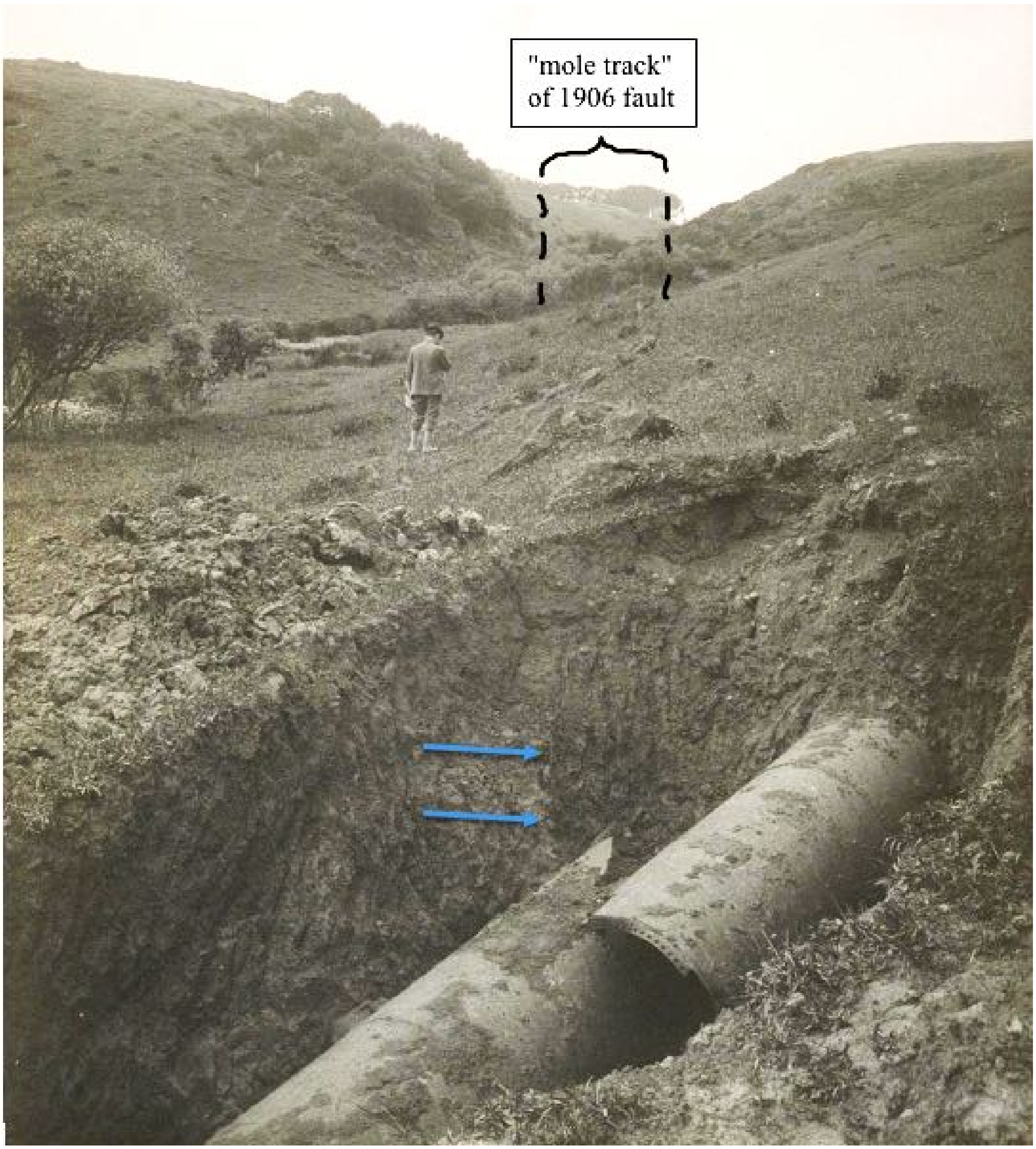


Figure 4.1.6-5. Crossing FX-3. Looking northwesterly along trace of 1906 fault rupture. Failure of Pilarcitos 30 inch pipeline. (Photo: ASCE 1907, p 16)

4.1.7 Site 7. FX-3 South

Figures 4.1.7-1 and 4.1.7-2 and 4.1.7-3 show the damaged pipe at Site 7. The pipe here is on a wooden trestle. This site is about 100 feet south of FX-3 (Site 6), where the pipe crossed a small swale of San Bruno Creek on a wooden trestle.

Figure 4.1.7-1 shows a gate valve for a blow off that could be used to drain the pipe into the small creek below. The high compression has sheared the girth riveted joints, and the pipe had telescoped neatly on itself about 58". The two sides of the wood box have twisted, indicated by top level twisted 4x4s that would have been perpendicular to the pipe before the earthquake. The far side (east side) of the wood box has been displaced southerly compared to the west side, suggesting the fault offset may have bisected the wooden box too.

Figure 4.1.7-1. South of FX-3. Pipe has telescoped 58" on the trestle. Just south of Sneath Rancho. Looking northerly. (Photo: Schussler 1906 HS1)

Figure 4.1.7-2 shows the same location as Figure 4.1.7-1, looking easterly. Just a few of the girth joint rivets for the outer pipe are seen at the top: the edge of the girth joint has folded in on itself as the pipe telescoped in compression. FX-3 is just to the north of this location, and the sense of slip placed the pipe into compression.

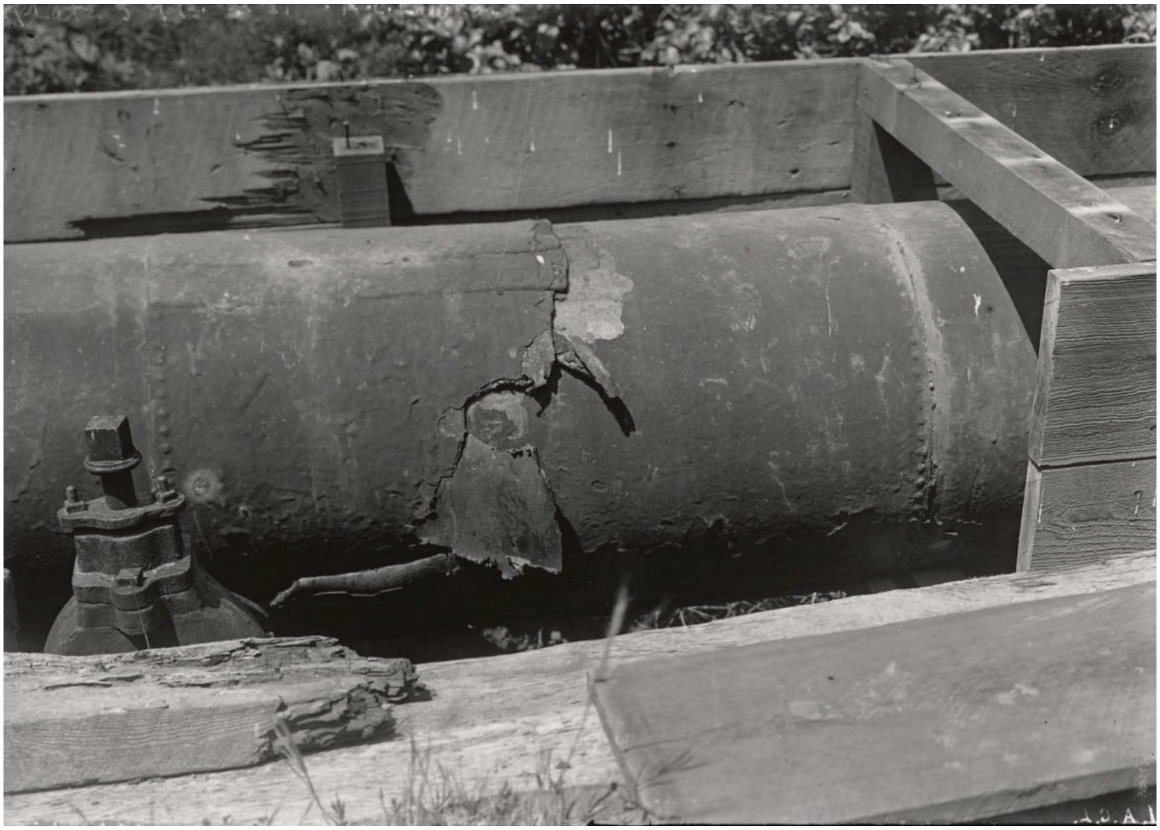


Figure 4.1.7-2. South of FX-3. Failure of Pilarcitos 30 inch pipeline. About 1 mile northwest of San Andreas Reservoir. Looking easterly. (Photo: Lawson 1908)

In Figure 4.1.7-3 shows another view of the telescoped section of this pipe.

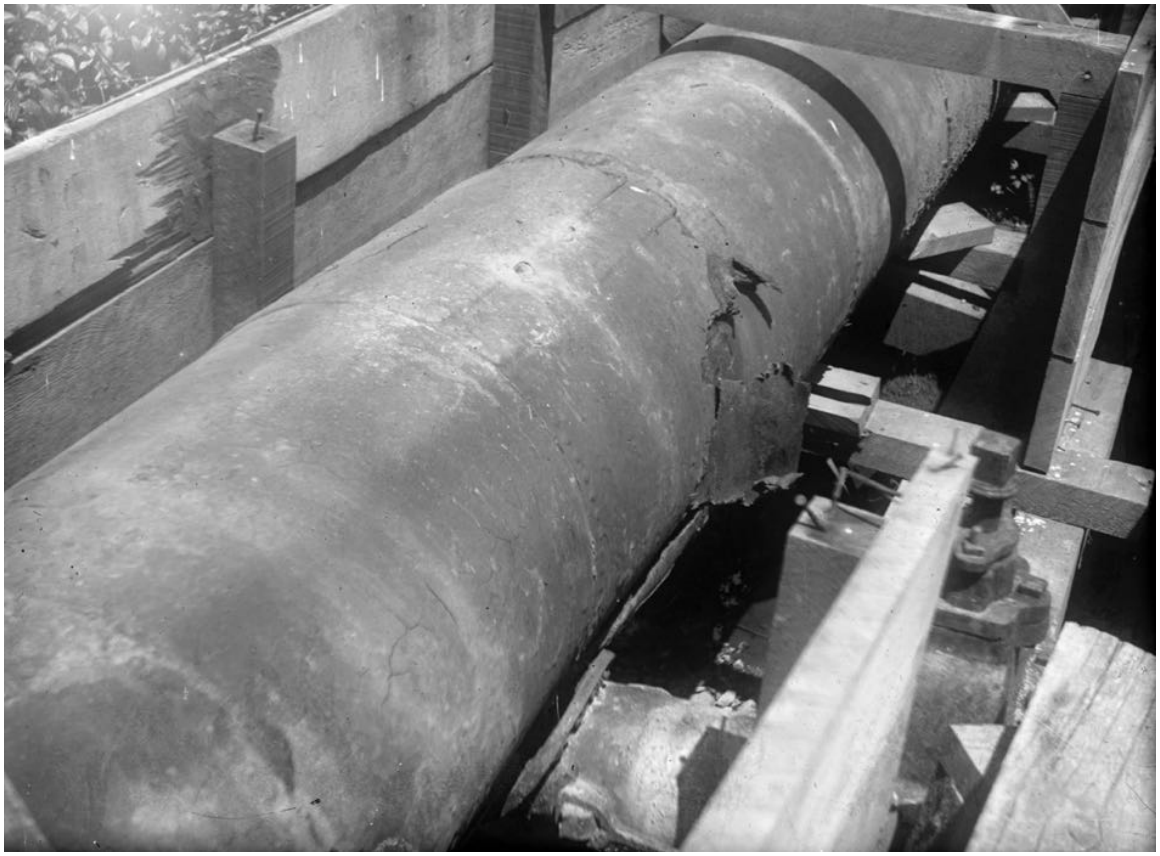


Figure 4.1.7-3. South of FX-3. Pipe has telescoped on the bridge. Looking southerly. (Photo: SVWC 1906)

4.1.8 Site 8. FX-4

Near the north end of the San Andreas reservoir, the fault crosses the pipe. We call this "Fault Crossing 4", or FX-4 (primary offset) or FX-4N (secondary offset).

Figure 4.1.8-1 provides a sketch that shows our interpretation of what might have happened at Site 8.

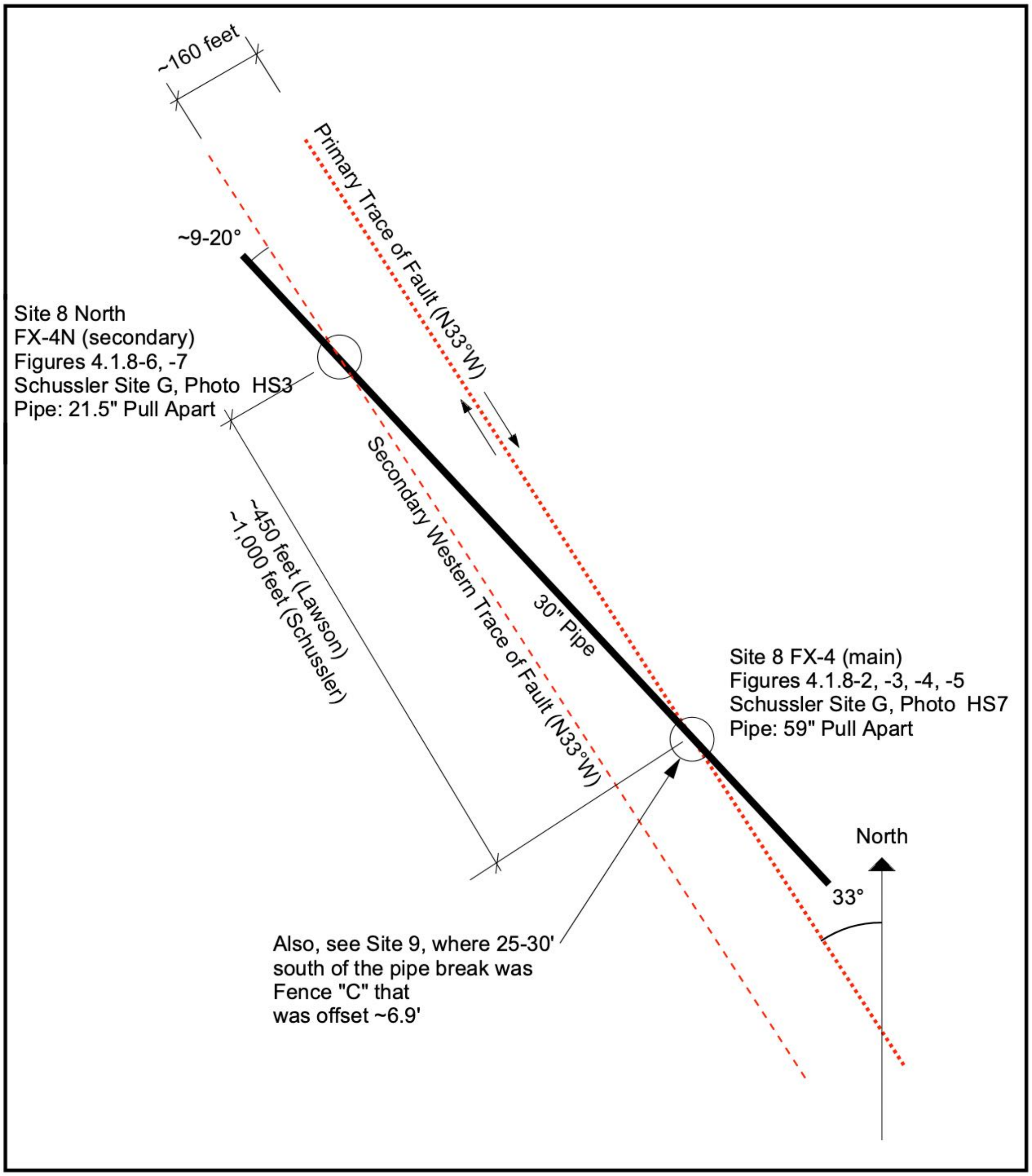


Figure 4.1.8-1. FX-4, FX-4N. Orientation of the Pipe, Fault and Pipe failures at Site 8

We describe the fault offset in this vicinity as two "Sites". Site 8 describes what happened to the pipe. Site 9 describes what happened to an adjacent fence (Lawson's "Fence C"). The source material for our assessment comes from the following sources:

- Schussler 1906. Figures 4.1.8-2 and 4.1.8-6 show the pipe damaged at two locations. Schussler does not provide quantified dimensions as to the distance between these two breaks, but his hand-drawn sketches suggest about 1,000 feet.

- Lawson 1908. Figures 4.1.8-4 and 4.1.8-7 shows the pipe damaged at the same two locations. Lawson suggests that the more northerly pipe break occurred about 150 yards to the north of the more southerly pipe break.

- The survey of the fence (Figure 4.1.9-3) is probably reasonably accurate, showing a primary offset (~7 feet) and a secondary offset to the west (~3') separated by about 160 feet.

Given the approximations in the distances involved, one cannot now be absolutely confident as to the precise azimuth of the pipe relative to the fault. However, if one assumes that the pipe was originally laid straight between the two break locations, which is reasonable, we can say with high confidence that:

- There were primary (FX-4) and secondary offset (FX-4N) zones at Site 8.

- The primary offset had "about" 5 feet (as measured by the pipe offset) to 6.9 feet (as measured by the fence offset) of right lateral offset.

- The secondary offset had "about" 2 to 3 feet of right lateral offset.

- The zone of deformation of the western (secondary) offset zone was about 70 feet wide.

With the above interpretation of the geometry of Sites 8 and 9 in mind, the following describes the pipe damage.

At Site 8, the pipe runs at an angle of about 9° to 20° from parallel to the fault. Here, the pipe was pulled apart at two locations. Figures 4.1.8-2, -3, -4 show the pipeline pull apart at the primary fault crossing.

At the primary fault offset pipe break location, the pipe was pulled apart 59 inches. There was transverse offset of the pipe of 4 inches at the break. So-called "Fence C" was nearby and the fence crossed the fault just south of the primary offset break at FX-4; this fence was offset 6.9 feet (see Fence C description at Site 9).

This pipe failure at the primary offset zone reflects that the right lateral offset of the fault put high tension along the longitudinal axis of the pipe, easily overcoming the capacity of the riveted girth joint.

Figure 4.1.8-2. FX-4. Failure of Pilarcitos 30 inch pipeline. At north end of San Andreas Reservoir. Looking Northwesterly. Pull Apart ~59". North segment of pipe is ~4" to the right (transverse) of the south segment. The wood box see in this photo encapsulates a valve, and is so-marked in Figure 4.1.8-3; it is the same wood box seen in Figures 4.1.9-4 and -5. (Photo: Schussler HS7 1906)

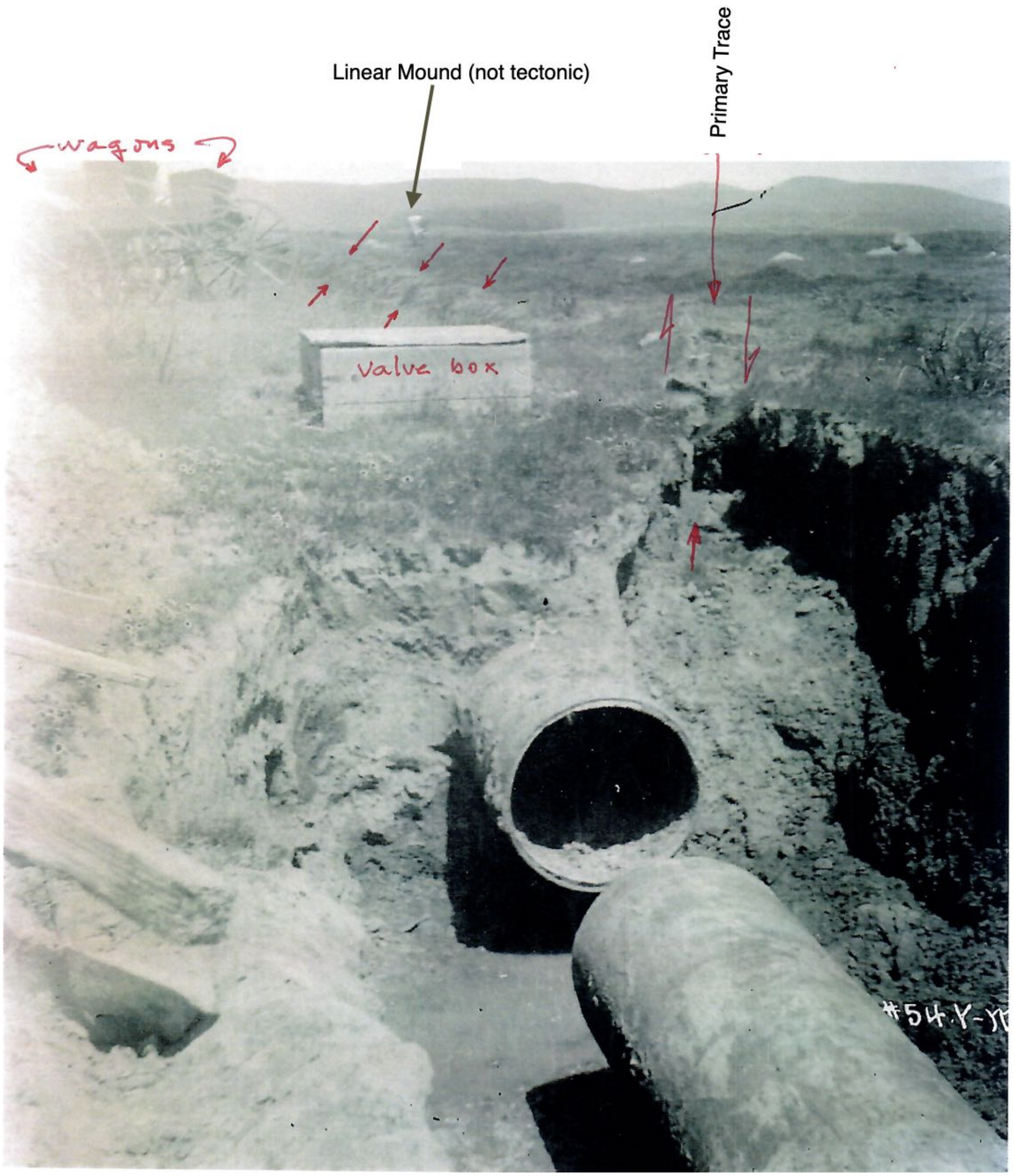


Figure 4.1.8-3. FX-4. Same as Figure 4.1.8-2, with Author's notes

Figure 4.1.8-4 suggests that the azimuth of the primary offset is about 10° clockwise from the azimuth of the pipe. If we take tan(angle) = 4"/59", then the angle = 4°; but visually the angle between the pipe and fault (see Figure 4.1.8-3) is more than 4°. If one combines the nearby fence offset (Site 9), we see that at this site, there was a main trace (offset about 6.9 feet) and a secondary west trace (offset about 3 feet), measured about 160 feet to the west. Assuming the original pipe is set straight through this zone, then the azimuth of the pipe to the fault was about $9° = \tan^{-1}(160/1000)$. with 90° being perpendicular, and 1° nearly parallel). The lumber on the left is remnants of the damaged fence (Figure 4.1.9-3). The "Linear Mound" seen in the distance beyond the valve box "might" reflect the excavation at the pipeline where it crossed the west trace, but this is not certain.

Figure 4.1.8-4. FX-4. Failure of Pilarcitos 30 inch pipeline. At north end of San Andreas Reservoir (Photo: Lawson 1908)

Figure 4.1.8-5 shows the torn joint at the primary offset location. The serrated edges of an edge-distance failure is seen on the left joint.

Figure 4.1.8-5. Crossing 4. Failure of Pilarcitos 30 inch pipeline at the main trace. Looking Westerly (Photo: SVWC 1906)

Figure 4.1.8-6 shows the pulled apart pipe at the northern break location (FX-4N) across the western trace. Based on the available evidence, we interpret this photo was taken about 900-to-1200 feet north of the primary trace at FX-4 (but, Lawson suggested 150 yards, which would put the angle of the pipe at 20° = $\tan^{-1}$(160/450). Here the pull apart of the pipe is about 21.5 inches, based on the tape measure seen in these photos. The edges of the rivet holes on the closer pipe segment are entirely missing, indicating that in tension, the failure mode was edge failure.

We tend to put more credence as to the distance between the two pipe breaks as 450 feet (150 yards), as reported by Lawson, rather than 1000 feet, as reported by Schussler.

Assuming our interpretation is correct, then Site 8 displayed a fairly wide zone of faulting, and this pull apart (Figures 4.1.8-6, -7) was the result of offset on a western strand.

Figure 4.1.8-6. Site 8. FX-4N. Failure of Pilarcitos 30 inch pipeline. Pull Apart ~ 21.5 inches. (Photo: Schussler HS3 1906)

Figure 4.1.8-7. Failure of Pilarcitos 30 inch pipe at FX-4N. Pull Apart ~ 21.5 inches. Note edge distance tears at rivets. (Photo: Lawson, 1908)

4.1.9 Site 9. Adjacent to Pipe FX-4. Fence 2 (Lawson's Fence "C")

Site 9 is a very important site for study of the Pilarcitos pipeline, because it is here that active faulting intersected both the pipe (see Site 8) and a property boundary fence at nearly right angles (Site 9) (the pipe and Fence "C" are highlighted in yellow in Figure 4.1.9-1).

At Site 9, which today rests within the SFPUC watershed and thus has not been disturbed by urban development over the past century, tectonic-geomorphic features have formed over the millennia along the major plate boundary are still readily observable in 2023. However, related features have suffered wholesale destruction during urban development over the past century in other places along the fault, beginning about 2 miles or so to the north of Site 9. The total surveyed offset of Fence "C" is 16'-9", composed of ~7' of slip at the primary trace, 3' of slip corresponding to the western secondary trace, and 6'-7" of offset over an eastern zone (extending about 725' east of the primary slip) that we call the zone of ground warping.

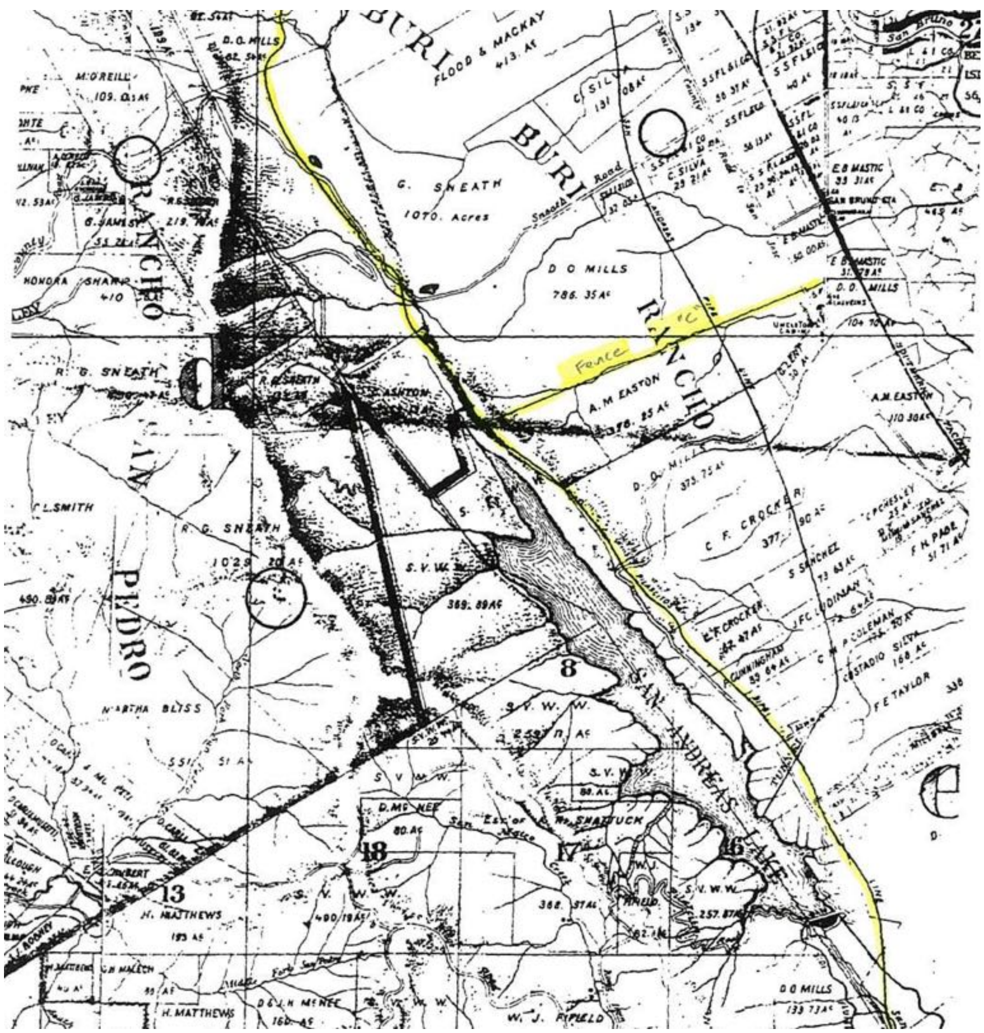


Figure 4.1.9-1. Location of Jersey Farm Building Complexes (Base Map: 1894)

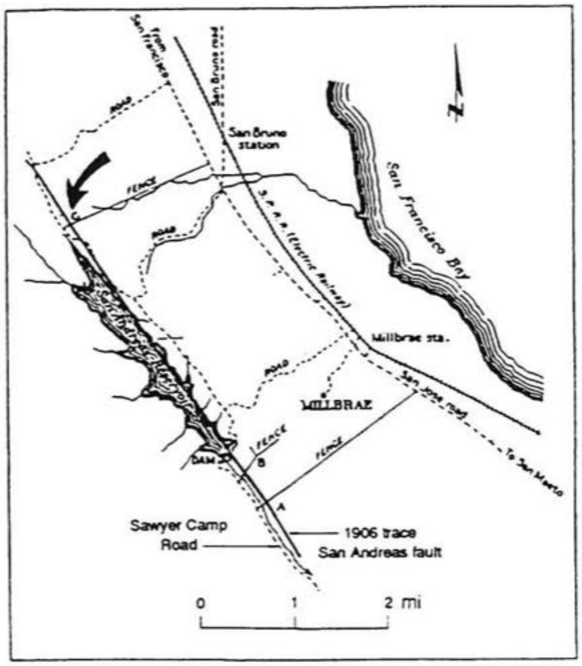


Figure 4.1.9-2. Arrow Marks Location of Fence "C" (after Lawson, 1908, Fig. 30)

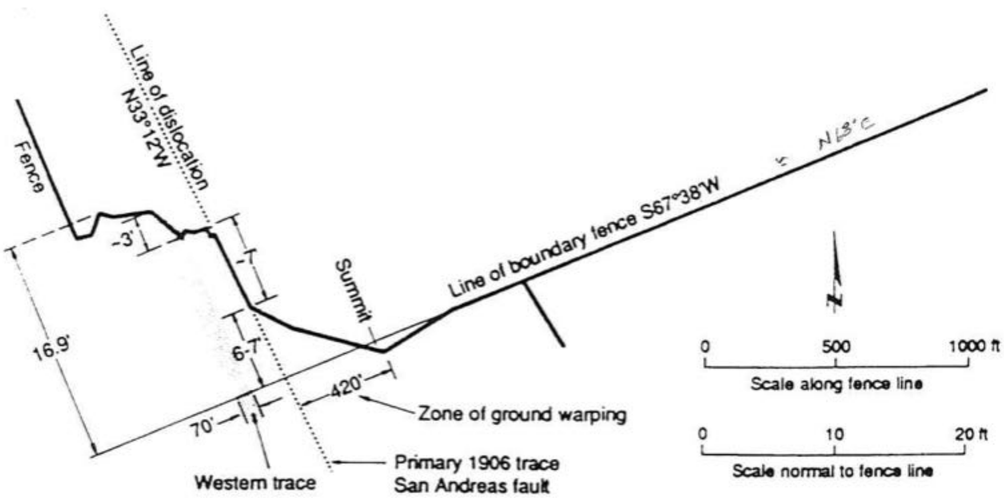


Figure 4.1.9-3. Details of Fence "C" (After Lawson, 1908, Fig. 31)

Figures 4.1.9-2, -3 (Site 9) show the location of Fence "C". The configuration of Fence C following the 1906 earthquake shows a western trace, the primary trace, and an eastern zone of ground warping.

Like Fence "1" described at Site 4, Lawson's Fence "C" no longer exists, but its location is recorded in historic maps and vintage photographs that have been used to reconstruct its location. Babel (1990, p. 69) contains an official map of San Mateo County dated 1894 that shows the location of large land parcels along Buri Buri Ridge, including the northeast-trending boundary between lands of D. O. Mills and A. M. Easton (Figure 4.1.9-1). This fence line is very visible on aerial photographs taken in 1946 and can be located quite accurately today from existing topography and roads that have not changed.

The approximate location of the 1868-vintage Pilarcitos pipeline is also shown in Figure 4.1.9-1.

Excerpts from what Lawson (1908, p. 96-7) had this to say about Sites 8 + 9 fault/pipeline/fence intersection are as follows: *"Near the head of the lake (San Andreas Reservoir) …the pipe line runs almost parallel with the fracture…the movement was in the same direction as before (i.e., pipe extension as seen at Site 8 FX-4, FX-4N), therefore a pulling apart of the pipe took place instead of a compression. There occurred two breaks in the pipe, the main one at the crossing of the fault, and the other 150 yards away on the northwest* [corrected by authors, Lawson incorrectly wrote northeast] *side of the fault, but very near it, the pipe being almost parallel to it. At the main break, the pipe was pulled apart 59 inches* (Figures 4.1.8-2, 4.1.8-3, 4.1.8-4, 4.1.8-5) *and at the other one 21.5 inches* (Figures 4.1.8-6, 4.1.8-7)*, making a total displacement of 6.7 feet. The pipe was not quite parallel with the fault and therefore was a slight offset, at right angles to its direction, of 4 inches at the main break and 2 inches at the minor one, or a total of 6 inches. A fence which crossed the fault at the main break is offset 6.5 feet."*

Figures 4.1.9-4 and 4.1.9-5 show Fence "C", looking towards the southwest (same photo, without and with author's notes). Figure 4.1.9-6 shows a close up of the fence offset, including 5 members of the investigation team seen in Figure 0-1. At the center of the photos can be seen the primary fault offset of 6.9 feet in the fence (corresponds to the ~7' offset in Figure 4.1.9-3). In the distance, marked "western trace, offset ~2.5' " (corresponds to the ~3' offset in Figure 4.1.9-3). At the right side of the photo is marked "valve box", which corresponds to the wooden box seen in Figures 4.1.8-2, -3, -4. Just to the left of "valve box" is marked "excavated dirt exposing Pilarcitos Pipe" (corresponds to the dirt piled up on the right side of Figures 4.1.8-2, -3, -4).

Figure 4.1.9-4. Fence C, View to Southwest (Photo: SVWC 1906)

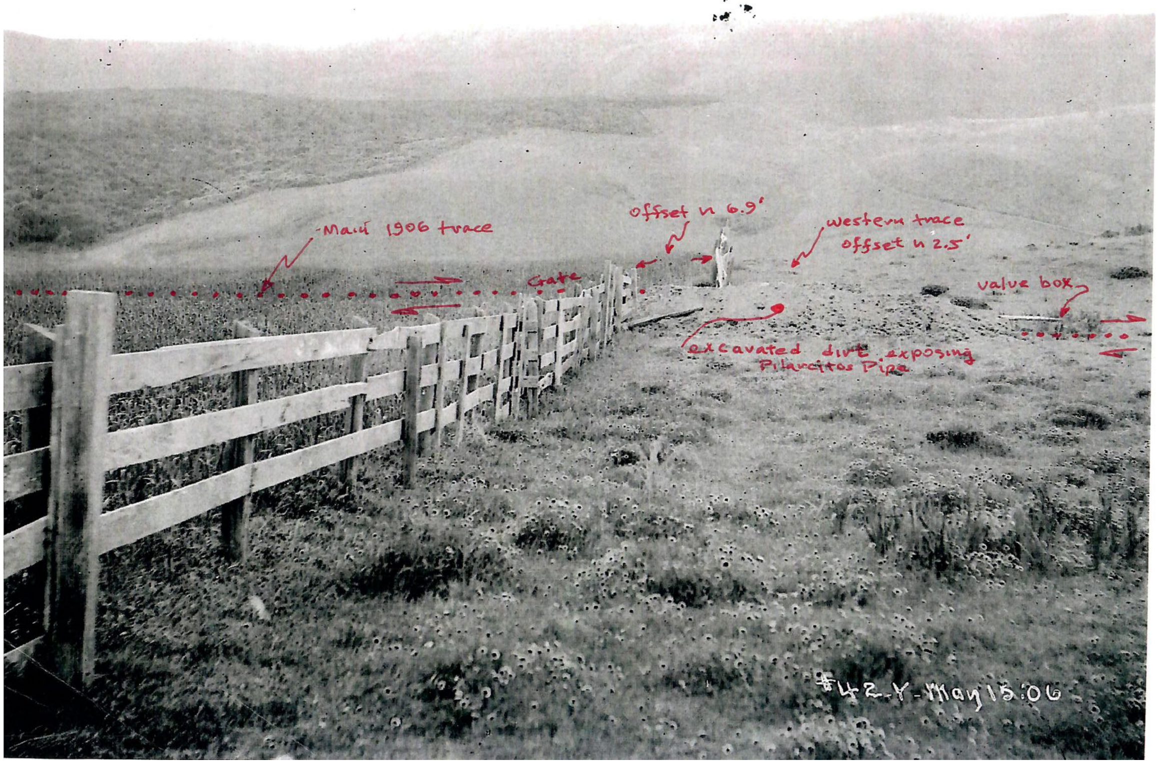


Figure 4.1.9-5. Fence C, View to Southwest (Photo: Schussler 1906) with Author's notes

Figure 4.1.9-6 Fence C, View to Northeast (Photo: SVWC 1906)

Figure 4.1.9-7 Fence C, View to Northeast (Photo: Lawson 1908 Plate 60C)

Pampeyan (1983) situates Fence "C" in his map (MF-1488). However, Pampeyan appears to have mislocated the Pilarcitos pipeline FX-4 crossing (our Site 8) several hundreds of feet southeast of Fence "C".

4.1.10 Site 10. San Andreas Dam Outlet Works

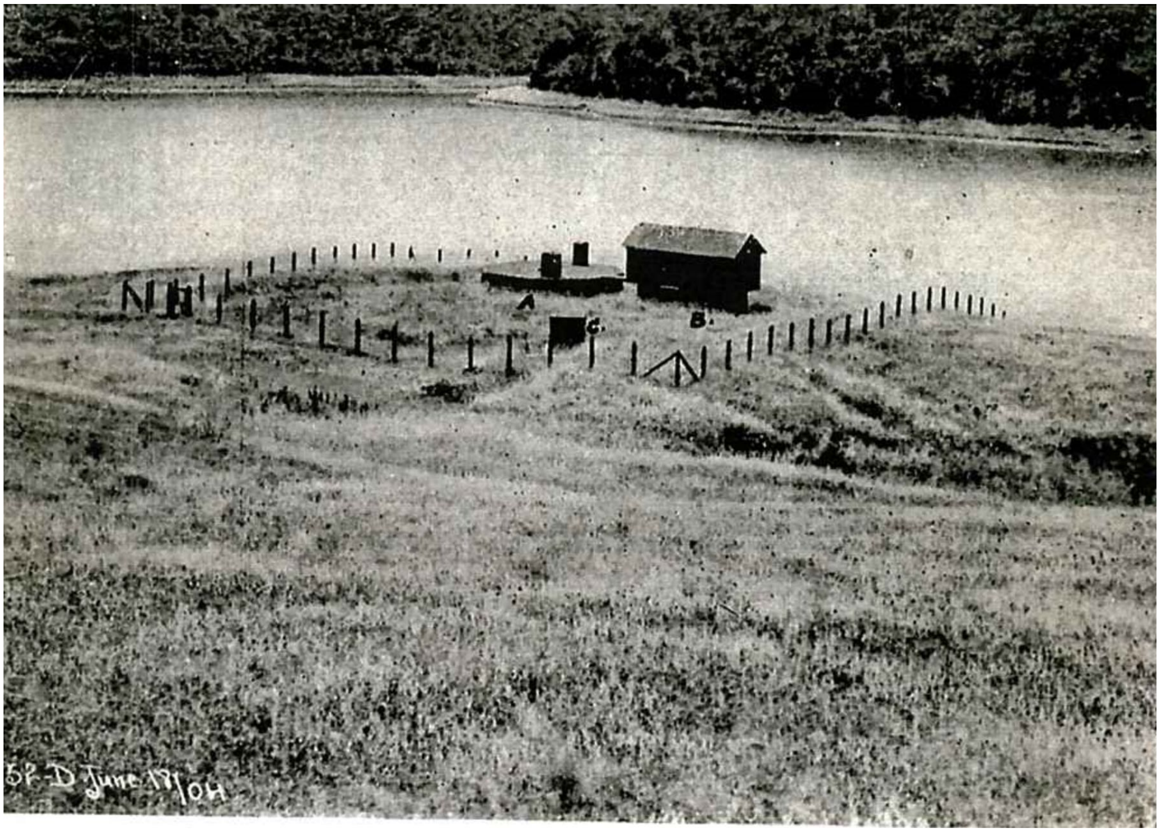


Figure 4.1.10-1. San Andreas Dam Outlet Works, looking Westerly (Credit Schussler 1906)

Figure 4.1.10-1 shows San Andreas Reservoir outlet works as of June, 1904. Three structures can be seen, labelled A, B, C:

- A: Original 1868 brick-lined circular shaft
- B: Wooden building over 1898 concrete-lined rectangular shaft
- C. Manhole Access to connection between A and B.

Figure 4.1.10-2 shows the ground surface rupture of the San Andras fault, as of June 1906. The photo direction is south-southwesterly, and the three structures A, B, C in Figure 4.1.10-1 can be seen in the background. The primary ground rupture extends along the uphill eastern side of structure A.

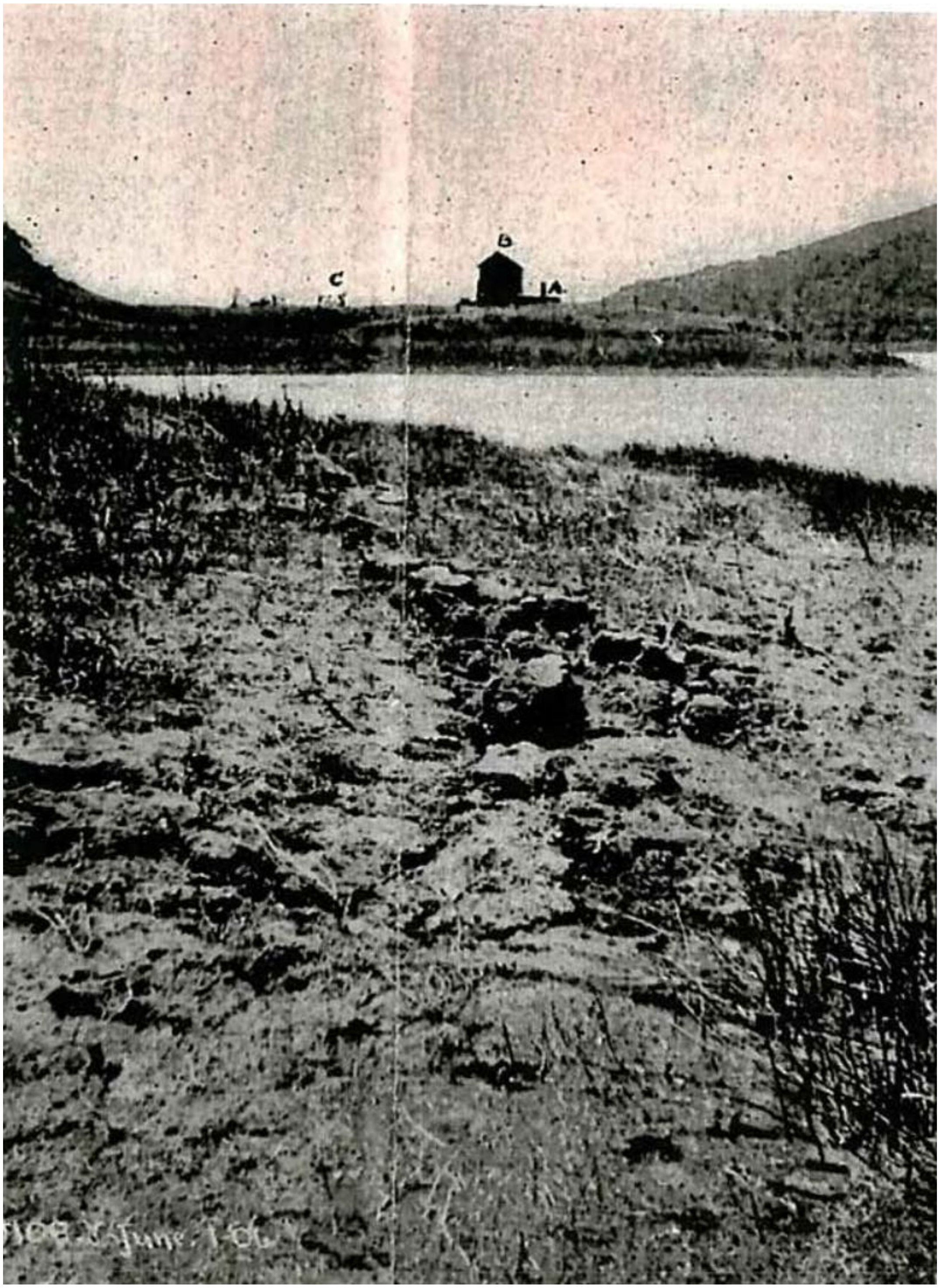


Figure 4.1.10-2. San Andreas Fault Rupture (Credit Schussler)

Figure 4.1.10-3 shows the original 1868 and 1898 outlet works for San Andreas Reservoir. The original outlet works consisted of a 26-foot diameter brick-lined vertical shaft, 80 feet deep; a 3'-6" x 4'-6" 250-foot long tunnel, timbered, attached to a 38" diameter cast iron pipe that extended a further 150 feet into the reservoir; and an outlet on the east into the 2,820 foot-long Bald Hill Tunnel (Figure 4.1.10-8). The woodwork (planking) atop the shaft is at 445'. The bottom of the shaft is at 362'. The function of the original circular brick-lined shaft was to provide two slide gates to allow isolation of the reservoir water from Bald Hill Tunnel, should the need arise.

Around 1898, an adjacent concrete forebay (B) and concrete shaft (C) were constructed. The arrangement of slide gates in the new concrete forebay indicate that the system was set up to allow drafting from either the northern or southern inlet works from the reservoir, or both. The intake pipe to the new concrete forebay is only about 95 feet long, nearly 300 feet shorter than the original 400-foot-long intake. Possibly, the 1897 construction was done to allow inspection and repair to some works while the other remained in service; and/or to allow drafting water from a higher elevation in San Andreas reservoir; and/or to increase hydraulic capacity related to the upsizing done in 1885 of a portion (from Bald Tunnel outlet to Baden) of the original San Andras pipeline from 30" to 44".

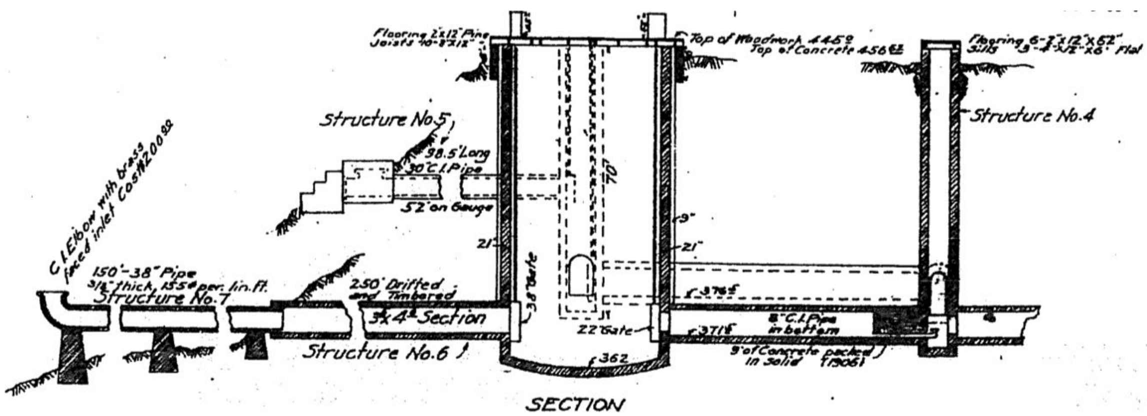


Figure 4.1.10-3. Cross Section of San Andreas Outlet Works, 1914 (SVWC Drawing)

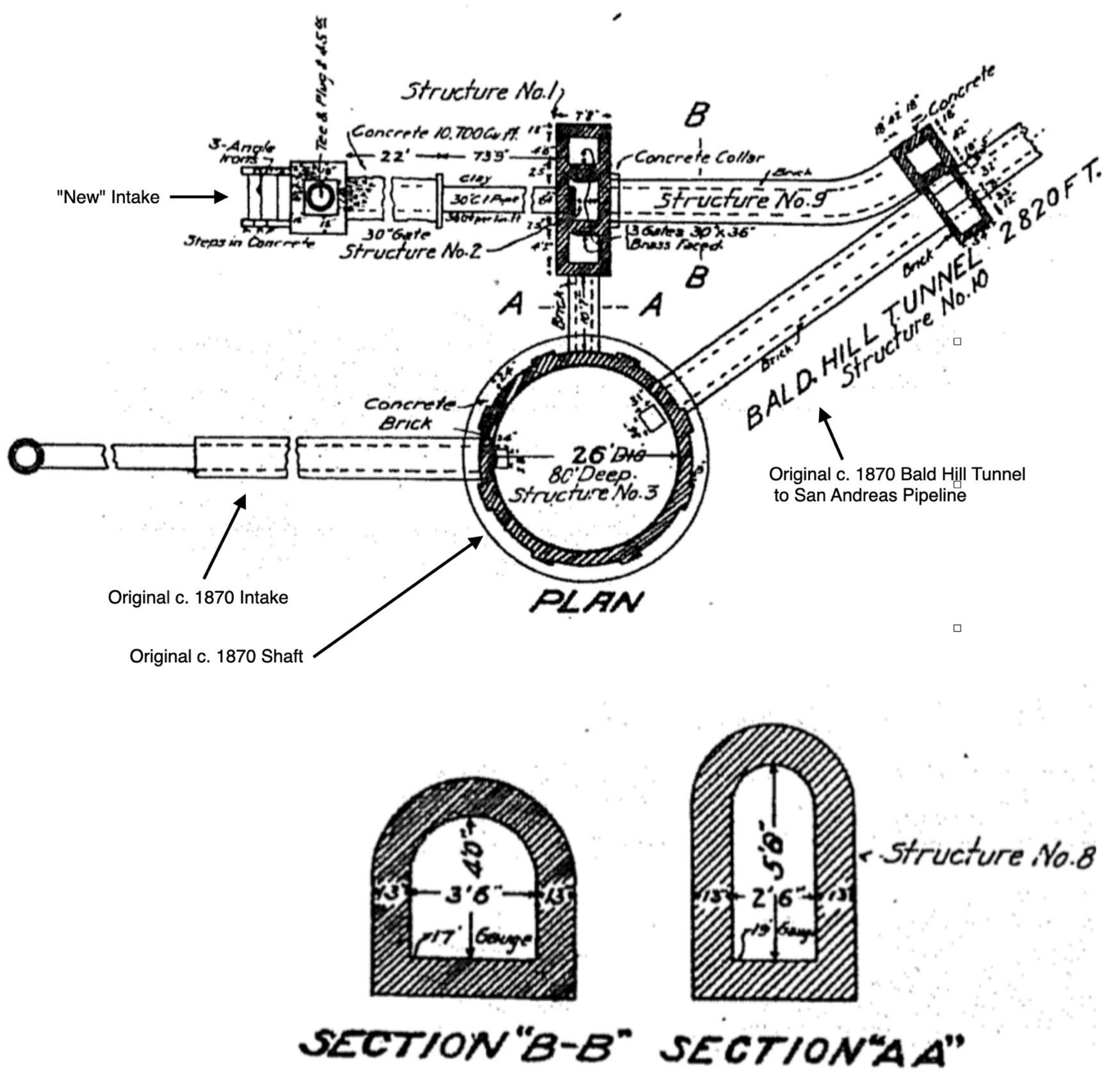


Figure 4.1.10-4. Plan and Details of San Andreas Outlet Works, 1914 (SVWC drawing)

Figures 4.1.10-5 and 4.1.10-6 show the damage to these outlet works from the 1906 earthquake.

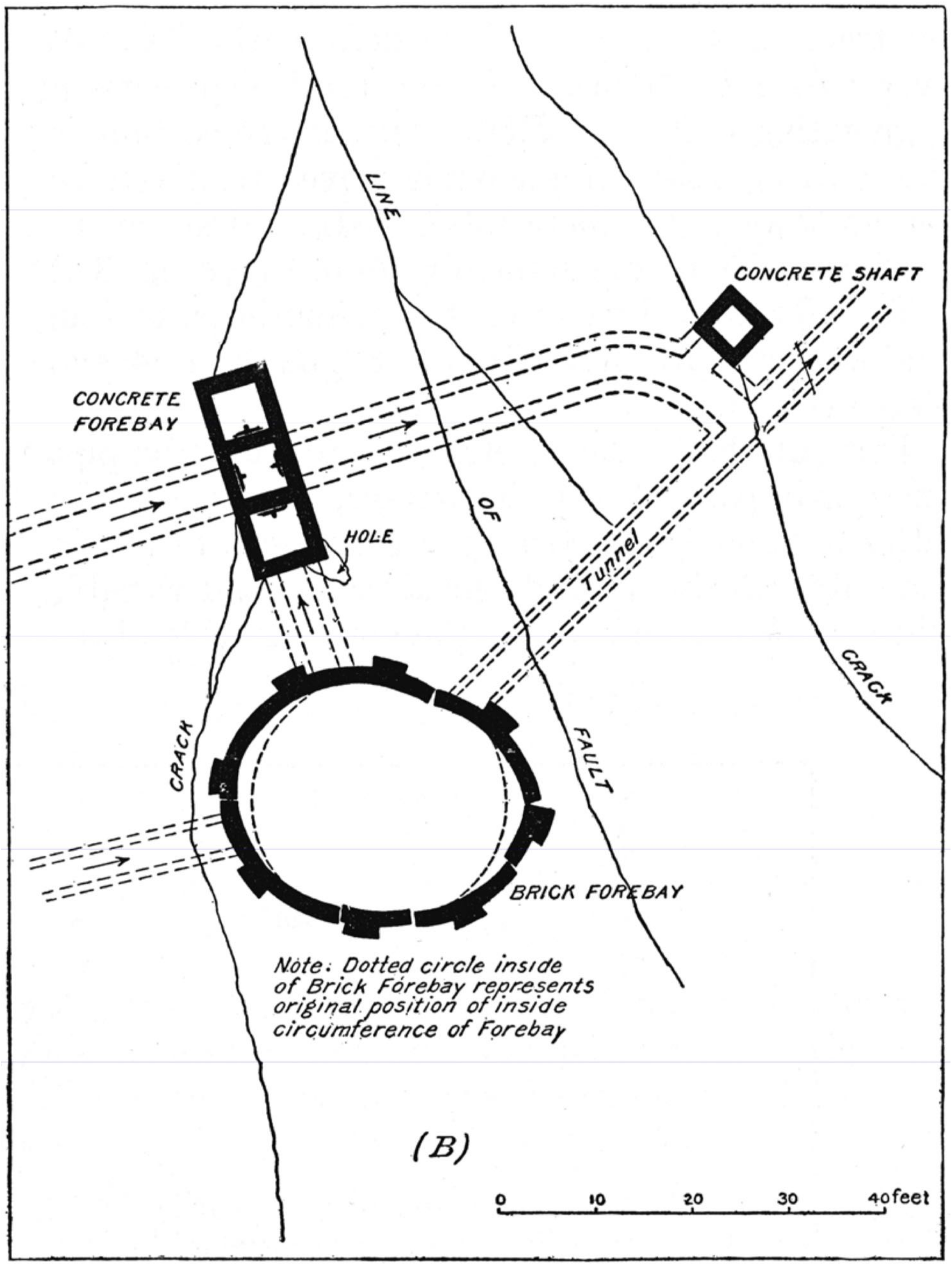


Figure 4.1.10-5. San Andreas Reservoir Outlet Works with Damage (Credit: Schussler)

Immediately after the 1906 earthquake, water from the lake went undisturbed into the Bald Hill Outlet Tunnel, even though there was major damage to the brick forebay. Figure 4.1.10-6 shows the damage to the brick forebay at the ground level. The cracks in the brick walls correspond to the breaks in the brickwork seen in Figure 4.1.10-5.

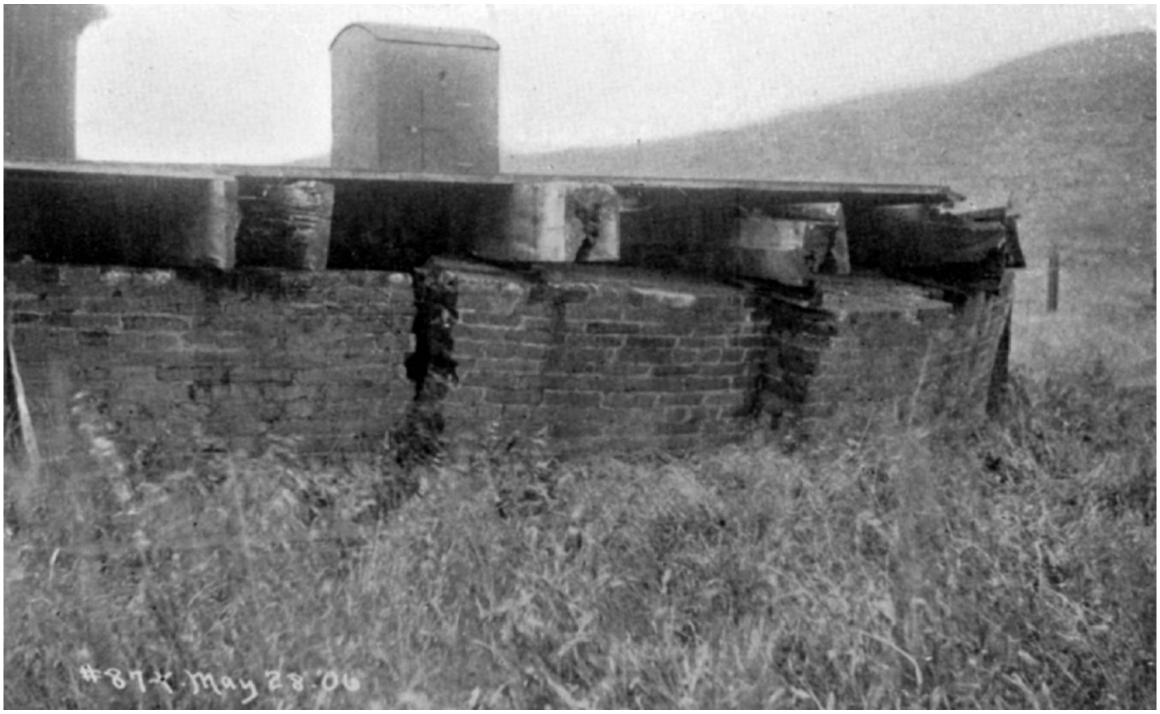


Figure 4.1.10-6. Brick forebay damage (view looking northerly) (Photo: Schussler)

The Bald Hill Outlet Tunnel was kept in service until the new San Andreas No. 2 pipeline and intake structure (about a mile north of the original) was constructed in 1928, at which point the forebays and tunnel shown in Figure 4.1.10-5 were abandoned. In 1983, in an effort to document the offset of the San Andreas fault in the vicinity of the original outlet works and tunnel, our Author Tim Hall, Earl Pampeyan of the USGS and 4 other interested people accessed the Bald Hill Tunnel form its easterly end for an inspection. They initially considered entering the tunnel via the concrete shaft in Figure 4.1.10-5; but the iron climbing rungs were rusty and thought unsafe, and the group decided it was not suitable to enter at that location, being nearly 80 feet from the ground to the bottom of the shaft. Instead, they accessed the tunnel from the east end portal works, about half a mile to the east. For most of its length, the height of the tunnel was under 5 feet (see Figure 4.1.10-8), and the team had to walk "stooped over" for half a mile each way. During the inspection, fresh air was circulated from the concrete forebay to the east end. Earl Pampeyan of USGS and his crew re-entered the tunnel probably by the concrete access shaft noted in Figure 4.1.10-5, and successfully measured the 1906 fault slip as summarized in Figure 4.1.10-7.

They reported the following observations:

- Schussler (1906) noted that "*The brick tunnel, connecting the concrete gate-well and the main San Andreas Bald Hill tunnel, was somewhat damaged by the earthquake, but not so as to interfere with the flow of water through the same… the fissure will be easily closed by cement grouting*".

- Figure 4.1.10-7 documents the findings in 1983. At about station 0+75 along the Bald Hill Tunnel, there was a repair made; and a concrete ring was placed around the damaged brick shaft.

- About half way through the Bald Hill Tunnel, the tunnel was damaged and squeezed. Hall hypothesized that the tunnel traversed a zone of squeezing clayey soils within the Franciscan bedrock. At this location, there is no mapped surface trace of the Serra fault; but that fault is inclined, and thus this zone may (?) correspond to a shear zone associated with the Serra fault (this is speculative).

- At the west end of the Bald Hill Tunnel, near the base of the air shaft and just east of the fault crossing, a 40 pound racoon was defending its territory. The inspection party wisely retreated, thus abandoning the goal of directly measuring the fault offset, lest an adverse interaction with the racoon end up in injury.

- A second inspection led by Pampeyan was done later. The racoon was gone, and the measurements recorded in Figure 4.1.10-7 were taken.

Soon thereafter the second 1983 inspection, the SFPUC pumped concrete into the shaft and west end of the Bald Hill Tunnel. As of 2024, the tunnel is now plugged, and further investigation of the 1906 damage from the interior of the Bald Hill Tunnel is no longer feasible.

Nobody claims to know what happened to the racoon.

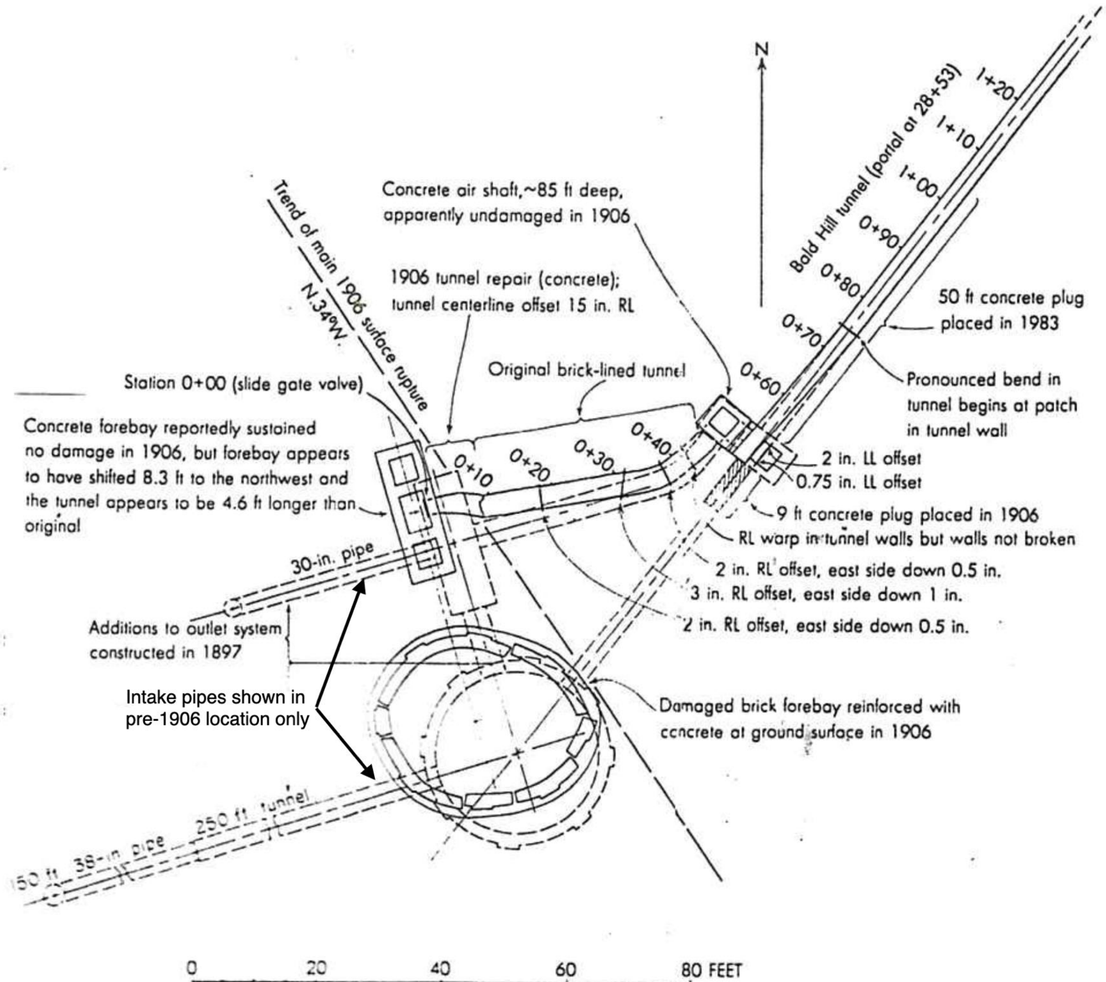


Figure 4.1.10-7. Survey of Outlet Works, 1983 (adapted from Pampeyan 1983)

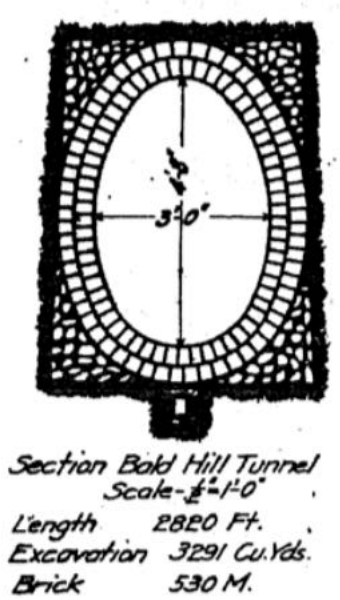


Figure 4.1.10-8. Bald Hill Tunnel Cross Section (Credit: SFPUC)

4.1.11 Site 11. San Andreas Dam and Road Across Crest

Figure 4.1.11-1 shows the general location of the San Andreas dam plus the Bald Hill intakes and outlet tunnel. The fault bisected the two outlet structures (see Site 10 for details). Note that in this figure, the crest of the dam is shown as being straight between embankment structures 1 and 2. However, there is a change of orientation here, as correctly shown in Figure 4.1.11-2.

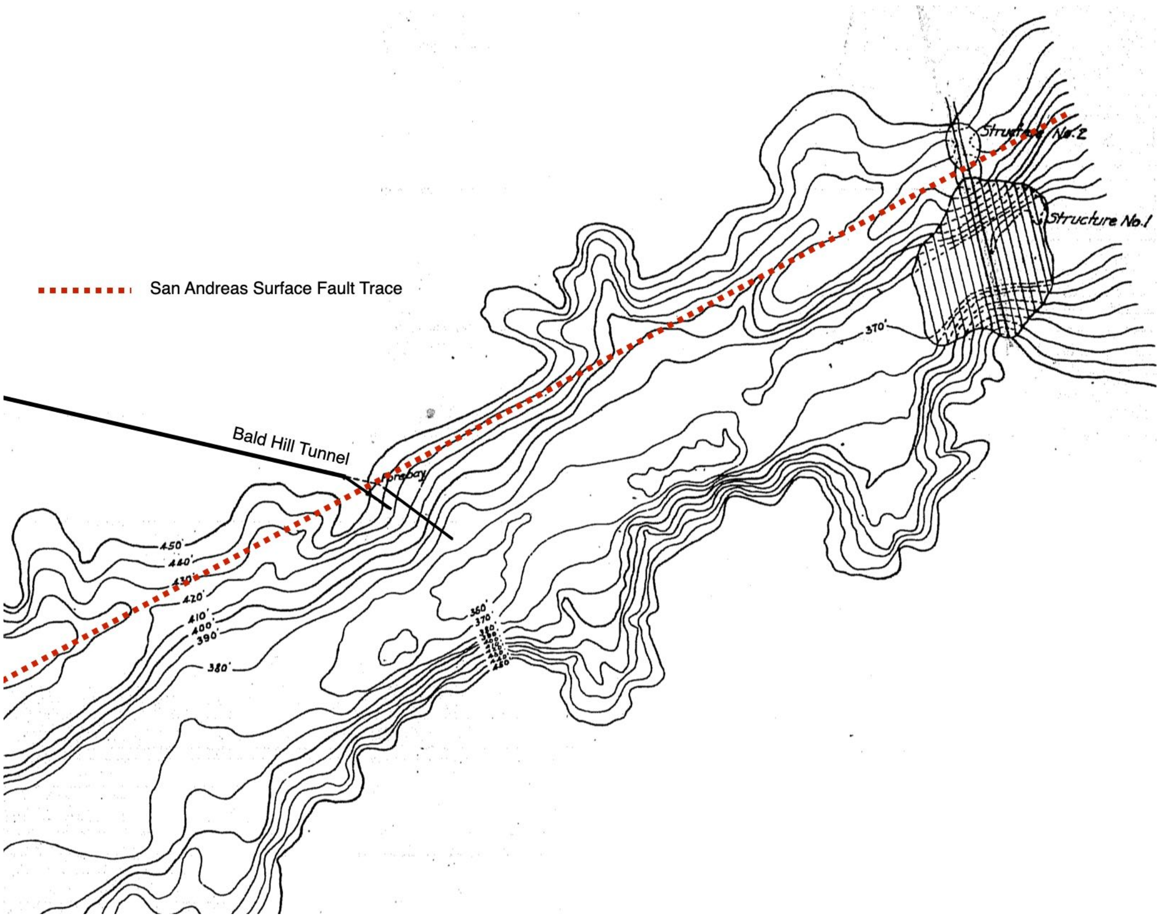


Figure 4.1.11-1. San Andreas Reservoir Topography, Fault, Dam Structures (Credit: SVWC, 1908 P-240)

Figures 4.1.11-2 and 4.1.11-3 provide an overview of San Andreas Dam and shows where the line of the 1906 fault rupture crossed the crest *between* embankment structures 1 and 2. It also shows the relationship of the San Andreas fault to the brick waste water tunnel and the northern end of the Stone Dam/Locks Creek flume where it empties into the San Andreas Reservoir. Although the 44" wrought iron discharge pipe from the flume and a concrete culvert were very close to the fault, they were not damaged. However, an ~80-foot-long section of the flume that fed into this pipe and was located a bit further from the fault, collapsed just south of the crest of the dam. The dashed lines below the dam highlights where this section of the flume was probably demolished by a combination of strong ground shaking and potentially influenced by some fault slip as further described herein. The damage to the brick waste water tunnel at the fault crossing and its wooden outlet flume are also documented and assessed as described in Section 4.1.12.

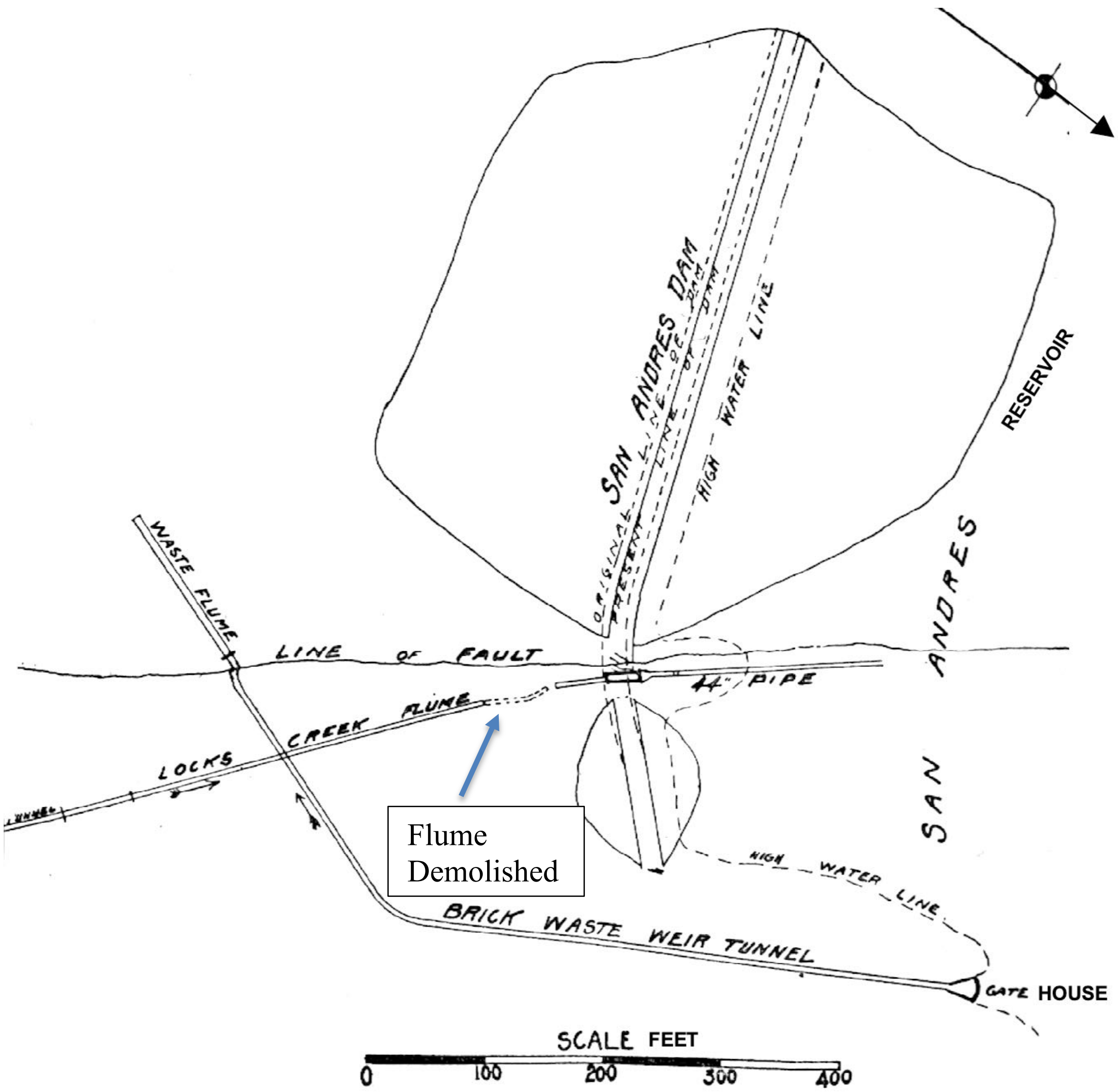


Figure 4.1.11-2. San Andreas Dam
(Sketch: Schussler 1906)

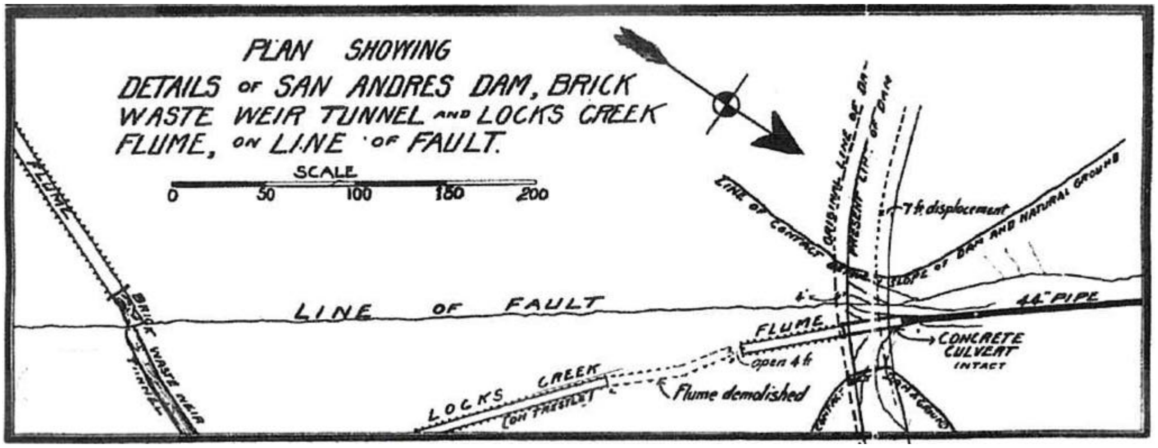


Figure 4.1.11-3. San Andreas Dam
(Sketch: Schussler 1906)

What is startling in Figures 4.1.11-2 and -3 from an engineering perspective is that they show the dam crossed a major active fault whose presence here was apparently unknown at the time the dam was constructed in the 1860s. Then came the 1906 earthquake! Today we know that this fault is one of our planet's major tectonic plate boundaries, and therefore, lacking suitable seismic design provisions, is a less than safe place to store vital water supplies! Fortunately, surface fault slip at the dam crest was probably largely confined to a low ridge of ancient Franciscan Assemblage bedrock located between the two engineered embankments.

<u>Dam Construction:</u> The original construction of the dam started on May 7, 1868 with the laying out of the cut-off wall trench, and was completed in 1870. The dam crosses the north branch of the San Mateo Creek (sometimes now called San Andreas Creek). At the time of its construction under the supervision of Hermann Schussler in 1868-1870, this dam was one of the largest earth fill gravity dams found anywhere. It has a 20-foot-wide clay puddle core, an impermeable “curtain” that stretched from the base of the embankment to its top and extended downwards 45 feet into a cut-off trench excavated into the earth materials below the dam (Figure 4.1.11-4). At the time of the 1906 earthquake, the dam embankment was 93 feet high and about 800 feet long.

From a geological perspective, this dam was unique in that the builders incorporated a highly sheared, clay-rich “bedrock” ridge of Franciscan Assemblage mélange into the area between the two embankments of the dam (Figure 4.1.11-2). This not only reduced the amount of fill necessary to construct the embankment, it also contained the then unknown main active trace of the San Andreas fault, which provided a pathway that kept the 1906 fault slip from slicing through the man-made embankments. Despite being crossed by the active fault, San Andreas Dam survived both the 1906 right-lateral fault slip of 7 feet as measured by Schussler, and the accompanying severe ground shaking in 1906. The dam remains in service today (2024).

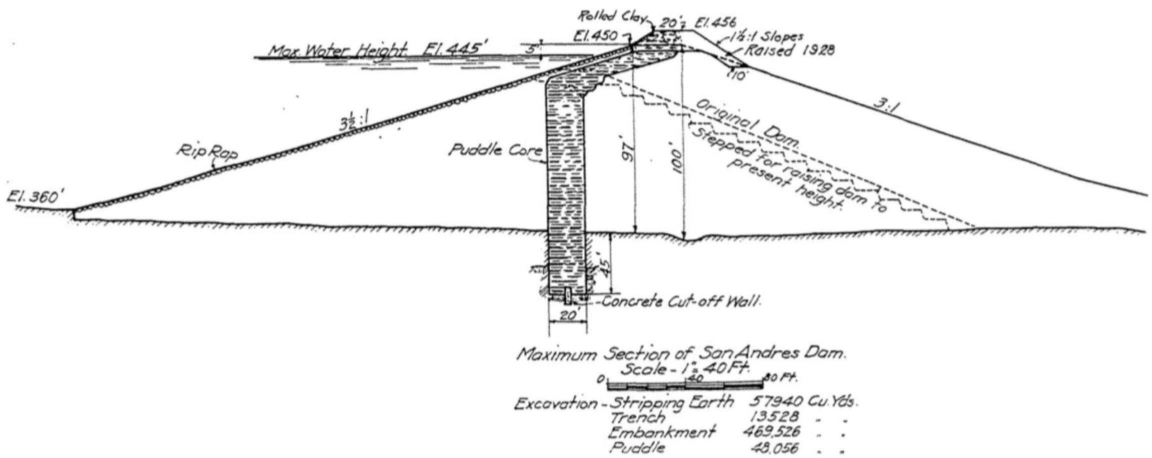


Figure 4.1.11-4. San Andreas Dam Cross Section through Structure 1 (Babel, 1990)

Figure 4.1.11-4 shows the cross section through the widest part of the dam. The dam had been raised twice, by 20 feet (1874) and another 10 feet (1928). The cross section shows the dam in its 1928 configuration, along with its prior structure. At the time of the 1906 earthquake, the top was at elevation 450 feet, with maximum water height of 445 feet. The dashed line "Original Dam" represents the original 1868 construction. After the 1928 modifications, the length of the dam (at the crest) was 950 feet, with a resulting storage capacity of 6.2 billion gallons.

Figure 4.1.11-5. San Andreas Dam Soon after 1870 Construction, Looking Easterly (Babel, 1990)

<u>Response of the Dam to the 1906 Earthquake:</u> While we do not know the exact age of the photograph in Figure 4.1.11-5, it was likely taken decades before the 1906 earthquake. If you look carefully at the upper right part of the photo, you should be able to see the benched quarry area that supplied the earth materials from which the dam was constructed. You might also be able to see a white building in the upper right corner and the Stone Dam/Locks Creek flume trestle that carried water from Pilarcitos Reservoir to the dam. To the right (southeast) of this white building, the wooden flume sits directly on the ground and collapsed in two nearby places from strong 1906 ground shaking. These system failures are documented in Site 12 below. A more complete story of the full impact of the 1906 quake had on the Locks Creek flume system is presented in Section 4.6.

Post earthquake investigators were obviously very concerned about the integrity of San Andreas Dam and reported their observations of cracks that had formed within it. Of most concern would be cracks transverse to the alignment of the embankment, especially at the abutment areas, that might provide conduits for water to pass through the edge of the dam, erode the fill materials and cause the dam to fail. Longitudinal cracks, parallel to the embankment, were of lesser concern as they usually do not allow water to flow through the dam. They typically form in response to shaking-induced settlement of the fill materials and usually are not considered serious unless the earth fill materials have failed by liquefaction and/or land sliding; or the elevation of the crest has fallen enough to allow overtopping of the dam.

A committee of engineers who assessed the effects of the 1906 earthquake on San Francisco's water-works structures did, however, report the following observation: *"The main body of the dam shows a crack, from two to three inches in width, extending longitudinally along the center line for the entire length of the dam" (Ambraseys)* ASCE 1907, Vol. LIX, p. 2). Unpublished geotechnical investigations by Earth Sciences Associates of Palo Alto (ESA 1980, 1982) found that this longitudinal crack was probably due to minor settlement of the clay puddle core and posed no hazard to the safety of the dam, nor did any other of the cracks in the dam that were observed after the earthquake.

Our principal interest at the dam site is the documented expression of the zone of active faulting where the main trace of the San Andreas fault crosses the crest of the dam. Professor Derleth tentatively estimated 5 to 6 feet of fault slip occurred here and described the fault-dam intersection zone as follows: *"The ground is considerably scarred by cracks running north northwest on the eastern bank of the dam where the nose of a hill naturally projects to form its abutment. These cracks, which are quite pronounced, are in the abutment and not in the dam itself."* (Schussler, 1906, p. 41.) The cracks were, in fact, within pervasively sheared Franciscan mélange "bedrock" that crops out in the gap between the two engineered embankments.

Figure 4.1.11-6 shows three northwest-trending extensional cracks developed in the upstream face of the dam near the left abutment of the larger embankment. These cracks might have been caused by slumping, settlement and/or ground warping of the Franciscan bedrock along the west side zone of active fault slip, but did not cause the dam to fail. As shown in Figure 4.1.11-7, the San Andreas fault slices across the center of this photo and passes the near side of structure "G".

Figure 4.1.11-6. View of San Andreas Dam looking northeasterly. Item "G" is a concrete vault atop the dam at the high point of the 44" discharge Locks Creek pipe. To the left (north) of the concrete vault is see the top part of a man, standing next to what appears to be a standpipe on the 44" pipe. (photo: Schussler, HS32)

The concrete structure labelled "G" in this figure is an undamaged concrete culvert on the Stone Dam/Locks Creek transmission system that connects the wooden flume coming from the south with the 44" iron pipe that discharges into the reservoir (Figure 4.1.11-3). This connection is within the central zone of faulting but was not reported to have been disrupted by fault slip. Although hard to see, the hillside beyond this culvert, but in front of the building, is scarred by what appear to be north-trending, left-stepping en echelon ground cracks and scarps commonly observed on the eastern side of main San Andreas fault trace in this area. We believe these are caused by ground warping along the active trace. The building beyond, which is partially visible in the upper right corner of this photo, is the gate house for the waste water weir system that is discussed next in Section 4.1.12.

1906 Fault Slip: Schussler's sketch shown in Figure 4.1.11-3 depicts a ~50+-foot-wide zone delineated primarily by north-trending, left-stepping en echelon cracks that are characteristic of the right-lateral San Andreas fault's surface expression within the ridge of highly sheared, clay-rich Franciscan Assemblage mélange. Mélange (i.e., a mixture) is just another name for "mega" fault gouge that was formed in an ancient subduction zone where oceanic crust of the Farallon Plate slid beneath the North American Plate. Here Schussler also shows his measurement that the crest of San Andreas Dam had been displaced right-laterally 7 feet by the 1906 event. Why this magnitude of right slip is about 30% less than that was documented by other nearby strain gauges like the fences and pipes reviewed in this study is uncertain, but may be related to the fact that active right slip in 1906 was confined to numerous, pre-existing, weak clay-lined shears within the mélange that may have distributed and dissipated some of the fault slip across a zone of ground warping at least 50+ feet wide.

Points A and B in Figure 4.1.11-7 are located on the ends of an approximately 75-foot-long, 4- feet x 6-feet-wide wooden flume segment that was reported by Schussler to have collapsed and been pulled apart 4 feet. According to Schussler's caption, the flume was destroyed from A to B. *"Point B"* (which marks where the intact flume passes beneath the road atop the crest), *"moved farther away from "A" than before the earthquake."* We cannot tell from his sketches if the A-B flume segment was elevated on a short trestle or placed on the ground. Clearly the topography of the dam site shows that the flume on the downstream face of the dam well below "A" was built on a much taller trestle that extended southeastward to near the white building identified in Figure 4.1.11-5. This trestle may have reached heights of 14 feet or more near the waste water tunnel / fault crossing (Site 12).

Figure 4.1.11-7. Fault Offset Near Flume, Looking northwesterly. Yellow dashed line D-E-F is the primary trace of the San Andreas fault (Photo: Schussler 1906 HS53)

We noted some discrepancies in Schussler's documentation of the performance of the Stone Dam / Locks Creek flume here where it approaches and crosses beneath the crest of the dam. Both of Schussler's sketches show the collapsed flume segment ending about 50 feet south of point B, located on the south edge of the dam crest, and not at B itself as described in Schussler's photo caption. Figure 4.1.11-7 was take 41 days after the quake, time enough after the quake to remove after debris from a failure of the flume from the site. We have studied the available evidence from this reported collapse to constrain the cause of this flume failure to: either 4 feet of ground extension cause by fault slip, structural collapse of the flume in response to strong ground motions or a combination of both processes.

Figure 2-22 has provided us with a distant look at this area where the Stone Dam / Locks Creek Flume, San Andreas Dam crest and San Andreas fault all converge. This photo was taken in about 1900 before the quake and shows the following pertinent features:

- Site B where the flume crosses the fence marking the downstream edge of the dam crest and the flume is covered by the crest road;
- The concrete culvert and 44-inch wrought iron pipe connection on the upstream side of the dam, both of which were reported by Schussler as not damaged by the quake;
- The 44" pipe is supported within a low trestle which allowed light to pass beneath the trestle, and:
- An apparently opaque wall system (no light passing through) that is part of the wooden flume on the south side of the dam.

These observations do not give us a definitive answer as to the cause(s) if the flume failure between points A and B. These observations do no allow the hypothesis of fault slip as the cause of flume separation at point B to be summarily discarded.

Schussler's sketch (Figure 4.1.11-3) of the dam crest shows that the Stone Dam/Locks Creek flume lies just east of fault's eastern boundary (defined by points D-E-F on Figure 4.1.11-7) and is essentially congruent with the main trace of the fault in the middle of the fault zone as it reached the crest. This sketch also shows that there is one crack/fault trace that lies on the east side of the 44-inch pipe above the words "*concrete culvert"*. 1906 fault slip on this trace might help explain the 4-foot-long A-B separation of the flume, but it is entirely uncertain how the imposed forces due to net stretching action on the intact wooden flume on the south side of the dam could be transmitted to point B

Therefore, we the authors (Hall and Eidinger) are not entirely certain what caused the four feet of extension of the flume at its damaged northern end (point B) as reported by Schussler, but there is no doubt that the flume was not designed to accept extensional forces. Thus, its collapse here could have been due to high inertial loading of the wooden structure; high imposed water sloshing or impulsive loading of the carried water; by some type of fault offset loading at the flume / fault crossing; or perhaps by a combination of all three.

- First, it is possible that collapse of the flume, triggered by strong ground motions, might have contributed to the stretching of the flume. Eidinger suggests that the failure of the top of the wood flume to the east of the fault might have resulted in a "pull away" from the connection at its northern end (point B).

- Hall initially speculated that if the flume near the dam crest might have been located over an undocumented right step-over within an active fault trace, which might have caused the ground beneath the flume to stretch and settle within the right-lateral fault slip environment. Schussler did not sketch such a feature in the fault zone nor did Lawson (1908) discuss the 4-foot-wide ground offset and its possible cause(s). Hall notes that this type of feature was also not recognized in the Franciscan mélange exposed in trenches at the dam site (ESA, 1980), which is millions of years old and not especially prone to settlement along the zone of active faulting. In fact, periodic fault slip/shearing has probably caused the mélange exposed here to expand and squeeze upwards, a process that created the fault-parallel ridge within the fault zone that Schussler incorporated into the dam between Structures 1 and 2 (depicted in Figure 4.1.11.1).

- We do, however, agree that the gap in the flume might have been, at least partially, the result of right-lateral fault slip if there were an active strand (secondary fault zone) that trended more easterly than the flume itself and passed beneath it. It is likely that some fraction of the total San Andreas right slip in 1906 might therefore have placed the flume in tension and been responsible for at least part of the observed gap. This same geometry of intersection was also observed at Sites 8 and 9 where an active subsidiary fault trace within the fault zone crossed the Pilarcitos pipeline on a more westerly trend than the main fault. The intersection at Site 8 apparently did not include the entire width of the active slip zone because the pull-apart there was much smaller than the well documented pull-apart further south at Site 9 where the Pilarcitos pipeline and nearby Fence "C" crossed the main trace.

- In retrospect, we are firm with the conclusion that the available evidence of the the Stone Creek/Locks Creek flume at the dam crossing is an imperfect strain gauge for recording total San Andreas fault slip in 1906. Here only part of this water delivery system crossed the fault. We conclude that the 4-foot-long gap extension of the collapsed flume recorded by Schussler at Point B might have been due to either strong ground shaking or some dispersed secondary right-lateral fault slip from the 1906 quake, or combination of both.

Future Stability of San Andreas Dam: Derleth's parting thoughts in 1906 regarding the "health" of San Andreas Dam are worth repeating: *"The earth dam at San Andreas appears to fulfill its functions as well as ever, although it is directly on the line of the main fault, and has been greatly scarred"* (Schussler, 1906, p. 42). This assessment was confirmed in the late 1970s with in-depth investigations of the both the dam itself and a modern understanding (i.e., the plate tectonic paradigm) of its tectonic environment. This stability study and safety analysis was required of the San Francisco Public Utilities

Commission (SFPUC), current owner of the dam, by the California Division of Safety of Dams (DSOD) and was performed by Earth Sciences Associates of Palo Alto (ESA 1980, 1982).

See Hall (1984) for a summary of the geologic and seismic-tectonic findings developed more than 40 years ago as they related to the stability and potential longevity of this dam. These investigations involved geotechnical sampling and lab testing, geologic mapping, and analysis of displaced (offset) stream channels that crossed the fault. Measuring the radiocarbon age of sag pond sediments deposited along the fault established that, for at least the past 3,000+ years, the active trace of the San Andreas fault has not changed its location. This means that the next inevitable slip event on the San Andreas fault is very unlikely to change location and cut across either of the man-made earthen embankments of San Andreas Dam. As it has many times in the recent geologic past, future right slip will very probably again pass through the highly sheared and squeezed-up ridge of Franciscan mélange between the two embankments and will, as in 1906, be unlikely to compromise the stability of the dam.

4.1.12 Site 12. San Andreas Dam Wastewater Tunnel and Locks Creek Flume near San Andreas Dam

Notes to Reader: Site 11 describes the failure of the Locks Creek flume just south of San Andreas Dam. Site 12 describes the failure of the Locks Creek flume about 1,400 feet south of San Andreas dam. Section 4.6 describes other failures of flumes elsewhere in the SVWC system. The Locks Creek flume was so-named around 1870 upon its initial construction; between 1870 and 1906, portions of the Locks Creek flume were rerouted and the portion from Stone Dam was sometimes referred to as the Sone Dam flume.

Wastewater Tunnel and Exit Flume

About 300 feet downstream from where it crosses the crest of the dam, the main trace of the San Andreas fault intersected the SVWC's brick-lined waste water tunnel. The function of the tunnel was to drain, when necessary, San Andreas Reservoir water into the stream (San Andreas Creek, aka San Mateo Creek) below the dam. This tunnel was constructed in 1868-70, as part of Schussler's original construction of the dam.

At this fault crossing, right slip in 1906 created some of the most dramatic damage to San Francisco's water supply system in the San Mateo County area. Figure 4.1.11-2 in Site 11 provides an overview of the waste water system from its inlet on San Andreas Reservoir, the fault/brick-lined tunnel crossing and the wooden flume that drained the tunnel into the stream below the dam. Also shown on this map is the northern end of the Locks Creek flume where it discharged into the San Andreas reservoir; see Section 4.1.11 for a description of a section of that flume where it collapsed just below the dam.

In Figure 4.1.12-1, the primary fault trace follows points A_1-A-B-C-C_1, and the brick wastewater tunnel and exit wood flume traverse the fault, roughly from points B_1 (left side of photo) to B_{11} (right side of photo). The photo is taken from near the top the San Andreas dam, just west of the Locks Creek flume, and looking southeasterly. The transition from the brick tunnel to a downstream wooden flume was located a few feet (~15-20 feet) to the west of the fault crossing. The wooden flume is quite visible near point $B_{11.}$ Point C_1 near the top of the photo marks where the San Andreas fault continues along the east side of the fault valley and passes into Lower Crystal Springs Reservoir.

Figure 4.1.12-1. San Andreas Fault Track through A_1 – A – B – C – C_1). Dotted line B_1 – B_{11} is the alignment of the buried wastewater tunnel outlet. Looking Southeasterly (Credit: Schussler HS31)

In Figure 4.1.12-2, the Brick Wastewater Tunnel and Exit Wood Flume traverse the fault (green dotted line). Point "A" in Figure 4.1.12-2 corresponds to point "A" in Figure 4.1.12-1. The fault rupture path is indicated by the yellow dashed line, The photo is taken from the downstream face of the dam, west of the Locks Creek flume, and looking southeasterly. This photo shows that the trace of the main fault here was marked by fault-parallel open cracks and not by the north trending, left-stepping en echelon cracks typically seen elsewhere along the fault in this area. It is possible that strong earthquake shaking might have caused the ground here to “feel” the fault and spread towards the free face of the nearby stream channel to the west

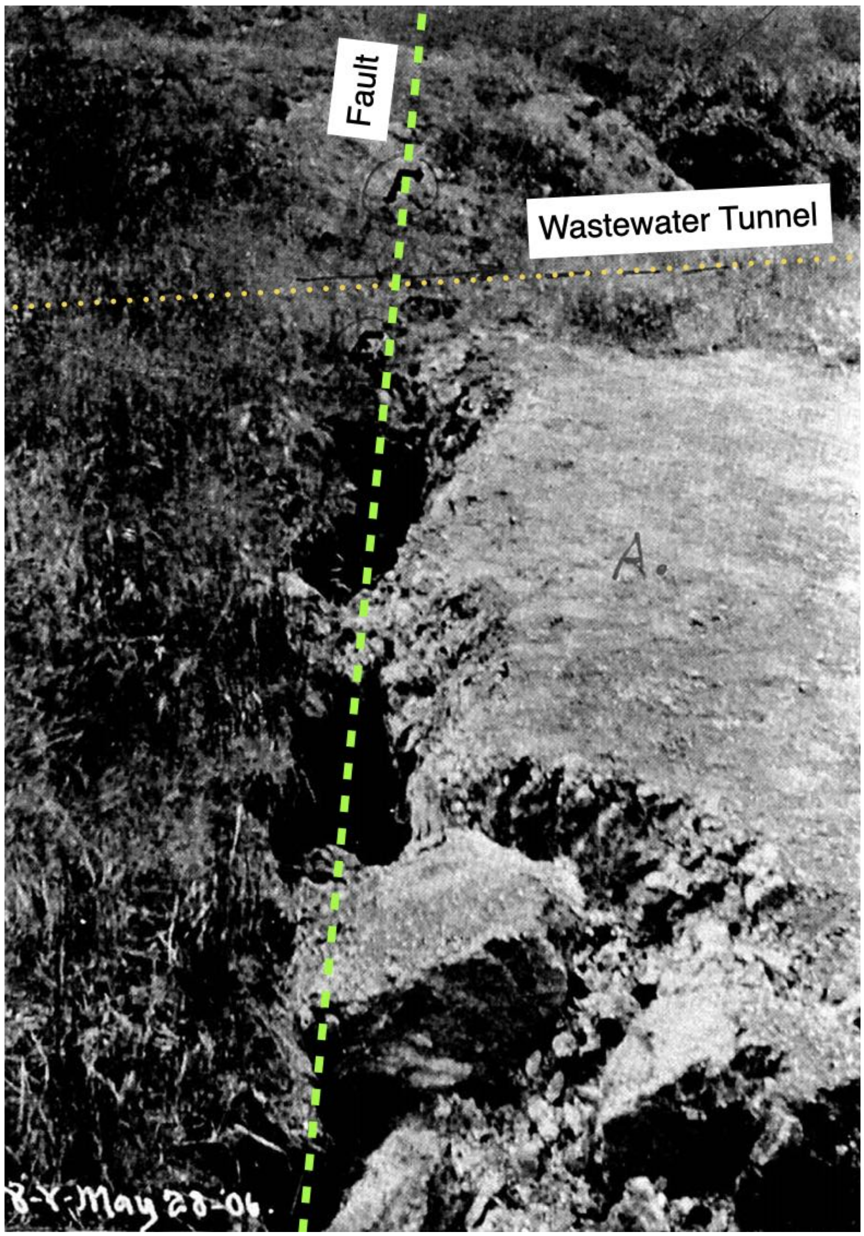


Figure 4.1.12-2. Closeup of San Andreas Fault Trace Looking Southeasterly (Credit: Schussler 1906 HS 29)

Wastewater Tunnel

As shown in Figure 4.1.11-2, the intake for this tunnel was a gate house located on the east edge of the San Andreas reservoir about 420 feet due north of the fault/dam crest crossing. This was a brick-lined tunnel. The function of the tunnel was to drain, when necessary, the San Andreas reservoir into the stream (San Andreas Creek) that continued and drained to the southwest towards San Mateo Creek. This tunnel was constructed in 1868-70, as part of the original construction of the dam.

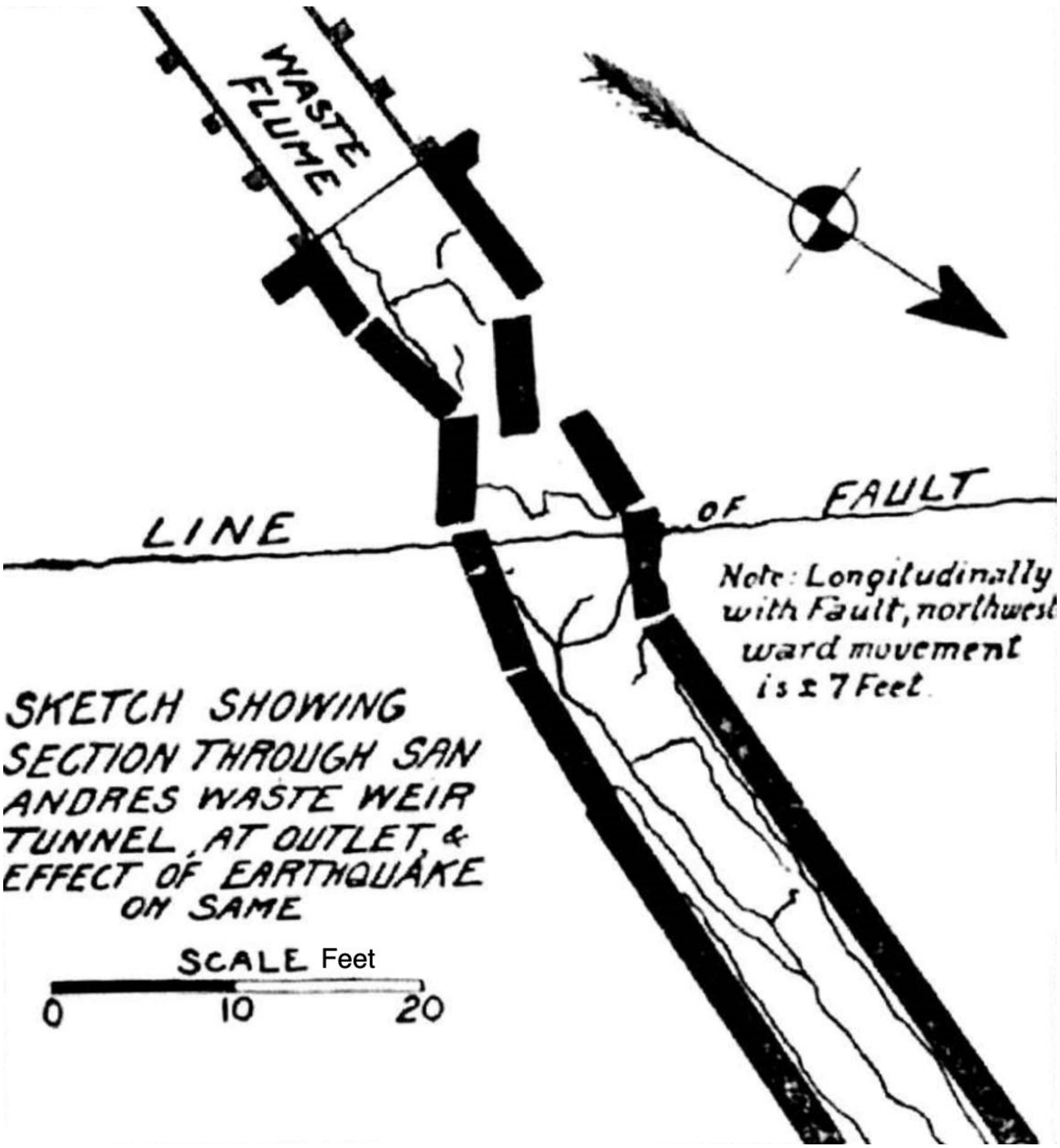


Figure 4.1.12-3. Line of Fault Through Wastewater Tunnel (Sketch: Schussler)

The tunnel crosses the fault at a ~45° angle to the strike of the fault, an orientation that placed the tunnel in compression. 15 to 20 feet to the south of the fault crossing, the brick tunnel ended and was continued as a covered exit wooden flume that was built with 12" x 12" timbers and whose purpose was to complete delivery of reservoir water to the creek below the dam.

The main tunnel was several feet wide, and built with four layers of cement and brick both of good quality. When the fault slipped, cracking occurred equally across both brick and mortar, i.e., the bricks did not pull away from the mortar, see Figure 4.1.12-4. Lawson (1908, p. 100) reported that the tunnel was "*stove in and smashed in pieces for a distance of about 28 feet*" and was offset about 5 feet. Schussler also made a map of the tunnel cracks and estimated that right slip across the fault here was ~7 feet (see Figure 4.1.12-3). Schussler also photographed the brick tunnel and the wooded flume:

- Figure 4.1.12-4. Shows damaged wastewater brick tunnel.

- Figure 4.1.12-5. Shows damaged wastewater brick tunnel.

- Figure 4.1.12-6. Shows the interior of the damaged wastewater wood flume, looking southwesterly.

- Figure 4.1.12-7. Shows the interior of the damaged exit wastewater wood flume, looking northeasterly. Note the separation of the horizontal wood 12x12s from the vertical 12x12s, which had been connected with ~0.5" diameter steel dowels ("dogs" using Schussler's description).

- Figure 4.1.12-8. Shows the exterior of the damaged wastewater exit wood flume, looking northeasterly. In the distance is the elevated Stone Dam Flume, which, when delivering water to San Andreas Reservoir, would have flowed right to left (northerly) in this photo. Just to the left of Figure 4.1.12-8, the flume collapsed (see Figures 4.1.11-2, -3). Letters "C-C" indicate the transition from wood flume to brick tunnel. The hill to the right of right-side "C" in this photo is the striped bedrock knob seen to the right of point "B" in Figure 4.1.12-1.

Figures 4.1.12-6, -7 show many ~1x8 (possibly ~2x10) lumber planks resting on the floor of the tunnel. The evidence suggests that these planks were lightly nailed to the interior of the 12x12s to form a fairly smooth interior surface for when the tunnel was flooded. More than 90 percent of these nailed connections failed, allowing this lumber to fall to the floor (a few connections staying intact, with a couple of planks now diagonally resting in the damaged flume).

We estimate that the zone of tilted columns and beams in the exist flume was at least 20-feet-long downstream of the tunnel-flume junction.

The strength of these connections using a steel spike bent into a drilled dowel hole is much lower than the native strength of the lumber itself. The single shear strength of a 0.5" mild steel dowel might be about 4 kips (0.20 sq. in. x 20 ksi in single shear). The shear strength of a rough-sawn 12x12" Oregon pine might be about 10 to 14 kips (70 to 100 psi * 144 square inches). The dislocation of the steel dowel of about 3 inches (top right in this photo) suggests that the dowel was simply bent into the lumber, and not continuous through the lumber.

The question arises as to the nature of the seismic forces that led to damage to the buried wooden flume. Two hypotheses are suggested:

- Hypothesis 1. Primary offset traversed nearby through the brick tunnel. The distortion of the brick tunnel may have imposed high forces onto the wood structure, leading to its demise. This is suggested by the rupture of the first horizontal 12x12 beam nearest the brick tunnel as seen in Figure 4.1.12-6..

- Hypothesis 2. There was high active soil loading onto the exterior lumber walls. These high lateral loads could not be balanced by passive resistance on the other side of the lumber structure, owing to the very weak bending moment capacity through the 12x12 columns to 12x12 beam "dog" / "doweled" connections.

We think the Hypothesis 1 is the primary failure mode. This reflects that the vertical 12x12s on the south side of the wood flume are tilted about 20° to the south, being there pushed by the façade of the damaged heavy thick-walled brick tunnel. However, Hypothesis 2, being the lack of good connections in the lumber, would also have allowed racking of the structure due to the inability of the structure to transfer the active loading to be resisted by the passive soil resistance on the other side of the lumber structure. Overall, whichever hypothesis has the more weight, the bottom line is that both the brick-lined tunnel and the wood flume failed grossly; had there been necessity of draining the reservoir quickly, this outlet system, having been seriously compromised, would have allowed considerably lower flow rates than originally intended.

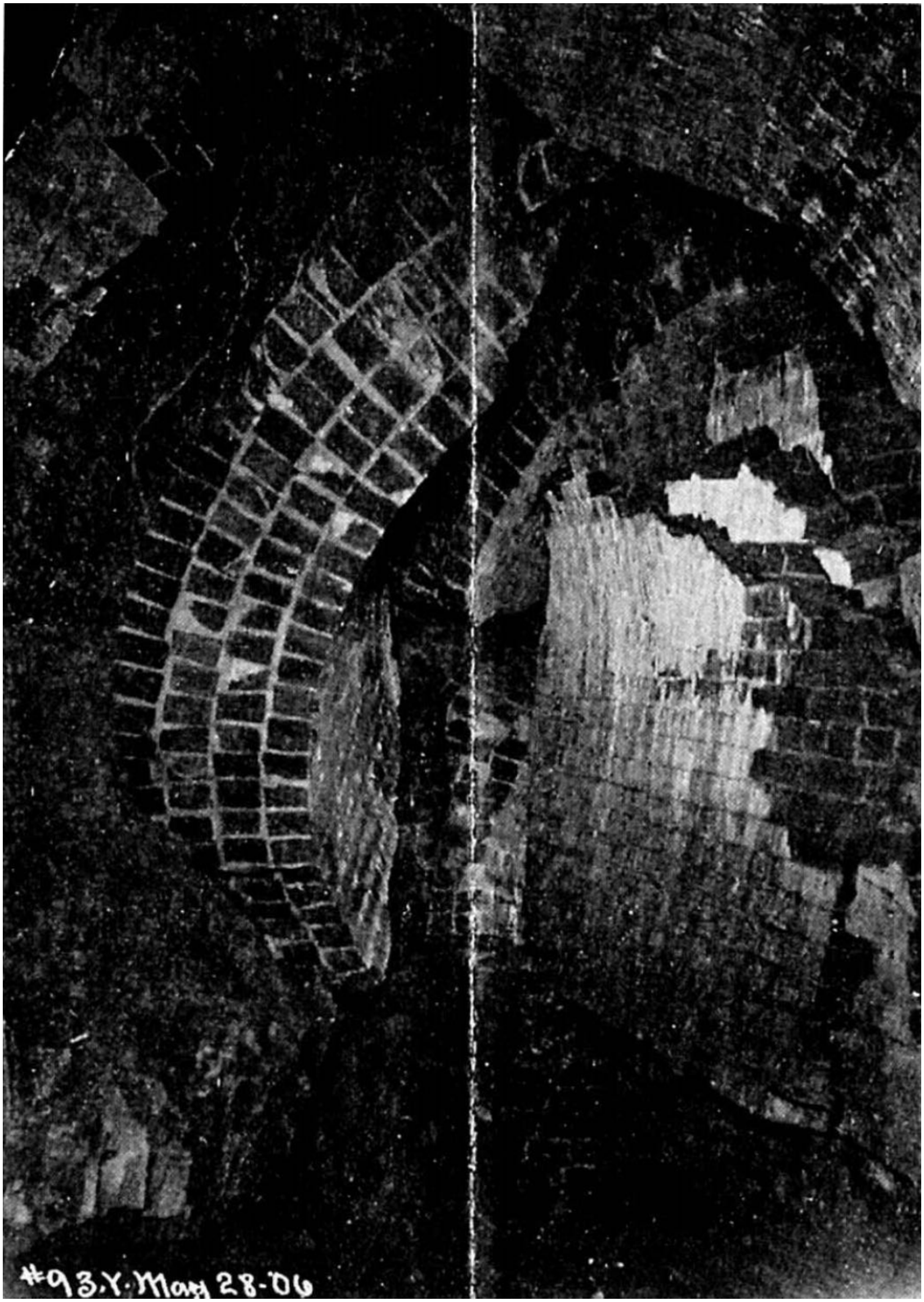


Figure 4.1.12-4. Wastewater Tunnel looking northerly (photo: Schussler HS33)

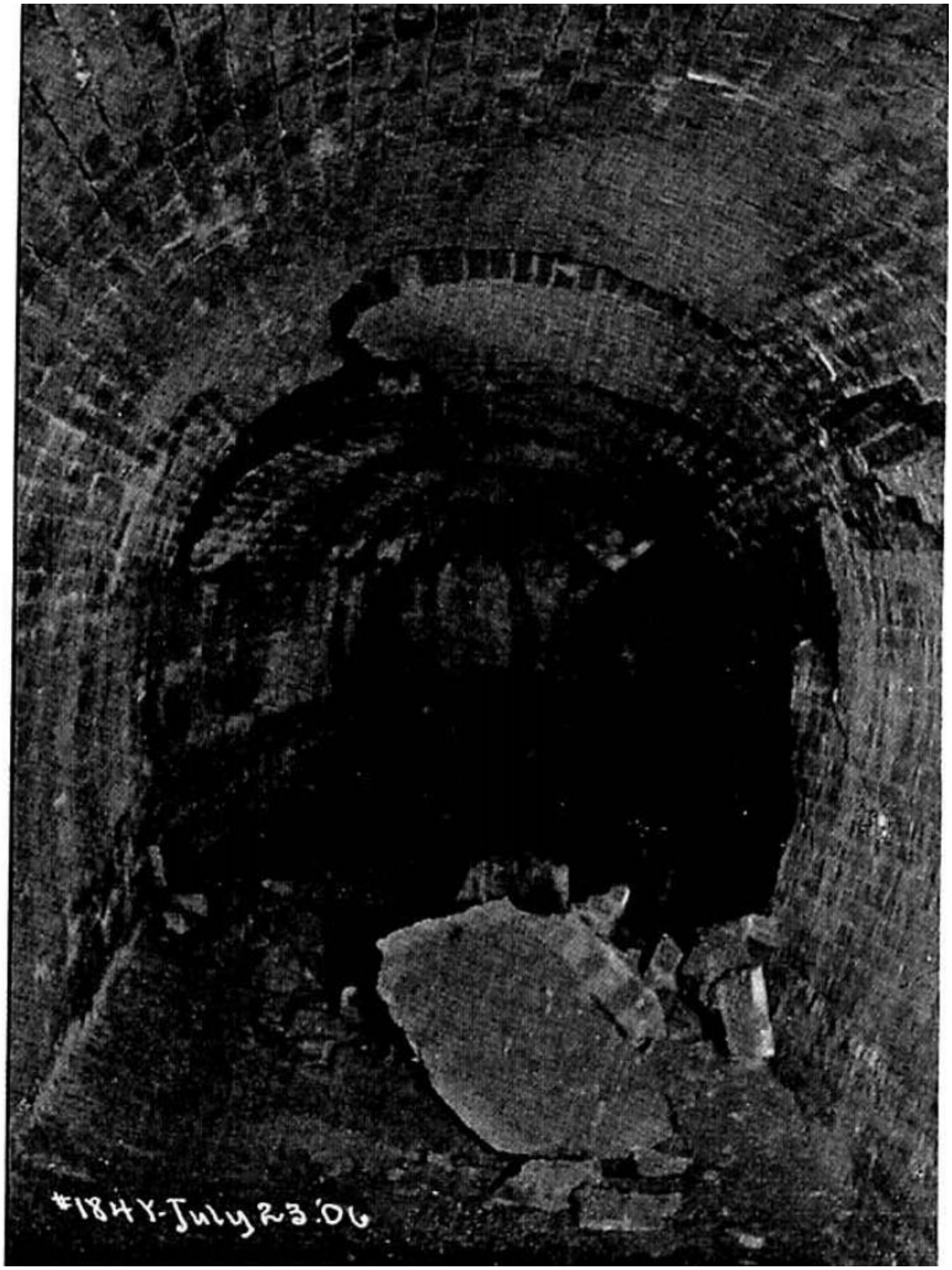


Figure 4.1.12-5. Wastewater Tunnel looking southerly (photo: Schussler 1906)

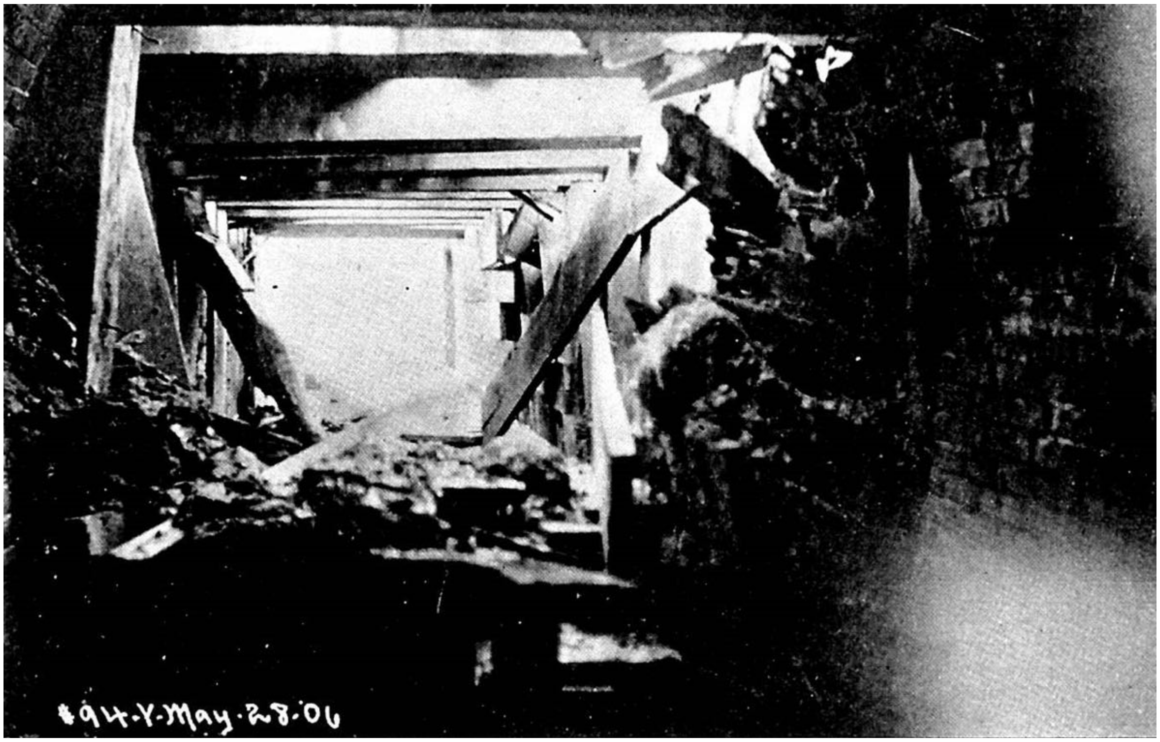


Figure 4.1.12-6. Interior of Wastewater Flume, Looking Southwesterly (photo: Schussler H34)

Figure 4.1.12-7. Interior of Wastewater Flume, Looking Northeasterly (photo: Schussler HS35)

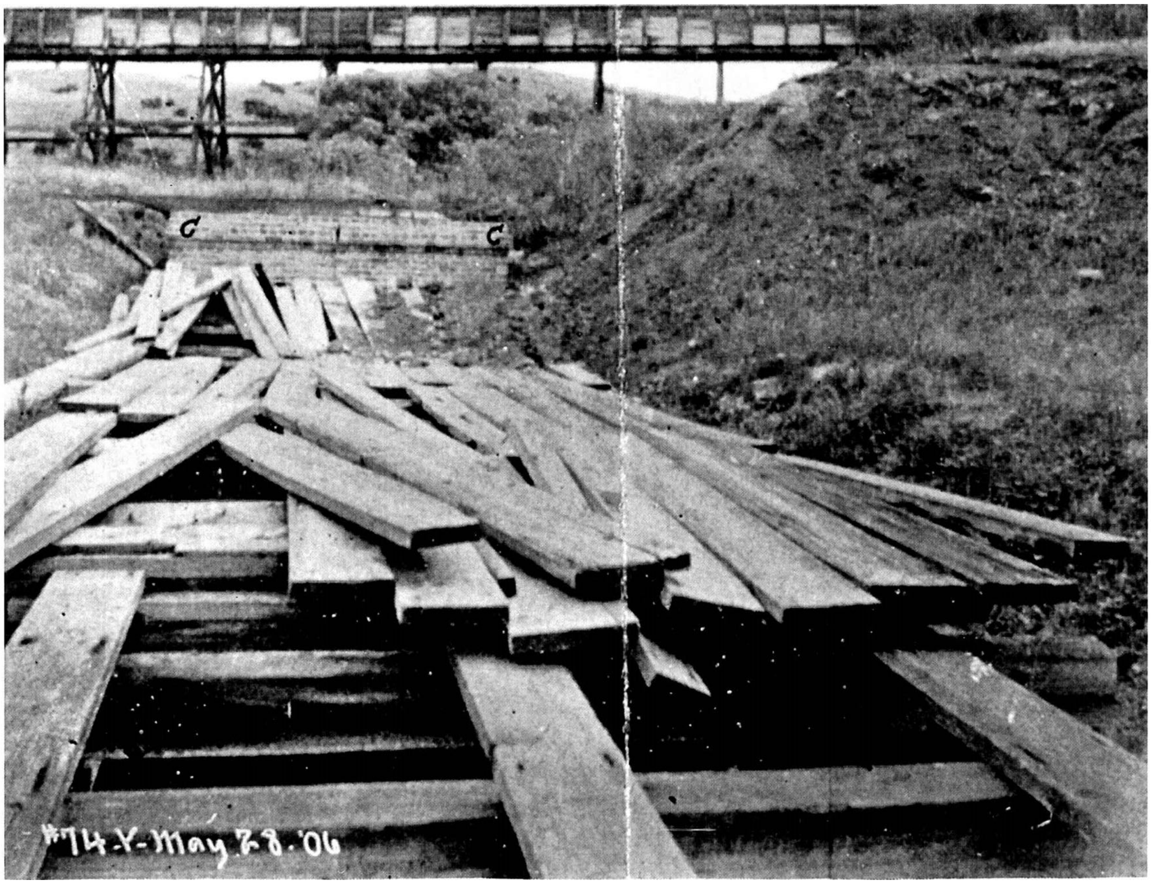


Figure 4.1.12-8. Damaged Exterior of Wastewater Exit Flume, Looking Northeasterly. Undamaged Portion of Elevated Stone Dam Flume in Distance (photo: Schussler HS52)

In the early 1980s, Earl Pampeyan of the USGS also entered the repaired wastewater tunnel (Site 12), like he did the Bald Hill Tunnel (Site 10), and measured it carefully (Pampeyan, 1983, Figure 2). He reported that the trend of the fault through the tunnel is N35ºW, longitudinal cracks patched with mortar extended 100 feet from the fault crossing. Pampeyan reported that and that the 8.25 feet of measured displacement of the tunnel was the result of 9.57 feet of right slip in the plane of the fault in 1906. These measurements are about a third higher than the ~7 feet of right lateral displacement at the crest of the dam near this location reported by Schussler in 1906. The difference in these measurements could be attributed to:

- Less offset in the Franciscan mélange at the crest of the dam
- More displacement in the softer materials likely surrounding the brick tunnel
- A difference in the baseline measurements. It is likely that Schussler's 1906 measurement was ~7 feet in the primary fault offset zone, whereas the Pampeyan 1980s measurement was over a wide zone, including both primary offset and secondary offset.

Locks Creek Flume

Wood flumes were very common in California in the 1850 – 1890 time frame. Several thousand mile of them were constructed in the Sierra Nevada mountains, to bring water to various mines for hydraulic mining.

While no standard design was used, Figures 4.1.12-9 and -10 show two common situations: one for the case when the flume is going over relatively flat land, and the other, where the flume was elevated. In Figures 4.1.12-9, and -10, the vertical 4x6 bents are spaced at 4 feet. In Figure 4.1.12-10, the trestle supports are typically spaced at 14 feet, and the 6x8 stringers rest atop the 6x8 cap.

The reader will note that the collapsed flume segments in Figures 4.1.12-12, -13 have 7 boards atop the flume; whereas the details below provide show 5 or 6. These are the best drawings presently available from the 1906 era, and it would seem that there were many field variations from the drawings.

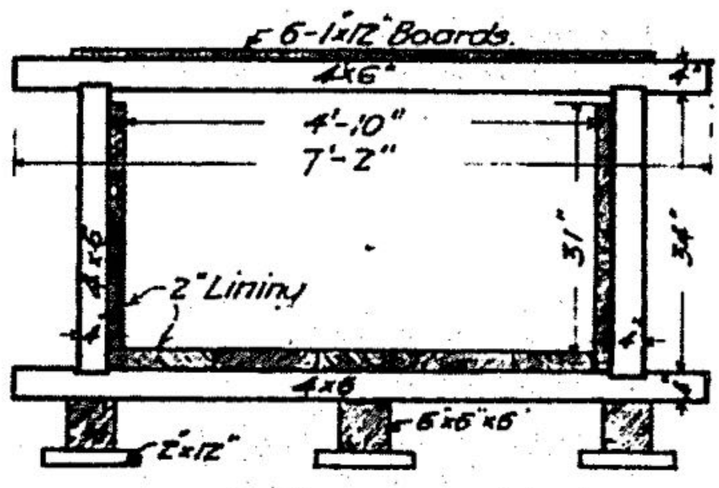


Figure 4.1.12-9. Cross Section of Typical At-Grade 5'x3' Flume (Pilarcitos Side Flume)

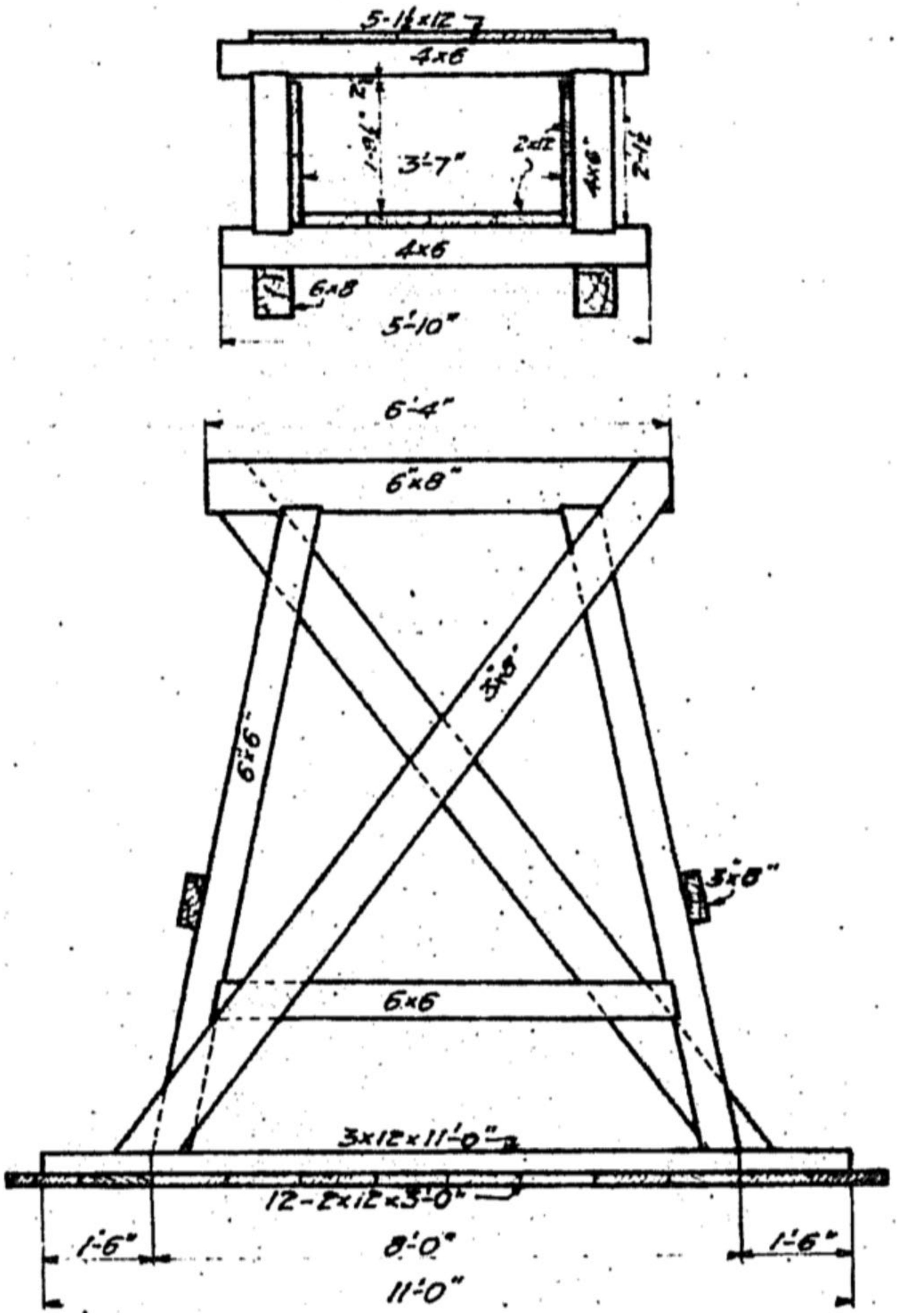


Figure 4.1.12-10. Cross Section of Typical Elevated Trestle for 4'x2' Flume

Figure 4.1.12-8 shows the elevated trestle of Locks Creek flume crossing over the wastewater tunnel on its way to the 44 inch-pipeline at the crest of the dam (see Figures 4.1.11-2 and -3 for overall map). Near the dam, the topography is such that the elevated trestle reverts to a low-height wooden flume.

Figures 4.1.12-11, -12, -13 show about 250 feet of the Locks Creek flume that was wrecked, between points "A" and "B" in these photos. The location of the failure is about 600 feet east of the main San Andreas fault offset, and about 1,400 feet south of the San Andreas dam. The cross section of the flume at this location was 6 feet wide by 4 feet high. The elevated flume was sound between points B and C. In the distance in Figures 4.1.12-11 and -12 at point D is the northern end of Lower Crystal Springs Reservoir.

Figure 4.1.12-11. Failure of Stone Dam Flume, Looking Southerly (Photo: Schussler 1906 HS50)

Figures 4.1.12-12, -13 show that this section of the flume has collapsed towards the west. The main fault does not approach this segment of flume. One question arises: was there an eastern secondary trace of the San Andreas fault that might have displaced perhaps a few inches, that led to collapse shown in Figures 4.1.12-11, -12, -13? We suspect not.

Figure 4.1.12-12. Failure of Stone Dam Flume, Looking Southerly (Photo: Schussler 1906 HS49)

Figure 4.1.12-13. Failure of Stone Dam Flume, Looking Northerly (Photo: Schussler 1906 HS51)

The possible underlying loading that lead to the observed failures of the two flume sections (Site 11 and Site 12) is described below:

- The flumes at these locations did not cross the primary active fault offset.

- The flume at the 80-foot long collapse location "may" have crossed an eastern secondary zone of minor fault offset.

- There are no clearly observed landslides in these locations (Figures 4.1.12-11, -12, -13, also Figures 4.6-3, -4).

- The flume failures did not extend indefinitely: the bulk of the length of the flumes remained standing. The style of construction was similar along the entire length, and the height of water would have been the similar along the length.

- Could high inertial loading have contributed to the observed failures?. The photos suggest that the 4x6 vertical bents rotated and that led to the collapses. This type of failure mode is consistent with a large sideways inertial loading (weight of water plus lumber, acting sideways). The toe nailing and small dado joints would have been sufficient to resist opposing hydrostatic water forces, but under seismic loading, all forces can be to one side, and these joints were not strong enough to resist the applied moments.

- In the trestles, the 6x6 to 6x8 joints were supplemented by "dogs". A "dog" (using Schussler's parlance) was either a ½" or ¾" steel rod, drilled and pressed into adjoining pieces of lumber.

- Empty, the weight of one 14-foot-long span of trestle-supported empty elevated flume might have been on the order of 14 kips, and with PGA ~0.7g at this location, and a fundamental frequency on the order of 3-5 Hz, the inertial loads would have been about 28+/- kips in either horizontal direction, coupled with a strong vertical component. If full of water, the weight of water per 14-foot span might about been 62.4 pounds per cubic foot x 15 square feet x 14 feet ~ 13 kips (1 kip = 1,000 pounds). Considering the cross section flow area of the flume, the bulk of the water (say lower two-thirds) would tend to move almost completely with the flume, with the top portion sloshing up and out of the top of the flume (or breaking the top boards that tended to be lightly (if at all) nailed to cross members.

- The strength of the wood connections would have assuredly been enough for high wind loads. At the time of construction of these flumes, they were likely designed for 30 psf sideways wind pressure, plus gravity loads. The wind load per 4-foot span would have been 30 psf x 4 x 4 = 0.5 kips; over a 14-foot span, about 1.7 kips.

- The construction of the flume suggests a lumber weight about 3.7 kips per 4 foot length. If nearly full of water with an internal 3x5 foot water flow cross section, the weight of water would be about 3x5 feet x 62.4 pounds per cubic foot x 4 feet = 3.7 kips per 4 foot span. Thus, at 3 to 5 Hz fundamental frequency, seismic lateral load would be about 0.7g x 2.5 x (3.7 + 2.5) kips = 11 kips per 4 foot span (presumes 2 feet of water moves with the trestle). The bending moment applied to the 4x6 connections would be about 11 kips x 1.5 feet = 16 kip-feet. These connections would have been designed for wind load (under 1 kip-feet) or hydrostatic load (about 1.4 kip-feet). Thus, the seismic load would greatly overload the 4x6 connections. Connection failure would be expected when applied seismic loads are high and the water level is high.

- Whether full (certain outright collapse) or empty (yielding / failure of connections) we cannot be now sure, as we do not now know the water level in the flumes at the time of the earthquake. Given the time of year (mid-April), we can surmise the flume likely had some water in it at the time of the earthquake. The lack of outright collapse of other segments of the flume does not mean that the joints were undamaged; and upon refilling the flume after the earthquake, they might have had some leaks (easily repairable).

- Consider all the SVWC trestles and flumes exposed to shaking in the earthquake:

    - There were no flume failures along the Sunol Aqueduct (PGA ~0.05g to 0.15g) or along the northern Pilarcitos Conduit near Lake Honda (PGA ~0.3g±).

    - There were many wood trestle failures (about 1,600 feet of 4,000 feet) along the Crystal Springs pipeline, in areas with long period amplified soil motions. These were likely aggravated by the lateral thrust of the unrestrained 44-inch water-filled pipeline atop the trestle, and the "stacked" shims under that section of trestle.

    - There were sporadic flume failures in the Peninsula area (Figure 4.6-1, PGA ~0.5g to 1.0g) due to inertial loads. Perhaps 500± feet failed due to inertial loading / secondary offset and another 150 feet or so due to landslide; but more than 90% of these flumes survived without major damage. Flumes 5, 6, 8 were likely carrying some level of water flows at the time of the earthquake; Flume 7 was likely empty. Flume 7, being empty, did not fail. Had they been full (such as at times of flood and large stream discharges), there would likely have been more flume failures.

    - The collapse of the ~80-foot long segment of flume just south of the San Andreas dam (described with Site 11) was most likely due to the combination of high inertial forces coupled with some amount of primary (less likely) or secondary fault (more likely) offset. Hall and Eidinger do not have direct evidence of secondary fault offset at this location. But, on a whole, we suspect that there was some type of offset at this location, and that triggered the collapse.

- The collapse of the ~250-foot long segment of flume about 1,400 feet south of the San Andreas dam (described in Site 12) was most likely due to of high inertial forces; possibly exacerbated by some type of downslope landslide movement. At this location, the primary trace of the San Andreas fault was 600 feet to the west of the flume. Hall and Eidinger do not have direct evidence of secondary fault offset at this location.

4.1.13 Site 13. Fence 3

Figure 4.1.13-1 shows an aerial view of Site 13, highlighted in the circle. At this location a fence (yellow dashed line) was offset by 10.4 feet in the 1906 earthquake. The site is about 1,750 feet downstream of the crest of the dam.

The fence-line was surveyed by R. B. Symington. C. E., in 1906, at azimuth S32°41'W. He described the offset as 10.4 feet; Symington's survey suggested that there was some warping (secondary offsets, drag) occurred on both sides of the fault that was included in this offset measurement. Lawson estimated that the total offset was over a zone width of about 250 feet as measured normal to the fault.

The surface fault rupture is azimuth at the fence offset location is drawn at N36°9'W based on the trace lines in Qfault (2018), but was listed as N33°40'W in the 1906-era survey. The exact location of the fence-fault offset is not known with precision; the fence no longer exists today (2024).

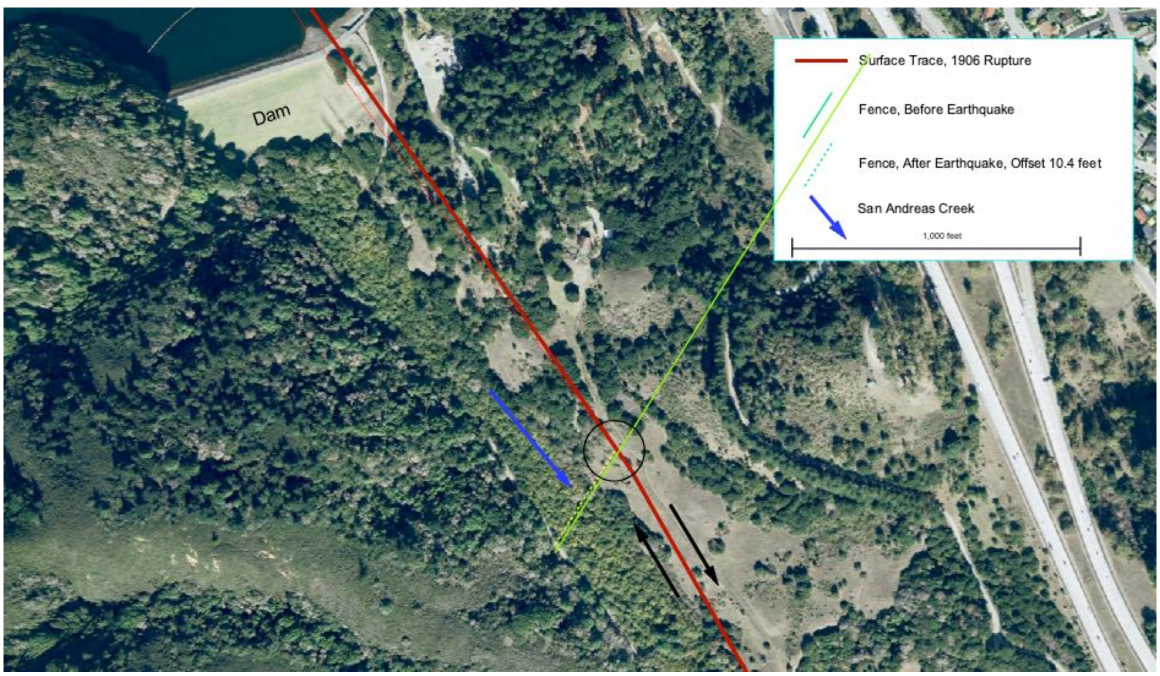


Figure 4.1.13-1. Site 13 (Aerial Photo: 2006, USGS)

Lawson (1908) calls this "Fence B". Schussler (1906) called this "Fence L". A survey by Bonilla et al (1978, p. 350) concluded that 8.9 feet of right slip occurred here in 1906.

Given this information, we list the total offset at this location as 10.4 feet. For modern pipe design at this location, assuming pipe function class II (see Table 3-4), if the pipe were normal (90°) to the fault, then we would design the pipe for a primary offset of 10.4 feet; or a primary offset of 8.9 feet (knife edge) plus 1.2 feet of offset anywhere within ±125 feet normal to the fault.

Perhaps ~1,600 feet southeast of Site 13 is a photo of the fault offset trace, Figure 4.1.13-2. This photo is believed to have been taken looking southeasterly. Schussler's 1906 report places this photo someplace between Sites 13 and 14. Based on a trench excavated at the base of this boulder, Hall suggests that this photo is in fact about 600 feet north of Site 14. At this boulder, Schussler describes the offset here as about 7 feet. In the middle of the photo is a short segment of riveted wrought iron pipe, resting on a tectonic "knocker" of Franciscan chert. It is uncertain if this is a 30" or 44" diameter WI pipe from the Pilarcitos pipe, or a 37.5" or 44" pipe from the Locks Creek pipe.

Figure 4.1.13-2. About ¼ miles southeast of Site 13, looking southeasterly (Credit: Schussler 1906). Believed to be within 600 feet± of Site 14, FX-5

Figure 4.1.13-3 shows the fault surface rupture trace looking south, from the vantage point of the rock seen in Figure 4.1.13-2. The cracks in the ground suggest some en echelon cracking, which reflects an overall right lateral offset pattern, coupled with some extension.

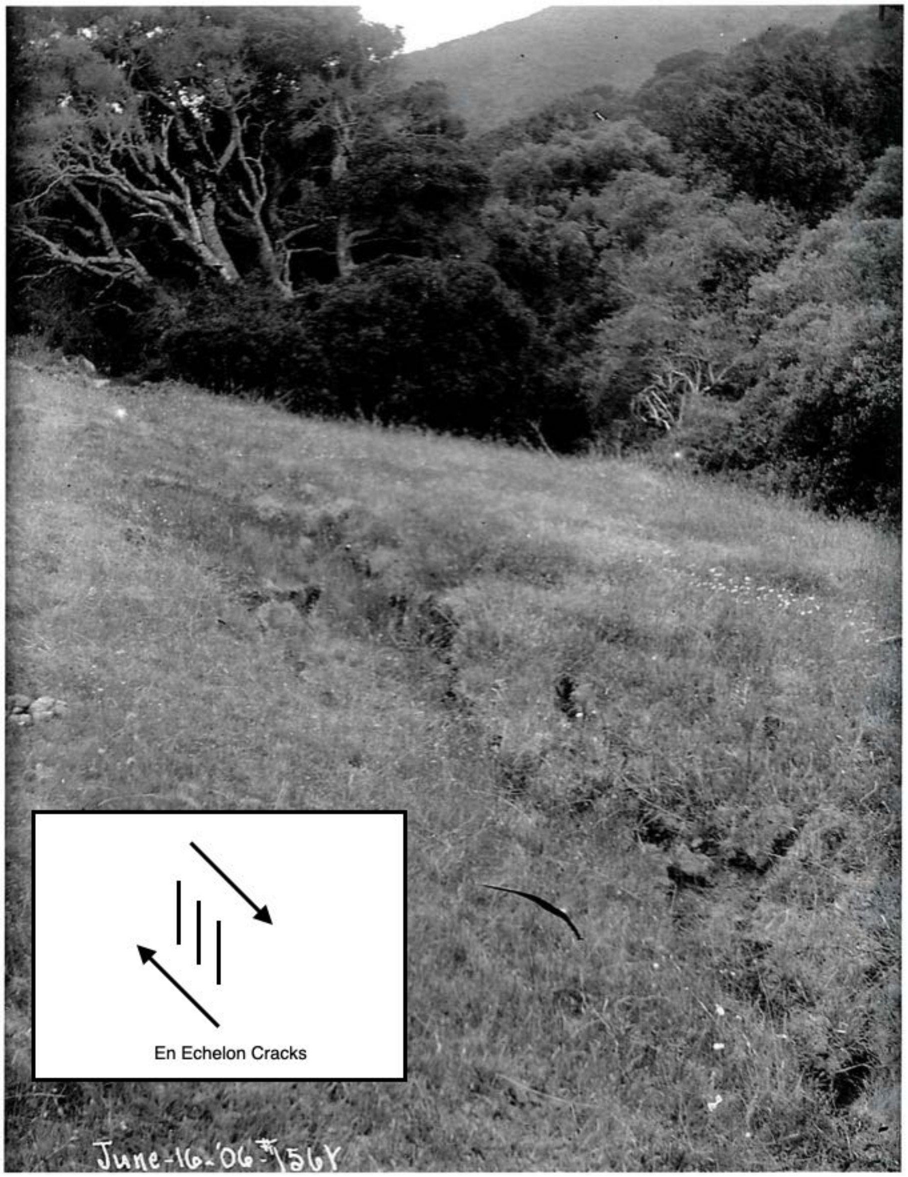


Figure 4.1.13-3. Some distance Southeast of Site 13, Looking Southeasterly. Photo taken from atop the rock in Figure 4.1.13-2. (Credit: Schussler 1906)

From this data we conclude that a minimum of about 9 feet of discrete right slip probably occurred here and was likely augmented by at least 1+ feet of warping.

The "tectonic knocker" seen Figure 4.1.13-2, is one of the common very hard rock type of marine origin found in Franciscan mélange; it demonstrates clearly that the fault, seeking to navigate the path of least resistance through the earth to reach the surface, will not necessarily be able to choose a straight path. Schussler's caption on this photo says the fault here slipped 7 feet, but does not tell us what sort of feature he found to measure this displacement. Another 0.1 mile southeast along the fault from this chert boulder is our well-located site 15, which where the San Andreas fault crossed Lawson's Fence "A". In any case, we believe that seven feet of right slip for Site 13 is likely a minimum value and indicates there might have been an unrecognized fault strand near the chert knocker or at least two or more feet of ground warping in this neighborhood that was not recognized or recorded.

4.1.14 Site 14. FX-5

Figure 4.1.14-1 shows that the Pilarcitos pipeline (blue line) diverged well east of the San Andreas Reservoir between fault crossings FX-4 and FX-5. Prior to the construction of the 30" WI pipe here, there was a prior flume version of the Pilarcitos conduit, also running east of the reservoir, but at a different elevation than the pipe. The alignment shown in this figure reflects a collage of available historic maps of where the pipe was actually located. We relied mostly on Scowden's 1875-vintage survey (Figure 2-24). Schussler's hand drawn map in his 1906 report suggests a rough location of the pipeline in this area. It can be assured that the invert of the pipe was always under 600 feet elevation through this zone; most of the hilly terrain east of the reservoir is between 450 feet (lake level) and 550 feet. Between its original construction in 1868 and 1906, there were a few blowouts of the pipe in this area; sometimes the pipe was repaired in place (adding external clamps), and sometimes the pipe was re-laid over a few hundred feet. Scowden's 1875 survey strongly infers that the pipe crossed the county road twice, and this is adopted in the blue line. Overall, the reader should understand that the precise location of the pipe in 1906 is and will remain uncertain.

About 3,000 feet south of the south end of San Andreas Reservoir, the Pilarcitos pipe crosses the fault. Figure 4.1.14-1 shows an aerial photo of San Andreas reservoir, with overlay of key items: the surface rupture of the San Andreas fault (red dashed line), the Bald Hill Tunnel (solid black line), the Pilarcitos pipeline (blue line, approximately located, see discussion above), and the locations of fault crossings FX-4 and FX-5. Not shown in this map is the location of the Pilarcitos force main between the Pilarcitos pump station (at the east end of Bald Hill Tunnel) and the Pilarcitos pipeline.

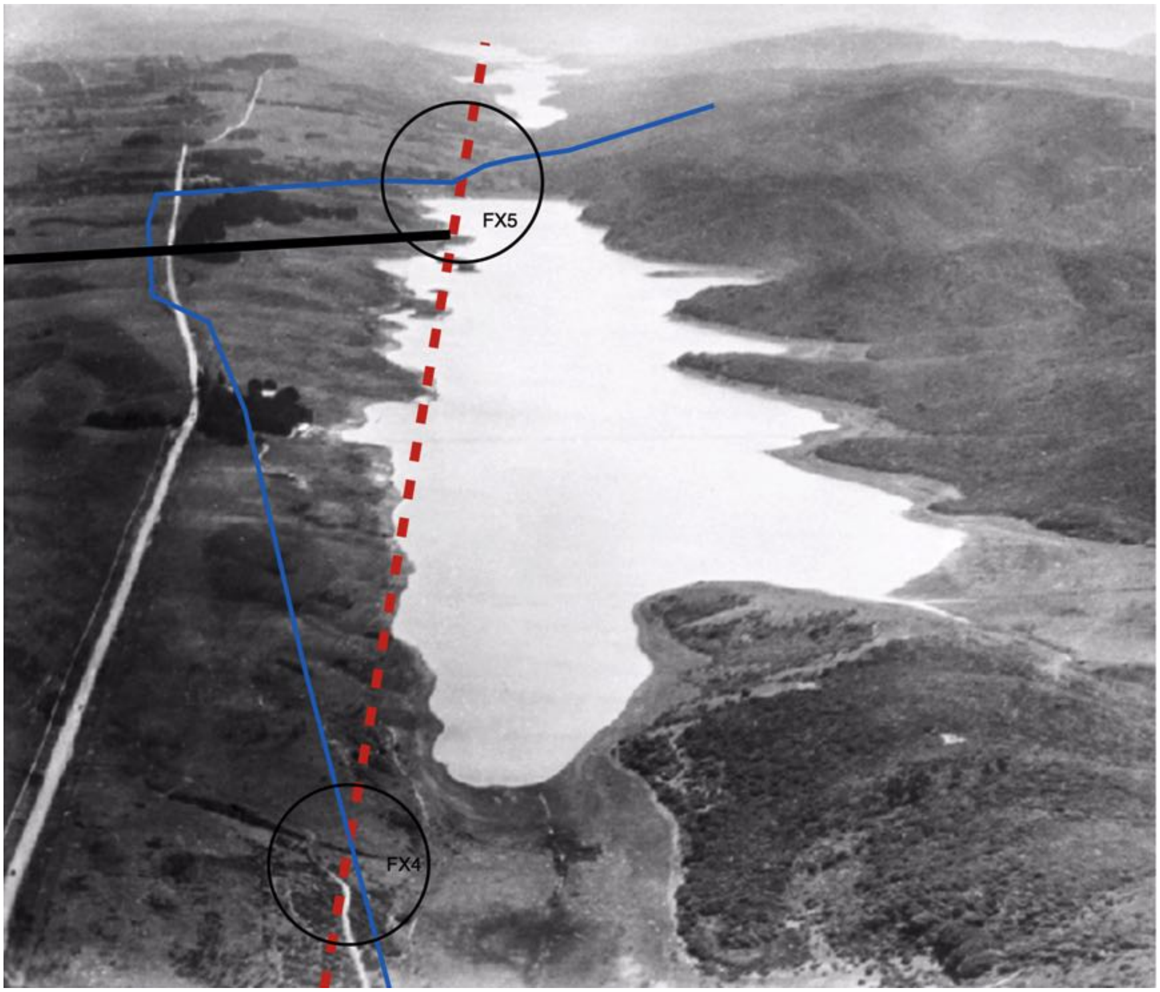


Figure 4.1.14-1. Pilarcitos Pipeline and San Andreas Reservoir, Looking southeasterly (Credit: Horace Chaffee, 1928). Crystal Springs r

Reservoir in background.

At FX-5, the pipe was on a 50-foot long wooden bridge, crossing San Andreas Creek. The pipe alignment azimuth was about N 25°E, making an angle of about 65° with the strike of the fault (90° = perpendicular to fault). Figure 4.1.14-2 shows the profile of the pipe near FX-5. The sense of the fault offset placed the pipe into net compression coupled with a lot of bending.

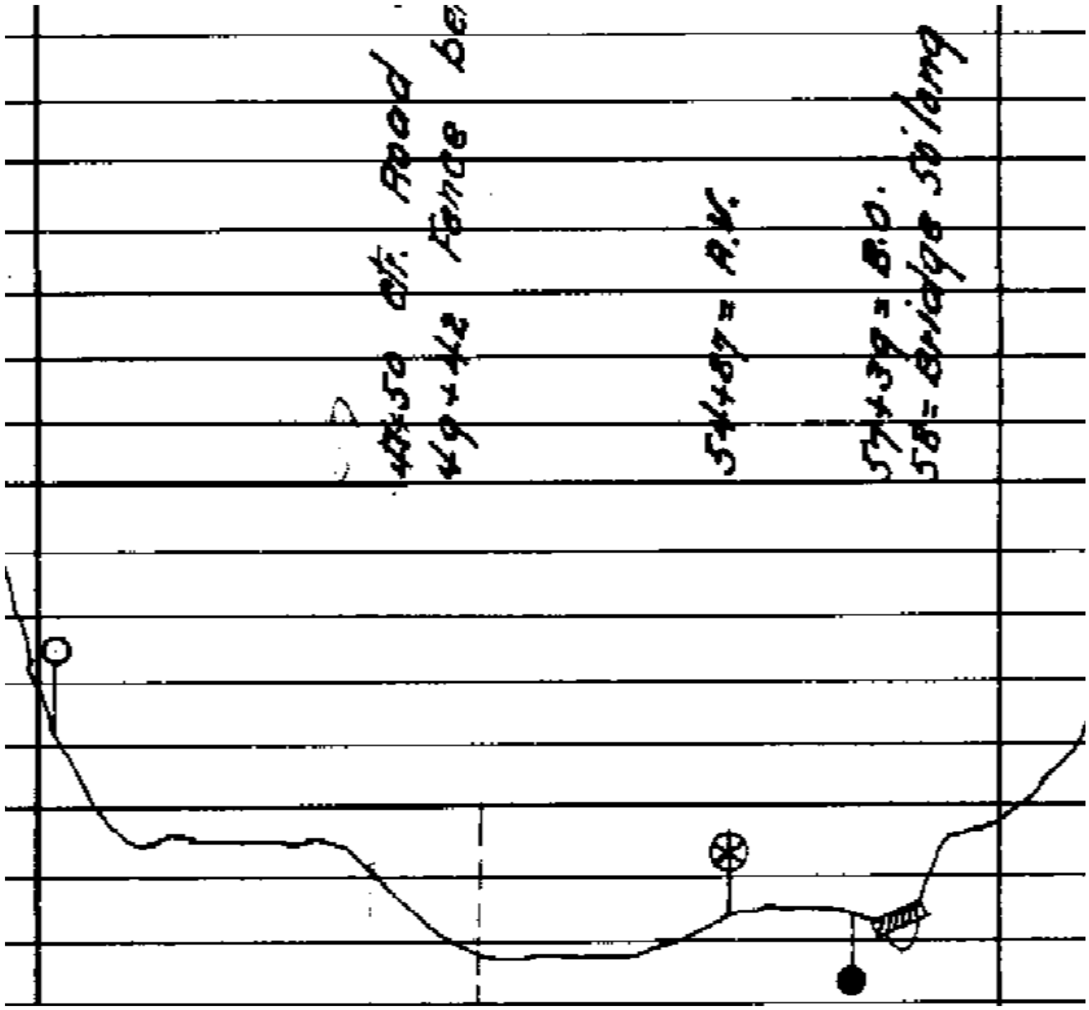


Figure 4.1.14-2. Pilarcitos Pipeline Profile at the San Andreas FX-5 Fault Crossing (left = west; right. = east). Source: SVWC drawings P189, P194).

On the bridge, the pipe was a 24" cast iron pipe with bell and spigot joints, and 1" thick wall. Figures 4.1.14-3, -4 show the damage of the pipe at FX-5. Note the clamp on the left pipe segment (Figure 4.1.14-3) (foreground in Figure 4.1.14-4) and a cable; presumably these were restrained joints for the bridge crossing; but these restrained joints were insufficient to accommodate anything resembling ductile response of the complete cast iron pipe when subjected to the right lateral offset. The collapse of the bridge in Figure 4.1.14-4 indicates that the cast iron pipe segment in the foreground must be similarly disconnected to the continuing cast iron pipe behind the photographer's location. Further, we have assumed that these photos were taken looking northerly or easterly (Figures 4.1.14-3, -4 respectively); but given the shadows, a case could be made that the photos were taken looking in the opposite directions.

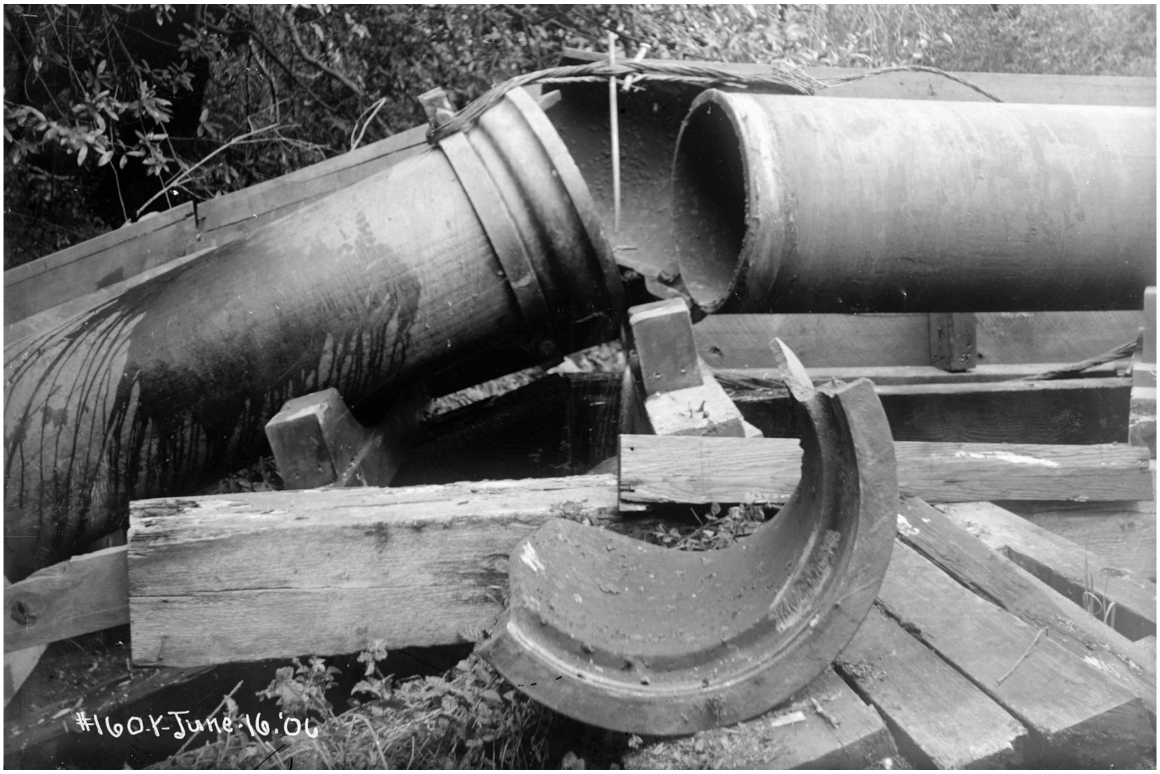


Figure 4.1.14-3. Crossing 5. 24" Pilarcitos Cast Iron Pipe. Elbow crushed. View looking north. (Photo: Schussler 1906 HS11)

Figure 4.1.14-4. FX-5. 24" Pilarcitos Cast Iron Pipe, Looking east. East end of fault crossing zone. The pipe in the distance has moved to the right (southerly) relative to the pipe in the crossing zone. This is the same location as 4.1.14-3, but looking easterly along the pipe alignment. (Photo: Schussler 1906 HS12)

Just east of the fault, the pipe takes an upward bend, as the pipe rises to the 600-foot high hills to the east of the San Andreas reservoir. The pipe broke at an upward bend, see Figure 4.1.14-5. Here, the pipe is 24" cast iron. The pipe has cracked in the main body a few inches away from the bell. An elbow at the bend was crushed by the compression and thrown down, while the two remaining ends were brought about 22 inches nearer together. At the same time they were faulted past each other a distance of 20 inches (Lawson 1908).

Figure 4.1.14-5. FX-5. 24" Pipe has telescoped ±1'. About 100' north of FX-5. (Credit: Schussler 1906 HS13)

Schussler (1906) estimated the primary fault offset at FX-5 to be about 7 feet.

Hall suggests that there might have been about 28" of right lateral slip at the location where the cast iron pipe telescoped (Figure 4.1.14-5). The question is open as to whether the damaged at Figure 4.1.14-5 is due to some type of local fault offset, or from forces transmitted through the pipe at the main FX-5 crossing to this location. Eidinger thinks the damage shown in Figure 4.1.14-5 is due to the high compressive forces imposed on the pipe, coupled with some local bending, which then cracked the cast iron body; this factors in that the observed pipe offsets at the wood trestle are insufficient to take up the full 7 feet of offset; but Hall's explanation could also be correct.

Today (2024), the pipe no longer exists. At no time during the post-earthquake repair effort was a careful survey done to map the final movements of the cast iron pipe and the wood trestle near FX-5. The undamaged cast iron pipe crossing the San Andreas Creek valley was uncovered and relocated for another purpose in San Francisco City distribution system, sometime later in 1906 to 1907.

In Table 3-2, the amount of fault offset for Site 14 is listed as 7.0 feet. This reflects the measurements / observations by Schussler (1906) and Reid (1910). If one attributes the damage in Figure 4.1.14-5 as due to a secondary trace of the fault that is not documented by Lawson (1908) or Reid (1910), then the total right lateral slip across the fault at FX-5 would be about 8.3 feet.

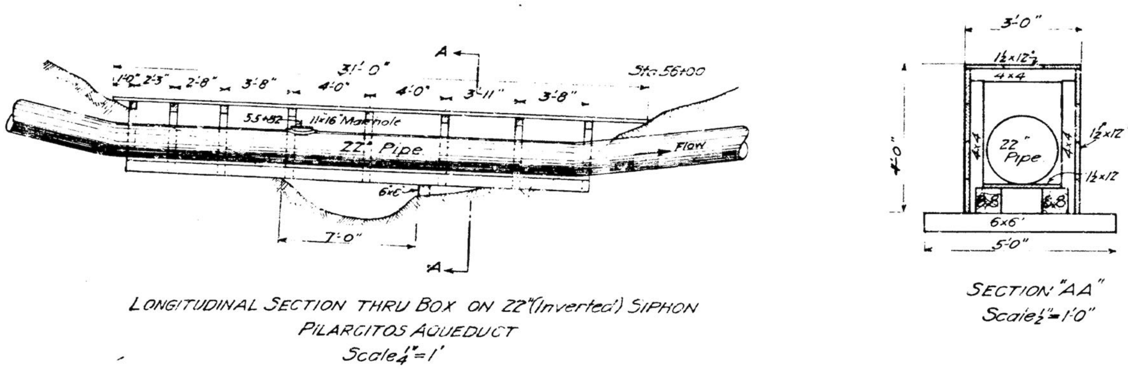


Figure 4.1.14-6. FX-5. 24" Pipe on Wood Bridge across creek (typical style of construction) (SVWC drawings)

Figure 4.1.14-6 shows the details of the wood bridge that supported the Pilarcitos pipe across San Andreas Creek. These details do not exactly match the observed damage in Figures 4.1.14-3, -4:

- The details are sufficient for an OD 22" pipe, with inside width of 36" – 4" – 4" – 1.5" – 1.5" = 25" (leaving 3" clear space); or possibly just enough for a 24" OD pipe (as long as the bell connections are not placed at the 4x4 posts); but not sufficient for a ID 24" pipe.

- Section AA shows the pipe supported by horizontal 1.5x12[18]. The damage pictures post-earthquake show the pipe was supported on ~6x6 saddles that have been shaped to match the OD of the lower ~120° of the pipe, and which in turn rest upon ~4x8 that span to the longitudinal 8x8.

- The width of the boxed section is 3 feet, just large enough to contain the pipe. But Figure 4.1.14-4 shows a large lateral offset of the pipe, on the order of ~3 feet. This strongly suggests that the primary offset went directly through the wooden bridge.

[18] Note to reader: all lumber sizes in this report are in inches. Most lumber was full dimension, meaning a 12x12 was actually 12" x 12".

- The explanation for these differences could be:

- The wood bridge (and possibly pipe) had been replaced sometime between 1868 and 1906 (1868 is the implied date of Figure 4.1.14-6, corresponding to original construction of the Pilarcitos pipeline). The new larger pipe (24") was installed to get somewhat higher flow rate through the pipeline.

- Using a 1.5 x 12 inch beam at 4 feet spacing to support a fully loaded 22" cast iron pipe is possible, but seems "light".

- The saddle + beam supports in Figure 4.1.14-6 match closely the design used for the 1898-built Alameda Pipeline across the San Francisco Bay margins. The cut saddle to match the pipe is a far better support than the point loading offered by a 1.5 x 12 beam.

- We conclude that the most likely reason for the mismatch between the drawings and the observed wood trestle system is that the drawing is outdated (from 1868). With the fire that burned SVWC headquarters in downtown San Francisco, many pre-1906 drawings and documents were lost. Although copies were also held at the Millbrae offices, and that is where Figure 4.1.14-6 was located, it is possible that not every document was held at Millbrae.

As a side note: the cast iron pipe at FX-5 is variously reported in Schussler (1906) and other SVWC documents from circa 1900-1910 as either 22" or 24" diameter. In this report, we adopt 24" diameter at the actual inside diameter of the cast iron pipe here.

The reader may wonder, as do the authors, why the pipe here is cast iron and not wrought iron. To the west of this location, Schussler used a 44" wrought iron pipe at the outlet of Tunnel 2; and to the east and south of this location, Schussler used a 30" wrought iron pipe. Here is the surmised reasoning:

- The 44" pipe was sized to carry the combined flow from Pilarcitos Reservoir via Tunnel 2 to both Lake Honda and to San Andreas Reservoir. Downstream of this split, the 30" diameter pipe was sufficient hydraulically to bring the remaining the flow to Lake Honda.

- The 30" pipe was sized to carry the hydraulic flow to Lake Honda under gravity flow. Several standpipes were included along its length, to control the maximum hydraulic static head. Where the pipe was exposed to low pressure (overflow at 620 feet, pipe invert about 400 feet), the wall thickness on the 30" pipe was set at thin as economically feasible while still maintaining a factor of safety of 2 on internal pressure (12 gage in locations, t = 0.104").

- The 24" cast iron pipe was at a much lower elevation, about 320 feet. This would put extra pressure on the pipe. So, Schussler could have ordered a thicker wall wrought iron pipe (higher cost), or perhaps he used an available 24" heavy wall cast iron pipe that he already had in inventory. This is the preferred explanation; as we cannot interview Schussler, the reader is advised that this explanation is just an informed guess.

At FX-5, Schussler (1906, p. 79) estimated that the 1906 faulting had displaced the pipe about 7 feet.

At FX-5, Lawson (1908, p. 100) reported the observations Robert Anderson made at this pipe/fault crossing: *The pipe here trended N25°E, while the fault's strike is N40°W making an intersection of 65°. The pipe experienced 22 inches of telescoping, which indicates 52 inches of right slip in the plane of the fault, and 20 inches of right-lateral separation.* If these measurements are added, they indicate a total right slip of 6 feet occurred at this fault crossing. Note: we adopt the N25°E azimuth as reported by Anderson; but see the opening discussion in this section about the accuracy of the plan locations of the pipe in this vicinity.

Hall notes: At the eastern pipe failure location (Figure 4.1.15-5**),** Schussler documented another break in this 24" cast iron pipe about 100 feet to the north of the FX-5. At this northerly break, the pipe was telescoped about 1 foot, which if the angle of the pipe/fault intersection has not changed (which is speculative), indicates right slip in the plane of the fault of ~28". If the observed two measurements of telescoping are added, the amount of right slip at this wide fault crossing due to shortening of the pipe is about 80" or 6.7 feet. This matches the magnitude of 6.75 feet of right slip along the fault plane here that was calculated by Reid (1910, V.II, p. 37).

If the observed lateral dislocation of 20 inches from Figure 4.1.15-5 is added to the total measured pipe shortening, the total fault slip at this crossing might have been as much as 8.3 feet. One of the objectives of this report is to make a *reasonably conservative* assessment of the Peninsula segment of the San Andreas fault's slip hazard. So we are more comfortable with the larger estimate and would not consider modern design using a knife edge right lateral offset value of 6.7 feet as sufficiently conservative or suitable for design. Rather, we prefer 8.3 feet (knife edge) or 6.7 feet (knife edge plus 1.6 feet (secondary).

4.1.15 Site 15. Lawson Fence "A" or Schussler Site "N"

This property boundary wire fence trends N52°E and crosses the 1906 San Andreas faulting at almost a right angle making it a potentially high-quality strain gauge for measuring fault slip. Schussler's sketch map of this area (Figure 4.1.15-1) identified two parallel cracks about 90 feet apart with a combined right lateral slip of 13 feet as measured by the fence offset (center fence in map below). Using Schussler's terms, the *"west crack line of fault"* break manifested the larger amount of slip.

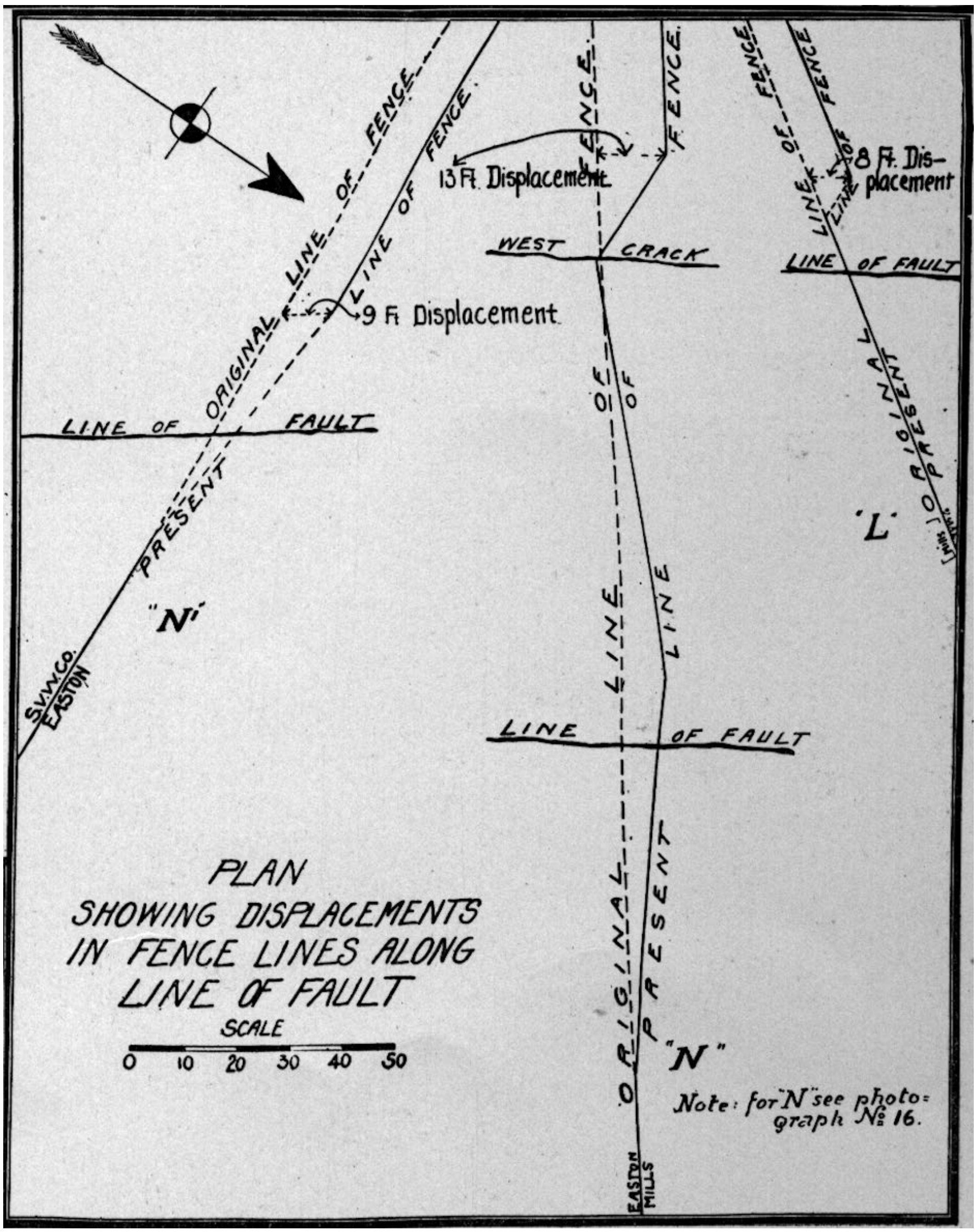


Figure 4.1.15-1. Map of Faults and Fences (Credit: Schussler 1906)

Lawson (1908, Fig. 38, p. 101) presented another map of this area based on professionally surveyed data prepared by R.B. Symington, C.E. that showed this fence and the geometry of how it was deformed across the fault offset zone. Figure 4.1.15-2 redrafts that c. 1908 survey using a 1:1 scale; Figure 5.1.15-3 redrafts using a 50:1 scale. The original fence is denoted by the dashed line, and the post-earthquake fence by the solid line. To the east of the primary offset zone, the fence has dislocated about 3.4 feet to the left; to the west of the primary offset zone, the fence has been dislocated 9.3 feet to the right (left and right as oriented looking southwesterly along the fence). If one measures the "total" fence dislocation, one gets 3.4 + 9.3 = 12.7 feet, or nearly the same amount as indicated by Schussler in 1906 in Figure 4.1.15-1; but Schussler's stated amount of 13 feet clearly is not the correct amount of the actual primary fault offset, which is better measured using the difference between the stone monuments 1 and 3. In Figure 4.1.15-2, the fence azimuth between Stone monument 1 and 2 is 52.27°; and between monument 2 and the primary offset zone is 52.17°.

Map of Faults and Fences (Credit: Schussler, 1906)

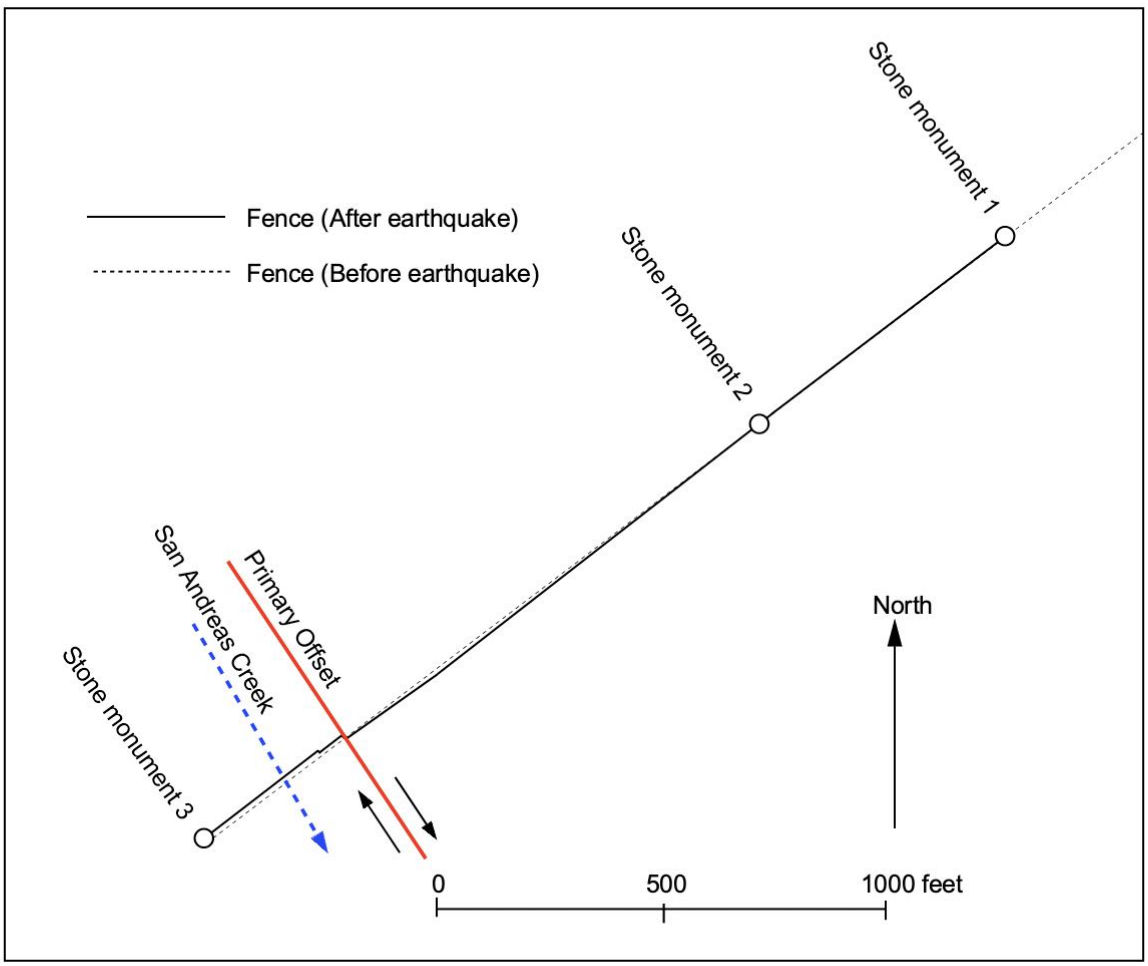


Figure 4.1.15-2. Map of Fault and Fence "N" (After Symington 1908, in Lawson 1908)

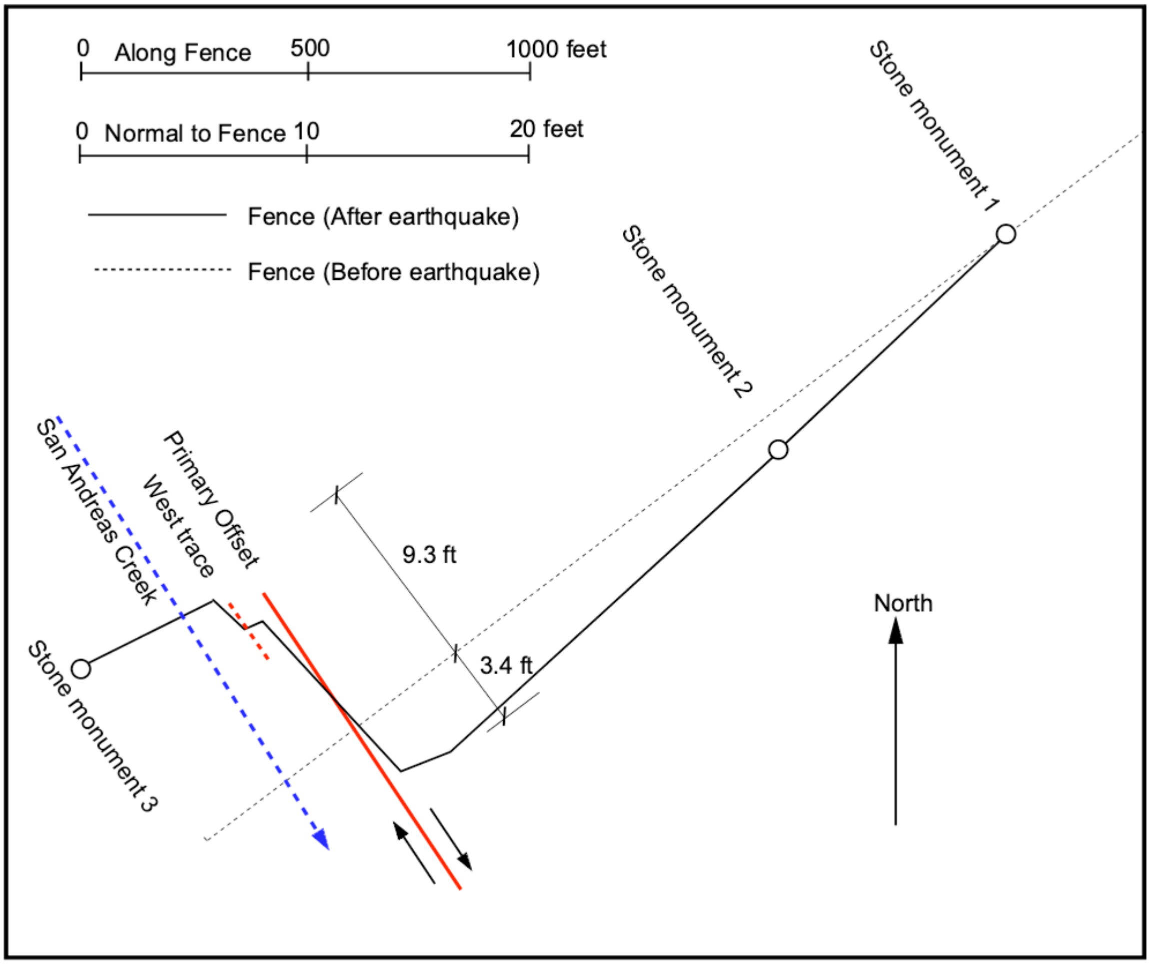


Figure 4.1.15-3. Map of Fault and Fence "N" (Exaggerated Scale, After Symington 1908, in Lawson, 1908, Fig. 37)

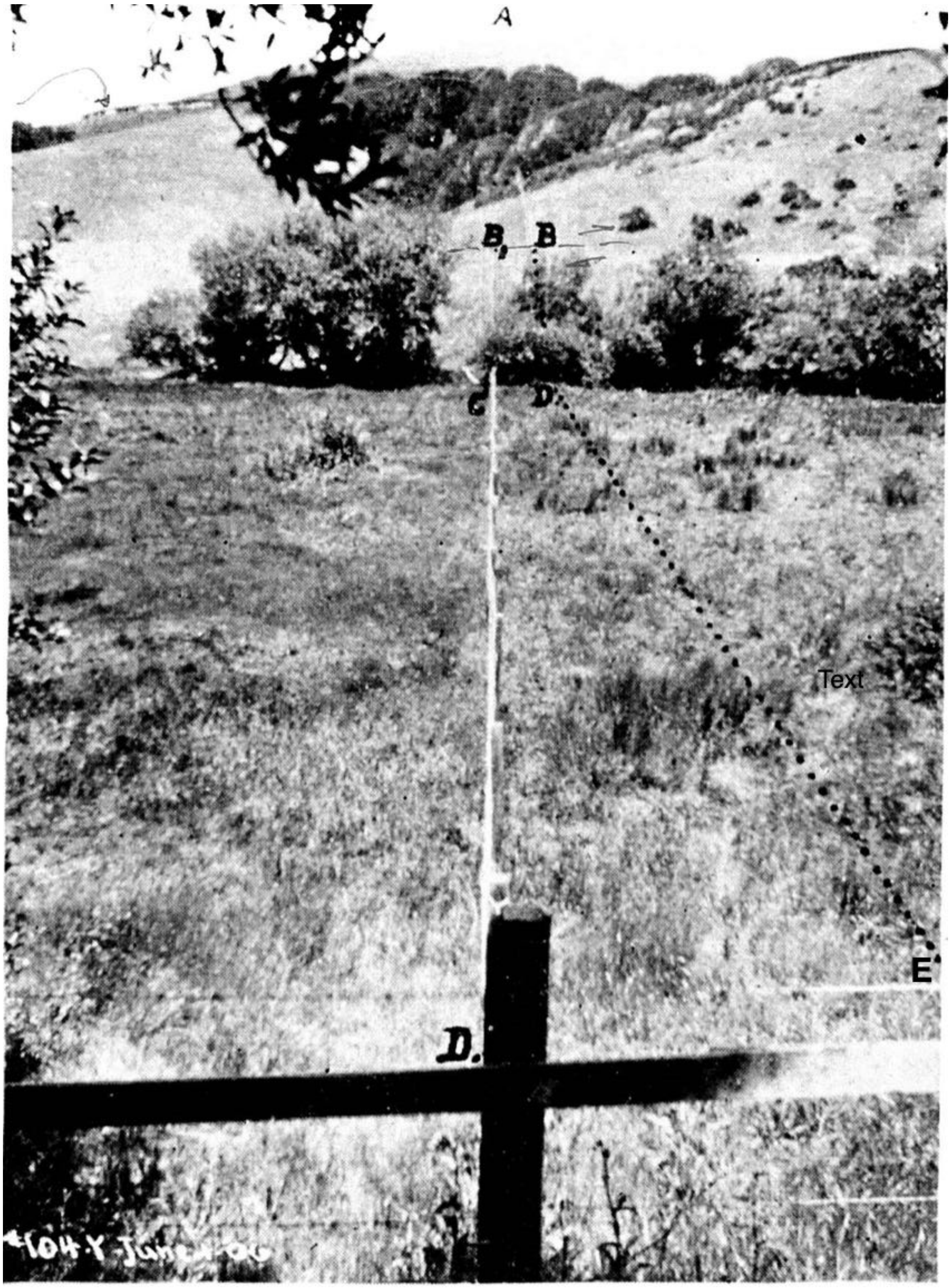


Figure 4.1.15-4. Offset of Fence N, looking northeasterly (Credit: Schussler, 1906)

4.1.15-4 is a photo by Schussler (1906). The post-earthquake location of the fence is A-B-B_1-C-D_1. Schussler hand-drew in the dotted line (Point D to E) as to original location of the fence. We interpret the seemingly "left lateral" offset suggested by the angle between DE and C-D_1 as an expression of the vanishing point perspective. In other words, the "triangular" shapes drawn by Schussler as "present line of" and "original line of " in Figure 4.1.15-1 at "line of fault" is incorrect; and the "line of fault" at the bottom of the sketch in Figure 4.1.15-1 is also incorrect and did not exist.

Schussler noted that the primary offset is nearly normal to the fence line, just beyond B_1-B.

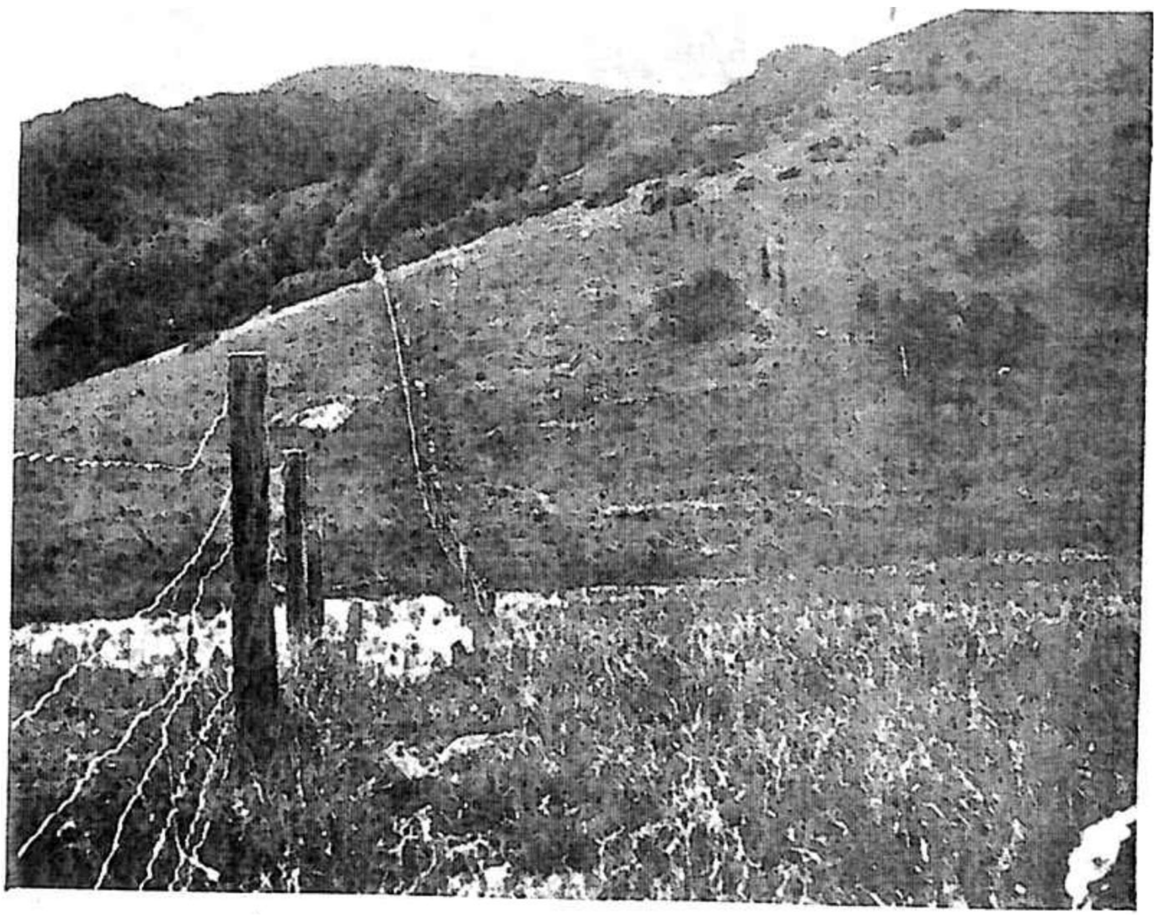


Figure 4.1.15-5. Offset of Fence N, looking northeasterly (Lawson, 1908)

4.1.15-5 is a photo by Branner, published as Plate 60D in Lawson (1908). We interpret this photo as looking to the northeast, with the low spot being where the fence crossed a sag pond at about elevation 320 feet. In this photo, the offset of the fence is about 6 feet according to the caption for the prior-mentioned Plate 60. Hall trenched this site in 1980 and interpreted that this fence offset location as the primary offset zone.

On the other hand, Symington (in Lawson 1908 Fig. 38) interpreted that the fence had been displaced right laterally a total of 12.7 feet.

Because of obvious discrepancies between these two renderings of this fence (Schussler's 1906 sketch and Symington's surveyed sketch), Bonilla and others, (1978, p. 350) converted Symington's diagram to a 1:1 scale to make it easier to measure distances and also compare it at the same scale to Schussler's diagram. From Symington's revised diagram, Bonilla measured 2.7 meters of displacement on the main eastern trace and 0.6 meters on the western trace that was located 50 feet away. This means that the total discrete slip here of Lawson's "Fence A", excluding ground warping, was approximately 10.8 feet.

Our interpretation of Symington's map, moving from NE to SW along the fence, shows:

- about 3.4 feet of left lateral offset spread uniformly over ~ 1000 feet (but, most likely an error influenced by Schussler's hand-drawn "D-E line"?)
- about 1 foot of right warping or drag occurred over ~190 feet, and
- about 8.8 feet of right lateral slip on the primary trace, and
- about 2 feet of right lateral slip on the western trace

Reflecting the unresolved discrepancies between the Schussler and Lawson measurements for 1906 fault slip recorded by this fence, we have more confidence in Bonilla's methodology for remeasuring the surveyed 1906 offsets that have yielded a total of discrete offsets of about 10.8 feet. If we incorporate the foot or so of ground warping at the eastern trace shown by Symington on his map, we believe that ~12 feet of right slip is a *reasonably conservative* estimate for this site.

Reflecting modern trenches through the site, we have no doubt that the primary trace is located along the west edge of a sag pond as shown in Figure 4.1.15-5. This photo shows the wire fence heading northeast up towards Buri Buri Ridge. It crosses a shutter ridge of Franciscan serpentinite in the foreground, descends into the sag pond with the posts visible (look carefully) at the west edge of the pond, then ascends the ridge beyond. This area was trenched by the U.S. Geological Survey in 1972 (Bonilla and others, 1972, p. 350) and Earth Sciences Associates (1980) and (Hall, 1984, p. 291). Sediment deposited in this sag area is more than 14 feet thick. Radiocarbon analysis of detrital charcoal within this sediment established that this closed basin/pond area, which has been created by recurrent slip on the San Andreas fault, has been active here for a minimum of the past 3,000 years and will very likely continue in the near future!

How does one explain the final deformed pattern of the wire fence? For design of new infrastructure crossing the fault, does one design for 12 feet? And what about the reverse trend (left lateral) of offset between the Primary offset zone and stone monument 1?

If one assumes that the fence can transmit no material forces, and that the wood fence posts moved almost exactly as the ground, then there appears here to be a primary offset zone, coupled with two smaller secondary offset zones, one either side of the primary offset zone. A conservative design approach would be to set PGD = 12 feet, with load case 1 = 12 feet as knife edge offset, and load case 2 = 9 feet + 3 feet (secondary on either side) and load case 3 = 9 feet primary + 1.5 feet secondary on each side. The primary offset zone would be designed as "knife edge" (but practically over a 10-foot wide zone), and the secondary zones each 125 feet wide.

If one were to trench the site prior to final design, the trench walls may show multiple offset zones, and this can aid in setting the total width of offset zones (primary + secondary).

A question that the authors have had a "few" times over the past 30+ years of investigations: does the observed presence of offset as observed in trenches mean that the next large earthquake will rupture to the ground at the same locations? In the 1980s, the answer was "definitely "yes"; but after observations in the 1992 Landers earthquake and subsequent earthquakes, the answer is "well, maybe".

- The true answer is likely to be site specific. For example, the offset stream channels surveyed by Hall (1984) show that here, south of San Andreas Dam, the main active trace has not changed locations for several thousand years. It is also likely that post-earthquake field investigations have identified additional zones of small displacement that have escaped prior detection.

4.1.16 Site 16. Schussler Site N'

Fence line N[1] is denoted by the fence line sketched by Schussler in Figure 4.1.16-1. Figure 4.1.16-2 shows the same area mapped by Hall in 1984. Here, a property boundary is marked by a fence and a row of Cypress trees that were offset 9 feet right laterally. Figure 4.1.16-3 clearly shows the young trees, the bent fence and a geologist standing bravely on the 1906 mole track.

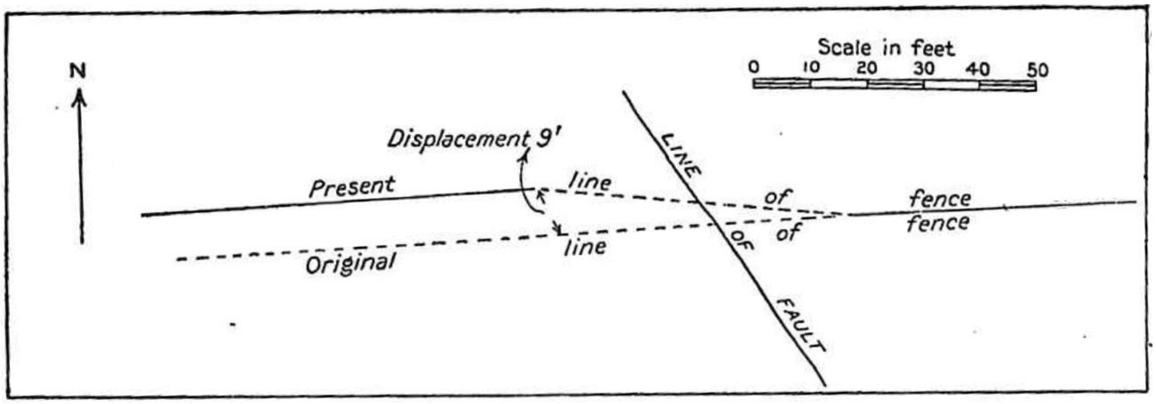


Figure 4.1.16-1. Map of Faults and Fences (Credit: Schussler 1906)

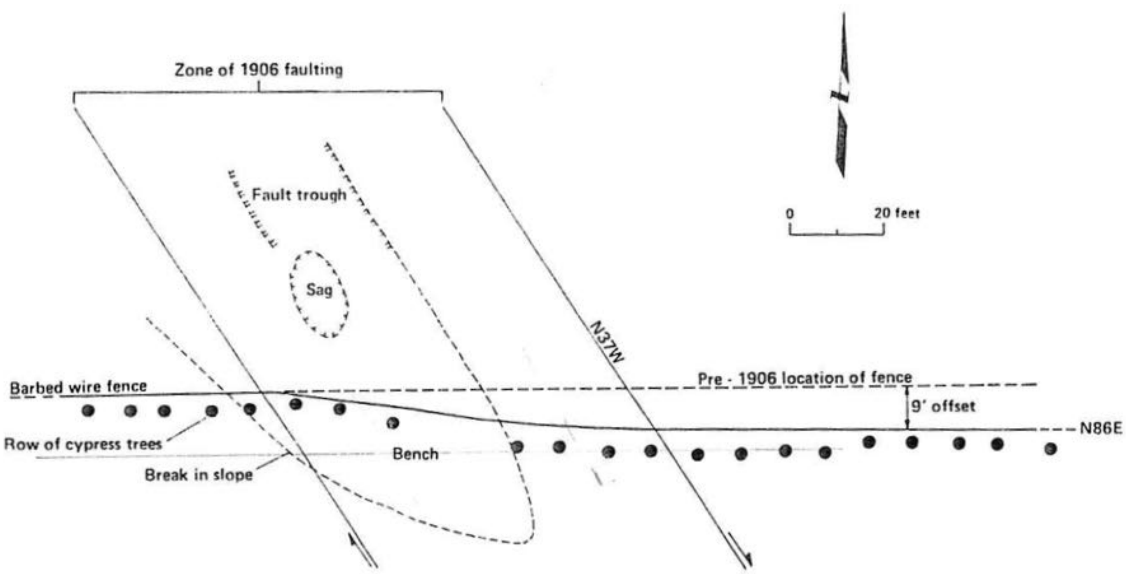


Figure 4.1.16-2. Map showing fence and row of cypress trees offset by 1906 faulting (Credit: Hall 1984)

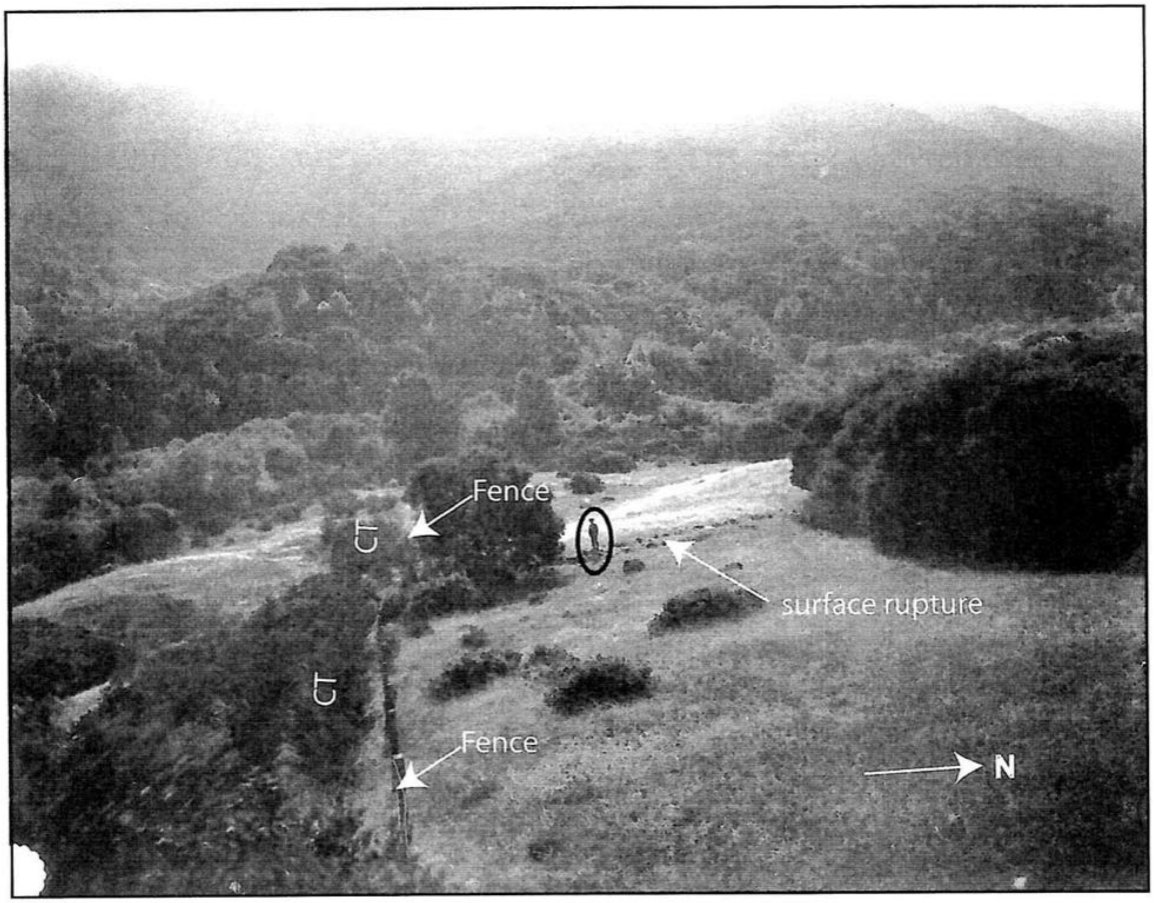


Figure 4.1.16-3. Photo showing surface rupture, fence and trees (Photo: Lawson 1908 Plate 61B)

Schussler (1906) and Lawson (1908) both sketched the site and both agreed on 9 feet or right lateral offset. Hall (1984, p. 286) also surveyed this site in 1980 and measured the same displacement even though the fence had obviously been repaired. Because the watershed lands are protected, the fence may yet exist today (2023). At the time of the 1980 survey, the tree trunks were several feet in diameter, making it difficult to measure their exact position when planted at least 80 years earlier. What the 1980 survey did show is that here the zone of maximum slip was at least 30 feet wide and showed evidence in the form of a hillside bench with a central trough and sag that indicated the ground surface along the fault here experienced some extension during fault slip. It is also interesting to speculate that the absence of two trees within the zone of concentrated slip probably had their roots sheared in 1906, which might have weakened them and led to their premature demise.

4.1.17 Site 17. FX-6. 44" Locks Creek Pipe

FX-6 is where a segment of the Locks Creek (alternatively called Stone Dam) pipeline crossed the San Andreas fault, near the north end of Lower Crystal Springs reservoir.

The Stone Dam conduit begins at the Stone Dam diversion on San Mateo Creek, runs through a flume, then a tunnel (southern Tunnel 2 in Figure 2-24) under Sawyer Ridge, then a flume, then a 44" wrought iron pipe through the bottom of San Andreas Valley, then a wood flume and finally via a 44" wrought iron pipe that emptied into San Andreas Reservoir. The function of the Stone Dam conduit was to collect water from San Mateo creek that was not otherwise captured by Pilarcitos Dam (elevation 696') and deliver that water into San Andreas Reservoir (elevation 449') by gravity flow.

Over its length, the Stone Dam / Locks Creek conduit was damaged in the 1906 earthquake at several places:

- Flume section destroyed by landslide (near San Mateo Creek) (see Figure 4.6-3).
- Pipeline section destroyed by fault offset, described herein as Site 17.
- Wooden flume sections destroyed by strong ground shaking and/or fault offset effects, described with Sites 11 and Site 12.

Figure 4.1.17-1 shows Schussler's sketch of the 44" riveted wrought iron pipe at Site 17. Figure 4.1.17-2 shows the re-drafted sketch by Lawson. Here, the pipe crosses the fault at an angle of about 70°, and right lateral offset would place the pipe into net compression, and well as much bending. On the east side of the fault, the pipe shows concentrated damage at two locations, about 30 feet and 50 feet away from the primary fault offset location. On the west side of the fault, the pipe shows concentrated damage at four locations, with compressive/bending failures at about 20 feet and 50 feet away from the primary fault offset location, and another tensile failure at about 400 feet distance from the fault or ±600 feet east of a county road.

The multiple damage locations either side of the fault is the natural condition of a beam (pipe) on nonlinear springs, when subjected to knife edge fault offset. The high bending moment ruptures the pipe in two locations either side of the fault, and this damage pattern was similarly duplicated by the Thames River 2.2 m diameter steel pipeline where it was exposed to similar right lateral fault offset in the 1999 Izmit earthquake (Eidinger, O'Rourke, Bachhuber, 1999b). The Thames River pipeline was butt-welded steel; so the failure mode was gross wrinkling of the pipe, rather than shearing the riveted joints as was the case for the 44" Locks Creek pipeline.

The distance (in feet) between the first two failure locations either side of the primary fault offset (about 50 feet in this case) if a function of the relative stiffness and strength of the pipe versus the stiffness of the backfill soils around the pipe: the stiffer / stronger the pipe and the softer the soil, the wider the distance between the two failure locations.

The four locations where the pipe was reported as "telescoped" are places where the net shortening of the pipe had to occur. If we allow that at a 55° angle and 8 feet of right lateral offset, then the net shortening should be about 96" sin 25° = 41 inches. Schussler computes 59.25 inches. We suspect the discrepancy is in the measurement of 52" at the telescoped failure just west of the fault; perhaps this was the maximum measured around the circumference, rather than the average. It is unclear as to the mechanism that led to the tensile failure and pull apart of ~3" at a distance of about 400 feet to the west of the fault.

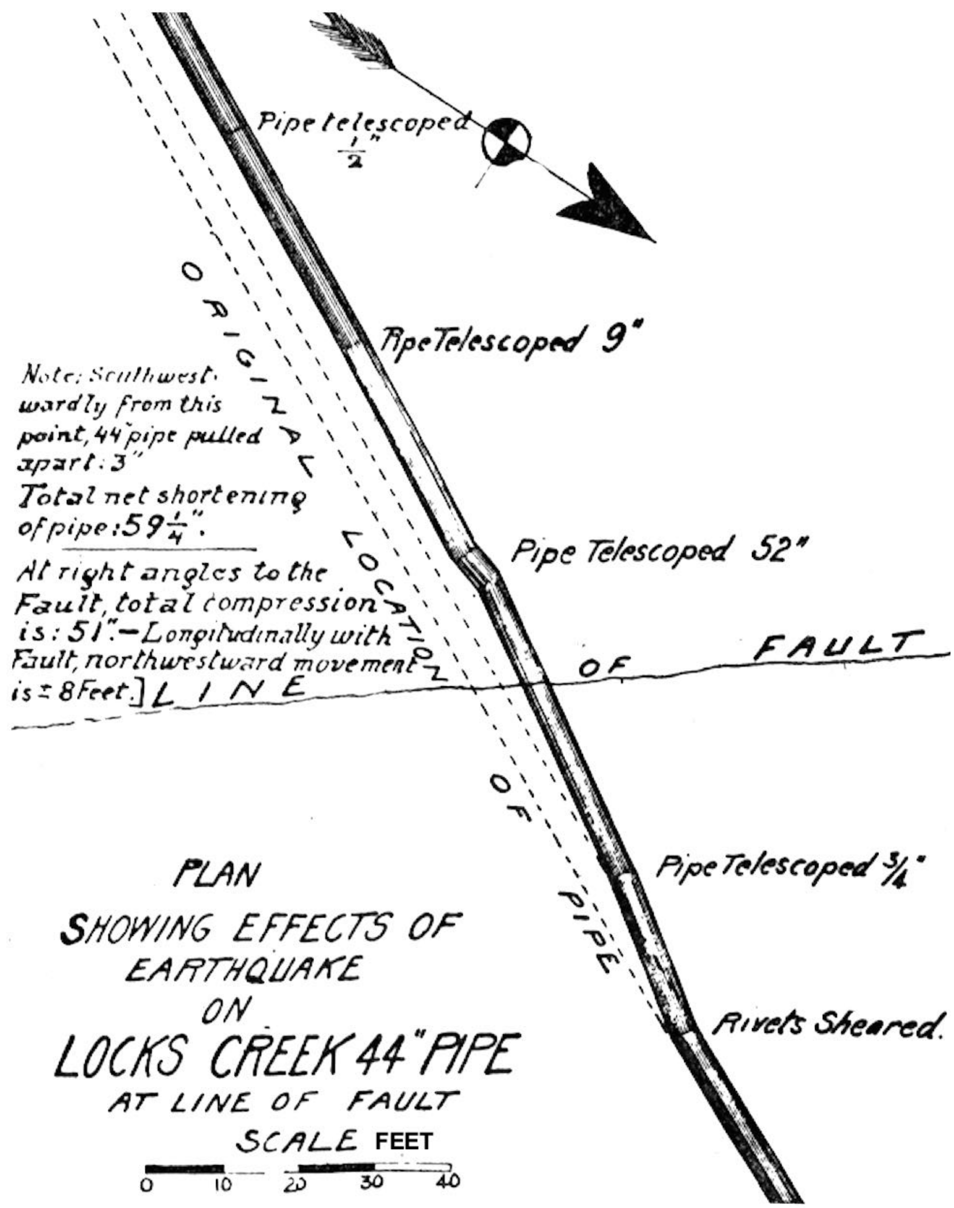


Figure 4.1.17-1. FX-6. Locks Creek 44" Wrought Iron Pipe (Schussler 1906)

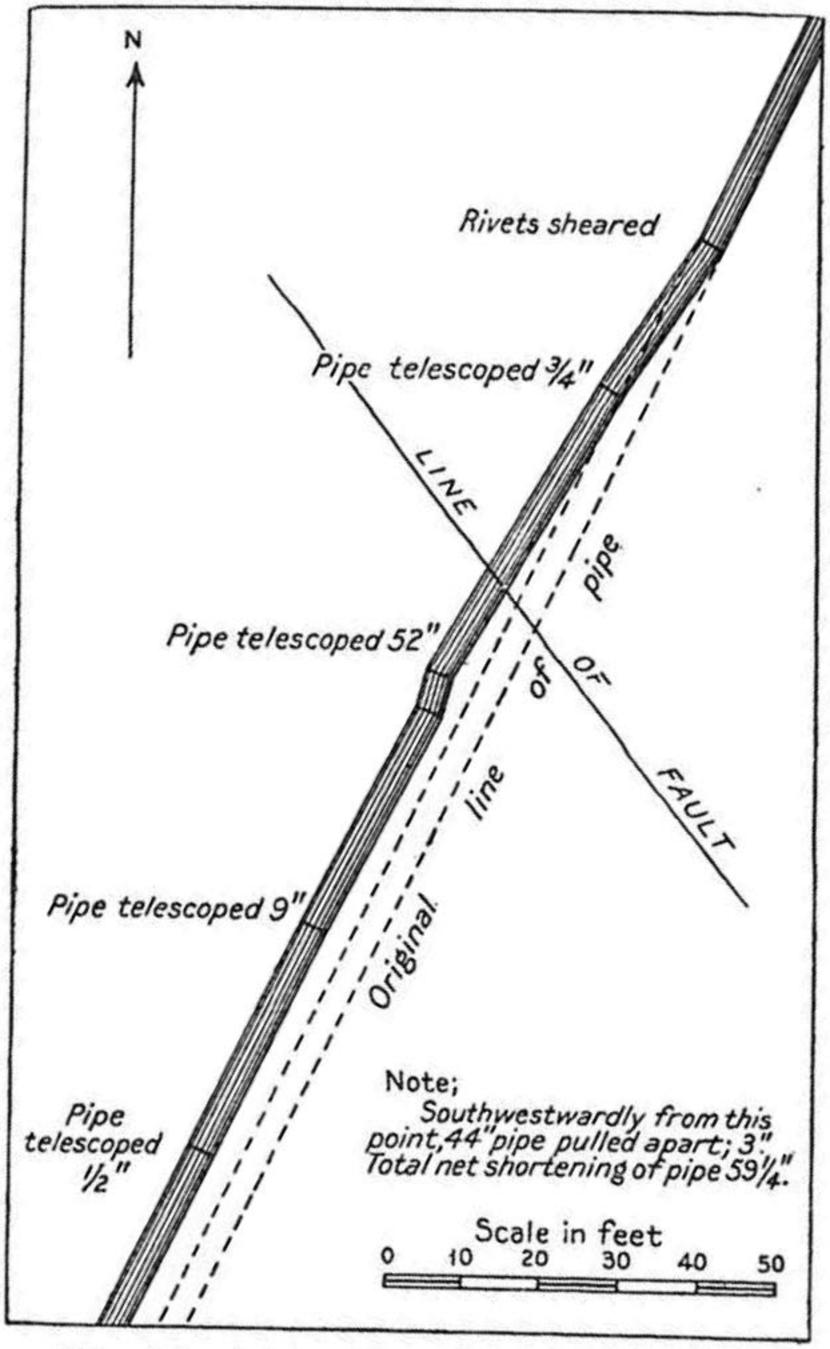


Figure 4.1.17-2. FX-6. Locks Creek 44" Wrought Iron Pipe (Lawson 1908 Fig. 39)

At this location, the 44" riveted wrought iron pipe was buried with 3-4 feet of cover and had wall t = 0.125 inches. This pipe runs up the hill from the San Andreas Creek valley in a direction of about N 28°E. The fault offset bisected this pipe at the base of the hill, with the fault azimuth being N 37°W. Thus, the intersection angle between the fault and the pipe is about 65°. At the intersection of the fault, the rivets were torn out all the way around at a girth joint and two pipe segments were telescoped into one another a distance of 52 inches. One observer suggested there was no lateral displacement, the whole movement being taken up by telescoping of the pipe, but there was bending of the pipes at the point of the break.

The hand-drawn before-and-after pipe locations in Figures 4.1.17-1, -2 suggest the pipe was offset laterally by about 1.5 pipe diameters (66"), but Schussler documents 14" of transverse pipe offset. The difference in these two figures (66", 14") cannot be readily reconciled as a sudden "knife edge" offset of the pipe; but could reflect the transverse offset over several tens of feet.

Figure 4.1.17-3. FX-6. Locks Creek 37.5" Wrought Iron Pipe is offset to the north about 14" and telescoped about 51". Looking easterly. Location is about 50 feet east of the County road between the San Andreas and Crystal Springs reservoirs. (Photo: Schussler 1906 HS14)

This pipe was also broken about 400 feet on the southwest side of the, see Figure 4.1.17-4. This break occurred at the junction of 2 sections, the rivets having been sheared off and part of the rim torn away at the rivet holes. The ends were pulled apart 3.375 inches

(Lawson 1908). This suggests the pipe here was in nearly pure tension. At the primary offset location, the pipe is under enormous stress, a combination of huge bending and some compression. The question arises as to how the pipe also failed some 400 feet away on the southwest side of the fault, and in what apparently is tension. If one assumes no applied PGDs between the primary trace and this location, then what produced the high tension?

- Possibility 1. The high bending and distortion at and very near the primary trace allows the pipe on the southwest side to be put into high tension. Over a ~350 foot length, there would be about 35 to 50 girth joints, and the tension forces should dissipate along the length as the pipe transfers the force into the soil via friction. Is it possible that 34 to 49 girth joints closer to the fault were all strong enough, and just the 35^{th} / 50^{th} girth joint weak enough to rip open? This possibility seems to be in opposition to basic strength of mechanics principles.

- Possibility 2. There is some lateral spread / landslide in the area. The break in Figure 4.1.17-4 is in tension, suggesting that at this location, the pipe is being pulled into tension. This location would be under water if the Crystal Springs Reservoir was full (it was not), but possibly there was liquefaction near this location. Neither Schussler or Lawson makes any notes about liquefacgtion-related effects in this area; but a few inches of movement might have been missed or not documented.

- Possibility 3. Clearly, there was strong ground shaking in the area. Elsewhere in this report, we describe the strength of the riveted joint being only half the strength of the main barrel of the pipe. Almost certainly, this is a low pressure pipe (D/t = 44 / 0.125 = 344, >> 200), as the required head would have been on the order of 100 to 150 feet only, between the two open channel flume sections at about elevation 500 feet (either side of the valley, and the fault location being about 325 feet, or 175 feet head or hydrostatic pressure of about 75 psi (pipe hoop stress = 175 / 2.31 * 22 / 0.125 = 13,300 psi). Assuming the pipe wall thickness was set to have F.S. = 2 under maximum static head, wall t is thin (and the rivet joints corresponding designed). Then, the longitudinal stress due to shaking might have been ~+5 ksi, and a water hammer stress about +5 ksi, and the stress due to internal pressure might have been +6 ksi (or so). Combining these three effects, the longitudinal stress (~16 ksi) might have been sufficient to break a particularly weak riveted girth joint.

Of these possibilities, the preferred answer is either possibilities 2 or 3. We cannot be sure, as it is no longer possible to survey the site for PGD effects. Allowing this to be the case, then the lessons for a modern day pipe designer are:

- In zones with high ground shaking (PGV > 30 cm/sec), for pipes that are important and should not break in the earthquake, for low pressure pipes (maximum hydrostatic internal pressures under 100 psi) girth joints should be designed to have equal strength as the main body of the pipe. This should provide sufficient strength for the pipe to sustain induced stresses due to transient ground strain, coupled with hydrodynamic (water hammer) stresses set up by the earthquake. This precludes the use of higher pressure (200 psi) push-on jointed pipe in these areas (like ductile iron with rubber gasketed joints) unless the joints have harnesses or other restraining mechanisms that have equal or greater strength as the main barrel of the pipe.

- Modern pipe design to sustain fault offset will often call for butt-welded steel pipe with D/t < 90 (and perhaps < 50) at the fault crossing location. For very high pressure pipe (like high pressure gas pipes at pressures > 1,000 psi), the heavy wall needs to be maintained throughout the pipe length. But, for moderate pressure water pipe (pressures about 200 psi), the heavy wall and butt welds at the fault can be reduced in thickness at some distance away from the fault; also the strength of the girth welds can transition from butt welds (equally or stronger than the main barrel) to double lap weld or even single lap weld at some distance from the fault, where PGD effects are nearly nil. In these causes, the pipeline designed is cautioned not to make this cost-saving transitions too close to the fault, for the following reasons:

    - Often time (but not always), for strike slip faults like the San Andreas, there will be secondary fault offsets and ground warping that occur one hundred to a few hundred feet away from the primary fault trace. This has been amply demonstrated for the San Andreas fault in the 1906 event. The same might be true for Hayward fault events. In zones with reverse faulting coming to the surface, there will often be a variety of back traces away from the main scarp. If sufficient study of the geologic record is done as part of the design (trenches for several hundred feet wither side of the primary trace), quite possibly the evidence for these secondary offsets will be observed. However, for many reasons, not all faults can be trenched entirely, so the pipeline designer is left with the decision as to how far back from the presumed primary fault offset location the fault-tolerant pipe design should be carried.

In zones with soils with highly susceptible to liquefaction, design the pipe for a few inches of PGD. Lacking detailed site specific study, it will be rare to be able to define the exact PGD profile. A lateral spread of >3 inches to the northeast may have occurred at this location, leading to the tensile failure observed in Figure 4.1.17-4, and the additional 9" telescoping location noted in Figures 4.1.17-1, -2.

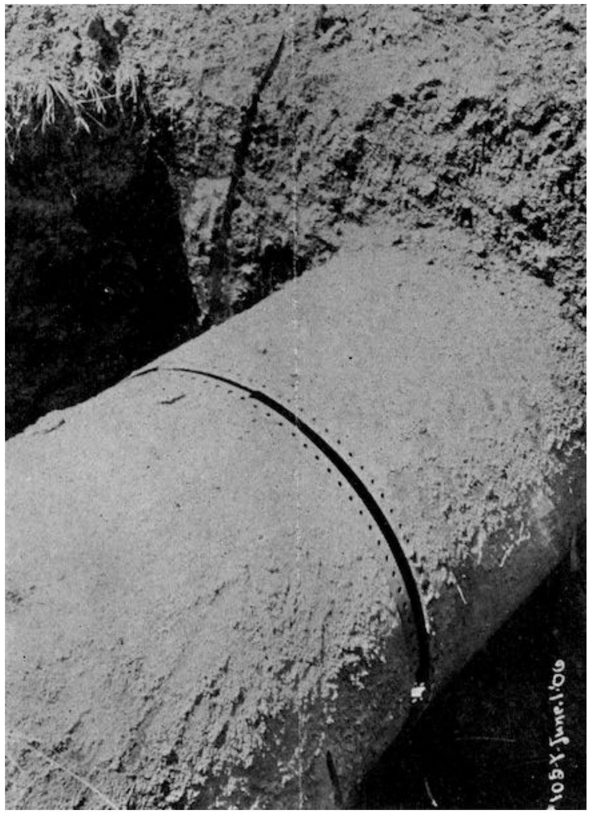


Figure 4.1.17-4. Locks Creek 44" Wrought Iron Pipe is pulled apart about 3.375" inches. (Photo: Schussler 1906 HS15)

4.1.18 Site 18. FX-7 Abandoned Stone Dam / Locks Creek 37.5" Pipe

Consider the map prepared by Scowden in 1875, prior to construction of the Lower Crystal Springs Reservoir, Figure 4.1.18-1. This shows Stone Dam on Pilarcitos Creek, followed by a flume, followed by a Tunnel (under Sawyer Ridge), followed by flume and pipe sections through San Andreas Valley (including proposed Lower Crystal Springs Reservoir), and then turning north towards San Andreas Reservoir. The Tunnel in this map could be filled either with water from Stone Dam or from the Locks Creek collection flume with water coming from to the bottom right of this map.

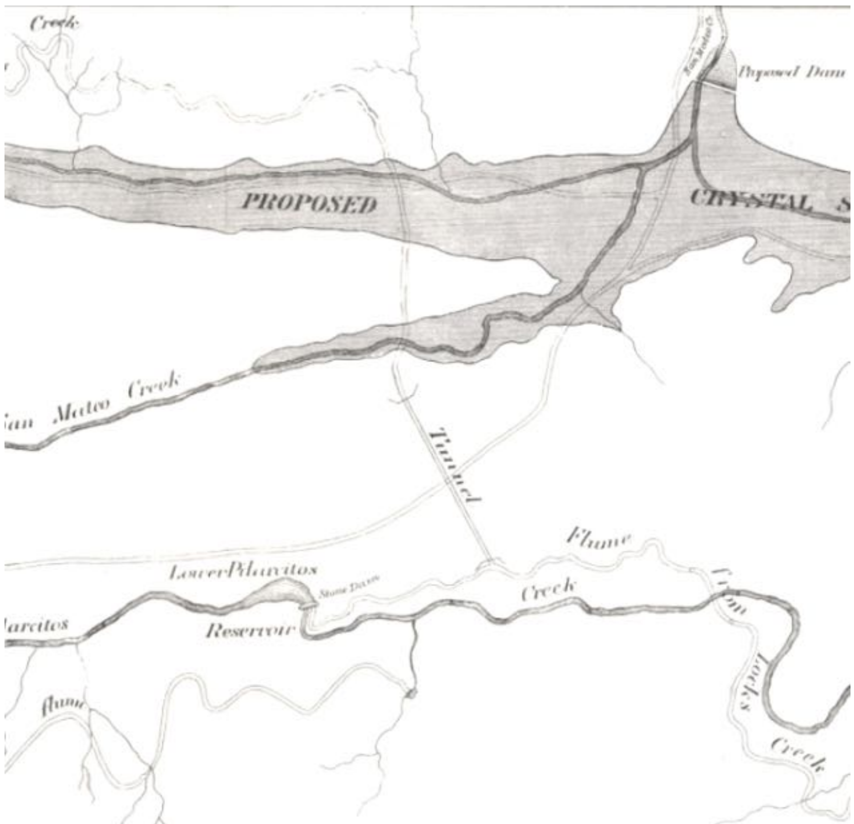


Figure 4.1.18-1. Old Stone Dam Conduit (credit: Scowden, 1875). North to the left.

With the construction of Lower Crystal Springs Reservoir, a portion of the Locks Creek conduit was re-routed (see Figure 4-2 for post-1888 re-routed Locks Creek Conduit).

At the time of the 1906 earthquake, the original c. 1873-vintage 37.5" wrought iron pipe had been abandoned and was under the lake.

In 1924, the lake level was lowered, and the 37.5" pipe was taken up. At the San Andreas fault crossing, it crossed at about 78° to the fault (90° being perpendicular), and the pipe was exposed to nearly pure bending offset, coupled with a small compressive component. Figure 4.1.18-2 shows the pipe being removed. This photo is taken looking westerly, and the lowered Crystal Springs Reservoir is seen in the background. The ~9-foot right lateral offset of the pipe at the primary offset zone is seen in the foreground.

Figure 4.1.18-2. 37.5" Abandoned Pipe, 8-25-1924, D-879 (Credit: SVWC 1924). Looking West

Figure 4.1.18-3 shows the 37.5" pipe being removed. This photo is taken looking easterly, and the lowered Crystal Springs reservoir is seen in the foreground. The mole track of the fault is denoted by the two arrows.

In the foreground of Figure 4.1.18-3, the pipe is seen fallen off a wood trestle, where it was originally built to go over San Andreas Creek. Whether that damage was due to fluid-structure loading in the 1906 earthquake, or reflects part of the disassembly process, is uncertain.

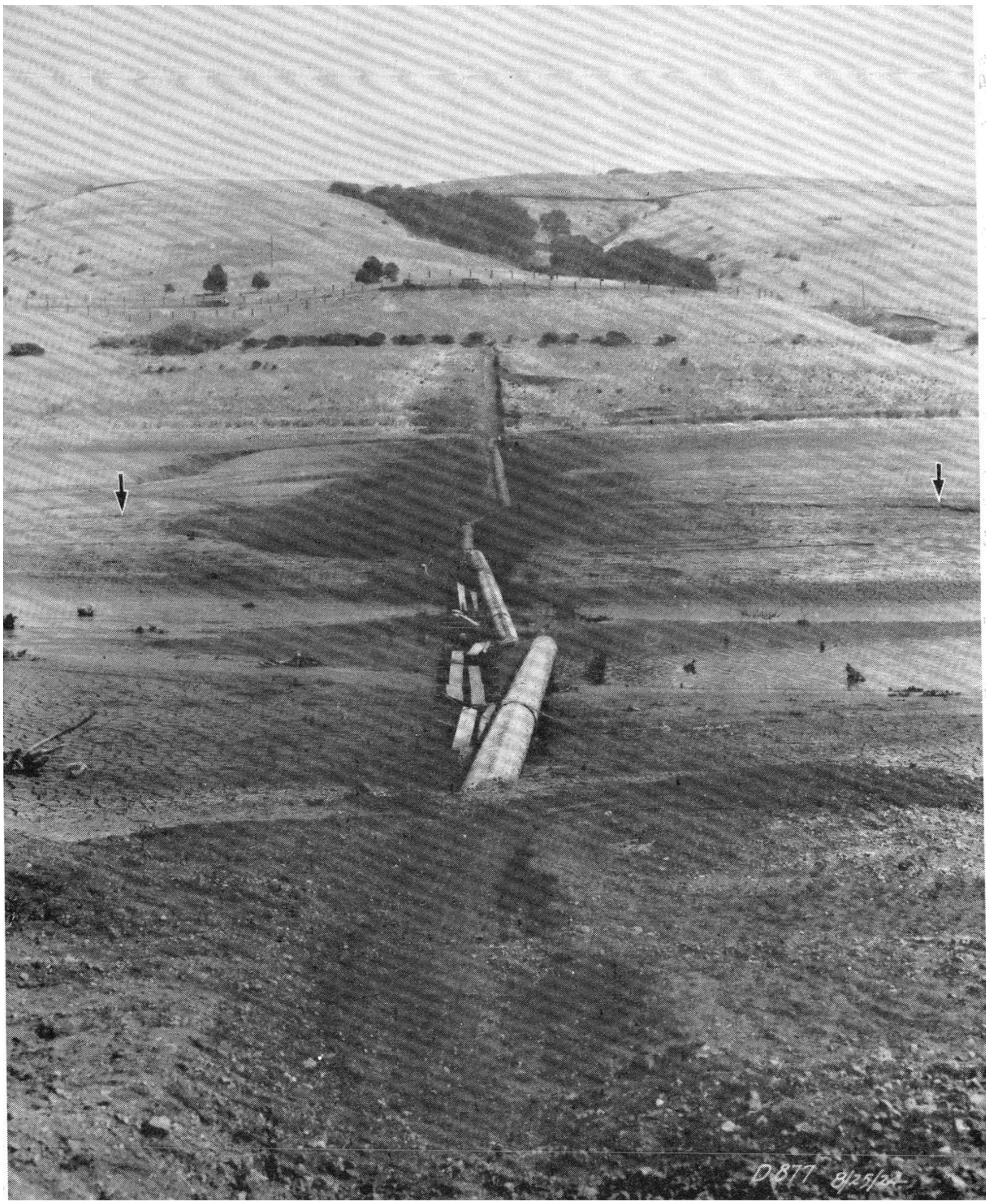


Figure 4.1.18-3. 37.5" Abandoned Pipe, 8-25-1924, D-877 (Credit: SVWC 1924). Looking East

Figure 4.1.18-4 was uncovered as part of a review of historical documents of the 1906 earthquake. However, the provenance and exact location of the photo, is undocumented. The photo shows a riveted wrought iron pipe that has failed its girth joint location and suffered several inches of telescoping. The pipe appears to enter a wooden-boxed location. The soils appear to be conglomerate that might be seen in the Franciscan Formation. It is possible that this damage was at a transition to a flume or boxed-enclosed trestle segment. It is also possible that this damage was on the 44" Crystal Springs pipeline at some location downstream of the Crystal Springs Dam and west of the Millbrae pump station.

Figure 4.1.18-4. Wrought Iron Pipe Failure. Site 18 (Photo: SVWC, 1906?)

4.1.19 Site 19. Old Hayward Dam, Lower Crystal Springs Reservoir

Figure 4.1.10-19 shows remnants of the original Hayward dam. This dam was built as an earthen embankment, and was used before 1887. This photo was taken in 1931 during low water. The large opening reflects that the dam was bulldozed to form a single basin as part of the construction of the Lower Crystal Springs Reservoir in 1888.

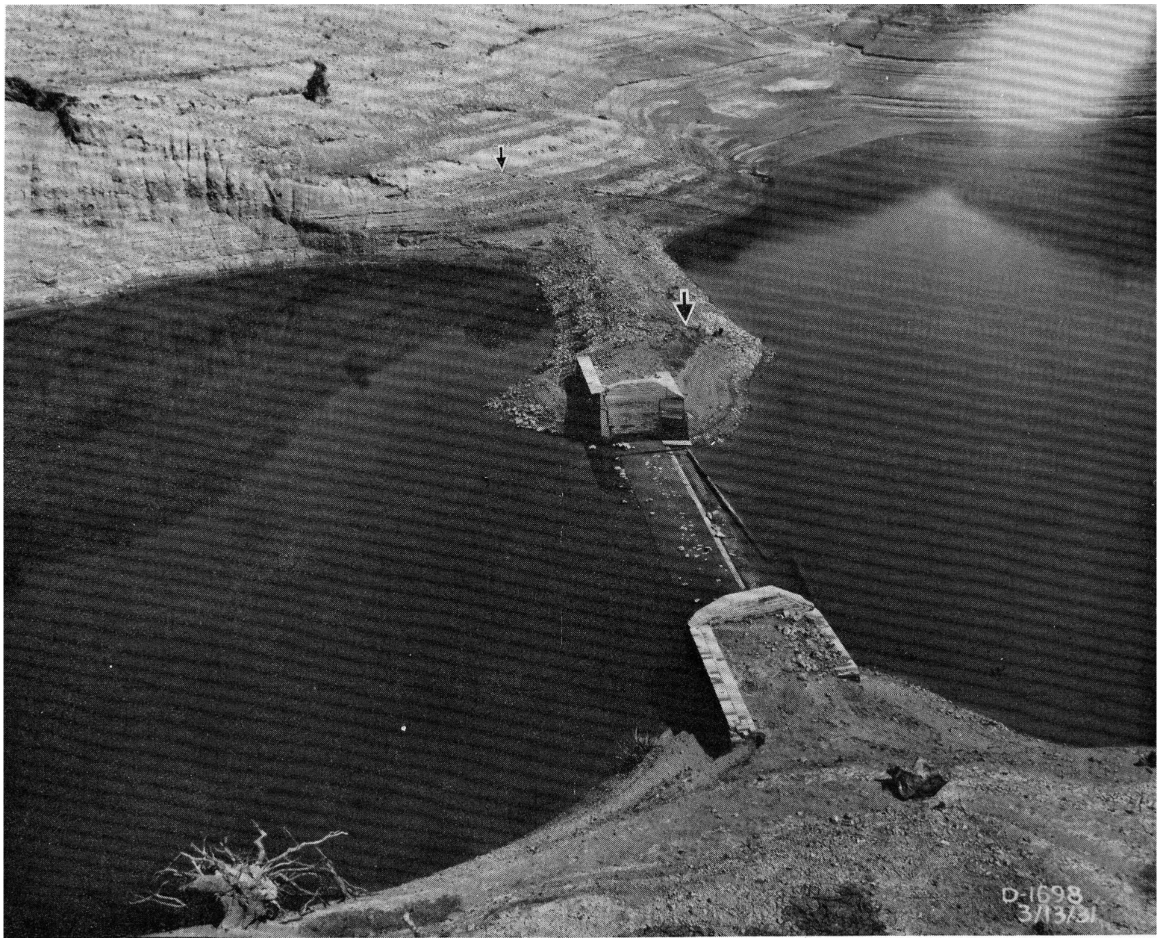


Figure 4.1.10-19. Hayward Dam, looking northeasterly (Photo: SFPUC)

According to Pampeyan (1983), this dam was also referred to by Berkeley Professor Louderback (1937) as the Old San Andreas Dam.

Wave action along the sides of the reservoir has stripped away the topsoil exposing Plio-Pleistocene sediments of the Merced Formation and several cracks, fractures and small faults that were commonly observed in the east side of the San Andreas fault in 1906.

The larger arrow in the middle of the photo shows a location with about 7 feet of right lateral offset. The small arrow in the background suggests another linear feature; if this is the case, then the 7 feet of slip measured at the large arrow is clearly a minimum value.

4.1.20 Site 20. Tunnel Between Lower and Upper Crystal Springs Reservoirs

Figure 4.1.20-1 shows the location of fault offset damage to the outlet tunnel between the Upper and Lower Crystal Springs reservoirs. (See Section 4.1.21 for more detail of the fault offset through the dam).

The earthen dam depicted below is about 6 miles south of San Andreas Dam. It was constructed between 1873 and 1877. When originally completed, the dam was 420 feet long and 70 feet high. In 1891, the dam was raised 20 feet to bring it to the same level as the newly-built (1887-1890) Lower Crystal Springs Reservoir Dam. The dam depicted below was again raised 3 feet in 1928. The Upper Reservoir predated the Lower Reservoir. This dam (plus heightening) is presently Highway 92 causeway.

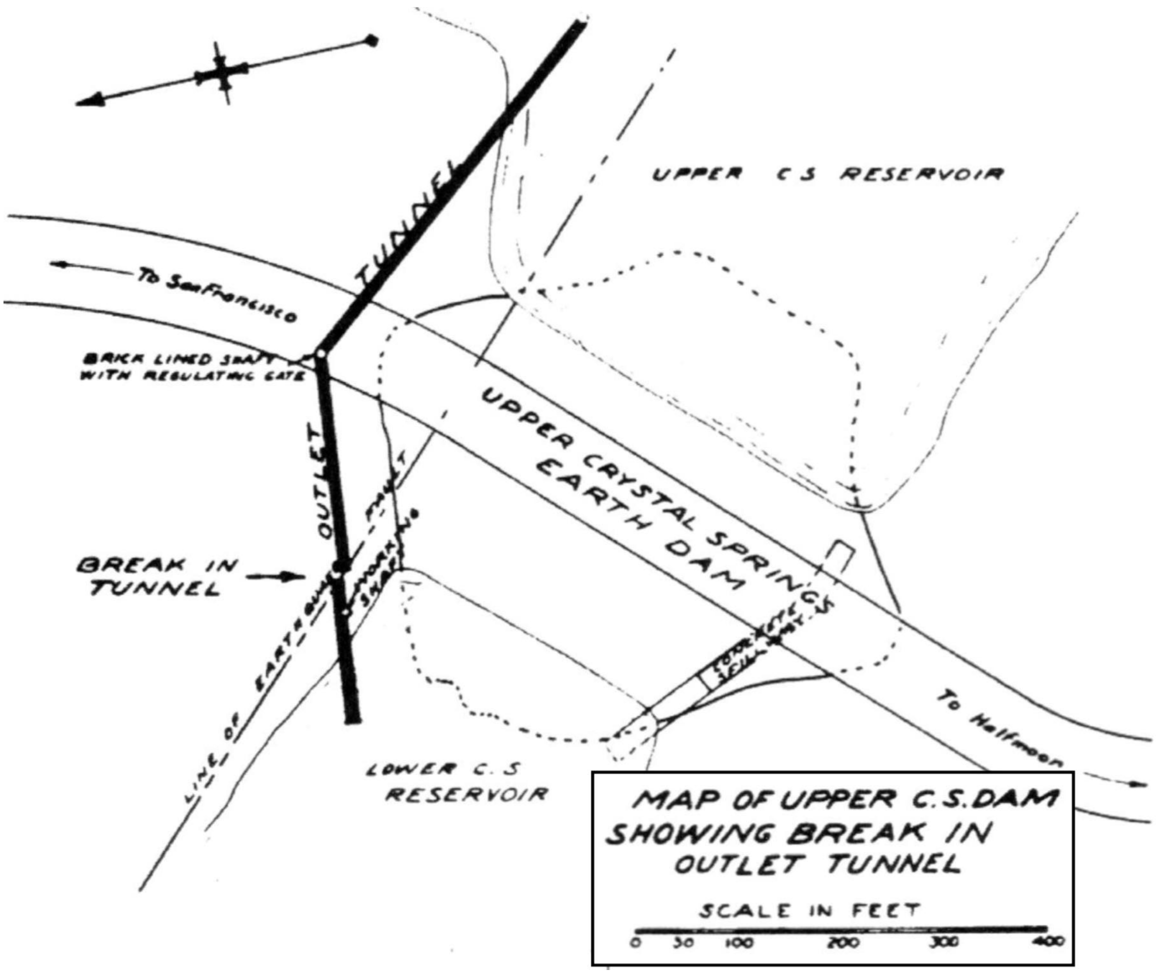


Figure 4.1.20-1. Outlet Tunnel Connecting Upper (southerly) and Lower (northerly) Crystal Spring Reservoirs (Credit: Schussler 1909)

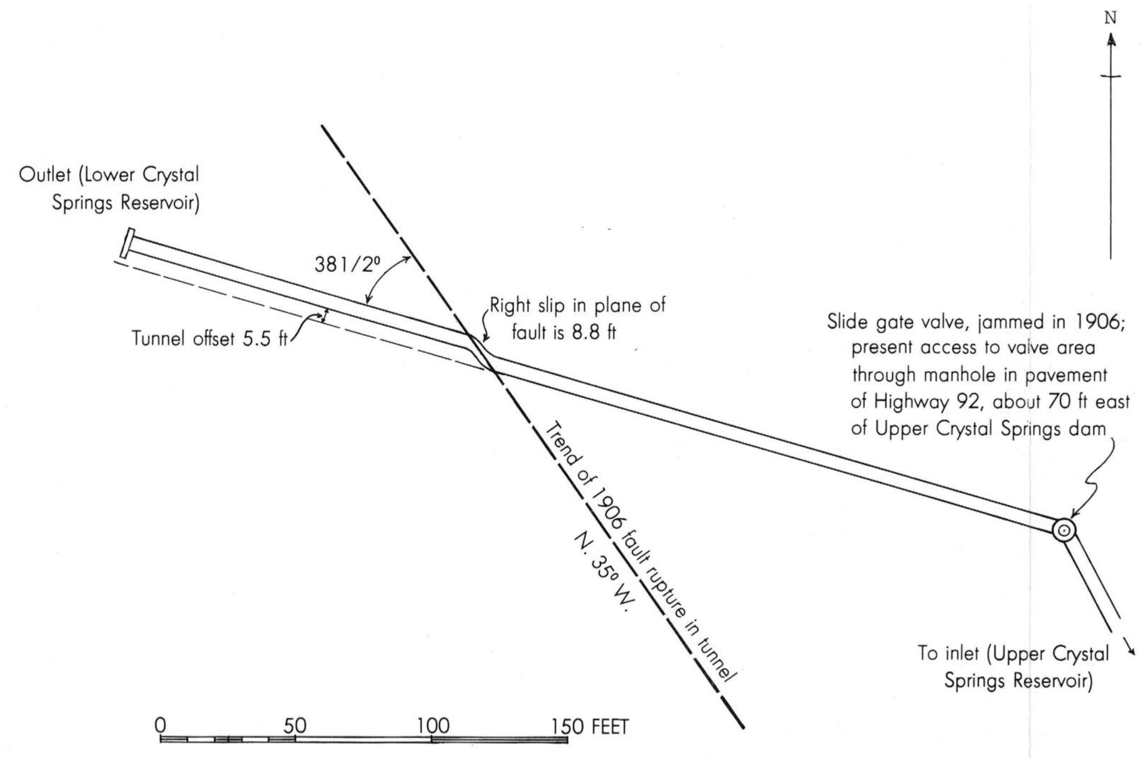


Figure 4.1.20-2. Tunnel Connecting Upper (southerly) and Lower (northerly) Crystal Spring Reservoirs (Credit: Pampeyan 1983)

A brick-lined outlet tunnel connected the Upper and Lower Crystal Springs reservoirs. This tunnel was 6 feet high, 5.5 feet wide, and 775 feet long. Within the tunnel was a 42" diameter wrought iron pipe.

The original purpose of this outlet tunnel and pipe was to allow operators to control the release of water from the Upper Crystal Springs r

Reservoir down towards San Mateo Creek (or presumably) into the original Crystal Springs pipeline.

Once the Lower reservoir was built to be at the same water elevation as the Upper reservoir, this outlet tunnel served no regular purpose. With the construction of the Lower reservoir, the original Crystal Springs pipeline below the dam was removed and re-constructed to begin at the Lower Crystal Springs Dam.

During the 1906 earthquake, the primary trace of the San Andras fault bisected the outlet tunnel. As the tunnel was no longer in regular usage, it was not until 1924 that it was repaired.

Pampeyan (1983) noted the offset was 5.5 feet in the outlet tunnel; given the azimuths, this translates to about 8.8 feet of right lateral offset of the fault at this location.

Pampeyan reports that the zone of major damage to the tunnel was about 20 feet long, and that the tunnel west of the fault break apparently dropped about 12 inches.

4.1.21 Site 21. Highway 92, Causeway Across Upper Crystal Springs Dam

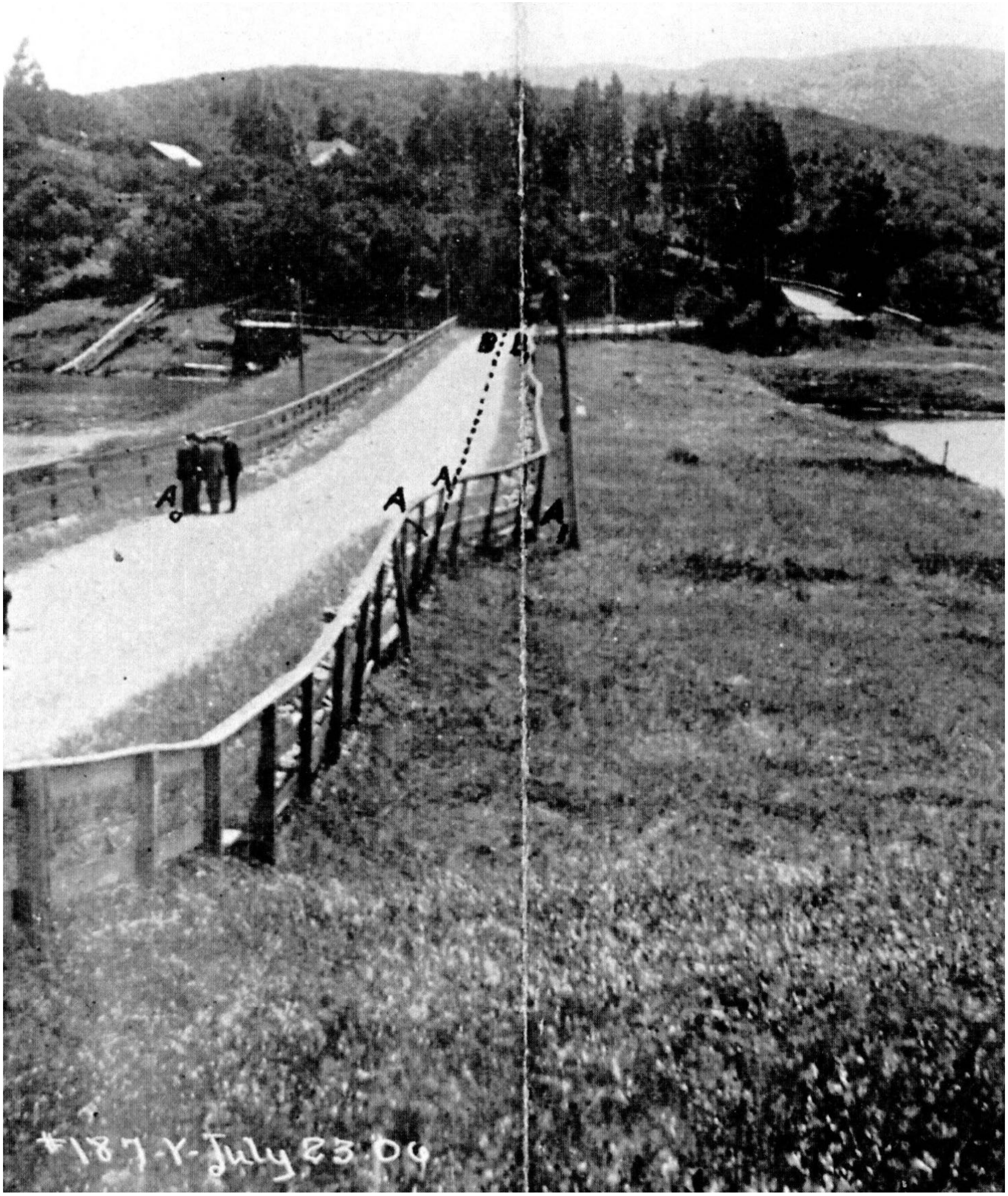


Figure 4.1.21-1. Upper Crystal Springs Dam, looking westerly (Credit: Schussler 1906)

Figure 4.1.21-1 shows a side view looking to the west of the Upper Crystal Springs Dam. The photo was taken on July 23, 1906. Figure 4.1.21.-2 shows a plan view sketch of the San Andreas fault going through the dam. The San Andreas fault rupture traverses the dam at azimuth N35°W, while alignment of the dam is about N22°E. Schussler states (1906) that there was about 8 to 9 feet of right lateral movement through the dam. Figure 4.1.21-1 shows the bulk of that offset concentrated at locations A_0 to A. The offset in the road and fence is clearly seen. The westerly 90% of the dam has no observable offset. The line A-B indicates the pre-earthquake location of the northerly fence. The line A_1 – B_1 shows the post-earthquake location of the fence. The telephone wires that crossed the dam on wood poles are sagged considerably, that shortening due to the faulting that moved the poles closer together.

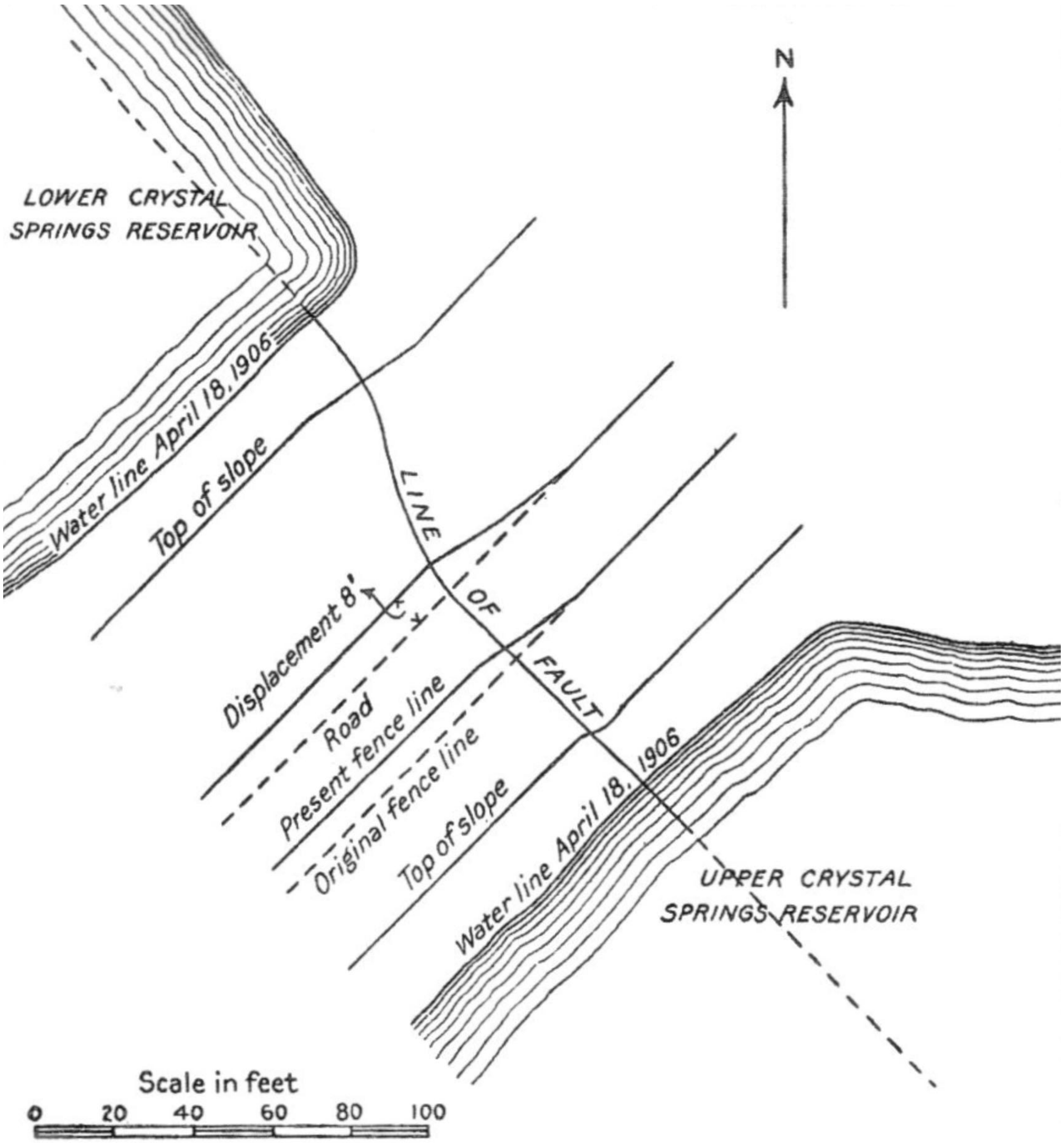


Figure 4.1.21-2. Upper Crystal Springs Dam, looking westerly (Credit: Lawson 1908 Fig. 40)

Trending more easterly than the fault, the dam experienced compression during the slip event, causing the fence boards to bend and shorten and the telephone wires to sag. However locally, the right step or bend in the fault is a local releasing environment that probably contributed to the complexity of cracking in the eastern abutment area.

Stephen Taber of Stanford University made his own measurements of the dam and published his findings in 1906, Figure 4.1.21-3. In this figure, Taber documents both the fault rupture location as well as the pattern of cracks that developed in the road surface and embankments. Cracks parallel to the long axis of the dam up to 6-inches wide developed in the embankments on both sides of the road; these cracks could be attributed to lurching and/or settlements of the embankment; but a pre- and post-earthquake survey of the elevation of the dam crest is not available, so the settlement of the dam is speculative. Taber also shows two sets of transverse cracks at both abutments. As the Lower reservoir (north of the dam) had the same water level at the Upper reservoir (south of the dam), the damage to the dam did not present any immediate life safety issue. Taber also reported that the road, where it crossed the fault at the northeast abutment area, was offset by about 6 feet of right slip. This translates to about 7 feet (after correcting for azimuth); this contrasts with Schussler's report of 8 to 9 feet; the discrepancy of Schussler's and Taber's offset amounts may reflect that Schussler measured the offset based on offset of the fences. Taber also reports: "*the fences on both side of the road were broken in a number of places, and the unbroken boards were bent and arched so as to give a serpentine appearance to the fences. The wires of a telephone pole line crossing the dam sag in great loops*". This is not at all surprising; given that the mapping (Pampeyan 1983) suggests about a 77° orientation of the fault strike versus the road alignment, which would impart some compression into the road assuming a perfect right lateral offset pattern. From a pipeline designer's point of view, should a new water (or other type) of pipe be installed across this dam (now called Highway 92), it should be evaluated for a primary offset of 7 feet over a width of perhaps a few feet (but knife edge offset is preferred for design), plus another 1 or 2 feet of distributed right lateral offset over a width of perhaps 25 feet either side of the primary offset, plus a shortening along the alignment of the pipe of 1 foot.

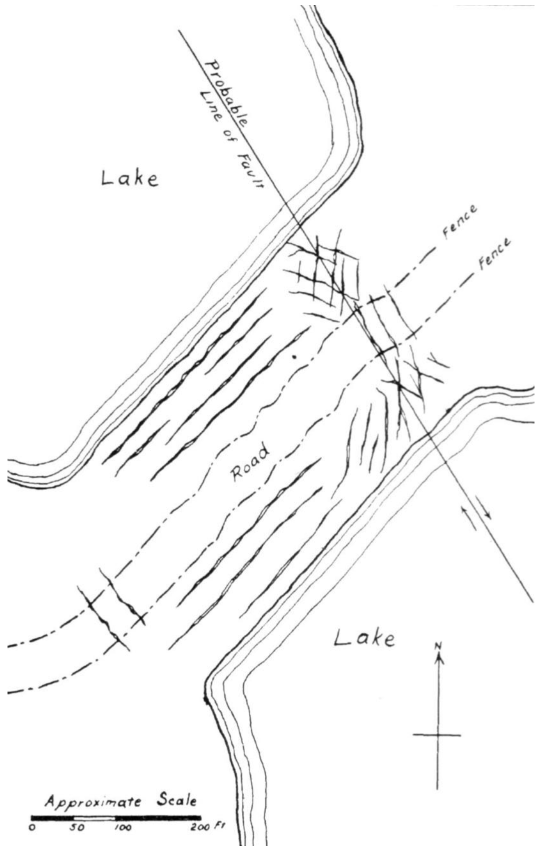


Figure 4.1.21-3. Upper Crystal Springs Dam, (Credit: Taber 1906)

4.2 San Andreas Conduit

During the initial development of Pilarcitos Reservoir, Mr. Schussler, in charge of that construction, identified that the Pilarcitos Creek watershed could actually deliver more water, and that the small dam along the Pilarcitos Creek could not hold back all this water.

Mr. Schussler identified that a dam could be constructed to form a much larger storage basin. SVWC, through agents, proceeded to buy up that land, with an additional 4 to 5 square miles of watershed. The construction of the San Andreas dam commenced in 1868, an earthen dam with clay core, 700 feet long at its crest, and 95 feet high. Schussler called this new storage basin the San Andres Reservoir. Over the years, the reservoir was renamed as the San Andreas Reservoir.

Unrecognized at the time of initial construction, the main trace of the San Andreas fault runs through the native materials near the eastern abutment of the dam (Figure 4.1.11-2).

In 1906, the San Andreas Reservoir could be filled in four ways:

- The reservoir could be partially filled from local drainage.
- The Pilarcitos to San Andreas flume, taking water from the east end of Pilarcitos Tunnel 2, via the Pilarcitos Side Flume to San Andreas Reservoir on its west bank (Figure 4.6-1).
- The San Andreas Reservoir could be filled from a diversion off the Stone Dam, which was built downstream of the Pilarcitos dam to capture the additional runoff from the downstream watershed. A tunnel, flume (locally elevated) and pipe moved this water from the Stone Dam and delivered it into the San Andreas reservoir via a flume on its east bank (Figure 4.6-1). This was commonly the largest source of water.
- The San Andreas Reservoir could be filled via the Crystal Springs pump station, force main and flume that connected with the Locks Creek flume (not often done).

Section 4.1.11 describes the San Andreas Dam. See Figures 4.1.11-1, -2, -3, -4 for nomenclature and orientation.

San Andreas Reservoir was constructed in 1868-1870. The San Andreas conduit was constructed and delivered water from the San Andreas Reservoir via the Bald Hill Tunnel to the College Hill Reservoir in the early 1870s, originally as a 30" diameter wrought iron riveted pipe; later, to increase flow capacity, the southern part of the pipe was replaced (c. 1898) with larger diameter 44" or 37" diameter wrought iron riveted pipe.

In 1897, the Pilarcitos Pump Station was built next to San Andreas Reservoir (just at the east end of the outlet Bald Hill Tunnel) to pump water from the outlet tunnel into the Pilarcitos conduit via a 1250-foot long pipe. This pump station provided redundancy should source water from Pilarcitos have adverse water quality or should Pilarcitos Tunnels 1 and 2 be shut down for maintenance. After the earthquake, this pump station was removed and relocated to be the Precita Valley pump station (see Figure 9-11).

At the time of the 1906 earthquake, the storage volume of San Andreas Reservoir nearly full at about 6 billion gallons. At the time of the earthquake, the San Andreas pipe was transporting water from San Andreas Reservoir (then overflow elevation 445') to the College Hill Reservoir (overflow elevation 255') by gravity flow. The outlet works from San Andreas Reservoir into the Bald Hill Tunnel and thence into the San Andreas pipeline was badly damaged, but still flowed water (see Section 4.1.10 for details). The San Andreas pipe failed in the 1906 earthquake at one location where it was on a trestle spanning over Colma Creek. It took water crews about 62 hours to make the repair and allow water from San Andreas Reservoir to once again flow to College Hill reservoir.

Figure 4.2-1 shows the profile of the San Andreas pipeline at the time of the 1906 earthquake. The numbers "24, 25" at the left side of the "Baden Trestle" over Colma Creek was the location of the broken pipe. This is near the south end of the Holy Cross Cemetery.

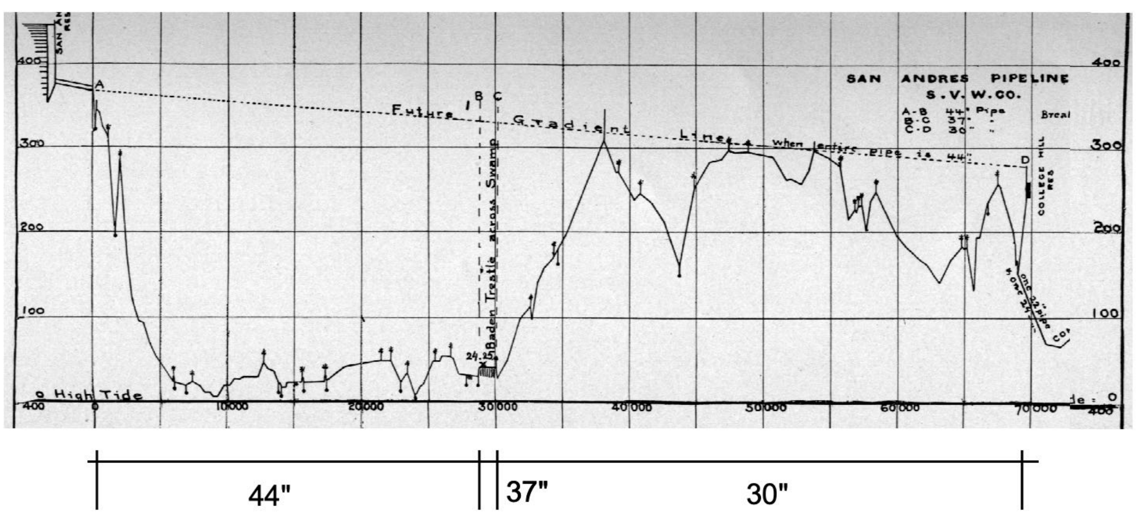


Figure 4.2-1. San Andreas Conduit Profile and Pipe Diameters (SCWV drawing)

Selected features along the San Andreas pipe are listed in Tables 4.2-1, -2, -3. This information is adapted from 1914-vintage survey of the pipe.

Station	Invert Elevation Feet	Invert Diam Inch	Trestle Number, Length	Comment
0.00	366.68	44		Exit Bald Hill Tunnel, Beginning of pipe
0+19		44	Trestle 1 L=52'	
1+24		44	Trestle 2 L=23'	
3-42		44	Trestle 3 L=23'	
18+00		44	Trestle 4 L=57'	
61+11		44	Trestle 5 L=60'	
68+72	20	44		Enters County Rd
140+77		44	Trestle 6 L=30'	
156+65		44	Trestle 7 L=55'	
174+15		44	Trestle 8 L=52'	
230+50		44	Trestle 9 L=15'	

Table 4.2-1. San Andreas Pipeline Features Bald Hill to Baden, adapted from P311 – Dillman Survey, F-258

Station	Invert Elevation Ft	Diam Inch	Trestle, Length	Comment
0.00	56	37		
15+65		36	t=0.25"	950' 36" pipe on 2 trestles
16+18	22	36	Trestle 10 L = 550'	Baden Gulch
25		36	Trestle 11 L = 100'	
25+80		30		
72+07	115	30	Trestle 12 L = 200'	
84	105	30	Trestle 13 L = 400'	
122	115	30		
160	130	30	Trestle 14 L = 60'	
168+80		30	Standpipe overflow 210'	See text: 210' elevation likely wrong
209+40				South line Lake Merced
237	105	30	Trestle 15 with concrete piers	Knowles Gulch L=50' est
268+20	170	30		Lake Merced Force Main
268+40	170	30		Lake Merced Suction Main
270	170	30		Force Main
274+05	188	30		Daly's Hill. Top Standpipe 463.0

Table 4.2-2. San Andreas Pipeline Features Baden to Lake Merced, adapted from P146 – Williams Survey

Station	Invert elevation Ft	Diam Inch	Trestle, Length	Comment
0+00	50			Air Valve
20+00	30			SPRR xing Baden
24+70	45		Bridge Start	AV
34+90	45		Bridge End	AV
53				Baden
64			Pipe Bridge	Failure location 1906
116	312	30	12"ø standpipe	Standpipe Top 348.97 Structure 7 Top 347.78' Holy Cross
183	245	30		Crosses Pilarcitos pipeline
250+11.7	260	30		SPRR
261+86.3	251	30		OSRR
308+65	205	30	Trestle 16 L = 70	
388+68	132	30	Trestle 17 L = 30'	
420+87	190	30	Trestle 18 L = 70'	
428+28.8		30		Standpipe
428+79.6	230	30		Gate
428+90.4	230	30		Flume
428+91.3	230	30		College Hill Res

Table 4.2-3. San Andreas Pipeline Features, Baden to County Line to College Hill, adapted from P191

The Williams survey shows the standpipe near San Pedro at 210' overflow, while the P191 survey shows the same standpipe at 348.97'. There are inconsistencies in the elevations between the two surveys. The 348.97' elevation is consistent with the Bald Tunnel elevation at 367'; the 210' elevation is likely wrong, as water would not flow to the College Hill reservoir with overflow elevation 250'.

Figure 4.2-2 shows the modern (2002) San Andreas Reservoir, along with Interstate 280 to its immediate east. The modern Harry Tracy Water Treatment Plant (see arrow) is along the eastern edge of the reservoir, just before I-280 curves to the north. The eastern shoreline is presently heavily wooded, unlike the situation in 1928 (compare with Figure 4.1.14-1).

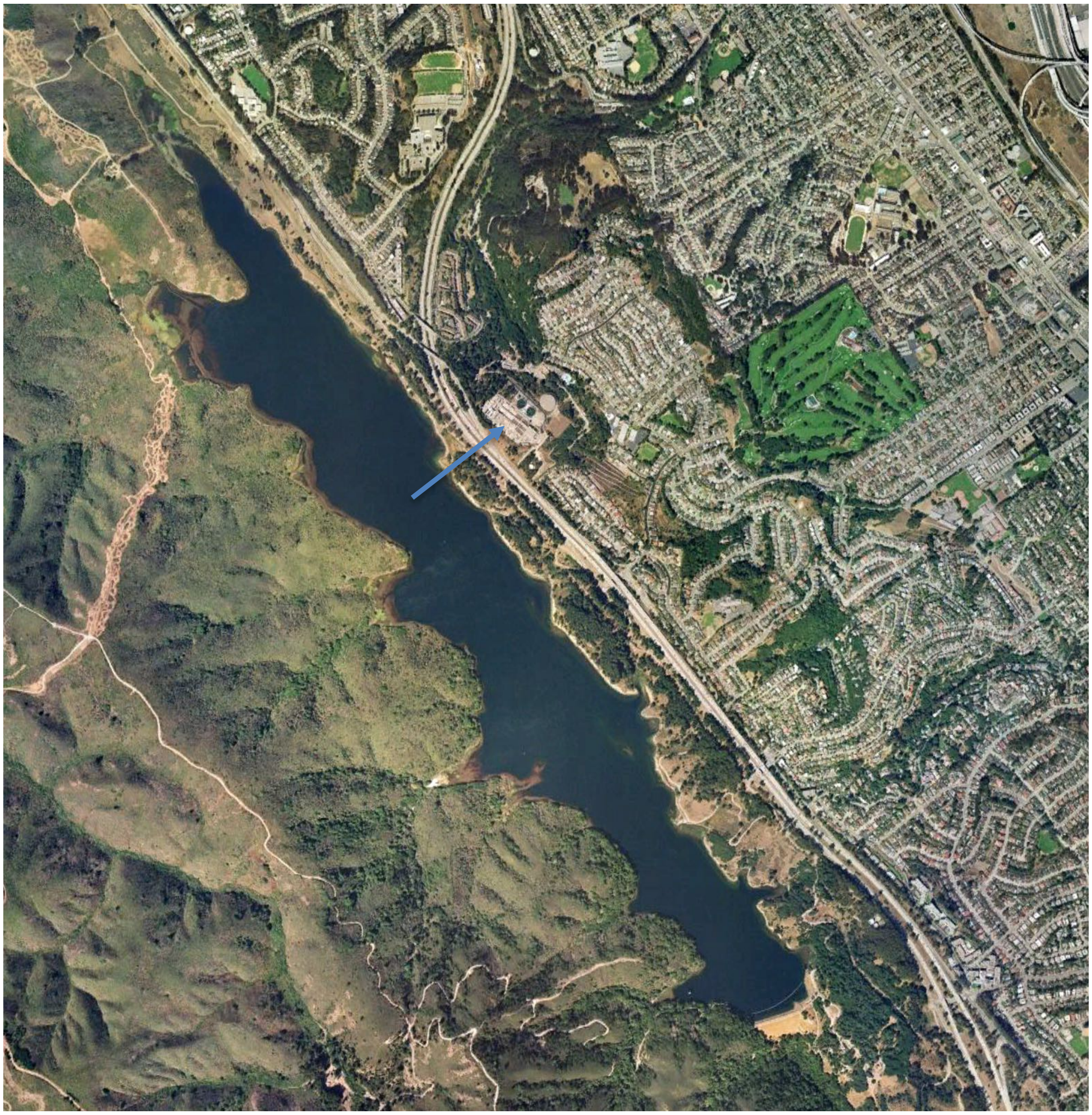


Figure 4.2-2. San Andreas Reservoir (September 2002, courtesy Google)

Figure 4.2-3 shows San Andreas Dam, as of 2020. Compare with Figure 2-22 (1900). The 1906-vintage wastewater brick tunnel (Site 12) has been replaced with a surface level spillway. The 44" wrought iron pipe that filled San Andreas Reservoir with water from Stone Dam has been removed.

Figure 4.2-3. San Andreas Reservoir Dam (September 2020, courtesy Google)

Figure 4.2-4 shows the repair of the 37" San Andreas pipeline atop a wood trestle at Colma Creek, near Baden. At this location, the pipe had a slip joint of the type seen on the Crystal Springs pipeline in the foreground in Figure 4.3-1. The slip joint was formed by inserting two ends of pipe into a larger-diameter steel ring, filled with lead. In this manner, the pipe could contract or expand perhaps a couple of inches or so. These slip joints were used by Schussler adjacent to valves (for purpose of assisting replacement / maintenance of the valve), or along long reaches of above ground pipe (for thermal expansion growth / contraction purposes). Exterior wire ropes were attached to the pipe either side of the slip joint to provide some axial restraint.

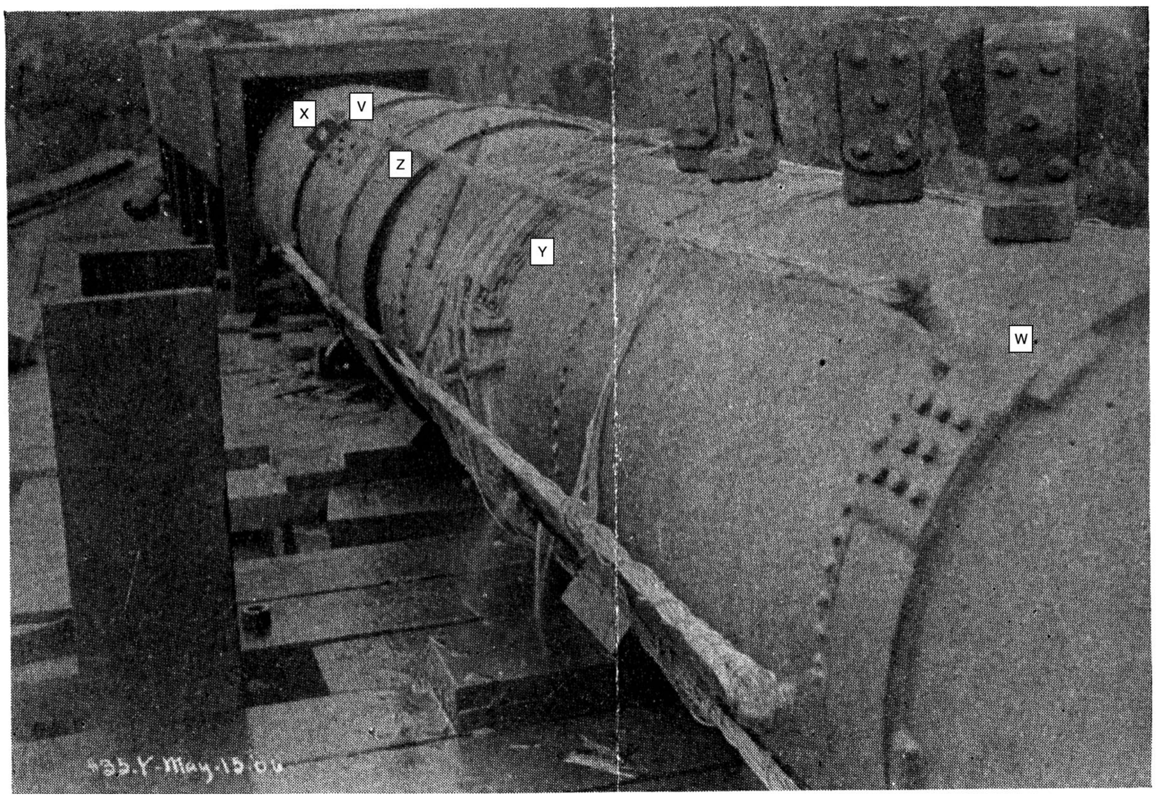


Figure 4.2-4. San Andreas Pipe Repair at Colma Creek Crossing (Credit Schussler 1906 HS24)

At the Baden crossing, the damage consisted of 4 iron lugs that had been torn off by the earthquake, for example see the lug at point "X" in Figure 4.2-4. When the lugs were torn off, they left behind 4 ragged holes in the pipe, each about 8"x 10". The holes were closed by installing patch plates at "Y"; the plates were from an old pipe, put on with tap bolts and rubber gaskets. The assembly was then strapped with wires; thereafter the slip joint at "Z" was straddled by 6 wire ropes between bands "V" to "W".

Near the border with Daly City, there was also a break in a main leading from the San Andreas pipe at Capitol Avenue and Sagamore Street, supplying a small suburban district.

From Schussler's description of the damage and repair at Baden, it can be interpreted that the 37" pipe originally had a slip joint at "Z" that was reinforced longitudinally by tie rods that were attached to the pipe "ears". During the earthquake, the pipe either moved to open at the slip joint (due to long reach of continuous pipe with a single slip joint due to travelling wave phenomena), or bent sideways due to inertial loading of the pipe on the trestle. The travelling wave phenomena is the preferred explanation as to why the joint tried to open during the shaking. As the joint opened, the tie rods underwent tension to try to limit the opening; clearly, the "ears" were put into high tension, and the rivets that held the ears and underlying plate to the main pipe were grossly overloaded and sheared off at the 4 locations.

Figures 4.2-5 and 4.2-6 show the repaired 37" wrought iron San Andreas pipeline at point "Y".

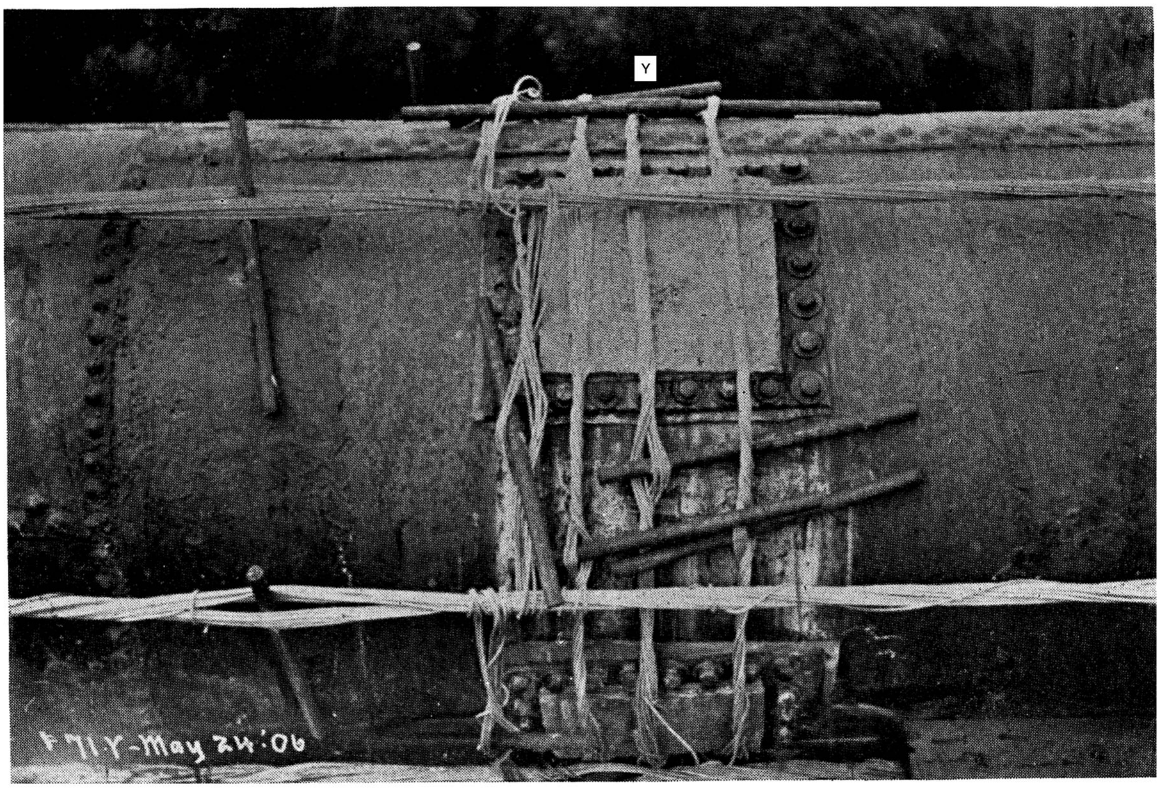


Figure 4.2-5. San Andreas Pipe Repair at Colma Creek Crossing (Credit: Schussler 1906 HS25)

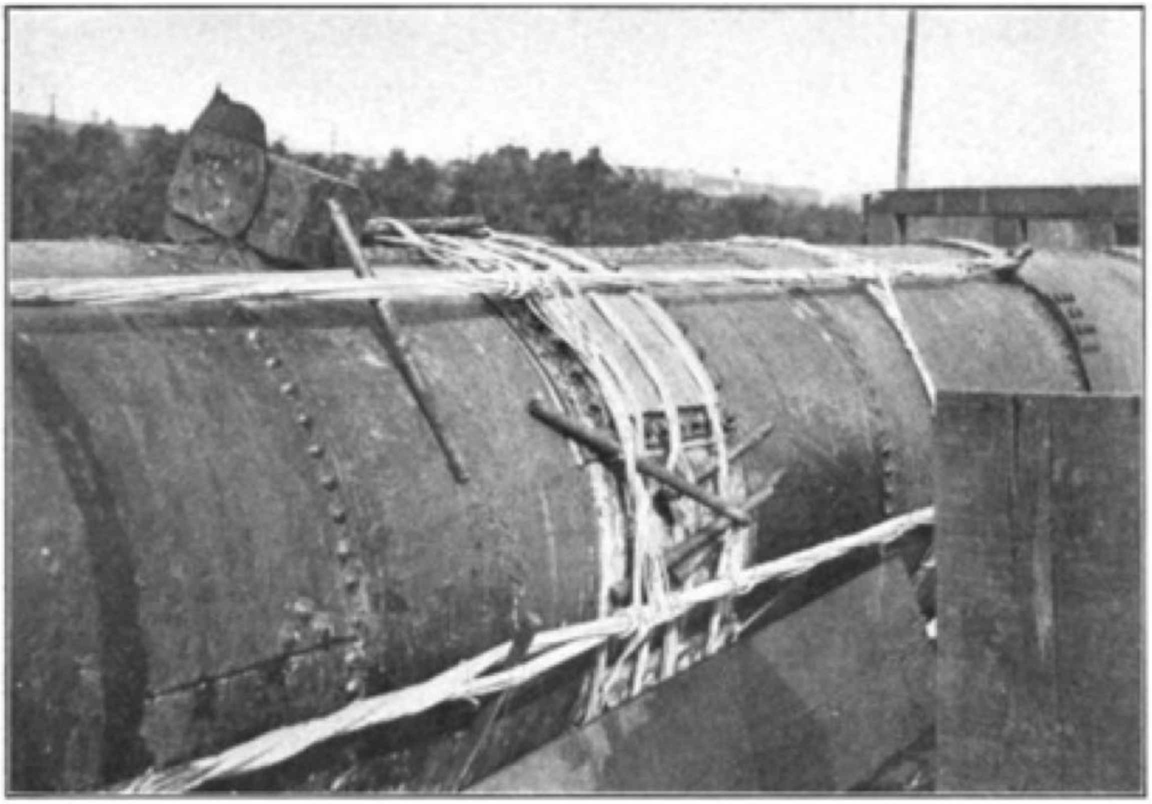


Figure 4.2-6. San Andreas Pipe Repair at Colma Creek Crossing (Credit: ASCE 1907)

Figure 4.2-7 shows College Hill Reservoir, the terminus of the San Andreas pipeline. In the 1906 earthquake, water sloshed out of the reservoir, but no major damage occurred.

Figure 4.2-7. College Hill Reservoir, Terminus of San Andreas Pipeline (Credit: Schussler 1919)

4.3 Crystal Springs Conduit

With the ever increasing demand for water, the Crystal Springs reservoirs were constructed between 1877 and 1890. The Upper reservoir was formed by building an earthen dam in 1877, and impounded water from local creeks. The Lower reservoir was formed by building a concrete dam (sometimes called the Lower Dam or Crystal Springs Dam) between 1887 to 1890. For the Lower Dam, Schussler decided that a stone masonry or concrete dam was more suitable than an earthen dam; lacking a suitable nearby quarry for large stones, he opted for concrete.

Figure 4.3-1. Crystal Springs 44" Pipeline and Gate Valve, At Lower Crystal Springs Dam outlet works, 1888. Note restrained slip joint in lower right of photo. (Photo SVWC)

The Lower Crystal Springs reservoir (the northern-most basin) had its concrete block dam foundation begun in 1887, and was built to elevation 280 feet by 1890.

By the time of the 1906 earthquake, the Lower Dam had been increased in height to an overflow height of 289 feet. With the construction of the Lower Dam, and the water heights of the basins (Upper and Lower) were equalized and floated together, with a combined impoundment capacity of 19 billion gallons when filled to elevation 289 feet. The Upper Dam was increased in height to form the Highway 92 causeway. The long term plan was to eventually increase the height of the Lower Dam to elevation 323 feet, to eventually impound 33 billion gallons; the most recent renovation of the Lower Dam was completed in 2012 with a storage capacity of 22.5 billion gallons.

After the 1906 earthquake, the diversion from Stone Dam, which had spilled into San Andreas Reservoir, was re-routed to spill into Crystal Springs Reservoir.

With the construction of the Bay Division Pipeline #1 in 1923 (see Section 9 for a description of the Hetch Hetchy system), Sunol Valley SVWC water could be delivered into the Upper Crystal Springs Reservoir for purpose of filling the lake. It was not until 1934, with the completion of BDPL #2 and the opening of the recently completed Irvington Tunnel, that Hetch Hetchy water finally spilled into Crustal Springs Reservoir.

At the time of the 1906 earthquake, a brick tunnel conduit through the west side of the Upper Dam served to allow water in both basins to balance. This conduit was damaged by the earthquake (see Site 20, Section 4.1.20) and after the earthquake a 22" pipe was laid as an inverted siphon to balance the lower and upper reservoirs.

In 1924, with the raising of Highway 92 (the Upper Dam), and the completion of the BDPL 1 pipeline, this 22" inverted siphon was no longer suitable. SVWC investigated the damage to the brick tunnel (it had been offset by the fault, see Site 20), repaired it, and put it back into service.

The Lower Crystal Springs Dam is a few hundred feet east of the fault; no damage was apparent in the 1906 earthquake. At the time of the earthquake, the dam had crest height of 146 feet; after the earthquake, it was increased in height to 170 feet.

The clay core of the Upper Crystal Springs dam between the lower and upper basins of Crystal Springs reservoir was offset about 8-9 feet by the fault (see Section 4.1.21 for details). At the time of the earthquake, both basins were at the same elevation, connected by tunnel around the Upper Crystal Springs Dam.

The Crystal Springs pump station, built in 1898, can take water from the Crystal Springs Reservoir (289') and pump it, via pipeline and flume, to the San Andreas Reservoir (465').

In 1889, the Millbrae pump station was built to pump water from the either the Alameda 54" pipeline or the Crystal Springs 44" pipeline into the San Andreas 44" pipeline (see Section 4.4 for further description of the Millbrae pump station).

The 44" Crystal Springs riveted wrought iron pipe was built in 1885, to initially deliver water from the Upper Crystal Springs reservoir to the University Mound Reservoir (165') by gravity flow. With the completion of the Lower Crystal Springs Reservoir in 1890, the 44" pipe was disconnected from the Upper reservoir, and reconnected to the Lower Reservoir (Figure 4.3-1).

The Crystal Springs conduit is described in Table 4.3-1 based on a survey from 1914. The conduit includes 17-trestle-supported sections; 2 bridge-supported sections, and 2 tunnels. The diameter is 44" over its entire length, with pipe wall t = 0.194" (6 gage) or t = 0.179" (7 gage). There are standpipes at the Millbrae pump station and north of Sierra Point, used to control the head.

Station	Invert El. Feet	Diam. Inch	t, gage	Description	Comment
					Top of Reservoir 288.85' (gage 114' = 280' above high tide)
0.00	160.52		7		Top flange AV
0+84.8	149	44	7	Trestle 1 L =100'	6,831 ft 44"
3+00	147	44	7	Trestle 2 L = 160'	
28+06	159	44	7	Trestle 3 L = 80'	
57+	126	44	7	Trestle 4 L = 30'	
62+70	118	44	7	Trestle 5 L = 60'	
68+31	108	44	6		59,735 ft 44"
100+00	78	44	6		
123	120	44	6		Local hill
214	45	44	6	Trestle 6 L = 40'	
226	30	44	6	Trestle 7 L = 45'	
248+50	25	44	6	Bridge 1 L = ?	
264+50	25	44	6	Trestle 8 L = 50'	
282-95	25	44	6	Bridge 2 L = 30'	
342+49	12	44	6	Trestle 9 L = 60'	
462+24.6	21	44	6	Trestle 10 L = 40'	
479+03 493+81.5	15	44	6	Trestle 11 L= 1478.5' on Concrete piers	San Bruno Marsh
541+48.5 571+87.4	5	44	6	Pile Trestle 12 L = 3038.9' on piles	San Bruno Marsh
584+46 587+17	10	44		Trestle 13 L = 272'	
666+01	70	44	7		
666+84		44	7	Sierra Point	
671+81		44	7		
670	70	44	7	Trestle 14 L = 400'	
674	100	44	7	Trestle 15 L = 50'	
681+25.2	165	44	7	Standpipe	
684+62	75	44	6		
693+59	5	44	7		
696+27.4	52	44	7	Trestle 16 L = 90'	

Station	Invert El. Feet	Diam. Inch	t, gage	Description	Comment
706+64.9 709+64	165	44	7	Tunnel 15 L = 299'	
724+98	26	44	6		
731+35.7 750+96.8	2	44	6	Trestle 17 L = 1961'. Piles	Guadalupe Valley
751+64	17	44	7		
759+96.9	169	44	7	Standpipe	
797+98	17	44	6		
799+33.4 806+99	4	44	6	Trestle 18 L = 766'	Visitacion Valley
857+75 879+31.9	169	44	7	Brick Tunnel L = 2145'	
883+64.8	106	44	7	Trestle 19 L = 110'	
894+40	150	44	7	Standpipe Top 172.6	
896+68.52	162	44	7	Top Rese 171.5'	University Mound

Table 4.3-1. Crystal Springs Pipeline Features (1914) from P251

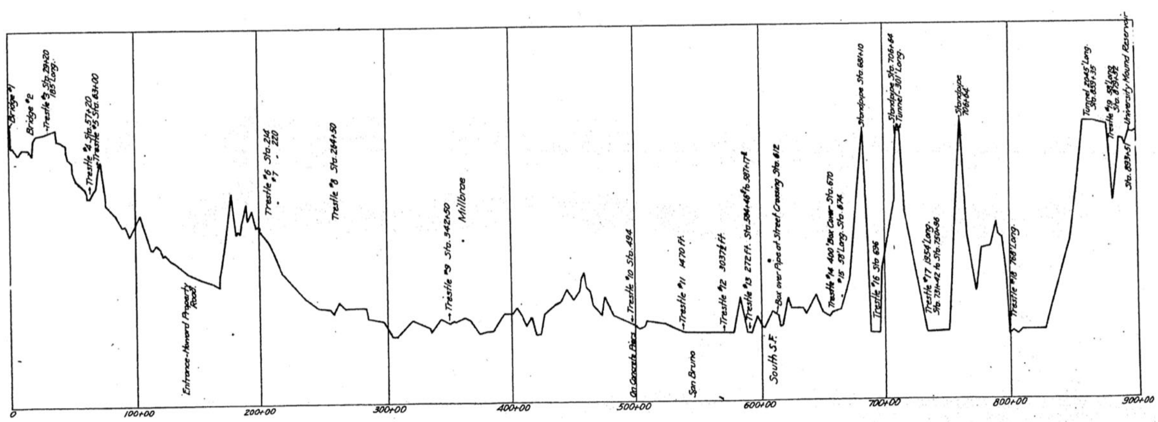


Figure 4.3-2. Crystal Springs Pipeline Profile Condensed (Based on SVWC Drawing 1914)

Figure 4.3-3 shows the 44" pipe being installed along El Camino Real in San Mateo, c. 1885-86.

Figure 4.3-2. Crystal Springs 44" Pipeline Being Installed, El Camino Real, 1888 (Journal of the San Mateo County Historical Association, Volume xlvi, No. 1, 2018)

Figure 4.3-4 shows locations of 7 spots ("X"s) of damage on the 44" pipeline between the Crystal Springs Dam outlet and south of the Millbrae pump station.

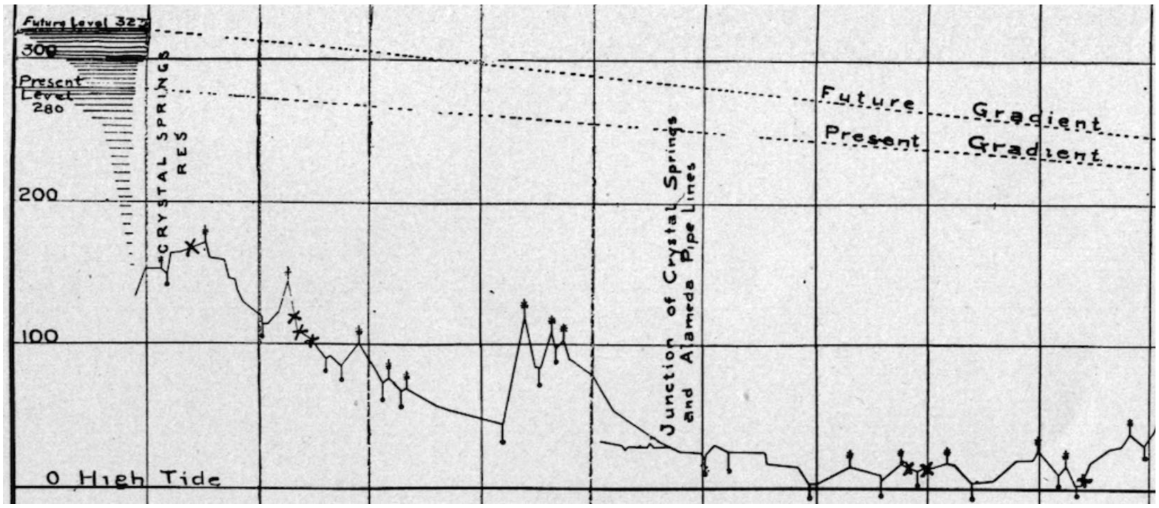


Figure 4.3-4. Location of Upper Crystal Springs 44" Pipeline Damage ("X"s) (Schussler 1906)

Table 4.3-2 lists the locations of observed damage to the Crystal Springs pipe, based on the noted locations in Schussler (1906).

Station (Approx)	Invert El. Feet	Diam. Inch	t, gage	Description	Damage Location Number
20	160	44	7		1
69	120	44	7		2
70	110	44	7		3
75	101	44	7		4
340	25	44	6	Close to Trestle 9	5
350	25	44	6	Close to Trestle 9	6
420	25	44	6		7
545	5	44	6	On Trestle 12	8 San Bruno Marsh
550	5	44	6	On Trestle 12	9 San Bruno Marsh
560	5	44	6	On Trestle 12	10 San Bruno Marsh
565	5	44	6	On Trestle 12	11 San Bruno Marsh
570	5	44	6	On Trestle 12	12 San Bruno Marsh
740	5	44	6	On Trestle 17	13 Guadalupe Valley
745	5	44	6	On Trestle 17	14 Guadalupe Valley
805	5	44	6	On Trestle 18	15 Visitacion Valley
810	5	44	6	On Trestle 18	16 Visitacion Valley

Table 4.3-2. Locations of Damage along Crystal Springs Pipeline 1906

Figure 4.3-5 shows an exposed segment between San Mateo and Millbrae, soon after the earthquake. Here, the buried pipe has been exposed and isolated to stop the flow northwards towards San Francisco, and thus maintain pressure and supply for the City of San Mateo.

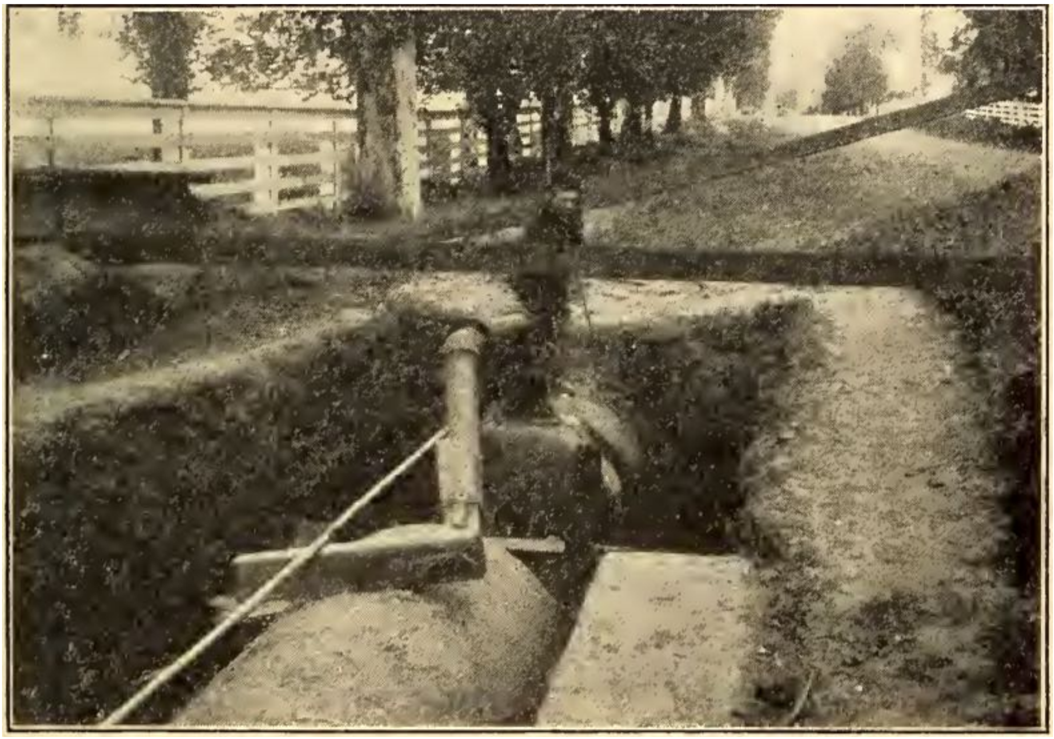


Figure 4.3-5. Crystal Springs Pipeline between San Mateo and Millbrae (Photo: Derleth, 1907)

Trestle 11 is at the southern end of San Bruno Marsh, see Figure 4.3-6. It is 1,470 feet long. The 44" pipe sat atop 2x12s that in turn sat atop 4x12 transverse sills that sat atop concrete piers at 14' spacing. A light wood enclosure is placed around the pipe for corrosion control. There were 105 concrete piers, with 103 of them being 3 feet tall, and 2 of them being 6 feet tall. Unlike Trestle 12, there was no reported damage atop Trestle 11. Perhaps this reflects the shorter (and stiffer) concrete piers for Trestle 11 versus the longer (and more flexible) wooden piles for Trestle 12.

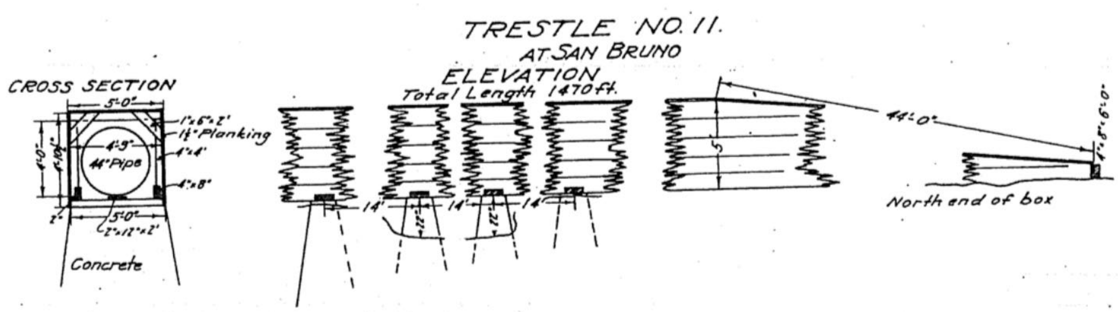


Figure 4.3-6. Crystal Springs Trestle 11 (1,470 feet long)

The drawings below show some of the repairs along Trestle 12. The station numbers are to the closest ±500 feet or so, following the station numbering in Table 4.3-1, based on Schussler (1906).

Trestle 12 is 3,038.9 feet long, see Figure 4.3-7. It consists of wood pile supports spaced at 14 feet.

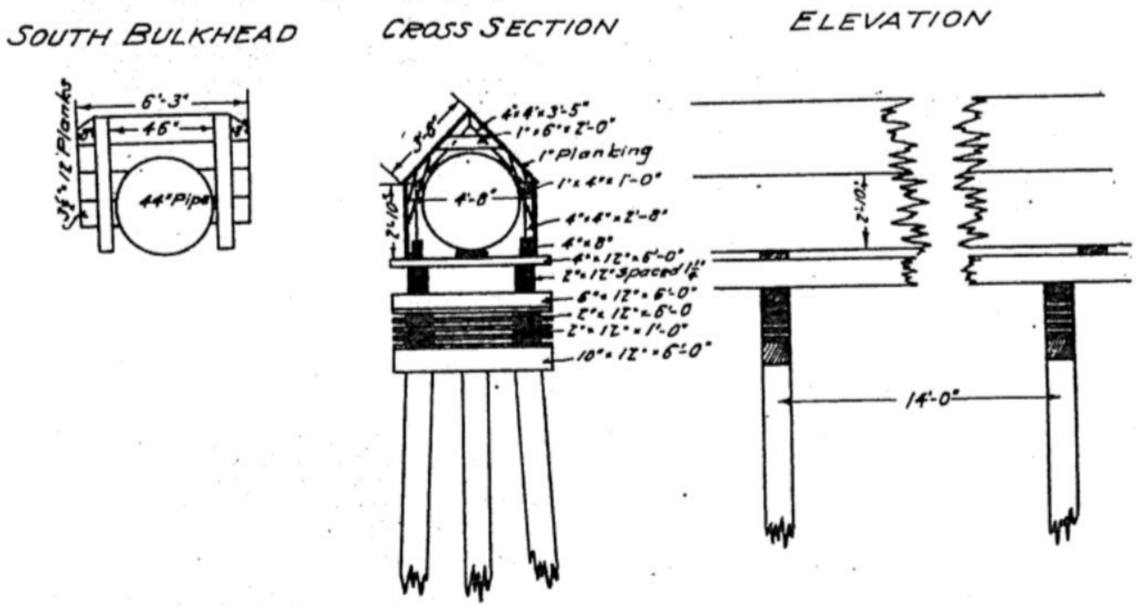


Figure 4.3-7. Crystal Springs Trestle 12 (3,039 feet long) (SVWC Drawing)

Figures 4.3-8 and 4.3-9 show the details of the wood trestle that supported the pipe through Guadalupe and Visitacion Valleys, respectively. The pipe failed at multiple locations atop both these trestles. The trestle details are very similar to those at Trestle 12, where the pipe also failed at multiple locations. There are 140 support bents (Guadalupe), or 54 support bents (Visitacion Valley) at 14-foot spacing. The available historical evidence suggests that the pipe had restrained slip joints at about 500-foot spacing, or likely at about 4 locations along these two trestles. Under high lateral inertial loading, the pipes would impart high lateral loads on the longitudinal stringers, which would have a tendency to roll over.

The historical records suggests that the pile system was not damaged in the earthquake. Trestles 11, 12, 17, 18 all traverse mapped liquefaction zones. We interpret that liquefaction, per se, did not directly lead to the pipe failures at these locations.

The question arises: why did the pipe not fail atop the other 15 trestles along the Crystal Springs alignment? Was there something "special" about the design of these three specific trestles that led to the multiple failures? There are several hypotheses:

- Long trestles were prone to pipe failure, short trestles were not prone to pipe failure. This hypothesis has some merit. Short trestles 1, 3, 4, 5, 6, 7, 8, 9, 10, 16 had no observed pipe failures. All these trestles are under 100 feet long.

- For very short trestles, there may not have been any thermal expansion joints on the pipe. Without expansion joints, the pipe would behave at a beam, and for moderate lengths, could likely withstand inertial loading on the order of 1g sideways, for lengths on 40 to 60 feet or so; the weak spot would be excessive high bending moment on the riveted girth joints, and as long as those loads were less than about 50% to 75% of pipe yield level, the girth joint would be okay.

- Through the marsh lands, the soils are deep and soft. This leads to amplified ground motions at medium periods, especially 1 second or longer. Trestles 11, 12, 16, 17, 18 all traverse zones mapped as having high liquefaction susceptibility, and also would have amplified longer period ground motions. But, the historical evidence for the damage atop trestles 12, 17, 18 implies that the pile systems were practically undamaged, but the lumber above the pile cap was a tangled mess; and the pipe fallen off the trestles onto the adjacent ground, with no damage to riveted girth joints, but pulled apart at expansion joints. Segments with broken expansion joints would likely also have torn out the lugs on the restraining cables, in a manner similar to the San Andreas pipeline at Baden (see Section 4.2).

- Trestle 11 was built using shallow concrete piers. Trestles 12, 17, 18 had long wood piles. The more flexible Trestles 12, 17 18 would have tended to amplify long period shaking of the flexible supported pipe.

- The built-up stacks of lumber ("shims") needed to establish a flat grade for the pipe, as used in Trestles 12, 17, 18, would have been a weak lateral load path.

- What were the original lateral design loads on these trestles? It is quite clear that Schussler had no guidance to quantify earthquake loads. But, certainly he would have had the trestles designed for wind loads. The practice for design for wind loads in the 1880s time frame might have been to design for a static pressure from 20 psf to 30 psf. Assuming 30 psf, the lateral force over a 14-foot span would have been 30 psf x 6 feet (typical vertical exposure) x 14 feet = 2.5 kips. Most likely, the wood structure could sustain that force.

From a seismic point of view, the forces would been about:

- Lumber: about 420 pounds per foot on pipe length (about 20 board feet of lumber per foot)

- 44" pipe (6 gage, t = 0.194"). Area = 26.8 square inches.

- Pipe Weight = 92 pounds per foot (steel pipe plus rivets)

- Pipe Water Weight = 660 pounds per foot (water contents)

- Total weight per foot 1,170 pounds
- Total weight per 14 foot span = 16,400 pounds
- PGA = 0.4g (approximate best estimate median transverse)
- Spectral Acceleration (T = pipe frequency, 5% damping) ~ 1.0g
- Seismic horizontal force per span ~ 16 kips
- The seismic lateral force of about 16 kips would be applied each horizontal direction at the pier caps. A comparable vertical force would also have been applied to the combined pipe – trestle system.
- Coupled with these inertial loads are seismic-induced water hammer forces near elbows and bends, plus incremental loads due to settlements and/or lateral spreads.

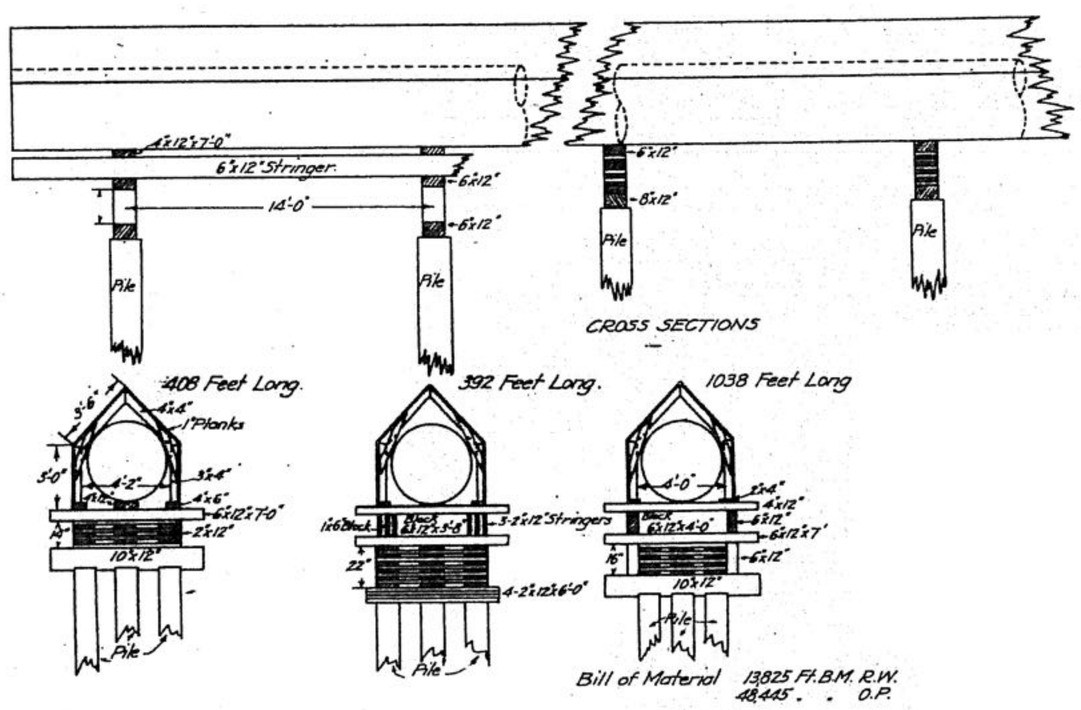


Figure 4.3-8. Crystal Springs Trestle 17 (1,961 feet long) Guadalupe Valley (SVWC drawing)

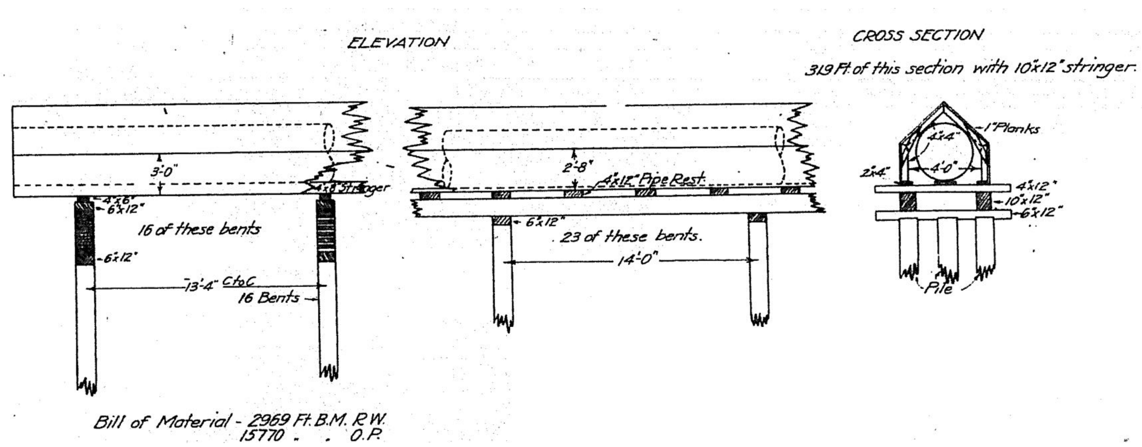


Figure 4.3-9. Crystal Springs Trestle 18 (766 feet long) Visitacion Valley (SVWC drawing)

The University Mound Reservoir was originally constructed as a 33 MG open cut reservoir in 1878, and received water from the 44" pipeline. In 1898, a large screenhouse, with a capacity to screen 16 million gallons per day, was built at the University Mound Reservoir. This screenhouse served to improve the quality of the water leaving the University Mound Reservoir and into the City Distribution system.

The Crystal Springs pipe is a 17-mile long wrought iron pipe, 44" diameter. Girth seams were connected using rivets. Most of the pipe was buried in trenches, with the exception of where the pipe traversed through 7 "swamp" zones, where it was supported on wooden trestles that have previously been described.

In the above ground sections, the pipe was encased in wooden boxes. The wood boxes were an attempt to limit external corrosion due to salty fogs or where the pipe traversed over alkaline soils. Decades later, it was determined that the damp environment outside the pipe and inside the wooden boxes promoted the growth of fungus on the outside the metal pipes, promoting erosion and pitting of the exterior of the pipes. By the 1950s, all remnants of these wooden boxes had been removed on the similarly-installed Bay Division pipelines across the bay, the pipe surfaces scoured; and this erosion process was effectively stopped.

In the marsh zone north of Colma (now mapped as a high liquefaction susceptibility zone), the 44" Crystal Springs pipeline was thrown off its trestle for a distance of 1,300 feet (variously reported as 2,850 feet over all trestles).

Overall, the 44" Crystal Springs pipeline was also damaged at several locations:

- Buried section, parallel to and just north of San Mateo Creek, to the east of the Lower Crystal Springs Dam. Damaged at 7 locations.

- Trestle 12, across San Bruno Marsh (Colma Creek). Worst damage, over a length of about 1,600 feet (variously reported as 1,300 feet). Here, the pipe rested on a wooden floor, supported by pile bents. The pile penetration was commonly 40 feet. After the earthquake, the pipe was replaced atop a re-built trestle, taking 28 days. The trestle had to be rebuilt, as many of the timbers had rotted. Few (if any) of the piles had to be rebuilt. Humphrey (in Lawson 1908) reported that the where the Crystal Springs 44" pipeline failed atop a trestle crossing Colma Creek, the pipe had telescoped 42 inches, shearing off a 8" gate valve. Along the long trestle through the San Bruno marsh, the 44" pipe was thrown off the trestle by 4 to 5 feet, either in a easterly or westerly direction.

- Trestle 17, across Guadeloupe Valley.

- Trestle 18, across Visitacion Valley.

In the three trestle-supported segments, the pipe was thrown completely off the trestles; the trestles were demolished above the pipe and cap foundations (but no damage in most cases to the piles). A total of 2,580 feet of pipe was thus affected. Some pile caps were crushed, possibly when the pipe jumped upwards and then came down with high impact loading. The timber pile caps were bolted to the tops of the wooden piles.

One ~800-foot long section of the 44" pipe, lying on the ground to the west of the trestle, was so curved that is made quite a snake-like appearance; this pipe was carefully examined, and observed that there was no damage to the girth joints, nor the asphaltum coating. Survey was done and showed that the piles and pile caps had not settled or otherwise displaced during the earthquake. The damaged trestle was repaired, and the 800-foot long pipe lifted back into place.

At the three trestle locations, the pipe was made of laminated wrought iron, 6 gage in thickness and with 0.5" diameter rivets used for girth joints. Hoop stress, near the Bay Shore, under hydrostatic conditions with high Lake level and 300 feet of head (considering a future increase in dam height) would be about 300/2.31 * 22 / 0.194 = 14,730 psi.

Figures 4.3-10 to 4.3-16 show the pipe in various stages or repair atop the Trestle 12 at San Bruno Marsh (now called Colma Creek liquefaction zone).

Figure 4.3-10 shows the pipe in the process of being rebuilt on a wood trestle. The opening in the pipe is to receive flexible strapped lead joint. San Bruno Mountain in background. There are wooden telephone poles to the right (east). The shoreline of San Francisco Bay is to the right (east) of the pipe.

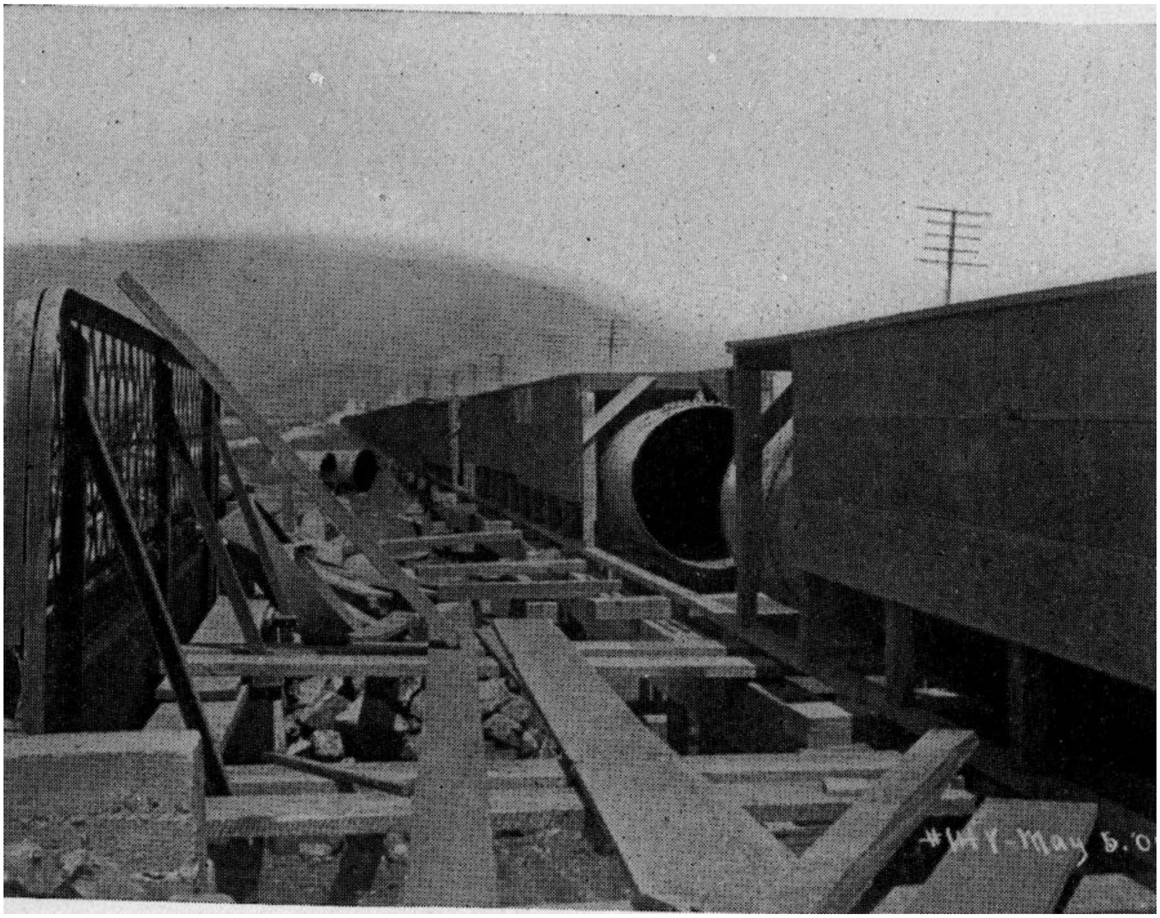


Figure 4.3-10. Crystal Springs 44" at San Bruno Marsh (Colma Creek), showing repair process. View looking northeasterly. (Photo: Schussler HS20)

Figure 4.3-11 shows the 44" Crystal Springs pipe atop the trestle at San Bruno Marsh. The blocking and stringers are made of 2-inch thick wood planks. The riveted girth joint indicates 80 rivets for about the circumference. The handrail in the foreground is for a steel bridge. This photo was taken May 7, 1906, 20 days after the earthquake: the repair of the pipe is then about two-thirds complete.

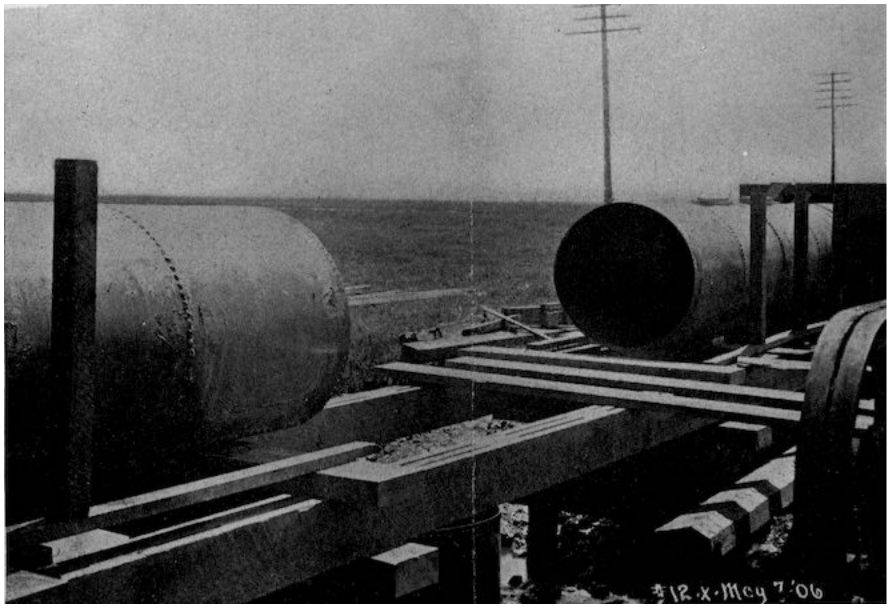


Figure 4.3-11. Crystal Springs 44" at San Bruno Marsh, showing repair process. Photo viewing southeasterly. (Photo: Schussler HS21)

The trestle design appears to be as follows:

- See cross section (middle) in Figure 4.3-7.

- The 44" pipe lies directly on 4x12s. These are nominally spaced at 14 feet, but in practice, at intervals as little as 4 feet. The pipe can easily span 14 feet, so the extra support at shorter intervals is not required for dead load. The pipe contact with the 4x12 provides gravity support, but no lateral resistance (except for minor friction). This design contrasts with the shaped wooden saddles that underlie the Alameda 36" pipe across the San Francisco Bay, which performed without major damage in the 1906 earthquake.

- The beginnings of the wood "box" around the pipe are being formed. These boxes could provide some lateral support for the pipe, but the bending moment capacity of the 4x4 posts to the 4x12s is far too weak. Practically, they are nearly worthless for seismic resistance under high seismic loading.

- The 4x12s are supported by two longitudinal stringers. The longitudinal stringers are composed of 3 parallel 3x12 stringers. At other locations, the stringers are 6x12. These stringers span 14 feet between piles.

- The stringers are supported atop a 6x12, laid flat, 7 feet long, at 14 feet spacing.

- The 6x12s are supported by built-up lumber to achieve the correct height for the pipe. This lumber is a mesh if 2x12s and 1x12s, laid flat.

- This mesh of lumber is supported by a 10x12 pier cap.

- The 10x12 pier cap is supported by 3 12-inch diameter piles. The piles are driven to a depth to assure they are able to support the dead load of the pipe, likely with a minimum factor of safety of 2 (likely higher).

Figure 4.3-12 shows the 44" Crystal Springs pipe atop a trestle at San Bruno Marsh. The pipe enters from the right from "firm" marsh on original bents and stringers, to "soft" marsh on left. The photo is dated May 7, 1906, showing the reconstructed blocking on pile caps and plank stringers.

The purpose of the wood box around the pipe (sides and top) was an attempt to limit the salty air environment from attacking the exterior of the pipe. The riveted girth joints are spaced at about 3.5 feet.

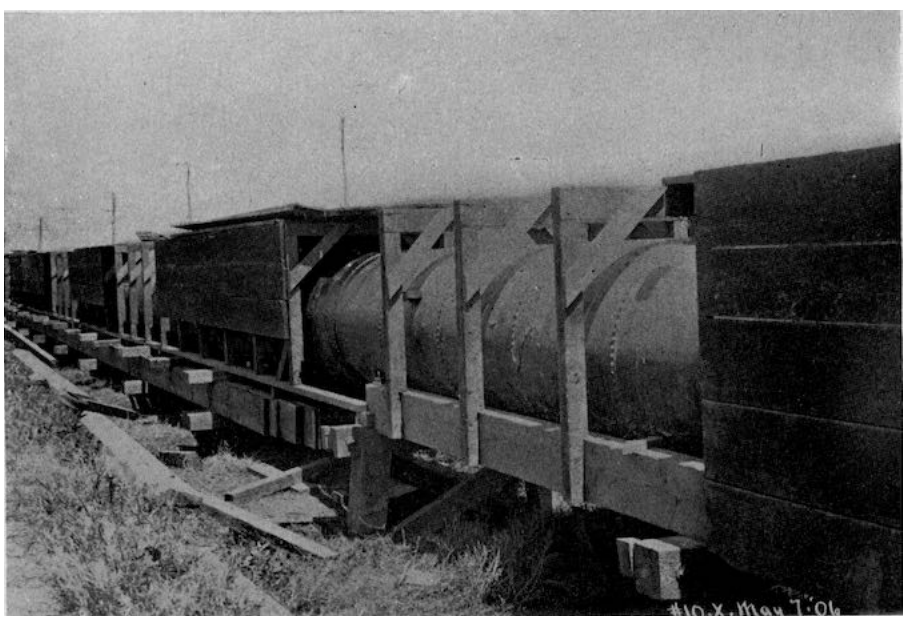


Figure 4.3-12. Crystal Springs 44" at San Bruno Marsh (Trestle 12) (Photo: Schussler 1906 HS22)

Figure 4.3-13 shows a flexible joint installed along the pipe, with the photo taken a few days later, at the same location as Figure 4.3-10. This joint is similar to that used for the 37" San Andreas pipe across Colma Creek. The ropes used to restrain the expansion joint are made of four 1"ø galvanized wires. The slip joint is packed with lead.

The need for slip joints for the above ground pipe is predicated that the pipe must be allowed to expand / contract a considerable amount over a 3,000 foot run, when the pipe is empty. For example, the change in the strain in the pipe for a temperature change from 40°F to 80°F over 3,000 feet is 0.0000065 * 40°F = 0.000260. Without any expansion joints, this would put the pipe into 7.5 ksi compression on a hot day. With expansion joints, the pipe can be kept unstressed, but the joints would need to be able to open / close about 9.4 inches over this 3,000-foot long stretch. Assuming Schussler allowed for each joint to take ±1 inch of movement for a 40 degree temperature swing, there might be as many as 9 or 10 joints over the length of the trestle. The net result is that the pipe would have 9 or 10 slip joints along its 3,000 foot length.

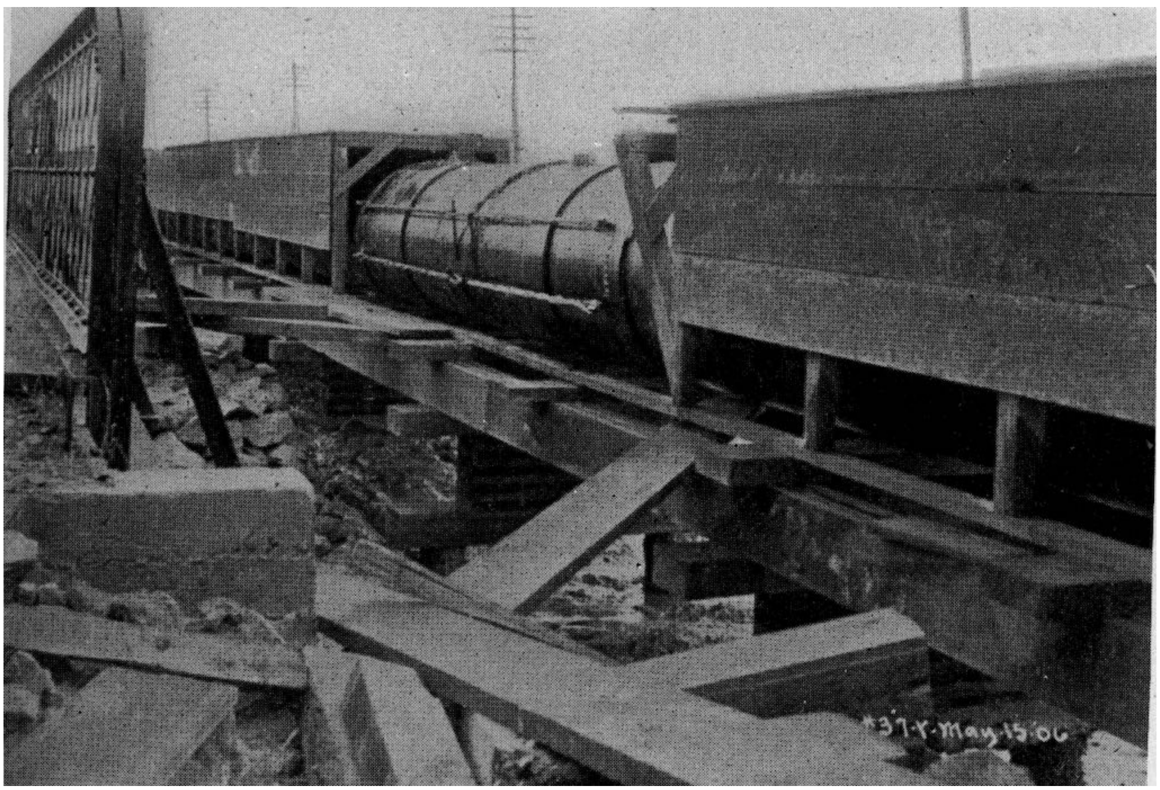


Figure 4.3-13. Crystal Springs 44" at San Bruno Marsh, showing original pile foundation and caps. The plank stringers and blocking are made of 2x12 redwood, spiked cross and lengthwise and 6x12 pine caps. (Trestle 12) (Photo: Schussler 1906 HS23)

Figure 4.3-14 shows the damaged Crystal Springs pipeline during the restoration process (about May 2, 1906) where it has already been placed back atop the trestle in the San Bruno Marsh area. The open pipe is awaiting connection, likely with a slip joint. The wood “box housing” has not yet been installed.

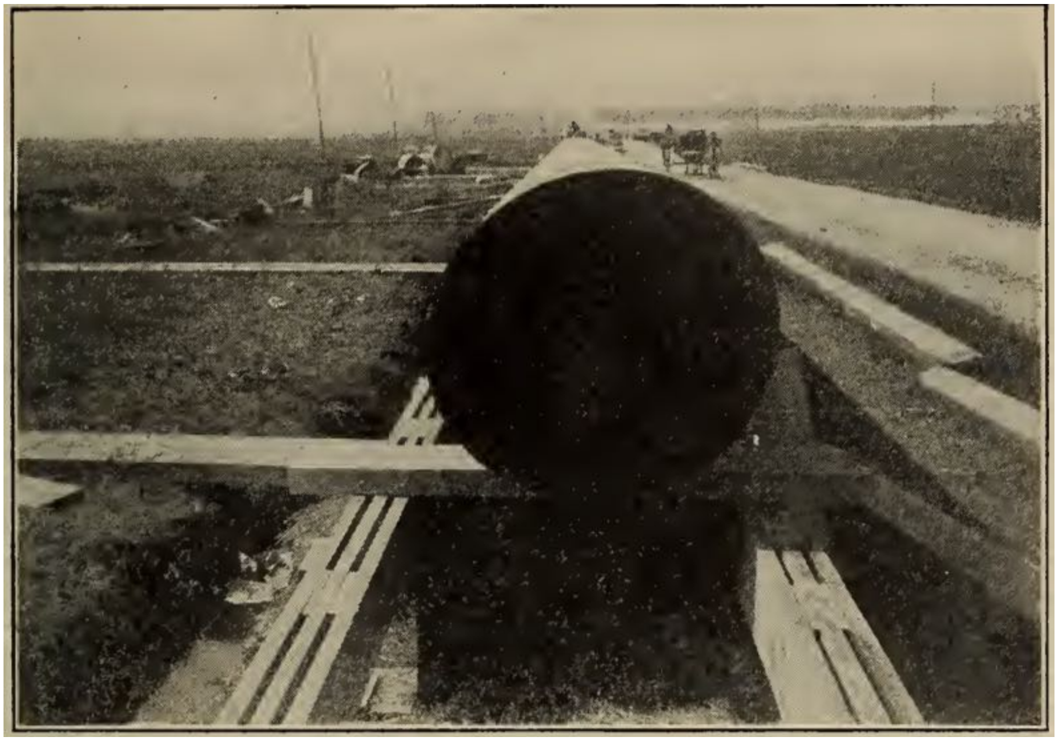


Figure 4.3-14. Crystal Springs 44" at San Bruno Marsh, during the repair process (Photo: Derleth 1907)

Figure 4.3-15 shows the Crystal Springs Pipeline repair process as of May 2, 1906. Here, the riveted pipe segments that had fallen off the damaged trestle, have been restored atop temporary stacked wood supports akin to the detail in Figure 4.3-7; and two segments of the pipe have been positions awaiting connecting the girth joints by rivets. Redwood planks were sometimes used for the temporary sills and stringers in part because larger timber was not quickly available.

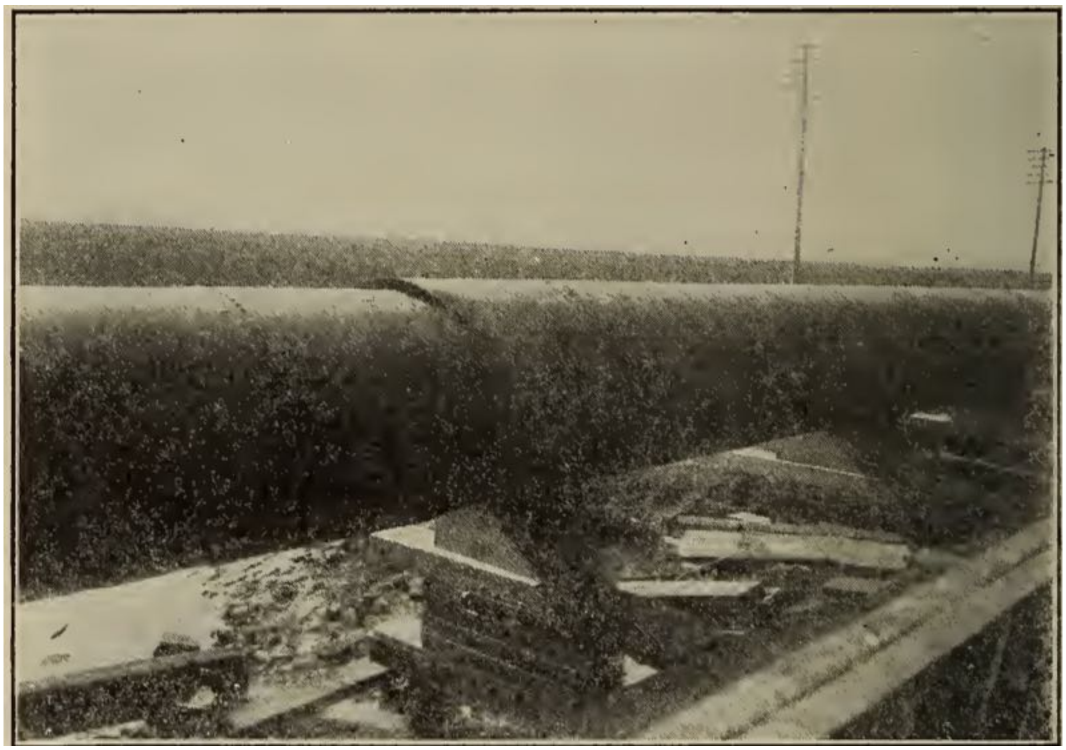


Figure 4.3-15. Crystal Springs 44" at San Bruno Marsh, during the repair process (Photo: May 2, 1907 Derleth)

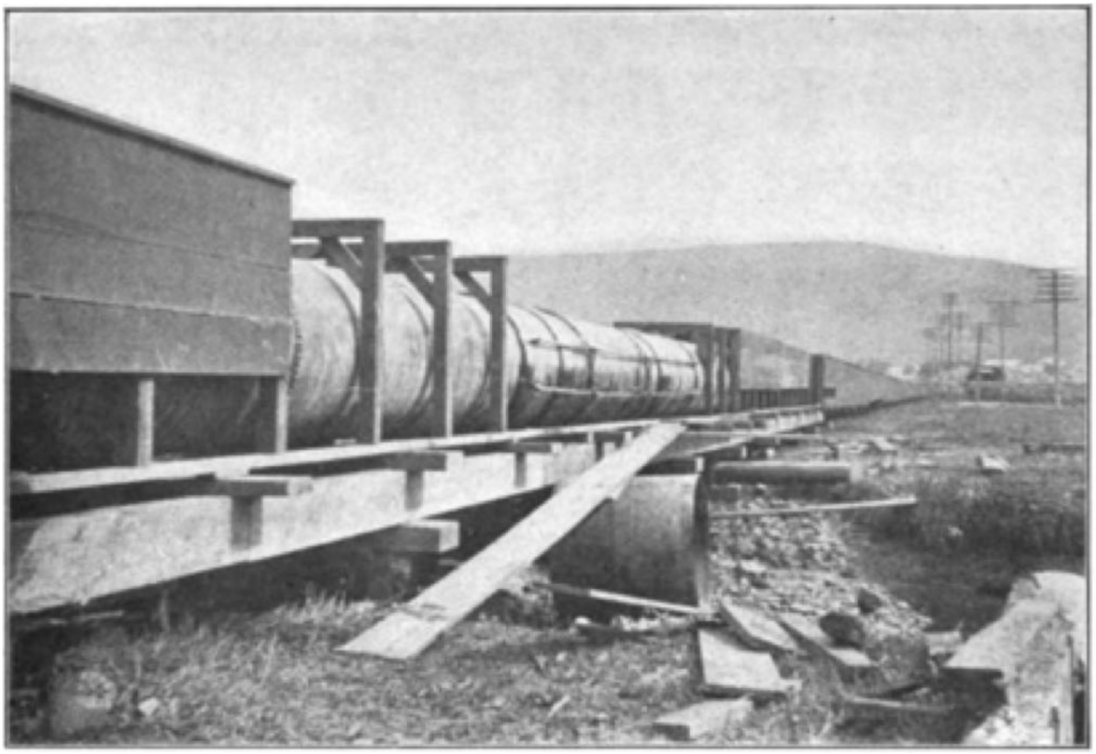


Figure 4.3-16. Crystal Springs 44" at San Bruno Marsh, during the repair process (Photo: ASCE 1907)

Figure 4.3-17 shows the 44" pipeline after the 1906 earthquake. The photo is taken looking north, with San Bruno Mountain in the background.

Figure 4.3-17. Crystal Springs Pipeline after the 1906 Earthquake, through San Bruno Marsh (Photo: SFPUC)

In contrast to this 1878-vintage design, which was apparently repeated in the 1906-vintage repair, Schussler opted for a better design for the 1898-vintage Alameda 36" pipe. That pipe is supported on ~16,500 feet of wood trestles across the Dumbarton Strait. While the level of shaking there was perhaps half of what it was at the San Bruno Marsh, the sliding wood saddle system provided a lot of lateral resistance (before friction is overcome), and once sliding, provides a lot of damping. The net result was no failures of the 36" Alameda pipeline, but massive failures of the 44" Crystal Springs pipeline.

4.4 Alameda Conduit

In the late 1800s, Spring Valley Water Company had purchased major tracts of land and obtained water rights from Alameda Creek and other drainages and wells in the Livermore Valley.

By 1888, a diversion dam had been built along Alameda Creek (west of the Niles Canyon), and a flume delivered that water to the 36" Alameda riveted wrought iron pipeline. That pipe crossed the bay as twin 16" submarine pipes across Newark Slough and the Dumbarton Strait. The water pressure was boosted at the Ravenswood pump station, and the water then continued to the Belmont pump station, where it was again boosted to match the gradient from the Crystal Springs Reservoir, and the 36" pipe connected to the Crystal Springs 44" pipe near Burlingame.

By 1900, diversion works were bult to collect the surface water in (east of the Niles Canyon) and deliver that water into the Sunol Aqueduct. The Sunol Aqueduct consisted of five tunnels and four flumes, traversing through the Niles Canyon. At the west end of the canyon were the Niles Tanks. The 36" pipeline was connected to the Niles Tanks. With source water from the Sunol Aqueduct, the downstream option of obtaining water from the Almeda Creek west of the Niles Canyon was rarely used.

By 1903, the Alameda pipeline was upgraded to a higher flow rate by installing 2 more 22" submarine pipes under the Bay, an upgraded Belmont pump station, and a new 54" pipe paralleling the 44" Crystal Springs pipeline, to the Millbrae pump station. At the Millbrae pump station, water could continue, joined with water from Crystal Springs reservoir, to the University Mound Reservoir at a rate of 25 MGD; or some of the water could be pumped into the San Andreas pipeline to be delivered to the College Hill reservoir.

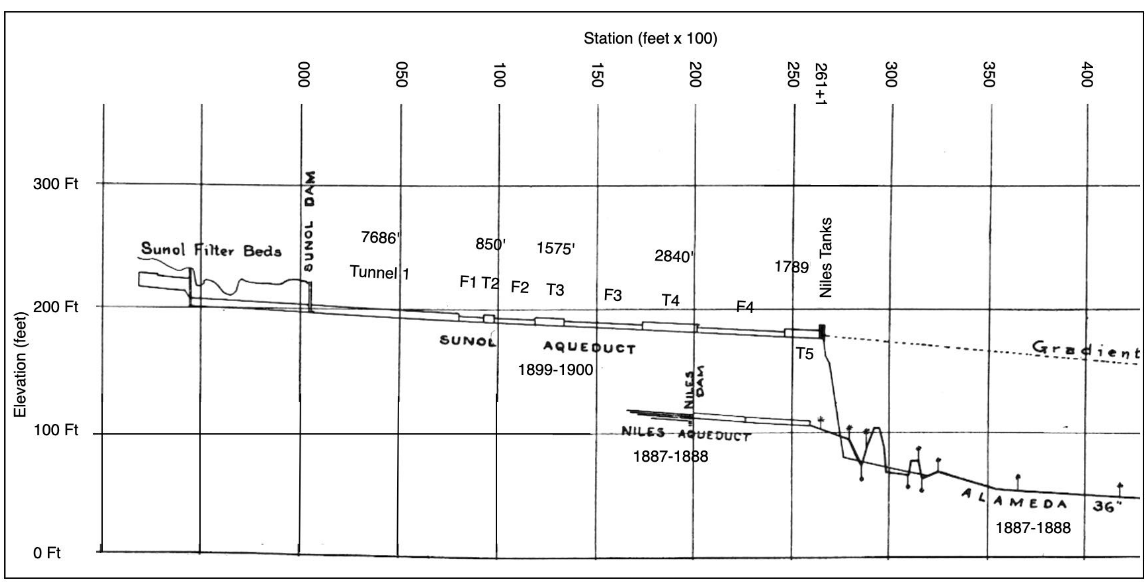


Figure 4.4-1. Sunol Aqueduct and Niles Aqueduct Hydraulic Profile (SVWC drawing)

Table 4.4-1 shows the key points along the Alameda alignment. Elevation is Crystal Springs datum.

Station (From Sunol Dam)	Invert El. Feet	Diam. Inch	t (gage or Inch)	Description	Comment
0+00 76+85.5	197			Tunnel No. 1	Sunol Dam
76+85.5 86+91.5	189.53			Flume 1	
86+91.5 95+41	189.3			Tunnel No. 2	
95+41 114+09.6	188.35 187.29			Flume 2	
114+09.6 129+85.8	187.29 185.88			Tunnel No. 3	
129+85.8 170+29.5	185.88 183.38			Flume 3	
170+29.5	183.38			Tunnel No. 4	
198+69.5	181.38			Flume 4	
243+21.5 261+10.9	178.14 175.45			Tunnel No. 5	Niles regulating tank
261+64.1	171.71	36	7		Begin 36" Pipe
309+00.7	69	36	9		
403+30	47	36	9		
434+68	42	36	0.25"		Railroad crossing
435+99	42	36	7		
440+49	40	36	9		
462+66	33	36	7		
581	12	36	0.25"		Under SPRR Newark
582+10	12	36	7		
624+44.9	3	36	7		Begin 2,686' on Mud sills
652	4	36	7	Trestle	
741+13	4	36	7		
741+13		2-16 2-22		Submarine L = 790'	Newark Slough
745+71.9	4	36	7	Trestle	
821+12.7 885+47	-58	2-16 2-22		Submarine L = 6,434'	Dumbarton Strait
885+47.4	4	36	7		
912+28.9	4	36	7		Ravenswood Booster
982+86.3	9	36	7		
1116+34.1	15	36	9		

Station (From Sunol Dam)	Invert El. Feet	Diam. Inch	t (gage or Inch)	Description	Comment
1170+00	15	36	9		
1310+00	9	36	9		Finger Creek
1398+54.7	4	36	9	Belmont pumps	Standpipe Reservoir
1404+84.5	5	36	9		
1520	12	36	9		Laurel Creek
1572+35.2	5	36	9		
1644+73.2	29	36	9	12" connection	
1655+55	22	36	9		San Mateo Creek
1711+40	33	36	9		
1749+06	28	54	5/16		Burlingame
1800+30	16	54	5/16		
1916+51.2	25	54	5/16		Aqua (Millbrae)

Table 4.4-1. Alameda Pipeline Features (adapted from P251)

Figure 4.4-2 shows the cross section through Flumes 1, 2, 3, 4, as of 1913. Flumes 1, 2, 3, 4 were not known to have suffered any major damage in the 1906 earthquake; the level of shaking along these flumes was likely on the order of PGA = 0.10g to 0.15g. At the time of the earthquake, the flume was likely carrying water flows on the order of 5 to 10 MGD.

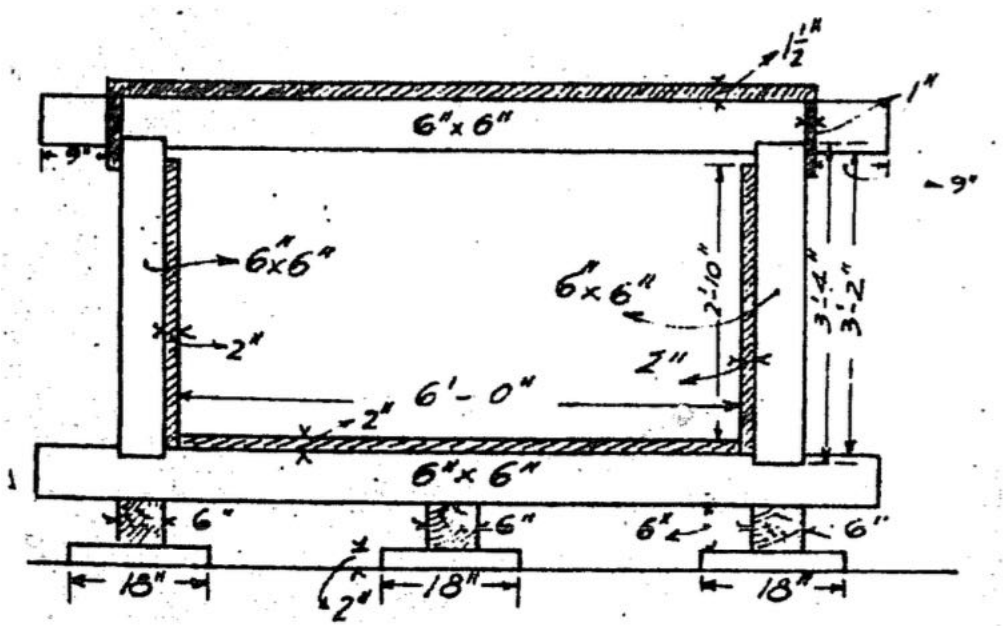


Figure 4.4-2. Typical Sunol Aqueduct Flume (trestles not shown) (SVWC drawing)

Beginning at Niles Dam, the 1888 Niles Aqueduct construction was:

- 2,760 feet of masonry aqueduct
- 3,200 feet of wood flume (similar to Figure 4.4-2, but 4 feet wide; or which ~990 feet supported on wood trestles at 14 feet centers
- 3,446 feet of 36" wrought iron riveted pipe
- Wood screen tank
- 2,165 feet of 36" wrought iron riveted pipe
- Steel bridge
- 253 feet of 36" wrought iron pipe to connection with main 36" Alameda pipeline

The Sunol Aqueduct takes water from the Sunol Filter beds to Niles, through Niles Canyon. This aqueduct consisted of 5 concrete tunnels and 4 heavy redwood flumes. The water is stored in tanks at Niles.

At Niles, a 36" wrought iron riveted pipe begins, gradually descending about 8 miles through Centerville and Newark. At Newark, the pipe is supported on a wooden trestle for 9,000 feet. Then, the pipe goes under Newark Slough (Figures 4.4-3, 4.4-4), a navigable slough, which is about 30 feet deep and 300 feet wide. Through this slough, there are two 16" submarine pipes (built 1877) and two 22" pipes (built 1901). Each submarine pipe has two gate valves at its east end. At the west side of the slough, the 4 pipes are combined into one 36" pipe; there are blow offs and gate valves for each submarine pipe. The 36" pipe continues on a wooden trestle for 7,000 feet. At this point, the 36" pipe again divides into 4 ball-jointed submarine pipes (two 16" and two 22"). The 16" pipes (Figures 4.4-5, 4.4-6) are about 90 feet to the south of the newer 22" pipes. The 4 submarine pipes join together at the Ravenswood shoreline, into one 36" pipe, supported on a wooden trestle for 2,000 feet. At the west end of the wood trestle is the Ravenswood pump station (Figure 4.4-7) that could be optionally used to boost pressures and flows from Niles to Belmont. From the Ravenswood pump station, the 36" pipeline continues for 9 miles in a trench, to the Belmont pump station (Figure 4.4-8), where the 36" pipe discharges into a reservoir (Figure 4.4-9). The Belmont pump station boosts the pressure in the pipe, with maximum grade line limited by the Belmont standpipe (Figure 4.4-10). From this Belmont pump station the water is pumped northerly to the Millbrae pump station where the water could continue to the University Mound reservoir or pumped into the adjacent San Andreas pipeline.

Figure 4.4-3 shows the twin 16" pipes at Newark Slough, looking easterly. Note the standpipe (air chamber in Figure 4.4-4) on the east bank, designed to release pressure should there be a water hammer event. In the 1906 earthquake, water was ejected from this overflow. Figure 4.4-4 shows the details.

Figure 4.4-5 shows where the twin 16" ball-jointed submarine pipes approach the shoreline at the west side of San Francisco Bay. Figure 4.4-6 shows where the two extra 22" twin submarine pipes were added to the existing 16" ball-jointed submarine pipes approach at the east shore of the main Dumbarton Strait, 1902.

All four of the 16" and later 22" submarine pipes were laid on the floor of Newark Slough and the main crossing of the Bay, without trenches.

While none of the submarine pipes broke in the 1906 earthquake, subsequent surveys showed that the underwater pipe alignments (by 1950) were anything but straight: some ball joints were rotated to their 15° limits. Whether such movement was due to the earthquake (like a lateral spread) or due to the ongoing movements of the Bay sediments slowly over time, is unknown.

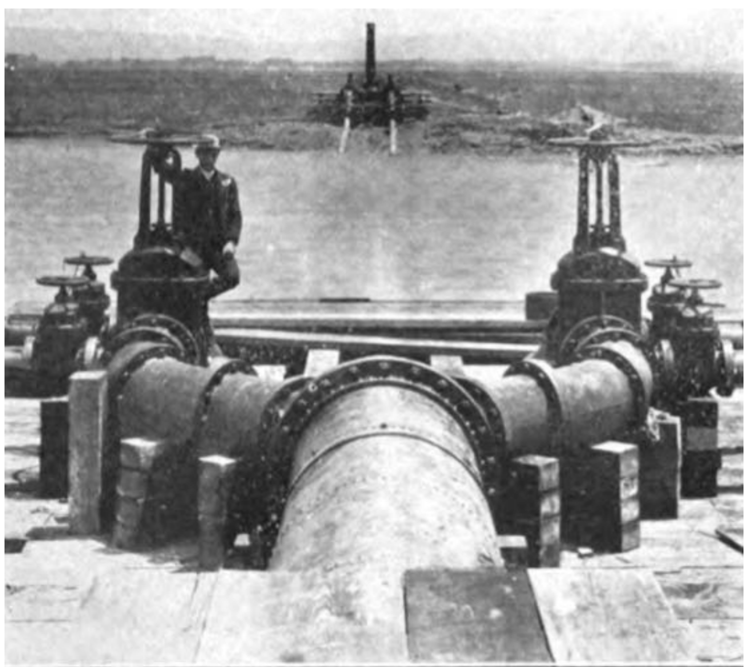


Figure 4.4-3. Twin 16" submarine pipes at Newark Slough. Looking Easterly. (Schussler, 1909)

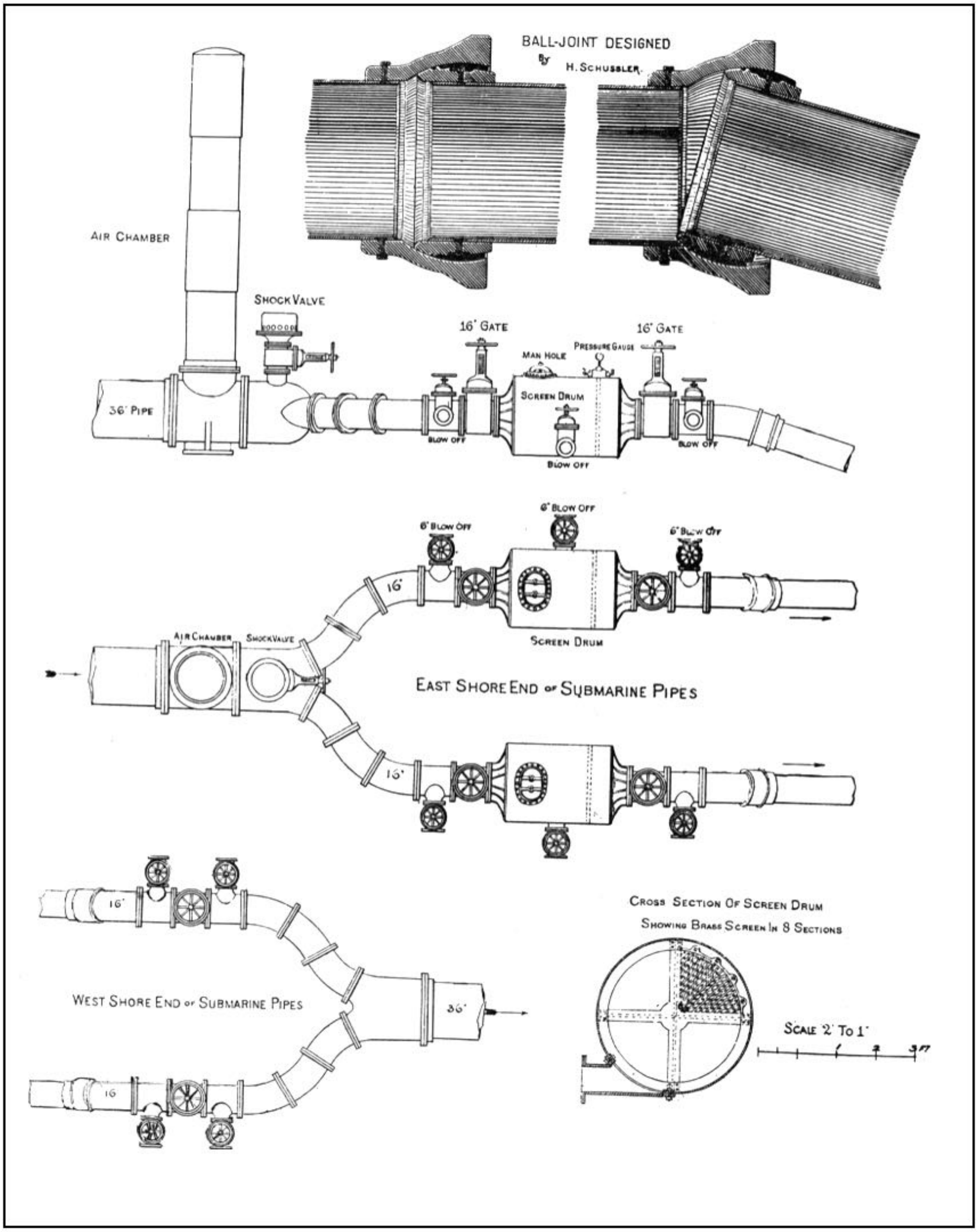


Figure 4.4-4. Twin 16" submarine pipes at Newark Slough. Looking Easterly. (Schussler, 1906)

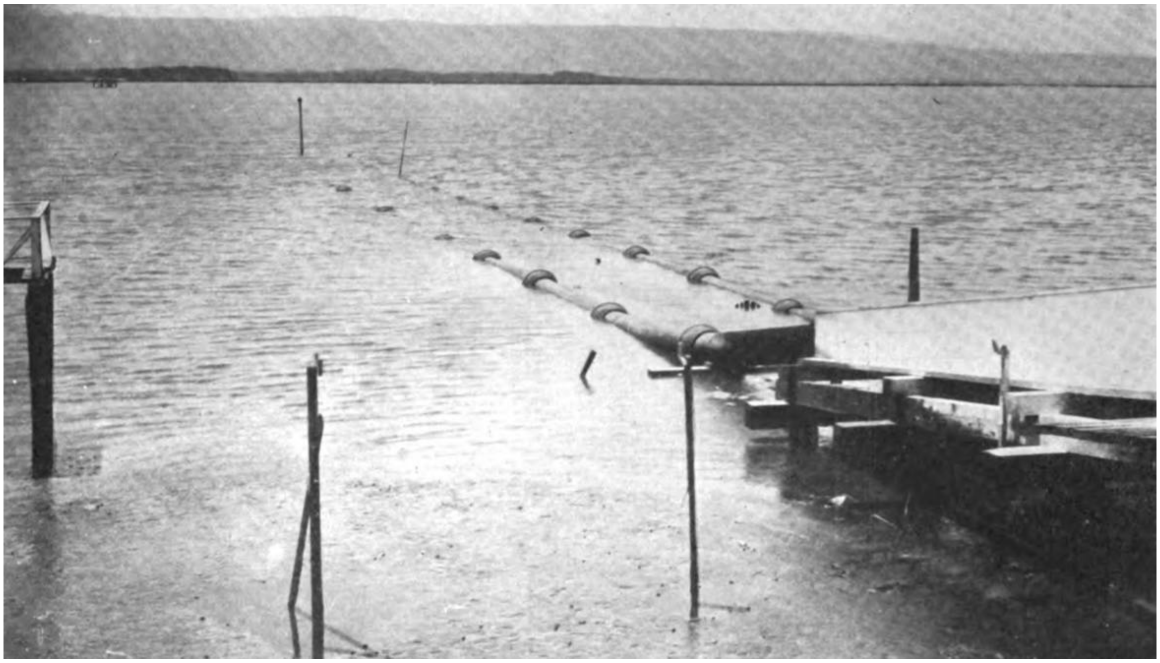


Figure 4.4-5. Twin 16" submarine pipes at the west shore of San Francisco Bay, Looking Easterly (Schussler, 1909)

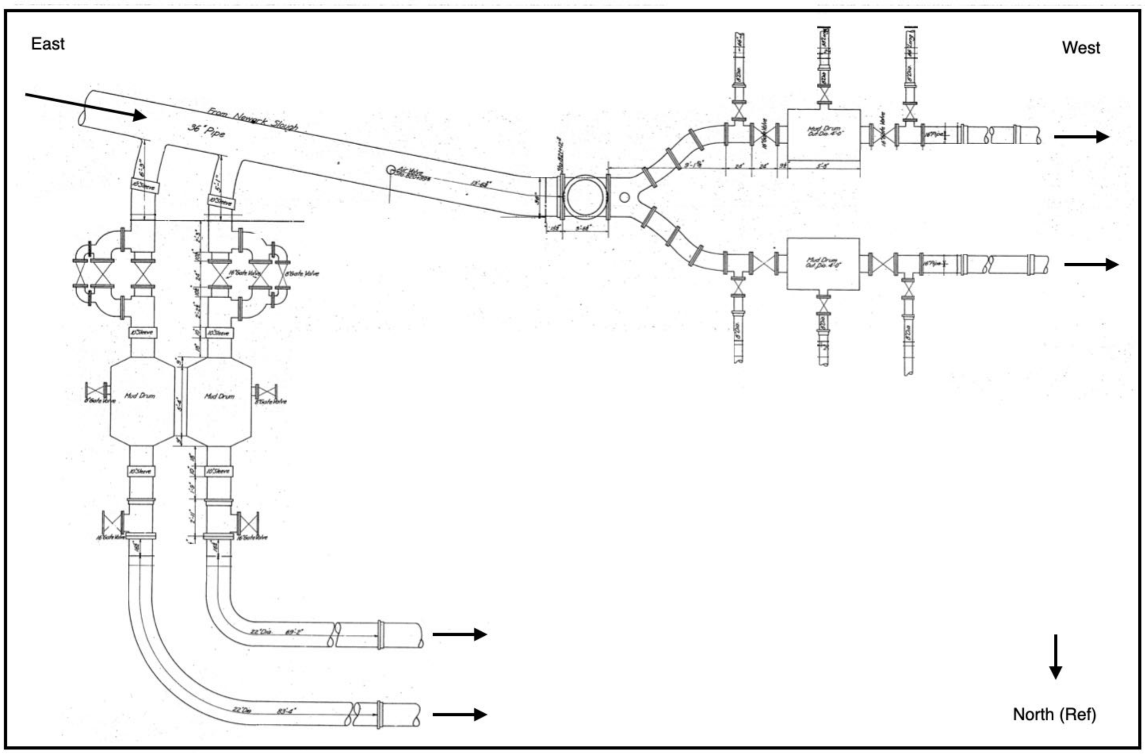


Figure 4.4-6. Twin 16" and 22" submarine pipes at Dumbarton Strait (c.1902, enclosure building removed for clarity)

On the east side both the Slough and Bay crossings, there is an automatic safety valve, designed to lessen or avoid all shock danger (hydrodynamic water pulse) to the 8 or 9 miles of 36" pipe that might be caused by the sudden shutting off of the submarine pipe gates. These automatic safety valves had a number of large rubber disks, which were designed to open automatically at the slightest hydrodynamic pressure pulses above the normal pressure. Each shock valve is a tall air chamber (see distant vertical standpipe in Figure 4.4-3), where any air in the 36" pipe would collect and could be let out, in part to avoid any air that might get into the submarine pipes. East of the air chamber was placed a vacuum valve on top of the 36" pipe, which would open instantly and automatically if the pressure was taken off the pipe by a break, or whenever it was emptied for repair purposes, by opening a blow-off gate.

The Ravenswood pump station was located at the east side of the Bay Crossing. It was used to boost pressure in the 36" Alameda pipeline, when needed.

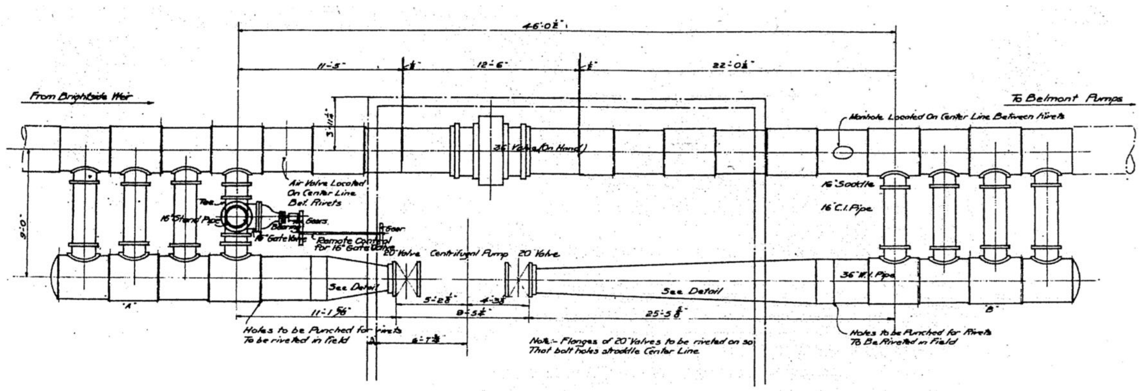


Figure 4.4-7. Ravenswood Pump Station Pipe Arrangement (SVWC drawing)

The pump station was powered from a 60 kV PG&E transmission line, included 3 single phase 60 kV x 2.3 kV transformers (each 250 kW), plus spare, which powered a single 800 HP motor and centrifugal pump. Under normal flow (low flow) operation, the water continued by gravity flow to the Belmont pump station via the 36" pipeline (here t = 5/16", riveted with ¾" diameter rivets at center-to-center 2.25" spacing).

At Ravenswood, the 36" pipe included a 36" motorized valve, which would be closed to allow operation of the booster pump. 16" Tees were installed either side of the pump, into a parallel 36" pipe with 36"x20" reducers. Two 20" motorized valves were installed either side of the pump. When operating, the pump discharged into the Peninsula segment of the pipeline, leading to the Belmont pump station.

The Belmont pump station site included several components:

- Pump station, with 5 pumps, boilers, fuel supply. (Originally 2 pumps, expanded in 1902 to 5 pumps).

- Pump station building. Composed of cast iron columns, trusses, wood-truss roof system.

- Rectangular reservoir, 120 x 250 feet in plan dimension at the base, 175 x 300 feet at edges, sloped sides made of clay puddle 18" thick covered by rip rap, covered by roof on 12 trusses, supported on the interior by 6x6 wood columns at 12-foot by 20-foot spacing throughout the open cut reservoir. Water capacity 3.741 million gallons. This reservoir received water from Ravenswood via the 36" Alameda pipeline, and served as suction supply to the 5 pumps.

- Standpipe.

As part of the Alameda system upgrades in 1902, the Belmont pump station was configured to normally operate as follows:

- Water from the Sunol Aqueduct would flow by gravity flow into the Belmont receiving reservoir, Figure 4.4-9.

- The Belmont pump station would take suction from the receiving reservoir and boost the water up to a 337 foot grade line controlled by the nearby standpipe, Figure 4.4-10. This 337 foot overflow was set to match the grade line coming from the Crystal Springs reservoir, so after line losses, the water from the Alameda pipeline and Crystal Springs pipeline could be merged at the Millbrae pump station, and thence flow by gravity to University Mound Reservoir.

- From 1898 to 1902, before the 54" Alameda extension was built, the Belmont pumps were operated so as to merge the combined flows of Alameda and Crystal Springs pipelines at the points where the 36" and 44" pipes connected south of Millbrae.

At the Belmont pump station, the 36" pipe is connected to a standpipe. The standpipe was 5-feet diameter at the bottom, and 3'-11" diameter at the top. There is a 300-foot long 36" t = 0.18" pipe from the reservoir to the pump station, a 800-foot long 30" t = 5/16" pipe to the standpipe, a 300-foot long 30" t = ¼" pipe to the standpipe.

The Belmont standpipe had overflow elevation of ~337 feet. The original 1898-vitage pump station had two pumps; the pump station was expanded to 5 pumps in 1902. Pumps were driven by oil or coal. In the 1906 earthquake, 1 of the 5 pumps failed. In 1911, the standpipe height was increased to ~362 feet. Lumber for the standpipe tower was 8x8 columns and 4x8 diagonals. Connections (8x8 post to 8x8 beam to 8x8 post) were formed with 16" long x 9/16" diameter steel spikes. Connections of diagonals to the posts and beams were made with ¾" diameter steel dogs; each dog being L-shaped, 12" x 4" (long and short legs). Each post was through bolted to ¾" thick angles that in turn were anchored into concrete footings. Six levels of the structure were guyed in 4 directions.

Figure 4.4-8. Belmont pump station works and standpipe (Schussler, 1909)

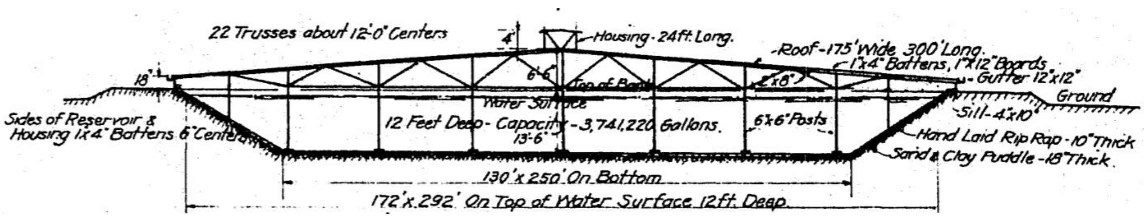


Figure 4.4-9. Belmont Reservoir Cross Section (SVWC drawing)

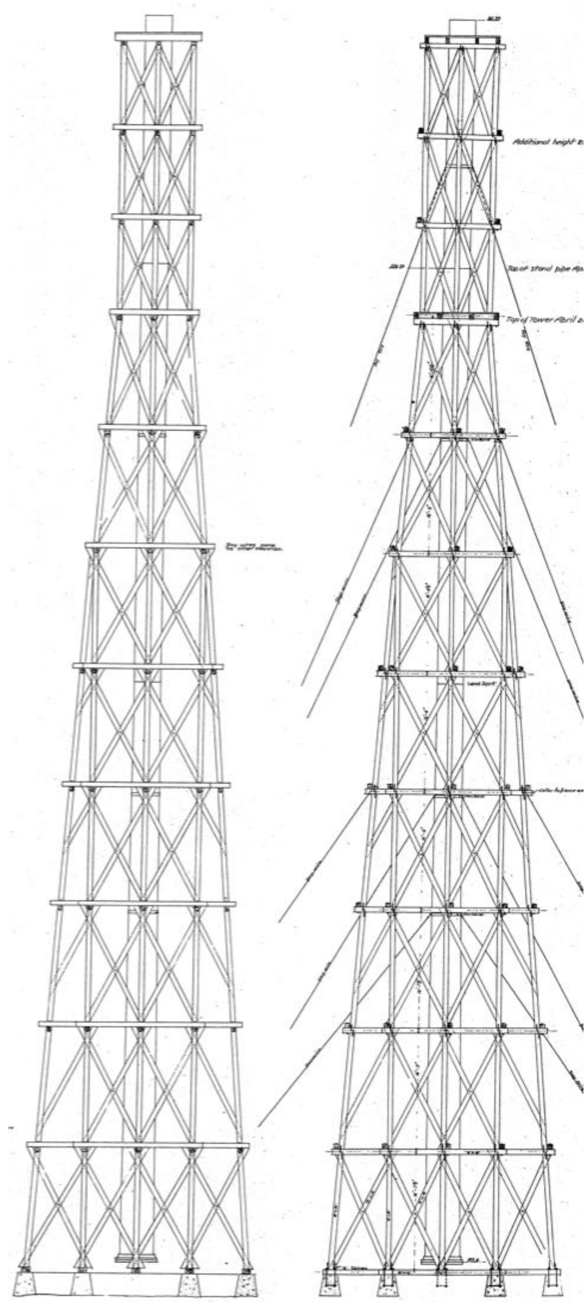


Figure 4.4-10. Belmont Standpipe (1898, height increased 25 feet in 1911) (SVWC)

In 1902, the original 36" Alameda pipeline was extended by the 54" pipe from Burlingame to Millbrae. This 54" wrought iron riveted pipe was built to increase the flow capacity. The 54" pipe began at Sta 1748+71 of the Alameda pipeline, paralleling it until Sta 1916+51 (about 16,880 feet long).

Schussler reports that the 36" Alameda pipe was damaged at 4 locations, one location about 1.5 miles south of the Belmont pump station, and three locations within ½ mile north of the Belmont pump station.

Figure 4.4-11 shows the standpipe and support tower at the Millbrae pump station. The overflow elevation of the standpipe is 215 feet (Crystal Springs datum). The function of the standpipe is to limit the maximum static head in the Crystal Springs pipeline north of the Millbrae pump station and University Mound reservoir. The exterior wood structure is composed of 10x10 wood posts and 4x8 diagonals. The standpipe is 30" diameter pipe. The inset on the right shows the common connection hardware, composed of 5/8" diameter "dogs" (385 total) plus a 3/4" diameter bolt (120 total) that connects the 8x8 horizontal beams, plus two ½" diameter bolts (385 total) that connect the diagonals to the column. The standpipe was not damaged in the 1906 earthquake.

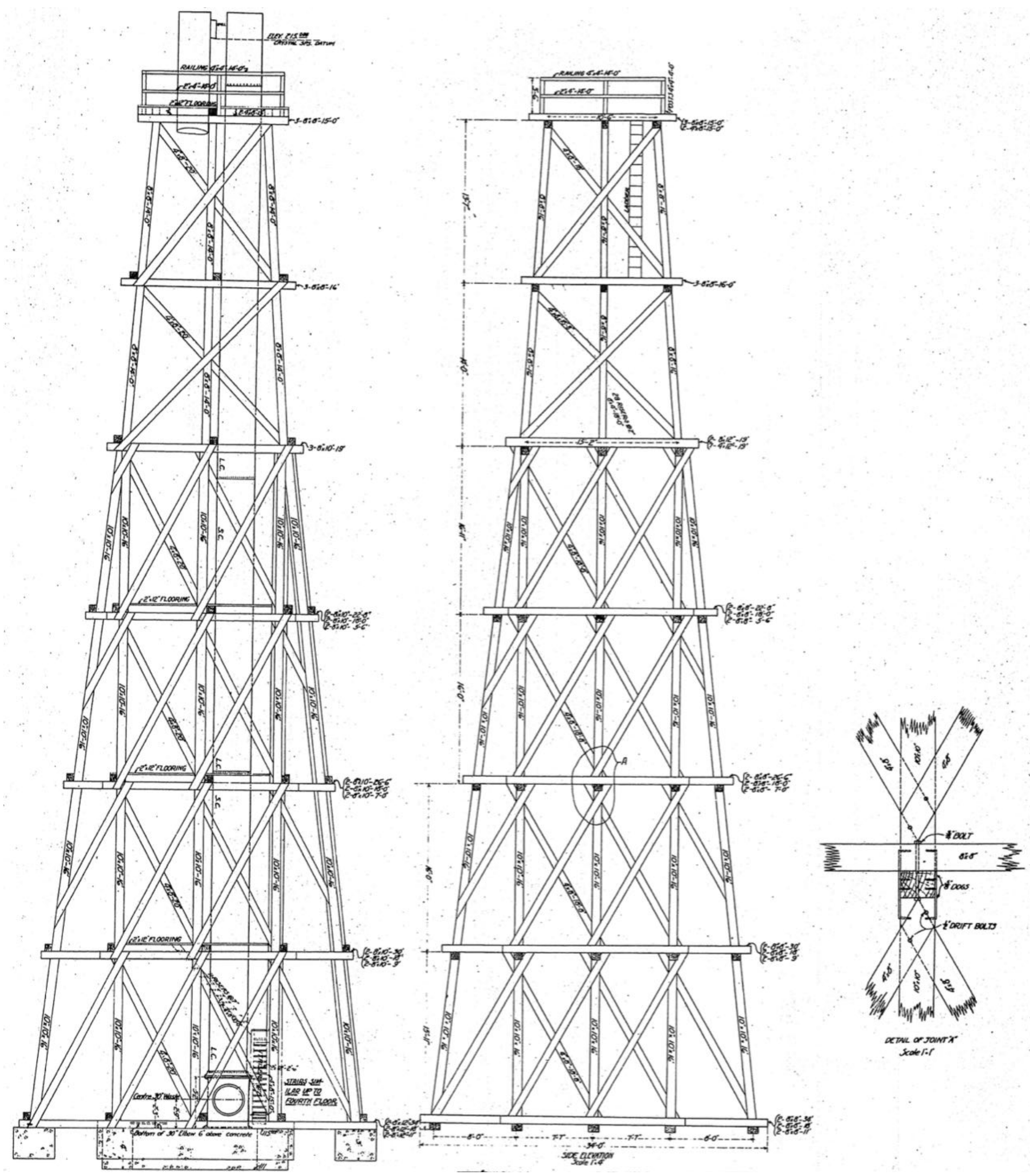


Figure 4.4-11. Millbrae Standpipe, Constructed 1898 (SVWC)

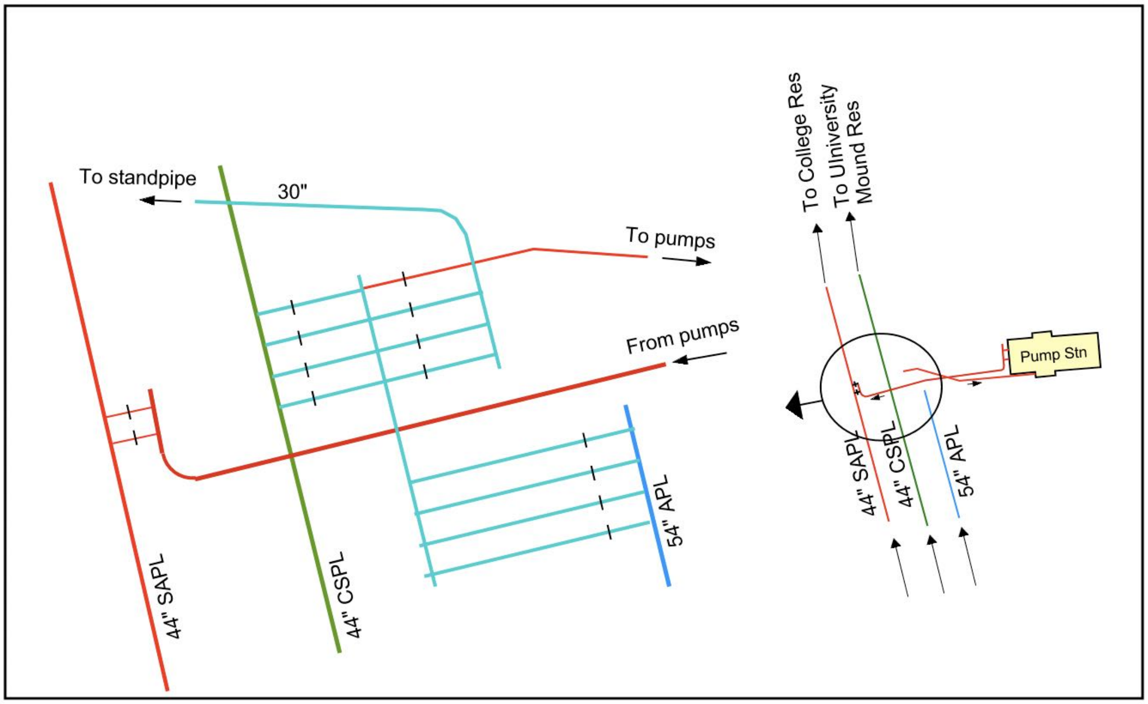


Figure 4.4-12. Millbrae Pump Station Arrangement (not to scale)

Schussler (1906) reports:

Neither the Sunol filter beds on the Alameda Creek System, nor the Sunol Aqueduct and 36" pipeline on the east side of the Bay, nor the four submarine pipes were injured; only a slip joint, on one of the two 16" short connections, was pulled apart several inches, on the east side of the bay; and two 8" blow-offs, at the west shore connection of one of the 16" pipes, were broken off by the shock. These minor injuries were repaired, and then Sunol Valley water could again cross under the San Francisco Bay and be pumped at Belmont Pumping Station. As of July 1906, San Francisco was receiving from the Alameda system about 14.5 MGD, similar to what was being delivered before the earthquake.

At the time of the earthquake, on the morning of April 18, the water was coming westerly at a rate of 16 MGD, with a mean velocity of 3.5 feet per second. When the shock of the earthquake arrived, the vacuum valve (located just east of the Newark Slough, Figure 4.4-4) instantly dropped and let air into the pipe. The vacuum valve fell down, then the valve closed suddenly, throwing up a stream of water into the air while closing. At the same instant, the safety valve nearby opened automatically, closing when the shock passed, and thus by discharging quite a quantity of water, relieved the long 36" pipe to the east from the effect of the shock, which might have been disastrous.

Neither of the tall of steel standpipes were damaged (including one at Belmont and one at Millbrae).

The San Francisco Call newspaper of April 19, 1906 reported that at Niles, large boulders displaced from the hills crashed through the SVWC pipeline, and the flood of water released from the big main washed out the tracked of the Southern Pacific Railroad Company, delaying trains for several hours. Schussler's report (1906) does not mention this damage, but after the earthquake, SVWC did replace the wooden flume sections in Niles Canyon. Today (2023), it is unsure as to which section of the aqueduct was damaged. It is not unprecedented that earthquakes trigger rock avalanches, and it is quite possible that the level of shaking in Niles Canyon (likely PGA range ~0.10g to 0.25g or so) could have triggered multiple rock avalanches, with some debris impacting the flumes. The downstream Niles Regulating Reservoir, being undamaged, would have continued to supply water into the downstream Alameda system for perhaps a few hours (until emptied).

4.5 Lake Merced

Lake Merced is a natural fresh water lake in southwest San Francisco, at elevation 26 feet. As the demand for water in San Francisco increased, SVWC acquired the water rights for Lake Merced, and had bought up almost 3,000 acres of lands near the lake.

By the late 1870s SVWC had built a pump station to take this water and boost it College Hill (elevation 255') via the San Andreas conduit. This pump station and pipeline (22") is referred to as the "Old Merced" pump station and pipeline. The "Old Merced" pump station and 22" pipeline had both been removed from service prior to the time of the 1906 earthquake.

Water quality in Lake Merced was not very good, and was always considered only to be used as an emergency supply.

In 1897, a new settling reservoir was constructed at the south end of Lake Merced. This settling reservoir receives flood water and allows sediment to settle before the water is released into the main Lake Merced. This was done as an attempt to improve water quality in the main Lake Merced.

In 1897, a 1.5 mile long flume (Figure 4.5-1) was built to convey flood water from Ocean View Canyon into the lower settling pond of Lake Merced. From there, the flood water flows through a 4,000 foot-long brick tunnel to the ocean, with discharge outlet 2.5 feet above high tide. The purpose of these works was to divert flood waters out of Lake Merced, and thus preserve the water quality of Lake Merced for possible use / emergency use for the City of San Francisco potable water distribution system.

A "New Merced" pump station (Figure 4.5-2) and 30" pipelines were constructed in the late 1890s, to deliver that water to the Pilarcitos or San Andreas pipelines near the San Francisco – San Mateo county border.

The New Merced pump station proved fortunate, as in the 1906 earthquake, all supply pipes from the Pilarcitos, San Andreas, Crystal Springs and Alameda water sources were broken in the earthquake. The "New Merced" supply infrastructure was turned on soon after the April 18 1906 earthquake, and was used to provide flows of about 6 MGD into the Pilarcitos and San Andreas pipelines and thence to Lake Honda / College Hill reservoirs.

To this day (2023), there is a pump station and pipe works to take Lake Merced water and deliver it into the City's distribution system, should ever the need arise.

Figure 4.5-1. SVWC Flume discharging water into a Lake Merced settling pond, June 9, 1904 (credit: San Francisco Library)

Figure 4.5-2. "New" Lake Merced pump station, near Brotherhood Way and Lake Merced Boulevard, looking north, June 9, 1904 (Credit: Schussler 1909)

4.6 Locks Creek System

The Locks Creek system refers to a number of flumes, pipes and tunnels that collect water from the various streams and deliver that water to the Pilarcitos, San Andreas or Crystal Springs reservoirs. Figures 2-23, 2-26, 4.6-1, 4.6-2 show the main elements.

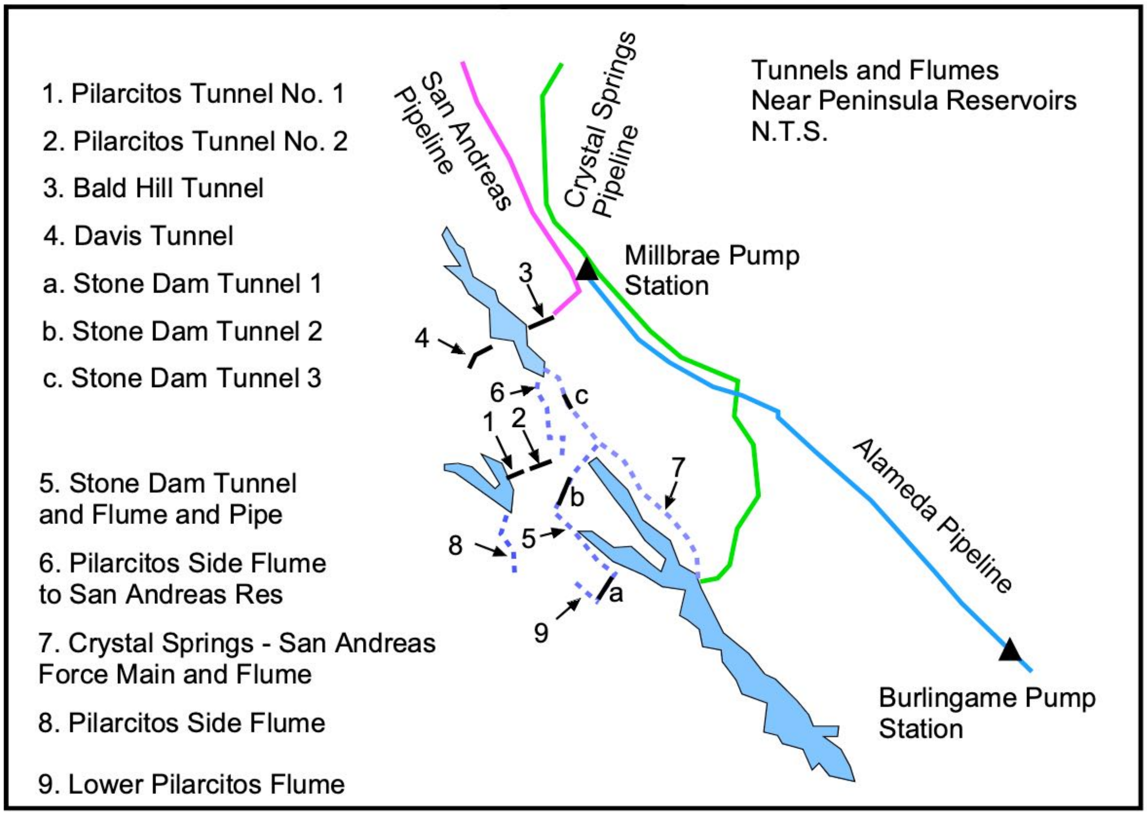


Figure 4.6-1. Location of Tunnels and Flumes Along the Peninsula (1912) (Solid black lines: tunnels. Dashed blue lines: flumes or pipes of the Locks Creek system. Solid purple, blue, green lines: main transmission pipes). See Figure 4.6-2 for details of Items 1, 2, 8.

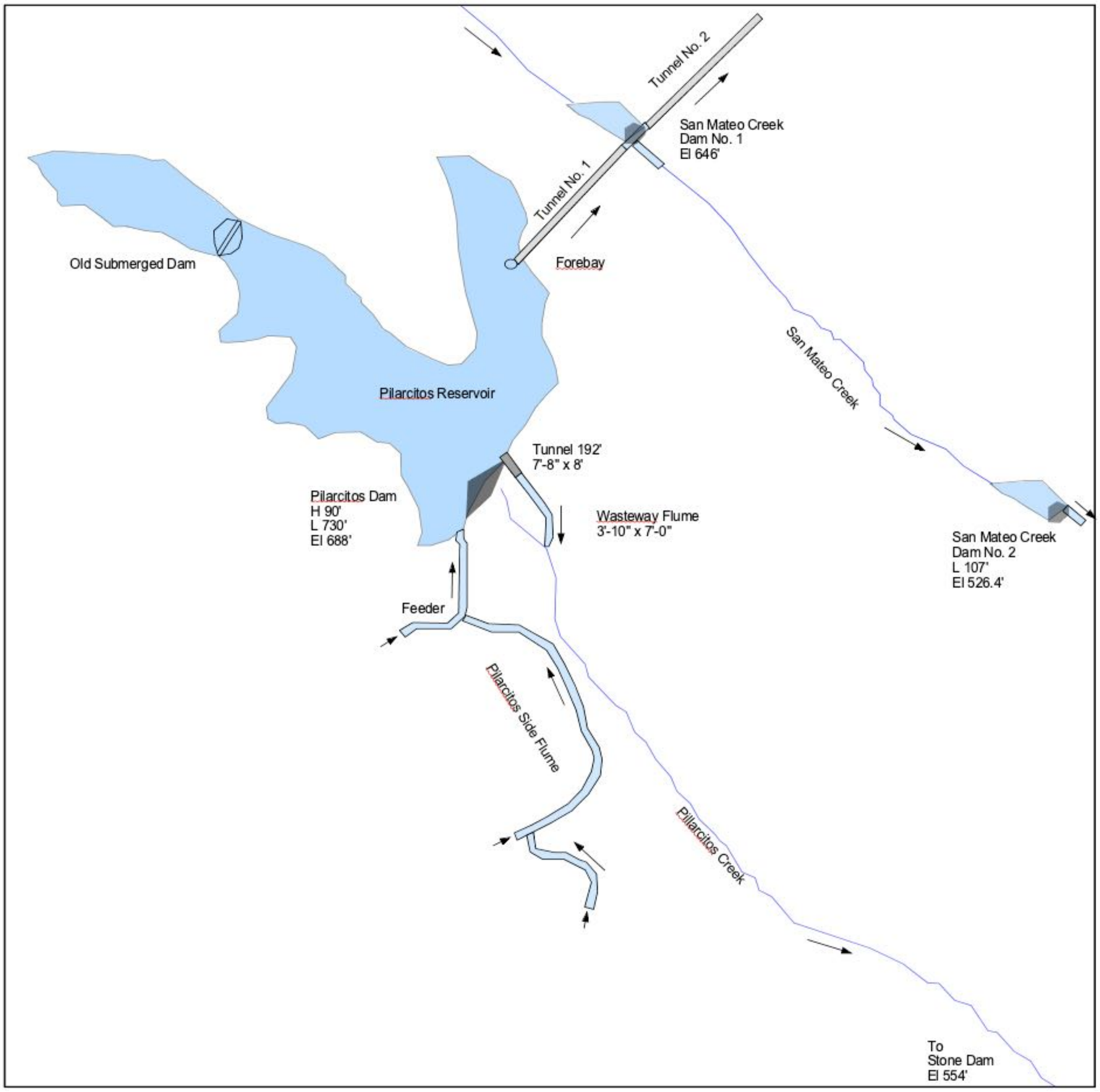


Figure 4.6-2. Location of Tunnels and Flumes Near Pilarcitos Reservoir (1912)

Components of the various raw water collection flume / pipe / tunnel systems are described in Table 4.6-1. The lengths shown reflect original construction; and exclude Davis Tunnel and the re-routed Locks Creek system.

System (Vintage)	Wood Flume (feet)	22" WI Pipe (feet)	37.5" WI Pipe (feet)	Tunnel (feet)	Comments (location maps)
Locks Creek (1875). Feeds San Andreas Reservoir	78,365	12,154	3,664	3,200	Collects Locks Creek and Apanolio Creek water. A portion abandoned under Lower Crystal Springs in 1888 (FX-7) and re-routed (FX-6). Figs 2-24, 2-26 (1870). Items a, 5, b, 7, c in Fig 4.6-1.
Pilarcitos (1906). Feeds San Andreas Reservoir	4,600	6,000		3,240	Collects San Mateo Creek water. Pilarcitos Tunnel No. 2 in Fig 2-23. Items 2, 6 in Fig 4.6-1.
Lower Pilarcitos (1906). Feeds San Andreas	4,300				Collects Pilarcitos Creek water from Stone Dam to Tunnel No. 2 in Figure 2-23. Fig 2-24. Item 9 in Fig 4.6-1
Pilarcitos Side Flume (1875). Feeds Pilarcitos	26,400				Fig 2-24 (1875). Figs 4.6-1, 4.6-2 (1912)
Total	113,665	18,154	3,664	6,440	

Table 4.6-1. Partial Inventory of Raw Water Conduits to Fill Peninsula Reservoirs

The Stone Dam Tunnel No.1 was built in 1873, to transport into San Andreas Reservoir a portion of the waters of the watershed of Pilarcitos Creek, which otherwise would flow into the Pacific Ocean.

The original Locks Creek conduit was completed in 1875, being nearly 20 miles long. See Figures 2-24, 2-26, 4.6-1, 4.6-2. In 1875, the entirety of the Locks Creek conduit consisted of the following:

- Stone dam on Locks Creek; then 7,500 feet of wood flume on the southwest bank of Locks Creek; then 22" wrought iron pipe 1,595 feet long; then 8,100 feet of wood flume on the east bank of Locks Creek; then 22" wrought iron pipe 1,515 feet long; then 1,300 feet of wood flume; then 22" wrought iron pipe over Apanolio Creek, where it merged with 10,000 feet of wood flume fed from a

> stone dam on Apanolio Creek. At the merge, 2,400 feet of wood flume; then a 22" wrought iron pipe over M'Peaks Creek; then 6,800 feet of wood flume; then a 22" wrought iron pipe 1,662 feet long; then 3,350 feet wood flume; then a 22" wrought iron pipe over two small gulches, 925 feet and 1,170 feet long connected by a 300 foot-long flume; then 5,850 feet of wood flume; then 22" wrought iron pipe over Pilarcitos Creek; then 6,500 feet of wood flume to the inlet of brick-and-cement lined Lock's Creek Tunnel 3,200 feet long (the southern so-called Tunnel 2 in Figure 2-24); then 1,265 feet of flume; then a 37.5" wrought iron pipe across San Mateo Creek, 1,050 feet long; then a 1,450 feet long flume, then a 37.5" wrought iron pipe 2,614 feet long across San Andreas Creek (Site 18, FX-7); then by wood flume 24,000 feet long to discharge into the southeast shoreline of San Andreas Reservoir.

The Pilarcitos Side Flume consisted of 5 miles of wood flume that collected water from various creeks and delivered that water northwestward into Pilarcitos Reservoir. The original flume is shown in Figure 2-24, which had been shortened by 1912 (Figures 4.6-1, 4.6-2).

The Crystal Springs to San Andreas line was completed in 1899 to bring water from the Crystal Springs pump station to San Andreas Reservoir. See Item 7 in Figure 4.6-1. This included a pump station at the base of the lower Crystal Springs Dam, a force main to lift that water up to the original Locks Creek flume that followed the contours east of Crystal Springs reservoir. This included an elevated trestle-supported flume and a ground-supported flume about a mile south of San Andreas reservoir, sections of which collapsed in the 1906 earthquake.

A portion of the original 1875-vintage Locks Creek Aqueduct was taken out of service with the construction of Lower Crystal Springs Reservoir in 1888. The removed sections included wood flume to the southwest of the flooded reservoir; the original 37.5" wrought iron pipe (FX-7) was abandoned in place when the reservoir was flooded. The re-routed Locks Creek Aqueduct is shown in Figure 2-26, consisting of wood flume along San Mateo Creek, a tunnel under Sawyer ridge, and then flume and 44" wrought iron pipe (FX-6) until the connection with the original 1875-vintage wood flume on the east side of San Andreas Creek.

The upper portions of the original 1875-vintage Locks Creek Aqueduct, consisting of wood flumes and 22" wrought iron pipes above Apanolio Creek crossing, being in bad conditions and in need of repairs, were taken out of service by 1911.

The Davis Tunnel was built in 1897, and was 1,200 feet long. This tunnel diverts water from the upper reaches of San Mateo Creek into San Andreas Reservoir.

The Pilarcitos Waste Water Conduit takes water from Pilarcitos Reservoir via the Pilarcitos Tunnels 1 and 2, a 44-inch wrought iron pipe and a flume, and then diverts the waste water to fill San Andreas reservoir. This waste water conduit includes three sections of wooden flume and 3 sections of 22-inch diameter steel pipe. Figure 4-8 shows a profile of the Waste Water Conduit.

In Figure 4-1, the "x-s" along the Locks Creek system represent:

- Failure of 44" wrought iron pipe crossing the San Andreas fault just north of Crystal Springs Reservoir (FX-6). This pipe was built c. 1890 once the Lower Crystal Springs reservoir required abandonment of the original pre-1875 Locks Creek 37.5" pipe. The pre-1906 purpose of the 44" pipe was to deliver raw water collected at Stone Dam and deliver it into the flume that then delivered water northwesterly into San Andreas Reservoir. After the 1906 earthquake, this pipe was not repaired and that section of Locks Creek system was abandoned, with a diversion built to deliver that water into an arm of Crystal Springs reservoir. (See Section 4.1.17).

- Failure of two segments of a wooden flume (6' x 4') that ran parallel to and east of the San Andreas fault. One segment was about 80-feet long, immediately south of the San Andreas Reservoir dam (described in Site 11); this segment was likely affected by surface fault offset at the crest of the dam.. The other segment was about 250-feet long, about a quarter mile south of the San Andreas reservoir dam; this segment was about 600 feet east of the main trace of the San Andreas fault, and likely failed as a result of string inertial shaking, possibly (?) aggravated by minor landslide movement (described in Site 12).

- Failure of wooden flumes that collected water from creeks southwest of Pilarcitos reservoir and delivered that water into San Andreas Reservoir.

Other damage to the Locks Creek system in the 1906 earthquake also included:

- 37.5" wrought iron pipe, broken where it crossed the San Andreas fault. FX-7. Also damaged where it crossed beneath Crystal Springs Reservoir. (See Section 4.1.18).

- The Stone Dam flume downstream sprung only a few leaks. (Lawson, p.253, 1908). The Stone Dam was uninjured.

- There are reports of other Locks Creek wood flume sections with failures; especially in the drainages of various creeks to the west of Pilarcitos Reservoir; the details and locations of this damage are unknown, but by 1911, all these flumes were abandoned, as they were in bad condition and in need of repairs.

Figures 4.6-3, -4 show another wooden flume that collapsed due to inertial forces. Schussler notes that this flume (about 6' wide and 4' high) is on the opposite side of the San Andreas Valley from the fault rupture. In the distance the linear feature is believed to be the Crystal Springs to San Andreas flume (Number 7 in Figure 4.6-1). Figure 4.6-4 is just a little to the north of Figure 4.6-3.

We interpret the correct location as being along the flume section denoted "6" in Figure 4.6-1. The manner of failure appears similar to that in Figure 4.1.12-12, with the flume collapsing sideways to the east, probably due to inertial forces. This appears to be an inertial failure; although it is possible it was initiated or aggravated by a landslide under this section.

Figure 4.6-3. Failure of Pilarcitos Waste Water (Side) Flume to San Andreas Reservoir, Looking Northerly (Photo: Schussler 1906 HS47)

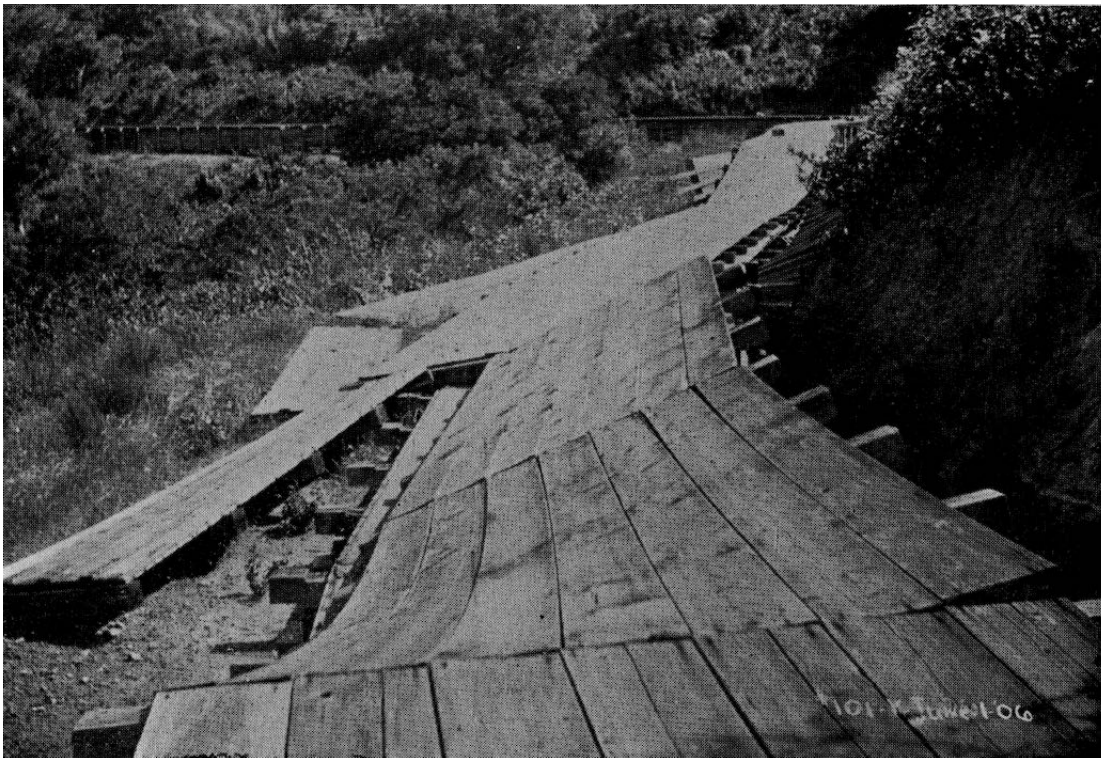


Figure 4.6-4. Failure of Pilarcitos Waste Water (Side) Flume to San Andreas Reservoir, Looking Southerly (Photo: Schussler 1906 HS48)

Figure 4.6-5 shows the collapse of a flume section that Schussler described as being in Upper San Mateo Creek canyon. Based on the V-shaped valley we believe this to have occurred along flume section Number 5 in Figure 4.6-1. This section of flume was destroyed by a landslide with head scarp above the flume.

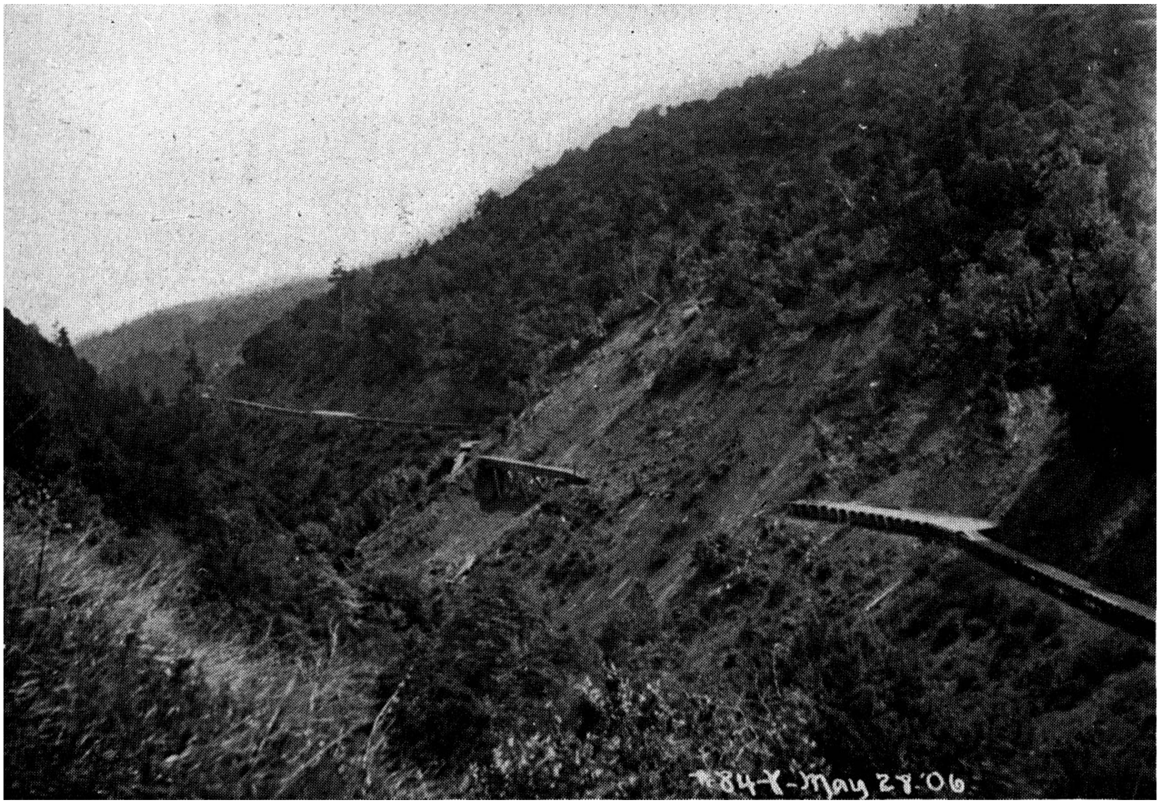


Figure 4.6-5. Collapse of Pilarcitos Side Flume between (here 5′ x 3′) in Upper San Mateo Canyon. Photo dated May 27, 1906. (Photo: Schussler HS46).

Landslides along the Locks Creek flumes were not uncommon. Figure 4.6-6 shows another landslide failure from March 1907. It is uncertain if this landslide was initiated by the 1906 earthquake, or sometime in the following year's rainy season. It is believed this failure occurred in the Upper San Mateo Creek Canyon (No 5 in Figure 4.6-1) or possibly the Pilarcitos Side Flume (No. 8 in Figure 4.6-1). Figure 4.6-7 shows the repaired flume.

Figure 4.6-6. Collapse of Flume due to Landslide. (Photo: SVWC, 1907).

Figure 4.6-7. Repair of Flume. (Photo: SVWC).

Figure 4.6-8 shows another section of flume. It is believed that this section of flume was above the Pilarcitos Creek Canyon, possibly No. 8 in Figure 4.6-1.

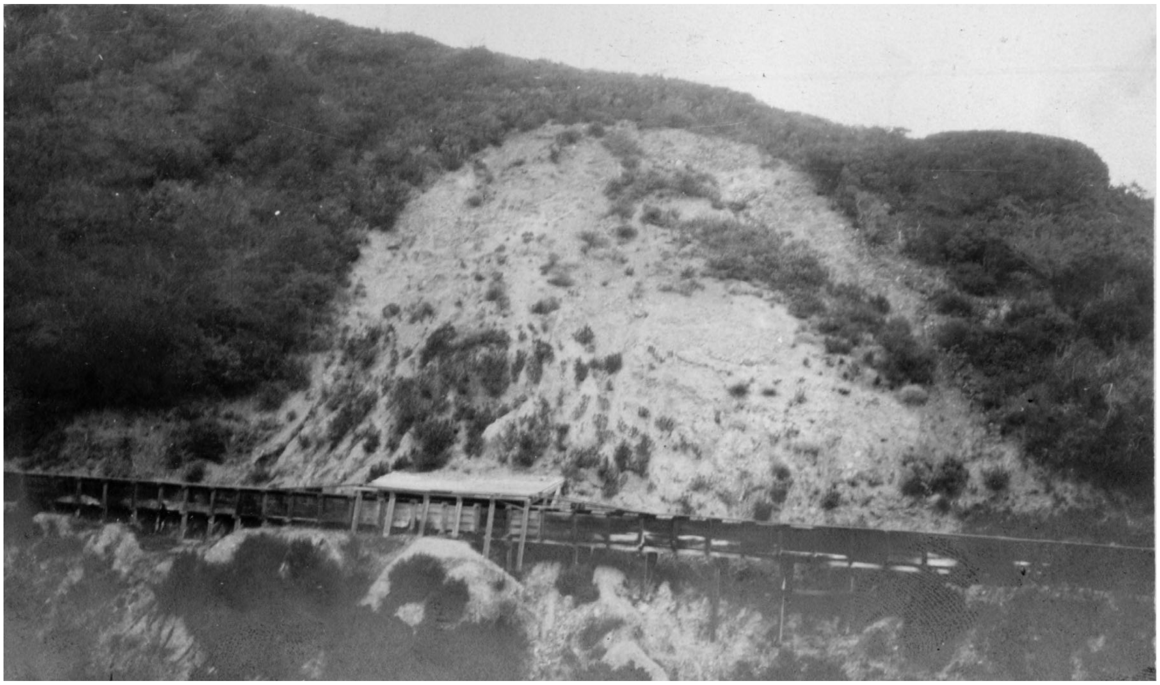


Figure 4.6-8. Portion of Flume. (Photo: SVWC). Note the wooden "slide shed" through a portion of the slide zone.

4.7 Other Damage

At the time of the 1906 earthquake, the Spring Valley Water Company's headquarters building near Union Square. It was a 6 story building. The offices were open on April 18, 1906, the day of the earthquake. But the spread of the fire on April 19 into the Union Square area effectively destroyed the building and much of its contents, see Figure 4.7-1. Essentially all records at this office building were lost to the fire. Fortunately, a backup set of many documents were held at the company's facilities in Millbrae.

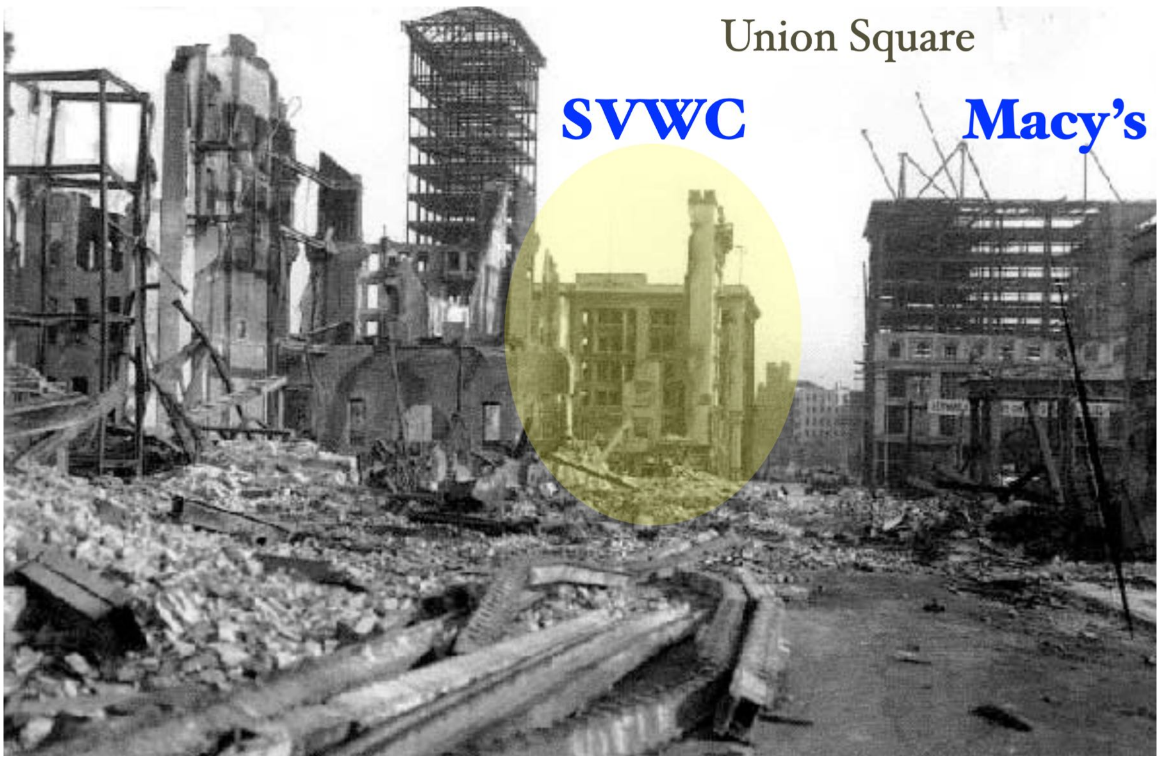


Figure 4.7-1. SVWC Office Building, Looking South, After 1906 Fire

The building had a steel skeleton (Figure 4.7-2). Partitions, column protection and floor arches were made of hollow clay tile. Many floor arches failed. Many clay tile walls failed. The 2-inch thick tile on columns generally failed (see Figure 4.7-3). The columns in the southeast corner of the building buckled, and the upper floors collapsed.

Figure 4.7-2. Interior of SVWC Office Building after 1906 earthquake. Call building in the background. (photo: Courtesy Mike Housh, SF Historian)

Figure 4.7-3. Interior of SVWC Office Building after 1906 earthquake (photo: Courtesy Mike Housh, SF Historian)

5.0 What Went Right? What Went Wrong?

There were many things that went "right" in the performance of the water system in the 1906 earthquake:

- No dam failed in the SVWC system.
- No open cut reservoir failed.
- No tunnel failed due to shaking.
- The large reservoirs in each of the three major pressure zones in San Francisco (Lake Honda, College Hill, University Mound) could be supplied with water from multiple sources (assuming no upstream pipe or pump station damage):
    - Lake Honda Reservoir could be supplied by gravity flow from Pilarcitos Reservoir, or by pumped flow from Lake Merced, or by pump flow from the San Andreas pipeline (either via the Pilarcitos pump station or the Millbrae pump station). The multiple sources for Lake Honda proved critical. This allowed water to be used for fire-fighting purposes to help control the spread of fire west of Van Ness or further into the Mission district.
    - College Reservoir could be supplied by gravity flow from the San Andreas pipeline or the Pilarcitos pipeline, or pumped flow from Crystal Springs Reservoir or the Sunol waterworks, via the Millbrae pump station.
    - University Mound Reservoir could be supplied by gravity flow from Crystal Springs Reservoir, or pumped flow from the Sunol water works by Belmont pump station (and Ravenswood pump station if taking supply from the Alameda Creek directly).

There were also many things that went "wrong" in the performance of the water system in the 1906 earthquake:

- The City distribution system suffered ~299 pipe breaks (mostly to cast iron pipe). This prevented water from reaching hydrants in the lower two pressure zones serving the bulk of the South of Market and the high value commercial downtown areas. 80% of the City burned down.
- The water transmission system suffered major failures at ~52 locations. Every pipe that crossed the San Andreas fault failed. About 10% of the wood trestles that supported transmission pipes failed. A few sections of wood flumes failed, although most survived.

- In the transmission system, the majority of failures were at the single riveted girth joints. In tension, the failure mode was dominated by edge distance tear-out of the steel; this was non-ductile. The design of the rivets and pipe hole edge distances did not allow the ductile wrought iron pipe to yield to accommodate ground PGDs. In compression, the failure mode was folding of the rivet plate area caused by high bending due to the eccentricity of the joint, which then led to rivet failure (combination of high shear and bending). There is no evidence that any pipe failed by compressive wrinkling; which would have required mobilization of the steel pipe to modestly exceed the compressive yield level.

- The wood trestles were not designed for high enough lateral loads to accommodate strong seismic shaking. The fact that about 90% (by length) of the wood trestles survived the 1906 earthquake does not mean that these were reasonably designed (except for the design used for the Alameda trestles) for earthquake loading. Ideally, there should have been zero failures for trestles that supported pipes or flumes that delivered water to terminal reservoirs (University Mound, College Hill, Lake Honda) (or at most one failure that could be repaired within 24 hours). But in practice, nearly 2,000 feet of wood trestles collapsed, most of which supported the Crystal Springs pipeline, and about 100 feet supported the Pilarcitos pipeline. The multiple collapses of trestles and flumes in the Locks Creek system did not impact water delivery to the terminal reservoirs, so those collapses were of less importance.

- The placement of slip joints in above ground steel pipes requires careful detailing. For cases where the single slip joint occurs after many thousands of feet of continuous pipe, strong ground shaking and travelling waves can try to open and close the joint by many inches, often well in excess of the movement planned to accommodate thermal motions.

- Very thin walled steel pipe ($D/t > 250$ for low pressure pipe) fared much worse than thicker-walled pipe at comparable shaking levels. The possible reasons that this was so are several: the axial restraint offered by girth joints in low pressure pipe was overcome by hydrodynamic pressure loads (possibly on the order of 60 psi) induced by the earthquake; accumulated corrosion led to wall thinning that resulted in failures when incremental seismic inertial loading was applied. The thrust loads at pipe bends caused by earthquake-induced hydrodynamic loads are commonly ignored by pipeline designers, and this leads to failures of weak girth joints (like in the 1906 earthquake) or pull-out of push-on joints for segmented pipe (as has been observed many times in a variety of earthquakes over the past century).

- Cast iron pipes laid through liquefaction zones are highly vulnerable. This is where the bulk of the damage occurred in the City distribution system. Installing buried water pipes in marshy or filled lands requires careful seismic design: this was not done in San Francisco prior to 1906. Until the recent advent of seismic-resistant pipes, the preferred strategy would be to simply avoid installing pipes through liquefiable (or landslide) zones. Unless the local zoning jurisdiction sets rules that no development can take place in such zones, the water utility is often compelled to lay water pipes to service the customers that do exist in such areas. The physics of water hydraulic networks are such that just a few pipe breaks in one area can depressurize the remaining unbroken pipe network, leading to loss of water at hydrants at the time it is most needed. Unfortunately for San Francisco prior to the 1906 earthquake, these lessons were unknown.

- The lesson that cast iron pipes are vulnerable in liquefaction zones was not learned in this earthquake. Within a few years (1909-1912), the City of San Francisco built a parallel cast iron water system to fight fires (AWSS). The concept was to add restrainer rings at each pipe joint to limit the potential for the pipe to pull out. This concept proved to be faulty, as the cast iron pipes failed at 7 locations in the 1989 Loma Prieta earthquake, leading to system de-pressurization, and no water coming out of hydrants where needed to fight fires.

- Many other cities built water systems with cast iron (and other seismically-vulnerable) pipes from 1910 to 1990, and these remain today extremely vulnerable to failures in future earthquakes, where exposed to PGDs.

- 3 tunnels were damaged due to fault offset. The Bald Hill Tunnel was deformed but remained in service, where it crossed the primary offset zone, Section 4.1.10. The San Andreas wastewater tunnel collapsed, where it was exposed to primary fault offset, Section 4.1.12. The Crystal Springs outlet tunnel collapsed where it was exposed to primary fault offset, Section 4.1.20.

What could have been different? It is easy to play "arm chair quarterback" in retrospect. So, let's dabble:

- Prior to the October 1868 earthquake on the nearby Hayward fault, it is doubtful that SVWC would have had any knowledge of earthquakes. The Pilarcitos and San Andreas dams and pipelines were built (or construction started) before this earthquake.

- Even after the 1868 earthquake, there was little understanding of earthquake phenomena. The concepts of PGA, PGV, PGD and Response Spectra were not invented until well after the 1906 earthquake. Review of the historic record shows no evidence that any seismic lateral force factors were applied during the construction of the Crystal Springs conduit in 1878-1880, nor the Alameda conduit in 1897-1902. Certainly, the above-ground sections of those conduits were designed for wind loads, but those loads equate to perhaps PGA = 0.03g seismic loading, far too low to provide a reliable seismic performance during the actual 1906 earthquake.

- As seismic understanding increased, the first adopted "earthquakes standards" began after the 1933 Long Beach earthquake; but these standards were still inadequate. For example, V = 0.1 W[19] was the seismic design standard used for the construction of the 1936 San Francisco – Oakland Bay bridge. A portion of that bridge failed in the 1989 Loma Prieta earthquake. Today (2023), essential infrastructure in high seismic zones, having ductile detailing, is often designed for V = 0.50 W (or so). Today (2023), high voltage electrical equipment (generally non-ductile) is shake-table tested to V = 1.62 W.

- Between 1862 and 1906, two types of pipe were used in the water system: cast iron pipe for small diameter (≤ 24") distribution and wrought iron riveted pipes for large diameter (≥ 30") transmission. These were the best pipe materials in the world, with the technology of that time. Welded steel pipes were not commonplace until the 1920s, and even then, welding techniques were sometimes not of high enough quality. For example, the 1923 60" Mokelumne Aqueduct was originally supposed to be welded; but during construction, switched over to being riveted, reflecting that the welds were unsatisfactory. Reflecting this, the 1923 BDPL 1 60" pipe was riveted; and the 1927 San Andreas 54" No. 2 pipe was lock-bar joined. It was not until the 1930s that welding techniques improved so sufficiently so that newer pipes were welded (1933 BDPL 2 66" pipe is welded, and all newer SFPUC transmission pipes are welded).

Had Schussler had a copy of modern seismic standards and geologic hazard maps for water pipe design (for example, ALA 2005), and modern pipe products, he would have avoided zig-zagging the Pilarcitos pipeline 5 times over the San Andreas fault. Instead he could have:

- Designed the Pilarcitos pipeline to cross the fault at 1 location, and with fault tolerant design; and he could have designed all the wood trestles to remain reliable without major damage under seismic loading of at least PGA = 0.5g. Most likely, he would have avoided using thin walled pipe with multiple standpipes to control over-pressurization; and instead have adopted a thicker-wall pipe able to sustain the full water pressure from Pilarcitos Reservoir to Lake Honda (about 300 foot head), along with suitable air and vacuum release valves, along with stronger girth joints.

- Designed the Crystal Springs pipeline and all its trestles to sustain high lateral loads.

- Designed slip joints on pipes to be "long throw" or with restraint systems capable of mobilizing the full strength of the pipe.

[19] V being the lateral seismic base shear for design; W being the dead weight of the structure.

- Installed seismic fault tolerant pipe in zones prone to liquefaction: like fusion bonded HDPE; chained ductile iron; heavy butt welded steel pipe.

- Had the ~400 MG Industrial Reservoir been built in 1894 in San Francisco, then the failures of the Pilarcitos, Crystal Springs and San Andreas pipes would not have been especially important. Why? At a flow rate of 100 MGD (even allowing for major leakage), substantial water could have been available by gravity flow to the fire zone, for at least several hours post-earthquake. This could have been sufficient to controlling the initial fires and prevent the large conflagration.

- Had the ~20 MG Market Street Reservoir been built in the mid-1890s, along with a 16" pipe down Market Street that was otherwise not connected to pipes in the liquefaction zones, then fire-fighting water at multiple hydrants along Market Street at a combined rate of 10,000 gpm would have been available for 24 hours. This certainty would have limited fire spread and structures like the Palace Hotel and the Call Building on Market Street may have been saved; the major commercial areas north of Market Street could have all been saved; and the spread of fire to the Mission Street area around Dolores would likely have been prevented.

- With these provisions, it is conceivable that the 1906 earthquake would have resulted in a just a few leaks or repairable damage here and there, and with nearly every fire hydrant in San Francisco charged with water at good pressure at for the first 24 hours after the earthquake. Still, the initial ignitions in the South of Market Street area might have burned several structures; and a few others scattered elsewhere. Thus, the bulk of the conflagration that consumed 80% of San Francisco would have most certainly been avoided.

There are those who will ask: what about fire boats? What about deploying 5-inch hose via multiple pumpers from the Bay to a distant fire? What about cisterns? These too are elements of the modern AWSS:

- Fire boats. These were certainly effective in limiting fire along the San Francisco waterfront in the 1906 earthquake. They saved nearly all piers and wharves and many nearby buildings. But, they have nearly no value in controlling the fires more than a few hundred feet from the waterfront.

- Above ground hose and pumper relays. These are good solutions for disasters like floods, where the time element to move large volumes of water is hours or days. But the earthquake environment is different. If it is windy, and a fire ignites at an area without flows from hydrants, then there can be just a few minutes before the fire spreads to adjacent buildings. The time and manpower needed to deploy 2,500 feet of 5" (or 6", 8", 10" or 12") large diameter to ultra large diameter hoses is substantial. Unless water can be applied to the fire within a few minutes of ignition, the fire has a good chance to spread. Post-earthquake, fire department personnel are in great demand, for fighting fires, victim extraction at damaged buildings and other emergencies. To the extent that hose is available, this adds to the fire fighter's arsenal for managing disasters. But, relying on overland long hose runs to fight fires post-earthquake, is not a very effective solution.

- Cisterns. This is a simple technology first used in San Francisco starting in 1851, prior to a piped water system. There were 23 cisterns in place at the time of the 1906 earthquake. Most did little (or nothing) to stem the conflagration. The amount of water (commonly 30,000 gallons for those built prior to 1906, commonly 75,000 gallons for those built post 1930) is too little to fight a conflagration, but can be adequate to control an initial ignition while the fire remains small. However, it is far preferred to have water from hydrants, which is often nearly unlimited in quantity (although always limited in flow rate), but more importantly, available immediately and under pressure. If there is no damage to the piped water system, water from hydrants (commonly spaced at 500 feet on every city street) is the far better choice.

- Cisterns remain in the 21st century in common use in some cities in Japan. In Kobe, cisterns were placed to supplement water quantity in parts of the older water piped systems with 2" and 3" (50 mm to 75mm) pipes, where the piped water system could not provide high flow rates. In the 1995 Kobe earthquake, no water from its cisterns was used at any fire grounds: in the part of the city with cisterns, there were essentially no fire ignitions; but at one site, where the fire department did attempt to use water from a cistern, they were unsuccessful, as ground distortion (liquefaction) in that area made prying open the hatch to the cistern practically impossible.

6.0 Outcomes of the 1906 Earthquake

The failure of the water system was a major contributing factor to the fire conflagration that burned 80% of San Francisco.

Somewhat surprisingly, much of San Francisco was rebuilt within 2 years. This reflected that there were insurance funds available for reconstruction; as well as the continued economic growth of California.

With regards to water systems, two major developments occurred:

- An Auxiliary Water Supply Systems (AWSS) was built in San Francisco. Voters approved a bond for $6,000,000 in 1907, and the system was initially built between 1909-1912. Through 2023, this AWSS has been expanded a few times, and remains in service. Today (2023), San Francisco is the only city in the United States with two parallel water systems. Section 7 describes the 1906 fire, upon which the design of the AWSS was developed. Section 8 describes the AWSS system that was actually developed.

- A new source of water supply for San Francisco was established, called the Hetch Hetchy system. Voters approved a bond for $45,000,000 in 1910. Congress approved the flooding of the Hetch Hetchy Valley in Yosemite National Park in the Raker Act of 1913. Construction of the Hetch Hetchy Reservoir was completed in 1923 and first water deliveries were made to the Crystal Springs Reservoir in 1934. Section 9 describes the Hetch Hetchy development.

With regards to the seismic design of water systems, it was a mixed bag:

- The AWSS system was constructed using restrained cast iron pipe, traversing the same zones of liquefaction that failed so many pipes in the 1906 earthquake. When put to its first major test in the 1989 Loma Prieta earthquake, the AWSS suffered 7 pipe breaks and leaks, and failed to deliver water via the pipe system to the major fire in the Marina District of San Francisco. The City of San Francisco has continued to build additional cisterns, to this day, even though the cisterns in the 1906 earthquake were of little to no practical use to preventing the conflagration. The City of San Francisco has purchased some above ground 5-inch diameter hose and appurtenances, to be used in emergencies to delivery water to fires. Fire boats have been maintained to provide salt water fire flows within a few hundred feet of the waterfront. The San Francisco civil grand jury (1999) called upon the SFPUC to seismically upgrade the AWSS pipe system, but with a projected price tag in excess of $6 billion, it remains to be seen what will actually be done.

- The City purchased the SVWC system serving San Francisco in 1930 for about $40 million. This included the distribution pipes serving end users in San

Francisco, including fire hydrants on nearly every street in San Francisco. This system has expanded over time, and presently has some 1,200 miles of pipe serving a population of about 825,000 (in 1906, it had 430 miles of pipe serving 375,000 population). A significant portion of these 1,200 miles of pipe remain cast iron, and today (2023), more than 99% of all pipes have no seismic design provisions. In the 1989 Loma Prieta earthquake, this system had more than 65 main breaks and a similar number of service lateral breaks; and the system could not deliver water to hydrants near the major Marina District fire.

- By 1990, the SFPUC recognized there were seismic and reliability weaknesses in the Hetch Hetchy water transmission system, that included original SVWC transmission pipes dating back to the 1870s and original Hetch Hetchy pipes dating back to the 1920s and 1930s. Between 1990 and 2022, the SFPUC have spent some $4.6 billion in upgrading this transmission system, with about half that cost geared to providing seismic upgrades, and the other half geared to other resiliency or capacity upgrades. SFPUC's goal was to upgrade the system to reliably deliver potable water via the transmission system at winter day flow rates to nearly all of its wholesale customers within 24 hours after major earthquakes on the San Andreas, Hayward or Calaveras faults.

6.1 Did Water Utilities Learn Much About Seismic Design?

Schussler's report (1906) has long been widely available to all water utilities. He showed clearly that:

- Riveted steel pipes that cross traces of faults that are subject to surface fault offset are likely to fail.

- Cast iron pipes that traverse liquefaction zones are likely to fail.

- Riveted steel / wrought iron pipes, interspersed with expansion joints, that cross liquefaction zones, can fail.

- Tunnels that cross traces of faults that are subject to surface fault offset are likely to fail.

- Cast iron pipes subject to moderate to strong shaking are occasionally going to fail.

Did water utilities in California learn from these 1906 lessons? Until the mid-1990s, the answer is largely: not too much. For example, the largest water utilities (including EBMUD, LADWP, SFPUC) continued to build riveted steel pipe and tunnels across active faults until the late 1920s, even while knowing that they are extremely vulnerable to earthquakes. Below are some examples :

EBMUD. 1923: The Claremont Tunnel was designed in 1923 and put into service by 1929. This tunnel is the critical last segment of the Mokelumne Aqueduct, was constructed across the Hayward fault. It took EBMUD 90 years to recognize this weakness, and in the early 21st century, EBMUD built a parallel tunnel across the fault capable of withstanding fault offset without shutting down the tunnel.

EBMUD continued to use cast iron pipe for its water distribution system. Many of these cast iron pipes failed in the 1989 Loma Prieta earthquake. Today, there remain some 1,300 miles of cast iron pipe in the EBMUD system.

LADWP. The Los Angeles Aqueduct Number 1 (233 miles long) was built between 1908 and 1913; Number 2 was built in 1970 (177 miles long). Both Aqueducts were damaged in the 1994 Northridge earthquake (Eidinger and Avila, 1999a). The type of damage included failed riveted pipe, as well as failed canal segments, failed concrete pipe segments, failed single lap welded steel segments. Figures 6-1 and 6-2 shows the Author, Tim Hall, holding a damaged large diameter LADWP riveted steel pipe; this segment of pipe was in the San Fernando Valley, and was exposed to very strong shaking in the 1994 Northridge earthquake.

Figure 6-1. Tim Hall with Segment of Damaged LADWP Riveted Pipe, 1994

Figure 6-2. Close Up View of Damaged LADWP Riveted Pipe, 1994

LADWP had over 1,000 pipe repairs in the San Fernando Valley in the 1994 Northridge earthquake; most of these repairs were for cast iron pipes.

SFPUC (Hetch Hetchy). SFPUC (current agency charged with design, operation and maintenance of the Hetch Hetchy system) continued to use single line of rivets for design of new pipes that are part of the Hetch Hetchy system in 1923.

Figure 6-3 (2008) shows a photo of the Bay Division Pipelines 1 and 2 where they cross the San Francisco Bay near Dumbarton Strait. The first pipe, called BDPL 1, is a riveted steel pipe (single line of girth rivets). This same style of construction was used where BDPL 1 crossed the active Hayward fault. The SFPUC removed the riveted section of the BDPL 1 pipe and the single lap-welded BDPL 2 pipe at the Hayward fault crossing in 2003, replacing both of them with heavy-wall butt welded steel pipes. The SFPUC bypassed this section of the BDPL 1 and 2 pipelines with a new tunnel (called BDPL 5) in 2015. Chapter 9 of this report describes design of the Hetch Hetchy system in some detail.

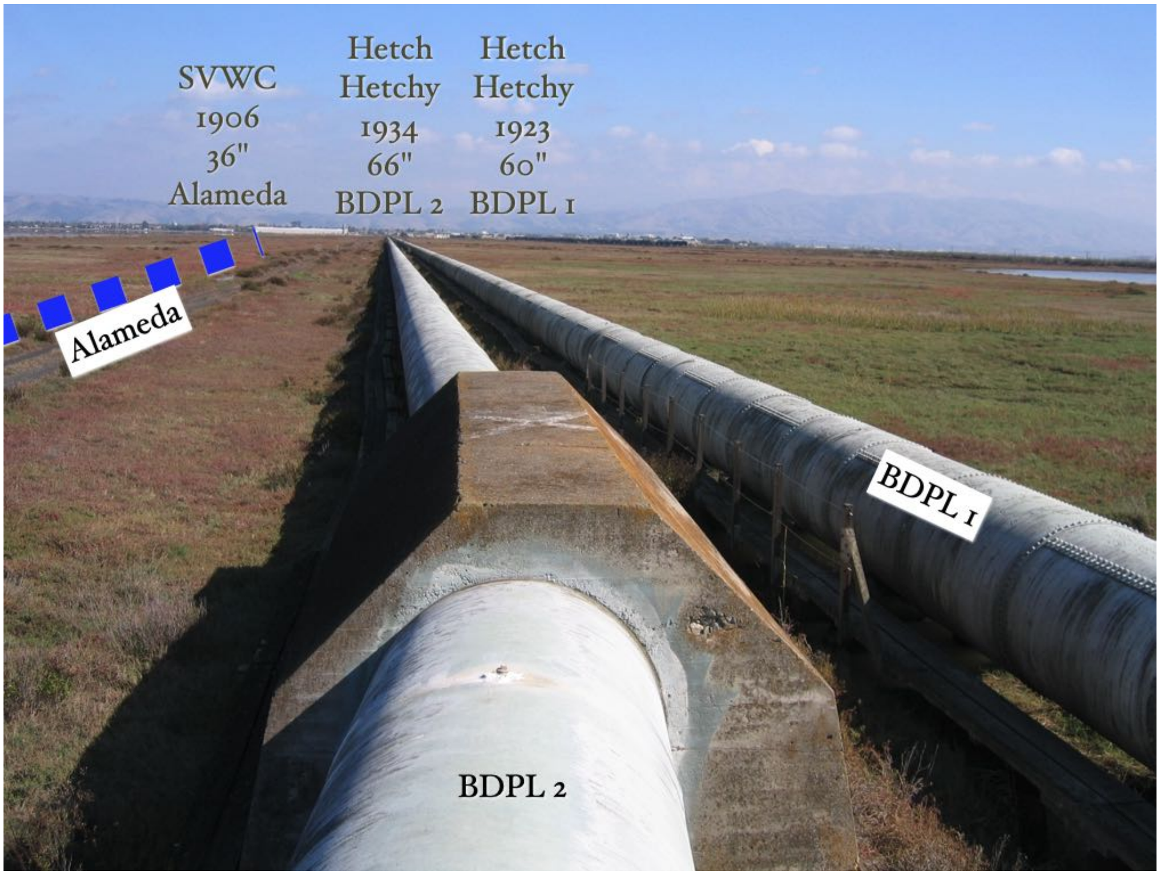


Figure 6-3. SFPUC's Hetch Hetchy Aqueduct BDPL 1 and 2 Pipelines (2008)

Figure 6-4. SFPUC's Hetch Hetchy Aqueduct BDPL 1, 2, 5 Pipelines where they cross the Hayward fault in Fremont (2023)

There are nearly 1,000 water utilities in California. Between 1906 and the early 1990s, it would be reasonable to say that essentially none of these utilities installed seismic-resistant water pipes. Today (2023), there are over 100,000 miles of water pipes in California, of which more than 99.8% are not designed for earthquakes. Since the mid-1990s, some of the largest water utilities, like SFPUC, LADWP, EBMUD, and some of the medium size water utilities, are actively designing and installing a portion of their new water pipes to be earthquake resistant so that they will either not break in future earthquakes, or be damaged at an extremely low rate. The Metropolitan Water District of Southern California, and the San Diego County Water Authority, have taken the approach that they will try to repair large diameter water pipe breaks post-earthquake, and have built large reservoirs to hold water for post-earthquake usage; and they inform their wholesale customers to be prepared for a potentially long water outage; meaning that water for fire flows must be available through other sources (local tanks, etc.)

Overall, it would be fair to say that most California water utilities, as well as others in other high seismic risk areas like Washington and Oregon states, are now adopting seismic provisions in new pipeline installations. These new provisions build upon the observed damage to SVWC's damaged pipes in the 1906 earthquake, as well as other lessons learned in the 1989 Loma Prieta and the 1994 Northridge earthquakes, as well as many other earthquakes that have occurred around the world over the past century or so.

The important take aways from this, are that:

- Essentially all water utilities in high seismic hazard areas in California and elsewhere have largely ignored seismic issues for water pipes for installations from 1906 through about 1990.

- Beginning about 1990, new seismic-tolerant water pipe styles of construction were developed and began to be recognized. These include butt welded high density polyethylene pipe (distribution), butt welded heavy wall steel pipe (transmission and distribution), chained earthquake-resistant ductile iron pipe (transmission and distribution); more types of earthquake resistant water pipe continue to be developed.

- In Japan, many water utilities have been quite active in replacing their older non-seismic water pipes with these new seismic-designed pipes. Today (2023), perhaps 20% of all important water pipes in Japan now use seismic resistant pipes. To reach this level, has taken a concerted effort over the past three decades, especially since the devastating 1995 Kobe earthquake.

- In California, Oregon and Washington, around a dozen water utilities have begun to replace their older non-seismic water pipes with these new seismic-designed pipes. Today (2023), some important water pipes in the west coast of United States now use seismic resistant pipes.

- If water utilities adopt a 1% per year pipe replacement effort, then in many cases, in about 10 years, each water utility can replace their most vulnerable seismic pipes with seismic-designed pipes. Priority should focus on replacing important pipes through liquefaction, fault offset and landslide zones; recognizing that many pipes still remain vulnerable to strong shaking. Over a 100 year time frame, the bulk of the seismic weaknesses for water pipes can be substantially mitigated.

- For those water utilities that continue to build new water pipes using non-seismic design, the risk of water outages and, much worse, potential subsequent fires, will continue to plague communities.

7.0 Fire Following Earthquake

7.1 Fire Area

Despite the strong shaking, liquefaction and surface faulting, the vast majority of the damage caused by the 1906 earthquake, and especially in San Francisco, was due to fire.

The conflagration following the 1906 earthquake was a complex fire, actually consisting of several separate major fires that grew together until there was one large burnt area, comprising the northeast quadrant of the city and destroying over 28,000 buildings. Figures 7-1, 7-2 and 7-3 show three maps of the ultimate fire area:

- Figure 7-1. The USGS (1907) produced a map showing the ultimate extent of the fire. This map shows the largest fire area of the three source maps discussed here. This map correctly shows the ultimate fire bounds and corresponds well with the historic photos of the burnt area that are shown later in Chapter 7.

- Figure 7-2. Under the direction of Marsden, Connick and Ransom (1907-1908) Figure 7-2 is a map showing the ultimate extent of the fire. This map shows a smaller burnt area as compared to the 1907 USGS map. This map omits the fire in the residential areas of the Mission District; the industrial / commercial areas south of Howard Street; and the Chinatown / North Beach areas.

- Figure 7-3. Sanborn (1911) produced a map showing the ultimate extent of the fire. This map shows an even smaller burnt area as compared to the 1907 map. This area represents primarily burnt zones with large commercial buildings.

In all three figures, the fire outlines have been traced by the author onto a base map of San Francisco dated 1908. The reader is cautioned that some of the street grid, as mapped in 1908, did not exist in 1906: especially the low elevation zones around Beach Street (presently called the Marina District), and around 3rd Street (then called Mission Bay). Soon after the 1906 earthquake, the City of San Francisco was in a major re-building effort, and this included filling in low lying areas of the San Francisco Bay to create more land upon which to develop. The methods used to fill in these areas generally used hydraulically-placed fill, and (in places) debris from the 1906 earthquake. Today (2024) much of these zones are considered to be highly liquefiable.

Which of these 3 maps is "correct"? The available literature from the era is now more than 110 years old, and one cannot now ask the original authors what exactly was their intent when drawing the fire boundaries. The authors of this report put full weight to the USGS (1907) map, for the following reasons:

- The USGS map of 1907 (Figure 7-1) was prepared by Richard Humphrey in 1907. In the preface of that report, by Mr. Holmes, it is noted that Mr. Humphrey, then secretary of the National Advisory Board on Fuels and Structural Materials (in Washington DC) was sent to San Francisco on April 19 1906. In that report, photos are presented about the general destruction of Russian Hill from fire, with just a block or so of structures left standing. This photographic evidence provided in the photos in Chapter 7, is compelling that the ultimate fire boundary clearly extended well outside of the red-colored boundary zones in Figures 7-2 and 7-3.

- Figure 7-2 was prepared in part as a basis for developing the AWSS (see Chapter 8). It would seem that Manson, Connick and Ransom were trying to layout the pipes for the AWSS in a manner as to provide the maximum coverage (perhaps by size of building) using pipes and hydrants of the soon-to-be-built AWSS, for a given cost.

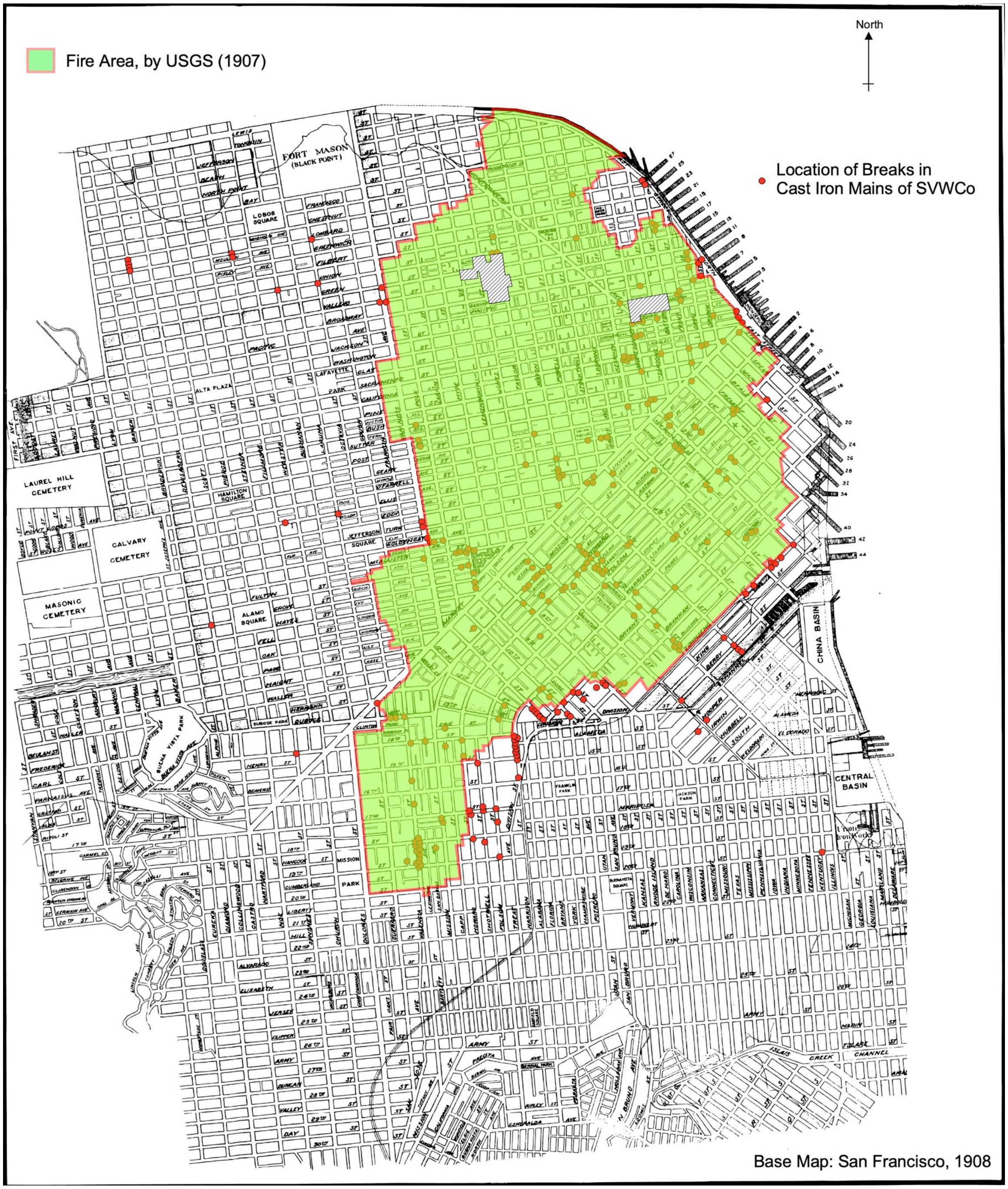


Figure 7-1. San Francisco 1906 Fire – heavy red line and light green color shows final limits as mapped by USGS (1907)

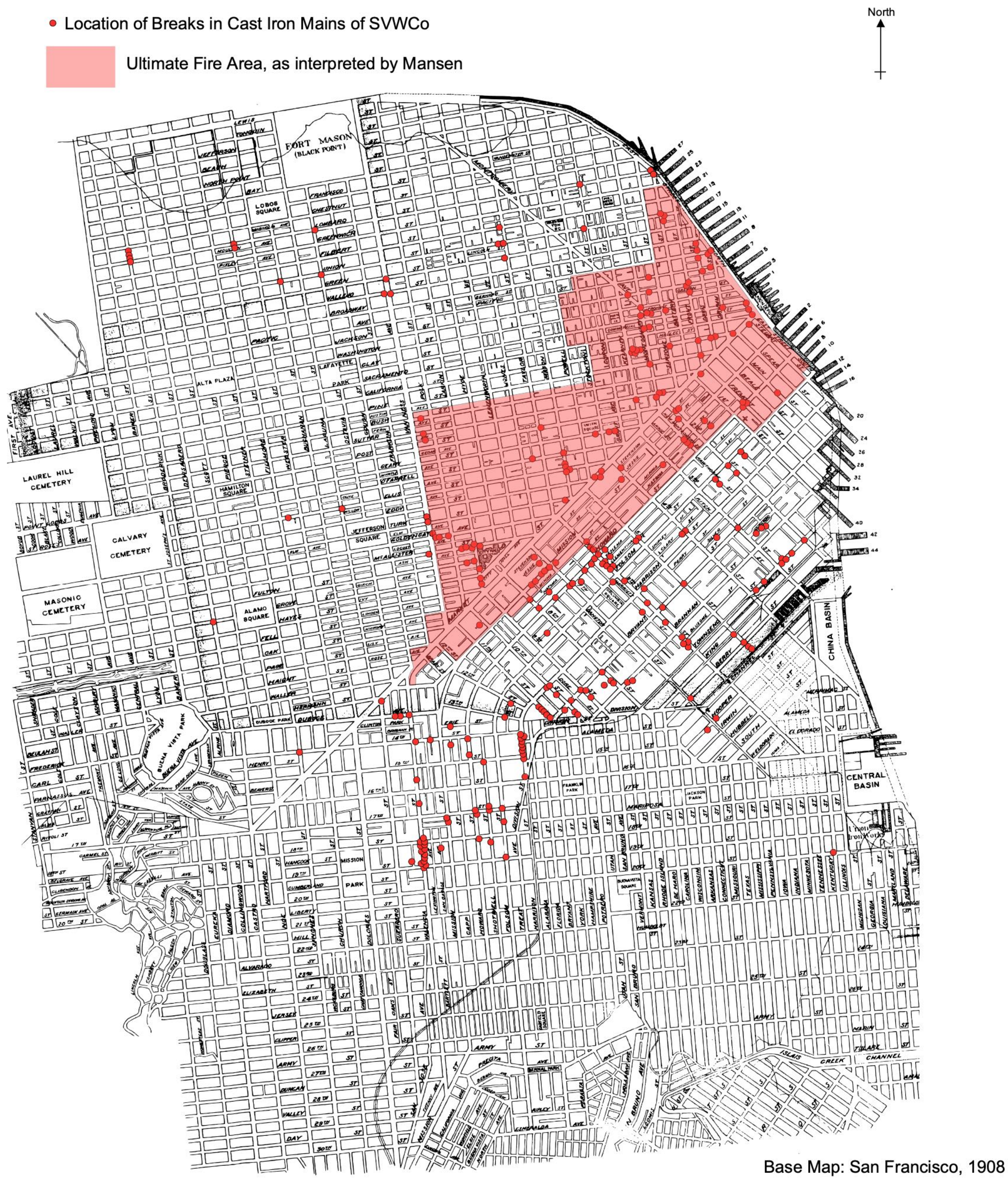


Figure 7-2. San Francisco 1906 Fire – final extents in shaded area as interpreted by M. Manson, H. D. Connick and T.W. Ransom during the years 1907-1908; breaks to cast iron mains in the water distribution system shown as red dots, as interpreted by H. Schussler, 1906; base map by Manson et al, 1908.

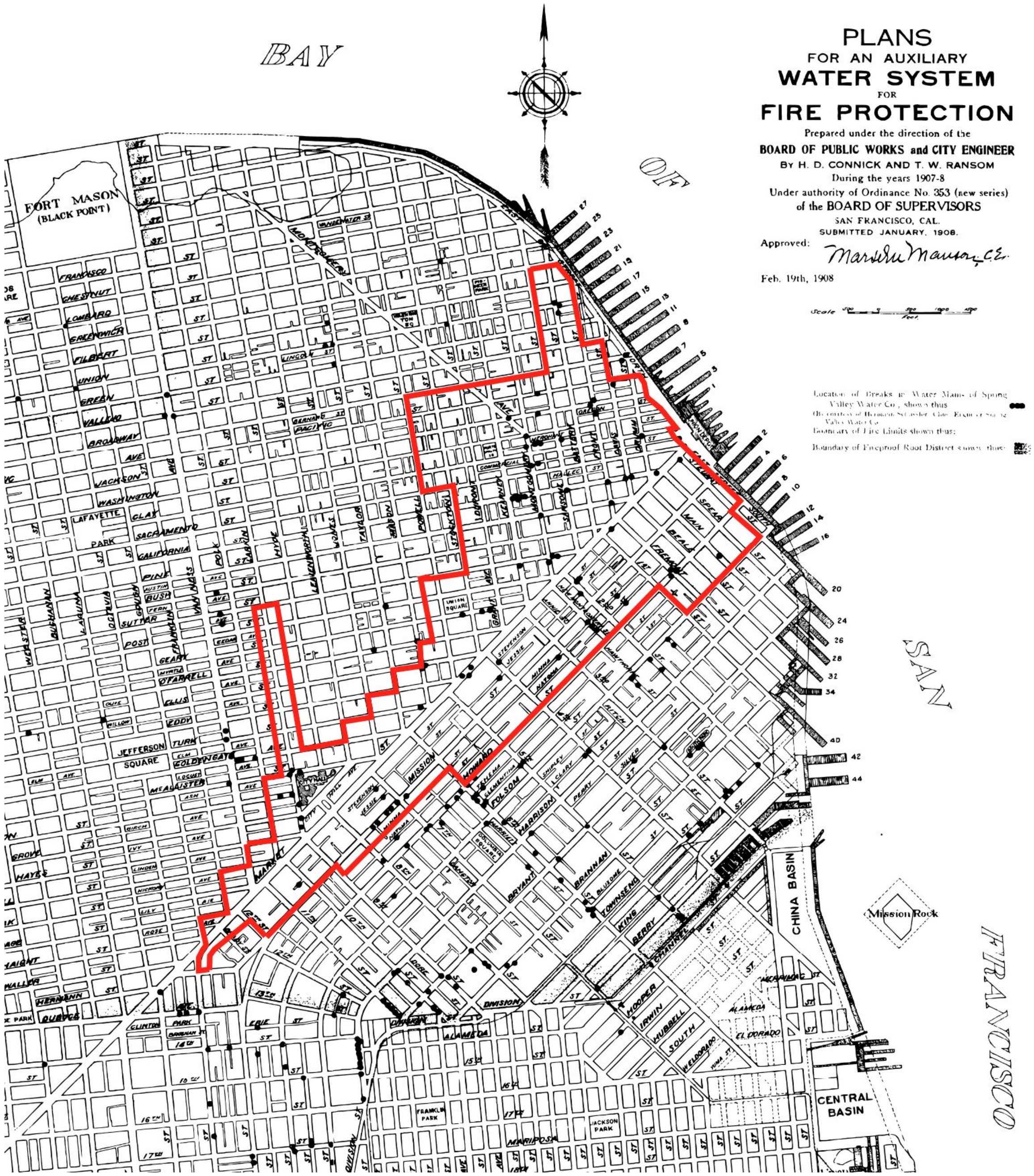


Figure 7-3. San Francisco 1906 Fire – heavy red line shows final limits as mapped by Sanborn (1911). Breaks to cast iron mains in the water distribution system shown as black dots, as interpreted by H. Schussler, 1906; base map by Manson et al, 1908.

7.2 Fire Ignitions

The number of fire ignitions from the 1906 earthquake is not known with 100% certainty. In preparing the fire ignition model in HAZUS (1994), and further described in the book *Fire Following Earthquake (Eidinger et al 2004)* 52 ignitions was adopted as the number of independent fire ignitions that required fire department response.

Reed (1906) reports that it was difficult to determine the number and location of the original fire ignitions. The earthquake occurred around 5:13 am April 18, at which time there was daylight in the streets. Figure 7-4 shows 6 initial fires, as derived from the report of Reed (1906); coupled with the ultimate fire spread boundary.

Humphrey (in USGS 1907) reports that the numerous fires that were ignited all over the city were "doubtless caused by the collapse of chimneys and breaking of electrical connections". Humphrey goes on to state that by 8 am on the morning of April 18, more than 50 fires were recorded. After 3 days, the spread of the fire was checked, by a combination of wide city avenues, by changes in the direction of the winds, by water available from the Lake Honda zone west of Van Ness, by water from Fire Boats along the waterfront area, through efforts by the fire department using water pumped from the bay at the foot of Van Ness avenue (via Black Point pump station); and by water available (and lack of building inventory) to the north of the Mission Creek Channel.

Kennedy (1908) reported that "the acting Chief of the Fire Department, John Dougherty, had 52 fires reported to him." Kennedy noted that of these 52, 2 were from another fire (Oakland?), but that subsequent documentation found 2 more fires not recorded by Mr. Dougherty. Therefore, the number "52" is perhaps speculative, but has been used in developing fire ignition models (Eidinger et al, 2004, HAZUS 1994).

Even considering the observations by Reed (1906), Humphrey (1907) and Kennedy (1908), the exact number of independent ignitions for purpose of modeling fire spread is not known with certainty.

Where (and when?) were these initial fire ignitions? A reliable record (although perhaps incomplete) was developed by Kennedy in 1908. Kennedy relied on various reports from the fire department, as well as ongoing legal proceedings, to establish the locations of fire ignition. Kennedy describes 25 ignitions in some detail. Figure 7-5 shows the location of initial fire ignitions (23 mapped, 2 others not mapped), derived from the report of Kennedy (1908). The blue lines show the major water pipelines in 1906. Table 7-1 lists the confirmed ignition sites and short descriptions if the fire was initially controlled / extinguished, or if it spread.

These 25 fires were all ignitions that occurred on April 18 between 5:13 am (time of earthquake) and reported by April 18, 10 am. The dots shown in yellow were quickly extinguished / controlled by the fire department, or in one case, by the police department; without much spread beyond the initial structure. The dots shown in orange spread to adjacent structures, commonly spreading about 1 city block or so by about 12 noon April 18.

No	Location	Description
1	London St and France Ave	Extinguished
2	Clement, Richmond District	Extinguished
3	22nd and Mission	Extinguished. 6 engines worked for 4-5 hours. Water found 2 blocks distant
4	Golden Gate and Buchanan	Burned 5 hours. Large fire department response between 5:13 am and 10 am April 18
5	Pacific and Leavenworth	Drug store fire. Extinguished
6	Polk and Austin St	Drug store fire. Extinguished
7	Hayes and Laguna	Drug store fire. Extinguished
8	O'Farrell and Taylor Street	Drug store fire. Extinguished
9	Fremont, east side of Mission and Market	Mack & Co. drug store. Fire spread west, east across Beale Street to Holbrook, Merrill and Stetsons about 9:30 am
10	Fremont, east side between Mission and Howard	Martel Power Company. Spread rapidly through the block. By noon, block bounded by Fremont, Beale, Mission Howard was destroyed
11	Occidental Hotel, Bush and Montgomery	Drug store fire. Extinguished by policemen
12	6th and Folsom	Collection of fires; others further east on the south side of Market Street; and a number in the wholesale district. Extinguished
13	Stuart street, east side of Mission.	Alices lodging house. Spread south, igniting Sperry Flour Co. warehouse, south side of Stuart. Spread south across Mission by 10 am to Howard by 12:30 pm. Buildings on both sides of Mission Street east of Stuart were saved by water from Engines 1 and 9, drafting water from the tug Governor Irwin at the Mission Street Wharf
14	Howard and Third	Fire left overnight in furnace at Chinese laundry, fire ignited when earthquake occurred. Spread both directions along Howard, then south to Folsom where it was checked. Reached 2nd at 2 noon where firemen relayed water from a cistern at 1st and Harrison and 2nd and Folsom.
15	4th between Mission and Howard, 282 Natoma	Small frame dwelling house. Spread north, crossed Minna, burning Grand Opera by 9:30 am. Call building burning by 11 am
16	Mission and 6th	Spread north toward Market
17	5th and Minna, between Mission and Howard	Spread north toward Market
18	Near 7th btw Folsom and Harrison	Spread north toward Market, to the south west of 7th. At noon, Folsom was the southern limit. Water pumped from sewers helped for a while.
19	California and Davis	Rapidly burned the Hanford Block. By 10 am, reached the Terminus hotel.
20	Sansome north of Pine	Spread to adjacent buildings by 8:30 am. Burned entire block bounded by California, Pine, Sansome and Battery by noon.
21	Front near Sacramento	Anglo California bank on fire by 8:30 am. Spread east and north.
22	Davis near Clay	Armour Packing house, spread east.
23	Hayes and Gough	Ham and Eggs fire. Ignited 9:00 am as a cooking fire in a stove. Fire department all engaged. Crossed Gough Street to the west, Franklin to the east, Hayes to the south, spreading by noon. Flying embers starts a fire on the roof of the Mechanics Pavilion. Burned a larger area than all others.
24	O'Farrell btw Powell and Stockton	9 pm April 18. Started in Alcazar building by soldiers making a campfire. Spread east and west. By 1 am April 19, it had burnt to Grant Ave near Post Street, and to Powell and O'Farrell
25	6th and Harrison	Incendiary fire

Table 7-1. Confirmed Fire Ignitions (adapted from Kennedy 1908)

Figure 7-6 shows the initial fire spread from the ignitions (orange dots in Figure 7-5) that could not be initially controlled. The arrows show the general direction of spread at each fire location. By 12 noon April 18, the initial fires had spread in three areas:

- South of Market. About half of the area bounded by Market and Harrison and 7th and the Bay was burned. 8 ignitions in this area had spread beyond the initial structure. There was zero water at the SVWC water hydrants due to pipe breaks on the 33" pipe (University Zone) and 16" and 22" pipes (College Zone) where they traversed the Mission Creek liquefaction zone. Water from two cisterns had been used to stop the spread of the fire south of Folsom and 2nd. Water from storm sewers had been used to stop the spread south of Harrison Street around 6th. Water from a tug boat docked at Mission wharf was used to stop the fires along East Street (now called the Embarcadero) to save the Ferry building and nearby wharves. The rate of spread of the fires was commonly around 50 to 200 feet per hour, with the direction of spread commonly easterly, northerly or southerly; but very little westerly. The fire spread map shows no spread northeast of 2nd Street; and this may have been due (at least partially) to water available at salt water hydrants from the undamaged Olympic Club pipe that went down 3rd.

- Waterfront. About 40% of the area bounded by Market and Washington Streets, east of Sansome Street to the waterfront, was burning. This area would have had limited water via hydrants for perhaps an hour after the earthquake, coming by gravity flow from the Francisco and Lombard reservoirs to the north. Good water coverage during that time frame would have been north of Jackson Street; the only ignition north of Jackson Street was quickly controlled. But there were many cast iron pipe breaks south of Jackson Street, and these breaks would have de-pressurized much of the downtown area. In any case, by about 8 am April 18, the water in the Lombard and Francisco reservoirs would have been emptied (theoretically, they could be resupplied via Lake Honda, but high water demand in the Lake Honda zone would have precluded much water reaching the Francisco and Lombard reservoirs).

- Gough and Hayes. A fire was ignited at around 9:00 am by a woman cooking. This is sometimes referred to as the so-called "Ham and Eggs" fire. While the fire department tried, they were unsuccessful in stopping the spread. The fire quickly spread easterly and reached Market Street by noon. Ultimately, this ignition would burn more city blocks than any other.

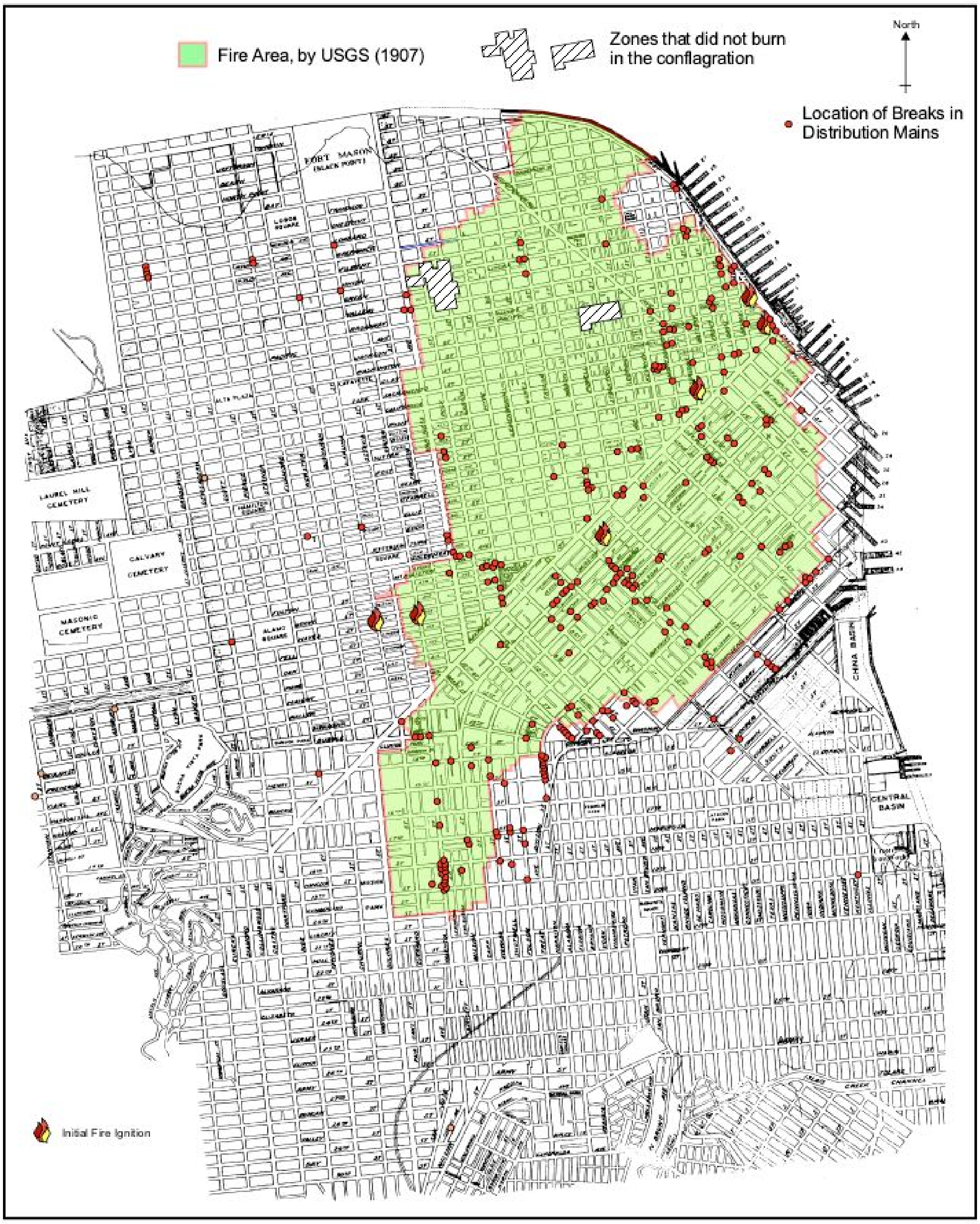


Figure 7-4. Fire Ignitions based on Reed (1906)

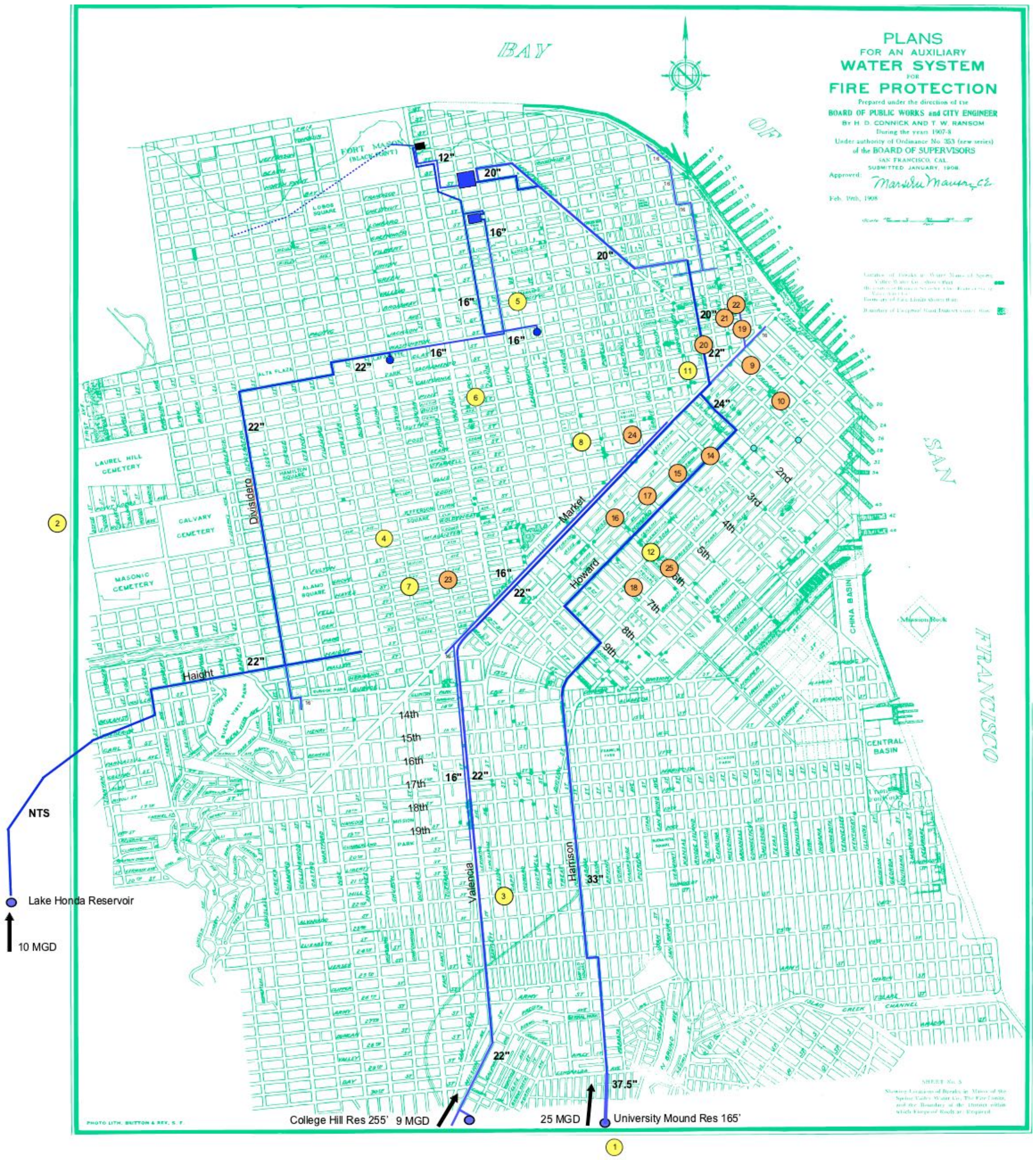


Figure 7-5. Fire Ignitions (April 18, 5:13 am to 10 am). Yellow dots are ignitions that were quickly extinguished. Orange dots are ignitions that spread. Blue dots are cisterns where water was accessed at some point during the April 18-20 time frame.

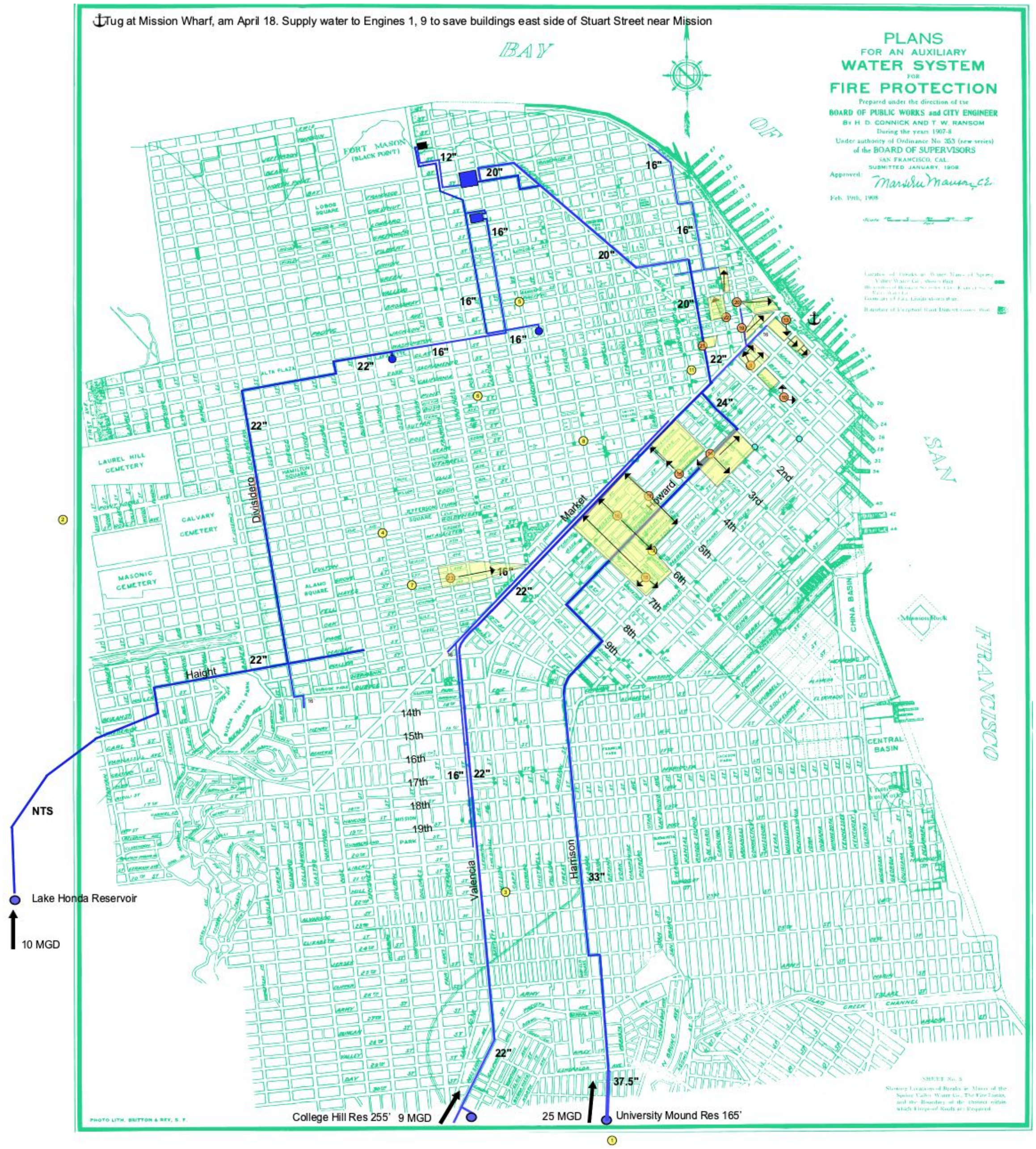


Figure 7-6. Fire Spread based on Kennedy (1908). (April 18 5:13 am to noon). Blocks colored yellow had spreading fires as of April 18 noon). Arrows indicate initial direction of spread.

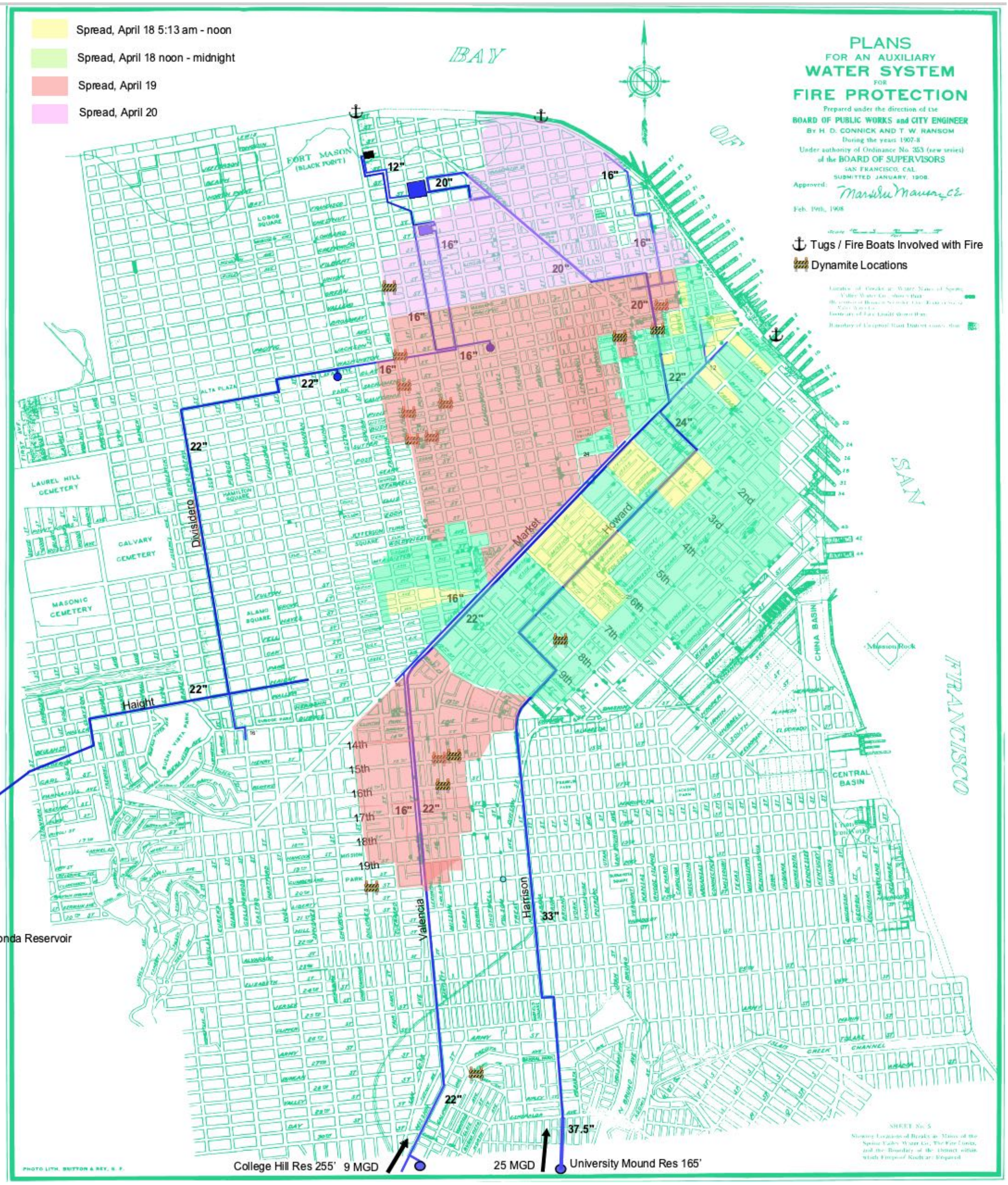


Figure 7-7. Fire Spread based on Kennedy (1908) (April 18 to April 20). Anchors show locations where fire boats supplied water. Barriers show where dynamite was used to create fire breaks.

The fire alarm headquarters were in a brick building on Brenham Place, near City Hall. The building was wrecked by ground shaking in the earthquake. Fire alarms were commonly sounded using alarm boxes, wired to indicate the alarm point at this building. Reportedly, only 2 of the many wired fire alarm circuits were still working after the earthquake. The battery system upon which this system depended, fell over in the earthquake, and ignited a fire that was soon extinguished. Later, the conflagration fire reached this building and destroyed the shaking-damaged building entirely.

The general telephone system broke down over a considerable portion of the City, right after the earthquake. No doubt, many attempts to call in fire ignitions using the phone system were unsuccessful.

On the account of several eyewitnesses (Reed 1906), within a few minutes of the 5:13 am shock, there were several fires visible. Reed reports that about 50 fires were burning by 8:00 am of April 18, but this contradicts the documentation by Kennedy (1908), which only identified 25 initial fires.

Reed reports that there was little doubt that all of the original fires were either located South of Market Street or East of Sansome Street / North of Market Street, with the exception of one ignition west of Van Ness and north of Market, at the corner of Hayes and Laguna Streets. The ignition at Hayes and Laguna Street was in a 2 story wood frame house, and was quickly extinguished by the fire department on the morning of April 18.

The concentration of initial fire ignitions in the South of Market Street area corresponds to the area with collapsed wooden buildings in the Sullivan Marsh area. This is strong evidence that the ignitions were related to damaged wooden buildings. When the wooden structure collapses, the remnant wood is broken into small pieces, like kindling, which are much easier to ignite than solid pieces of wood. This same phenomenon was observed in the Kobe 1995 earthquake, where the collapse of many fragile wooden structures led to many ignitions. This gives strong evidence that to reduce the chance of fire ignition, design the buildings (even wooden buildings) to remain structurally intact from the ground shaking, even factoring in the potential for liquefaction (or landslide / fault offset) PGDs.

As tabulated in Table 4-2, and shown in Figures 7-1, 7-2, 7-3, 7-4, there were many breaks to water pipes (and gas pipes) in the South of Market area. The lack of water via hydrants led to the inability to control the fire if not responded to until after several minutes. Still, some ignitions, like room and contents fires, can be controlled with the limited amount of water on modern fire trucks (commonly about 500 to 750 gallons) or small amounts carried on backpacks carried by fire fighters, even if there is no water available from nearby hydrants. The damage to gas pipes in the area would have meant there was escaping of gas (at that time, coal-based gas, not natural methane gas that is currently used). This escaping gas would have been a fuel that could be ignited. With the collapsing buildings, there would have been lots of opportunities for initial ignition of escaping gas.

The South of Market area is also the location where there was the greatest loss of life.

Within wooden houses, the collapse or partial collapse would have led to fracture of gas pipes leading into the house, as well as damage to electrical connections leading into the house. Similarly, the collapsing houses would have damaged internal gas pipes (such as to kitchens for cooking or to heaters), and to internal electrical wires. Internal wiring in the late 1800s / early 1900s may have used bare wires, and distortions due to building damage could have led to electrical faults; with collapsed wood, an electrical spark from faulted wires could have ignited nearby paper, kindling or leaking gas or other flammable materials.

This points to the importance of preventing general collapse of buildings, as a way to reduce fire ignitions. For example, in the modern City of Sendai, Japan, with a population of nearly 1.5 million people, the M 9 Great Tohoku earthquake of 2011 produced zero fires that required water supply from the water system. The level of ground shaking in Sendai would have been on the order of PGA = 0.3g to 0.5g in many areas, similar to that which would have been experienced in San Francisco in 1906. However, in Sendai, the vast majority of buildings were seismically designed, and only a single structure in the entire city collapsed outright. Further, the buried gas pipe system in Sendai was constructed primarily with MDPE pipe, and suffered very few failures in the 2011 earthquake. Lest the reader assume that Sendai was blessed with solid ground and spared the effects of PGDs, but that is not the case: in the 1964 Miyagi earthquake, there were many zones of liquefaction that damaged buried pipes; but with diligence, new infrastructure in these areas had largely been constructed in the interim years with earthquake-resistant pipes, and several Japanese water utilities have made diligent efforts to replace old non-earthquake-resistant water pipes with new earthquake-resistant water pipes.

In contrast, the City of San Francisco's modern water system (both the potable water system and the AWSS) are largely constructed with non-earthquake resistant water pipes. New earthquake-resistant water pipes could have been installed, which have been readily available since the mid to late 1990s. It was suggested to the SFPUC to install a "chained" water pipe for a large diameter water pipeline in liquefaction-resistant zones as recently as 2008, but the SFPUC rebuffed the idea of using these chained pipes, stating "the concept is not yet proven for large diameter pipes" and "we might try this new concept on lesser important smaller diameter pipes". If one does not start a pipe replacement program, one will never complete the effort. With prudence, a water utility can replace all of its more vulnerable and critical water pipes in a decade or so, by budgeting to replace about 1% of its water pipeline grid every year, and to prioritize earlier replacements for the pipes in PGD zones and those with have had a long history of failures even without earthquakes, such as due to corrosion. Many water utilities are resistant to changing their normal practices, and there often is inertia of doing business the same way it has always been done before. Even so, there have been a dozen or so California water utilities that have begun the process of replacing old seismically vulnerable water pipes with new seismic-resistant water pipes, including water utilities such as EBMUD, the Santa Clara Valley Water District, the City of Palo Alto, the Alameda County Water District, and others. The author notes that if 1% of all water pipes are replaced annually, then in 25 years' time, much of the seismic weaknesses of modern water utilities can be eliminated, as commonly less than 10% of all water pipes are in zones prone to PGDs.

Another source of fire ignitions may have been due to faults in overhead trolley-wire systems, either due to shaking effects, pull downs due to collapses of structures that supported trolley-wire systems, or due to falling debris from adjacent buildings. Most of the trolleys in San Francisco were then operated using electrical power. Reed (1906) reports that electrical power was not cut off for at least several minutes after the earthquake. In Oakland, where the rate of shaking-related damage was perhaps ½ (or so) of the intensity as that in San Francisco, electrical power apparently had been nearly instantaneously shut off. While one fire ignition did occur in Oakland, there was no fire spread, even though the wind and wooden building stock style of construction would have been rather similar to that in San Francisco.

Another source of fire ignitions was due to stove and lamp fires. At 5:13 am, there would have been fires already started for building boilers, as well as kerosene lamps burning in lodging, restaurants and hotels of the cheaper class (Reed, 1906), which were numerous for the few blocks of the South of Market area. Among the buildings where an initial ignition is known, were a frame restaurant on Mission Street between 5th and 6th Streets, a wholesale grocery brick warehouse north of the Ferry building, and the Terminal Hotel at the foot of Market. There was a market and produce district north of Market and east of Sansome, already active at the time of the earthquake, probably using gas and other lights; some serious collapses of buildings occurred in this quarter, possibly accounting for some initial ignitions.

Another fire ignition was reported to have occurred due to the toppling of furniture, where fallen matches reportedly ignited some nearby fuel; this was quickly extinguished by the occupants.

The collapse of the Valencia Street Hotel near 18th Street was possibly the most serious structure failure of the earthquake. The hotel was 4 stories tall, and of wood frame construction. The collapse was likely triggered by liquefaction beneath the building, part of the Mission Creek drainage. No fire ignition occurred in this collapse; but the subsequent conflagration and fire spread did ultimately consume the structure. Section 7.7 examines the Valencia Street Hotel collapse in more detail.

The building inventory in the South of Market area was largely brick (including Mission and Howard Streets) and then mostly wood (Folsom, Harrison and areas further south). It should be noted that fires can ignite within both brick and wood buildings. Once ignited, the spread of fire within wood buildings might be somewhat faster than in brick buildings. With nearly none of the buildings being sprinklered, (and ignoring that much of the water supply in this area was originally cutoff), any fire ignition that was not rapidly extinguished by occupants, was likely to spread within the building, perhaps in 10 to 30 minutes, and was likely to spread to adjacent structures if there was no fire department response to control the initial fire and prevent its spread.

There were no initial ignitions along Market Street.

Some of the fire spread is attributed to unprotected windows in the various buildings, including high rise buildings that had survived the earthquake with limited damage. This can occur when there is no fire department (or occupant) response, and the radiant heat of adjacent fires is transmitted through the windows and ignites material within. Windows with wood sashes could also be similarly ignited.

7.3 Fire Spread

The study of the fire of 1906 forms one of the bases to develop Fire Ignition and Fire Spread models, as documented in the book *Fire Following Earthquake* (Eidinger et al, 2004). In that book, the number of independent fire ignitions for the 1906 earthquake, in San Francisco, is listed as 52; and 7 more in other cities including Santa Rosa, Berkeley, Oakland, San Mateo, Santa Clara, and San Jose.

During the early hours of Wednesday April 18, the wind was generally light from the west, carrying fires away from Market and Sansome Streets and into a territory of low, strung out buildings, bounded by the San Francisco Bay on the east. During this time, fire ignitions in the Lake Honda pressure zone, which had water available at hydrants, were successfully controlled by the fire department.

Had water been continuously available in the South of Market area during the morning of April 18, it is reasonable to presume that all (or most of) the fires would have been controlled and the subsequent conflagration would have been largely avoided.

It is not easy to map out accurately the progressive history and spread of the conflagration. An approximation is given in Figures 7-6 and 7-7, in which the spread boundaries are shown for four different periods over a total of three days.

The wind conditions are reported in Table 7-2 for the period up until noon on April 18, and then after April 20. The information through noon April 18 was gathered using an anemometer atop the Spreckels Building. The Spreckels Building was burned out at around noon on April 18.

Day	Time	Wind Direction	Wind Speed, mph
4/18	5 am – 6 am	S.W.	2 (est)
4/18	6 am – 7 am	W	2 (est)
4/18	7 am – 8 am	W	4
4/18	8 am – 9 am	W	5
4/18	9 am – 10 am	W	10
4/18	10 am – 11 am	N.W.	12
4/18	11 am – noon	W	19
4/20	4 pm – 5 pm	W	26
4/21	4 am – 5 am	W	10 (est)
4/21	4 pm – 5 pm	W	20 (est)

Table 7-2. Wind Speed

In Sacramento, about 90 miles to the northeast, the wind speeds were described as:

- April 18. S.E. light
- April 19 E. Light
- April 20 S.W. light
- April 21 S. 8 mph

The progress of the fires, as reported by Reed, is divided into 4 time periods:

- Period 1. Wednesday April 18, 5:13 am - 6 pm.
- Period 2. Wednesday April 18, 6 pm - Thursday April 19 noon.
- Period 3. Thursday April 19, noon - Friday April 20 1 am.
- Period 4. Friday April 20, 1 am - Friday April 20 night.

Kennedy (1908) also describes the fire spread over 4 time periods, somewhat differently:

- Period 1. Wednesday April 18, 5:13 am - 1 pm. This period includes the initial ignitions, the stopping of some of these fires by the Fire Department and others.
- Period 2. Wednesday April 18, 1 pm - Wednesday April 18 midnight. The initial uncontrolled fires were spreading.
- Period 3. April 19. The fires were spreading up to Van Ness Avenue, North of Market Street, and to south to 20th and Dolores streets in the Mission.
- Period 4. April 20. One fire that ignited on April 20 on Van Ness Avenue and burned eastwards joining the fire from the north that burned North Beach.

Figure 7-7 shows the approximate bounds of the fire at the end of each of the four periods (based on Kennedy). The reader should understand that the bounds shown in Figure 7-7 are an interpretation of areas that the fire had burned at various times; precise records of the burn area at various intermediate times are not available.

Based on the available information, it can be said that the spread of the fires was ultimately stopped as follows:

- Along the eastern waterfront largely due to water available from tugboats / fireboats and limited lengths of handlines that could go to the interior only for a block or two.

- Along Van Ness and a few blocks west of Van Ness when the wind shifted from the east to from the west. A modest amount of water from the Lake Honda zone was available along Van Ness; this water did slow or stop the fire's spread west of Van Ness at some but not all locations. The water plus the wind shift were both important to halting the fire along Van Ness.

- Along the Valencia Street / Mission Street zones in the southwest, when the winds shifted to blow to the northeast or east. Water from the Lake Honda zone would have also helped.

- Along Townsend, using water from the Islais Inlet; coupled with relatively little fuel load in the rail yards in that area.

Had there been no water supply from Lake Honda at all, it is then likely the fire would have spread faster to the west of Van Ness. Similarly, the water supply (salt water from the bay via fire boats) saved many structures along the Bay (piers and wharves) as well as about half of all factories and warehouses located within 3 blocks of the shoreline (more or less within the reach using hoses from fire boats).

Had there been water supply via hydrants in the University Mound zone, at perhaps 90% of the pre-earthquake level of capability, then almost without doubt, the initial ignitions would have been largely controlled, and perhaps only 100 to 300 structures would have ultimately been buried from the initial 52± ignitions. While losing 2 to 6 structures per ignitions is a much worse result than under non-earthquake conditions, it is a far better result than what actually occurred: some 28,200 burned structures.

The observed average rate of fire spread was about:

- 2 to 3 feet per minute during ~12 hours of Period 1 (wind speeds were very low)

- 3 feet per minute during ~ 18 hours of Period 2 (wind speeds had increased)

- 1 – 1.5 feet per minute during ~ 12 hours of Period 3 (with active suppression efforts by the fire department with water)

- 2 feet per minute during ~ 24 hours of Period 4.

7.3.1 Fire Spread During Period 1: Wednesday April 18 5:13 am until 6 pm.

A serious ignition occurred at Hayes and Gough (ignition #23 in Table 7-1), said to have been made in a kitchen fire in a stove with a wrecked chimney. This fire was not brought under control, and was eventually responsible for the fire spread of the district north of Market Street. The spread of this fire towards the east was relatively slow; most of the time, the columns of smoke were near vertical. The spread from building to building was due to a variety of factors; there was only modest spread to the west. During this time, Engine 3 took suction from a cistern at 1st and Folsom and successfully protected the buildings at that corner. Engine 3 also took suction from the Bay and protected some nearby buildings. This fire burned a larger area than all the others.

The two State Harbor Commission tugs, as well as a Navy boat, a revenue cutter and independent vessels, were used to protect the wharves and as far inland as their hoses would allow. The ultimate fire zone map (Figure 7-1) show that fires did not spread to the many warehouses and piers along the water front.

The spread of the fire south of Townsend was limited by the lack of building inventory and by the water supply available from Mission Creek channel that ran about a mile inland. A successful stand was made near the Southern Pacific Railroad yards, and at the corner of 7th and Townsend.

By Wednesday April 18 afternoon, the Palace Hotel and the Call Building on Market Street had succumbed to fire. Fire had not yet consumed structures to the north of Market street and west of Sansome Street.

At the corner of 22nd and Mission Streets (Ignition 3) a fire broke out at Lippman's Dry Goods Store. Six engines worked there for 4 or 5 hours, finding water about 2 blocks distant, and finally prevented the fire from spreading.

At the corner of Golden Gate Avenue and Buchanan Street (Ignition 4) another dangerous fire started, and took all the attention of a large part of the fire department until 10:00 am, burning 5 houses before it was controlled.

Five fires ignited at drug stores: at Pacific and Leavenworth (Ignition 5); at Polk Street and Austin Avenue (Ignition 6); at Hayes and Laguna Streets (Ignition 7); at O'Farrell Street near Taylor (Ignition 8); in Mack & Cos wholesale (Ignition 9). Why so many? Possible because at that time, drug stores had many bottles of flammable materials stored on shelves, easily dislodged and dropped to the floor during the earthquake; some of which ignited.

- The ignition at Laguna and Hayes (Ignition 7) was in a 2 story wood building. It was easily put out by the fire department. There was adequate water at hydrants, with those hydrants being in the Lake Honda pressure zone.

A small fire at Wakelee's drug store under the Occidental Hotel (Ignition 11) was extinguished by two policemen.

There were several fires around 6th and Folsom Streets (Ignition 12, plus others not listed in Table 7-1).

There were other fires South of Market Street to the east of 6th.

There were other fires in the Wholesale District.

7.3.2 Fire Spread During Period 2: Wednesday April 18, 6 pm until Thursday noon April 19.

By the evening of Wednesday, fires had spread in locations South of Market, but the rich business district north of Market Street (such as Union Square, the Mills Building on Montgomery Street), as well as the high class residential district of Nob Hill, had not yet been burned at all. The wind was still from the west, although it had veered to blow from the southwest and had risen somewhat since the morning, but still the wind was not strong (under 10 mph).

A stand was being made at Market and Gough Streets, where there was water available from hydrants from the Laguna Honda pressure zone. During the evening, the wind shifted to come more from the south, and wind speeds increased, rendering a working fire defense untenable.

By Thursday, two Oakland fire engine companies had arrived, but returned soon thereafter, as it was found they could be of no use on account of lack of water.

During Wednesday night, it is likely that the fire jumped the 120-foot-wide Market Street at some point. Alternatively, the spread of the fire to the north side of Market Street could have stemmed from fire spread near City Hall. This fire was said to have originated from an original ignition at Hayes and Gough (Ignition 23) that had ignited around 9 am April 18, see Figure 7-5. The Mechanics Pavilion, located a short distance southwest of City Hall, burned at this time. The spread was rapid and the fire worked through the evening through the theater district on O'Farrell street and the large retail stores on the south side of Union Square, including parts of the area north of Market. This district included older hotels of poor construction, large clubs, many stores and apartments, some being wood frame. Taller buildings, such as Crocker, got the blast of hot air / flames in their upper stories, which ignited ahead of the fire reaching the base of the building. The more fire-resistant buildings, the Mills Building (Montgomery at Bush) and the Merchants Exchange, had served to limit the spread during the day of Thursday, but by Thursday evening, these buildings were also reached by fire coming from the south and west, and became involved with the rest.

A stand was made at the foot of the fireproof Fairmount Hotel, with water coming via 0.75 miles of hose with source water coming from a fireboat at the San Francisco Bay.

Most of this hose was later lost as the fire continued to spread. By the morning of Thursday, the Fairmount Hotel, as well as all the surrounding high class residential neighborhoods were involved, and the west and north sides of Union Square were burning, including the Spring Valley Water Company building, the St. Francis Hotel, Shreve, Sloane, Bush Street Telephone Exchange, Hotels Alexander and Hamilton, Bullock and Jones Building, and four unfinished steel frame buildings.

The Hall of Justice, badly wrecked by the ground shaking, caught fire early Thursday morning.

During Thursday morning, the wind had lightened, and turned its direction and blew from the east. By Thursday morning, Chinatown had been reached and was wiped out.

During Thursday morning, fire swept up through the wood frame district between Russian and Telegraph Hills.

At 10 pm April 18, the Occidental Hotel was destroyed by fire, which swept unchecked across Montgomery Street and attacked the block bounded by Montgomery, Sutter, Bush and Kearney. Shortly after 10 pm the fire had eaten its way southward from Portsmouth Square to Kearney and California streets.

7.3.3 Fire Spread During Period 3: Thursday noon April 19 through Midnight

By Thursday afternoon, the wind was blowing from the east, which served to ensure the safety of the Appraisers Building and its westerly neighbors, as well as to check the fire advance towards the Ferry Building.

The strong southwest wind of Wednesday night had checked the advance of the fire to the west. But now, an easterly wind was blowing the fire into the Western Addition, towards and west of Van Ness Avenue. All Thursday afternoon and night a stand was made at this 125 foot wide street, all forces being concentrated to protect the neighborhood to the west. At this time, explosives were used (Figure 7-7 shows locations where dynamite was used) to blow up practically all large buildings several blocks in width east of Van Ness, along a mile of Van Ness, and extensive back fires were started. Water was obtained using relays with three engines, with water originating at Buchanan, 5 blocks west of Van Ness. Water was also obtained via fire boat at the north end of Van Ness near the Black Point pump station, via three engine relay lines of 1,000 to 2,000 feet each. 3 blocks of Van Ness hydrants were also supplying water between Golden Gate and Ellis Street, with source water from the Lake Honda Zone. The wetted remains of the blown up buildings possibly had some success in slowing the spread. Still, the Van Ness Avenue defense was breached at several locations, and fire continued to spread west of Van Ness for 3 blocks until reaching Octavia Street.

During the evening of Thursday, the fire swept into the wood frame dwelling district on the southwest side of Nob Hill, and swept up and over it.

7.3.4 Fire Spread During Period 4: Friday April 20 early hours through Friday night

By Friday morning, there was doubt whether the advance of the fire could be stopped at all. Then, the wind from the east ceased, and a strong wind from the west started. This finally ended the advance towards the west across Van Ness and southwest south of 20th Street.

During Friday, the wind started blowing from the west, then from the northwest, then from the southwest. These winds carried the fire into previously unburned areas in the northeast part of the city. One area of fire spread down Russian Hill towards North Beach, crossing over Montgomery (now Columbus) and into Telegraph Hill, destroying the "Little Italy" district, with wood frame construction, as well as renewing attack on the east shore wharf district, where there were factories that had not previously been affected, but some were saved by means of water suction from the adjacent Bay.

Blasting activities at the base of Montgomery Avenue (now Columbus) may also have checked the spread.

Individual work also saved a scattered group of high class dwellings on Russian Hill.

The northwest wind of Friday afternoon was very strong.

7.3.5 Saturday April 21

A heavy rain on Saturday brought the situation practically under control. A few smoldering fires occasionally flared up along the east waterfront.

In the unburned districts, damaged chimneys, gas and electrical wiring remained a hazard, especially as many areas of the City were without water via the hydrant system.

7.4 Fire Outcomes

Figures 7-8 to 7-39 show photos of some of the damaged buildings and fire scenes. Photo credit (if not listed otherwise) is the U. C. Berkley Bancroft library. The photos are presented in approximate chronological order, from the morning of April 18 to April 20; followed by a few photos that show the aftermath.

Figure 7-8. April 18, am. Beginning of the Fire. View southwest of 1st Street, towards Minna Street.(Photo: SFHistory / wnp37.00489)

Figure 7-9. April 18, am. View south on New Montgomery Street towards Crossley Building. Grand Hotel at left, fire burning (hand colorized) (Photo: OpenSFHistory / wnp59.00046)

Figure 7-10 shows the Mills Building, left side, early in the morning of April 18. The photo is taken looking eastward from near the top of a building at the corner of Sutter and Montgomery Streets. Smoke from fires along the waterfront and along California Street are seen in the background. Market Street, the diagonal road on the right side of this photo, has no fires.

Figure 7-11 is the continuation to the right of the panorama photo in Figure 7-10. Montgomery Street is in the foreground. Heavy smoke is rising from the South of Market area, around Howard Street.

Figure 7-13 is the continuation to the right of the panorama photo in Figure 7-12. The unburned Union Square area is identified with the incomplete steel frame building.

Figure 7-10. April 18, am. Beginning of the fire. Looking Northeasterly. Large building on left is the Mills Building, at Montgomery and Bush. The superintendent of the Mills Building reported that he was awoken by the earthquake at 5:13 am; inspected the building, and seeing not much damage, started up the boilers for another day of regular business; but by the end of the day, he shut down the building as the fire approached.

Figure 7-11. April 18, am. Beginning of the fire. Looking Easterly. Street on left is Sutter ending at Market; Market and Montgomery intersection at right.

Figure 7-12. April 18, am. Beginning of the fire. Looking Southeasterly. Market and Montgomery intersection at left. Palace Hotel in center.

Figure 7-13. April 18, am. Beginning of the fire. Looking Southwesterly. Unfinished steel building frame on far right is near Union Square. Fire is burning in distance south of Mission Street. Palace hotel on left.

Figure 7-14 shows the beginning of the conflagration. This view is from Jefferson Square Park, looking to the southeast. The fire is then burning generally South of Market. The spread to the north side of Market Street has not yet occurred. The small fire on the left (around Gough and Eddy) was quickly controlled.

Jefferson Square, in the foreground, was then an 11 acre park. After the earthquake, it housed some 20,000 people in tents.

Figure 7-14. April 18. View is from Mint Hill (Buchannan and Hermann), looking southeast. Fires in the Mission District. Market Street is the large street in foreground. (Photo: OpenSFHistory / wnp27.5007)

Figure 7-15 shows fires burning east of Battery, generally east along California Street and environs, in the morning of April 18. Fire boats were then being used to prevent these fires from burning adjacent wharves and piers.

Figure 7-15. April 18. Looking northerly along Battery Street from Market Street in the foreground. The first day of the conflagration.

Figure 7-16. April 18. Looking southerly along 7th Street. Mission Street is the cross street the foreground. The tilted wood pole reflects the major liquefaction movements at this corner. There is no water available at any hydrant near here. The fire is burning near 7th and Howard.

Figure 7-17. April 18 about 10:17 am. View looking southerly on Kearny Street. Fire is still South of Market, but soon to encroach upon the Call Building (tall building with ornate dome).

Figure 7-18. April 18 About 10 am. View looking easterly on O'Farrell Street. Fire is still South of Market, but soon to encroach upon the Call Building (tall building with ornate curved top floors).

Comparing Figures 7-17 and 7-19, fire has not yet reached the Call Building.

Figure 7-19. April 18 About 1 pm. Call Building (upper center). Looking Southeasterly. Photo taken from atop Nob Hill (near Powell and California) (Photo: W. E. Worden, 1906)

Figure 7-20. April 18 About 1 pm. Call Building (upper center). Looking Southeasterly. Photo taken from atop Nob Hill (near Powell and California)

Figure 7-21. About 3 pm, April 18. Looking southerly. Jones Street is on left, sloping down to Market Street in background. Fire in distance in on south side of Market Street. Undamaged north-side façade of Hibernia Bank to the right.

Figure 7-22. April 18, About 4 pm. Larkin Street, looking southerly, between Golden Gate and McAllister. Fire is raging south on Market Street, about to encroach on City hall (dome in left)

Figure 7-23 shows the Hamman Baths on the west side of Grant Street. Military from the Presidio have arrived on horseback.

Figure 7-23. April 18, About 4 pm. Grant Avenue, looking southerly. Fire is burning south of Market Street. (Photo: T. Hecht, 1906)

April 18, 2:30 pm. Figure 7-24. Left: The flames had invaded the "fireproof" Palace Hotel (New Montgomery and Market. There was an extensive standpipe system in the Palace hotel, fed by water kept on site in a massive cistern located in the building's basement; by nightfall April 18, the cistern had run dry. Right: By 6 pm April 18, the Palace is an empty, burned out shell. Looking westerly on Market Street; Call building in background on right image.

Figure 7-24. Left. April 18 By 2:30 pm. Left photo identified as copyright 1906. Right: after fire. Source: http://thepalacehotel.org

Figure 7-25. April 18 About 2:30 pm. Union Square, looking east. The fire is actively burning south of Market Street. Call building dome in distance right. 166 Geary Street steel frame (then under construction) is center of photo. SVWC office building is just to the right of this photo, and its offices are open for business on April 18; but it will burn on April 19. Unfinished steel frames of two buildings are seen.

Figure 7-26. A fire department steam engine is in the center. Fires are actively burning in the 8 story building to the right, and in the background. At this time, there is no water via the piped water system here, so it is surmised that this engine is pumping out water from a local cistern, but to little effect. It is possible this photo was taken the morning of April 19.

Figure 7-26. April 18 pm. California Street, between Sansome and Market. (Photo: W. E. Warden, 1906)

Figure 7-27. April 18 (About noon). Looking easterly from Nob Hill (near Stockton Street and Clay Street) towards the San Francisco Bay. Clay street on left. Mills Building on Montgomery Street is the tall building on the right. Fires are actively burning (dark smoke) between Clay and Washington, near Battery Street. Winds are light (0-5 mph) indicated by the mostly vertical rise of smoke.

Figure 7-28. April 18 (pm). Fires are breaking out in the upper Mission area. Looking north along Harrison Street. City Hall dome in background.

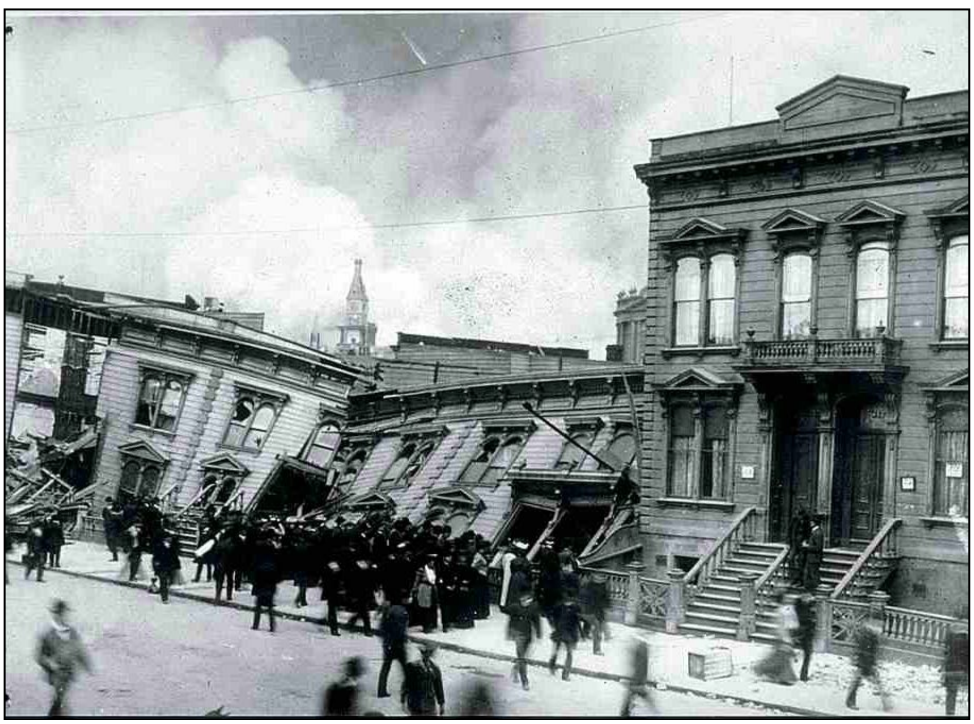


Figure 7-29. April 19. Mission District. Collapsed building, fire in background

Figure 7-30. April 19. View down Sacramento Street

Figure 7-31. April 20, pm. View looking easterly from top of Nob Hill, down California Street., at Powell. Chinatown area is actively burning. Flood Mansion on right foreground. Fairmont Hotel at left. (Photo: W. E. Warden, 1906)

Figure 7-32. April 20. Refugee camp near the Presidio. Fire is burning in northern San Francisco in the background (Photo: Warden, 1906)

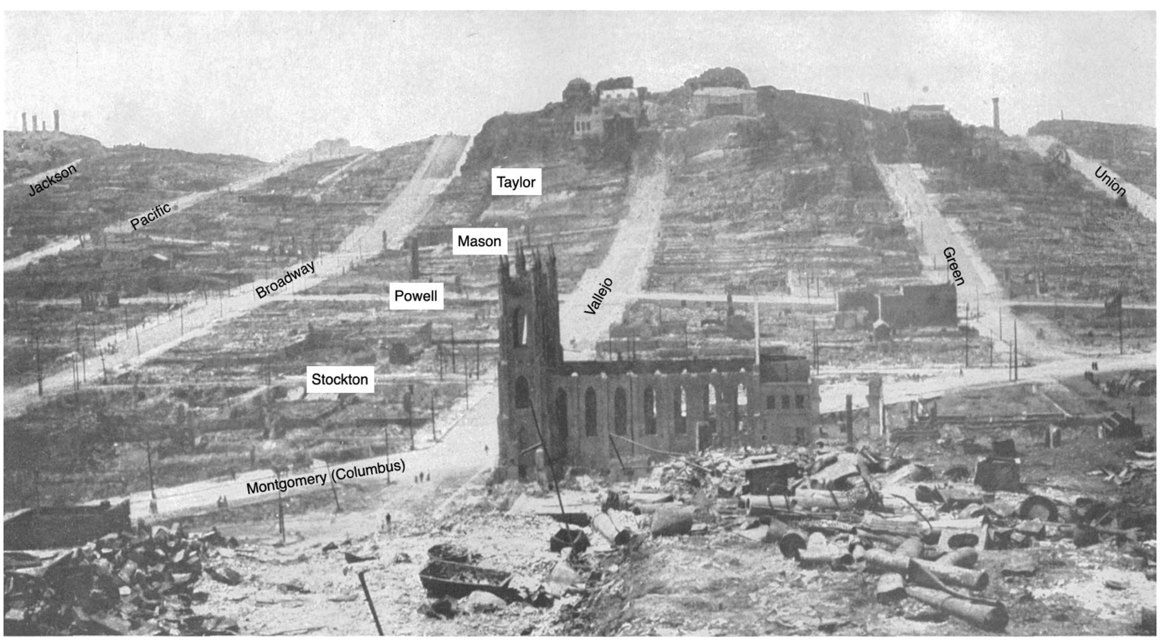


Figure 7-33. After the fire. View looking west from Telegraph Hill, showing unburned houses on summit of Russian Hill. St. Francis Roman Catholic Church, with excellent brick walls in foreground. (Photo: Frank Soule 1906)

Figure 7-34. After the fire. Downtown Ruins, Looking westerly along Market Street from top of Ferry Building Tower

Figure 7-35. After the fire. Downtown Ruins, Looking southerly from Telegraph Hill. Broadway in foreground. Montgomery Street is long road leading to the distance.

Figures 7-36 to 7-39 were taken between May 5 and May 29, 1906, 2 to 6 weeks after the earthquake. Debris has been largely removed from the streets by this time.

Figure 7-36. After the fire. View to the southeast, captured from the Lawrence Captive Airship from a height of 1,500 feet. (Library of Congress, George Lawrence, 1906)

Figure 7-37. After the fire. View to the south, captured from the Lawrence Captive Airship from a height of 1,500 feet. (Library of Congress, George Lawrence, 1906)

Figure 7-38. After the fire. View of the South of Market Street area, captured from the Lawrence Captive Airship from a height of 600 feet above Folsom, between 7th (far left) and 6th (center) streets. May 5, 1906. (Library of Congress, George Lawrence, 1906)

Figure 7-39. After the fire. View of the South of Market Street area, captured from the Lawrence Captive Airship from a height of 600 feet above Folsom, between 6th (front left) and 5th (far right) streets. May 5, 1906. (Library of Congress, George Lawrence, 1906)

A photo essay with 40 additional fire- and post-earthquake photos was published recently by the Atlantic in 2016[20]

[20] The Atlantic, Photos of the 1906 San Francisco Earthquake, by Alan Taylor, April 11, 2016; accessed October 19 2023, https://www.theatlantic.com/photo/2016/04/photos-of-the-1906-san-francisco-earthquake/477750/.

The following is adapted from the writings of Jack London. He then lived in Oakland, and soon after the earthquake took a ferry boat to San Francisco to witness firsthand what had happened.

> By April 18 afternoon, about 12 hours after the earthquake, about half the heart of the city was gone. At this time, London had approached the City by boat, having started out from the east bay. In the bay, London reported that it was dead calm, not a flicker of wind stirred. But, in the City, the rising hot air from the fire created a chimney effect, leading to inflow of wind from all directions. London reported that day and night (April 18, 19) the calm wind conditions prevailed away from the City.
>
> April 18, 9 pm, London reported: "*I walked the heart of the City [presumed to mean near the modern Union Square area, near Kearney and Market]. Here there were no fires. All was in perfect order. Every building had its watchman at the door. Any yet, all this area was doomed; there was no water. At right angles, two different conflagrations were sweeping down upon it.*"
>
> During April 18 night saw the destruction of the heart of the city. Dynamite was used lavishly.
>
> April 19, 1 am, London continues: "*I walked through the same section [Kearny and Market]. Everything still stood intact. There was no fire. And yet there was a change. A rain of ashes was falling. The watchmen at the doors were gone. The police had withdrawn. There were no firemen, no fire-engines, no men fighting with dynamite. The district had been absolutely abandoned. Kearny Street was deserted. Half a dozen blocks away it was burning on both sides. The street was a wall of flame. Surrender was complete. There was no water. The sewers had long since been pumped dry. There was no dynamite. Another fire had broken out uptown, and now from three sides conflagrations were sweeping down. The fourth side had burned earlier in the day; in that direction stood the tottering walls of the Examiner Building, the burned out Call building, the smoldering ruins of the Grand Hotel, and the gutted, devastated dynamited Palace Hotel.*"

7.5 Fire Department Response

In the years before the 1906 earthquake and fire, the history of fire losses in San Francisco was 2 to 3 times as high as other cities having ordinary fire protection (USGS, Humphrey, 1907). The National Board of Fire Underwriters, NFBU, (1905) called out the following deficiencies in the San Francisco business district: a) bad exposures and unprotected openings; b) an absence of sprinklers, automatic fire doors, wire glass; c) poor construction; d) excessive height in non-fireproof structures. The report states that in the congested business district, 2.2% of structures were fireproof, 68.3% were wooden joisted brick, and 29.3% were frame buildings. A bad feature lay in the fact that so-called "fireproof[21]" buildings were surrounded by non-fireproofs. The mixture of dwellings and minor mercantile buildings surrounding the congested-value district greatly increased the hazard. The NFBU report considered the then-current water system ample for the then-existing conditions. NFBU recommended that a separate fire-main system be built[22], and all dead ends of pipe mains be looped wherever practical, and gate valves be installed at 500- to 800-foot spacing so as to limit the number of customers shut off should there be a pipe break. It was noted that there were many narrow streets, an absence of fire breaks between many buildings, and the prevailing high winds, all factors to make the chance of conflagration high.

In 1905, NFBU had prepared a report about the fire hazard for San Francisco. There were a number of criticisms and suggestions. The recommendations in that report included that the water system should be owned by the city and not a private operator; and that a second parallel fire water system should be built. Today (2023) one cannot be sure if these NFBU statements were entirely apolitical, given the long-fought battle between the City of San Francisco and the Spring Valley Water Company.

On April 24, 1906, S. Albert Reed arrived at San Francisco to document the fire conflagration. His findings are included in Reed (1906), and present a clear description of the general conditions of the fire. Reed reports the following:

- After the earthquake, there was an immediate breakdown of the water system serving the congested central business district and all other areas of San Francisco, save for the western most dwelling sections.

[21] The word "fireproof" is a misnomer, for no building is absolutely fireproof, and the resistance to fire is only to a degree: if the heat be sufficiently high and prolonged, nothing can withstand it.

[22] From 1900 to 1905, SVWC was in fact building parallel large diameter pipe for high fire flows in the congested area. Between 1900 and 1905, the Board of Supervisors reduced payment for building these pipes. By 1903 to early 1906, new construction of large diameter pipes had been largely curtailed.

- The loss of water supply at hydrants produced entirely abnormal conditions from a fire-fighting point of view, and reduced the contest to a series of forlorn-hope stands on the part of the Fire Department.

In October 1905, the NFBU reported that the City of San Francisco Fire Department, including relief, consisted of 585 men, all fully paid; 38 engineers, 15 in reserve; 10 ladder trucks, 5 in reserve; 7 chemical engineers, 2 in reserve; 76,700 feet of leading hose; no fire boat, but 2 fire tugs maintained by the State Board of Harbor Commissioners. One of these tugs had fire flow capacity of 1,400 gpm and the other 900 gpm; and combined with 1,100 feet of 3-inch hose.

The distribution of these companies was well conceived, being centered about the congested high value district (i.e., the Central Business District, known in San Francisco as the Financial District), with 24 engine, 8 ladder, 1 water tower and 7 chemical companies within 2 miles of the center of the Central Business District. All but two of the 38 steam engine companies dated from 1890 or later, and were rated at an average of 680 gallons per minute (gpm), although the eight engines tested in 1905 averaged only about 70% of their rated capacity, and the "ability of the men handling the engines was in general below a proper standard". The rated pumping capacity of the 38 first line and 15 relief and reserve engines totaled 35,100 gpm. In summary, the department was rated by the National Board of Fire Underwriters (NBFU, 1905) as efficient, well organized and, in general, adequate. The NBFU however concluded in 1905 that:

> *"...In fact, San Francisco has violated all underwriting traditions and precedent by not burning up; that it has not done so is largely due to the vigilance of the fire department, which cannot be relied upon indefinitely to stave off the inevitable."*

On the day of the earthquake, April 18, 1906, the fire department was commanded by Chief Dennis T Sullivan; he was disabled by the wreck of Chemical Engine House 3 on Bush street, where he was sleeping; he succumbed to his injuries later. Assistant Chief John Dougherty was in charge. No engines were seriously disabled by the earthquake, and all went into service. The lack of water in the Central Business District and lack of communications meant anything like systematic action impossible.

After the fire, the Fire Department reported having lost 3 engines, 1 ladder truck, 1 battery, 37,000 feet of hose of 2.5- and 3-inch diameter; 16 engine houses burned down or otherwise had serious damage; 1 fireman was killed at Engine House No. 4 at 3rd and Howard; another fireman was injured.

The fire in 1906 practically destroyed the San Francisco business district. The maximum temperatures, lasting for a few minutes in each locality, was probably 2,000°F or 2,200°F, while the average temperature did not exceed 1,500°F. At temperatures much over 1,000°F, steel loses about half its strength. There were many examples of buckled steel columns due to the high temperatures. For example, in the Mills Building at Montgomery and Bush, the superintendent awoke that morning, inspected the building for damage from the shaking, and having found just a modest amount, proceeded to start up the boilers for another day. It was only later that the building was consumed by fire. After the fires were put out, the building was re-inspected and found to have suffered buckled steel columns due to the heat of the fire.

Although ten fire stations sustained major damage, the earthquake seriously disabled no engines and all went into service (NBFU, 1906). Street passage was in general not a problem, and a number of fires were quickly suppressed, although many more could not be responded to. That is (NBFU, 1906):

> *"…fires in all parts of the city, some caused directly by earthquake, some indirectly, prevented an early mobilization of fire engines and apparatus in the valuable business district, where other original fires had started and were gaining headway".*

The NBFU Conflagration Report (Reed, 1906) concluded:

> *"the lack of regular means of communication and the absence of water in the burning district made anything like systematic action impossible: but it is quite likely that during the early hours of the fire the result would not have been otherwise, even had none of these abnormal conditions existed".*

That is, the NBFU concluded that even under normal conditions the multiple simultaneous fires would have probably overwhelmed a much larger department, such as New York's, which had three times the apparatus (NBFU, 1905). Nevertheless, Bowlen (n.d.) concluded that by 1 PM (i.e., about 8 hours after the earthquake):

> *"the fire department, except that it was without its leader, was in fairly good shape, that is the men and horses were in good trim for firefighting, the apparatus was in shape and could be worked where there was water. There is not one report of an engine or man going out of commission during the early hours of the fire, and the department was hard at work all the time, even though there was little to show for its effort".*

By April 19, 2:20 pm, the telegraph office, which had continued to function after the earthquake, sent out its last telegraph:

> "*The city practically ruined by fire. It's within half block of us in the same block. The Call Building is burned out entirely, the Examiner Building just fell in a heap. Fire all around in every direction and way out in residence district. Destruction by earthquake something frightful.*"

7.6 Fires Outside of San Francisco

Table 7-3 tabulates the earthquake-caused fires in communities outside of San Francisco. The data is Table 7-3 is adopted after the observations by Nason (1982).

Location	Estimated Structures Burned	Description
Berkeley	0.01	Shaking tipped over a kerosene lamp. Room and contents fire, quickly extinguished without fire department response.
Berkeley	0.1	Ignition at chemical laboratory of El Dorado Oil works. Shaking upset chemical that exploded. Fast fire department response, fire was quickly controlled.
Berkeley (North end)	0.1	Chimney fire.
Oakland (Fruitvale area)	0.1	Ignition at a drug store. Fire was checked with but slight loss.
Martinez	6	Flames damaged part of Grangers Wharf; 6 houses were destroyed despite fire department response.
Oakland	1.2	Ignition caused by movement of gas range which the shaking caused to become disconnected. 2 story wood house, 442 Edward Street. Fire alarm and response by the fire department, but there was no water at the location. The building was a complete loss. Adjacent buildings at 440 and 446 Edward Street also had slight fire damage.
Oakland	0.01	A lighted kerosene heater. Quickly extinguished by a resident without fire department response.

Table 7-3. Fires Outside of San Francisco

7.7 The Valencia Street Situation

Special mention is made here of the damage along Valencia Street, in particular the collapse of the Valencia Street Hotel between 18th and 19th Streets, and the restoration of SVWC water supply.

Perhaps the largest loss of life in the earthquake occurred at the Valencia Street Hotel in the upper Mission District along Valencia Street between 18th and 19th Streets. This L-shaped four story wood frame structure on a 75' x 100' lot was built in a filled area atop Mission Creek. The depth of fill here was on the order of 30 feet. The earthquake triggered liquefaction, and the building dropped down about three full stories. Along Valencia Street immediately in front of the hotel, the 16" and 22" water pipes coming from College Hill Reservoir broke.

Figure 7-40 shows the Valencia Street Hotel, circa 1898. This photo is taken looking northwesterly, between 18th and 19th streets.

Figure 7-40. c. 1898. Valencia Street Hotel (Photo possibly by Marcel Tanron, Online Archive of California, The 1906 San Francisco Earthquake and Fire Digital Collection, U. C. Berkeley, Bancroft Library)

Figure 7-41 shows the main water pipe lines in the vicinity of the Valencia Street Hotel. The green box outline shows approximate location of the hotel. The red dots show locations of water main pipe damage (all diameters). Smaller diameter pipe (3" to 12") are not shown. Compare this with Figure 2-28, showing all water pipes 8" and larger. The normal direction of water flow in the 16" and 22" pipes along Valencia Street and the 33" pipe along Harrison Street would be northbound, coming from the College Hill and University Mound reservoirs, respectively. See Figures 3-3 and 3-5 for maps of the original shorelines and drainages in this area. The location and density of pipe breaks (red dots) closely follows the location of Laguna Dolores / Mission Creek.

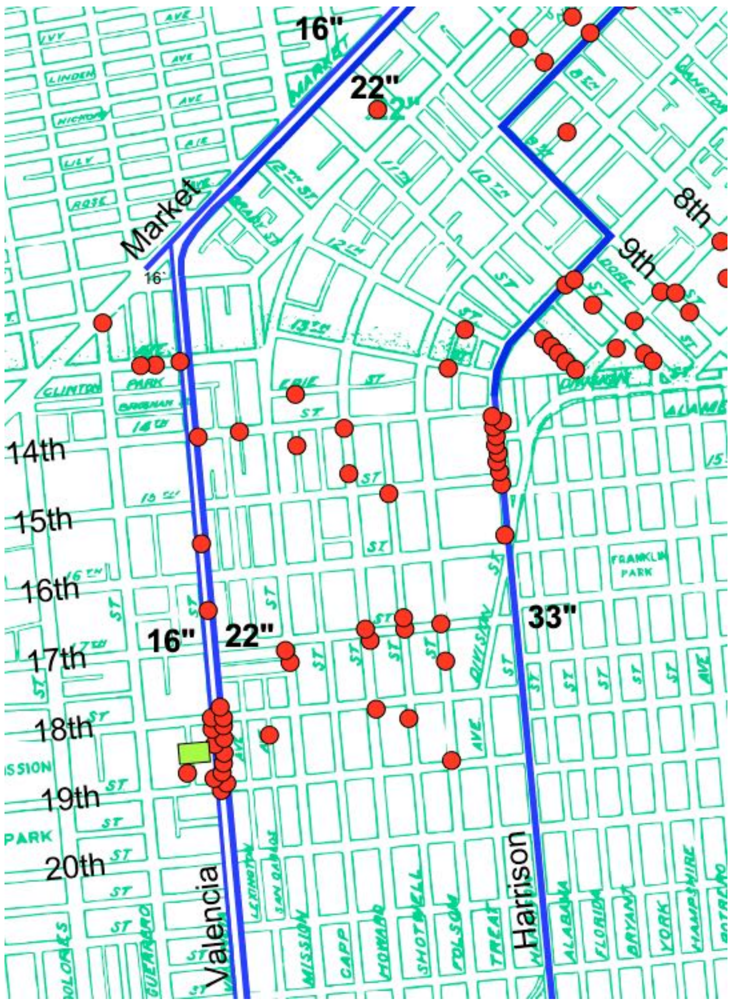


Figure 7-41. Water Mains (16" - 33") in Vicinity of Valencia Street Hotel (green rectangle)

Figure 7-42 shows the collapse of the Valencia Street Hotel. This photo was taken the morning of April 18. The large crowd is possibly more than 200 people. The front of the building has sunk and collapsed some 30 feet or so, with just the fourth floor remaining above ground and displaced sideways into Valencia Street. People are attempting to rescue occupants via a 4th floor window. This building, along with most of the other smaller buildings on the block, were constructed atop a filled-in area of the former Dolores Laguna, a tidal area connected to the Bay via Mission Creek. The area liquefied during the earthquake.

Note that the lightweight telegraph poles remain standing; some are tilted, possibly reflecting the temporary loss of bearing resistance during the time the soil was liquefied; or possibly aggravated by wire pull down forces from the nearby collapsed or partially collapsed buildings.

Figure 7-42. April 18 am. Collapse of Valencia Street Hotel (Photo credit Marcel Tanron, Camera Craft, Vol, 27 1921, Online Archive of California, The 1906 San Francisco Earthquake and Fire Digital Collection, U. C. Berkeley, Bancroft Library)

Figure 7-43 shows the Valencia Street Hotel during the early evening of April 18. By this time, the street in front of the hotel has been cordoned off, with bystanders still seen in the background at 18th Street. A sink hole has opened up in the foreground, reflecting the release of water from the damaged 22" main on the east side of the street. The decorative steeple of the hotel has been removed.

Figure 7-43. April 18 pm. Sink hole opened exposing broken SVWC 22" water main. It is unclear if the 4 people in the foreground are onlookers. (Photo credit: Bear Photo Co. 1906, Online Archive of California, The 1906 San Francisco Earthquake and Fire Digital Collection, U. C. Berkeley, Bancroft Library)

Figure 7-44 shows a wider view of Valencia Street, showing the damage to wood buildings on the east side of the street. This photo is believed to have been taken the morning of April 19, and the fire, then about 16th street, is in the background. The streetcar was stopped at the south side of 18th street. At this time, the street has been evacuated.

Figure 7-44. April 19. Looking North. The fire that was burning near Market Street on April 18 has advanced and is making its way southwards along Valencia Street. Liquefaction had wrecked other wood buildings on the east side of Valencia Street. (Photo credit: Online Archive of California, The 1906 San Francisco Earthquake and Fire Digital Collection, U. C. Berkeley, Bancroft Library)

Figure 7-45 shows Valencia Street looking south. The streetcar in the foreground is "nearly" level, and the rail tracks have buckled upwards. The "buckling" of the rails suggest that there was a lateral spread that pushed the railed northwards, and they would easily buckle upwards under the compressive action. The collapsed Valencia Street Hotel is on the right. The fire has not yet reached this area. On the east (far) side of the street, the overhead wires appear intact. On the west (near) side of the street, the overhead wires are partially pulled down. On the east side of the street, the power / telegraph poles are square. On the west side of the street, the power / telegraph poles are round.

Figure 7-45. April 19. Looking South. (Photo credit: Online Archive of California, The 1906 San Francisco Earthquake and Fire Digital Collection, U. C. Berkeley, Bancroft Library)

Figure 7-46 shows a close up of the damaged Valencia Street Hotel. The photo is believed to have been taken in the afternoon of April 19. The dark smoke of the fire indicated active burning around 17th Street. The twin trolley car tracks are sunken suggesting a continuing settlement in the liquefied zone over a 24± hour period.

The fire will soon reach the area and all the buildings will be consumed by the fire.

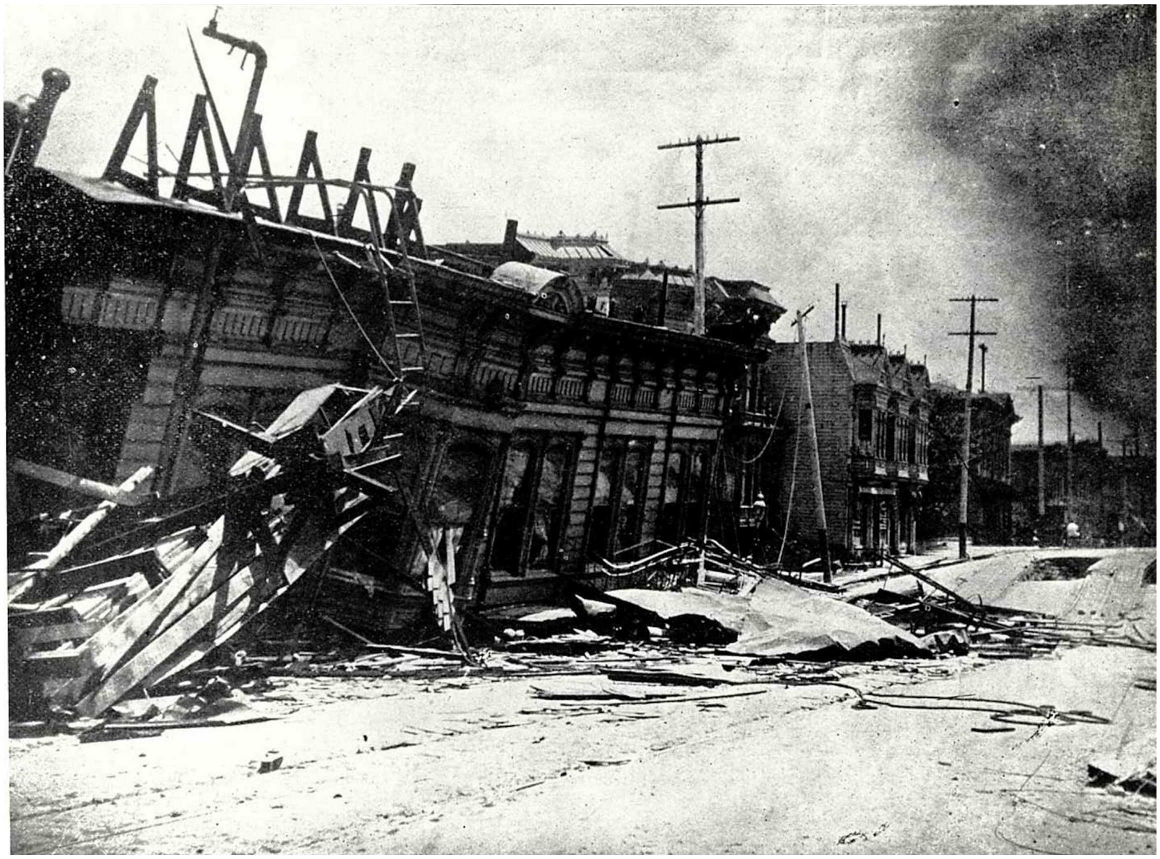


Figure 7-46. April 19. Valencia Hotel Collapse (left foreground); fire approaching from the north. (Photo: provided courtesy USGS). The fire will eventually consume all the buildings seen in this photo. (Photo credit: courtesy of USGS)

Figure 7-47 shows the area as of May 16, 1906 (28 days after the earthquake). SVWC was able to restore water to College Hill Reservoir from San Andreas Reservoir about 62 hours after the earthquake (April 20). The maps in Figures 2-28, 7-5, 7-41 show that restoring flow to the downtown area (Market Street) would need repair of the 16" and 22" pipes on Valencia Street (at least one of them). The great amount of settlement precluded simple patches on the buried pipe; SVWC elected to construct two new (temporary) above ground pipes instead. The historic photos suggest the temporary 16" pipe (west side of street) was installed first.

Figure 7-47. May 16. 1906. View of Valencia Street between 18th and 19th street, looking northeast. In the foreground is an above-ground 16" pipe laid by SVWC as a temporary bypass. In the background is the above-ground 22" pipe laid by SVWC as a temporary bypass on the east side of the street. City Hall dome is dimly seen in the distance just above the group of people in the center of the photo. The cross-arms on the power / telegraph poles have been lost to the fire, but most poles remain standing. (Photo credit: Bear Photo S.F. 401; Online Archive of California, The 1906 San Francisco Earthquake and Fire Digital Collection, U. C. Berkeley, Bancroft Library)

Figure 7-48 shows the temporary pipe on the west side of the street.

Figure 7-48. c. May 16 1906. View of Valencia Street between 18th and 19th street, looking south. In the center is an above-ground pipe laid by SVWC as a temporary bypass of the broken buried pipes. Several extra segments of temporary pipe are seen; pipe joints are apparently unrestrained, not an ideal situation for an above ground pipe, but theoretically feasible over a short straight run. (Photo credit: Online Archive of California, The 1906 San Francisco Earthquake and Fire Digital Collection, U. C. Berkeley, Bancroft Library)

It is reported that SVWC and Mayor Rolf were at odds during the water system restoration process. The Mayor desired to have all valves open so that water would be available to those who needed it. Schussler told Mayor Rolf that valves upstream of areas with pipeline damage should be shut, so that leakage could stop, reservoirs filled, and water pressure built up in areas without damaged pipes. Hydraulically, Schussler's approach is correct, as this restores water pressure and service to as many customers / hydrants as possible as quickly as possible, without wasting water; the politician's approach ignores engineering principles.

Figure 7-49. c. May 16 1906. View of Valencia Street between 18th and 19th street, looking southwesterly. The two temporary pipes are cast iron with belled joints; no restraints are seen placed across the segmented joints. Each segment is typically supported by two sets of wooden planks. (Photo credit: Online Archive of California, The 1906 San Francisco Earthquake and Fire Digital Collection, U. C. Berkeley, Bancroft Library)

Figure 7-50 shows another view of the temporary pipes. The smaller 16" pipe is on the west (right) side of the street, and the larger 22" pipe is on the east (left) side of the street.

Figure 7-50. c. May 16, 1906. View of Valencia Street between 18th and 19th street, looking south. (Photo credit: Online Archive of California, The 1906 San Francisco Earthquake and Fire Digital Collection, U. C. Berkeley, Bancroft Library)

The historic photographic record is not clear as to which pipe SVWC laid first: the smaller (16") or the larger (22"). Practically, this would depend on which diameter pipe SVWC had most available in its yard, and which was easiest / quickest to install. To make the connections to the College Hill Reservoir, the old damaged pipes buried in the street would have had to have been excavated and exposed, and then suitable joinery made; this appears to have been done as straight connections to the undamaged buried pipes either side of the liquefaction zone.

It is the damage of these two pipes, along with the nearby parallel 33" pipe, that are the primary contributors to loss of water supply to the fire areas South of Market Street. Manual closing of valves to isolate smaller damaged pipes might have been done a few hours post-earthquake, but with the loss of these larger diameter pipes, no water would have been available. The technology to install buried water pipes able to sustain this level of settlements without leak did not exist in 1906; but it does today (2024).

8.0 AWSS

The Auxiliary Water Supply System (AWSS) of San Francisco, as of 2023, is composed of several components:

- A grid of water pipes (mostly 10- to 20-inch diameter) that can deliver sweet water or salt water to fire hydrants throughout the core Central Business District (CBD) and other parts of the City of San Francisco.

- Three reservoirs that are filled with sweet water, that normally supply the water pipe grid.

- A number of cisterns throughout the CBD and most residential parts of the City.

- Two salt water pump stations that can supply salt water from the Bay into the water pipe grid (but rarely do so).

- Two fire boats that can deliver several streams of salt water to douse fires at or within a few hundred feet of the San Francisco shoreline.

- Multiple lengths of 5" large diameter hose (LDH) that can be used by fire trucks to move moderate quantities of water (about 1,000 gpm) over distances of about 500 feet, with modest hydraulic head loss.

This history of the AWSS is long and complex. In a nutshell, the following are the main parts of the history of the AWSS.

- In 1903, the San Francisco Board of Supervisors commission the City Chief Engineer, Mr. C. E. Grunsky, to lay out a salt water fire-fighting system, that would be owned and operated by the City of San Francisco, and be entirely independent of SVWC's potable water system.

- The April 1906 earthquake and subsequent fire conflagration destroyed nearly 500 city blocks and about 80% of the assessed value of San Francisco.

- The Board of Supervisors, supported by the press, condemned the SVWC for the disastrous fire. Essentially, the Board (and press) stated that the SVWC was undersized for fighting fires.

- In 1908, the City passed a $6,000,000 bond to construct the original AWSS, including a grid of water pipes, three reservoirs, 2 pump stations, 2 fire boats, and 70 cisterns. The original system was built by 1909-1912. The pipe grid was nominally located to "avoid infirm (liquefaction) ground areas", but in fact, did not.

- As the City population grew and geographically expands, the water pipe grid was extended into new areas, notably including the reclaimed infirm ground (liquefaction zone) of the Marina District.

- In the 1989 Loma Prieta earthquake, the AWSS water pipe grid failed to deliver water to the major fire in the Marina District. The failure was due to seven breaks and leaks in the AWSS water pipe grid, including one in the Marina District. These breaks and leaks effectively de-pressurized the grid, rendering the water pipe grid useless.

- In 1991, the 5-inch large diameter hose (LDH) of the AWSS was deployed to help fight a urban interface fire in Oakland. The hose was deployed about 3 hours into the blaze, to help deliver water to an area of Oakland (upper Rockridge) that had been built with 4- and 6-inch cast iron water pipe around 1909-1929. This small diameter pipe was unable to deliver water to all hydrants near the fire due to overwhelming water demand and excessive head loss in the heavily tuberculated[23] cast iron pipe. The hose initially worked as intended, delivering water to fight the fire at one location; but then failed when a vehicle ran over the hose.

- In 2015, the City passed a bond to refurbish the AWSS. Most of the money was to refurbish the two original salt water pump stations, the fire boats, procure more lengths of LDH and refurbish the main sweet water reservoir of the AWSS. Little money was assigned to address the seismic weakness of the AWSS water pipe grid.

- In 2019, the San Francisco Civil Grand Jury issued a report that called for a stop-gap solution by purchasing 20 more sets of LDH trucks that include pumps that can draw water from cisterns or lakes, at about $1 million each. The Grand Jury suggests that these should be strategically placed in areas that only have low pressure potable water pipes and cisterns. In response, the SFPUC budgeted for 5 of these LDH hose tender trucks, and the SFFD noted that to add 20 more apparatus would require more infrastructure to house them, etc., which was unfunded.

- In 2020, a $682.5 million bond measure passed with 81% of the San Francisco vote. The bulk of the money was to improve fire stations and emergency facilities across the city. $154 million of this amount was slated to expand the AWSS pipe grid into the Richmond and Sunset Districts with some new large diameter pipes

[23] Tuberculation is the development or formation of small mounds of corrosion products inside of cast iron pipe. These mounds increase the roughness of the inside of the pipe. After the 1991 fire, some of the old 1909-vintage pipe was removed and it was observed that the net flow diameter had decreased in some places under 2 inches, which was hydraulically modeled and calibrated by the author by assigning "C" (Hazen William coefficient) to 40.

for that areas, as well as an upgraded pump station at Lake Merced to provide increased flows under emergency conditions.

- In 2021, the SFPUC issued a report on the seismic resiliency of the AWSS. That report forecasts that the AWSS would need to supply 255,000 gpm after a repeat of the 1906 San Andreas earthquake; of which the current AWSS could supply 80,000 gpm. [Author's note: these fire flows are far from certain; the number of fire ignitions and other assumptions are likely over estimated. For example, in the recent M 9.0 Great Tohoku earthquake, the City of Sendai, Japan (population about 1.5 million) had zero fires and no fire flows required, even though the city was exposed to very strong ground shaking (PGA > 0.5g in many places) and duration of strong shaking > 1 minute. While Sendai's water system was damaged (including failure of a main steel transmission pipe at many places, as well as various failures to local distribution pipes), the temporary loss of water supply did not amount to serious economic losses, nor did it result in any fire conflagrations. The remarkable differences between Sendai Water Department (gradual replacement of key water pipes with earthquake-resistant pipes) and the forecast in this 2021 report, suggests that the SFPUC should consider a long term strategy to make the City potable water system more earthquake resistant, and hence reduce reliance on the AWSS, and reduce the potential for fire conflagration.

- The 2021 SFPUC report recommends spending between $4 to $6.1 billion by the year 2046 (25 year time line) to seismically strengthen the water pipe grid, either relying on the potable water system, the salt water system, or a combination. Relying mostly on potable water system plus an upgrade Lake Merced pump station would cost $4 billion. Relying on a potable water system without the upgraded Lake Merced pump station, plus an upgraded salt water system, would cost $5.7 billion. A third option, including both the upgraded Lake Merced pump station and new salt water pumps, would cost $6.1 billion The report also recommends initial installation of new large diameter pipe in the Richmond and Sunset districts, relying on source water from Sunset Reservoir (potable water), along with various valve controls, to improve the seismic resiliency of the AWSS grid in those areas.

8.1 Addressing Future Fires

The following sections delve into some depth as to the history and seismic ability of the AWSS. The core findings are as follows:

- The continued construction and use of cisterns to fight fire conflagration fires in San Francisco is perhaps a fool's errand. Cisterns are not generally not effective to fight conflagration fires.

- The AWSS pipe grid was seismically defective at the time it was initially constructed between 1909-1912.

- The extension of the AWSS pipe grid into the Marina District was seismically defective at the time it was initially constructed around 1916.

- The two salt water pump stations are an expensive luxury with little practical use after earthquakes, if the water pipes are not seismically-robust.

- The use of fire boats is effective for fighting fires near the water front.

- The purchase of many lengths of LDH (5" portable hose) provides the fire department with some flexibility to delivery water to areas with broken water mains (whether the AWSS pipe grid or the potable water pipe grid). The time needed to deploy LDH makes them poorly suited for preventing initial fire spread. Other water departments (notable EBMUD) have purchased Ultra Large Diameter Hose (ULDH, 12-inch portable hose) to deliver significant volumes of water about a day after an earthquake, primarily to speed up restoration of water supply to customers due to damaged pipes that cross earthquake faults, landslide and liquefaction zones.

- A potentially better solution to spending many $ billions to upgrade the AWSS pipe grid is to spend a far lesser amount to seismically upgrade the City's potable water pipe grid. Once the potable water pipe grid is suitably upgraded, the AWSS pipe grid, salt water pump stations and cisterns can be abandoned over time. This solution can provide a robust water system for fighting fires and prevent conflagrations after earthquakes, and ultimately save the San Francisco water rate payers and tax payers considerable cost.

- It would seem that the SFPUC approach and the suggestions above do not agree on what is the best path going forward. What started out as a $6 million system (capital cost $15 per capita in $1908 dollars) has mushroomed into a $5 billion (or so) future system $6,250 per capita in 2023 dollars. Allowing for a consumer price index multiplier of 32.21 for inflation from 1908 to 2022 (source: Bureau of Labor Statistics consumer price index, accessed July 14, 2022), the original $15 per capita cost is now $483 per capita to service about 400,000 people, while the $6,250 per capita cost is to serve about 800,000 people.

Without question, the potential for fire ignitions, per capita, is substantially lower in 2023 than it was in 1906. Why?

- In 2023, the quality of earthquake-resistant construction is vastly superior to that in 1906. Relatively few unreinforced masonry structures remain in San Francisco in 2023, and eventually all the remaining will be either upgraded or removed. Similarly, so-called soft story structures (wooden or otherwise) are being upgraded. Many fire ignitions in1906 occurred due to outright building collapses from shaking. The rate of building collapses due to future ground shaking should be far lower in 2023 than it was in 1906. Over time, this rate should continue to decline.

- In 2023, the natural gas system in San Francisco is made almost entirely from MDPE pipe. In 1906, it was made almost entirely from cast iron pipe. MDPE pipe is vastly superior in terms of seismic performance than 1906-vintage cast iron pipe. Far fewer natural gas-fed fires are expected in future earthquakes as compared to what happened in 1906.

- In 2023, essentially nobody uses coal-fired (or wood-fired) open hearths for cooking, as was common in 1906. In 2023, modern cooking appliances (whether electric or natural gas) are considered to be nearly (but not entirely) immune from ignition due to earthquake, assuming the building remains intact.

- In 2023, very few unreinforced brick chimneys remain in San Francisco. Fewer chimney-related fires are expected.

- In 2023, it is thought that drug stores no longer store flammable chemicals in glass bottles on shelves (or at least, far fewer than in 1906). In 2023, many flammable materials are kept in earthquake resistant shelves / storage units.

Overall, the fire ignition rate in San Francisco is likely to be much reduced as compared to what it was in the 1906 earthquake. The common assumption is that in 1906, there were 52 initial fire ignitions. Allowing that in 2023 there is double the inventory (about 800,000 people in 2023 versus 400,000 people in 1906), then perhaps one could expect about 25± ignitions in a future San Andreas M 7.8 repeat event. With slower than non-earthquake response times, these ignitions will need about 1,000 to 2,000 gpm each, or on the order of 30,000 to 50,000 gpm total to control. If there is no wind, about 20 – 30 structures may be lost to fire. If there is light wind, about 80 – 120 structures may be lost to fire. The real concern is if there is high wind at the time of a future earthquake, and if there is no water available at the original ignition site once the fire department shows up. In this unlikely case (but cannot be ruled out), fire spread and conflagration is likely in wood-structure areas with tiny setbacks (still common in most areas east of Van Ness).

The question is then posed: given the 2023-vintage AWSS and City potable distribution systems, both being seismically vulnerable, what percentage of the grid will have water (or have no water) (at 20 psi or higher) in the first 5 to 30 minutes post-earthquake? In areas with water, if there is no wind, the fires will almost certainly be quickly controlled. In areas with no water, if there is wind, the fires will possibly spread.

One presumes that the SFPUC have evaluated these questions using modern understanding about earthquakes, before issuing a report that recommends between $4 and $6.1 billion of water system upgrades to deal with fires. For sure, any such report should be open to peer review: in 1903 (and again in 1908), the AWSS design was not well conceived with regards to seismic robustness, and mistakes were made. The result was a complete failure to deliver water in a timely fashion (via either the MWSS or AWSS pipe grid networks) to the fires in the Marina District in the 1989 earthquake. Had there been wind at the time of the 1989 earthquake, a general conflagration may have ensued well before the LDH tenders were able to deliver moderate volumes of salt water to the fire grounds some 45 minutes to 1 hour post-earthquake. This issue is complex, but a reasonable path forward might be as follows:

- Over the next 10 years, replace all cast iron (or other non-seismic pipe) in areas with infirm ground in San Francisco with new seismic resistant pipe (ERDIP[24], butt welded steel, HDPE[25], etc.). Allow that there are about 50 miles of such pipe. Replace about 5 miles per year at a cost of $3 million per mile, or $15 million per year.

- In 10 years, the vast majority of the seismic risk to the potable water system will have been eliminated, at a cost of $150,000,000. Add to this 20% for engineering, and planning, the total cost is about $180,000,000.

- This is a capital cost of $225 per capita, or a tiny fraction of the SFPUC's recommended $6,250 per capita. Capitalized over 10 years, the recommended upgrade is about $23 per capita per year, or under $2 / month / capita. Quite possibly, this cost can be absorbed into the regular capital improvement plan of the potable water system, meaning that the end user customer may see zero to perhaps a dollar (or so) increase to their monthly water bill.

Recognize that no amount of water system upgrade will be of much use if there are multiple ignitions in an earthquake that overwhelm fire department response, and if it is windy at the time of the earthquake. To deal with this extreme contingency, other strategies will be needed, such as:

- Create a forced power outage system, to be invoked if PGA > 0.25g plus PGV > 15 inches per second. This could be implemented for several $ tens of millions, by the power company. By de-energizing the power grid within 5 seconds after the damaging S waves arrive, about a third to half of all ignitions may be avoided.

- By zoning, remove all certificates of occupancy from extremely hazardous buildings, like unreinforced masonry structures. Remove such buildings. Do this within 10 years.

- By zoning, remove all certificates of occupancy from non-qualified buildings located in liquefaction or landslide zones. For a building to be qualified, it would need a report from a duly qualified engineer, that the building will reliably not undergo material deformations that cause damage to internal pipe / wiring

[24] ERDIP: Earthquake Resistant Ductile Iron Pipe

[25] HDPE: High Density Polyethylene Pipe

systems, for a San Andreas M 7.8± earthquake. Perhaps 0.5% to 2% of all existing building infrastructure in San Francisco would be under this ordinance, primarily in the Marina District, the Sullivan Marsh District, and the former Mission Creek areas. Do this within 10 years.

- By zoning, require 10 foot minimum setbacks between all non-fire-resistant buildings. This will apply to many buildings in the Potrero Hill, Russian Hill, Nob Hill and other districts east of Van Ness. Do this over 30 years. Replacement construction would need to be able to resist high heat / open flame for a sufficient time as to allow fire department response a reasonable chance to contain the initial fire (say 1 hour).

- By zoning, require all new appliances to use electric-start natural gas ignitions, and within 20 years, require that all existing appliances be removed entirely if they rely on gas pilot lights.

- By zoning, require all new construction having regular occupancy to have maximum $R \leq 3$ (earthquake response modification code in the IBC code) for the median level motions for a San Andreas M 7.8± event (or 475 year probabilistic motions), or $R \leq 4$ for the 84^{th} percentile motions (or 975 year probabilistic motions). These goals are intended to preclude outright collapses, and keep major drifts and damage-causing drifts to perhaps 0.1% of the new building stock. Rw values of 6 to 8 to 12 (working stress design) (or R values of 4.25, 5.7, 8.6 for strength design) have been adopted for many buildings constructed in San Francisco between 1950 and 2000; these R values are too high to prevent serious damage.

- By zoning, all future manufactured houses (mobile homes) must be seismically designed with anchor systems capable of sustaining V = 0.36W elastically. All existing and future natural gas services to manufactured housing must have meters (and associated pipes) located at least 1 foot from the building, and flex hoses capable of safely sustaining 2 feet of relative displacement. For mobile homes that do not meet this criteria, all services must include either automatic shut off devices that are activated at PGA $\geq$ 0.2g; or gas flow restriction valves; the cost to install such devices shall be paid by the customer.

- There are a number of practices that should be adopted by the Fire Department, such as keeping potentially seismically-vulnerable garage doors open; automatic roving patrols post-earthquake (do not wait for call); upgrade of communication system (cell phones, radios, repeater stations, etc.) to be seismically robust with a minimum 24 hour battery power reserve or reliable standby power supply, etc. Manpower and apparatus (currently around 1,500 manpower and 62 apparatus) is likely sufficient for non-conflagration situations. Many other aspects of fire department response are not addressed in this report.

8.2 AWSS Salt Water Pipe System Design of 1903-1904

In 1903, the Board of Supervisors directed that the plans should be developed for a "Salt Water System" for fire protection. In response the City Engineer for San Francisco, Mr. Grunsky outlined the following: (1903, Report of City Engineer):

- The total quantity of water used for fire protection, per year, is about 32 million gallons.
- Due to corrosion-related issues, while salt water is nominally free from the surrounding ocean and Bay, fresh water is preferred in the pipes.
- Salt water fire-fighting systems had previously been used in Eastern cities.
- It is desired to have a total flow rate of 10,000 gpm, or about as much as used by 20 fire engines, in the heart of the business district, at a pressure of 200 psi in the main.
- The project will have a large reservoir at elevation 755 feet near Twin Peaks.

Consideration was made to make use of the existing Olympic Salt Water Company system (see Section 2.1.4). Mr. Grunsky asked the Olympic Salt Water Company as to what would be the cost to expand the salt water system in such a manner so that 6,000,000 gallons per day would be available from the Laurel reservoir (see Figure 2-12) and to have the pump station be available to replenish salt water, day or night, after a fire general alarm has been sounded? To this, the Olympic Salt Water Company noted that there would be substantial cost to do this. To this response, the City reported that the City would not grant a contract to the Olympic Salt Water Company for more than 1 year. To this response, in lieu of new construction, the Olympic Salt Water Company offered to the City a capacity of 3,000,000 gallons per day, at a cost of $3,000 per month. Mr. Grunsky declined this offer, and instead Mr. Grunsky planned on a completely separate system.

Mr. Grunsky's report lays out a salt water system that is similar in many ways to the one actually built, and funded by a bond issue in 1908.

The AWSS pipes were selected as cast iron, as being the best pipe material. All pipes located at or below 400 feet elevation (i.e., prone to high pressure) would be made with double scored bell ends. The lead in the joints would be suitably alloyed to give it sufficient hardness, and whenever static pressure exceeds 200 psi, a cast iron retaining ring would be bolted to the end of the bell and drawn up snug against the lead in the joint. In other words, add a mechanical external restraint system able to resist the thrust force at 200 psi pressure.

A seismic evaluation of the seismic resiliency of this type of 1908-era restrained cast iron pipe is as follows. Say the pipe is 12-inch diameter, 0.5 inch wall. The water cross sectional area = 113 square inches and the water thrust force at 200 psi = 22,600 pounds. Allow that the cast iron pipe has metal area = 12.5 * 3.14 * 0.5 inches = 19.6 square inches, and the cast iron strength is 20,000 psi. Then, the cast iron pipe breaks in tension at 392,500 pounds. Clearly, the as-conceived restrained jointed connection (Py perhaps 30 kips, somewhat higher than the water thrust force) is much weaker than the pipe (Py perhaps 200 to 300 kips). Therefore, when exposed to PGDs that impose high tensile (or bending) loads on the pipe, one would expect the restraining rods to fail well before the cast iron body, save for slight yielding and opening up of the leaded joint. In other words, the system designed by the City of San Francisco Chief Engineer Mr. Grunsky was bound to fail whenever significant PGDs would be imposed on the pipes. The proof of this is the failure of the AWSS pipe grid in the 1989 Loma Prieta earthquake, where 7 pipe breaks and leaks de-pressurized the grid, and the pipe damage in the Marina District prevented any water from the piped AWSS grid to be put on the large fire in the Marina District that broke out after that earthquake.

The 1903 "backbone" system was envisioned to cost $642,770, inclusive of one salt water pump station, a 10,000,000 gallon reservoir atop Twin Peaks, 5.12 miles of 16- to 22-inch pipe, one intermediate elevation tank; excluding the cost of hydrants; excluding the cost of distribution mains north of Market Street and southeast of 7th and Market Streets. The backbone main of the salt water system would run down Market Street. The City Engineer stated that operating costs would involve "no extra expense beyond the pumping of salt water to the reservoir atop Twin Peaks".

It would appear that Mr. Grunsky was over selling the 1903-version of a planned AWSS to an all-too-willing San Francisco Board of Supervisors, who were actively looking to put the SVWC out of business by constructing a parallel Hetch Hetchy water system, the general disdain for private enterprise by the political leaders (Mayor Phelan and the majority of the Board of Supervisors), all reinforced by the clamoring and vitriol of the Press against the SVWC. How could Mr. Grunsky claim that there would be "no extra expense", when clearly every water system needs ongoing funds to maintain pumps, repair buried pipes, replace buried pipes as they age, corrosion protection, testing and maintenance of fire hydrants, etc.? While Mr. Grunsky wrote what perhaps the Politicos of 1903 wanted to hear, he was not serving the public well, by not disclosing that a parallel water system would be expensive to maintain, and possibly not work in earthquakes, and that the alternative choice to seismically strengthen the potable water system, could be the superior option.

The staff of Fire Engineering (1898) reported the following as of April 8, 1898:

- Another tunnel, and flume, was being built to deliver water into San Andreas Reservoir.
- A new brick and cement reservoir was built at the summit of Potrero Heights, 300 feet above tide; the reservoir is supplied by a 2 mile long 12-inch pipe.

- 13.86 miles of new distribution mains have been installed in the City Distribution system.

- The Pilarcitos pump station, 4.5 MGD capacity, was built at the outlet of the San Andreas Reservoir outlet tunnel, with a large cast iron pipe that connects this pump station with the main Pilarcitos pipeline. This pump station provides two water sources for the Pilarcitos pipeline near its headworks, therefore increasing system reliability should there be an upstream pipe break, or water quality of other event at the Pilarcitos Reservoir.

- Construction of the Millbrae pump station, 16 MGD capacity, was initiated. This pump station would be available, as needed, to pump either water from the Crystal Springs 44-inch or Alameda 54-inch pipes into the adjacent San Andreas pipe. This pump station serves to increase system reliability, should a lack of rainfall in the Pilarcitos / Peninsula mountain area result in a shortfall. This pump station allows water from the Alameda watershed (with a much larger watershed and greater delivery capacity) to be directly available to the higher elevation areas of the City.

- This 1898 document goes on to note that the cost of purchasing and developing the Alameda watershed serves the dual purpose of increasing the reliability of water supply to San Francisco for times of drought; as well as increase reliability for fire flows. While today (2023) this is obvious to all, it should be recognized that in the latter half of the 19th century, the San Francisco Board of Supervisors was against paying for any Spring Valley Water Company improvement that was not necessary to meet current water needs; while at the same time, was paying for the development of plans to secure new sources of water to deliver a flow not needed for another century, and an entire new delivery system, including new parallel pipes in the City. Clearly, the Board of Supervisors was playing politics, spending money to plan for a new parallel municipally-owned water system, at the same time trying to starve funds from SVWC. This was a policy failure, and the long standing attempts by the Board of Supervisors to starve / deny SVWC funds, was a material and significant factor that led to the 1906 fire conflagration.

8.3 AWSS Salt Water Pipe System Design of 1907-1912

The history and performance of the Auxiliary Water Supply System (AWSS) has been a matter of much discussion over the past 130 years or so.

As described in Section 8.2, the AWSS was under consideration to be built even before the 1906 earthquake.

In 1907, the Board of Supervisors authorized two engineers (Connick and Ransom) under the direction of the City Engineer, Marsden Manson, to develop a design and cost estimate for the AWSS. Figures 8-1 to 8-4 show their original design, and this is reasonably close to what was actually constructed between 1909 and 1912. As will be described below, this design had serious flaws, and was pretty much doomed to fail in future earthquakes.

The available documents suggest that Manson was sensitive to the idea that the new AWSS pipeline grid should supply water to the areas where the most fires were in 1906, while at the same time avoiding laying new pipes in streets that had been subject to major ground deformations. The best pipe material available in 1908 time frame (for diameters under 30 inches) was cast iron pipe, and Manson recognized that the Grade 53 (rated 150 psi) cast iron pipe with leaded joints, as installed prior to 1906, did not fare well in the 1906 earthquake, especially at locations with PGDs. Manson ultimately selected Grade 56 (rated 300 psi) pipe, with leaded joints, and with supplementary tie bars to provide tension restraint in zones thought susceptible to PGDs in future earthquakes.

By early 1913, much of the planned AWSS was built. F. H. Porter of the Fire Underwriters Inspection Bureau (The Adjuster, 1913) reported the progress as follows:

- Pump Station 1 has been completed.
- Pump Station 2 is nearing completion, and should be ready for use by July 1, 1913.
- Twin Peaks Reservoir is completed, overflow 758 feet.
- Ashbury Tank is completed, overflow 462 feet.
- Jones Tank, overflow 388 feet, should be completed by July 1, 1913.
- Filling the entire system with fresh water is scheduled for second half of 1913. Initially, the system was filled with salt water.
- Fire Department wagons carry reducers to fit hydrants, regulating the pressure according to the amount desired.

In Figures 8-1 to 8-4, zone gate valves as larger "crosses" within circles. As originally conceived by Manson, Connick and Ransom, these valves were all to be normally open, and that should there be pipeline breaks, crews would be dispatched to close the needed valves to isolate the broken area.

But, this is a fatal flaw in the design of the AWSS. After an earthquake, it might take hours (or even days) to identify broken pipes. More than a third of all pipes traverse the infirm ground areas. It is beyond rational for Manson to have laid cast iron pipes along Valencia Street, an area that subsided about 5 feet in the 1906 earthquake. Ground settlements and lateral spreads along Dore Street, 7th Street and other locations were commonly 1 to 3 feet. 12-inch pipes, if broken, will often leak at a 5,000 gpm rate. Even 8-inch service laterals to hydrants will leak at 1,000 gpm to 2,000 gpm rate.

In the moderate Loma Prieta earthquake, there were 7 breaks and leaks in the AWSS pipeline system, 6 of which were south of Market in the liquefaction zone, the other in the Marina District, also in a liquefaction zone. With the breaks and leaks, perhaps in the range of 1,000 to 5,000 gpm each, the overall leak rate might have been on the order of 10,000 gpm, which would a) drain the Jones Street tank in 75 minutes, and b) de-pressurize the remaining grid, so that even if more water from Twin Peaks (or Ashbury) tanks were made available, or water from the salt water pump stations, the majority of the flow would go out the broken pipes, and there would be low pressure (or none) at many of the remaining hydrants.

The map in Figure 8-2 highlights that the larger diameter pipes (generally 18-inch) that provide the backbone to move water from the Salt Water pump stations (or the reservoirs) to the grid, were purposely installed outside the infirm ground areas. While this was sound design, the fundamental error in the AWSS design still remains: the cast iron pipes in the infirm ground area are going to break in earthquakes that trigger PGDs; and the time needed to manually identify, send crews, and turn valves will always be more than 1 hour (and could easily be several hours). Any initial fire ignitions, if not controlled within 10 minutes or so, can readily spread to adjacent buildings, especially if it is windy.

There are two flow paths (redundancy) from either pump station to Twin Peaks as well as to the Jones and Ashbury tanks. Redundancy is good. However, this redundancy is only valid after the broken or leaking pipes are isolated. As minutes count for fighting fires, and humans, no matter how well trained, cannot reliably identify and isolate broken pipes within a very few minutes after an earthquake, the system is de-facto non-redundant.

All of Manson's proclamations of his genius, and placing the two pump stations on "solid rock" appear to be just a wish.

All this leads to the following conclusions:

- The pipes, reservoirs and pump stations of the AWSS design of 1907-1908, as constructed, do not fulfill the stated and oversold mission.

- After 110 years of ownership, the Municipal AWSS pipe + reservoir + pump station system still remains seismically vulnerable.

- There is temptation by the Municipal authorities at the SFPUC to add band-aids to the AWSS pipes + reservoirs + pumps to cure these weaknesses. Vendors are happy to sell hundreds of $ millions (or $ billions) of pipe and work to the City-owned system. Raising millions (or billions) of dollars keeps the authorities in well-paid jobs and requires a large supporting bureaucracy. Water rates today remain very expensive like they were in 1906, even after adjusting for inflation.

True, today's water supply includes a higher level of treatment (chlorination, disinfection for Hetch Hetchy-sourced water, full treatment of water from local reservoirs) than was done in 1906, and this costs money, and that can explain some of the increased cost. But the inescapable observations is that it cost about $10,000 per mile to install a mile of pipe in 1906 (range of 10-inch to 20-inch), and perhaps $3,000,000 (8-inch) to $19,000,000 (30-inch) million per mile in 2023. Inflation over that time frame is about 30x. Therefore, today's municipally-owned water system charges about 10x to 60x more, even after adjusting for inflation, to install a mile of water pipe. Certainly, some of this increase is due to new rules for worker safety, etc., but also, the increase is due to the large bureaucracy and administrative rules that is the reality of today.

- What is the "right" thing to do? Almost certainly, an overhaul of the combined two water systems, into one water system, is the way to go. There are about 100 miles of pipe that remain in infirm ground areas. If one replaced 10 miles of seismically-vulnerable pipe per year, then in 10 years, with new seismically-designed pipe that will not break in those inform ground areas, the combined system will be made vastly more reliable.

- Cisterns could be abandoned. Cisterns have little to no use after large earthquakes to control conflagrations. They did not help in the 1906 earthquake. Cisterns did not help in the 1995 Kobe earthquake. It is perhaps best to stop building new ones, and reallocate the money either to savings for the citizens, or to cover the cost of creating a modern seismic-resilient piped water system.

- Consideration should be made to abandon the two salt water pump stations. Injecting salt water into the underground pipe network has serious issues with regards to water quality, and corrosion, plus the greater damage to property when using salt water to control fires, etc.

- The major asset of the AWSS system is the pipes. Either abandon them entirely, or clean out, then line, and then merge them (outside of infirm soil PGD zones) with the potable water system.

- In the infirm soil areas, one quick and low cost strategy would be to remove the entire pipe at-risk grid. This would materially increase the reliability of the remaining grid. This would cost little, only the disassembly of the pipes (closing the gate valves is not sufficient). Call this Phase 1. This might cost about $1 million to implement (say 100 locations at $10,000 per location).

- Phase 2: replace the pipes in the infirm soils with new seismic-designed pipes, that will not fail given the design-level PGDs. This will cost on the order of 50 to 100 miles x $2 to 3 million per miles = $100 million to $300 million. This should be done in stages, perhaps $10 to 30 million per year, and incrementally change the pressure zones.

- Phase 3. Add a series of automatic isolation valves to the system. This could be done for about $500,000 per valve, with triggers based on a combination of PGA, PGV and sudden drops in pressure. Manual overrides would be incorporated, in a manner so that if there is a fire, the operator can elect to open valves wide open for fire flow purposes, factoring in that water used there (including possible pipe damage) will be to the detriment of the remaining undamaged system.

- From 1890 to 1905, the potable water system was adequate to control over 6,500 fires in the San Francisco, without conflagration. Fire losses, per capita, in San Francisco were not much different than in other major US cities. The water system in San Francisco was generally superior (better pipe grid) to those in major European capitals, such as London or Paris, but the fire losses per capita in Europe were historically about 1/5 to 1/4 that in the US… why? The answer is that in Europe, nearly all construction was stone or masonry, which is much more tolerant against fire spread than the large wood-building building stock in the US.

- Today (2023), there is scant use of wooden buildings in the downtown business district of San Francisco north of Market. Over the past 20 years, much (but not all) of the wooden building stock in the South of Market area have been replaced with modern buildings made from concrete and/or steel.

- Today, the potential for fire ignitions is much lower than it was in 1906:

    - Brick chimneys are almost non-existent in the infirm soil areas in the financial district (a few may remain in the South of Market area).

    - Coal-based cooking fires are almost non-existent in San Francisco.

    - Natural gas pipes today are almost all MDPE. MDPE pipes are far more seismic resistant than the cast iron pipes of 1906.

    - The seismic quality of the generally building stock in 2023 is far superior than in 1906. Only a very small percentage of the current building stock is likely to collapse or be seriously damaged as compared to 1906. The rate of fire ignitions is especially high in buildings that have collapsed.

- Can the Municipal-owners of this system do the right thing? It could be said that SVWC, being a privately owned company and more nimble than Municipal bureaucracies, could have acted faster and smarter and cheaper to upgrade the water system to be more resilient in earthquakes.

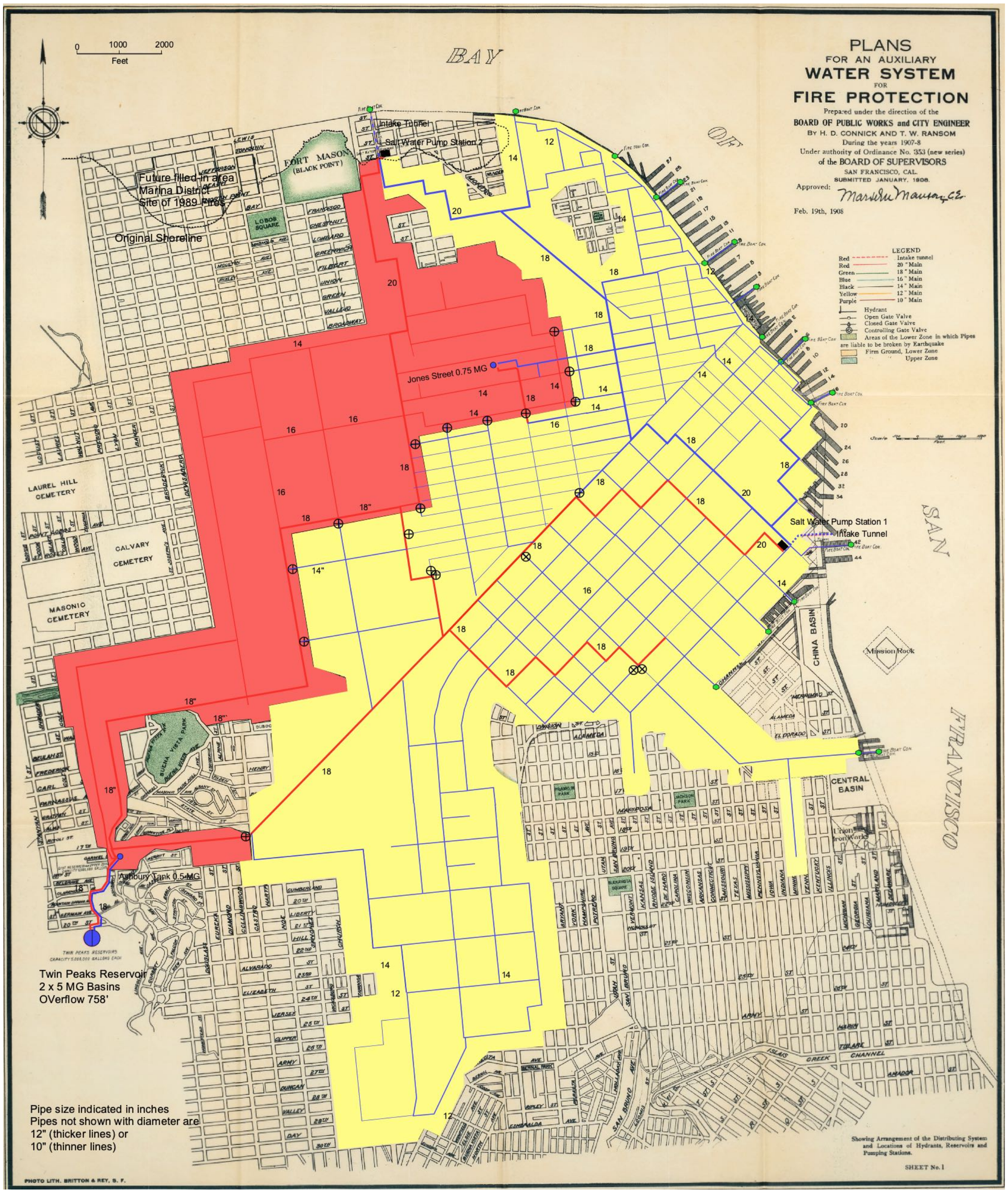


Figure 8-1. The AWSS Water System, 1908 (Base map by Manson, 1908. Blue lines: water pipes (12-inch diameter unless noted). Yellow: lower pressure zone. Red: upper pressure zone. A tiny area is in the uppermost pressure zone directly beneath the Twin Peaks reservoir.

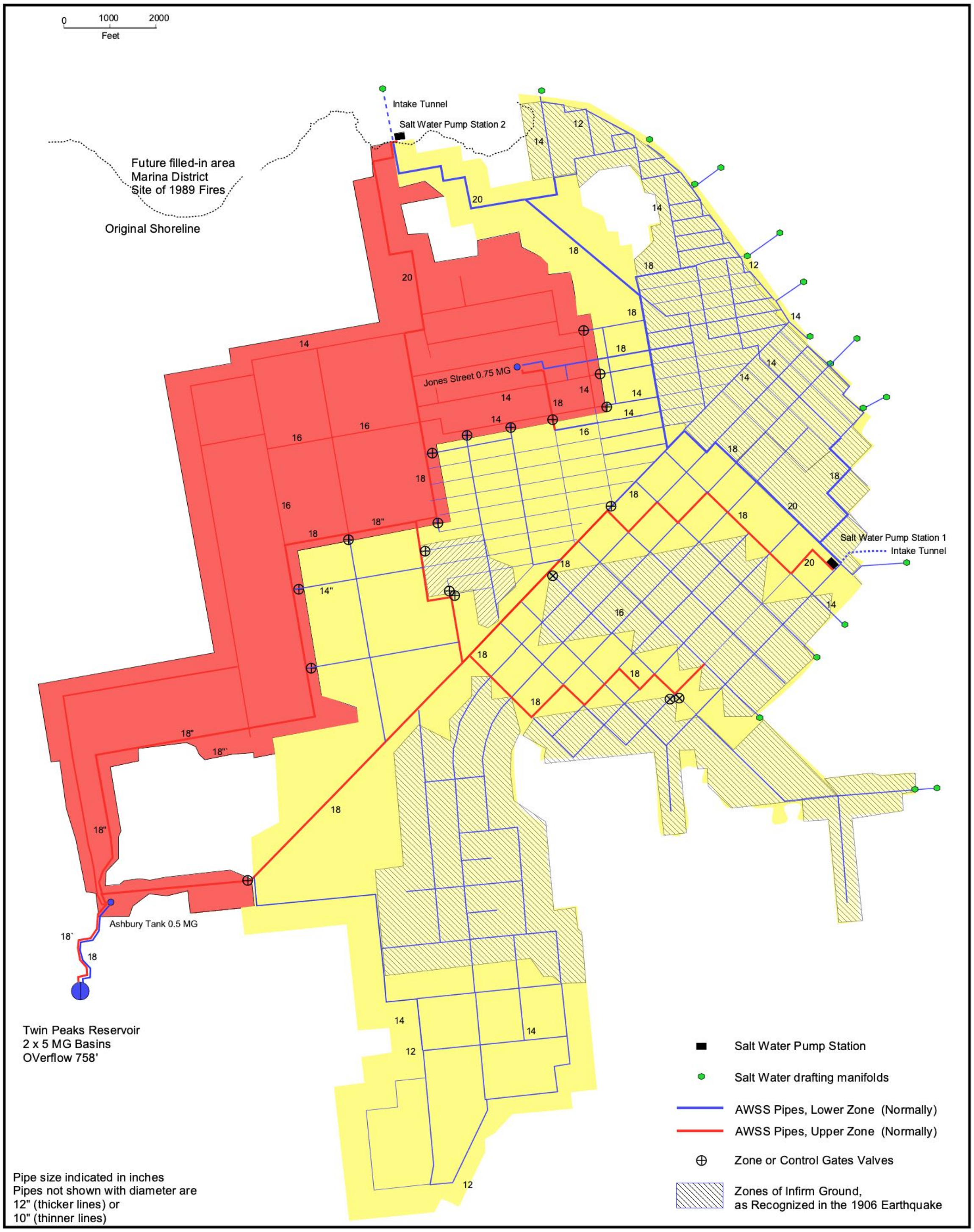


Figure 8-2. The AWSS Pipe System, 1908. Zones of Infirm Ground Highlighted by hatched areas. Red and yellow-colored areas are the pressure zones, same as in Figure 8-1

Figure 8-3 shows the planned AWSS system, this time highlighting the location of cisterns. The green and blue cisterns were in place (and filled) at the time of the 1906 earthquake. The red cisterns were those proposed to be built as part of the 1908 bond issue.

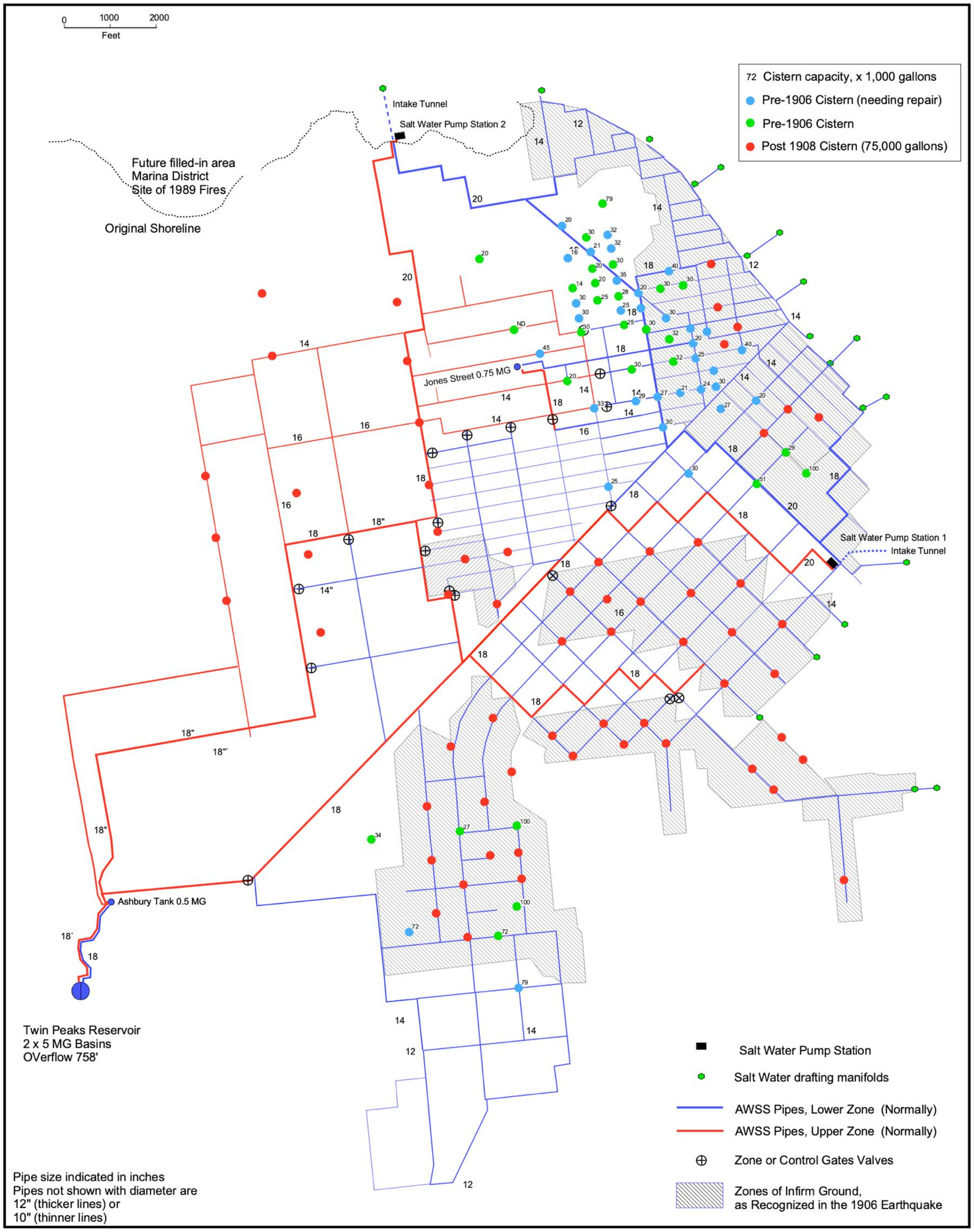


Figure 8-3. The AWSS Cistern and Pipe System, 1908, With Zones of Infirm Ground Highlighted

Figure 8-4 overlays the ultimate fire burn area with the location of the then-existing (and planned future) cisterns. It is evident that the vast majority of the 1906-existing cisterns were located within the ultimate fire boundary. The 11 cisterns in the area burned in Day 1 (mostly in the South of Market and the Mission Creek areas) were largely ineffective in controlling the initial ignition fires, nor the initial spread, even during Day 1, when winds were light. Not shown in Figures 8-3 and 8-4 are an additional 35 cisterns to be built as part of the 1908 bond issue, with locations to be picked by the fire department.

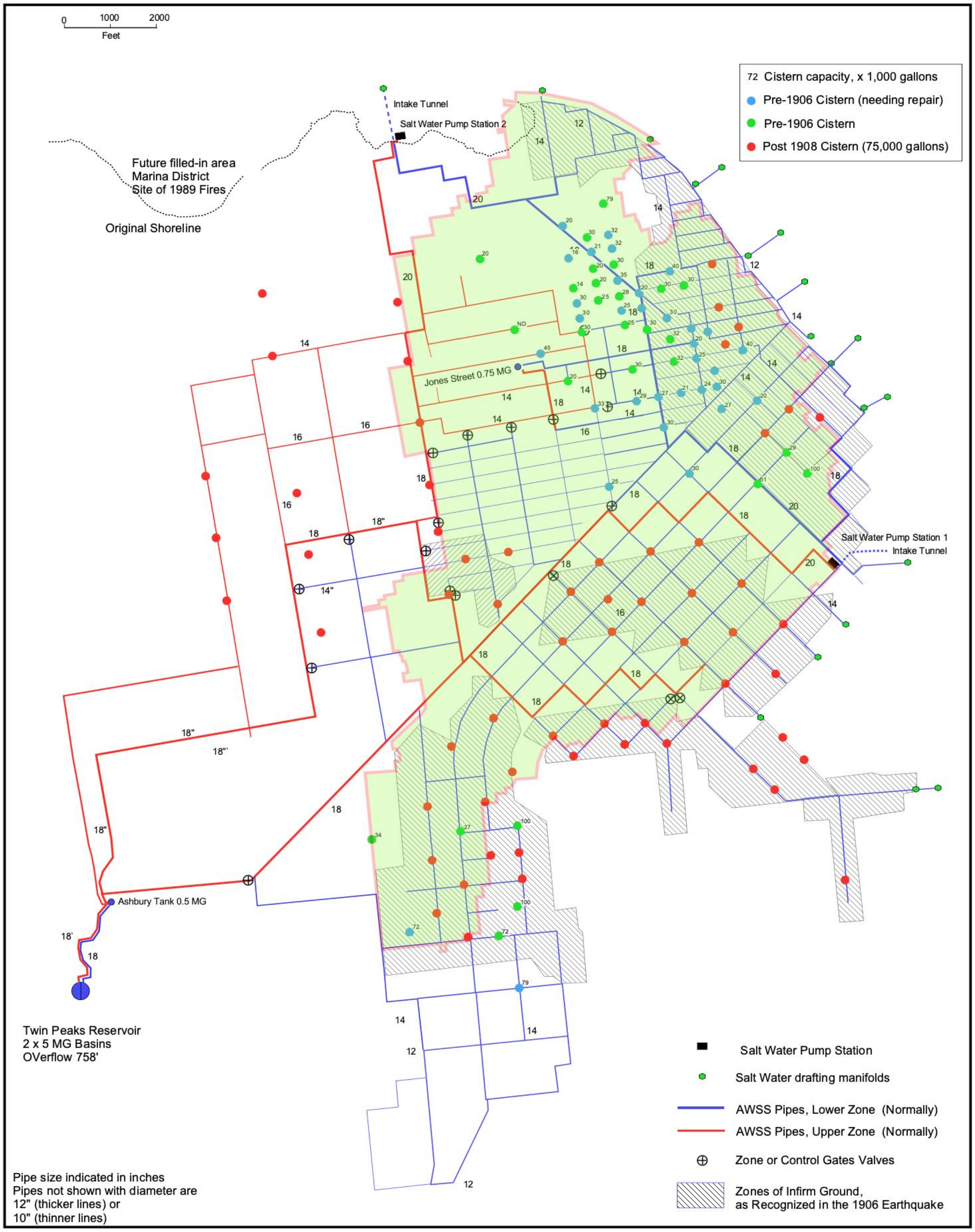


Figure 8-4. The AWSS Cistern and Pipe System, 1908, With Zones of Infirm Ground (cross hatch) and the Ultimate Burned Area (shaded) from the 1906 Earthquake Highlighted

The location of many of the new planned cisterns (red dots in Figures 8-3 and 8-4) are within the infirm ground areas. This poses the question: if there are to be PGDs in these areas, would the buried cisterns, constructed of brick or perhaps reinforced concrete, remain serviceable, when exposed to PGDs? To some extent, "yes", if the PGDs are from settlement only and are located above the level of the cistern's foundation. But, to some extent "no", if the PGDs are below the bottom of the cistern, or if the site is exposed to differential lateral spreads. In any case, having some water in a cistern is arguably better than having no water than all.

Figure 8-4 also shows that the 1908 design largely omits placing cisterns in areas to be served by water pipes (either AWSS or SVWC) in areas of firm ground; as well as along and within a few hundred feet of the waterfront, where fire-flow water coverage could be provided by fire boats.

Reviewing Figures 8-1 through 8-4, we see that the "heart" of the piped AWSS system is to deliver water from the Twin Peaks and/or Ashbury tank through a trunk pipeline along Market Street. This is almost precisely the same design as proposed by Schussler in 1894 (new 16 MG Market Street Reservoir and pipeline with hydrants along Market Street).

Schussler's 1894 design appears to have been far better than Grunsky's 1903 design. Critically, Schussler purposefully omitted the pipe grid that would extend into the infirm ground zones. In contrast, Grunsky, and later Manson, included a vast water pipe grid in the infirm ground areas, a serious and fatal flaw of the AWSS pipeline system.

In the 1894 to 1908 time frame, there were no types of water pipes that could be laid in zones prone to PGDs that would be highly reliable. The best solution in that time frame would be to entirely avoid these areas. Schussler's 1894 design was correct. Grunsky's and Manson's 1903-1908 designs for the pipe system were fatally flawed.

Credit should be given to Grunsky and Manson for placing the majority of cisterns in the infirm ground zones. This recognizes that they knew that the pipe system in those areas were highly vulnerable. However, the efficacy of cisterns to fight conflagration fires, even with 75,000 gallons, is questionable. Cisterns proved to be of nearly no use in the 1906 San Francisco fire, nor the 1995 Kobe fire. The primary usefulness of cisterns is to provide limited water for fire flows in areas without any piped water system, such as was the case in 1851 San Francisco. With a reasonably designed piped water system, cisterns have essentially no use for day-to-day fires (non-earthquake), as the water system provides more water at higher pressures in less time.

The voters passed a bond issue in 1908 to construct the AWSS. The bond issue was for $5.2 million (with premiums, about $6,000,000 was realized by the City). This included funds to build two salt water pump stations, purchase two fire boats, purchase more fire hose, purchase pipe for a new parallel water system that could use either salt water or sweet (but non-potable) water, the Twin Peaks Reservoir and a tank, and more cisterns.

While some of the public (and some of the politicians) in San Francisco commonly think of this as a salt water system, in fact the water in the system is normally (>99.999% of the time) designed to operate as a fresh water system, and only under extreme emergency, would it be charged with salt water. In the 112 year history of the system, from 1912 to

2024, it is understood that the system has never been operated using salt water to provide fire flows after earthquakes.

The AWSS pipe system was designed in 1908 to operate in three pressure zones:

- Lower Zone (mapped in yellow in Figure 8-1). This zone covers the area of the City under 150 foot elevation. The Lower zone is normally controlled hydraulically by the Clay Tank. Comparing the Lower Zone area (Figure 8-1) with the 1906 fire bound area (Figures 8-4), we see an almost exact duplication of the area. Why? This reflects that the thinking was that a future fire conflagration would be in the same area as the 1906 conflagration. This is a dubious assumption, and in the 1989 Loma Prieta earthquake, the major fire was in the Marina District, outside of the Lower (or Upper) AWSS zones as constructed by 1912.

- Upper Zone (mapped in red in Figure 8-1). This area covers the area above 150 feet elevation, covering much of the residential area west of Chinatown that burned in the 1906 earthquake. The Upper zone is normally controlled hydraulically by the Ashbury Tank.

- Excluded from the Lower Zone (or even the Upper Zone) is Telegraph Hill. Why? Two reasons: first, Telegraph Hill did not burn in the 1906 fire, so the idea was that it was less likely to do so in a future earthquake; second, the extra cost to extend the pipes of the Upper Zone to Telegraph Hill was an ever present consideration.

- Manson described the effective coverage areas of the Lower and Upper zones as anywhere within about 1 city block of a AWSS pipe. Beyond 1 city block (about 500 feet), Marsden recognized that water from the AWSS hydrants would be ineffective, as the common largest diameter fire hose is either 2.5" or 3" diameter, and the head loss through the hose would be so high as to limit flows beyond ~500 feet practically useless. Even so, Manson and the Fire Department both easily understood that beyond 500 feet, the water from a AWSS hydrant could be used by connecting the hydrant to a pumper fire engine, commonly using 5-inch hose, then boosting the pressure; in this manner, a chained set of pumper trucks could even apply water from the AWSS hydrant at a distance of over 1,000 feet, and also with considerable elevation gain, such as for Telegraph Hill.

The design in Figure 8-1 is often attributed to Manson, who at the time was a City of San Francisco Employee and sometimes called the City Engineer of San Francisco. The historical records suggests that the AWSS design was heavily influenced by Hermann Schussler of SVWC. Between the two of them, the following attributes of the original AWSS were set:

- Both Schussler and Manson (as well as nearly everyone) recognized that the failure of the cast iron pipes along Valencia Street between 18'th and 19th and on the various streets around Mission Creek and Sullivan Marsh led to the loss of water supply along Market / South of Market areas. This was the root cause of the inability to control the initial fire ignitions, which then led to the disastrous fire spread.

- Both Schussler and Manson recognized that cast iron pipes with leaded push on joints were seismically vulnerable at locations where the pipes crossed "infirm" ground.

- Soon after the 1906 earthquake, Schussler initially suggested that SVWC would (could) design, construct and operate this parallel water system. But, given the 35+ years of bickering between SVWC and San Francisco, the Board of Supervisors had no reservation about creating a new bond to raise the money to construct the AWSS, and put the San Francisco Fire Department in charge of building, operating and maintaining this second water system.

- This proved to be a mistake and resulted in a AWSS that failed to deliver water via the pipe system to fight the large fire in the Marina area due to the 1989 Loma Prieta earthquake. The AWSS pipe system that remains, to this day in 2023, is an expensive parallel water system that costs a lot of money and has had little use. Maintaining the AWSS has deprived the funds needed to modernize the modern potable City Distribution Water System to be seismically-resilient and able to provide both potable and fire flows from a single system.

Figures 8-5 and 8-6 show Pump Station 2, as of 1912. These were substantial facilities.

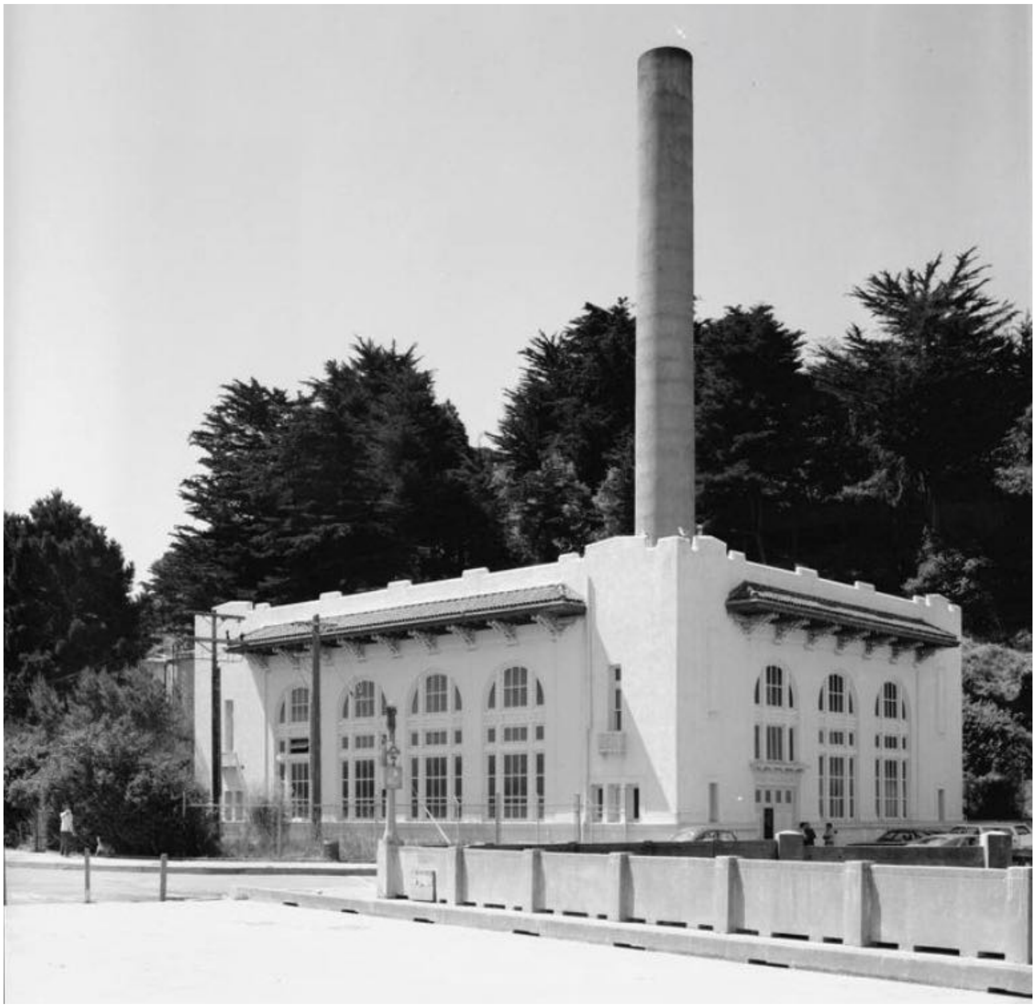


Figure 8-5. AWSS Pump Station 2, c. 1912 (photo: Manson)

Figure 8-6. Interior of AWSS Pump Station 2, c. 1912 (photo: Manson)

8.4 Salt Water Pipe System Performance in 1989 Earthquake

In the 1989 Loma Prieta earthquake, the lower zone of the AWSS suffered 7 pipe breaks / leaks. Figure 8-7 shows the locations of the pipe damage. The pipe grid shown is that from the original 1907 design; what was actually built resembles this grid.

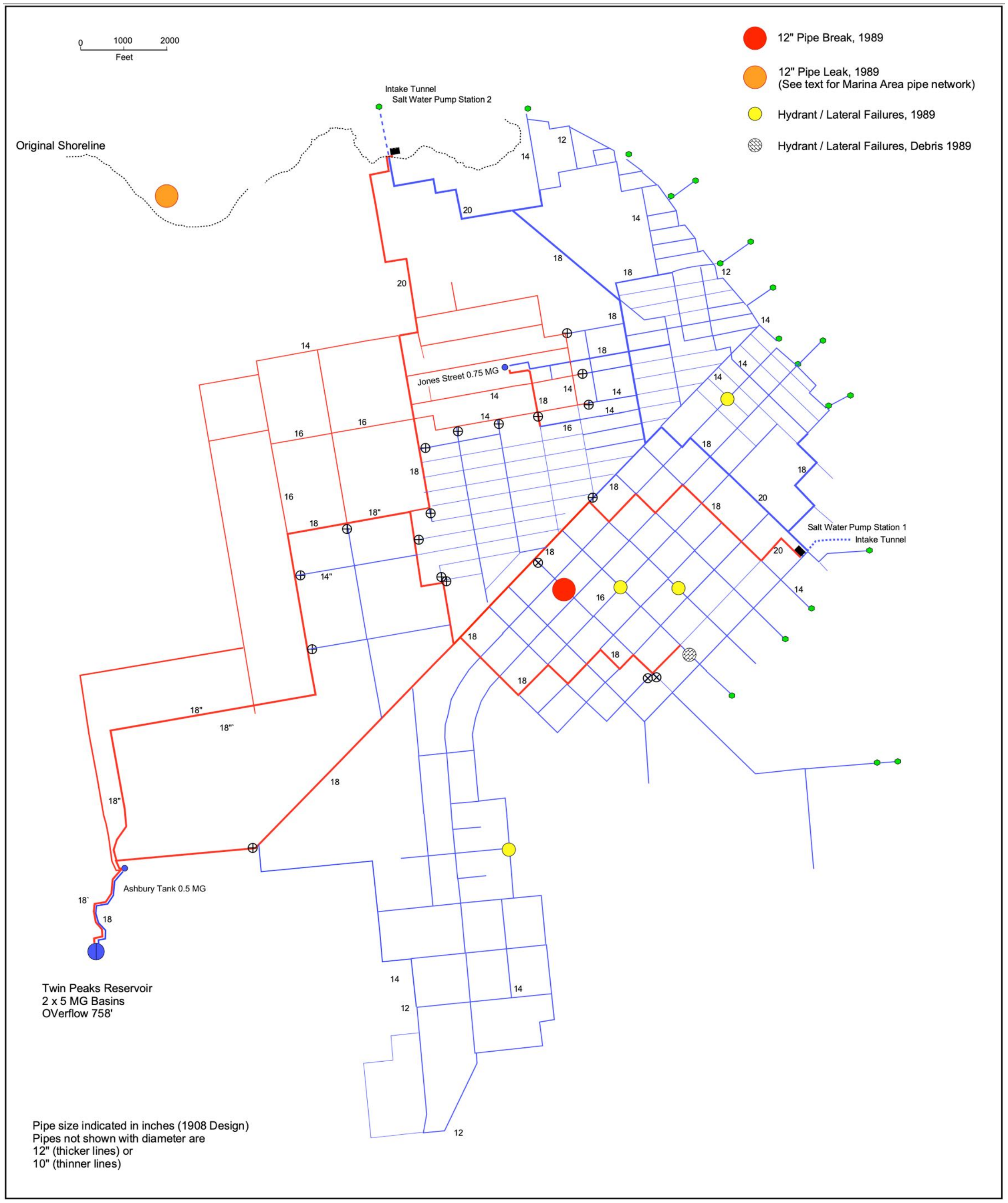


Figure 8-7. Damage to AWSS Pipe Network, 1989 Loma Prieta Earthquake

The pipe damage in 1989 is documented as follows:

- 1 x 12" cast iron pipe break on 7th and Natoma, between Market and Howard streets. Break was about 6" x 18". This was the most serious break in the AWSS system, and was principally responsible for depressurizing the bulk of the lower pressure zone. The pipe passed under a sewer.

- 1 x 8" hydrant lateral break on 6th between Folsom and Howard. Broken at 45° elbow where lateral passes over sewer.

- 1 x 8" hydrant lateral break at Mission and Fremont Streets.

- 1 x 8" hydrant lateral break on 5th between Harrison and Bryant Streets

- 1 x 8" hydrant lateral leak at a hydrant tee on the hydrant side of the tee of the main (low flow leak), at Folsom and 18th Streets (Mission Creek Zone)

- 1 x 8" break at elbow below a hydrant that was impacted by the partial collapse (falling brick work) of a building, on Bluxome Street

- 1 x 12" leak at a tee on the main (low flow leak), at Scott and Beach Streets (Marina zone)

Immediately after the 1989 earthquake, the upper zone of the AWSS remained in service, with water available from the Ashbury tank. There were no fires in the upper zone. The SF Fire Department decided to keep all zone gates between the upper and lower zones closed.

Immediately after the 1989 earthquake, the Twin Peaks Reservoir (the 10 MG main source of sweet water) was isolated from the twin 18" pipes that would allow water from that reservoir into the rest of the AWSS pipe system. There was an electrically-operated valve that could be remotely opened, but loss of offsite power meant that only manual actuation could be used to open the valve. It took 3 hours after the earthquake before the Fire Department manually opened the valve to allow water to flow from the Twin Peaks reservoir into the upper zone.

Immediately after the 1989 earthquake, the two salt water pump stations, while available to pump salt water into the lower zone, were not activated, reportedly as operation staff were unsure as to the status of the leaks and breaks in the lower zone. The net result was that no water from the AWSS was supplied to any hydrant near the fire at Divisadero and Beach in the Marina District.

The AWSS (piped system, including salt water pump stations) was ineffective in fighting the major fire at Divisadero and Beach after the 1989 Loma Prieta earthquake. This poor performance shows that the piped AWSS system that was designed in 1908, and expanded over the years, was fatally flawed from its outset.

In reviewing the defective performance of the AWSS in the 1989 Loma Prieta Earthquake, the Museum of the City of San Francisco writes:

- "The upper zone of the AWSS functioned normally through the earthquake period and was used to suppress earthquake-caused fires". The author notes that the potable water system also functioned normally, in the upper zone areas, which were exposed to modest levels of shaking and no PGDs; so arguably there was no need to have two parallel sets of hydrants to supply water to control fires in those areas.

- "Falling structures destroyed one AWSS hydrant and damaged another". The author notes that as much of the AWSS pipeline systems is 12-inch diameter pipe, any single break (like through a damaged hydrant) can lead to a leak rate on the order of 5,000 gpm. 5 such breaks could lead to a leak rate on the order of 10,000 to 20,000 gpm, depending on the location of the breaks and hydraulic attributes of the pipe grid. With such high flow rates to the breaks, most of the remaining pipe grid will become de-pressurized, and nearly zero water would flow to undamaged hydrants, no matter how much water is in the Jones Street tank (or supply form the salt water pump stations). It is clear that Manson's initial 1908 design was defective, as it assumed zero damage to the AWSS, or damage that "somehow" would not cause leaks. Clearly, damaged pipes always cause leaks until valves are closed to isolate the leaks. Worse, if the leaks occur on part of the pipe grid where there are no parallel loops, then closing the valve closes the leak, yet zero water is available downstream (and this was the essentially the case in the 1906 earthquake).

- "The two AWSS salt water pump stations functioned as designed". The author notes that this is wrong. Neither pump station was turned on to pump salt water at the time of the earthquake 5:17 pm, October 18, 1989. It took 2 hours 43 minutes for the operators at the pump stations, until 8:00 pm that day, to turn on the pumps. By this time, the large fire in the Marina was raging, and one reason that the fire did not spread and cause a general conflagration, possibly rivalling that of 1906, was that there was essentially no wind at the time of the earthquake. The key question arises: why did the AWSS in the lower zone, where there was a significant fire, not provide water? The lower zone could source water either from Jones Street Tank (by gravity flow) or either salt water pump station (by pumped flow). The answer lies in two areas:

    - One. Gravity flow was not available as the pipe breaks in the lower zone sent the water to waste through the damaged pipes; and essentially none to where it was needed, in the Marina.

    - Two. The SFFD, coupled with all available resources, was not equipped (manpower-wise or technology-wise) to both rapidly find the initial pipe breaks and leaks in the AWSS, and then send crews out there to valve out those breaks and leaks. Had the damaged pipes been valved out within 5-10 minutes of their occurrence, water from Jones Street tank would likely have been available to control the initial fires in the Marina area.

- Why 5-10 minutes? If a fire strike team can arrive at a fire ignition site within 5 to 10 minutes after initial alert, experience shows that should they have access to a sufficient water supply (on the order of at least 500 gpm for 30 minutes), they can usually control the initial ignition and prevent fire spread. Ideally, they would like to have 1,000 to 1,500 gpm for 2 hours, to provide for near certainty of controlling and putting out the initial fire. But, if no water is available, then the odds of controlling the initial ignition fall substantially, and if it is windy, the chance of fire spread and perhaps conflagration increases.

- Waiting nearly 3 hours for water supply via either the SFWD or SFFD systems, as was the case in 1989, is not a sound fire-fighting strategy.

- Fortunately, the portable hose (5-inch LDH hose) with suction from the nearby Bay via fire boat "Phoenix", was available, and these modest flows were sufficient to control the actual fires in the Marina; fortunately as there was no wind.

But, lest the reader think that these 5-inch LDH fire hoses are "perfect solutions", consider the following:

- In the 1991 Oakland Hills fire, this same fire hose system was deployed along Ocean Avenue to draft water from the lower Berryman pressure zone (from large diameter pipes with nearly inexhaustible supply) to control the fire that was burning up hill along Ocean Avenue. During this operation, a news van drove over the hose, and broke it.

- Subsequently, a portable hose vendor provided a demonstration to the Oakland Fire Department about the efficacy of their system for fighting post-earthquake fires for downtown Oakland. On a Sunday morning, they laid the 5-inch hose system from a fire boat near Jack London Square, and showed how they could put that water onto a fire ground at Oakland City Hall (about a mile inland, over flat terrain). During this demonstration, a city bus drove down Broadway, and came to the curb to let off / let on passengers. The bus tires pinched the 5-inch hose (just before the flow test) and broke it. Had the hose been pressurized, the water thrust from the broken hose would have been 100 psi * 3.14 * 2.5 * 2.5 ~ 2,000 pounds, more than sufficient to let the hose move wildly, possibly hitting and injuring pedestrians. To compound this, the test was done under very low traffic conditions (Sunday morning), and with dozens of people laying out the hose, installing and monitoring ramps, etc. to allow cars to drive over the hose. During the test, the author witnessed a car directly driving over a 5-inch pressurized hose (not using a ramp, and also not breaking the hose); but as evidenced by the city bus that pinched a hose against a sidewalk curb with hose failure, and the news van in the 1991 fire, the chance of hose failure is not negligible. In a large post-earthquake, there will likely not be enough personnel to provide traffic control to avoid all vehicle / hose adverse interactions.

In contrast, EBMUD does include Ultra Large Diameter Hose (ULDH) (generally 12-inch diameter) as part of their post-earthquake restoration plan. The EBMUD strategy is to deploy the 12=-inch hose to bypass broken water mains, and restore water supply, with a target of temporary restoration using the 12-inch hose within 24 hours after the earthquake. The use of 12-inch ULDH hose is not for providing water for firefighting purposes within 5-10 minutes after ignition: the manpower and logistics to deploy the hose in such a short time frame is not thought to be feasible by the water department.

Further confounding the issue were the 59 years of failure of the SFWD (since 1930) to identify that their water pipes in the Marina area, being mostly cast iron, and the "infirmn" ground in the Marina area (placed by hydraulic fill methods after the 1906 earthquake) were entirely inadequate. The few inches of PGDs in the Marina area in the 1989 earthquake were sufficient to cause over 100 breaks / leaks in that area, leading to zero water available by the city potable water system in that area.

- After the 1906 earthquake, the City and its Board of Supervisors clearly had no confidence in the SVWC. The City's arguments over cost, rates, reliability, are all well documented.

- As owners of the water system between 1930 and 1989, today one can make the exact same argument about the SFWD. The SFWD's failure to replace pipes in the Marina area with seismic-resistant pipes, is clear. The SFFD's failure to replace pipes in the South of Market area with seismic-resistant pipes, is clear. The coordination and technology to find and isolate leaking pipes (either water system) was missing by both the SFWD and SFFD, in the minutes and hours immediately after the 1989 earthquake.

All of the above, when taken in its entirety, suggests the following:

- Manson at al was wrong. In 1908, he and his designees designed an AWSS system that was bound to fail when it was needed most. His successors were not successful over the following 8 decades to address these defects. In 1989, it failed.

- Since 1989, San Francisco has continued to pour good money after bad. While the efforts to upgrade the two salt water pump stations (like removing animal growth at intake pipes, modernize old equipment, repair aging reservoir roof, etc.) are laudable, the cost to do this is high, and the benefits small, as the pipes remain seismically weak. Over time, the pipes will continue to get weaker as they age.

- A more prudent approach would be to develop a master plan to upgrade the SFWD potable water system, with an initial 5-10 year effort to install seismic-resilient pipe in infirm soils zones, then 90-100 year plan to upgrade the rest of the system. Such a plan would over time, provide for "blocked" zones that could be automatically isolated (within 3± minutes) if they sense sudden drops in pressure (and ideally verified with no fires). As the system gets upgraded over time, the "blocked zone" system becomes less important, as the number of pipe breaks is reduced to perhaps a handful. This plan likely affords a large improvement in safety in the shortest time (in the first 5 to 10 years), at the lowest ultimate cost to rate payers and tax payers.

- One hopes that the SFPUC considers and adopts such a plan.

- Building even more cisterns in the 21st century is a modest misuse of the public purse. The money can probably be better spent elsewhere.

- Maintaining two parallel water systems in the 21st century is a major misuse of the public resource. The money can probably be better spent elsewhere.

AWSS Attributes

Watt (in 1907) reported the design of the AWSS as follows (with updates to reflect documents from 1911 and what was built by 1925):

- The area to be protected, about 3,000 acres, was determined in consultation with the Fire Chief, the secretary of the Merchant's Association, and a number of insurance companies.

- The Twin Peaks Reservoir, near 20th and Cole Streets, was to have two 5,000,000 gallon basins; overflow 758 feet. The reservoir was to be kept full at all times. The total storage was set to supply 20 fire trucks continuously for 16 hours (average flow rate of 10,400 gpm).

- Two 18-inch pipes will lead (by separate paths) from Twin Peaks Reservoir to the upper Ashbury Tank, from where pipes will lead to the lower elevation Jones Tank.

- The water in the Ashbury Tank (overflow 494 feet, 500,000 gallons, steel circular tank, 29 feet high, 55 feet diameter, base elevation 463 feet) and Jones Tank (overflow 369 feet, 750,000 gallons, reinforced concrete circular tank, 60 feet diameter, height 36 feet) will serve as supply for ordinary fires.

- Hydrants will be placed to allow up to 15,000 gpm in an area of the old congested district (i.e., near Market Street east of Montgomery Street, South of Market

Street, etc.); 8,000 gpm to 12,000 gpm elsewhere. Gate valves will be located so any block can be cut off, without affecting hydrants on other blocks.

- It is doubtful whether it is possible to construct pipelines in such a manner that they will not be apt to be rendered useless in ground that is likely to suffer serious displacement because of earthquake shock.

- None of the main pipes (18-inch and larger) will be laid in streets in the filled-in (infirm ground) portions of the city; in those areas, all pipes will be small diameter, and be able to be cut off by closing not more than 10 gate valves, thus minimizing the danger of an earthquake disabling the entire system by breaking a large number of pipes in a comparatively small area. [Authors note: this is a deficiency in the design.]

- The fire boats will be used to protect the wharves and shipping. In the event of damage to pipes, the fire boats can pump directly into the AWSS pipes. Each fire boat can pump 10,500 gpm. The fire boats can deliver 25 streams of saltwater. The fire boats can connect to manifolds along the waterfront to deliver salt water for several blocks inland. But their main use is for fire in ships and along the docks.

- New cisterns will be located so that they will provide maximum protection to filled-in areas and localities where the distribution system is most liable to injury. By 1925, 54 original cisterns (brick, mostly 30,000 gallons, each) had been built, and 85 new reinforced concrete cisterns (mostly 75,000 gallons each) had been built.

- All the cisterns as well as the Twin Peaks, Ashbury and Jones street tanks are normally filled with sweet water from the SVWC system. If necessary, salt water from either salt water pump station (No 1 at 2nd and Townsend, No. 2 at Fort Mason) can be used to fill any of the three tanks / reservoirs, or to supply any hydrant in the system.

- Flow from a single high pressure hydrant is limited to about 10,000 gpm when using all 3 outlets.

- Source water can be from Jones, Ashbury or Twin Peaks reservoirs, by suitably opening gate valves. Opening these gate valves requires coordination by various staff.

- The piped system includes pipes from 10- to 20-inch in diameter. The pipes cover the congested high value district, the important retail, wholesale and hotel districts and a large part of the (1911-vintage) residential district.

- There were 1,320 hydrants and 1,120 gate valves in the original system of 1911.

- SVWC water is mainly taken from the Clarendon Height zone to the Ashbury Pump station, where it is pumped up to Twin Peaks at a rate of 700 gpm. Ashbury Tank is filled by gravity flow from SVWC's Clarendon Heights tank (600 feet) via a 6-inch pipe. Jones tank is filled from Ashbury tank; or, in emergency, could be filled from SVWC's Clay Street tank.

- Lower zone has about 77 miles of pipe, 673 hydrants, covers an area of 2.5 square miles. Upper zone covers an area of 2 square miles with 216 hydrants, and is connected to the lower zone via 8 zone gates.

- Hydrants are connected to mains with 8-inch laterals. A gate valve is located on the lateral, ideally nearly adjacent to the main.

- There are bypasses on all street gates.

- There are 7 gate valves located at the dividing line between firm and infirm ground; in case of emergency, these could be closed in a short time.

The Lower zone has a grade line of 150 feet, controlled by the overflow of the Jones Street Tank. Fire hydrants in the lower zone have blue-tops. Fire hydrants in the Upper zone have red tops. Fire hydrants between the Twin Peaks Reservoir and Ashbury Tank have black tops.

The Twin Peaks Reservoir is a 10.5 MG open cut reservoir located below Mount Davidson / Twin Peaks.

The Jones Street Tank was constructed in 1913[26]. It is 35 feet tall and has capacity of 750,000 gallons. This tank provides sweet water to service the Lower pressure zone of the AWSS. This tank could be filled using potable water from the SVWC through a series of pipes and meters at this location.

On October 23, 1913, City Chief Engineer O'Shaughnessy declared, in a report to Rolla V. Watt of the Board of Underwriters, that the AWSS was recently completed, and:

- "*The AWSS is superior to any other in the United States or the worl*d"

[26] SF Ordinance, ordering the construction of a 750,000 gallon tank on Jones Street Hill (in the block bounded by Sacramento, Jones, Leavenworth, Clay) as part of the AWSS, Municipal Record, page 58, February 20, 1913. Contracts were awarded March 20, 1913 for a cost $27,300 (the tank) and $11,186 (pipe and fittings).

- "*I have visited New York, Boston, Philadelphia and Baltimore, studying their fire protection systems. I can unhesitatingly state that the system constructed in San Francisco is superior to any other in this country*"

- "*With the two pumping stations and the Twin Peaks reservoir, all widely separately and founded on solid rock, as the main sources of supply, the two fireboats as powerful auxiliary sources, the distribution system provided with numerous gate valves to permit cutting out any part which maybe injured; and the 136 cisterns, San Francisco today is provided with the best and most extensive fire protection system in the world*"

- "*Even the occurrence of an earthquake of equal or greater intensity than that of April 1906, could not result in disabling any considerable part of the system, and property owners in this city can rest assured that the great fire of 1906 will never be duplicated*".

Today, 2024, history shows that O'Shaughnessy was mistaken. By building the AWSS, the fire insurance underwriters were placated to reduce fire insurance rates, and in that respect, the AWSS might be considered a success. One of the original selling points of the AWSS was that its initial $6 million cost would "pay for itself" with greatly reduced insurance rates over a number of years[27]. The 1989 Loma Prieta earthquake, which was a relatively modest earthquake in San Francisco (with about ¼ the level of shaking and ¼ the duration of the 1906 event) led to the hydraulic failure of the piped-AWSS and no water from that piped system, its reservoirs, or its pump stations, or the fire boats via the manifolds, reached the fire sites in the Marina District. Had it been windy at the time of the earthquake, a general conflagration might well have ensued. The entire Marina District and possibly much of the Presidio, and neighboring areas, could have been nearly entirely burnt, had the winds been 10 to 20 mph and blowing from the east to the west, as is not uncommon in September and October of every year. The Army's (and now the National Park Service's) water system in the Presidio is not sized to fight urban-interface fires. The 1991 Oakland Hills fire showed that fire breaks like 8-lane freeways are insufficient on windy days; and water pressure zones designed to provide 1,000 gpm to 1,500 gpm (generally 6-inch pipe) are insufficient to fight fires with multiple fire fronts in a single pressure zone. Today (2023), a complete re-think is called for, to consider the cost and effectiveness of keeping two parallel and vulnerable water distribution systems.

Why did O'Shaughnessy make these statements? Well, after the City had just spent some $6 million to build it (via Bond issue), he was primed to overstate (dare one say, "boast"); with intention of placating the NFBU (so that fire insurance could be available at reasonable cost); and perhaps "rubbing in salt in the wounds" of the SVWC, where lawsuits between San Francisco and SVWC were ongoing. The author is hesitant to describe this boasting as a "lack of honesty" or evidence of "corruption", but the underlying issues clearly point to the fact that the citizens of San Francisco were not and

[27] SFFD, Civil Service test, 1911.

have arguably not been well served by having a Municipally-owned fire-fighting water system that has not worked to deliver water via the pipe grid to large fires after earthquakes.

Clearly, O'Shaughnessy was wrong about the ability of cast iron pipes in the AWSS to survive intact after even a modest earthquake; never mind a future larger earthquake; and entirely wrong about the ability to "*cut out any part that may be injured*" within a short-enough time frame to be of much practical use.

Today (2024), the City has "discovered" these weaknesses, and the SFPUC have developed a plan, costing about $6 billion, (currently unfunded save $150 million for some initial pipes to be built in the Sunset area) to upgrade the AWSS system by the year 2046.

9.0 The Hetch Hetchy Water Supply

9.1 The Hetch Hetchy System Design, 1867 - 1910

In 1867, the San Francisco Board of Supervisors created the "San Francisco Water Company", incorporated July 22, 1867. The purpose of this entity was to investigate sources of water that could supplement and/or replace the SVWC water system. Through 1872, a series of consultants were retained to investigate the issues. A series of surveys were conducted to prepare concepts and cost estimates to deliver new water supplies from sources such as Pescadero Creek, Clear Lake and Lake Tahoe. In (Scowden, 1875), the following describes the findings of some of these consultants.

Prof. George Davidson (of the U.S. Coastal Service) observed:

- "*Clear Lake and Lake Tahoe have been suggested as available, but apparently for the sole reason that the supply is large and the elevation is great. The former is 80 miles straight line to San Francisco; the later 150; and both would have to cross the Bay of San Francisco. While it is a maxim of engineering that nothing is impractical with skill, time and money, yet the proposition to bring water from these distances, borders on the chimerical.*"

- "*I believe that the proposed sources of water on the Peninsula of San Francisco [including Pescadero Creek and other drainages on the southern Peninsula] are the most unfailing within practical engineering distance: that they furnish an adequate supply, even in the driest seasons, for a population of over one million people; that the supply can be largely increased from the more southern parts of the Peninsula; and that the works of engineering are not difficult.*"

General B. S. Alexander (U.S. Army Corps of Engineers) observed:

- As to the "*lakes of the Sierras, [they] possess the one prominent feature of unlimited source of supply and afford water of a purer quality than ordinary…. your Committee believes that the great distance of these water sources from this city, would so increase the cost of a proper and permanent system of works or required capacity as to defeat the grand object of securing such supply at a reasonable cost. The tax upon the enormous cost of an extended line of works necessary to carry out some of the stupendous schemes proposed, would be excessive and burdensome upon our population*."

- "*We are of the opinion that the water sources of the [San Francisco] Peninsula within a reasonable distance, are amply sufficient to furnish an abundant supply of good, pure, fresh water to provide for the wants of San Francisco for at least 50 years*."

- "*That the City should own and have absolute control of the waterworks is a fact self-evident and requires no favorable argument from us.*"

In the various reports by the city-retained consultants, there is unanimous opinion that the water supply for San Francisco, for at least the next 50 years, should come from the Peninsula sources. The authors point out that the then-developed Pilarcitos and San Andreas watersheds (owned by SVWC) could reliably produce 8 MGD, which could be supplemented by waters of the Pescadero and related creeks to 60 MGD. This supply would be sufficient for a city of 1,000,000 people (forecast by 1950 or so) at a rate of 60 gallons per capita per day.

The city-retained consultants were quite clear that the water system should be city-owned. Of course these consultants were paid by the City, who wanted to hear just that. Inconsistent with City politicians demanding that water should be owned by the public, the City today (2023) has no qualms about selling water from the Hetch Hetchy system to some modern privately-held water systems, such as those serving Atherton, South San Francisco, Stanford University. It would seem that the Politician's core issue was not so much the style of ownership, but that Absolute Control is what the City wanted.

Following these reports, the San Francisco Board of Supervisors passed an Act on March 30, 1874, to Authorize the City and County of San Francisco to Provide and Maintain Public Water-Works for said City and County, and to Condemn and Purchase Private Property for that Purpose. In this Act, the position of a Chief Engineer was created, at an annual salary of $9,000, with that person charged with determining the costs for purchase of the SVWC properties, and to build any new properties from any new source of water supply. The first person to hold this position was Mr. Theodore Scowden. Mr. Scowden was engaged by the City of San Francisco to investigate the water question. As part of his work, he prepared a map of the Supply System then in place along the Peninsula (see Figure 2-24). Scowden's report (1875, including appendices and various responses) showed that the SVWC was valued at $8.75 million, but a new City-owned water supply system could be built using a new Calaveras Reservoir, at a cost of $10.65 million. The City requested SVWC to submit a price at which SWVC would sell its water system to the City; to which SVWC submitted on July 26, 1875 a sales price of $14,500,000 for the Peninsula System, and an additional $1,000,000 for the Calaveras properties. At the completion of his report, Scowden resigned as City Engineer, his work done. The City then passed resolutions to agree to purchase SVWC, once the matter would be publicized for 90 days in local newspapers. Alas, the public and political body and SVWC could not reach agreement, and the sale was not consummated in 1875; instead, many bad feelings and insinuations occurred. It would be fair to say the parties were aggrieved.

This adverse attitude between the politicians, the newspapers, and SVWC went on for another 55 years. The human effort and cost for this feud cannot be quantified; but possibly, had that effort and cost be spent on building better water works, the great fire of 1906 might have been avoided.

In Figure 2-24, a tunnel and pipeline and flume is shown crossing the "Proposed" Lower Crystal Springs Reservoir. With the construction of the Lower Crystal Springs in 1888-1890, the pipeline and flume section were drowned by the new reservoir and were abandoned (see Section 4.1.18 for details); and relocated with a new flume and a new 44-inch wrought iron pipe that crossed the San Andreas fault as FX-6; see Figure 4-2 for location and see Section 4.1.17 for details.

Scowden considered various possible sources of water from the Sierra and other places, and concluded: "*That is the place – Alameda Creek. You can develop something like 75 to 100 MGD there and near home. Don't go to the Sierra Nevada for the present*."

Figures 9-1 and 9-2 show the 1876-vintage concept of using Alameda Creek for San Francisco's water supply. In Figure 9-2, the black line represents the San Andreas fault (added by the Authors – Schussler did not know of the fault in 1876). The orange lines represent:

- E. Solid Line. Pilarcitos pipeline ending at Lake Honda (30")

- F. Solid Line. San Andreas pipeline ending at College Hill Reservoir (30" at that time)

- G. Dashed line. Planned Crystal Springs pipeline taking water initially from the Upper Crystal Springs Reservoir (heavy blue lake), and planned from the (yet unbuilt) Lower Crystal Springs Reservoir (light blue lake), ending at Brannan Street Reservoir (later named University Mound reservoir). The alignment of line G was shown west of the "Salt Marsh" zone near San Bruno; but when the pipe was actually built, the alignment was moved through these Salt Marsh zones, where the pipe, on trestles, suffered a great amount of damage in the 1906 earthquake, taking 28 days to repair and restore to service.

- H. Dashed line. Pipeline (yet unbuilt) to deliver water from the (yet unbuilt) Calaveras Reservoir in Alameda County all the way to Lake Honda. Part of the alignment was eventually adopted by Freeman for the South Bay Alignment of the Bay pipes for the Hetch Hetchy Aqueduct (see Section 9.2) for similarly-located present-day (2023) BDPL 3 and 4 pipes (built 1949 – 1971) around the south bay (Milpitas to Redwood City), including the Pulgas Tunnel (built 1934). Calaveras Reservoir construction began in 1923 and its latest seismic upgrade was completed in 2015. As will be explained in Section 9.2, the Calaveras Reservoir plays an important role in the overall Hetch Hetchy system, being the largest Bay Area terminal reservoir in the present day (2023) Hetch Hetchy system; this storage is key to being able to sustain a major drought or a major calamity (like a tunnel collapse, etc.) in the upstream Hetch Hetchy system.

- Lobos Creek Flume. In 1875, this delivered up to 2 MGD to the Black Point pump station, from where it was pumped to Francisco Street Reservoir, Lombard Street Reservoir and Clay Street Reservoir.

- City Distribution System (key pipes only). This shows that in 1876, the higher elevation areas were supplied from Lake Honda, medium elevation areas from College Hill Reservoir, and lowest elevation areas from the Market Street Reservoir.

- Market Street Reservoir. By 1876, this was in service was as a 2 MG reservoir, designed in part to reduce pressure from Lake Honda. This is the site that Schussler wanted to expand with a new reservoir to 16 – 20 MG capacity, along with a pipeline studded with hydrants down Market Street; it would appear that such was the animosity and lack of trust between SVWC and the City that in 1893, the Board of Supervisors rejected this upgrade, and instead cut a street through the reservoir site, zoning the area for residential and commercial construction, thereby increasing the City's tax base. Had this reservoir and pipeline been built in 1893, the fire conflagration of 1906 might have largely been avoided.

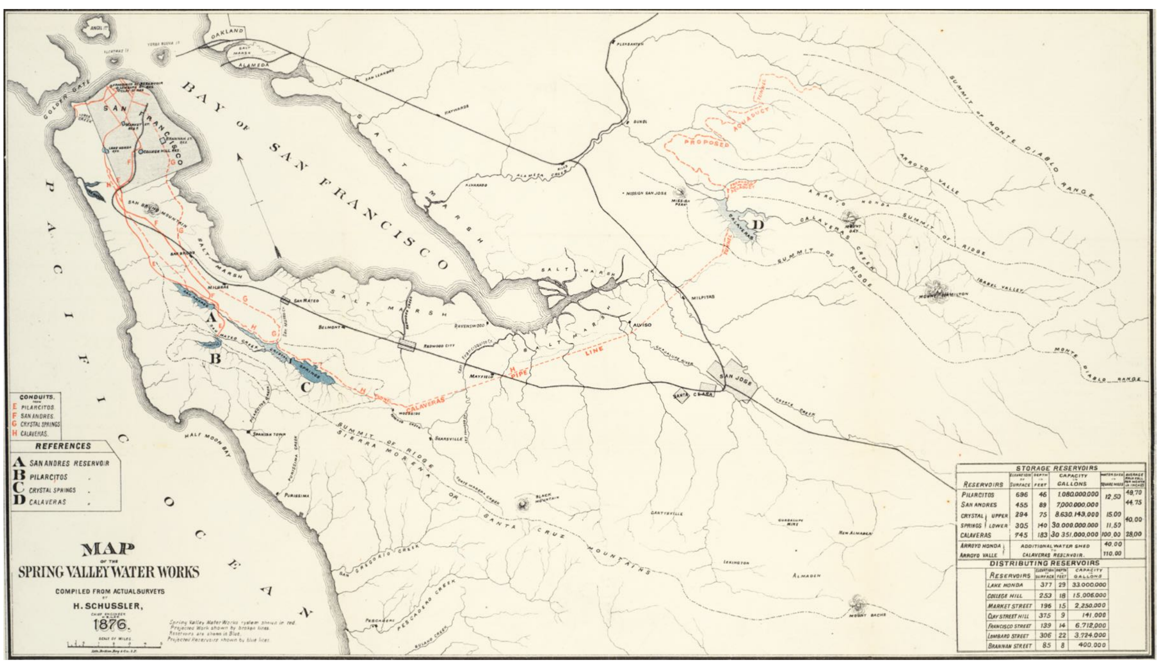


Figure 9-1. SVWC Peninsula Water System, 1876, with planned expansion. Base Map by H. Schussler, 1876

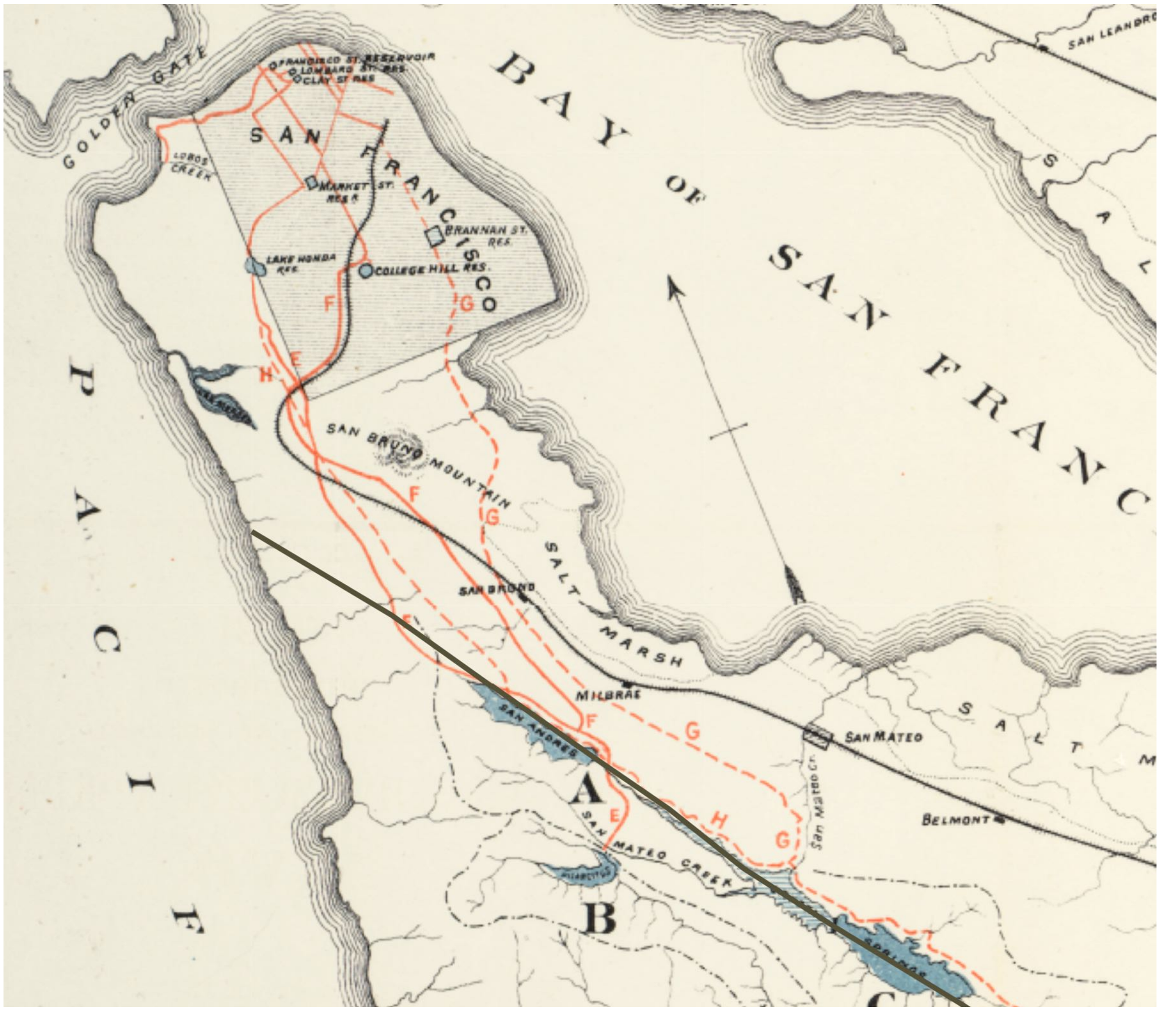


Figure 9-2. SVWC Peninsula Water System, 1876. Heavy Black Line is San Andreas Fault. Base Map by H. Schussler, 1876; fault line added by Authors

In 1877, the City got together with SVWC to see if the City could buy SVWC. SVWC asked for $16 million. The City offered $11 million, excluding the Alameda "cow pasture". SVWC counter proposed $13,500,000, just for the Peninsula and City systems. The City would not raise its offer, and so there was no sale.

By 1880, SVWC had spent $13,245,000 on capital costs. By 1890, this increased to $21,389,000. By 1900 this increased to $28,135,000. By 1908, this increased to $32,850,000. These values represent the cash cost actually paid for properties and works constructed, ignoring the effects of inflation.

Beginning the 1890s, the Modesto Irrigation District (MID) and Turlock Irrigation District (TID) were productively using water from the Tuolumne River for irrigation and other purposes.

In 1900, San Francisco Mayor Phelan set a stake claiming the Hetch Hetchy water shed (some 438 square miles) was to be City's (reportedly he paid $1 for the claim as a private citizen, and then transferred the rights to the City). He didn't ask the U.S. National Park Service (then the Department of the Interior) if he could survey the lands or claim the water in Yosemite National Park; he just did it.

In 1900, C. E. Grunsky was hired as City Engineer. One of his tasks was to develop a design to bring Hetch Hetchy water to San Francisco.

In 1900 – 1901, Grunsky's first design of the Hetch Hetchy system called for delivery of 60 MGD to San Francisco. That flow, coupled with about 40 MGD that could easily be produced by SVWC, would be sufficient for 100 MGD demand forecast by the year 1950. Such was the animosity between the Board and Supervisors and SVWC, that Grunsky laid out the initial 1901 design of the Hetch Hetchy water system to include constructing 455 miles of 4-inch to 48-inch distribution pipe in San Francisco, to parallel all of SVWC's distribution pipe (then about 430 miles), at a cost of $8,807,000, or $19,400 per mile, inclusive of all hydrants, meters, gate valves, engineering and contingency. This was in addition to the $30,724,000 for the entire initial supply system, including the Hetch Hetchy Reservoir, tunnels, transmission pipelines, pump stations, and hydroelectric system.

Mr. Grunsky's plan for Hetch Hetchy, on behalf of Mayor Phelan, was submitted to the Secretary of the Interior in 1901. In 1903, the Secretary of the Interior (E. A. Hitchcock) denied this application.

In 1902, Grunsky updated his plan for Hetch Hetchy.

In 1905, the application to the Secretary of the Interior was renewed, but permission was again refused.

Then, plans were submitted to President Teddy Roosevelt to have the lands of the Hetch Hetchy Valley and watershed revoked from Yosemite National Park, and placed into Stanislaus National Forest Reserve. These plans were denied.

Then, by Act of Congress, plans were submitted to have the Hetch Hetchy Reservoir sites deeded to the City of San Francisco. This also failed.

By 1907, the Board of Supervisors of San Francisco then declared by resolution that the Hetch Hetchy source of water was unavailable and practically abandoned it.

By 1907, the Politicians in San Francisco were no longer satisfied with a supply for only the City of San Francisco, but instead imagined themselves as the center of all of the Greater San Francisco Bay Area, and called upon themselves to develop a Metropolitan Water District, to deliver water to San Francisco, Oakland, Berkeley, Richmond, San Jose, and the future communities in between. Thus, their forecast was for a water supply of between 160 MGD by the year 1920 (to be split 50 MGD to San Francisco, 50 MGD for filling Crystal Springs Reservoir, and 60 MGD for all the other cities), and as much as

400 MGD by the year 2000, when the forecast population of the Bay Area would increase to about 3,500,000 to 4,000,000 people. They used the assumption, common for that era, that daily water usage per capita would remain about 100 gallons per day.

In 1907, the City changed course and again re-applied to the Secretary of Interior James Garfield for the rights to the Hetch Hetchy water supply. At no time from 1901 and 1908 were the Turlock Irrigation District or Modesto Irrigation District prior water rights mentioned in these applications. On July 24, 1907, TID objected to the Secretary of Interior as to the City's application, and wrote to Grunsky and Manson that the Hetch Hetchy and Lake Eleanor reservoir sites would not provide sufficient storage as to provide for both the City of San Francisco and the TID / MID water demands (this turns out to be correct, and today (2023), the Don Pedro Reservoir, downstream of La Grange, provides storage for up to 2,000,000 acre-feet for benefit of TID and MID; and the combined storage of the 3 City reservoirs on the upper Tuolumne River is about 655,000 acre-feet: Hetch Hetchy (360,360 acre-feet), Cherry (268,810 acre-feet) and Lake Eleanor (27,100 acre-feet).

In 1908, on consideration of the disastrous fire of the 1906 earthquake, Secretary of the Interior Garfield issued a revokable permit allowing the construction of Eleanor Dam initially. This permit was based on the 1901 Grunsky plan, calling for about 100 MGD to San Francisco.

The 1908 Garfield permit required a revision to the Grunsky plan, in that it required that water from Lake Eleanor be developed first. This triggered a revision of the 1902 Grunsky plan, updated by Manson between 1908 and 1911.

In 1909, newly elected President Taft appointed Richard Ballinger to succeed Garfield as Secretary of the Interior.

In February 1910, Secretary of the Interior Richard Ballinger called on San Francisco to show why the Hetch Hetchy Valley and reservoir site should not be permanently denied and the 1908-permit revoked.

In response, the City retained Mr. John Freeman. Grunsky said of Mr. Freeman: "*San Francisco was thus put on the defensive and, due to lack of confidence of various of her official departments in each other, placed this case in the hands of an expert called in from the East*". That expert was Mr. John Freeman. Mr. Grunsky then declared: "*the natural result was that thousands of dollars were needlessly expended in the accumulation of a mass of statistical information*".

In July 1912, Mr. Freeman had updated the conceptual design of Hetch Hetchy. The updated design was for the system to initially deliver at Irvington portal a minimum of 160 MGD (drought years) and 250 MGD (normal years); and during drought years, with 50 MGD delivered to the distribution system for daily consumption in San Francisco, 50 MGD going to fill Crystal Springs Reservoir when needed, and 60 MGD being sold to other cities (Oakland and San Jose, etc.), all at a cost of $36,981,000 (which excludes cost to build a parallel distribution system in San Francisco). Freeman's cost estimate was based on common labor being paid $2.25 per 8 hour day. Freeman's design was for the tunnels all to be initially sized to flow at 400 MGD, and up to 500 MGD with pumping; with pipelines designed for the initial flow rate, with allowance that parallel pipes could be built as demand increased over time.

With the Freeman report in hand, the U. S. Board of Army Engineers concurred with his findings. The subsequent report submitted to the Secretary of Interior resulted in enactment by Congress of the Raker Bill (Raker Law).

The Raker Bill (alternatively called the Hetch Hetchy Bill, H.R. 7207) was introduced by Mr. John Raker, representative of California, to the House or Representatives on August 1, 1913, thereupon the bill was passed by the U. S. House 183 to 43, and was passed by the U. S. Senate on December 6 1913, 2-to-1, and then signed into law by the President Wilson on December 19, 1913, and then concurred unanimously by the City. The City consented to the practical guarantee that TID and MID would retain the right and use of the full flow of the Tuolumne River and its tributaries up to 2,350 cubic-feet per second (1,265 MGD) at La Grange diverting dam when those districts can beneficially use it, provided such lands do not exceed 300,000 acres; and 4,000 cfs (2,150 MGD) from April 15th to June 14th of each year. The City's engineers concluded that this would leave the City's own future supply at 400 MGD for domestic purposes, unimpaired.

To meet these flow criteria, the Hetch Hetchy Reservoir was required if the full flow of the Tuolumne River was to be conserved.

Per the Raker Bill (1913), the City is compelled to develop power along the Hetch Hetchy system, and to sell a large part of this power at cost to MID and TID; with the remaining power available for use in San Francisco for its municipal purposes.

Grunsky stated in 1916: "*despite the unfortunate circumstances of the past, San Francisco may yet achieve an adequate and in every way satisfactory water supply. Nevertheless, the danger should be recognized that competent management of today under the political system may be followed by incompetent or even corrupt management tomorrow*".

In 1916, funding for the Hetch Hetchy system had been approved, land and water rights were being secured, but construction had not yet proceeded to any great extent. A report in ASCE (1916) on the status of water supply for San Francisco, Grunsky stated (paraphrased):

> "*Which of the remote sources [of water] should be developed? Pumping from the San Joaquin or Sacramento rivers has frequently been advocated, with that water to be made fit for consumption using filtration and by treatment with hypochlorite. Although this may be true, no one who has the choice would*

> *advocate the preparation of a filthy water for domestic use, when, with the limit of the means at command, a pure mountain water can be made available*".

Grunsky then goes on to state that based on his exhaustive analyses in 1901, that water from the Sierra would not cost much in excess of water that could be developed from local resources. Grunsky reported in 1916 that he favored the acquisition of the SVWC by the City, as part of the greater Hetch Hetchy system; but that he was disappointed in the result of subsequent proceedings between the City and SVWC about such an acquisition. Grunsky went on to say that the development of Hetch Hetchy on the Tuolumne River in Yosemite National Park was opposed by two irrigation districts (Turlock Irrigation District TID, Modesto Irrigation District MID, whose water rights on this watershed date back to the late 1880s, predating those for San Francisco) that depended upon the Tuolumne River, as well as "misguided Nature lovers". [notably John Muir, as first president of the Sierra Club, and was opposed to the construction of the Hetch Hetchy Reservoir in Yosemite National Park].

9.2 The Hetch Hetchy System Design, 1912

Tables 9-1 and 9-2 list the observed flows from the Tuolumne River. It is this data, from 1896-1905, that formed the basis of the Raker Act (1913), whereby the City of San Francisco was entitled to average day flows of 400 MGD and the MID and TID the remaining ~1,600 MGD.

Table 9-2 shows that for the 10 year period from 1896 to 1905, the average yearly flow of the Tuolumne River was 1,973,868 acre-feet, so San Francisco's claim for 448,000 acre-feet amounted to about 23% of the total, and the remaining 77% split between MID and TID.

MGD	Cubic Feet per Day	Cubic Feet per Second (CFS)	Acre Feet per Day	Acre Feet per Year
100	13,360,000	155	307	112,000
200	26,720,000	310	614	224,000
300	40,080,000	465	921	336,000
400	53,440,000	620	1228	448,000

Table 9-1. Water Claims of the City of San Francisco (Marsden, 1908)

Year	Acre Feet in One Year	CFS at La Grange in July	Average Discharge over a year, CFS
1896	1,968,100	960 to 5,330	2,342
1897	2,422,827	480 to 4,840	2,364
1898	854,496	88 to 750	1,182
1899	1,126,793 to 1,672,341	331 to 2,538	2,315
1900	1,573,498	140 to 1,873	2,160
1901	2,538,990	1,440 to 9,960	3,537
1902	1,459,385	353 to 6,550	2,022
1903	1,968,955	407 to 4,507	2,732
1904	2,862,378	1,046 to 5,530	3,948
1905	1,440,000	427 to 3,403	1,995
Average	1,973,868		

Table 9-2. Discharge of the Tuolumne River as measured at La Grange (Marsden, 1908)

In 1912, John Freeman was hired by San Francisco and he re-designed the Hetch Hetchy system for an ultimate average day flow of 400 MGD, and for a peak flow of 500 MGD (under gravity flow); potentially higher if supplemental pumping were installed. However, the water rights of MID and TID had to be factored in. This was codified into Federal Law by the Raker Act of 1913, whereby San Francisco was granted water rights for 400 MGD and the remainder split between MID and TID.

Freeman laid out the Hetch Hetchy Aqueduct system in recognition of the 1868 and 1906 earthquakes on the Hayward and San Andreas faults. To this effect, he avoided tunnels crossing the Hayward and San Andreas faults, keeping the tunnels about ½ mile away from the fault lines, and instead laid out steel pipes from the tunnels to cross these faults. The concept was that steel pipes could be relatively quickly repaired, and without impact to downstream customers if there was enough terminal storage to sustain demands until repairs could be completed. His idea was that the steel pipes would always be very accessible and could be quickly repaired by boiler makers or steel ship builders from stock that would always be on hand; plus keeping about 1 year water supply in local nearby reservoirs. With these provisions, Freeman stated: "*I believe that serious [earthquake] dangers to any important part of the [Hetch Hetchy] works, or such as could put them out of business long enough to threaten a water famine, are so highly improbable and so remote that they need not be further considered*".

Today (2023), we would tend to agree with Freeman's earthquake assessment, except that he did not address the important aspect of providing water for fighting fires. We cannot blame him, as his charter was to design the regional transmission system from Hetch Hetchy to terminal reservoirs, and not to re-design the local water distribution systems. Today (2023), there remain just a few instances where communities continue to rely on water and flows directly from the Hetch Hetchy transmission system for fighting fires. Today (2023), that system has been seismically upgraded, and modern system goals are to restore water supply within 24 hours. The remaining goal of providing water for fighting fires, still remains an open question for many communities.

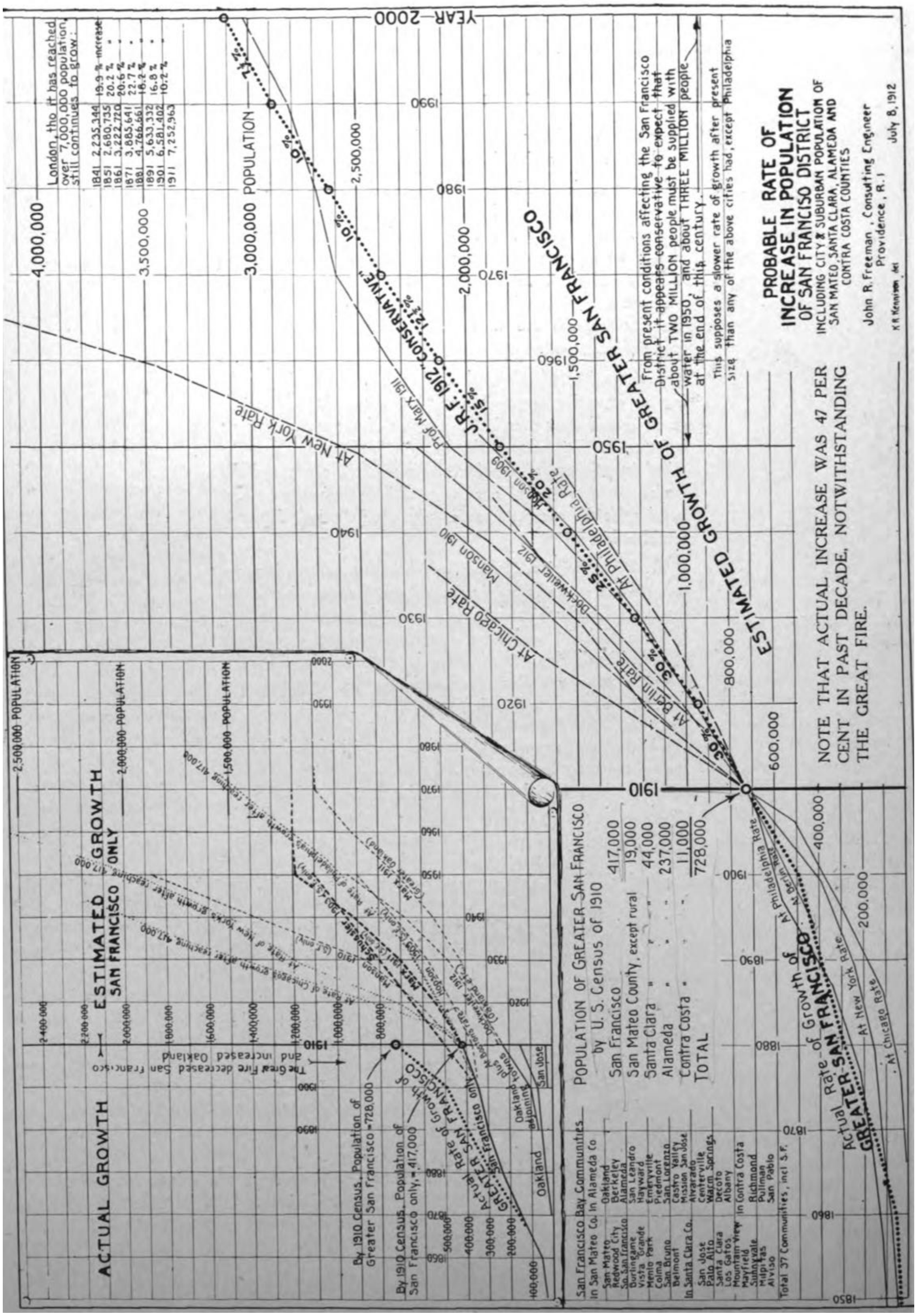


Figure 9-3. Probable Rate of Population Increase, 1850 – 2000 (Freeman, 1912)

Figure 9-3 tells the story behind the development of Hetch Hetchy system. Here, Freeman is basing his computations for water demands of about 65 MGD (entire Bay Area) in 1912, and forecasting water demand forward to the year 2000. Herein lies the concept of a Greater Metropolitan Water District, including San Francisco as well as 36 other cities. Ultimately, the East Bay cities refuse to join, and created their own EBMUD. But importantly, the seeds of a plan to have BDPL 3 and 4 are planted, in order to deliver water to Santa Clara, San Jose, Sunnyvale, Milpitas, Mountain View, Los Gatos, Palo Alto, Belmont, Menlo Park, San Bruno, Burlingame, South San Francisco, San Mateo, Redwood City, Hayward, Colma, Vista Grande, Mayfield (later part of Palo Alto), Alviso (later North San Jose). It is only with the addition of these cities does a supply of 400 MGD make sense, as even today (2023), San Francisco consumes only about 80 MGD.

During Freeman's design process in 1912, he contacted Professor J. C. Branner (acting as Consulting Geologist) of Stanford University, to get his opinion as to the proposed layout of the Hetch Hetchy Aqueduct, both with respect to geologic conditions, and earthquakes. Branner was one of the field investigation team in May 1906, so he was well aware of the San Andreas fault and its impact on buried pipes and tunnels.

Branner replied to Freeman: "*I can call attention to two places which cannot be avoided and at which special provisions will need to be made for possible interruptions by earthquakes. One of these is just north of the town of Irvington, where there is evidence of a recently active fault line which the pipes of the system must necessarily cross (the Hayward fault). The other point is where the line crosses the San Joaquin River. The danger here, however, is not due to presence of a fault line, but simply to the soft and wet condition of the ground which would favor high intensity [shaking] in case of a rather severe earthquake in the neighborhood*."

In modern parlance, Branner correctly identified the Hayward fault; but he missed entirely the Calaveras fault across which the Aqueduct must cross.

Figures 9-4 and 9-5 show the conceptual layout around the Bay in Freeman's 1912 plan. Much (but not all) of this layout was eventually built. The following describes the major construction, beginning at Crystal Springs Reservoir, and working easterly.

- Pulgas Tunnel, 4 miles long, that discharges into Crystal Springs Reservoir. The diameter of the Pulgas Tunnel was set to deliver maximum flow by gravity flow from Calaveras Reservoir to Crystal Springs Reservoir.

- Bay Division Pipelines (BDPL). Bay Crossing. Shown here and described as steel pipe, cement mortar lined, and 6.5 feet in inside diameter, connecting to the Pulgas Tunnel. The initial pipeline was sized to deliver 100 MGD to Crystal Springs Reservoir. What was initially built was BDPL 1 as 60-inch riveted steel pipe (1923) followed by parallel BDPL 2 as 66-inch welded steel pipe (1933). Freeman called for the construction of the pipe along the marshy shorelines across Dumbarton Strait, to be either built atop an embankment, or using concrete piles.

What was actually built through the marshy zone was two parallel steel pipes atop wooden redwood piles, with detailing nearly the same as the adjacent 36-inch Alameda pipeline. A critical aspect of the alignment was that surveys available to Freeman in 1912 showed that the marshy soft soils were underlain some 10 to 15 feet deep by hard clay-like soils, which would provide good vertical load bearing capacity for a pile-supported pipe.

- South Bay Alignment. Shown here as an Alternate Pipe route, an 80-foot wide right of way was eventually purchased, with space for three parallel pipes. Freeman considered this route initially, as it avoided crossing the bBay; but in consideration that the SVWC's Alameda 36-inch pipeline (on wood piles and with sliding saddles, and with submarine sections) survived the 1906 earthquake with nary a major problem, he decided that the longer length of pipe necessary for the South Bay alignment was not needed initially. Eventually, by the end of the Second World War, the population of the South Bay expanded sufficiently to outgrow local well water supplies, so the South Bay Alignment would eventually be needed to deliver water to the south bay communities of Union City, Newark, Fremont, Milpitas, North San Jose, Santa Clara, Sunnyvale, Mountain View, Palo Alto, Redwood City and adjacent areas. What was eventually built for the South Bay Alignment was BDPL 3 as 78- to 72-inch steel pipe (1956) followed by parallel BDPL 4 as 96-inch prestressed concrete cylinder pipe and 90-inch welded steel pipe (1973).

- Alameda Creek / Sunol Valley Siphons. Shown in Figures 9-4, 9-5 as a steel siphon, 8.75 feet in diameter, with one additional pipe in the future. Today (2023), there are 4 pipes crossing here (the newest Siphon 4 was designed to be fault tolerant across the Calaveras fault). At the siphons are interconnections to allow Hetch Hetchy water to spill into either Calaveras or San Antonio reservoirs, or for that water to be treated at the Sunol Valley Water Treatment Plant and then re-injected into the siphons.

- Irvington Tunnel. Shown here as having max / min hydraulic grade line of 410 / 343 feet. The tunnel elevation is set so that eventually the full flow of 400 MGD could be transported to a full Crystal Springs Reservoir, by gravity flow, once sufficient BDPL pipelines were constructed. A second Irvington Tunnel was envisioned by Freeman; it was eventually built in 2016, which would afford shutdown, inspection and maintenance as needed of the original tunnel; all while serving maximum day flows to all water customers. In the final construction, the Irvington Tunnel was relocated slightly to the south and lowered in elevation, to have a maximum grade line of about 330 feet at the Irvington portal and 303 feet at the Pulgas Tunnel exit to Crystal Spring Reservoir.

- The Lake Chabot pressure tunnel alignment from Irvington Portal was never built. Instead, a 24-inch and later a 36-inch steel pipe were built to deliver water to Hayward. More recently, the 36-inch pipe was extended to allow emergency intertie between the SFPUC and with EBMUD. The East Bay communities of

Oakland, Berkeley, Alameda, Richmond and adjacent areas never agreed to purchase any water from the Hetch Hetchy system; instead, they built San Pablo Reservoir and Upper San Leandro Reservoirs in the 1910s, and when rapidly growing population proved those supplies insufficient, EBMUD was formed, building the Mokelumne Aqueduct (first pipe built in 1923), another terminal reservoir (Briones), and with water rights to 330 MGD on the Mokelumne watershed. Lake Chabot was never enlarged, and instead was removed from service as a regular water supply for Oakland in 1950.

- Crystal Springs Bypass Aqueduct. Freeman lays out the so-called Crystal Springs Cut and Cover Aqueduct, beginning at the terminal of the Pulgas Tunnel, continuing all the way to the "San Miguel" Reservoir (to serve the upper pressure zone) or the University Mound Reservoir (to serve the lower pressure zone). This Aqueduct was meant to allow for the soft water of Hetch Hetchy to run directly to the houses in San Francisco, thereby without mixing that water with the harder water in Crystal Springs Reservoir. The pressure tunnels and pipes from the south end of Crystal Springs Reservoir all the way to San Francisco were not initially built. Eventually, a Crystal Springs bypass tunnel and pipe (96" PCCP) was built to parallel the reservoir (1970s), and this pipe was impacted during a very rainy winter season by a landslide (although not broken). The landslide was repaired and a second Crystal Springs bypass tunnel was completed by 2015. Therefore today, Hetch Hetchy (or San Antonio or Calaveras) water can flow by gravity all the way to San Francisco, and bypass Crystal Springs and San Andreas reservoirs completely.

- Lake Chabot to San Francisco Aqueduct. This alignment is shown on the map, traversing Alameda Island. This Aqueduct was never built.

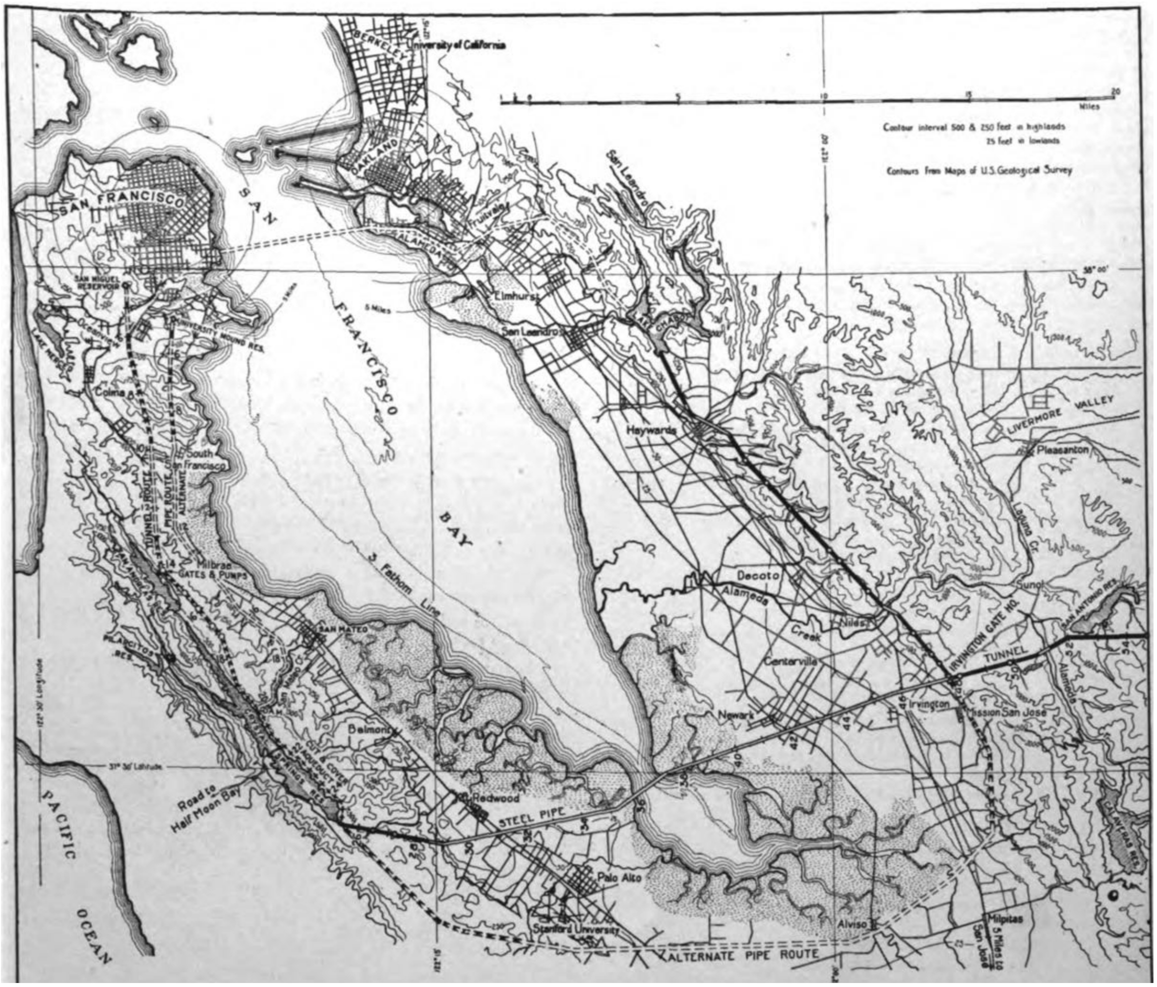


Figure 9-4. Hetch Hetchy Aqueduct Layout in Bay Area (Freeman, 1912)

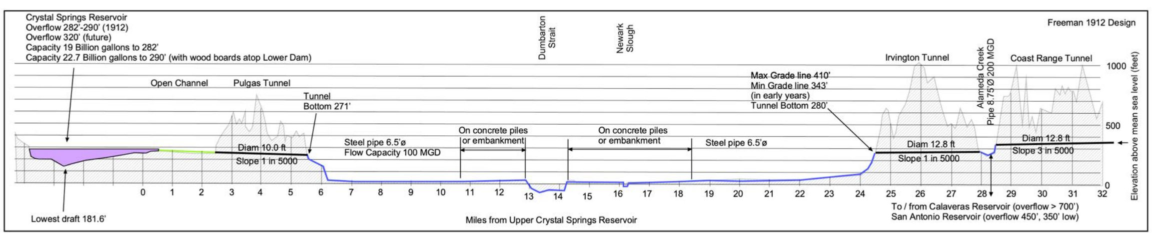


Figure 9-5. Hetch Hetchy Aqueduct Layout in Bay Area (Freeman, 1912)

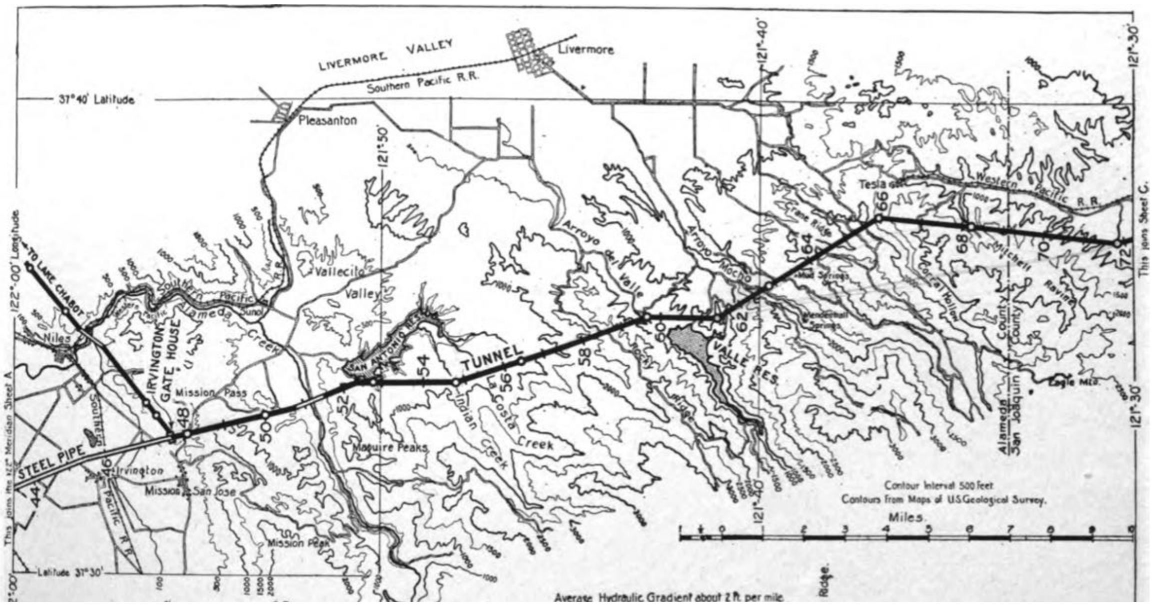


Figure 9-5. Hetch Hetchy Aqueduct Layout Coast Range Tunnel (Freeman, 1912)

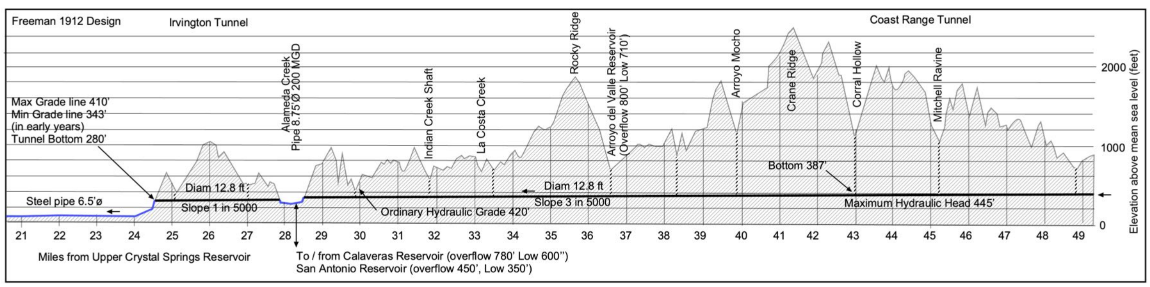


Figure 9-6. Hetch Hetchy Aqueduct Layout Coast Range Tunnel (Freeman, 1912)

Figures 9-5 and 9-6 show the planned aqueduct through the San Joaquin Valley. Here, the original design called for two 7.5 feet diameter steel pipes, one in the early years. Grade line at the eastern end of the Coast Range Tunnel would be 470 feet (with 2 pipes), or 430 feet with 1 pipe. With 1 pipe, the maximum flow rate was 240 MGD; with 2 pipes, 400 MGD could be moved.

Freeman noted that the pipes were intended to be supported on heavy concrete piles, to an elevation above the highest flood level envisioned in the valley. This was to avoid the corrosive action of the alkaline mud, and be of permanent construction not subject to decay. No wooden pile trestle supports, as in the prior Grunsky or Manson plans or in the SVWC Bay crossings, would be used anywhere on the aqueduct now proposed.

In actuality, BDPL 1 and 2 were supported for a length of about 16,000 feet, on redwood piles, where they crossed marshes either side of the Bay. Over their 90 year lifetime, one upgrade of the wood piles was done in the mid 1990s, to repair about 15% of the piles from ongoing decay. In the early 2010s, BDPL 1 and 2 pipes at the Bay Crossing were abandoned entirely, and replaced with a new parallel 10-foot finished diameter tunnel (with steel liner) under the bay (part of BDPL 5). The original BDPL 1 and 2 pipes either side of the Bay remain in service as of 2024, paralleled by the new BDPL 5 72-inch steel pipe.

Figures 9-7 through 9-9 show Freeman's design between Yosemite and the San Joaquin Valley.

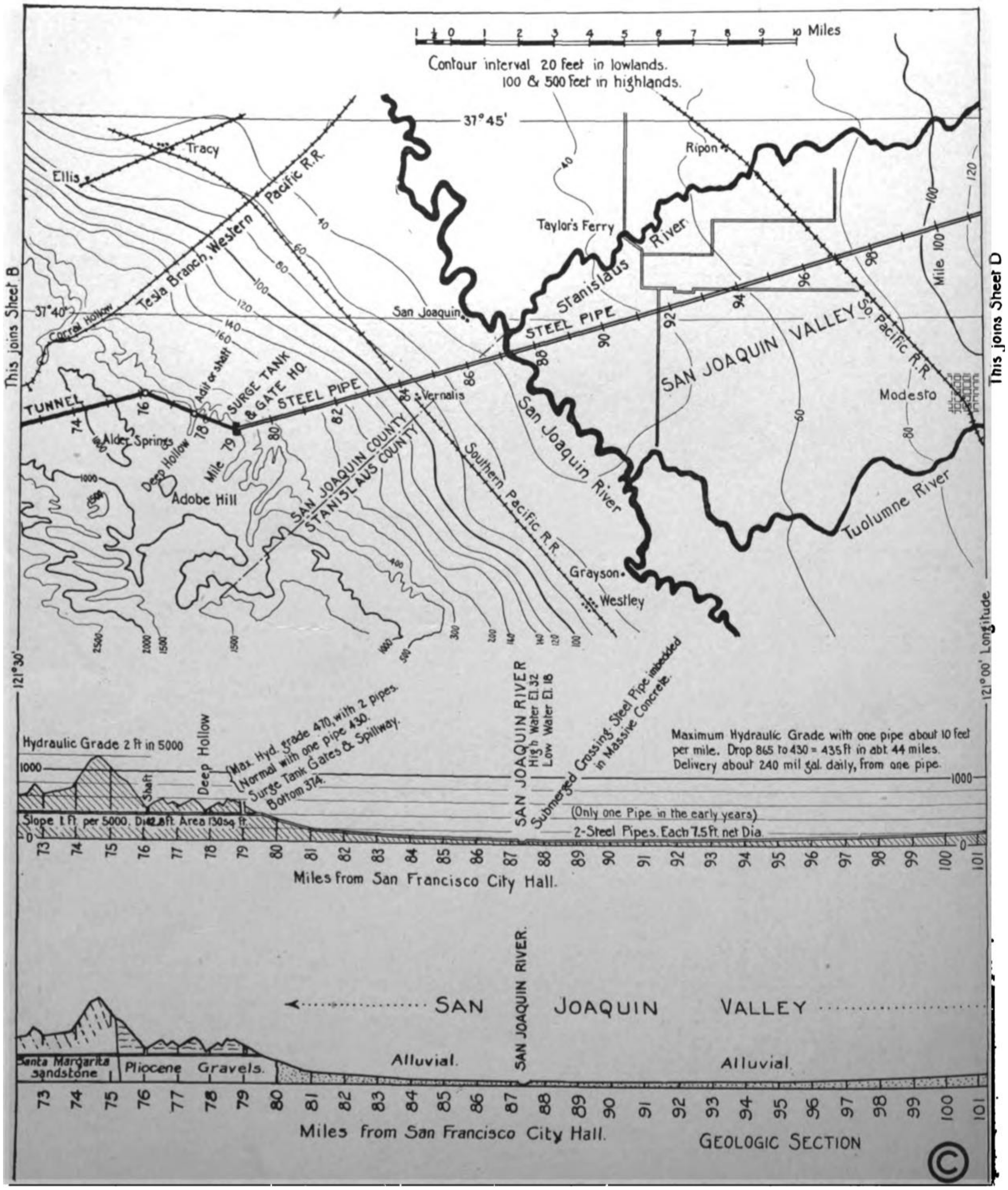


Figure 9-7. Hetch Hetchy Aqueduct Layout Western San Joaquin Valley (Freeman, 1912)

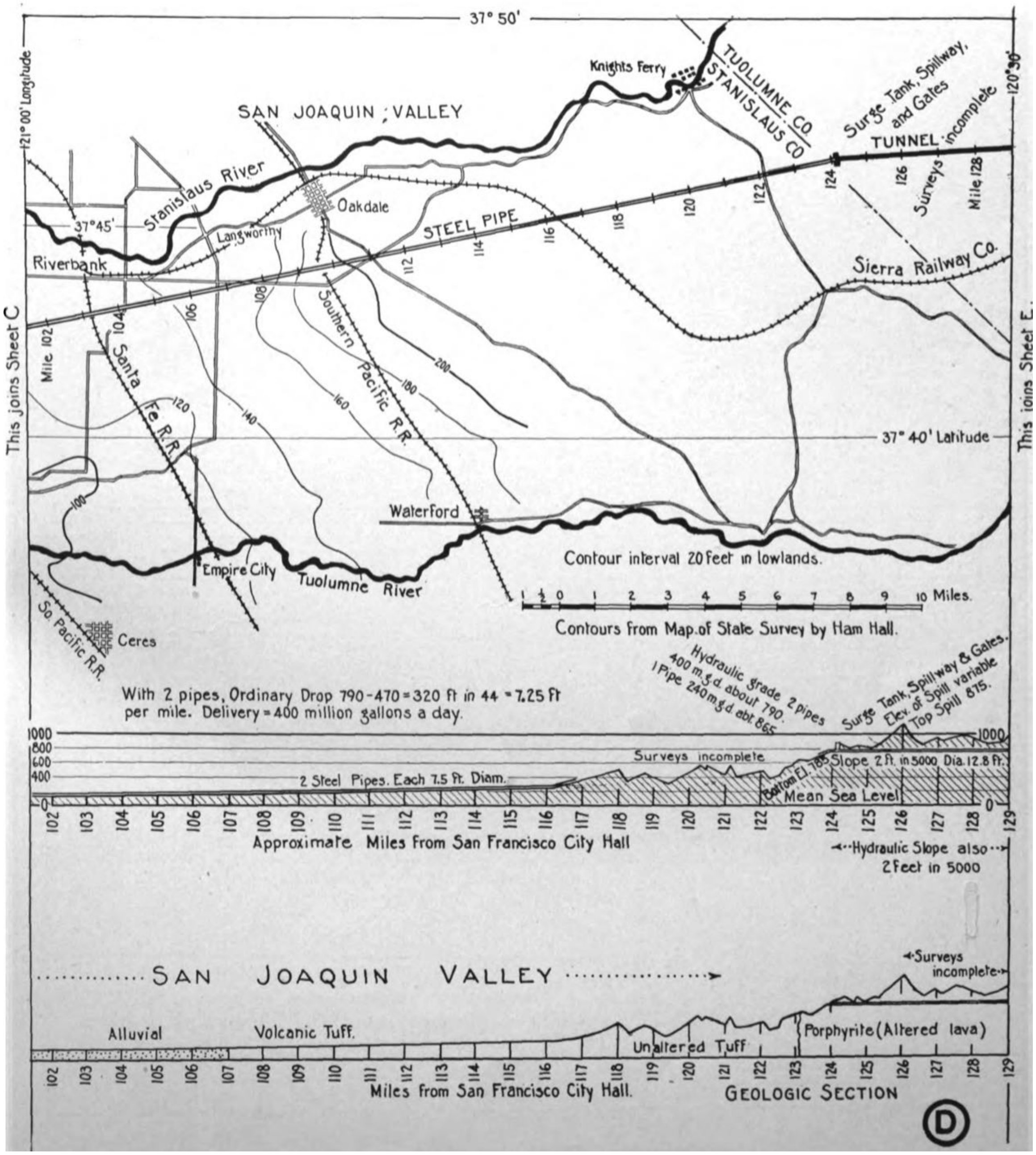


Figure 9-8. Hetch Hetchy Aqueduct Layout Eastern San Joaquin Valley (Freeman, 1912)

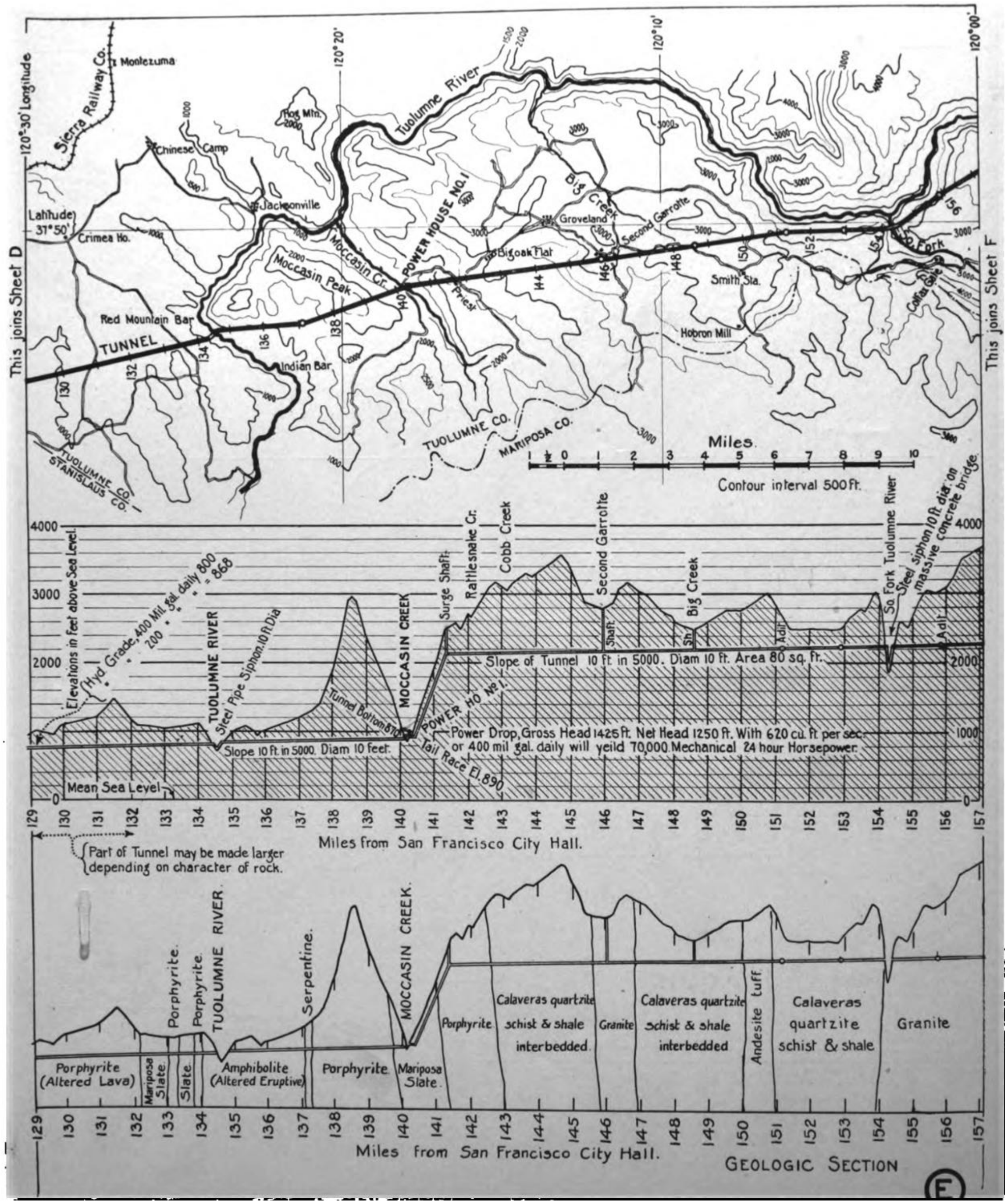


Figure 9-9. Hetch Hetchy Aqueduct Layout Moccasin Creek (Freeman, 1912)

In Figure 9-10, the note is made: "*Hetch Hetchy Reservoir will seldom be drawn lower than 60 feet below high water before November 1st under maximum use*." This is an important statement, as it gets to the heart of John Muir's opposition: Muir envisioned that lake would go empty each year in the autumn, and then fill each spring; when nearly empty, the debris would be apparent and the beauty of the valley destroyed. But, critically, the Freeman design, which allowed for drawing down downstream reservoirs in lieu of Hetch Hetchy in time of drought, has in fact preserved the beauty of an alpine lake at essentially all times over the past century. In many ways, the present Hetch Hetchy Valley is more pristine than nearby Yosemite Valley, with its millions of visitors, and a variety of hotels, shops, roads and parking lots.

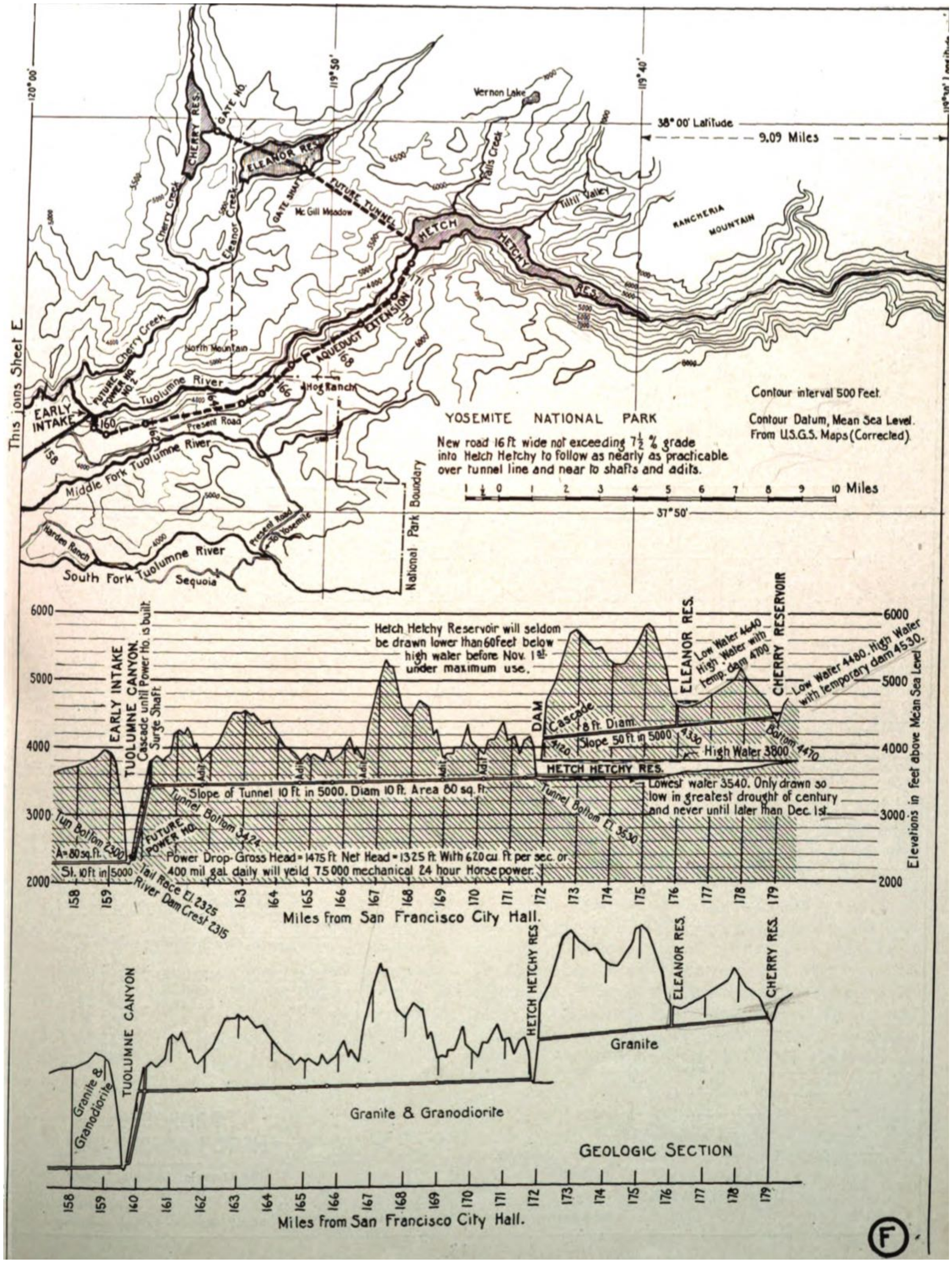


Figure 9-10. Hetch Hetchy Aqueduct Layout Early Intake, Cherry, Eleanor, Hetch Hetchy Reservoirs (Freeman, 1912)

The Hetch Hetchy Dam envisioned by Freeman was twice as tall as the dam envisioned by Grunsky ten years earlier. This reflects the upsizing of the system from 60 MGD to 400 MGD, thus requiring more storage to sustain future multiple dry years.

Freeman also considered the SVWC system in laying out the Hetch Hetchy system. In 1912, he sketched the SVWC system as shown in Figure 9-11. Figure 9-11 shows the same SVWC system as before the 1906 earthquake, except that the Pilarcitos pipeline is gone (damaged by the 1906 earthquake and removed); the new Baden-Merced 30-inch pipeline (conceived in 1907 using remnants of the old Pilarcitos pipe as well as new pipe), and the new Central pump station (needed to boost water from the San Andreas pipeline up to Lake Honda).

Freeman proposed building a new terminal reservoir in San Francisco, with 500,000,000 gallon storage, with overflow 392 feet; he called it San Miguel Reservoir. He wanted this in order to provide more terminal storage for the City should any pipeline break. He also considered the various changes in elevations in the Hetch Hetchy system that would be needed to allow for gravity flow into this reservoir. This concept is similar to Schussler's plan for the ~500,000,000 gallon Industrial Reservoir, albeit at a somewhat lower overflow elevation.

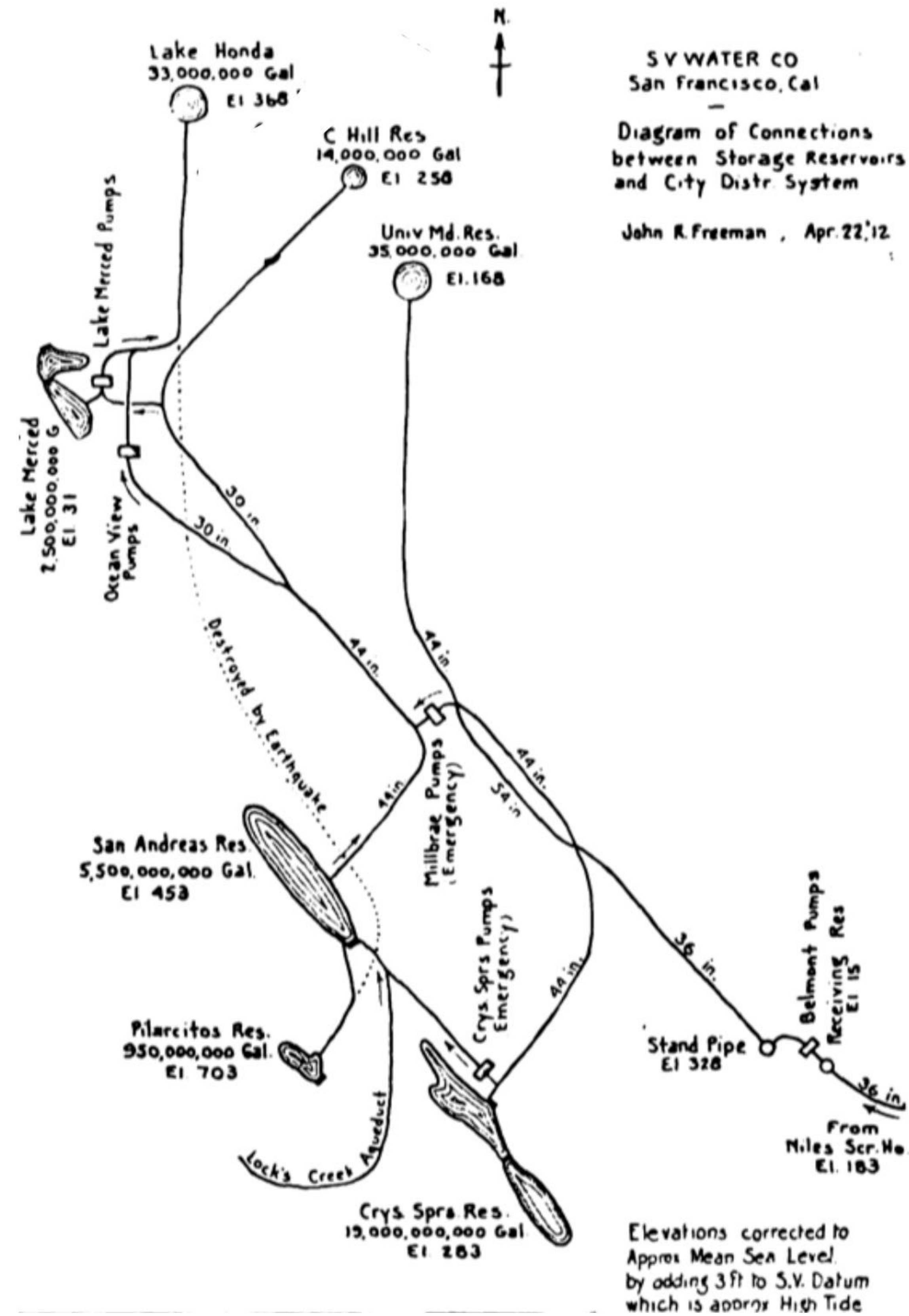


Figure 9-11. Peninsula Transmission System, After the 1906 Earthquake, Freeman (1912)

The City trunk line system sketch prepared by Freeman in 1912. Figure 9-12 highlights the main changes since 1906.

- The Precita Valley pumps were installed (relocated from the abandoned Pilarcitos pump station) to move water from the Crystal Springs zone up to the Lake Honda Zone; this was needed to reinforce the reliability of supply to the upper zone, given that its original supply pipeline (Pilarcitos) was no longer available.

- The 37-inch pipe down Harrison Street (through Mission Creek Marsh) and the 22-inch line down Valencia Street (through Mission Creek) are still shown. This suggests that the rebuild of the water system post-1906 was done as rapidly as possible, to get the city back in business. Conceivably, the Precita Valley pumps could bypass these liquefaction zones; but this is limited in flow, requires pumping, and a fair amount of manual turning of zone gates to achieve. Perhaps SVWC just abandoned fire flows as a core mission, as the City was building its parallel AWSS. Whichever the case, both the SVWC system (later to be bought and operated by SFWD) and the AWSS system (operated by SFFD) remained seismically vulnerable in 1912, and remains vulnerable in 2024.

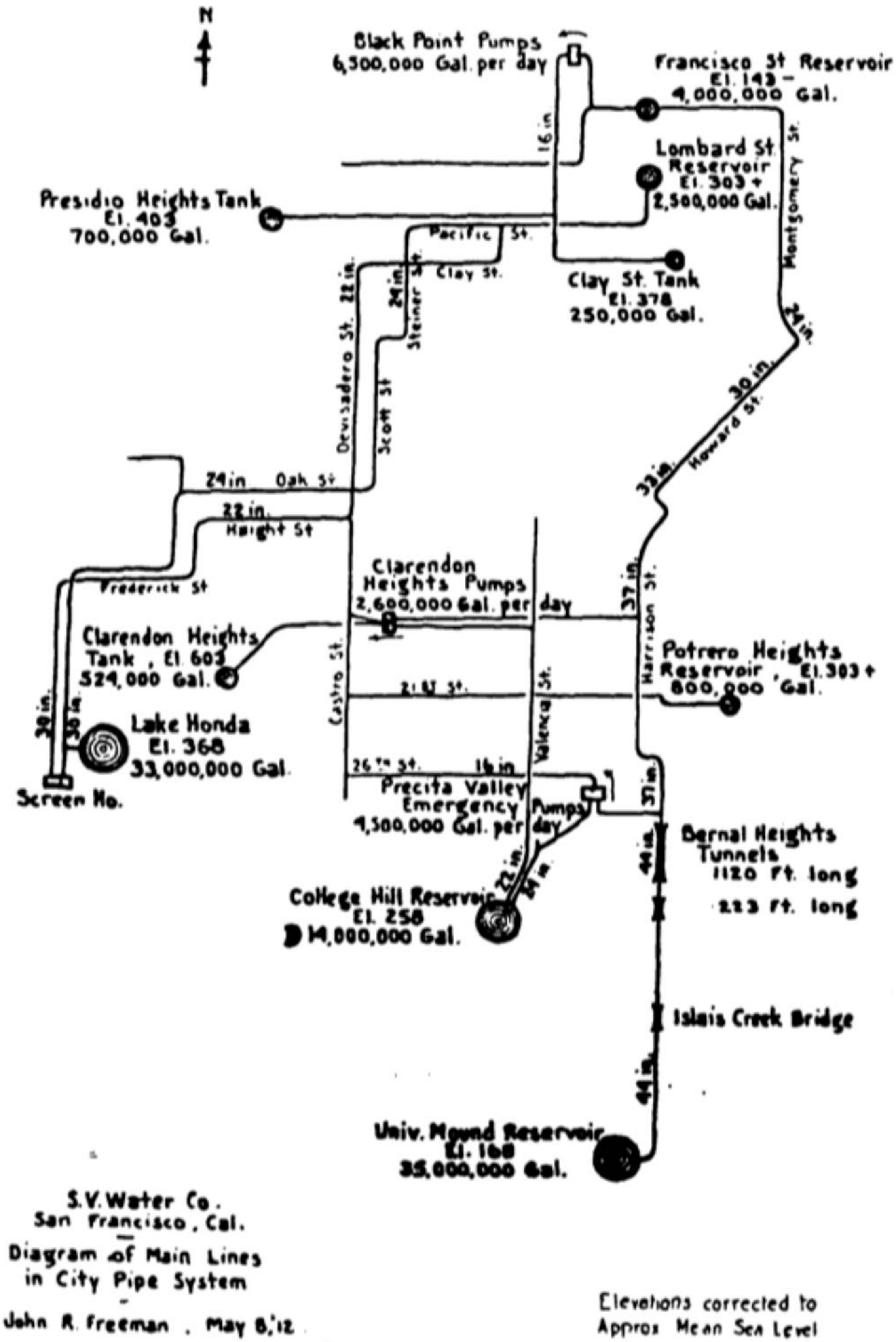


Figure 9-12. City Trunk Line System, After the 1906 Earthquake, Freeman (1912)

9.3 Comparison of the Plans, 1902-1912

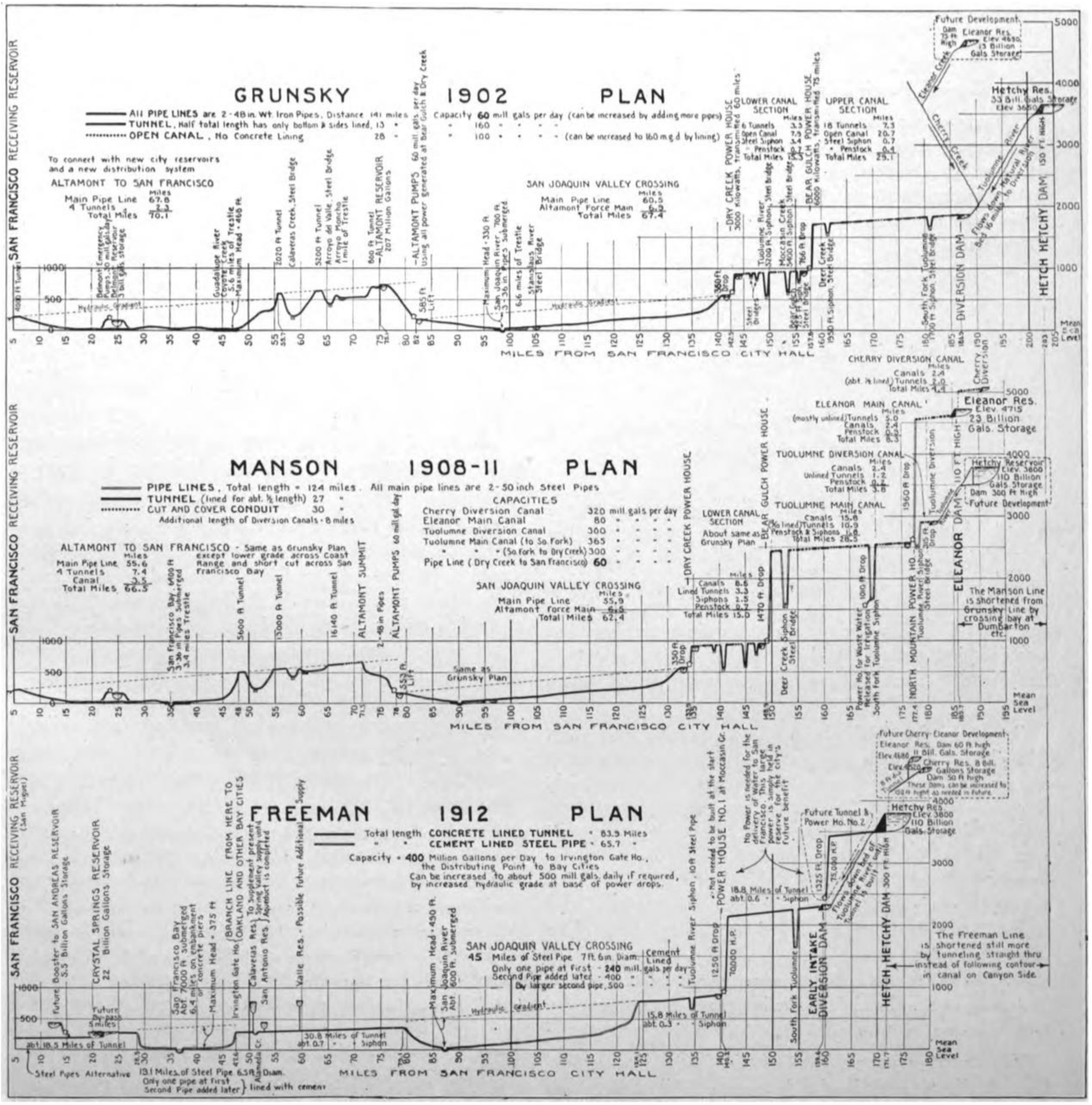


Figure 9-13. Comparison of the Hetch Hetchy Plans, 1902 to 1912

Freeman comments on the history of the plans:

- The Grunsky 1902 plan was for 60 MGD. The design is geared to controlling costs to be as low as practical. The 1902 plan is radically different from the 1912 plan. The 1902 plan had a 150-foot tall dam at Hetch Hetchy, followed by flow in the river a point 3 miles further downstream than the 1912 plan, followed by 44 miles of canals, tunnels and pipes. The various siphons were designed for 60 MGD, being twin 48-inch wrought iron pipes. The tunnels were to be 7.5 feet wide by 9 feet tall. The canals would be unlined initially, and possibly capture rainwater flows from adjacent hillsides. The canals would begin open water flow at 1,955 feet, ending at 1,800 feet; this is well below the floor of the Hetch Hetchy

Valley, so this head would be wasted for purposes of power development. Power development was based on 250 cfs with a drop of 756 feet. Water wheels would develop 12,000 horsepower, and generators developing 6 MW; power transmitted at 40 kV to the Altamont pump stations, at 40 kV. The power developed would be mostly used at the Altamont pump station, located on the west side of San Joaquin Valley; at this pump station, the water would be pumped up to about 750 feet. In total, the design called for 28.6 miles of open canal, 13 miles of tunnel, 141 miles of twin 48-inch diameter wrought iron riveted pipes. The twin-48-inch pipes would go around the south end of the Bay, including 5.6 miles on trestles where the pipes would cross the Guadalupe River and Coyote Creek.

- On (or about) July 28, 1908, City Engineer Manson was charged with updating the Grunsky plan. This variant was needed to satisfy the Garfield permit of 1908, which required that water from Lake Eleanor and Cherry Creek be developed before water from Hetch Hetchy. Otherwise, the plan was very similar to the 1902 Grunsky plan. The cost estimate presented to the Board of Supervisors on September 14, 1908 was the same as that by Grunsky, save for adding $2,000,000 for a 150-foot high dam to form Lake Eleanor. In 1910, Manson again revised the Grunsky plan by including a diversion on Cherry Creek to flow at 500 cfs in an open channel into Lake Eleanor, and adding in a powerhouse to capture the fall of water between Lake Eleanor and its junction with the Tuolumne River. He further planned to cover all canals downstream of Lake Eleanor. Later, he further updated the plan by replacing the twin 48-inch wrought iron pipes that would go around the south end of the San Francisco Bay, with two 50-inch steel pipes, crossing through Dumbarton Point with 3.36 miles of pipe submerged and 3.4 miles on trestles.

- The Freeman 1912 plan calls for initial flows of 240 MGD and ultimate flows of 400 MGD (620 cfs), with the opportunity of an additional 25% increase in flow if pumps are added. The 240 MGD was sufficient for all of San Francisco and many adjacent communities in the San Francisco Bay Area, including the entire East Bay. [Note: the East Bay communities of Oakland, Berkeley, Richmond and surrounding areas elected not to become part of the San Francisco water system, instead, they eventually built their own aqueduct from a different Sierra watershed]. Freeman noted that it would cost relatively little more to drive a tunnel sized for 400 MGD than for 60 MGD. Freeman noted that the minimum size for a tunnel, being the governing cost for a long tunnel, is determined by the room needed for railroad track and space for workmen; not by the volume of water needed to be moved. The 1912 plan avoids all canals: these open-air conduits would allow algae growth and degrade water quality; instead, the entire aqueduct is tunnels or pipelines. Power development was based on 620 cfs with a drop of 1,250 feet. The initial works had no power development, but the design allowed for future installation of powerhouses and penstocks able to generate 70,000 horsepower initially, and 157,000 horsepower ultimately; and that power could be used for any purpose, as there are no pump stations.

9.4 Cost of the Plans

Table 9-3 shows the projected costs of developing the initial Hetch Hetchy project, using the 1912 Freeman plan. The initial cost to reliably deliver 160 MGD from Hetch Hetchy to Crystal Springs Reservoir was $35,686,000 ($1912). The increased cost to develop Eleanor and Cherry watersheds to deliver 240 MGD was $38,898,000. These costs are developed based on information in Freeman (1912), including the Pulgas Tunnel to deliver water into Crystal Springs Reservoir. These costs include contractors profit, engineering, cost of bonds. These costs do not include already-spent costs from 1900 to 1911, which amounted to about $1,500,000, mostly for land acquisition, survey and engineering costs.

Item	Item	Cost
Calaveras Sunol Siphon	0.85 miles, steel cement lined pipe 8.75 feet diameter, 240 MGD capacity	$ 122,000
Irvington Tunnel	3.2 miles, 12.8 feet diameter tunnel, 400-500 MGD capacity	$ 1,133,000
Bay Pipeline	16.7 miles, 6.5 feet diameter steel cement lined pipe, on concrete piers across marsh, submerged under bay, tunnel into Crystal Springs reservoir, 100 MGD capacity	$ 2,682,000
Redwood (Pulgas) Tunnel	3 miles, 10 feet diameter, 60 percent timbered, $34.43 per foot, 33% overhead	$ 725,000
Coast Range Tunnel, Tesla to Sunol Valley	27.5 miles, 12.8 feet diameter tunnel, 400-500 MGD capacity	$ 10,262,000
San Joaquin river to Tesla Portal	8.3 miles, 7.5 feet diameter cement lined steel pipe, 240 MGD capacity	$ 1,211,000
Oakdale to San Joaquin River	36.6 miles, 7.5 feet diameter cement lined steel pipe, 240 MGD capacity	$ 6,291,000
Red Mountain to Oakdale	10.25 miles, 12.8 feet diameter tunnel, 400-500 MGD capacity	$ 3,168,000
Tuolumne River Crossing	0.4 miles, 10 feet diameter cement lined steel pipe, 240 MGD capacity	$ 182,000
Moccasin to Red Mountain	5.55 miles, 10 feet diameter concrete lined tunnel, 400-500 MGD capacity	$ 1,463,000
Diversion	Tuolumne River canal into conduit at Moccasin, 7.8 miles, 50 MGD	$ 275,000
Early Intake to Moccasin	19.5 miles, 12.8 feet diameter tunnel, 400-500 MGD capacity	$ 5,404,000
Hetch Hetchy Dam	160 MGD yield after TID and MID rights; 40 Billion gallon capacity reservoir	$ 1,138,000
Road	Rosasco to Hetch Hetchy, 62 miles	$ 1,288,000
Roads	Coast Range Tunnel	$ 36,000
Road	Scneic around Hetch Hetchy reservoir, 10 miles, also to Eleanor and Cherry	$ 306,000
Total (160 MGD)	Hetch Hetchy to Crystal Springs Reservoir	**$ 35,686,000**
	Hetch Hetchy to San Francisco City Hall	$ 36,981,000
	Difference	$ 1,295,000
Branch pipe Irvington to Oakland City Hall	4.5 feet diameter cement lined steel pipe, 50 MGD capacity	$ 2,247,000
Eleanor and Cherry Reservoirs to Hetch Hetchy	5.55 miles, 8 feet diameter tunnel in granite	$ 1,144,000
Eleanor and Cherry Dams	50 feet high earthen dams at Eleanor and Cherry (exclusive of water rights)	$ 1,170,000
Dam	Low Masonry for flooding Poopenaut Meadows	$ 898,000
Total (240 MGD)	Cherry, Eleanor, Hetch Hetchy to Crystal Springs Reservoir	**$ 38,898,000**

Table 9-3. Freeman's Cost Estimate to Construct Hetch Hetchy ($1912)

Also included in Table 9-3 were provisions to extend the Bay pipeline to deliver water to San Francisco City Hall, adding $1,586,000; and to include a pipeline to deliver water to Oakland City Hall, adding $2,247,000. Neither were built.

Table 9-4 shows that the actual cost to build the initial works (Hetch Hetchy to Crystal Springs Reservoir), was $105 million.

- One major difference of the actual construction by 1933 versus the Freeman plan of 1912, was that the Bay pipeline was actually built as two parallel pipes: BDPL 1 (60-inch diameter riveted steel) and BDPL 2 (66-inch diameter welded steel) instead on one 78-inch pipe; and BDPL 1 and 2 crossed the marshes of the Bay on wood piers (16,000 feet) instead of concrete piers, and crossed two submarine sections as ball-jointed pipes, and crossed the remaining Bay on a steel truss bridge.

- First water deliveries to San Francisco used BDPL 1 (built in 1923), with source waters being from the Sunol Aqueduct, via a newly built Irvington bypass pipeline to connect the Niles tanks to BDPL 1. It would take 10 more years before the upstream Coast Range Tunnel and other appurtenances would be complete to allow water from Hetch Hetchy Reservoir to flow all the way to Crystal Springs Reservoir. BDPL 1 paralleled the SVWC 36-inch pipe for much of its length, including the Bay Crossing at Dumbarton.

- The BDPL pipeline costs per Freeman's 1912 estimate were based on using 1.5-inch-thick cement-lined and exterior painted 78-inch finished inside diameter steel pipe with riveted joints, F_y = 30,000 psi, F_u = 60,000 psi; rivets F_u = 50,000 psi, with working hoop stress limited to 12,500 psi to 15,000 psi. Longitudinal seams joints were to be 88% efficient. Lap joints (girth joints) were to be 75% efficient. Wall thickness ½ inch, 3/8 inch or 1/4 inch, for maximum hydrostatic heads of 376, 240 or 160 feet, respectively. The pipe was to include submerged sections of 1,050 feet across Newark Slough channel, and 4,880 feet across the main Bay. Pile systems are based on driving down to firm clays

- First Hetch Hetchy deliveries into Crystal Springs Reservoir were made in 1934.

- Note that the $105 million actual cost reflects inflation from 1912 to 1933. In the interim, there was the first world war, the great influenza pandemic and the Great Depression.

- The future Canyon Tunnel (Hetch Hetchy to Early Intake, 12.1 miles) is not included in these cost estimates.

Item	Description, Year Complete	Actual Cost 1933	Freeman Estimate 1912
1.1	Hetch Hetchy Dam, 206,000 acre-feet, 1923	$9,100,000	$1,138,000 $1,288,000 $306,000
1.2	Raise Hetch Hetchy Dam, 360,360 acre-feet, 1938	$3,500,000	
2	Lake Eleanor, Cherry Lake, Early Intake		
3	Canyon Power Tunnel		
4	Mountain Tunnel (Early to Priest). 19 miles	$25,000,000	$5,404,000
5	Priest Reservoir	$1,000,000	
6	Priest bypass pipeline, 1,200 feet long, 2004	$13,000,000	
7	Moccasin power tunnel.	$2,500,000	
8	Moccasin power house. 1925	$2,400,000	
9	New Moccasin power house. 1969	$8,300,000	
10	Moccasin Reservoir (afterbay)		$275,000
11	Moccasin low head power plant, 1986		
12	Foothill Tunnel. 15.8 miles. 1929	$8,000,000	$1,463,000 $182,000 $3,168,000
13.1	San Joaquin No. 1 Pipe. 47.5 miles. 1932	$5,000,000	$6,291,000 $1,211,000
13.2	San Joaquin No. 2 Pipe. 47.5 miles. 1953	$12,300,000	
13.3	San Joaquin No. 3 Pipe. 47.5 miles. 1968	$19,500,000	
14	Coast Range Tunnel. 28.5 miles, 1934	$28,000,000	$10,262,000 $122,000 $1,133,000 $36,000
15.1	BDPL No. 1 Pipe. 21 miles. 1923	$6,000,000	$2,682,000
15.2	BDPL No. 2 Pipe. 21 miles. 1934	$4,000,000	
15.3	BDPL No. 3 Pipe. 34 miles. 1956	$10,000,000	
15.4	BDPL No. 4 Pipe. 34 miles. 1973	5,600,000	
16	Pulgas Tunnel. 1.7 miles. 1924 cost estimate	725,000	$725,000
	Total (see notes below)	$105,125,000	$35,686,000

Table 9-4. Actual Cost to Build Hetch Hetchy

Notes for Table 9-4:

- Freeman Cost Total. Items 1.1, 1.2, 4, 10, 12, 13.1, 13.2, 14, 15.1, 15.2, 16.
- Actual Cost Total. 1.1, 1.2, 4, 5, 7, 12, 13.1, 13.2, 14, 15.1, 15.2, 16. Items 13.1 and 13.2 have combined flow capacity similar to that planned by Freeman (120 MGD). Items 15.1 and 15.2 have combined flow capacity similar to that planned by Freeman (120 MGD).

- Financing. San Francisco passed bond issues for Hetch Hetchy of: $600,000 in 1908; $45,000,000 in 1910 (including a parallel city distribution system that was never built); $10,000,000 in 1924; $24,000,000 in 1928; $6,500,000 in 1932, $3,500,000 and $12,100,000 in 1933. Total bonds = $101.7 million.

- Fatalities. During construction from 1914 - 1937, 89 workers.

- Total estimated cost (Freeman plan, 1912): $36 million, estimated. ($1912)

- Total actual cost (to flow ~120 MGD with capacity to expand to 400 MGD). $105.1 million.

- The actual cost (adopting $105.1 million) versus forecast cost ($35.7 million) reflects a 195% increase in cost.

- On top of this cash construction cost, one should consider the 89 workers who lost their lives during construction.

- When the Hetch Hetchy project was being "sold", it was forecast to cost $45 million to deliver initially at up to about 200 MGD, with expansion eventually to 400 MGD by gravity flow, and would include a complete parallel water system in San Francisco.

- If one inflates these numbers to $2023, and include later upgrades, the present-day Hetch Hetchy system has cost about: $105.1 M * 30 (CPI inflation adjustment) plus $4.6 billion 1995-2023, and various other costs over the past century), then the present day sunk capital cost is at least $8 Billion ($2023) to secure a system that delivers, reliably, some 300 MGD, or about ¾ of the historic water rights.

- SFPUC reports the historic cost at $101.7 million (SFPUC 1994, 2005), reflecting the bond issues[28], not the actual cost. Whether one adopts $101.7 million or $105.1 million, this is but a ~3% difference. The difference in bond issues ($101.7 million) and actual cost ($105.1 million) is partially explained that there was annual revenue from some power sales and there was some rent received by the "renting" of BDPL 1 to SVWC for 6 years.

[28] $600,000 in 1910; $45,000,000 in 1910; $10,000,000 in 1924 (extra for Foothill and Coast Range Tunnels); $24,000,000 in 1928 (extra for Coast Range Tunnel and San Joaquin Pipelines); $6,500,000 in 1933 (extra for Coast Range Tunnel), $3,500,000 in 1933 (raise O'Shaughnessy Dam); $12,100,000 in 1933 (to build BDPL 2 and other improvements) for a total of $101.7 million in bonds. Add to this $41 million bond in 1928 to purchase the SVWC (final purchase price of $39.96 million).

O'Shaughnessy was hired in 1913 to implement Freeman's 1912 plan. He made new surveys and modified Freeman's original plan as follows:

- Item 1. The original Hetch Hetchy dam was built by July 1923 to 75% of the height envisioned by Freeman, which would develop 206,000 acre feet of storage. It was eventually increased in height in 1938, for a reservoir of 360,360 acre-feet in capacity, requiring a supplemental bond issue of $3,500,000 in 1933.

- Item 2. The Early Intake (see Figures 9-10, 9-13) construction started in 1917, with the intent to supply water for the Moccasin power plant. The power would be used support daytime and night time construction of the dams. To supply water for the powerhouse, he first built a dam on Eleanor Creek, creating a reservoir with 27,100 acre-feet capacity, placed into service in April 1918. While Freeman (1912) envisioned the eventual construction of Eleanor Dam and appurtenances, he omitted them from his 1912 cost estimate, figuring solely on the Hetch Hetchy Dam and aqueduct as part of his $36 million cost estimate.

- Item 4. The Mountain Tunnel was drilled to a diameter of 13.5 feet. It was built as unlined, 13.5 feet diameter in granite, for 38% of its length, and the remainder 10 feet diameter with a concrete lining. This allows a gravity flow of 470 MGD. The tunnel was completed in 1925 at a cost of $25,000,000.

- The Mountain Tunnel and Moccasin power house would be built as soon as possible. The Moccasin power house was excluded from Freeman's cost estimate (Table 9-3), but the design allowed for a future power plant (Freeman called this "Power House No. 1").

- Item 5. The Priest Reservoir is at the west end of Mountain Tunnel. It serves as a regulating reservoir for water to flow into the penstocks for the Moccasin power plant.

- Item 7. The Moccasin power tunnel is 5,750 feet long, horseshoe shaped, concrete lined, 19 ft to 13 ft diameter. Capacity 800 MGD. Connects to 4 penstocks, 5,349 feet long, dropping 1,316 feet to the Moccasin powerhouse. The 3 initial penstocks are riveted steel pipe.

- Item 8. Moccasin power house. Original (no longer in use). 80 kW capacity. Freeman called this "Power House No. 1", but excluded it from his $36 million initial construction estimate.

- Item 9. New Moccasin power house. Went into service in 1969, 100 MVA capacity.

- Item 10. Moccasin Reservoir. Constructed with a 50-feet high dam, serves as afterbay for the Moccasin power plant and provides some storage and the feed into the Foothill Tunnel. Water from the power plant can be diverted directed into the Foothill Tunnel, bypassing the Moccasin Reservoir. A 2,900-foot long pipeline can divert water from the upstream Moccasin Creek to be discharged downstream into the creek, should there be adverse water quality in Moccasin Creek.

- Item 11. Low head power plant. Built in 1986 to generate 3 MW from the flow though Moccasin Dam.

- Item 12. Foothill Tunnel. Begin at Moccasin Dam and end at Oakdale Portal. Includes a 9.5-foot diameter steel siphon across the Tuolumne River, just as Freeman envisioned.

- Item 13. San Joaquin Pipelines. Freeman planned for two 7.5-foot diameter pipes to be able to flow at 400 MGD by gravity, and included 1 of these pipes in his $36 million initial estimate. The first pipe No. 1 (56- to 72-inch diameter riveted steel, gravity flow capacity 70 MGD) was built by 1932. The second pipe No. 2 (61-inch diameter, 28.5 miles welded steel, 18.5 miles reinforced concrete, capacity 80 MGD). The third pipe No. 3 (78-inch diameter, 28.5 miles welded steel, 18.5 miles reinforced concrete, capacity 150 MGD).

- Item 14. Coast Range Tunnel. Actually now called two tunnels, the 24 mile long tunnel from Tesla to Alameda east portal, and the 3.5 mile long Irvington Tunnel from Alameda west portal to Irvington. The half-mile from Alameda east to west portals are presently connected by 4 pipes (Alameda Siphons No. 1, 2, 3, 4). The tunnel was originally slated to have construction start in 1925, but a lack of money caused delay for 2 years. Part of the reason for the delay was the Coast Range tunnel was a "gassy" tunnel; some suggested building a pumped pipeline over the Coast Range hills rated at 60 MGD; but eventually the gravity flow tunnel option was adopted, finished diameter 10.5 feet. (Freeman called for 12.8 feet diameter). In 1931, a methane gas explosion killed 12 workers. In 1924, an additional $10,000,000 bond issue was passed to pay for completion of the Coast Range Tunnel.

    - A new Irvington Tunnel No. 2 was built parallel to the original Irvington Tunnel, at a cost of $339,000,000 ($2014).

- Item 15. BDPL 1 would be built as soon as possible (it was built in 1923), a decade before the tunnels form Hetch Hetchy would be complete. The reason to build this section early was that water demand to San Francisco was growing, and SVWC was still the only provider; in order to SVWC to move more water from its Alameda watershed properties to San Francisco, SVWC would have to build a parallel pipe to its then-existing 36-inch Alameda pipeline. SFPUC and SVWC struck a deal whereby SVWC would "rent" SFPUC's BDPL 1 pipeline (60-inch riveted steel pipe) in order to move this water to San Francisco. Thus, SFPUC would receive "rent" monies from SVWC for a decade; all the while SVWC would recover that "rent" by "selling" that water to San Francisco end user customers. This is the type of accounting that politicians sometimes prefer to not talk about, to show that "free" Hetch Hetchy water is in fact "making rent money", all the while the actual costs to build Hetch Hetchy are being blown out of the water and greatly exceeding the original $45,000,000 bond issue.

- The City planned to request an additional $10,000,000 from voters in order to build BDPL No. 1, as all the original $45,000,000 bond issue had been expended. Rather than asking for this bond, the City asked SVWC to finance construction of BDPL 1. SVWC agreed, and advanced $1,000,000 as "pre-paid rent" for BDPL No. 1.

- In an Oakland Tribute editorial on December 12, 1924, it is said: "it seems a little incongruous that at the most critical period in the Hetch Hetchy war, and when the money was not available, the much-maligned SVWC came to the front to complete the job. Volumes might be written on the subject [authors note… this volume!], but suffice to say the company is to be commended… regardless of the fact that those who berated it and made it a target are some of those who are most prominent in Hetch Hetchy circles…"

- BDPL No. 1 is 60-inch diameter, riveted steel, flow capacity 50 MGD. Built 1923. Original 1923-vintage pipeline drawings show the Hayward fault, with slip joints on the pipe either side of the fault. In the 1990s, the authors were later involved with trenching the site, and found that the 1923-vintage drawings had mis-located the fault.

- BDPL No. 2 is 66-inch to 62-inch diameter, single lap-welded steel, flow capacity 60 MGD. Built 1936. Original 1933-vintage pipeline drawings show the Hayward fault, with slip joints either side. Runs parallel to BDPL 1. Both BDPL 1 and 2 have submarine crossings under Newark Slough and eastern side of San Francisco Bay, and are supported atop a 32-span steel trestle bridge crossing the west side of San Francisco Bay. With the construction of a new BDPL 5 tunnel in 2015, the original submarine and trestle portions of BDPL 1 and 2 have been abandoned.

- BDPL No. 3 is 78-inch to 72-inch diameter, single lap-welded steel, flow capacity 87 MGD. Built 1956. This pipe takes the south bay route, to deliver water to the post Second World War rapidly growing cities and communities (collectively, much of Silicon Valley) of Hayward, Union City, Newark, Fremont, Milpitas, North San Jose, Santa Clara, Sunnyvale, Mountain View, Los Altos Hills, Palo Alto, Stanford University, East Palo Alto, Atherton and Redwood City.

- BDPL No. 4 is 96-inch to 84-inch diameter, prestressed concrete cylinder pipe, flow capacity 110 MGD. Built 1973. Parallels BDPL 3.

- BDPL No. 5 is 72-inch to 60-inch diameter, double lap-welded welded steel (butt welded over Hayward fault, 10-foot diameter steel lined tunnel under the San Francisco Bay). With the abandonment of portions of BDPL 1 and 2, the new BDPL 5 retains a similar total gravity flow capacity from Irvington to San Francisco and other water customers of about 307 MGD. Built 2015.

- BDPL No. 6. Space is available next to BDPL 3 and 4 to build a 6th BDPL pipeline in the future. A future new BDPL 6 pipeline could increase gravity flow capacity to 400 MGD, to match San Francisco's original Hetch Hetchy water rights (or, low lift pumping along BDPL 1, 2, 3, 4, 5 could also increase total flow capacity to 400 MGD).

- Item 16. Pulgas Tunnel. 1.7 miles long. Connects BDPL 1 (and later BPDL 2, 3, 4, 5) and delivers that water into the south end of Crystal Springs Reservoir. Initially delivered SVWC water from the Alameda watershed into Crystal Springs Reservoir in 1924. With the completion of the Coast Range Tunnel in 1934, first Hetch Hetchy water deliveries were made into Crystal Springs Reservoir.

- Item 17. Pipelines from Calaveras and San Antonio reservoirs and the Sunol Valley Water Treatment Plant to / from the Alameda Siphons. These pipes can deliver water from SVWC's Calaveras and San Antonio reservoirs (later purchased by SFPUC) into the Hetch Hetchy aqueduct.

- In 1917, a 4-foot high diversion dam was built to move Cherry Creek water into the Lower Cherry Aqueduct (0.75 mile long flume / pipe / tunnel / canal to deliver 200 cfs (129 MGD) of combined Eleanor and Cherry water to a point 345 feet above Early Intake. While Freeman (1912) envisioned the eventual construction of Cherry Dam and appurtenances, he omitted them from his 1912 cost estimate, figuring solely on the Hetch Hetchy Dam and aqueduct as part of his $36 million cost estimate.

- At Early, the initial power plant was rated at 4,000 horsepower, and delivered power via 22 kV distribution overheads to the Hetch Hetchy Dam site (11 miles to the east) and 22 miles to the west to Moccasin. This power plant was operational in May 1918. The power plant generated some $750,000 in sales to third parties (PG&E, TID, MID, etc.) and saved some $550,000 of power purchases needed to build the Hetch Hetchy Dam by 1934. Freeman called this power plant "Power Plant No. 2", to be built at some point in the future, and was not included in Freeman's 1912 cost estimate.

- Since 1960, water retained behind Eleanor Dam is diverted via a mile-long tunnel to Lake Lloyd (Cherry Lake). The tunnels envisioned by Freeman to move water from Cherry Reservoir and Eleanor Reservoir into Hetch Hetchy Reservoir (see Figure 9-10) were never built.

- SFPUC (2005) reports that the initial cost to build Hetch Hetchy to deliver first water to Crystal Springs Reservoir in 1934, was just over $100,000,000. SFPUC (2005) reports that this cost was funded entirely by San Francisco, without State or Federal Assistance. SFPUC reports that at this price, San Francisco "bought a bargain". SFPUC (2005) does not mention the additional $4.6 billion cost in 2000-2020 time frame to construct "reliability" and "seismic" improvements to Hetch Hetchy; and an additional $6 billion requested (in 2021) to seismically upgrade the aging AWSS; and these amounts exclude costs to seismically upgrade the aging 1,200 miles of pipe in the potable water distribution system serving San Francisco.

SFPUC (2005) reports that "O'Shaughnessy's fiery temperament and abrasive manner over the years" led to his dismissal as Chief Engineer in 1932. In 1932, the SFPUC was formed, to administer the Hetch Hetchy project and other City departments.

9.5 Hetch Hetchy, 1934 - 2023

The Hetch Hetchy system has been in operation now for nearly a century. The reservoir in the Hetch Hetchy Valley in Yosemite National Park has served its purpose. It normally operates at near full capacity, and hikers and naturalists see it as a clear mountain like, surrounded by waterfalls and cliffs over 1,000 feet tall.

What about John Muir's concern that the reservoir would be filled every spring, and then run down in the fall, leaving behind "*an ugly mess of debris along the shorelines each fall*"?

It is the nature of the California environment that there can be consecutive wet years (a lot of snow to melt and keep the reservoir full) followed by consecutive dry years. When full, the reservoir can store about 360,400 acre-feet (about 118 billion gallons). Today (2023), an average day demand on the entire Hetch Hetchy system is about 230 MGD. As the population of the San Francisco Bay Area continues to rise, considering conservation, at some time in the future, the water demand may reach 400 MGD.

There are several other reservoirs in the Hetch Hetchy system (capacity when full):

- Hetch Hetchy Reservoir (360,400 acre-feet) (dam raised 1938)

- Lake Eleanor (26,100 acre-feet) (built 1918)

- Cherry Lake (Lake Lloyd) (273,500 acre-feet) (built 1956)

- Calaveras Reservoir (96,850 acre-feet) (dam replaced 2019)
- San Antonio Reservoir (50,500 acre-feet) (built 1964)
- Crystal Springs Reservoir (57,910 acre-feet) (dam raised 1888)
- San Andreas Reservoir (19,027 acre-feet) (built 1868, raised 1874, 1928)
- Pilarcitos Reservoir (3,200 acre-feet) (built 1862 - 1868)
- Total storage. 887,487 acre-feet (289 billion gallons).

At a future average day demand of 400 MGD, total system storage provides about 722 days' supply.

The Don Pedro Reservoir, serving MID and TID, and located downstream of Hetch Hetchy, has capacity of 2,200,000 acre-feet. Water in Don Pedro Reservoir is reserved for TID and MID (recall these two water districts are entitled to about 80% of the average annual flow from the Tuolumne watershed).

Figure 9-14 shows the annual rainfall from 1888 through 2023. This data is based on the rainy season running from July 1 to June 30 annually. This data is measured at Modesto, in the Central Valley, west of the Yosemite National Park. The long term average over 135 years has been 12.17 inches per year. The dots show the annual rainfall. The heavy blue line is a linear regression through the historic data, suggesting a slight increase in annual rainfall (about 1.05-inches more annual rainfall from 1888 to 2022). The "r^2" term of the regression is 0.005, suggesting that the data is nearly random, and that the slight increase in annual rainfall over the past 135 years suggested by the heavy blue line is not especially significant. Figure 9-15 shows a plot of the residuals (inches of rainfall), the distance from the heavy blue line to the actual data.

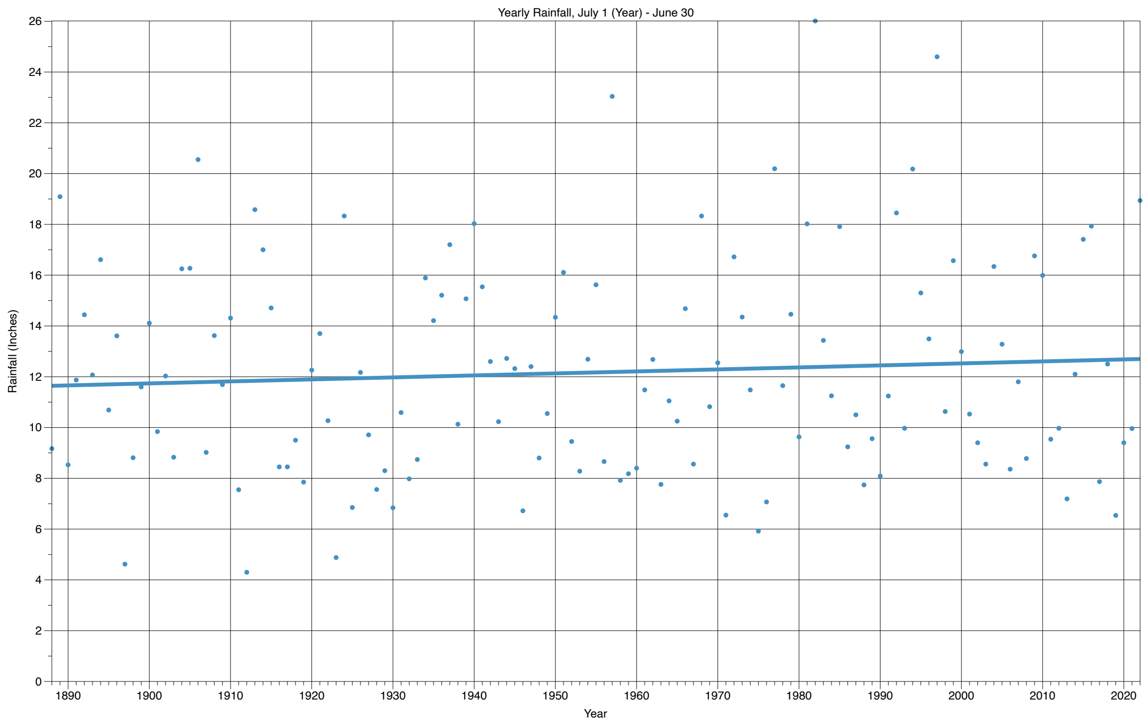


Figure 9-14. Annual Rainfall Amounts (Modesto)

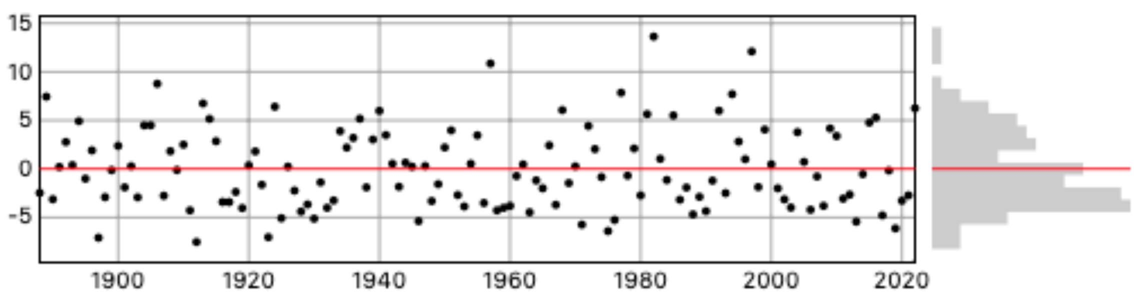


Figure 9-15. Annual Rainfall Residuals (inches)

The rainfall years 1911-1912 and 1912-1913 were consecutive especially dry years.

The data shows "drought" sequences (defined as 3 or more years in a row where rainfall is less than the average) as follows:

- 2017, 2018, 2019, 2020, 2021. 73% of 5 average
- 2011, 2012, 2013. 77% of 3 average
- 1974, 1975, 1976. 66% of 3 average
- 1958, 1959, 1960. 67% of 3 average
- 1927, 1928, 1929, 1930, 1931, 1932, 1933. 71% of 7 average

- 1916, 1917, 1918, 1919. 72% of 4 year average

The historic data shows that there have been 6 "droughts" in the past 135 years, lasting from 3 to 7 years. The worst drought (1927-1933) had a shortfall rainfall of about 2 years of average rainfall.

This historic data suggests the following:

- The original 1912 design concept of having reservoirs with storage for 3 years of average future day demand was rational.

- The area can expect a drought (3 or more years with below average rainfall) about once every 20 years.

- If at some time in the future, all the reservoirs were full at the beginning of a repeat of longest and most severe drought in historic time (1927-1933), then at the end of the drought, the reservoirs would be at about 1/3 full.

There have been some people who promote the removal of Hetch Hetchy Reservoir, allowing for the restoration the Hetch Hetchy Valley to its pre-development status. Removal of about 40% of system-wide storage capacity would seriously compromise the urban use of water during a future multi-year drought. Access of the Tuolumne River flood waters, say perhaps in the Delta near sea-level, would entail new pipelines and pump stations to lift that water to suitable grade line to re-enter the Hetch Hetchy Aqueduct system; the power needed to lift the water would likely require burning of fossil fuels. The water quality at the Delta is significantly poorer than in the Sierra, and this would require new water treatment plants to ensure the water quality meets minimum drinking water standards; and even with treatment, the water quality would be likely poorer than from the Sierra, given the confluence in the Delta area of the entire agricultural run-off of the Central Valley. There are those that suggest that such an effort, costing likely well over $10 billion ($2023) is worth it. There are those who say that the removal of Glen Canyon Dam on the Colorado River is worth it, to restore rapids along the drowned portion of the Colorado River through Cataract Canyon and restore Glen Canyon to its pre-drowned condition. These people all have strong arguments in favor of such restorations.

The author has rafted the Colorado River down Cataract Canyon and hiked around Hetch Hetchy Reservoir. The author has thought long about balancing the environmental upsides that would be available to people who wish to enjoy the great outdoors versus the loss of storage of water for domestic, agricultural, power supply and flood control needs serving tens of millions of people.

- Yes, it would be fun to be able to raft down 40 or more rapids in Cataract Canyon if Glen Canyon Dam were removed. But, presently, one can raft down about 23 rapids there. Is the extra couple of hours rafting through rapids, while fun and perhaps risky, truly that essential?

- Yes, it would be nice to visit Hetch Hetchy Valley in its pre-reservoir condition. But, the current Hetch Hetchy Valley with a pristine mountain lake, is also nice; and the lack of multitudes visitors makes the present-day Hetch Hetchy Valley in some ways, much better to visit than the nearby impressive Yosemite Valley with its millions of visitors. True, there are drought years when the lake is drawn down, and then the "bathtub ring" is obvious; perhaps once every couple of decades or so. But, the dam provides important flood control, and without it, downstream people will be much more prone to devastation and loss from inevitable future floods.

Overall, the benefits of the present day Hetch Hetchy Reservoir are important. It took 45 years of dreaming, the disaster of the 1906 earthquake, politicking and raising money from 1868 to 1913, to get Congress to vote and the President to sign into law the Riker Act of 1913.

There are those who may argue that what was actually built and operated over the past century is not exactly word-by-word what is in the Riker Act. Perhaps they might argue in Federal Court that the Riker Act should be overturned, and that the SFPUC, MID and TID, and the millions of people who benefit, should lose this facility. The 7th Amendment of the U.S Constitution provides that citizens have the right for a jury trial in Federal court for cases that exceed a certain dollar amount ($20 in 1791). Let a jury be chosen. Let the people speak.

9.6 Calaveras Dam

The lands around the future Calaveras Dam were purchased by SVWC in the 19th century, for about $1 million. The intent was that a reservoir would eventually be constructed on Calaveras Creek, for purpose of capturing the flood water of Calaveras Creek and Arroyo Hondo, and this would be part of the future water supply for San Francisco.

Figure 9-1 shows one of the earliest drawings showing a then-planned Calaveras Reservoir (dated 1876). This shows the reservoir at location "D", and with an outlet tunnel heading southwest, and thence to Crystal Springs Reservoir. The anticipated capacity of the Calaveras Reservoir would be about 31 billion gallons, with water level 745 feet. The size of the watershed would be about 140 square miles, with an average rainfall of about 28 inches. This could yield, on the order of 100,000 acre feet per year (about 32 billion gallons per year).

It was not until 1913 that construction began on this reservoir. By this time, Schussler had retired (1909), and between 1909 and his death in 1919, he provided various testimony to Congress about SVWC and the proposed future Hetch Hetchy system.

With regards to the construction of Calaveras reservoir, the historic record suggest that SVWC hired William Mulholland (of LADWP) to be its chief consulting engineer. O'Shaughnessy, by that time appointed to be Chief Engineer for the Hetch Hetchy aqueduct, apparently had reservations about this reservoir. He wrote to the San Francisco Board of Supervisors in 1913:

> "*I have read with a great deal of interest your thoughts and views on the present Calaveras Dam project now being constructed by the Spring Valley Water Company under the jurisdiction of Mr. William Mulholland of Los Angeles. For unknown reasons the Company [SVWC] has prosecuted a policy of great secretiveness with regard to this project and only took me into their confidence about six weeks ago to the extent of inviting me to see the progress…I think Mr. Eastman, the Vice President [of SVWC], is amenable to suggestion and desirous of doing things right, but I am afraid Mulholland and Hermann [successor to Schussler] are so intensely conceited that they imagine all they might do should be immune from criticism. As the City has no official knowledge of the progress of this work, its official[s] can assume no responsibility for the outcome of that undertaking. The project is of such great importance, however, that its successful completion and operation is of vital interest to the survival of this community for the next seven or eight years, or until the Hetch Hetchy project is completed that I took it upon myself to criticize severely the sloppy way in which this outlet work is being undertaken. …There is great hesitation on the part of our Engineering Profession to hurt the feelings of our brother members by adverse criticisms on their methods, but I did not refrain in this instance from almost overstepping the limits of politeness by emphasizing my objections to the reckless manner in which the construction of this outlet culvert was contemplated. …Both Mulholland and Lippincott have made a sad mess of much of their construction work on the Los Angeles Aqueduct and I warned Eastman that the reputation of the Company would be damaged except that same high standard of construction were followed in the present works as the previous high standards followed by Mr. Schussler. The latter's nose, by the way, is out of joint and will have nothing to do with and will not even look at the proposed structure in Calaveras Valley, as his plans and advice were ignored in the project.…Considering the extent of values of life or property over $10,000,000 between this dam site and San Francisco Bay, it would seem to have been prudent to have put another million dollars into this structure and allay public fears as to any catastrophe which might follow from disaster following a failure. The action of the San Andreas Dam under earthquake conditions, which straddled a fault line, impresses me strongly with the merits of this type of dam in an earthquake country…. Unofficially I am going to keep a watchful eye on this proposition so that the City will not inherit a 'gold brick' if it should take this property over.*"

As an afternote: the initial earthen Calaveras Dam collapsed before it was completed, in 1918; at the time, the dam was still being raised. The failure was that the upstream (wetted surface) of a portion of the dam slipped into the reservoir.

The second Calaveras Dam was earth and rock, and was opened in 1925. It straddled the Calaveras fault. Due to seismic safety concerns, the reservoir was lowered to about 1/3 of capacity in 2011.

The third Calaveras Dam was built in 2019 at a cost of about $810 million. This dam is about 1,000 feet downstream of the 1925-vintage dam. After it was completed, the 1925-era dam was removed.

10.0 Conclusions

This report examines why the water transmission system broke in the 1906 earthquake, considering modern engineering science. The damage was due to strong ground shaking, liquefaction and fault offset hazards; coupled with pipes and support trestles that were not designed for earthquake loads.

10.1 Summary of San Andreas Fault Slip Parameters in the Vicinity of the San Andreas Dam in 1906

Section 4.1 of this report summarizes how 21 sites along a twelve-mile-long stretch of the San Andreas fault, centered on the location of San Andreas Dam, responded to several feet of right lateral tectonic slip in 1906. Most of the data came from eye witness accounts by engineers and earth scientists who documented the impact of both the severe ground motions and ground fault displacements this great earthquake had on San Francisco's water supply, then as now, a critical lifeline. Included in these summaries are insights from the authors' combined decades of professional practice into the nature, cultural impacts, and strategies for mitigating the hazards posed by California's active seismic environment. We have focused almost exclusively on critical water supply facilities that, like the Pilarcitos pipeline, were crossed by the San Andreas fault. Only Site 1 was not directly impacted by on-site surface faulting, but its pipeline was destroyed by severe ground shaking.

The results documented in Section 4.1 are complex because the upward propagation of tectonic strain through very heterogeneous earth materials like the Franciscan Assemblage "bedrock" is exceedingly complex and mostly buried out of sight, making it for that reason largely unknowable. Additionally, the interaction between this tectonic strain and engineered structures like pipes and dams was not always fully documented or carefully measured after the quake. Restoring the water system after the quake had to be the immediate and highest priority of post-quake investigators.

The complexities of the surface expression of the San Andreas fault are well characterized by Stanford student Robert Anderson as reported in Lawson (1908, p. 93): "*...the trace of the fault* is *marked by a belt of upturned earth resembling a giant mole-track. The rupture may be traced along every foot of the way when not below the waters of the lakes* (San Andreas and Crystal Springs reservoirs). *It varies in width from 2 or 3 feet to 10 feet, but at times branches into several furrows that include a space of 100 feet or more in width. Such branches sometimes join again after a short interval. Sometimes it forms a crack 2 or 3 feet wide and several feet deep, and in other places shows a vertical wall of soil on one side or the other, several feet high. The typical appearance in turf-covered fields is a long, straight, raised line of blocks of sod broken loose and partially overturned."*

Detailed topographic maps that could be used as a base to record the exact location and surface expression of the active fault, as well as the location of the pipeline and other infrastructure, did not exist at this time. We have based the location of the Pilarcitos pipeline using a combination of surveys done in 1875 and 1901, coupled with observations after the 1906 earthquake. These are not always consistent. As a result, there are reaches of the Pilarcitos pipeline, which was removed after the earthquake, where we have not been able to determine accurately its original location in 1906.

We have relied on historical eye-witness reports, sketch maps, photographs, and professional surveys to piece together critical characteristics of the San Andreas fault traces active in 1906. To this data we have added insights from modern air photo interpretation, detailed field mapping, subsurface exploration in backhoe trenches, and modern surveying in developing a composite picture of this local part of fault and the probable hazards it poses to Bay Area Californians for the future. We have compiled the fault's local slip behavior in 1906 to guide future seismic hazard mitigation efforts. It is always in our minds:

- "It" happened in 1906
- "It" will happen again

Here are the important fault slip parameters we have pieced together from the performance recorded by post-quake investigators from four different types of strain gauges in 1906. These displacements reflect combined primary and secondary offsets, as would be suitable for designing a pipe that crossed this fault zone.

- Earthen Embankments: Sites 11, 19, 21; **average right slip = 7+ feet.**
- Brick Tunnels: Sites 10, 12, 20; **average right slip = 8.9 feet**; maximum observed slip = 9.57 feet; average width of crushed zone: = 20 to 40 feet.
- Pipelines: Sites 2, 3 (no data), 6, 7 (data incomplete), 8, 14, 17, 18; **average right slip = 9 feet**, maximum observed slip = 11.6 feet.
- Fences: Sites 4, 9, 13, 14, 16, 21; **average right slip = 9.7 feet**; maximum observed slip = 12 feet.

Number of active traces identified **in bold** at each site, their spacing and total slip:

- Site “1” no faulting present.
- Site “2” ***1***, total right slip = 8 feet.
- Site “3” no faulting measured.
- Site “4” ***3***, total estimated width = >80 feet; total right slip = 8 to 9 feet.

- Site "5" no data recorded; total right slip unknown.
- Site "6" ***2*** @ ~50 feet; total right slip = 7.9 feet.
- Site "7" ***1?*** limited data; minimum right slip = 6.3 feet
- Site "8" ***2***; total right slip 7.9 feet.
- Site "9" ***2*** @ 160 feet; total right slip = 9.5 feet.
- Site "10" ***1***; total right slip = 8.3 feet.
- Site "11" ***?*** multiple cracks on dam crest over zone ~ 50+ feet wide; total right slip = 7 feet.
- Site "12" ***1***; total right slip = 9.57 feet. ? possible secondary slip of a few inches east of the main trace.
- Site "13" ***1***; total right slip = 10.4 feet.
- Site "14" ***2***; @ 100 feet; total right slip = 8.3 feet.
- Site "15" ***2***; @ 50 feet; total right slip = 12 feet.
- Site "16" ***1***; 30 feet of concentrated shear, 40 feet of ground warping; total right slip = 9 feet.
- Site "17" ***?***; 4 pipeline breaks over 128 feet, total right slip = 11.6 feet.
- Site "18" ***1***; total right slip = 9 feet.
- Site "19" ***1***; total right slip = 7+ feet.
- Sites "20" and "21" ***1***; total right slip = 8.8 feet.
- Site "21" ***1***, total right slip = 8 to 9 feet.

Table 10-1 summarizes this information, with cross reference to Schussler, Derleth and Lawsons reports of 1906, 1907 and 1908, respectively.

Table 10-1. SUMMARY 0F FAULT CROSSINGS (FX),
FENCES ("F") AND WATER SUPPLY FACILITIES
NEAR SAN ANDREAS DAM

	Feature /Location	Mi to Dam	1906 Fault Slip (feet)	Notes	Schussler	Derleth	Lawson
	FX = fault crossing	approx	max. measured right slip (rs)	PP = Pilarcitos Pipeline	1906	1907	1908
	N = north; S = south				Map 13		"Fences"
1	PP @ Large Frawley Cyn.	5.7 NW	0.25 mi E if fault, PP trestle collapsed	100' of 30" PP pipe thrown down to ground	B	Fig. 35	
2	PP @ Small F. Cyn. FX-1	5.3 NW	8' right slip; PP telesc 7' 3", offset 15"	PP/fault @ 20°, bridge collapsed, PP exposed	C	Fig. 39	
3	PP located 660' south of FX-1S	5.1 NW	right slip unknown; PP buckled, collapsed	partial vaccum was possible cause	D	P. 169	
4	Fence "1"	5.0 NW	8-9' rt. slip, 3 traces: estim. W to E: 6', 2', <1'	est. zone 80' wide; See Prentice, (2006), Fig. 13	-		"Fig. 29"
5	FX-2	4.2 NW	No data or photographs	PP W of and parallel to fault	betw. D-E		
6	FX-3N, 100' N of San Bruno Ck. xing	3.95 NW	7.9' rs; 2 breaks over 50'; S telesc. 21", N 41"	PP/fault xing @ 30°-45°; fault visible to NW	E	Figs. 37, 38	V II p. 36
7	FX-3	3.92 NW	(6.3) min. rs; PP telesc. 58" on bridge	PP strike unknown	F	Fig. 36	
8	PP@ FX-4N	3.15 NW	7.9' rs, PP 2 breaks approx. 450' apart	PP sep. 21.5", 59"; approx. parallel to fault	Photo #3		p. 97
9	Fence "2" = L's Fence "C"; = FX-4	2.9 NW	9.5' rs, 2 traces: E ~7', W ~2.5'; sep. 160'	PP & fence cross main trace; fence @ ~80°	G	Figs. 6, 34	"Fig. 31"
10	SA Lake drain tunnel & forebays	0.6 NW	8.3' right slip offset in Bald Hill brick tunnel	See Pampeyan (1983, Fig. 1) for details	I		Fig. 35
11	SA Dam road across crest	0	7'+ right slip across crest of embankment	Locks Creek Flume pulled apart 4' at crest	J	P. 163-64	Fig. 36
12	SA Dam waste weir tunnel	0.07 SE	9.57' right slip offset in brick tunnel	See Pampeyan (1983, Fig. 2) for details	K	P. 164-65	Fig. 36
13	Fence "3" = L's Fence "B"	0.33 SE	10.4' rt. slip = 8-9' + ~ 1-2' of drag	no photos; see Pampeyan (1983) for details	L		"Fig. 37"
14	FX-5	0.57 SE	8.3' rt. slip, 24" PP telesc. 34" @2 65° flt/xings	PP @ S xing, pipe also offset by 20" right slip	M, M'		
15	Fence "4" = L's Fence "A"	0.67 SE	12' rt. slip, 2 traces: E 9.9' (incl. 1' warp), W 2'	traces 50' apart; fault loc. stable 3,000+ years	N		"Fig. 38"
16	Fence "5"	1.43 SE	9' rt. slip, incl. 30'-wide zone of conc. shear	fence prob. extant. See Hall (1984, p.286).	N'		"Pl. 61B"
17	FX-6	1.55 SE	11.6' rt slip, Locks Ck 44"; pipe/flt xing @ 65°	telesc. 59" over 120'+; joins PP ~1 mi to NW	O		Fig. 39
18	Old Locks Pipeline (removed)	3.40 SE	9' rt. slip of 37" pipeline; pipe/flt xing @ ~72°	See Pampeyan (1983, Figs. 3, 5) for details	P?		
19	Hayward Dam (submerged)	3.84 SE	7'+ rt. slip on pre-1877 embankment	See Pampeyan (1983, Fig. 6) for details	-		
20	Upper Crystal Springs Dam (UCD)	5.8 SE	8.8' right slip on brick outlet tunnel	See Pampeyan (1933, Fig. 7) for details	Q		
21	UCD embank., road, Fences "6"	5.85 SE	8'-9' rt. slip; now Hwy. 92 causeway on crest	See Derleth (1907), Pampeyan (1983) for details	R	P. 161, 62	Fig. 40

Table 3-3 does a statistical analysis of this data. There are several conclusions we can draw:

First, tectonic slip measured at the surface consists of two components, discrete faulting, which is readily visible, and ground warping, which is the aggregate result of small distributed displacements that may be recorded only by certain sensitive strain gauges such as surveyed lines and fences. The zone of concentrated strain recorded by the fences, i.e., the main trace and any subsidiary traces that may be present, are the major source of engineering concern. One or two subsidiary traces were observed in several places and varied in magnitude of right slip from < 2 feet to 3.4 feet. From a engineering design perspective, we suggest designing for two load cases: case 1, where the entire PGD is applied to the pipe as a single "knife edge" offset in a primary offset zone; case 2, where a portion of the PGD is assigned as a single "knife edge" offset, and the remainder PGD is assigned as smaller "knife edge" offsets in secondary offset zones. Table 3 provides data and some statistics based on what was observed in 1906.

Second, if we exclude what appear to be anomalously low displacements measured across earthen embankments, the pipes, fences, and tunnels within the study area, all recorded a remarkably consistent average right slip of **9 to 10 feet**. Because of the likelihood of some unrecognized, and thus unmeasured ground warping by the strain gauges available in 1906, the actual total amount of surficial slip along this segment of the plate boundary is possibly underrepresented. Modern seismic design guidelines for buried pipes across pipes, namely ALA (2005) and PRCI (2004), provide guidance as to have much margin should be considered for pipes of difference importance. The maximum PGD in the 17.5 km zone documented in this report was **12 feet**.

Considering all this, the six pipes that crossed the 1906 fault rupture could all have been reliable had they been designed and constructed in a manner to reliable sustain 12 feet of

PGD, without rupture of the pressure boundary. For a pipeline to be reliable, the entire length of pipe needs to be similarly designed.

But, what actually happened in 1906, was that none of the pipes could sustain 9 feet (or even 2 feet) of fault offset. Girth-joint riveted wrought iron pipe and cast iron pipe of the type used in 1906, simply cannot sustain much PGD.

Third, in addition to having a reliable estimate of the magnitude of future tectonic strain, it is also very important to have a realistic assessment of both the location and the width of the zone susceptible to tectonic shearing. The four sites considered in this study where there was clear evidence of multiple active traces, varied considerably in width from 50 feet to 160 feet. The width of the zone of tectonic deformation was estimated from observed post-quake condition of the various strain gauges that were impacted.

The influence of ground warping that seems to have occurred outside the secondary offset zones, is generally not a concern to well-made buried pipes. Most pipes can sustain very small differential displacements that might be imposed over long lengths (like 1 foot of smoothly applied offset over 1,000 feet of pipe length). But, placing pipes and other structures across zones where strain is concentrated can and did lead to catastrophic lifeline failures.

We have also been mindful during our assessment of fault zone widths of a cautionary caveat from Bonilla and others (1978, V. 6, No. 3, p. 350): "*Pipeline damage…is less reliable than fence damage as an indicator of the width of the zone of faulting, because rigid pipe can transmit stresses over long distances".* The same concern may also be considered for rigid masonry tunnels. The properties of strain gauges matter!

Fourth, and of great importance, is the location of the active traces of the San Andreas fault. The fault in this area has been mapped several times in the last half century, so its position is reasonably well constrained. See Pampeyan, 1975, 1983; Smith, 1981a, b, Hall, 1984. In 1972 California passed the Alquist-Priolo Earthquake Zoning Act that was designed to mitigate the fault rupture hazard posed by California's active faults by requiring studies that established their location, slip characteristics and potential for future activity. Our study area along San Francisco's Peninsula reservoirs has been conducted within a designated Special Studies Zone, and is an area that will not likely be developed for human occupation in the future. But several areas to the northwest of San Andreas Lake along the fault were developed before the Alquist-Priolo Act became law. Surface expression of the 1906 faulting in these older developments has been bulldozed away so the fault's location is now difficult to recognize. The next major slip event on this segment of the fault, which may only be a few decades away, will leave behind many deformed cultural strain gauges for engineers to measure that will clearly mark its location; but unfortunately property owners are surely to be impacted.

The data summarized above, although somewhat sparse, suggest a couple of tentative hypotheses. First, the tectonic strain or signal transmitted through earthen embankments appears to attenuate somewhat when compared to more brittle but rigid materials like masonry structures. Second, it looks on average as if the threshold amount of strain that might have to accumulate in the current seismic cycle across the main trace of the San Andreas fault prior to the next 1906 magnitude earthquake is about 10 feet for the Peninsula segment. If this is the case ***and*** if the annual slip rate assessment of 17 +/- 4 mm/year from the trenching investigation at the nearby Filoli Estate is reasonable (Hall, Wright and Clahan, 1999), then it might take only about another +/- 60 years of waiting. (This assumes, of course, that tectonic interactions among the multiple interacting faults that form the San Andreas Fault System, which stretches from the San Francisco shoreline to the east side of the Sierra Nevada at Reno, generate earthquakes with the regularity of Newtonian clockwork.) Then we will know, once again, where the active San Andreas trace lies buried beneath the highly developed suburban areas that stretch from the northern end of San Andreas Reservoir to Mussel Rock on the Pacific coast in Daly City. This post-1906 development will provide "fault finders" with hundreds of man-made strain gauges (roads, curbs, sidewalks, fences, walls, buried utilities, etc.) that will record where the fault traces are located and just how much slip they experienced.

Lest the reader forget: The San Andreas fault along the Peninsula does pose a significant threat to the built environment. In 1906, 6 pipes crossed the fault offset zone; all failed. Today, there remain a handful of water pipes as well as some other infrastructure (roads, power lines, gas pipes, etc.) that cross the San Andreas fault.

But, across the Bay, the Hayward fault poses a potentially much greater threat. It is estimated that there are presently over 1,000 buried water, sewer, gas pipes and power and communication cables that cross the Hayward fault. While the magnitude of future events on the Hayward fault (about M 6.8 to 7.0±) is smaller than for the San Andreas fault (about M 7.7 to 8.0±), the quantity of buried infrastructure crossing the Hayward fault is perhaps 100 times larger.

10.2 Summary of SVWC Water System Performance

Pipes at Fault Crossings. There were 7 locations where pipes crossed the primary offset zone of the San Andreas fault: 5 along the Pilarcitos conduit and 2 on the Locks Creek raw water collection system. Section 4 of this report describe these crossings in more detail.

- FX-1, FX-2, FX-3, FX-4. The buried 30-inch WI-thin Pilarcitos pipe (t = 0.104-inch) was exposed to primary fault offset at 4 different locations (about 7 to 10 feet PGD at each location, FX-1, FX-2, FX-3 and FX-4 in Figure 3-12), and many pipe segments broke at these locations, no matter if the offset placed the pipe in net tension or compression; always, the weak girth riveted joint broke; there was no evidence of pipe wrinkling as a failure mode.

- FX-5. The 24-inch CI Pilarcitos pipe was exposed to primary fault offset (about 10 feet PGD) (FX-5 in Figure 3-12), and 4 segments of CI pipe were broken at this location.

- FX-6. The 44-inch WI Locks Creek pipe failed with several broken segments where it crossed the San Andreas fault (FX-6 in Figure 3-12).

- FX-7. The 37.5-inch WI Locks Creek pipe failed with several broken segments where it crossed the San Andreas fault (Site 18 in Figure 3-12).

There were also 3 locations where the Pilarcitos (30-inch) and San Andreas (44-inch) pipelines crossed the Serra fault zone. At present time, there is insufficient evidence to show that there was any sympathetic offset of the Serra fault at these locations in the 1906 earthquake. The lack of pipe breaks where these pipes crossed the modern-mapped surface traces of the Serra fault suggest that if there was sympathetic offset at any of those locations, it would have been well under 1 inch, or small enough to preclude damaging those pipes.

SVWC and its successor SFPUC learned something about earthquakes in 1906! In 1923, the first segment of the Hetch Hetchy aqueduct in the San Francisco Bay Area was constructed, and the design included slip joints placed either side of the Hayward fault. In 1996, the Authors had a trench dug parallel to this 60-inch diameter riveted steel pipe, and found that the 1923 drawings, while well-intentioned, had mis-located the Hayward fault. In 1996, the riveted buried pipe was excavated, and found to have sustained the 73 years of fault creep (about 1 foot of right lateral offset) without a leak. Today (2023), this 1923 vintage pipe has been replaced with a butt welded steel pipe (D/t = 80), designed to accommodate several feet of right lateral offset.

Pipeline Design Prior to 1906. There are eyewitness accounts of the damage to the transmission pipes in two reports: by Schussler (1906) and by Lawson (1908). In the late 1970s, the California Division of Safety of Dams required the present water system operator, the San Francisco Public Utilities Commission, to investigate the stability of San Andreas Dam and evaluate its potential for failure during the next slip of the Peninsula segment of the San Andreas fault. The subsequent investigation included field mapping, air photo analysis, drilling and sampling, trenching, radiocarbon dating. The data in these two eyewitness reports, supplemented by the investigations of the 1980s through the present time, yield the following observations.

The 1906 zone of faulting was narrow and lay along the east boundary of the San Andreas Valley in the areas adjacent to the San Andreas and Upper Crystal Springs reservoirs. It is the only major active trace identified in this segment of the valley. This zone is denoted by the red line in Figure 3-11.

Geomorphic evidence in the form of right-laterally deflected (offset) stream channel segments, two of which are 180 and 260 feet long respectively where they cross the fault, are found in the area downstream of the San Andreas Dam along the east side the fault valley (Hall, 1984). The intervals over which it took these offsets to accumulate have been estimated using an annual rate of slip determined by radiocarbon dating of offset stream channel deposits located about 8 miles to the southeast of San Andreas Dam in the fault valley on the Filoli Estate in Woodside (Hall, Wright, and Clahan, 1999). Here the slip rate across the fault's principal active trace was determined to be 17 +/- 4 mm/yr. Using the median value to get an idea of the time it must have taken to accumulate these stream channel offsets, we get estimates of 3,227 and 4,662 years respectively. While these number are only approximations, they show that the fault location has been very stable for at least the past few thousand years and is therefore very unlikely to shift its position during the next slip event.

The San Andreas Dam earthen embankment incorporates a natural ridge of clayey earth materials, ancient Franciscan mélange "bedrock" that is not prone leakage. It was within this ridge that the 1906 fault slip was confined. The longevity of the deflected channels means that the faulting is very unlikely to shift location during the next slip event and thereby possibly penetrate and compromise the engineered dam embankment with its clay core. In other words, the dam survived the extremely severe 1906 test and performed well! As long as the fault's location remains stable, which it demonstrably has been for thousands of years, the dam should remain stable and not fail from fault slip events in the near future, assuming there has been no other age-related or other type of degradation of the dam.

When Schussler designed and built San Andreas Dam and all the pipelines shown in Figure 3-12, he was probably unaware of the presence and location San Andreas fault, which was not officially recognized until 1895. When re-built in 1868, the Pilarcitos pipeline was aligned to cross the primary trace of the fault five times; a modern designer would not zig-zag an important pipe over the fault multiple times. The outlet works of the San Andreas Reservoir are bisected by the fault; not a good design. The term "liquefaction" had not yet been invented, although Schussler was aware of ongoing settlement and pipeline failures at Mission Creek, because he laid pipe through these zones on buried wooden planks; and in 1893, he proposed to bypass that area entirely with a new 16-20 MG Market Street reservoir and pipeline system. Design for inertial forces from earthquakes was not done. There were no codes or guidelines for seismic design for buildings, and certainly no guidance for the seismic design of pipelines. The prevailing practice from 1860s to 1906 was to design above ground structures for a lateral wind pressure of 30 psf, and this was then considered to be adequate to address the impacts of earthquakes (not!).

Today (2024), the practice of earthquake engineering is far more advanced. Today, one would design the equivalent of the Pilarcitos pipeline to cross the San Andreas fault only once. At that location, a buried design could have D = 30-inch, t = 0.5-inch, ductile steel with Fy ~ 50 ksi and Fu = 80 ksi, and girth and longitudinal joints to be entirely butt welded with full strength of the pipe; such a design could accommodate one time offset of up to 10 feet, and keep strains within acceptable limits (ALA 2005). Alternatively, an above ground pipe could be placed across the fault, on a series of sliding supports, easily able to accommodate a one time offset of up to 20 feet.

To design successful buried fault crossings, the modern engineer must have an accurate picture of the fault's characteristics: its location and geologic/geotechnical setting, plus the likely amount, geometry and width of the displacement zone (i.e., the concentration of strain) and expected characteristic of the ground motions of the associated earthquake.

It is now widely accepted by the earth science community that, because of a documented rupture length of about 300 miles, the 1906 earthquake is probably the maximum credible event (M_w of 7.8 to 7.9) for the Peninsula segment of the San Andreas fault. The geomorphic study of displaced stream channels mentioned above also strongly indicates that in the area of San Francisco Peninsula's reservoirs, the location of the San Andreas fault is not expected to change significantly in the near future.

In 1870, the technology for pipelines was relatively primitive as compared to what it is today in 2023. Cast iron pipe was available, manufactured either in England or the eastern USA:

- Cast iron water pipe was considered the best available for underground water service, commonly for moderate pressures (on the order of 125 psi). The tensile strength of cast iron was commonly on the order of 15,000 to 18,000 psi. Common lay lengths for pipe segments was 12 feet. All cast iron pipe segments were to be hydrostatic tested to 300 psi.

- Wrought iron was available in sheets of various thicknesses. The tensile strength of wrought iron was on the order of 50,000 psi. It could be readily forged into shapes. Wrought iron is tough, malleable, ductile, corrosion resistant. The demand for wrought iron peaked in the 1860s. The sheets of steel could be rolled into pipe shapes, and then the longitudinal seams closed with a double line of rivets. The 2-line riveted connection, though, was still computed to only be about 70% as strong as the underlying base material. Therefore, when establishing the required wall thickness for a pipe, the common hoop stress formula used today (sigma = pr/t) was still used, but the allowable sigma was usually set at the tensile strength of the wrought iron divided by 2, 3, 4 or sometimes even 5, in other words, somewhere between 0.2Fy and 0.5Fu. As described above, the upper reaches of the Pilarcitos 30" wrought iron pipe appears to have been designed for a hoop stress on the order of 10 to 12 ksi, suggesting a factor of safety on yield on the order of 2 to 3. (In contrast, the common allowable hoop stress using modern steel pipes designed by AWWA M11 is 0.5 Fy). Under hydrostatic stress near bends in the pipe, the longitudinal stress is computed as (sigma = pr/2t), or exactly half the hoop stress. Therefore, only a single line of rivets was used to make girth joints.

- The strength of the girth joints in the wrought iron pipe (single line of rivets) was likely computed based on single shear strength of rivets. In the earthquake, at fault crossing locations, the actual failure mode was a combination of edge tearing (when the pipe was placed in nearly pure tension) of bending of the rivets (when the pipe was placed in bending or compression). In tension, the pipe was not ductile, as the girth joint was weaker than the main body of the pipe. In compression (or compression plus bending), the pipe was not ductile, as the eccentricity of the lap joint imposed both shear and bending on the rivets, with the result that the pipe edge quickly folded in on itself coupled with broken rivets.

- Pipeline designers of that era did recognize that iron in water pipes was susceptible to corrosion. For that reason, the wrought iron pipes were commonly dipped in coal tar.

- Pipeline designers of that era were well aware of hydraulic flow computations, The common closed form solutions (D'Arcy's law, etc.) presume some level of friction between the moving water and the inside of the pipe. As the larger pipes were all riveted, and the rivet heads protruding about ¾" into the pipe, the not uncommon assumption of that era was to assume a smooth pipe, but with inside diameter being 1.5" less than the actual nominal inside diameter, allowing for the rivets. This is now understood to be perhaps too conservative an assumption, but pipeline designers like to be conservative, and achieve somewhat higher water flows than presumed in design.

Hydraulic evaluations of the conduit reveal the following:

- If flow is taken from the Pilarcitos Reservoir outlet to Lake Honda, or supplemented by the Pilarcitos pump stations, by gravity flow only, the flow limit was about 11 MGD into Lake Honda.

- If flow is taken from both the Pilarcitos Reservoir outlet and the Pilarcitos pump station and the Lake Merced pump station, with source waters from Pilarcitos and San Andreas reservoirs and Lake Merced, flow was limited to 17 MGD into Lake Honda, controlled by the flume south of Tunnel 3. Note: After the 1906 earthquake, this flume was expanded in size.

- At a flow rate into Lake Honda of 14 MGD, the velocity of water in the 30" pipe is 4.4 feet per second. This appears to be a balanced design.

After the 1906 earthquake, the southern portion of the Pilarcitos was permanently removed from service. To fill Lake Honda via the northern portion of the Pilarcitos pipeline, a new pump station was constructed by 1914, called the Central Pump Station. This pump station is located on Sloat Boulevard. Along with the new pump station, taking suction from the San Andreas (and relocated undamaged portions of the Pilarcitos pipeline, renamed the Baden-Merced pipeline), a new force main was built to deliver water from the Central pump station into the northern Pilarcitos pipeline and hence to Lake Honda. With the removal of the southern section of the Pilarcitos pipeline, this new Central Pump station provided high flow capability to put water into Lake Honda, rather than relying on Lake Merced water (marginal water quality) or the older undersized Ocean View pump station.

1906 Earthquake Performance

Section 4 of the report documents damage to the pipelines. We use the available photographic record to describe the damage. The damage locations along the Pilarcitos pipeline are listed from north to south (in the opposite direction of water flow). Many of the images were taken by the SVWC (Schussler, 1906), and we retained Herman Schussler's photo numbering system from that report as thus: HS-5). In a few locations, we obtained additional photos from other sources.

Pilarcitos Pipe

There were at least 31 locations where the Pilarcitos pipe was damaged. The pipe zigzagged over the San Andreas surface fault rupture 5 times. In San Francisco County, where the Pilarcitos pipe was commonly 5 km or further from the rupture, there was no damage. By 9 pm on April 18 (16 hours after the earthquake), SVWC isolated the damaged Pilarcitos pipe south of Colma, turned on the pumps at Lake Merced, and pumped at a rate of 6 to 7 MGD from Lake Merced, through the undamaged Pilarcitos pipeline, to Lake Honda. This water, plus the 31 MG in Lake Honda at the time of the earthquake, kept the Lake Honda pressure zone (the Western Addition) in service throughout the three days of the fire.

The Pilarcitos pipeline alignment crossed over the San Andreas fault at 5 locations, and was supported by wooden trestle over nearly a dozen canyons or creeks. In 1868, when this pipe was originally built, there were no seismic design standards, and the presence of the San Andreas fault was unknown. There is no evidence in the historical record that Mr. Schussler knew of the San Andreas fault in 1868.

The prevailing attitude of the 19th and early 20th centuries was that if one designed an above ground structure for a wind load of 30 psf, that would be sufficient for any earthquake loads. Well, a hundred years later, we now know that to be wishful thinking. In fact, it is evident that the pipe was especially vulnerable to both fault offset as well as inertial overloads. In the 1906 earthquake, the upper reaches of the pipe were known to have failed at multiple locations due to fault offset and trestle failures. This explains only some of the failures, and the remainder may have been caused by a combination of high ground shaking, concurrent with earthquake-induced hydrodynamic pressure pulses; all along the stretch of thin-walled low pressure pipe. There were no pipe failures along the northern reach of the pipe, where the pipe was designed as a higher pressure pipe; although this area had somewhat lower ground shaking levels.

At least 20 ruptures along the wrought iron Pilarcitos pipe occurred at the riveted girth joints. No pipe wrinkling is known to have occurred. At one location, the pipe failed when the wood bridge it was resting on collapsed. At another location, the cross section of the pipe buckled, possibly due to the formation of a vacuum. Corrosion may have had a role in some of these failures.

San Andreas Pipe

The San Andreas pipe suffered only one failure: where a restrained slip joint failed atop a wood trestle over Colma Creek near Baden. ALA (2005) describes that slip joints located after long reaches of continuous pipes can try to open / close several inches under strong ground shaking. The cable restrainer system used by Schussler was not nearly enough to restrain the pipe as the earthquake tried to open the slip joint, and the restraints ripped open the pipe.

Crystal Springs Pipe

The Crystal Springs pipe suffered multiple failures. It broke at about 7 locations between the Crystal Springs Dam and Millbrae; these were quickly repaired. But, at 3 reaches of pile-supported trestles through three liquefaction zones, the pipe rolled sideways off the wood trestles, landing on the ground. The seismic lateral load resisting system along these trestles was entirely inadequate. It took 28 days to repair this trestle and reset the pipe atop the trestle.

Alameda Pipe

The Alameda pipe suffered a few minor failures. These were quickly repaired. This pipe was also supported on wooden trestles where it crossed the Bay-side marshes near Dumbarton Strait. Unlike the Crystal Springs pipe, here the Alameda pipe was supported on wooden cradles, that allowed slippage under thermal growth (or seismic) loads; such slippage would have generated a fair amount of friction / damping. The pipe was not injured on these trestles.

Flumes

A few sections of wooden flumes collapsed. All collapses were at locations subjected to high inertial loading (PGA > 0.4g), and in some places due to landslides. At one location, possible secondary fault offset triggered a collapse of 80 feet of flume. There was no damage to flumes subjected to low shaking (PGA < 0.10g). More than 90% (by length) of flumes in areas with high shaking survived the earthquake without collapse, although some minor leakage (easily repaired) did occur.

Tunnels

All brick-lined tunnels survived the earthquake shaking without collapse. Two tunnels suffered heavy damage where they were exposed to fault offset.

Dams

All of SVWC's dams in the San Francisco Peninsula survived the earthquake without serious damage; no reservoir leaked.

Pump Stations

All pump stations survived the earthquake without serious structural damage; one pump (out of 5) was damaged at one pump station.

Terminal Reservoirs and Tanks

One reservoir (Lake Honda) suffered some damage to masonry walls; this damage was repairable and did not require taking the reservoir out of service immediately after the earthquake.

The remaining open-air reservoirs (University Mound, College, Lombard, Francisco) are not known to have suffered any material damage; although no doubt they would have sloshed some water over their embankments.

No tank (Clarendon, Clay, Potrero, Presidio) is known to have had major damage.

Distribution Pipes

Nearly 300 distribution pipes (mostly 4" to 27" diameter, and mostly cast iron) were broken. At least 70% of these breaks were in liquefaction zones.

As many as 18,200 service laterals (mostly ≤ 1" diameter) were broken. These were mostly caused by burned or collapsed buildings.

10.3 Fire and Conflagration

As many as 52 fire ignitions occurred after the earthquake. In the lower two pressure zones, the lack of water (due to broken distribution pipes) was the primary reason that the initial fires spread. About 80% of the City burned.

10.4 Aftermath

Given the large fire, the City elected to build two new water systems and buy a third:

- AWSS. This is a parallel set of water pipes, on about 10% of city streets, capable of providing high fire flows. The source water is either sweet water from 3 gravity-fed reservoirs / tanks, or salt water from two pumping stations along the Bay. The initial system was built by 1912 at a cost of about $6,000,000 ($1909). Its brittle pipes run through liquefaction zones, and several broke in the 1989 Loma Prieta earthquake.

- Hetch Hetchy. This is an aqueduct and reservoir system that brings water from the high Sierra to San Francisco. In 1913, Congress approved use of Hetch Hetchy Valley in Yosemite National Park as a reservoir site. Construction began in 1916, and initial water was delivered to Crystal Springs reservoir in 1934, at a cost of $105 million.

- In 1930, the City purchased the Spring Valley Water Company properties and assets that delivered water to San Francisco, at a cost of about $40 million. This ended some 7 decades of bitterness and lawsuits between SVWC and the City. This municipal water system is now operated by the San Francisco Water Department.

Today (2024), the Hetch Hetchy system has been seismically upgraded, including reliability upgrades, at a cost of $4.6 billion. One goal of these upgrades is to reliably deliver water within 24 hours to wholesale customers (San Francisco and other cities), after major earthquakes on the San Andreas, Hayward or Calaveras faults.

Today (2024), the AWSS and the municipal water system still have significant seismic weaknesses. It is these two local distribution systems that are at the front line for providing water to fight fires after future earthquakes in San Francisco.

10.5 After Thoughts

Locating the Pilarcitos pipeline across the San Andreas fault in several places on its way to bringing fresh water to San Francisco turned out to be a very bad idea in 1906. This raises the question: should Schussler be held responsible for the many pipe failures that were triggered by the earthquake; the pipe and tunnel ruptures caused by tectonic shearing at multiple fault crossings; the collapse of wooden bridges and trestles at creek crossings, and the impact on thin-walled pipelines from subsidence of marsh lands and nonengineered fills near the City in response to severe ground shaking? Did Schussler give enough consideration to mitigating seismic hazards in his design and construction practices while Chief Engineer at the Spring Valley Water Company? The answers that emerge from our assessment of the impact of the 1906 earthquake on their storage, transmission, and distribution facilities are many faceted and largely speculative.

We assume that Schussler, when he arrived in this country from Europe in 1864, had little experience with earthquakes. His first experience probably was, until 1906, what was known as the “great San Francisco earthquake”. On October 21, 1868, this M 7.0 event ruptured the southern segment of the Hayward fault from Berkeley to Fremont with estimated maximum right-lateral strike-slip of about 6 feet. According to the Berkeley Seismology Lab, communities located along the fault and in San Jose and San Francisco suffered heavy damage. Appendix A shows a few photos of damage that occurred San Francisco. Engineering lessons learned and widely discussed from this quake, such as the hazards of building on "made ground" reclaimed from San Francisco Bay, were apparently forgotten by 1906.

We are certain Schussler must have been aware of the engineering consequences of strong ground shaking from the 1868 quake when he designed and built the Lower

Crystal Springs dam. Derleth (1907, p. 163) wrote: "*The engineer of this dam, Mr. Hermann Schussler, states that he made the batter of the inner face one in four because of earthquake possibilities, he having experienced the earthquake of 1868"*. We wonder now, considering the disastrous failure of the Pilarcitos pipeline, did Schussler fail to consider the additional hazardous consequences of active surface faulting observed in 1868 from this nearby Hayward(s) fault in the design and construction of the Spring Valley Water Company facilities he had supervised?

Schussler must also have been aware of another devastating earthquake, the Owens Valley (aka Lone Pine) earthquake of March 26, 1872 of estimated magnitude of M_w 7.4-7.9. This oblique-slip seismic event resulted from vertical movement of 15 to 20 feet and right-lateral slip of 35 to 40 feet along the east boundary of the Sierra Nevada. Schussler was working along this **same** Sierran structural boundary in the Lake Tahoe area from 1871 to 1873 to bring freshwater from Marlette Lake near Lake Tahoe to Virginia City and the mines of the Comstock lode. He designed and built a high pressure pipeline (syphon of 1,870 feet) that carried fresh water 7 miles from the east slope of the Carson Range eastward into the Virginia Range. When this major structural boundary slips here in the not-too-distant future, which it will, the Marlette Lake water system will go out of service for quite a while. We found no evidence in the records that he considered the fault slip hazard either here along the Sierran front or along the San Andreas fault whose existence first became public in 1895 (Lawson, 1895).

Another professional to be considered in this discussion of seismic hazard awareness for the San Francisco water supply system must include Berkeley Geology Professor Andrew Lawson, editor of the 1908 Lawson Report. He joined the faculty at Cal in 1890 and made a monumental contribution to the understanding of the very complex geologic evolution of California's Bay Area geology five years later. He recognized and named the San Andreas fault as a geologically young feature (Lawson, 1895). At the time, he did not recognize its great length in California nor was he able to show it on a map because suitable topographic base maps were not available at the time. He did, however, publish the first regional geologic map of the Peninsula on a shaded relief topographic map on which the linearity of San Andreas Lake and the fault running through its valley are obvious (especially to a geologist). He used this shaded relief map as the base for showing the location of the fault in the Bay Area in the Lawson Report (1908, Pl. 15). This, we believe, is the first official published map of this major crustal feature that unmasked itself in 1906.

We also suspect that before 1906, Schussler may not have been aware of the San Andreas fault or the hazards it posed to SVWC's water works. We find no evidence in the water company records that the potential impact of this fault on these facilities recognized by Lawson (1895) was ever considered by Schussler or Lawson before the earthquake. But, we find that Schussler repeatedly tried to build new reservoirs within the San Francisco City Boundaries to provide more reliability for potable water use as well as for fire flows should the upstream transmission pipes break; the City rebuffed these efforts.

Lawson the geologist, however, must have been very much aware of the destructive potential of an active fault, especially a long straight one like the San Andreas. Even though it occurred years before he came to California, the 1868 earthquake on the Hayward fault would have been an excellent role model for him to know how the San Andreas fault, once discovered, would probably behave in the future. He was aware of the negative impact the presence of a fault like the Hayward fault, that if known publicly, would have on the value of property that contained such a feature. He may have been concerned that he, the geologist, could be potentially held personally liable for property value losses by the making of a map showing the fault, especially on large parcels of developable land. This personal concern, given what we perceive to have been the legal environment of his time, is reflected in his monumental work, the U.S.G.S. San Francisco Folio (Lawson, 1914). In these small scale (1:62,500) maps of the Bay Area, the San Andreas fault is shown with a strong and labelled black line. The Hayward fault, by contrast, is not shown or named on the geologic maps, but its presence is obvious (to a geologist) by the juxtaposition of various geologic units. The Hayward fault is shown only schematically in a small illustration within the accompanying text. Given the legal/political environment following the end of the nineteenth century and the youthful stage of development of earth sciences at that time, this attempt at downplaying seismic hazards is disappointing but also understandable.

It is probably the case that Schussler and Lawson never collaborated about the San Andreas fault until after the 1906 earthquake. Without a map to warn him before the 1906 quake occurred that showed where the fault was located with respect to the water company's facilities and without Lawson’s sharing his geological expertise and concerns about the consequences of future earthquakes with Schussler, the Chief Engineer must have been blindsided by all the destruction that occurred in his world early that fateful April morning. The cultural/legal environment of the time did not promote or support a proactive approach toward mitigating environmental hazards.

Caveat emptor!

Tim Hall, June 25, 2024

11.0 References

Adams, Arthur L., Should California Municipalities Own Their Own Water Works, And If So, How Shall They be Acquired, Oakland, March 1903.

ALA, Seismic Fragilities for Water Systems, American Lifelines Alliance, March 2001, http://www.geEngineeringSystems.com.

ALA, Seismic Guidelines for Water Pipelines, American Lifelines Alliance, March 2005, http://www.geEngineeringSystems.com.

American Society Civil Engineers, *Report of committee on the effect of the earthquake on water-works structures*: A.S.C.E. Transactions, v. LIX, no. 1056, Appendix C, 23 p. 1907.

Babal, Marianne, *The Top of the Peninsula: A history of Sweeney Ridge and the San Francisco Watershed Lands, San Mateo County, California*: National Park Service D-102; Historic Resource Study; Golden Gate National Recreation Area, 148 p., 1990.

Bonilla, M.G., Alt, J.N., and Hodgen, L. D., *Trenches across the 1906 trace of the San Andreas fault in northern San Mateo County, California*: U.S. Geological Survey Journal of Research, v. 6, no. 3, p. 347-358., 1978.

Bozorgnia, Y., et al, NGA-West2 Research Project, Earthquake Spectra, Vol. 30, No. 3, pp 973-987, August 2014.

Brown, A.A., et al, Subsidence and the Foundation Problems in San Francisco, Report of the Subsoil Committee, ASCE, San Francisco Section, 1932.

Cates, Water H., History of Steel Water Pipe, Its Fabrication and Design Development, April 1971.

Civil Grand Jury, *Act Now Before it is Too Late: Aggressively Expand and Enhance Our High-Pressure Emergency Firefighting Water System*, a report issued by the City and County of San Francisco 2018-2019 Civil Grand Jury, 2019.

Derleth, Charles Jr., Report on the San Francisco Earthquake, Eng. News, vol. 55, no. 18, pp 503-504; May 3, 1906; no. 19, pp 525-526, May 10, 1906.

Derleth, Charles Jr., The Destructive Extent of the California Earthquake, Its Effect Upon Structures and Structural Materials Within the Earthquake Belt, *in The California Earthquake of 1906*, Edited by David Starr Jordan, A. M. Robertson, San Francisco, 1907.

Earth Sciences Associates, *Fault rupture analysis of San Andreas Dam:* unpublished consultant report prepared for the San Francisco Water Department, 35 p., 13 figures, with appendices, 1980.

Earth Sciences Associates, *Seismic safety analysis of San Andreas Dam:* unpublished consultant report prepared for the San Francisco Water Department, 46 p., with appendices, 1982.

Eidinger, J., Avila, E., Eds., *Guidelines for the Seismic Evaluation and Upgrade of Water Transmission Facilities*, ASCE, TCLEE Monograph No. 15, pp 208, 1999a.

Eidinger, J., O'Rourke, M., Bachhuber, J., Performance of a pipeline at a fault crossing, http://www.geEngineeringSystems.com, 1999b.

Eidinger, J., et al, *Fire Following Earthquake*, Revision 11 (2004), Revision 12 (2024) http://www.geEngineeringSystems.com, 2004.

Eidinger, J., Cheng, L., Wong, S., Ketchum, M., Seismic response of trestle-supported pipes at the Dumbarton Strait, http://www.geEngineeringSystems.com, 2006.

Eidinger, J., Performance of the SVWC Water System in the San Francisco 1906 Earthquake, Failure of the AWSS in the 1989 Earthquake, and the Future of San Francisco's Water Systems, http://www.geEngineeringSystems.com, 2023a.

Eidinger, J., and Hall, N. T. The Great San Francisco 1906 Earthquake: Why did the Water Transmission Pipes Break at 49 Locations, http://www.geEngineeringSystems.com, 2023b.

Fire Engineering, April 8, 1898.

Freeman, John Ripley, On the Proposed Use of a Portion of the Hetch Hetchy, Eleanor and Cherry Valleys: Within and Near the Boundaries of the Stanislaus National Forest Reserve and the Yosemite National Park as Reservoirs for Impounding Tuolumne Flood Waters and Appurtenant Works for the Water Supply of San Francisco, California and Neighboring Cities, Report to James Rolph, the City of San Francisco, July 15, 1912.

Grunsky, C.E. and Manson, M., Reports on Water Supplies for San Francisco, 1900 to 1908 Inclusive, published by the Authority of the Board of Supervisors, 1908.

Hall, N.T., *Holocene History of the San Andreas Fault Between Crystal Springs Reservoir and San Andreas Dam, San Mateo County, California,* Bull. Seis. Soc., Am., **74**, 281-299, 1984.

Hall, N.T., Wright, R.H., and Clahan, K.B., *Paleoseismic studies of the San Francisco Peninsula segment of the San Andreas fault Zone near Woodside, California,* Journal of Geophysical Research, V. 104, No, B10, pages 23,215-23,236, Oct. 10, 1999.

HAZUS, Hazard Loss Estimation United States, FEMA, 1994.

Hering, R., Present value of the Spring Valley Water Works, July 25, 1903.

Hovland, H. J., and Darragh, R.D., Earthquake Induced Ground Movements in the Mission Bay Area of San Francisco in 1906, Proceedings, 2nd Specialty Conference of the Technical Council on Lifeline Earthquake Engineering, ASCE, Oakland, CA, August 1981.

Idriss, I.M. and Boulanger, R.W., *Soil Liquefaction During Earthquakes,"* Monograph Series, No. MNO-12, Earthquake Engineering Research Institute, 2008.

Kennedy, Lawrence J., The Progress of the Fire in San Francisco, April 18-21, 1906, As Shown by an Analysis of Original Documents, Submitted as a Thesis for the Degree of Master of Arts, U. C. Berkeley, 1908.

Knudson, Keith, Sowers, Janet, Witter, Robert, Wentworth, Carl, and Helley, Edward, Preliminary maps of quaternary deposits and liquefaction susceptibility, nine-county San Francisco Bay region, California, U.S. Geological Survey Open file Report 00-444, V. 1.0, 2000.

Lawson, A.C., *Sketches of the Geology of the San Francisco Peninsula*, U.S. Geological Survey, Fifteenth Annual Report, p. 405-475, 1895.

Lawson, A.C. and others, *The California Earthquake of April 18, 1906*: Report of the State Earthquake Investigation Commission: Carnegie Institute of Washington Publication 87, v. 1, 2 pts., 451 p., atlas, 1908.

Manson, M., Connick, H.D., Ransom, T.W., Plans for an Auxiliary Water System for Fire Protection, February 19, 1908.

Muir. J., The Yosemite, The Century Co., New York, 1912.

Nason, Robert, Damage in Alameda and Contra Costa Counties, California, in the Earthquake of 18 April 1906, USGS Open File Report 82-63, 1982.

NFBU, Report on the City of San Francisco, California, issued by the National Board of Fire Underwriters, Committee of Twenty, No. 35, October 1905.

Olmstead, R., Olmstead, N, Pastron, A., San Francisco Waterfront: Report on Historical Cultural References, San Francisco Wastewater Management Program, City of San Francisco, December 1977.

O'Rourke, T. D., et al, Large Ground Deformations and Their Effects on Lifeline Facilities: 1906 San Francisco Earthquake, in Case Studies of Liquefaction and Lifeline Performance During Past Earthquakes, Vol. 2, NCEER Report 92-002, 1992.

Pampeyan, E.H., *Geologic Map of the San Andreas Fault Zone in San Andreas Lake, San Mateo County, California*: U.S. Geological Survey Miscellaneous Field Studies Map MF-652, scale 1:6,000, 1975.

Pampeyan, E.H., *Geologic Map of the Montara Mountain Quadrangle, San Mateo County, California*: U.S. Geological Survey Open-File Report 81-451, scale 1:12,000, 1981.

Pampeyan, E.H., Map Showing the 1906 San Andreas Fault Trace and Related Features in the Montara Mountain and San Mateo 7.5 Minute Quadrangles, San Mateo County, California, U.S. Geological Survey, Miscellaneous Field Studies Map MF-1488, Scale 1:12,000, 1983.

Perry, V. E., Pass Bearer Through Lines, Personal History of SVWC Water Supply on April 18 1906, 1954. *accessed from Museum of the City of San Francisco, September 1, 2023*.

PRCI, Guidelines for the Seismic and Assessment of Natural Gas and Liquid Hydrocarbon Pipelines, by D. Honegger and D. Nyman, Catalog No. L51927, 2004 (updated 2017).

Prentice, C.S., Bartow, G., Hall, N.T., and Liapes, M., The San Andreas fault on the San Francisco Peninsula, **in** Prentice, C.S., Scotchmore, J.G., Moores, E.M., and Kiland, J.P., eds., 1906 San Francisco Earthquake Centennial Field Guides; Geological Society of America Field Guide 7, p. 177-192, 2006.

Reed, S. Albert, The San Francisco Conflagration of April 1906, Special Report to the National Board of Fire Underwriters, Committee of Twenty, 1906.

Reid, H.F., The Mechanics of the Earthquake, v. II of The California Earthquake of April 18, 1906; report of the State Earthquake Investigation Commission: Carnegie Institute of Washington Publication 87, 192 p., 1910.

Roth, R.A., and Kavanajian, E., Liquefaction susceptibility mapping for San Francisco, CA, Bulletin of the Association of Engineering Geologists, Vol. 21, No. 4, November 1984.

San Francisco Water Company, Reports by Engineers and Others on a Permanent Supply of Pure Fresh Water to the City of San Francisco, 1872.

Schussler, H. The Water Supply of San Francisco, California, Before, During and After the Earthquake of April 18 1906, and the Subsequent Conflagration, Martin B Brown Press, New York, 103 p., July 23, 1906.

Schussler, H. The Water Supply of San Francisco, Journal of Electricity Power and Gas, Volume XXIII, December 11, 1909.

Scowden, T. R., Water Supplies, San Francisco Municipal Reports for Fiscal 1874-1875, pp 613-723. 1875.

SFPUC, A History of the Municipal Water Department and Hetch Hetchy System, SFPUC, Warren D. Hanson, June 1994.

SFPUC, A History of the Municipal Water Department and Hetch Hetchy System, SFPUC, June 2005.

SVWC. Various photos and drawings, 1906-1908 (unpublished).

Smith, T.C., *San Andreas fault, northern San Mateo area:* California Division of Mines and Geology Fault Evaluation Report FER 120 (unpublished), scale 1:24,000, 1981a.

Smith, T.C., Evidence of Holocene movement of the San Andreas fault zone, northern San Mateo County, California: California Division of Mines and Geology Open-File Report 81-6, scale 1:24,000, 1981b.

The California Earthquake of 1906, David Starr Jordan, Ed., Articles by Jordan DS., Branner JC, Derleth, C., Gilbert, GK, Taber, S., Omori, F., Fairbank, HW., Austin, M., A. M. Robertson, San Francisco, 1907.

Taber, S., *Local effects of the California earthquake of 1906*; Journal of Geology. v. 14, no. 4, p. 303-315, 1906.

The Adjuster, An Insurance Journal, Vol. 46, No. 1, San Francisco, California, January 1913.

USGS, The San Francisco Earthquake and Fire of April 18, 1906, and their effects on structures and structural materials, reports by Gilbert, G.K., Humphrey, R.L., Sewell, J. S. Suele, F., Bulletin 324, Washington, 1907.

Watt, Rolla V., Supplementary Particulars Concerning Proposed Auxiliary Water System for San Francisco, accessed from the Museum of San Francisco, 1907.

Wells, D. L. and Coppersmith, K. J., New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area and Surface Displacement, BSSA Vo. 84, No. 4, pp 974-1002, August 1994.

Witter, R.C., Knudsen, K.L., Sowers, J.M., Wentworth, C.M., Maps of quaternary deposits and liquefaction susceptibility in the central San Francisco Bay region, California, US Geological Survey, Open File Report 06-1037, 1:200,000, 2 sheets, 2006.

Appendix A. Earthquake of October 1868

This book would not be complete without at least a brief mention of the earthquake of October 21, 1868. This M 6.8 event occurred at 7:53 am local time, on the southern segment of the Hayward fault. Up to the time of the 1906 earthquake, it was called the "Great San Francisco Earthquake".

Relatively scant information is available about the performance of water systems in that earthquake. The Authors, while digging and inspecting a trench across the southern Hayward fault in 2000, discovered a 2-inch diameter pipe that was bent almost 90 degrees. We surmised that this pipe was a remnant of some pipe from a nearby well, that had suffered about 3 feet of right-lateral fault offset.

Clearly, Schussler would have been aware of the 1868 earthquake: he arrived in California in 1864, so likely he experienced the earthquake. The historic information suggests that he considered earthquakes in the design of the new Crystal Springs Dam; and that he wanted to place large terminal storage reservoirs in San Francisco in case the transmission pipes were damaged in earthquakes, or for any other reason. The Crystal Springs Dam was so-constructed, and performed well in the 1906 earthquake. The larger terminal reservoirs (Industrial site, ~400 MG; Market Street site, ~20 MG) in San Francisco were never built.

The following photos show some damage in downtown San Francisco from the 1868 earthquake.

Figure A-1. Clay Street East of Sansome (Photo: Thomas Woodward, 1868)

Figure A-2. Front and Sacramento (Photo: Thomas Woodward, 1868)

Figure A-3. Northwest Bush and Market Streets (Photo: Thomas Woodward, 1868)

Figure A-4. Southeast Front and Clay (Photo: Thomas Woodward, 1868)

INDEX

A

Alameda, 5, 9, 10, 28, 39, 44, 87, 88, 89, 91, 92, 93, 99, 104, 105, 109, 110, 141, 153, 253, 294, 306, 312, 313, 315, 316, 320, 321, 323, 325, 326, 327, 342, 343, 344, 368, 426, 453, 455, 464, 465, 483, 485, 504, 511
AWSS, 4, 5, 8, 14, 19, 21, 22, 23, 24, 40, 41, 45, 48, 50, 57, 77, 98, 110, 344, 346, 348, 356, 368, 417, 418, 419, 420, 421, 424, 425, 426, 427, 428, 429, 431, 432, 433, 435, 436, 437, 438, 439, 440, 441, 442, 443, 445, 446, 447, 448, 449, 450, 474, 486, 505,506, 510

B

Baden-Merced, 13, 100, 146, 151, 154, 156, 472, 502
Bald Hill, 88, 109, 135, 162, 207, 210, 211, 212, 213, 234, 247, 283, 284, 285, 344
BDPL, 10, 47, 57, 88, 89, 92, 93, 153, 294, 345, 351, 352, 353, 453, 463, 464, 467, 479, 480, 481, 483, 484, 485
Belmont, 91, 109, 116, 142, 313, 315, 316, 320, 321, 322, 323, 325, 342, 463
Bensley, 69, 70, 83
Berkeley, 9, 10, 12, 29, 41, 44, 45, 73, 95, 116, 132, 182, 275, 370, 405, 406, 408, 409, 410, 411, 413, 414, 415, 416, 456, 465, 477, 506, 507, 511
Black Point, 70, 75, 76, 77, 99, 109, 143, 360, 375, 454
Board of Supervisors, 4, 5, 18, 45, 49, 50, 65, 68, 69, 82, 83, 93, 94, 95, 96, 97, 98, 103, 105, 112, 402, 417, 424, 425, 426, 438, 445, 451, 452, 454, 456, 477, 491, 510
Branner, 13, 15, 29, 259, 463, 513
brick, 24, 64, 68, 105, 117, 135, 159, 166, 206, 207, 210, 211, 212, 226, 228, 229, 230, 234, 277, 289, 294, 327, 366, 369, 396, 402, 421, 425, 435, 442, 447, 491, 504
bridges, 5, 157, 162, 181, 506

C

Calaveras, 21, 23, 27, 32, 46, 54, 91, 92, 349, 452, 453, 463, 464, 465, 485, 487, 490, 491, 492, 506
cast iron, 6, 8, 19, 23, 24, 38, 48, 50, 54, 68, 74, 75, 78, 83, 99, 110, 133, 143, 146, 207, 249, 251, 253, 254, 321, 342, 344, 345, 348, 349, 350, 351, 358, 359, 362, 415, 418, 421, 422, 424, 425, 426, 427, 428, 430, 438, 442, 445, 450, 497, 501, 505
Centerville, 316
Chabot, 42, 70, 464, 465
Cherry Lake, 21, 480, 486
cisterns, 7, 8, 19, 65, 66, 68, 346, 347, 348, 362, 364, 417, 418, 419, 420, 433, 434, 435, 436, 446, 447, 449
Clarendon Heights, 109, 142, 448
Clay Street, 63, 76, 109, 393, 448, 454, 516
College, 7, 44, 76, 89, 99, 100, 104, 110, 142, 143, 145, 155, 157, 283, 284, 287, 292, 313, 327, 342, 343, 362, 406, 407, 413, 416, 453, 454, 505
Colma, 39, 125, 128, 152, 154, 163, 166, 181, 284, 290, 291, 292, 303, 304, 305, 308, 463, 503, 504
Conflagration, 404
corrosion, 17, 39, 81, 150, 151, 156, 157, 170, 181, 183, 299, 303, 343, 368, 418, 424, 425, 429, 501, 502
Crystal Springs, 4, 5, 6, 10, 13, 14, 17, 20, 21, 27, 30, 39, 40, 41, 46, 47, 57, 76, 86, 87, 88, 89, 91, 92, 93, 99, 100, 105, 109, 117, 131, 140, 141, 142, 146, 152, 153, 155, 159, 160, 162, 166, 237, 241, 248, 264, 267, 268, 271, 272, 273, 274, 275, 276, 277, 279, 280, 282, 283, 290, 293, 294, 295, 296, 297, 298, 299, 300, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 321, 324, 327, 330, 333, 334, 335, 342, 343, 344, 345, 346, 348, 426, 453, 456, 457, 463, 464, 465, 474, 478, 479, 485, 486, 487, 490, 493, 499, 504, 505, 510, 515

D

D/t, 17, 39, 152, 162, 180, 268, 269, 343, 499
Daly City, 290, 498
Del Valle, 91, 92
Derleth, 16, 17, 29, 44, 132, 146, 168, 171, 172, 177, 186, 299, 309, 310, 507, 509, 513
Dumbarton, 91, 99, 312, 313, 314, 317, 319, 351, 463, 477, 479, 504, 510

E

East Bay Municipal Utility District, 16
EBMUD, 23, 44, 54, 57, 349, 350, 353, 368, 420, 445, 463, 464

F

Fairbanks, 29
fault crossing, 5, 27, 39, 131, 177, 180, 187, 195, 212, 228, 234, 250, 254, 269, 272, 351, 501, 510
fault offset, 5, 25, 27, 31, 38, 39, 117, 129, 131, 136, 138, 140, 152, 177, 181, 182, 185, 191, 195, 203, 212, 234, 243, 244, 248, 251, 252, 256, 264, 266, 269, 276, 344, 349, 350, 354, 367, 493, 497, 498, 503, 504, 515
fire, 355, 357, 358, 359, 360, 370, 373, 374, 375, 376, 402, 405

Fire, 355, 357, 358, 359, 360, 370, 373, 374, 375, 376, 402, 405
fire-fighting, 18, 23, 103, 104, 342, 346, 403, 417, 424, 444, 450
flumes, 28, 29, 38, 39, 70, 84, 92, 99, 105, 153, 162, 235, 240, 241, 313, 315, 316, 326, 330, 333, 338, 342, 343, 504
Frawley Canyon, 125, 132, 135, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 180, 184
Freeman, 9, 15, 41, 45, 46, 47, 453, 457, 458, 460, 461, 462, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, 479, 480, 481, 482, 483, 485, 486, 510

G

gas, 15, 24, 25, 124, 138, 269, 367, 368, 369, 376, 405, 421, 423, 430, 483, 498
Gilbert, 29, 513
Girth, 152, 303, 497
Grand Jury, 21, 418
Grunsky, 9, 40, 44, 45, 46, 47, 48, 49, 94, 97, 417, 424, 425, 436, 456, 457, 458, 459, 467, 472, 476, 477, 510

H

Hayward, 17, 23, 27, 32, 54, 135, 269, 275, 344, 349, 350, 351, 353, 460, 463, 464, 484, 485, 498, 499, 506, 507, 508, 515
Hetch Hetchy, 4, 8, 9, 10, 11, 14, 16, 19, 21, 40, 41, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 88, 89, 91, 92, 93, 95, 97, 112, 114, 147, 294, 348, 349, 351, 352, 353, 425, 429, 451, 452, 453, 455, 456, 457, 458, 459, 460, 461, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 476, 477, 478, 479, 480, 481, 482, 483, 484, 485, 486, 487, 489, 490, 491, 499, 505, 506, 510, 513
Highway 92, 135, 276, 279, 281, 293, 294
Honda, 7, 13, 83, 84, 89, 99, 100, 104, 109, 110, 111, 125, 129, 142, 143, 154, 155, 161, 162, 163, 166, 241, 253, 327, 342, 343, 345, 360, 362, 370, 372, 373, 374, 375, 453, 454, 472, 474, 502, 503, 505
Humphrey, 304, 355, 360, 402, 513
hydrant, 7, 8, 18, 26, 78, 94, 346, 376, 383, 437, 442, 443, 447
hydraulic fill, 124, 445

I

ignition, 23, 26, 64, 68, 346, 347, 360, 362, 367, 369, 373, 374, 421, 434, 444, 445
Industrial, 6, 18, 94, 103, 104, 157, 346, 472, 515

J

Jordan, 29, 509, 513

K

Kennedy, 360, 361, 365, 366, 367, 371, 511
Knowles Gulch, 168, 286

L

LADWP, 349, 350, 351, 353, 491
Lake Eleanor, 21, 114, 457, 477, 480, 486
Lake Merced, 99, 100, 109, 142, 143, 154, 155, 286, 327, 328, 329, 342, 419, 502, 503
landslide, 54, 241, 264, 268, 335, 338, 344, 354, 367, 420, 422, 465
lateral spread, 268, 269, 317, 411
Lateral spreads, 121
Lawson, 12, 13, 15, 16, 30, 44, 124, 125, 131, 132, 135, 144, 154, 173, 180, 181, 182, 184, 189, 192, 195, 198, 199, 200, 201, 202, 203, 205, 229, 243, 246, 251, 252, 254, 255, 256, 257, 259, 260, 263, 264, 266, 268, 304, 334, 493, 499, 507, 508, 511
liquefaction, 5, 6, 8, 16, 19, 24, 25, 27, 38, 39, 48, 50, 54, 68, 98, 103, 104, 111, 118, 124, 125, 143, 145, 146, 152, 180, 268, 269, 300, 301, 303, 304, 343, 344, 346, 347, 348, 349, 354, 355, 362, 367, 368, 369, 383, 406, 416, 417, 418, 420, 422, 428, 474, 493, 500, 504, 505, 511, 514
liquefiable, 123, 344, 355
Lobos, 42, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 83, 87, 99, 454
Locks Creek, 27, 91, 133, 135, 141, 147, 152, 162, 226, 227, 237, 244, 264, 265, 266, 267, 270, 271, 330, 332, 333, 334, 338, 343, 498, 499
Loma Prieta, 5, 8, 19, 48, 50, 98, 153, 344, 345, 348, 349, 350, 353, 418, 425, 428, 437, 438, 441, 442, 443, 449, 505

M

Manson, 40, 45, 47, 356, 358, 359, 426, 427, 428, 431, 436, 437, 438, 439, 440, 443, 445, 457, 467, 477, 510, 511
Marina, 8, 19, 50, 98, 124, 348, 349, 355, 418, 420, 422, 423, 425, 428, 437, 438, 442, 443, 444, 445, 449
Market, 4, 6, 7, 18, 19, 38, 51, 62, 70, 78, 83, 93, 94, 97, 103, 104, 112, 120, 342, 346, 361, 362, 367, 369, 370, 371, 373, 374, 378, 379, 381, 382, 384, 387, 388, 389, 390, 391, 392, 397, 399, 400, 401, 410, 413, 416, 425, 428, 430, 434, 436, 438, 442, 445, 446, 454, 500, 515, 518
Merrifield, 65, 66
MID, 9, 14, 47, 48, 53, 57, 455, 457, 458, 459, 460, 485, 487, 490
Millbrae, 92, 99, 109, 151, 166, 172, 253, 274, 294, 295, 298, 299, 313, 315, 316, 321, 323, 324, 325, 340, 342, 426, 504
Mission, 4, 6, 7, 38, 62, 64, 66, 69, 82, 103, 104, 111, 118, 120, 122, 123, 142, 145, 155, 342, 346, 355, 360, 361, 362, 369, 371, 372, 373, 380, 381, 383, 394, 406, 407, 408, 423, 434, 438, 442, 474, 500, 511

Mission Creek, 4, 6, 82, 103, 104, 111, 118, 120, 122, 123, 145, 360, 362, 369, 373, 406, 407, 408, 423, 434, 438, 442, 474, 500
MLWC, 57, 65, 67, 68, 69
Modesto, 9, 14, 45, 57, 455, 457, 459, 487, 488
Mountain Lake, 57, 65, 66, 67, 68, 69, 70, 72, 75
Muir, 9, 11, 14, 46, 51, 52, 53, 459, 470, 486, 511

N

Newark, 99, 313, 314, 316, 317, 318, 325, 464, 479, 484
NFBU, 16, 88, 98, 402, 403, 449, 511
Niles, 91, 92, 95, 99, 313, 314, 316, 325, 479

O

O'Shaughnessy, 9, 40, 45, 47, 48, 49, 53, 448, 449, 450, 481, 482, 486, 491
Oakland, 9, 10, 21, 42, 44, 46, 49, 70, 116, 123, 156, 345, 360, 369, 370, 374, 401, 405, 418, 444, 449, 456, 458, 465, 477, 479, 484, 509, 511
Ocean View, 109, 327, 502
Olympic, 77, 78, 79, 82, 362, 424

P

Pacific Gas and Electric, 16, 24
Palo Alto, 23, 116, 368, 463, 464, 484
Pampeyan, 30, 131, 205, 211, 213, 234, 275, 277, 281, 497, 512
Peninsula, 4, 22, 27, 28, 29, 30, 39, 46, 90, 91, 92, 102, 104, 107, 116, 129, 134, 137, 139, 140, 241, 254, 320, 330, 426, 451, 452, 454, 455, 473, 497, 498, 499, 501, 504, 507, 509, 511, 512
Perry, 12, 13, 144, 154, 512
PG&E, 24, 320, 485
PGA, 17, 115, 116, 140, 156, 177, 240, 241, 302, 315, 326, 344, 345, 368, 419, 422, 423, 430
PGD, 17, 25, 58, 136, 138, 139, 140, 144, 145, 260, 268, 269, 344, 368, 429, 496, 497, 498
PGV, 17, 58, 115, 116, 157, 268, 344, 422, 430
Phelan, 7, 18, 44, 49, 50, 51, 94, 97, 425, 455, 456
Pilarcitos, 5, 6, 12, 13, 17, 18, 21, 27, 28, 29, 39, 41, 46, 83, 84, 85, 86, 87, 90, 91, 99, 100, 105, 109, 111, 117, 124, 125, 126, 127, 128, 129, 132, 133, 141, 142, 143, 146, 150, 151, 152, 153, 154, 156, 157, 158, 159, 160, 161, 162, 163, 165, 166, 167, 169, 170, 171, 172, 173, 174, 175, 176, 178, 179, 180, 182, 184, 189, 190, 192, 196, 198, 199, 200, 201, 203, 205, 235, 241, 244, 247, 248, 249, 250, 252, 253, 264, 271, 283, 284, 287, 327, 330, 331, 332, 333, 334, 335, 336, 337, 338, 339, 342, 343, 344, 345, 346, 426, 452, 453, 472, 474, 487, 493, 498, 499, 500, 501, 502, 503, 506, 507
pipe, 175, 176
Precita, 109, 111, 142, 146, 284, 474
Presidio Heights, 109
Primary offset, 131, 138, 230, 260
pump, 8, 9, 14, 22, 23, 45, 65, 70, 76, 77, 78, 80, 82, 91, 92, 99, 100, 109, 110, 111, 142, 143, 146, 160, 162, 247, 274, 283, 284, 294, 295, 298, 313, 316, 320, 321, 322, 323, 324, 327, 329, 333, 342, 360, 375, 417, 418, 419, 420, 424, 425, 426, 428, 429, 436, 442, 443, 445, 447, 449, 454, 456, 472, 474, 477, 489, 502, 505
pumping, 7, 10, 14, 76, 111, 392, 403, 425, 449, 458, 460, 474, 485, 505
    pump, 111

R

racoon, 212
Raker, 9, 14, 20, 40, 46, 48, 53, 348, 458, 460
Ravenswood, 91, 99, 110, 313, 314, 316, 320, 321, 342
Redwood, 116, 310, 453, 463, 464, 484
Reed, 12, 13, 15, 16, 360, 363, 367, 369, 371, 402, 404, 512
rivet, 157, 188, 189, 199, 267, 268, 343, 502
riveted, 5, 6, 28, 39, 41, 83, 92, 99, 132, 150, 156, 157, 163, 170, 188, 191, 196, 244, 264, 266, 268, 274, 283, 294, 301, 306, 307, 310, 313, 316, 320, 323, 343, 345, 349, 350, 351, 463, 477, 479, 482, 483, 484, 497, 498, 499, 501, 502, 503

S

San Andreas, 4, 5, 12, 13, 17, 18, 21, 22, 23, 25, 26, 27, 28, 29, 30, 32, 39, 41, 44, 46, 54, 76, 86, 87, 88, 91, 93, 99, 100, 105, 109, 117, 124, 125, 126, 127, 129, 130, 131, 132, 133, 134, 135, 136, 137, 140, 141, 142, 147, 150, 152, 153, 154, 155, 158, 159, 160,161, 162, 163, 166, 173, 182, 184, 185, 190, 192, 194, 196, 198, 203, 206, 207, 208, 209, 210, 211, 214, 215, 216, 217, 218, 220, 225, 226, 227, 229, 246, 247, 248, 249, 251, 252, 253, 254, 255, 260, 261, 264, 266, 267, 269, 271, 272, 273, 275, 276, 279, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 294, 301, 308, 313, 316, 327, 330, 332, 333, 334, 335, 336, 342, 344, 345, 346, 349, 413, 419, 421, 423, 425, 426, 452, 453, 455, 460, 463, 465, 472, 487, 491, 493, 494, 497, 498, 499, 500, 501, 502, 503, 504, 506, 507, 508, 509, 510, 511, 512, 513
San Antonio, 21, 46, 91, 92, 464, 465, 485, 487
San Bruno, 135, 141, 152, 191, 295, 298, 299, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 453, 463
San Francisco, 148, 355, 357, 358, 359, 403
San Jose, 21, 116, 370, 456, 458, 463, 464, 484, 506
San Mateo, 27, 88, 91, 110, 112, 116, 153, 159, 160, 166, 202, 228, 264, 277, 297, 299, 303, 315, 327, 333, 336, 337, 338, 370, 463, 509, 510, 512, 513
Santa Clara, 54, 92, 116, 368, 370, 463, 464, 484
Schussler, 12, 13, 15, 16, 17, 18, 19, 27, 28, 29, 30, 40, 41, 42, 44, 47, 48, 50, 60, 78, 84, 86, 94, 95, 96, 97, 98, 103, 125, 131, 143, 144, 146, 151, 152, 154, 155, 162, 163, 169, 170, 171, 173, 174, 176, 178, 179, 181, 182, 184, 186, 187, 191, 195,

196, 199, 204, 206, 207, 210, 211, 215, 216, 221, 226, 227, 229, 231, 232, 233, 234, 237, 238, 239, 240, 243, 244, 245, 246, 247, 250, 251, 252, 253, 254, 255, 256, 258, 259, 260, 262, 263, 264, 265, 267, 268, 270, 276, 279, 281, 283, 290, 291, 292, 293, 298, 300, 301, 305, 306, 307, 308, 312, 317, 318, 319, 322, 323, 325, 326, 329, 334, 335, 336, 345, 349, 358, 359, 414, 436, 437, 438, 453, 454, 455, 472, 490, 491, 499, 500, 503, 504, 506, 507, 508, 513, 515
Scowden, 44, 91, 133, 247, 271, 451, 452, 453, 513
Secondary offset, 131, 138
Serra, 27, 32, 124, 125, 212, 499
service lateral, 111, 143, 145, 147, 349
service laterals, 143, 145, 428, 505, *See* service lateral
SFCWW, 58, 69, 70, 71, 72, 74
SFPUC, 10, 11, 21, 23, 24, 29, 30, 54, 58, 60, 75, 88, 89, 90, 100, 182, 201, 212, 213, 275, 311, 345, 348, 349, 351, 352, 353, 368, 418, 419, 420, 421, 422, 428, 446, 450, 464, 481, 483, 485, 486, 490, 513
South of Market, 7, 18, 38, 78, 105, 120, 430, 438, 446
standpipe, 91, 151, 163, 287, 316, 320, 321, 322, 324, 390
Standpipes, 151
Stanford, 13, 29, 41, 116, 281, 452, 463, 484, 493
Stone Dam, 117, 147, 152, 159, 225, 229, 234, 237, 238, 239, 264, 271, 283, 289, 294, 332
submarine, 91, 92, 99, 313, 316, 317, 318, 319, 320, 325, 464, 479, 484
Sullivan Marsh, 4, 6, 103, 104, 111, 118, 120, 121, 367, 423, 438
Sullivan's Marsh
Sullivan Marsh. *See*
Sutro, 80, 82, 143
SVWC, 4, 5, 6, 7, 9, 10, 12, 13, 14, 16, 18, 19, 20, 21, 24, 27, 28, 29, 38, 41, 45, 46, 47, 48, 50, 51, 58, 60, 76, 78, 82, 83, 85, 86, 88, 89, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 109, 110, 112, 114, 129, 130, 141, 143, 146, 147, 150,154, 155, 159, 160, 167, 172, 193, 198, 204, 205, 214, 253, 272, 273, 274, 283, 294, 325, 327, 328, 337, 338, 339, 340, 341, 342, 344, 348, 349, 353, 362, 391, 402, 406, 409, 413, 414, 416, 417, 425, 426, 430, 436, 437, 438, 445, 447, 448, 449, 451, 452, 454, 455, 456, 459, 464, 467, 472, 474, 479, 481, 483, 484, 485, 490, 491, 498, 499, 503, 504, 506, 507, 510, 512, 513

T

TID, 9, 14, 47, 48, 53, 58, 455, 457, 458, 459, 460, 485, 487, 490
trestle, 5, 39, 105, 117, 125, 135, 141, 151, 152, 153, 156, 168, 169, 171, 172, 191, 235, 237, 240, 241, 251, 253, 273, 274, 284, 290, 291, 295, 300, 302, 303, 304, 305, 306, 307, 308, 309, 310, 316, 333, 467, 484, 503, 504, 510
tunnel, 10, 70, 74, 91, 99, 109, 117, 135, 159, 162, 166, 207, 210, 211, 212, 226, 229, 230, 234, 237, 264, 271, 276, 277, 283, 284, 289, 294, 327, 333, 342, 344, 350, 351, 425, 426, 453, 463, 464, 465, 467, 477, 480, 482, 483, 484, 485, 486, 490, 506
Turlock, 9, 14, 45, 58, 455, 457, 459

U

Union Square, 340, 374, 375, 378, 380, 391, 401
University Mound, 7, 76, 89, 99, 100, 104, 109, 110, 111, 142, 143, 145, 155, 157, 294, 296, 303, 313, 316, 321, 324, 342, 343, 372, 407, 453, 465, 505

W

wrought iron, 5, 6, 28, 38, 39, 41, 50, 57, 83, 84, 99, 110, 133, 146, 151, 152, 153, 158, 162, 244, 253, 254, 264, 266, 274, 277, 283, 289, 291, 294, 303, 304, 313, 316, 323, 333, 334, 343, 345, 349, 453, 476, 477, 497, 501, 502, 503

Y

Yosemite, 4, 8, 9, 10, 14, 19, 21, 40, 46, 47, 51, 52, 53, 348, 456, 459, 468, 471, 486, 487, 490, 505, 510, 511