The Great San Francisco 1906 Earthquake: Why Did the Water Transmission Pipes Break at 49 Locations?

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Abstract: The M_w 7.8 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 116 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. There are three key questions. First, why did the water transmission pipes break at 49 locations with 91 broken segments? Second, why did the water distribution system fail to deliver water to hydrants? Third, has the salt water pipe system that was built in 1912, done much good? In this paper, we present the facts that led to 91 broken segments of the water transmission system. The second and third questions are addressed in a companion paper (Eidinger, 2023).

INTRODUCTION

SVWC built a water system from 1862 to 1905 that well served San Francisco. The system included 87 miles of transmission pipes and 420 miles of distribution pipes. There was no explicit seismic design for the water system. The system was very capable of delivering fire flows for day-to-day fires, with about 6,800 fires controlled without any material fire conflagrations for the 15 year period prior to the earthquake.

The April 18 1906 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. About 64% of the 299 breaks in the City distribution system were caused by liquefaction (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 29 million gallons per day. The earthquake broke all 4 conduits.

The 30-inch diameter 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 10 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 wooden trestle across Colma Creek.

The 36-inch to 54-inch Alameda pipe broke 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 are presently in use as part of the modern water transmission system that serves San Francisco.

The SERA (System Earthquake Risk Assessment) computer model was used to forecast the damage to the 1906 system. The model reasonably predicts the damage to the transmission system due to fault offset, liquefaction and ground shaking hazards. Table 4 highlights the fragility models used, 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 concentrated fault offsets along the pipes varied from 7 to 10 feet, which is low for a M 7.8 earthquake. New essential water pipes across the Peninsula segment of the San Andreas fault should be designed for about 20 feet of offset through the zone subjected to concentrated fault offset. By "concentrated", we mean the zone subject to significant sharp right lateral offsets, typically over a zone width of 10 to about 100 feet. Outside the concentrated fault offset zone, there was additional warping of the ground surface; this warping is not thought to be a contributor to pipeline damage in 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 remains extremely vulnerable.

A companion paper (Eidinger, 2023) examines the seismic weaknesses of the San Francisco local distribution system and its parallel Auxiliary Water Supply System. That paper outlines a possible pipeline upgrade program to resolve the core remaining weaknesses in the water distribution system.

THE WATER SYSTEM IN 1906

Figures 1, 2 and 3 show the regional and San Francisco distribution water system at the time of the 1906 earthquake. There were six sources of water into 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.

1862-1865 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 the new Pilarcitos conduit included 13 miles of 30-inch wrought iron (WI) 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, 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 encroach into the areas supplied from Laguna Honda. Lake Merced in Southwest San Francisco is a 2 billion gallon natural fresh water lake (elevation 26 feet). Water quality in the lake was variable: run-off from rain storms could result in adverse water quality events. A pump station and force main was able to pump Lake Merced water into the northern part of the Pilarcitos pipeline, should the need arise; this was done beginning about 8 hours after the earthquake. Interties allowed Lake Merced water to go either to Laguna Honda or College Hill reservoirs.

1870 San Andreas System. This 44-37-30-inch WI pipe brought water from San Andreas reservoir (449 feet) to College Hill reservoir (252 feet).

1880 Crystal Springs System. This 44-inch WI pipe brought water from Crystal Springs reservoir (288 feet) to University Mound reservoir (160 feet).

1888 - 1902. Alameda System. This 36-inch WI pipe brought water from an underground filtration system in Sunol to a point where the pipe joined the 44-inch Crystal Springs pipeline. In 1902, this system was extended with a 54-inch WI 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, Burlingame and Millbrae were used to boost pressure in the Alameda system so that water from Sunol could eventually reach University Mound or College Hill Reservoirs.

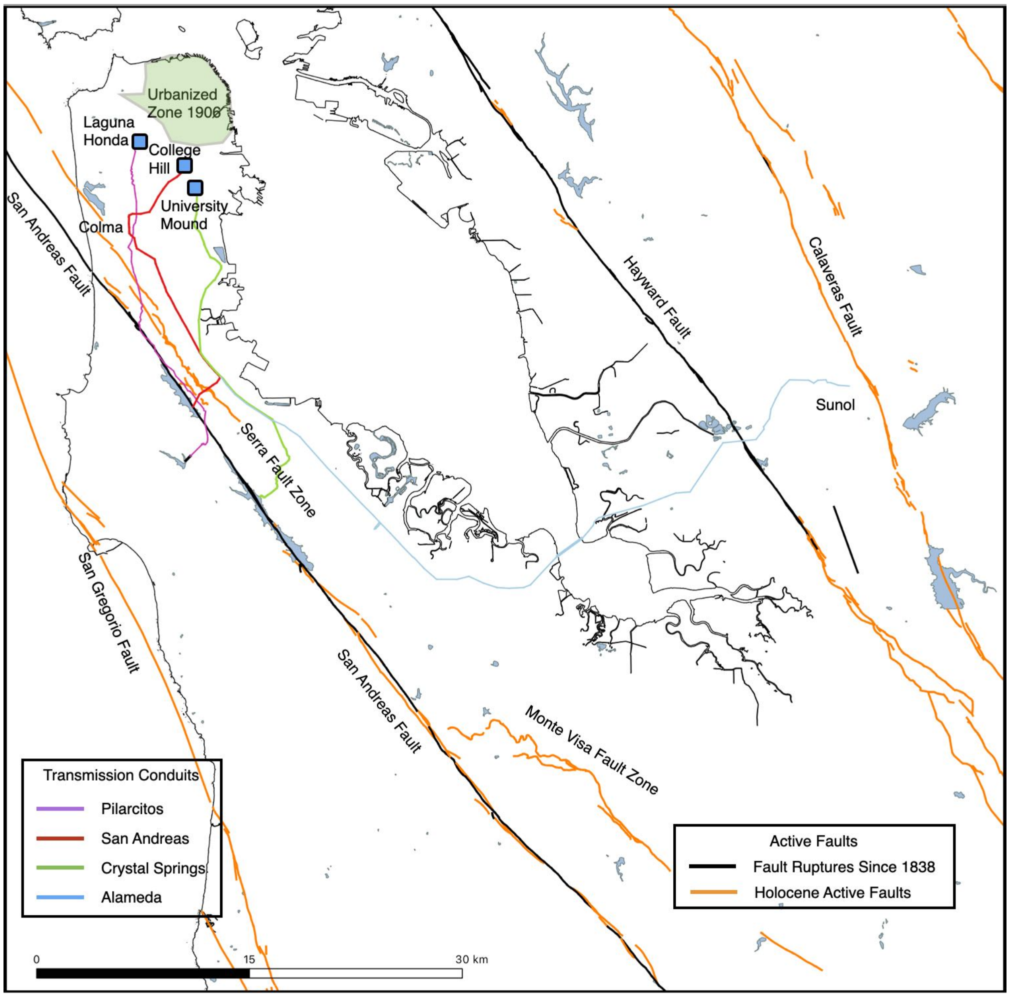

Figure 1. SVWC Regional Water Supply System, 1906

Figure 2 shows the main pipelines in the City system, as of 1894. Figure 2 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.

THE DAMAGE TO THE WATER TRANSMISSION SYSTEM IN 1906

In 1906, the water supply system consisted of 4 conduits, see Tables 1 and 2. By "conduit", it is meant a combination of buried pipe, pipe on wooden trestle, wooden flumes and brick-lined tunnels.

Table 1. Regional Water Supply System

Conduit	Pipe Diameter (Inch) and Type	Tunnels	Trestles	Flumes
Pilarcitos	44, 30 WI; 22 CI	3	8	2
San Andreas	44, 37, 36, 30 WI	1	14	0
Crystal Springs	44 WI	2	19	0
Alameda	36, 54 WI; 16 CIB; 22 CIB	5	2	4

Table 2. Conduit Inventory

Conduit	Pipe Length (feet)	Tunnel Length (feet)	Trestle Length (feet)	Flume Length (feet)	Submarine Length (feet)
Pilarcitos	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

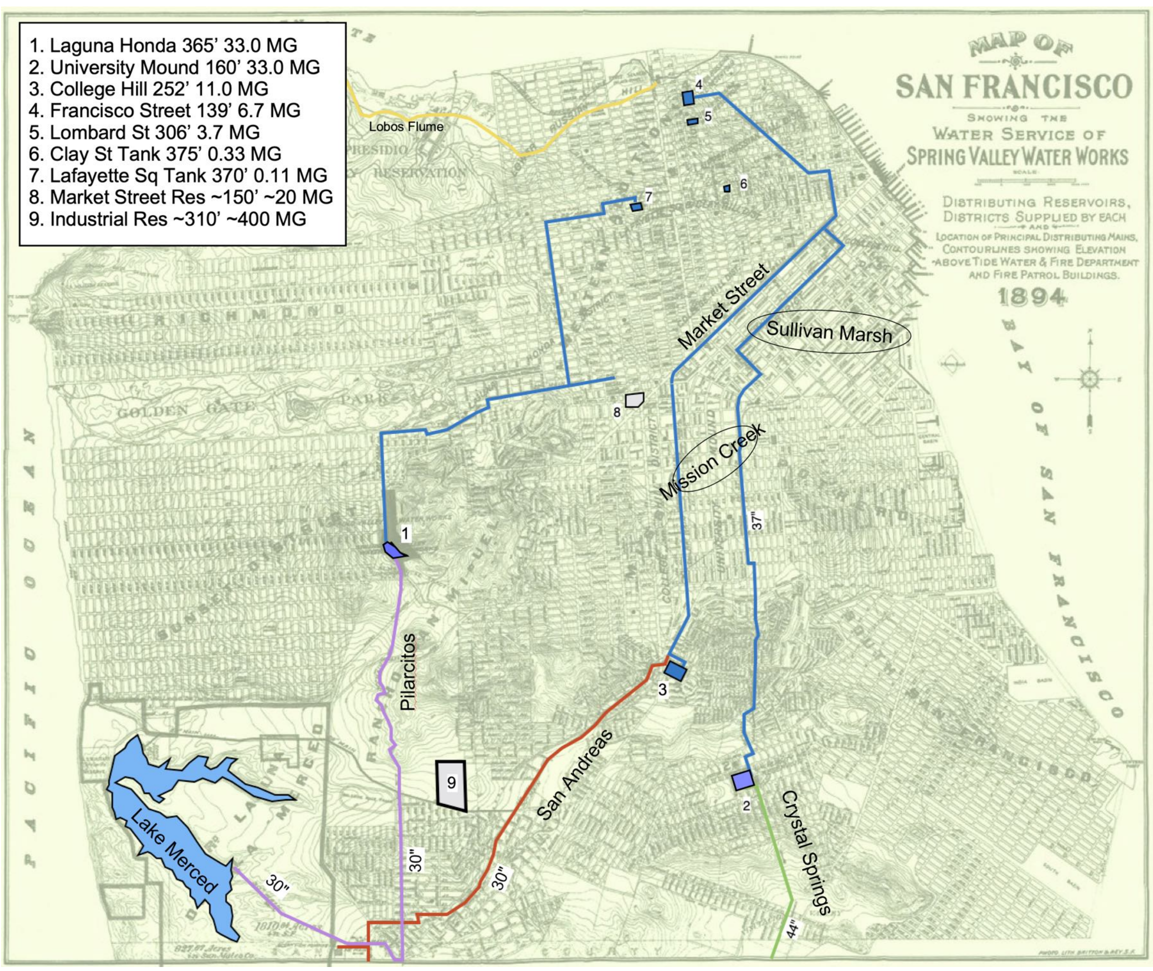

Figure 2. SVWC Water System – Main Pipes of the Distribution System - 1894

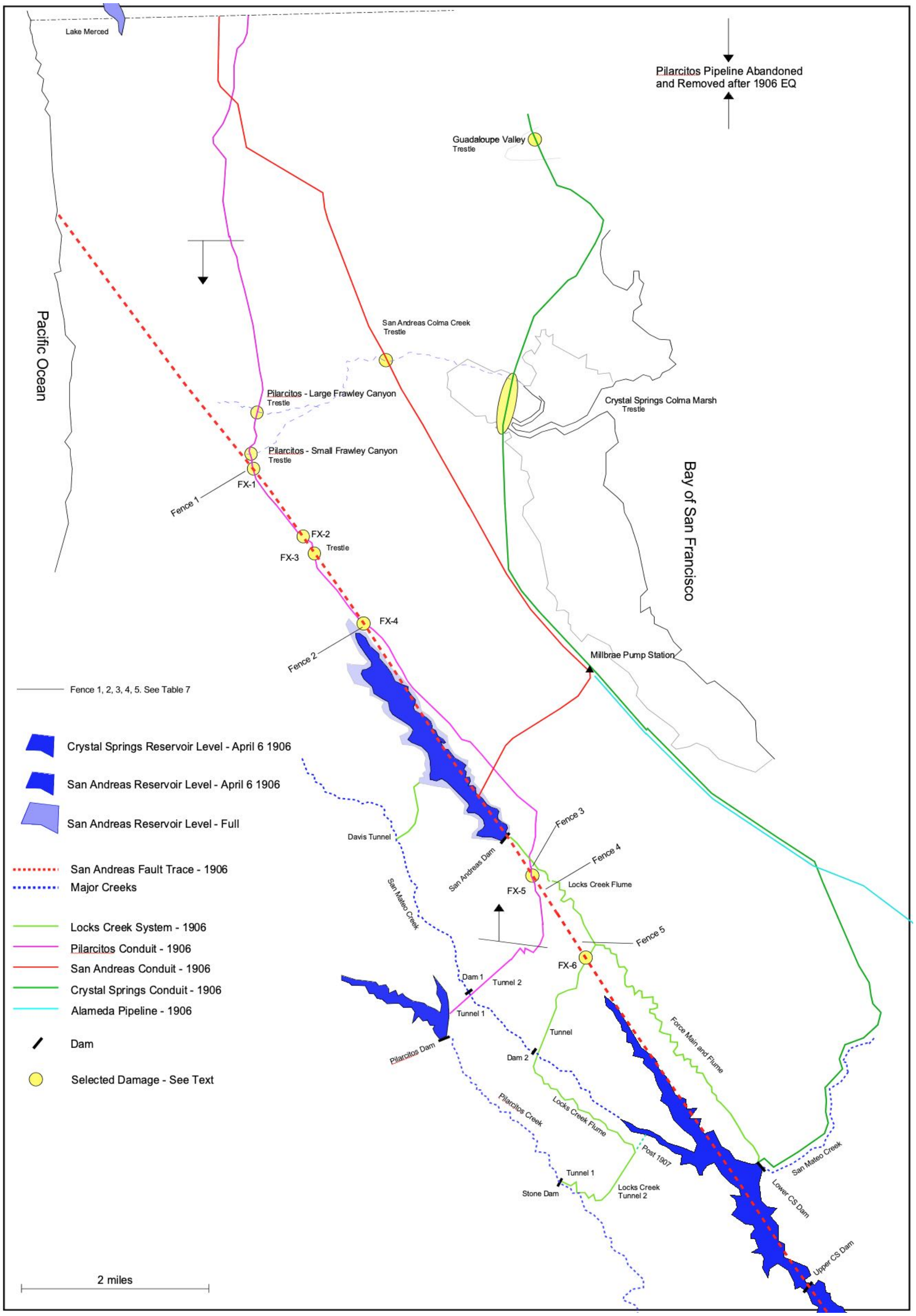

Figure 3. Location of Major Pipeline Damage in the 1906 Earthquake

Table 3 shows the damage to the Water Transmission System. In Table 3, a pipe break "segment" is the equivalent number of 10-foot long segments that would have to be replaced / 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; 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.

Table 3. Supply System Damage in the 1906 Earthquake

Conduit	Fault Offset Locations Actual	Collapsed Trestles / Flumes Actual	Pipe Break Locations Actual	Pipe Break Segments Actual	Pipe Break Segments SERA	Time to Restore Water Service
Pilarcitos	5	2	31+	~60	33.9	16 hours
San Andreas	1	0	1	2	3.0	62 hours
Crystal Springs	0	3	10	~22	23.5	28 days
Alameda	0	0	7	7	12.7	< 1 day
Total	6	5	49	91	73.1	

In Table 3 we use the term "break" to denote a loss of the pressure boundary, requiring the pipe to be shut down. Table 3 excludes damage that did not require repair in order to restore water service in the system. The "Actual" values in Table 3 are based on Schussler's account of the 1906 earthquake (1906, 1909).

The "SERA" values in Table 3 are based on a computer model used to forecast damage due to the 1906 earthquake, as follows. The 1906-era pipe transmission system was digitized, and a forecast of pipe damage was made using the computer model SERA, which computes damage to pipes using fragility models. Fragility models for various kinds of water pipe are described in ALA (2001), which were adapted for the present analyses as in Table 4. For thin-wall Wrought Iron pipe, the k_1 in the present analyses was 3.4, to reflect a combination of accumulated corrosion and hydrodynamic loading on the pipe. Table 4 also includes fragility models for belled cast iron pipes that were used for submarine crossings, as well as tunnels and wood flumes. For a M 7.8 event, the damage due to shaking is increased by 40% to reflect the longer duration of motion (25-30 seconds of strong shaking). This increase reflects that the fragility models in ALA (2001) are baselined for 15-18 seconds of strong shaking that occurred in the underlying empirical data used to set the k_1 values (commonly M 6.5 to 7.0 events).

Table 4. Pipe Fragility Models (Constant k_1 as per ALA 2001)

Pipe Type	ALA (2001)	SERA (this report)
Wrought Iron, D/t ≤ 150, Riveted, Asphaltum Lining and Coating, Diam = 30 to 54 inches	1.3	0.3
Wrought Iron, D/t >250, Riveted, Asphaltum Lining and Coating, Diam = 30 inches	1.3	3.4
Cast Iron, D = 20 to 24 inches	0.5	0.5
Cast Iron, D = 16 to 22 inches, Bell joints for submarine pipes	n.a.	0.25
Brick-Lined Tunnels	n.a.	0.03
Wooden Flume	n.a.	1.0

SERA applies a M 7.8 event along the San Andreas fault, and computes the ground motions due to shaking, liquefaction, landslide and fault offset along each of the pipes / tunnels / flumes shown in Figures 1 and 3. Liquefaction hazards along the conduits are established following Witter (2006). Fault offset PGDs based on Wells and Coppersmith (1994).

Fault Offset. For a M 7.8 event, a median value of 16 feet of right lateral strike-slip displacement would be expected from analysis of the worldwide earthquake database by Wells and Coppersmith (1994). However, as noted in Table 7, actual observed concentrated fault offset in the 1906 event, near the San Andreas Reservoir, was commonly in the 10 to 11 foot range, some as low as 7 feet. This slip occurred in 1 to 3 narrow zones of concentrated right shear within the fault zone. There were five fences that crossed the fault near the Pilarcitos pipeline, and the offsets were surveyed by a professional engineer (Lawson, 1908). When summed, these measurements of concentrated fault slip combined with broad ground warping, indicated the magnitude of tectonic offset across the fault zone ranged from 13 to 17 feet. 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.

There were 5 potable water transmission pipes that crossed the fault, (plus the 44-inch WI Locks Creek raw water pipe), and SERA forecasts multiple segments of each pipe (either WI or CI) would break at each location. All these pipes failed catastrophically, no matter whether they crossed the fault at angles to produce net tension, net compression or mostly bending in the pipes. See Schussler (1906) for photos of the damaged pipes at the fault locations. After the earthquake, SVWC decided to abandon the Pilarcitos pipeline in the zone where it zig-zagged five times over the San Andreas fault (Figure 3), and the Locks Creek system was re-routed to deliver water directly into Crystal Springs reservoir, thereby precluding a pipe crossing of the fault.

Liquefaction. Liquefaction-induced PGDs are forecast along the conduits. Almost all the 1906-pipes that were aligned through liquefaction-susceptible zones were supported above-ground on wooden trestles. The trestles were originally designed for gravity loads and wind loads. There were many pipe failures of the 44-inch Crystal Springs pipeline through three liquefaction zones, where a combination of amplified motions, weak wooden trestles and some liquefaction PGDs resulted in major damage. Most wood piles in the liquefaction zones were undamaged, but the pile caps were severely damaged and the supported pipe in many places displaced so far sideways that the pipe entirely fell off the trestles. The SERA model forecasts 33 pipe segment repairs for the pipes through these zones (the number of repairs reflects the maximum damage from either shaking or liquefaction hazards). In the actual earthquake, 2,850 feet of pipe in these liquefaction zones was damaged (no flow), taking 28 days to rebuild (a combination of repair to the wood trestles, and repair to the pipe at damaged slip joints).

Landslide. None of the pipes traversed zones with known active landslides. It remains open as to whether there were in fact some landslides along the slopes adjacent to San Mateo Creek which might have damaged the 44-inch Crystal Springs pipe at a few locations where the pipe was located uphill on the north slope above the creek. A earthquake-triggered landslide did collapse several hundred feet of the Locks Creek flume that delivered water to San Andreas reservoir.

Ground shaking. The level of ground shaking was computed for a M 7.8 event, using the average of four (or five in rock zones) Ground Motion Prediction Equation models (Bozorgnia 2014). Table 6 lists the exposures for median-computed surface level peak ground velocities (cm/sec) and the length of pipe (by material), tunnel and flume exposed (in km). Comparing the forecast damage with the actual damage, the following trends are observed:

- WI (excluding thin walled). There were 16 locations where WI pipe failed in the 1906 earthquake, where failure is attributed to ground shaking. The SERA forecast is 19. The ALA (2001) "k_1" value for riveted WI pipe should be reduced from 1.3 to about 0.3, comparable to other continuous steel pipe.

- WI-thin. The bulk of the southern low-pressure segment of the 30-inch Pilarcitos pipe had D/t ~ 30-inch/0.104-inch = 288. Where subject to up to 70 psi of hydrostatic pressure, the pipe failed at about two dozen locations due to shaking. This was aggravated by accumulated corrosion. The pipe was 44 years old at the time of the earthquake, and protected with asphaltum lining and coating. In 1904, a 500-foot length of this pipe failed: Figure 4 shows a hoop-related tear due to ongoing corrosion. The higher pressure and thicker wall t = 0.175-inch Pilarcitos pipe had no failures due to shaking. The underlying causes of the high failure rate in the thin-walled pipe was likely a combination of hydrostatic + hydrodynamic pressures that loaded the relatively weak girth riveted joints to about yield levels, coupled with corrosion-thinned-wall (either external or internal) action of 44 years of service. The ALA (2001) "k_1" value for thin-walled low-pressure riveted WI pipe with only passive corrosion protection should be increased from 1.3 to about 3.4. It is recommended that thin walled (D/t > 250) steel pipe should not be used in areas prone to strong ground shaking, unless the designer includes an allowance of about 60 psi for earthquake-induced hydrodynamic forces, and ensures that both hoop steel and girth joints can sustain these pressures, and that the steel be protected from corrosion / erosion effects that assure a residual factor of safety against hoop failure for an earthquake that occurs about 100 years after initial service. The target provision of 60 psi hydrodynamic loading may control for thin walled (D/t much over 200) steel pipe, while it will not control for heavy wall (D/t < 100) steel pipe. ALA (2005) provides a guidance for estimating earthquake-induced hydrodynamic pressure in lieu of complex computation. However the hydrodynamic pressure value is computed, the pipeline designer should not ignore that water pipes need to accommodate these forces in earthquakes, as well as accumulated corrosion effects, and if ignored, a high failure rate for thin-walled low pressure pipe (especially at bends, girth joints, or due to hoop overload) can be expected. The actual breaks is listed in Table 3 as 31+, with the "+" reflecting that Schussler (1906) observed that there may have been additional breaks along the Pilarcitos pipeline in between the locations with known breaks.

- CI. The 1.4 km of CI pipe was forecast to have about 0.2 failures due to shaking; none were observed. Much of this pipe was in very stiff soils west of the San Andreas fault. Given the short length of CI pipe, the results from the 1906 earthquake do not warrant any change to the ALA (2001) fragility models.

- CI-Bell. There were 9.3 km of submarine CI pipe with special belled joints in place at the time of the earthquake. No liquefaction PGDs are known to have occurred at these locations, but underwater surveys soon after the earthquake were never done. While none of these pipes (8 heavy-walled 16- and 22-inch pipe at two submarine crossings) are known to have leaked in the earthquake, subsequent surveys (by the 1990s) showed that the pipes were laterally deflected, with some ball joints at their 15° limits, but without evidence of water leaks. The provisional fragility model of $k_1 = 0.25$ may be reasonable.

- Tunnel. None of the 11 brick-lined tunnels collapsed in the 1906 earthquake, and the forecast of 0.03 repairs is reasonable. In 1982, one of the authors, Dr. Hall, walked through the 1862-vintage San Andreas reservoir outlet tunnel (so-called "Bald Hill" tunnel), and he observed the tunnel to be in good condition, except for one central location where the tunnel was ovalized, possibly due to some 120 years of squeezing ground, but almost certainly not due to ground shaking in the 1906 earthquake. The squeezed tunnel location (about mid-way along its length) more-or-less corresponds to the location of the Serra fault, but detailed survey of the squeezed tunnel was not done (a racoon chased Dr. Hall out of the tunnel).

- Flume. None of the 6 flumes failed in the earthquake. However, 1 flume along the Locks Creek raw water collection system (not included in the SERA model) did collapse, where it paralleled the San Andreas fault and was likely exposed to PGA ~0.7g / PGV ~ 90 cm/sec (median level). Another flume (part of the Locks Creek system) collapsed due to a landslide. The k_1 value (1.0) for fragility modeling of the 1906-era wood flumes appears reasonable, but in actual practice, the designer should compute the seismic withstand capability of the actual flume design. For flumes or wood trestles, the fragility level should factor in the actual lateral load capability, and should be adjusted to consider the effects of wood degradation over time.

Table 5. Length of Conduit Exposed to Liquefaction Hazards

Pipe Alignment Exposed (Miles) to PGDs	Miles
Zero PGD	64.4
1 – 4 inch PGD	18.6
4 – 12 inch PGD	0.6
12 – 24 inch PGD	0.2
24+ inches PGD	1.3

Table 6. Length of Conduit Exposed to PGV Hazards

PGV (cm/sec)	WI km	WI-thin km	CI km	CI-Bell km	Tunnel km	Flume km
10-20	2.4	0.0	0.0	0.0	2.5	3.6
20-30	0.9	0.0	0.0	0.0	0.0	0.0
30-40	7.5	0.0	0.0	0.0	0.0	0.0
40-50	8.5	0.0	0.0	0.4	1.4	0.0
50-60	16.4	0.0	0.3	8.9	0.4	1.1
60-70	9.5	0.0	0.0	0.0	1.0	0.0
70-80	17.0	4.6	0.8	0.0	0.0	0.8
80-90	14.0	4.7	0.0	0.0	1.1	0.0
90+	28.5	3.4	0.3	0.0	0.0	0.1
Total (km)	104.7	12.7	1.4	9.3	6.4	5.6

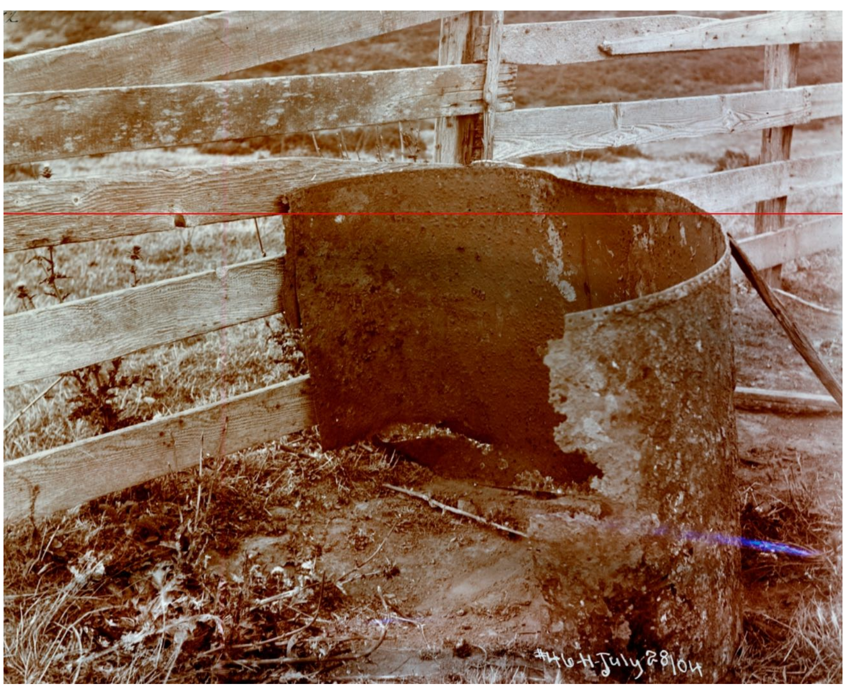

Figure 4. Failure of Pilarcitos 30" Low Pressure Pipe (WI-thin), July 28 1904

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, 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). In 1904, a 500 foot length of the 30-inch Pilarcitos pipeline (thin walled WI pipe directly east of San Andreas reservoir) failed: Figure 4 indicates the 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 the pipe traversed creeks, support the pipe atop a short wooden trestle over the creek. Figure 5 shows one such installation, constructed in 1907, supporting a 30-inch pipeline (a portion of the same Pilarcitos pipe that was dug up after the 1906 earthquake). 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. 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. 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, and at locations with high inertial shaking coupled with hydrodynamic loading. The strength of the girth joints was set to be one half that of longitudinal joints. This design assured that at locations where the pipe would sustain axial (longitudinal) elastic stresses much over 20 ksi, the girth joint rivets would break, resulting in a pipe break, which happened at 24 places with D/t > 250. 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.

- 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 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, which suffered a great amount of damage, was the thinnest-walled pipe in the transmission pipe, with t = 0.104-inches where hydrostatic pressures were less than 70 psi.

Pipes on Trestles. Of the 43 reaches of pipe supported on wooden trestles (Table 1), 6 reaches of pipe failed, due to inertial overload on the combined pipe / trestle system, coupled with the effects of liquefaction on the pile-supported trestles. 37 reaches of pipe atop wooden trestles survived without need for any immediate repairs.

The Pilarcitos 30-inch WI pipe (thin wall) pipe collapsed at two trestle locations (one ~100-foot long trestle, one ~60-foot long trestle), with about 160 feet of pipe broken and the two wooden trestles collapsed or with major damage. The San Andreas 37-inch WI pipe broke atop one trestle, where an expansion joint pulled open, requiring repair to 2 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 design of the Pilarcitos, Crystal Springs and San Andreas pipes on trestles provided gravity support; the pipe was commonly laid on wood stringers, supported only at the pipe's invert, and with the pipe free to slide sideways under seismic inertial loads. Restrained slip joints were placed about every 300 feet, to allow for thermal growth / contraction of the pipe. 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, 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, the pipe moved sideways 4 to 5 feet and fell off the trestle over a length of some 2,850 feet; except at the slip joint locations, the remaining pipe was almost uninjured, and once the trestle was repaired, the uninjured pipe was replaced atop the repaired wooden trestle.

1906 Earthquake Performance

Schussler (1906) provides an excellent treatment of the damage to the various pipelines and other SVWC facilities, including some 50 photos of the damage. Herein, we include a few additional photos that help explain the damage.

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 5. 30-inch Pilarcitos Pipe at Creek Crossing (1907)

Figure 6. 30-inch Pilarcitos Pipe Preparation of a Riveted Joint (1907)

After the 1906 earthquake, the southern reach of the Pilarcitos pipeline was abandoned, and the pipe was excavated and re-used to build portions of the Baden-Merced pipe constructed in 1907. Figure 5 shows the 30-inch pipe atop a trestle at creek crossing: the 15 wooden "steeples" are to support wood planking (not yet placed) to enclose the pipe against effects of external corrosion. Figure 6 shows the common buried pipe installation in the sandstone-like 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 (Figure 2) would be sufficient to continuously meet demand while repairs are made.

There were commonly 80 rivets for each girth joint. 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 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 has 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.

Pipes at Fault Crossings. There were 6 locations where pipes crossed the primary offset zone of the San Andreas fault: 5 along the Pilarcitos conduit and 1 on the Locks Creek raw water collection system. The 22-inch CI Pilarcitos pipe was exposed to primary fault offset (about 10 feet PGD) (FX-5 in Figure 3), and 4 segments of CI pipe were broken at this location. 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), 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, and there was no evidence of pipe wrinkling as a failure mode. The 44-inch WI Locks Creek pipe failed with several broken segments where it crossed the San Andreas fault (FX-6 in Figure 3).

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 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 leak. Today (2023), this 1923 vintage pipe has been replaced with a butt welded steel pipe (D/t = 80), designed to accommodate 6.5 feet of right lateral offset.

Seismic Deficiencies of 1906 and Strategies for 2023. 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 dashed line in Figure 3.

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 southeast 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 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 1, he was probably unaware of the presence and location San Andreas fault, which was not officially recognized until 1895. When built in 1865, 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 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 (2023), 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 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.

Table 7 documents the observed fault offsets around San Andreas Reservoir in 1906. The data in Table 7 is based on fault slip reported by Schussler (1906), Lawson (1908) and Pampeyan (1983).

- Slip across the zone of active faulting included both discreet offsets, especially the main trace and perhaps one or more subsidiary traces, plus ground warping. Total slip and ground warping was about 13 to 17 feet.

- The magnitude of concentrated strain recorded by the fences, i.e., the main trace and major source of engineering concern, varied in amount of right slip from ~6 to 9 feet and averaged 7.5 feet. One or two subsidiary traces were often also observed and varied in right slip from < 2 feet to 3.4 feet. Combined, the concentrated slip across the fault zone ranged from 10 to 11 feet.

- Photographs and field observations indicate that the width of the main trace by itself typically varied from 2.5± to 10 feet, but northeast-trending fractures branching primarily from the east side of the fault were also common. 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).

Table 7. Fault Offsets in the San Andreas Valley

Feature (NW to SE)	1906 Fault Slip (feet) West to East	Corresponding Location in Schussler (1906) or Lawson (1908)
FX-1, Fence 1	6, 2, 1; ~9 total	Schussler Site D, Lawson Fig. 29
FX-2	No data	Schussler between Site D-E
North of FX-3	7.2	Schussler Site E
FX-3	6.8	Schussler Site F
FX-4, Fence 2	3 (west trace), 7 (east trace); ~10 total	Schussler Site G
San Andreas Outlet Works	8.25 in tunnel	Schussler Site I, Lawson Fig. 35
Road Across S.A. Dam Crest	7	Schussler Site J, Lawson Fig. 36
S.A. Dam Wastewater Tunnel	8.25 in brick tunnel	Schussler Site K, Lawson Fig. 36
Fence 3, Lawson Fence B	8.75, ~1, 2 traces	Schussler Site L, Lawson Fig. 37
FX-5	6.7	Schussler Site M, M'
Fence 4, Lawson Site A	9.3 (east trace), 3.4 (west trace); 12.7 total	Schussler Site N, Lawson Fig. 38
Fence 5	9, 40' warp zone	Schussler Site N', Lawson PL 61B
FX-6	11.6	Schussler Site O, Lawson Fig. 39
Hayward Dam (submerged)	7	Pre-1887 earthen embankment
Upper CS Outlet Tunnel	8.8	Schussler Site Q
Upper CS Dam, Road	8 to 9	Schussler Site R. Lawson Fig. 40

See Pampeyan (1983) for further description of the offsets in and around Crystal Springs reservoir (last 3 entries in Table 7).

Professor Darleth 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; Darleth also noted that there may have also been additional failures to still-buried portions of the pipe. Darleth describes that pipe wall thickness as t = 3/16 inches (observed at the above-ground portion at Frawley Canyon crossings); but review of plans and profiles and historical pipe purchase data indicates the wall thickness for the buried Pilarcitos pipe at t = 0.107 inches.

North of FX-1, the Pilarcitos pipe collapsed where it was mounted on wooden trestles across two small canyons (historical named Small and Large Frawley canyons in Figure 3). The trestle collapse at Large Frawley Canyon (about 100 feet long) was due to inertial overload, and not by fault offset. The trestle collapse at Small Frawley Canyon (about 60 feet long) was also influenced by inertial overload. The offset at nearby FX-1 may have influenced the manner of the pipe failure just south of Small Frawley Canyon, where the pipe wall collapsed (buckled) inwards, possibly influenced by sudden depressurization owing to the downstream collapsed of the trestle, or possibly influenced by the right lateral fault offset that would have significantly ovalized the thin-walled pipe. Darleth noted that the timber trestle at Large Frawley Canyon was heavily built, about 100 feet long and 25 feet in maximum height; Darleth noted that "some of the timbers were partly decayed, but the structure, certainly, was not weak".

Right slip reported across the zone of faulting in 1906, varied from a low of about 7 feet (at water pipe or dam locations), to nearly 17 feet (along a fence line). The width of zone of deformation (discrete right lateral displacements plus ground warping as recorded by Symington) 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 might not be of significant concern for pipeline performance, to the extent that modern pipes are designed to accommodate up to 1 foot of offset at any location.

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 feet for the Peninsula segment. If this is the case *and* if the annual slip rate assessment of 17 +/- 4 mm/yr.

from the trenching investigation at the nearby Filoli Estate is reasonable, 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, 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.

CONCLUSIONS

This paper 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. A close approximation of the actual damage was forecast using modern computer models, of the type outlined in ALA (2001) and (2005). Corrosion and earthquake-induced hydrodynamic loading led to serious damage on thin walled low pressure pipe with $D/t > 250$.

During the fifteen years prior to the 1906 earthquake, nearly 6,800 fires occurred in San Francisco; the fire department and the pre-1906 water system was adequate to prevent any large conflagrations. Still, Mr. Schussler, the Chief Engineer of the SVWC, was well aware of the vulnerability of the water system both due to weaknesses in the water transmission system, and ongoing failures in infirm ground areas in San Francisco. In 1893, the City of San Francisco denied SVWC's request to build new reservoirs and pipelines to provide for high fire flows along Market Street, avoiding the infirm ground areas South of Market. This failure to build reliable water pipes was a major contributing factor leading to the great conflagration.

The Serra fault did not have sympathetic fault offset in the 1906 earthquake, at least at the locations where it crossed the 1906-vintage pipes. In the past 30 years, there have been many observations of sympathetic fault offset, such as in the 1992 Landers earthquake, and in other large magnitude events around the world. Today, new essential pipes can be readily designed for 1 to 2 feet of sympathetic offset across this fault.

The San Andreas fault offset in 1906, as reported along or near the Pilarcitos pipeline, was commonly 7 to 10 feet. Today, one might design for up to 20 feet of offset if one were building a non-redundant essential pipeline across this fault.

CREDITS

The photos shown in Figures 4, 5, 6 are used with permission by the City of San Francisco. These 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.

UNITS AND ABBREVIATIONS

This paper 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. 1 inch = 25.4 mm. 1 foot = 0.3048 meters. 1 mile = 1.609 kilometers (km). D = pipe diameter (inches). t = wall thickness (inches). 1 pound = 4.48 Newtons. psf = pounds per square foot. 1 psf = 47.8803 Newton / square meter. M = moment magnitude. SVWC = Spring Valley Water Company. PGD = permanent ground deformation. PGV = peak ground velocity. mph = miles per hour. WI = Wrought Iron pipe. CI = Cast Iron pipe with push-on joints. CIB = Cast Iron pipe will belled joints. MGD = million gallons per day. 1 gallon (US measure) = 3.7854 liters. Fy = yield stress. Fu = tensile stress. 1 kip = 1,000 pounds. 1 ksi = 1 kip per square inch.

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