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

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Abstract: There can be no dispute that the failure to deliver water to fires soon after the 1906 earthquake allowed the initial fires to spread and ultimately destroy 80% of San Francisco's buildings. There are two key questions. First, why did the water distribution system fail to deliver water to hydrants? Second, has the salt water pipe system that was built in 1912, done much good? This paper presents the facts that led to the failures of the water distribution system in the 1906 earthquake, and examines the effectiveness of the salt water system in the 1989 earthquake. Both present-day systems are seismically vulnerable. In 2019, the Civil Grand Jury of San Francisco issued a report that the SFPUC should immediately get on with seismic upgrading the AWSS. In 2021, the SFPUC proposed a $6.1 billion program to seismically upgrade the salt water system by the year 2046. In the Author's opinion, a better approach is to upgrade the existing potable water system by replacing 50 miles of vulnerable pipes in liquefaction zones by the year 2032.

THE 1906 EARTHQUAKE AND FIRE

The Spring Valley Water Company (SVWC) built a potable water system from 1862 to 1905 that well served San Francisco, The system included 87 miles of transmission pipes and 430 miles of distribution pipes. There was no explicit seismic design for the 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 1. 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.

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Table 1. San Francisco Fire Losses, 1891 – 1904 (NFBU, 1905)

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

The 5:13 am April 18 1906 (local time) earthquake resulted strong ground shaking in the City. Liquefaction occurred along Mission Creek and Sullivan Marsh, through which all the main water distribution mains to the downtown areas traversed, see Figure 1. There were 299 breaks in the City's distribution water pipes. Of those mapped, 166 breaks (64%) occurred in areas that underwent liquefaction, and 92 breaks (36%) occurred in other areas. Every major distribution pipe delivering water from the terminal water reservoirs to the South of Market and Central Business District areas were broken.

Multiple fire ignitions occurred within a few minutes of the earthquake, in the South of Market area. The winds were light at the time of the earthquake (about 2 mph, from the southwest), and the initial fires spread slowly to involve most of the South of Market area. There were many subsequent ignitions that started north of Market Street and east of Sansome Street; all told, about 52 ignitions were reported in the first 24 hours after the earthquake. At all but 2 of the ignitions, there was no piped water available to fight these fires. By the end of the day April 18, the fires had spread westerly to involve much of the South of Market area, and the upper Mission area. On April 19, the winds shifted to blow about 10 to 15 mph from the west / southwest, and the fire spread into Union Square and Chinatown. The spread of the fire stopped at Telegraph Hill on April 20. The control of the fires was achieved as follows:

- Southern Extent. The fires South of Market Street burned southerly toward Islais Creek, and the spread was stopped by the end of the day April 18 once nearly all buildings had been consumed (thus no further fuel load), and where the fire had spread within a few hundred feet from Islais Creek, where the fire department drafted water from the Bay.

- Western Extent. The fires were controlled by modest fire flow water available from the higher elevation Laguna Honda zone, coupled with the wind shift from the southwest on April 19. The Laguna Honda zone never ran out of water.

- Eastern Extent. The fires never burned the Ferry Building or piers along the San Francisco Bay. Water drafted from the Bay, coupled with fire boats, saved the bulk of the buildings within a few hundred feet from the waterfront.

- Northern Extent. Water from the Laguna Honda zone stopped the fire.

- A heavy rain on April 21 brought the fires practically under control.

The components of the water system that were ineffective in stopping the spread of the fire included:

- Water from the two lower pressure zones serving the City. The 37-inch pipe delivering water to the lower zone, broke across Sullivan Marsh, in at least 9 locations. The parallel 22-inch and 16-inch pipes delivering water to the mid-level pressure zone, both broke across Mission Creek, in at least 15 locations. The failure of these pipes cut-off the entire waterfront and Central Business District from their normal source of water.

- Water in the 23 cisterns. Water was drafted from 2 of the 23 cisterns, but this had no material effect in controlling or preventing the spread of the fires.

- Water from the then-existing Olympic Club salt water system had a pipe that went down 2nd Avenue. This system could deliver salt water by gravity flow at a rate of 2,000 gpm. This salt water system was entirely undamaged by the earthquake. While there were hydrants on this pipeline adjacent to some of the initial ignitions, the system was ineffective controlling the initial ignitions or ultimate spread of the fire.

THE WATER SYSTEM, 1862 – 1905

Figure 1 shows the water distribution system serving San Francisco, as it existed just prior to the 1906 earthquake. At the south side of Figure 1 are 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 87 miles of transmission pipes. 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 dots show the location of where 299 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 1 by the diagonal hatched areas. Areas that suffered PGDs in either the 1906 or 1989 earthquakes are shown in Figure 2.

Not shown in Figure 1 are the planned Market Street and Industrial reservoirs (see Eidinger and Hall, 2023, for locations). By the early-1890s, the SVWC intended for them to be constructed to be part of a much-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. Critically, 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.

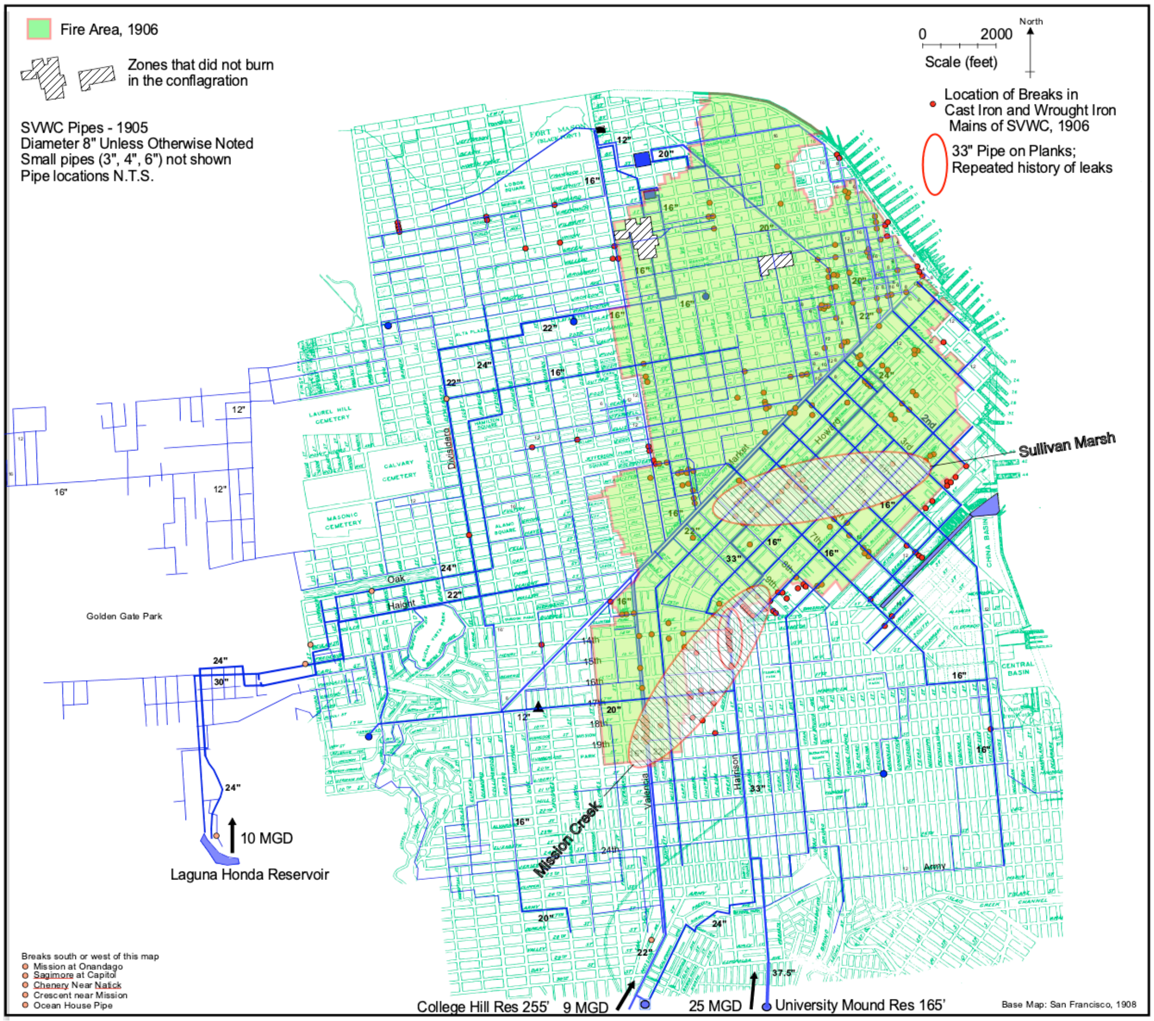

Figure 1. 1905 Water Pipe Breaks (Dots) in City Mains (Blue Lines) and Ultimate Fire Area

Table 2 lists the length of water pipe in the City Distribution system as of 1905. Table 3 gives the number of distribution pipe main breaks in the 1906 earthquake. The column "PGD 0 Inch" refers to locations where mains broke but where there were no observed Permanent Ground Deformations (PGDs) due to liquefaction. The category "36+" includes locations where PGDs reached as high as 72 inches. The PGDs are based on the estimated PGDs from historical photographs for each area. About 14% of all pipe main damage is not tabulated. Table 3 excludes damage to about 18,200 service laterals, the bulk of which occurred when buildings burned to the ground. Overall, there were about 1.47 repairs per 1,000 feet for pipes in zones that had PGDs.

Table 2. Length of Pipe in City Distribution System, 1905, Miles

Nominal Pipe Diameter (Inches)	Cast Iron Length (Miles)	Wrought Iron Length (Miles)	Total System Wide (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 3. City Distribution Pipe Damage Data

Pipe Diam Inch	PGD 0 Inch	PGD 1 Inch	PGD 2 Inch	PGD 3 In.	PGD 4 In.	PGD 5 In.	PGD 6 In.	PGD 8 In.	PGD 10 In.	PGD 12 In.	PGD 16 In.	PGD 18 In.	PGD 20 In.	PGD 24 In.	PGD 36+ In.
3-10	74	10	47	12	12	2	11	4	2	6	0	0	0	0	0
12	7	2	1	0	3	0	0	0	0	8	0	1	0	2	2
16	8	0	4	0	0	0	2	0	0	0	0	0	0	4	4
22	2	0	0	0	0	0	0	0	0	0	0	0	0	4	4
33	1	0	0	0	0	0	1	0	0	4	2	0	2	0	0
37	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0
Total	92	12	52	12	15	2	14	4	2	28	2	1	2	10	10

THE POLITICS OF THE WATER SYSTEM

Fact 1. The Spring Valley Water Company (SVWC) was the owner and operator of the water system serving San Francisco, from 1862 until 1930. Mr. Herman Schussler was the chief engineer for SVWC until his retirement in 1909. Mr. Schussler wrote and published a book about the 1906 earthquake, (Schussler, 1906) and in the author's opinion, this book remains perhaps the best record of what happened to a water system, ever written, in the history of the world.

Fact 2. Prior to 1860, there was no piped-water system in San Francisco. Beginning in the 1850s, City built underground cisterns (commonly 30,000 gallons each) to provide a local water supply to fight fires. Even so, fire conflagrations (fires that spread beyond the initial block) were then all too common in San Francisco, with several conflagrations in the 1850s.

Fact 3. Between 1862 and 1890, SVWC built four major water supplies to bring water into San Francisco, to meet the ever growing need for water for a population that had expanded from about 50,000 people in 1860 to nearly 400,000 people in 1905. See Eidinger and Hall (2023) for details of the transmission system and how it performed in the 1906 earthquake.

Fact 4. Between 1890 and 1905, nearly 6,800 fires occurred in San Francisco (see Table 1). Every one of these fires were controlled by the fire department, using the SVWC water system, and without large conflagration.

Fact 5. In 1893, Mr. Schussler appealed to the San Francisco Board of Supervisors to allow SVWC to build a new 20 MG reservoir at the head of Market Street, as well as a new 500 MG reservoir at the Industrial site (present day Balboa Park). A new large diameter pipeline was to be laid down Market Street, studded with hydrants, so as to prevent any fires that might start South of Market to spread to the Central Business District to the north. The Board of Supervisors denied these important extensions of the water system, and they were never built.

Fact 6. In 1895, a great fire occurred south of Market Street, after which the San Francisco Board of Supervisors 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 a new 12-inch or 16-inch pipe parallel to existing 6-inch or 8-inch pipes.

Fact 7. Then came the debacle with the new regime (Mayor James Phelan[2]) under a new City Charter (1900). Under the new regime, the City paid whatever they felt like paying, with payments to SVWC having a rapid decline after the year 1900. The City paid SVWC the following annual payments: 1898: $245,000. 1900: $226,000; 1902: $162,000; 1903: $93,000; 1906: $65,000.

[2] James Duval Phelan (1861 – 1930) served as Mayor of San Francisco from 1897 to 1902. As mayor, he advocated municipally-run utilities.

SVWC, faced with loss of funding, was compelled to decrease its extension of larger mains for fire purposes.

Fact 8. Then occurs the April 18 1906 earthquake and fire. Every major water main that brought water to the South of Market Street area, as well as downtown San Francisco, broke. All these pipes traversed major liquefaction zones. These zones were well known prior to the 1906 earthquake.

What was SVWC and Schussler doing? Schussler recognized that there was a serious weakness in the water system in the South of Market Street. The pipes were undersized to provide very high fire flows on many streets (6-inch and 8-nch) and all the water came from local reservoirs (University Mound and College Hill) via 16-, 22- and 37-inch cast iron and wrought iron pipes that all traversed major liquefaction zones. While the term liquefaction had not been established in 1906, both parties (SVWC and the City) were aware that the soils were constantly settling in these areas, water pipes (SVWC-owned) and sewers (City-owned) were breaking regularly. Schussler had plans (Schussler, 1909):

- Construct a large new reservoir (capacity 500,000,000 gallons) in the City, at elevation 310 feet. Water demand then averaged about 20 to 30 Million gallons per day, so this reservoir would provide about a 2 week supply in case the four conduits from the distant supply reservoirs would fail (which they did in the 1906 earthquake). But, the City (Board of Supervisors) in charge of water rates and was not inclined to allow for water rate increases. Schussler reported: "we had to live hand to mouth and practically stopped all work". The Industrial reservoir was never built.

- Construct a new reservoir at the head of Market Street on an elevated rocky knoll (capacity 16,000,000 to 20,000,000 gallons) to provide a large supply of water to a new independent large diameter pipe that would be laid down Market Street, studded with hydrants. The City answered by ordering a new Ridley Street be constructed through the reservoir site, putting a quietus on SVWC's plan for building a large fire protection reservoir right in the heart of the City. The Market Street reservoir and pipeline were never built.

THE AUXILIARY WATER SUPPLY SYSTEM (AWSS)

In 1903, the Board of Supervisors directed that plans should be developed for a "Salt Water System" for fire protection. Between 1903 and 1913, Mr. Grunsky, Mr. Marsden and Mr. O'Shaughnessy were successively San Francisco's City Engineers in charge of the design and construction of the Salt Water System. All three extolled the virtues of a City-owned parallel salt water system. Politically, it was important that this system not be owned by the privately-held SVWC. Mr. Grunsky outlined the Salt Water System as follows: (1903, Report of the 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.

Mr. Grunsky's report lays out a salt water system that is similar in many ways to the one that was actually built in 1912, and that was funded by a bond issue in 1909. This paper uses the historically-oft-used acronym "AWSS" to described the pipes and pumps and reservoirs of the system. Since 2020 or so, the SFPUC has been calling this the "EFWS", but the meaning is the same.

The 1912-vintage design specified the AWSS pipes as cast iron, as then 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 exceeded 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 the 1912-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 392.5 kips. The as-conceived restrained jointed connection (Py perhaps 30 kips, somewhat higher than the water thrust force) is much, much weaker than the pipe strength (Pu 392.5 kips). Therefore, when exposed to PGDs that impose high tensile (or bending) loads on the pipe, the restraining rods are expected 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 Mr. Grunsky was bound to fail whenever PGDs much over an inch or so 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 de-pressurized the grid (Figure 2), and the pipe failure in the Marina District prevented any water from the piped system 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-inch 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. Mr. Grunsky 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 oversold the 1903-version of a planned AWSS to an all-too-willing Board of Supervisors, who were then actively looking to put the SVWC out of business by constructing a parallel Hetch Hetchy water system. There was general disdain for private enterprise by the city's political leaders (Mayor Phelan and the majority of the Board of Supervisors), all reinforced by the constant clamoring and vitriol of the 4th Estate against the SVWC. How can 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, perhaps he was not serving the public well, as he failed to disclose that a parallel water system would be expensive to maintain, and possibly not work in earthquakes. It is the Author's opinion that the superior alternative was to seismically strengthen the potable water system; which was what Mr. Schussler had already recommended in 1893.

With the massive fire conflagration of 1906, the Citizens of San Francisco were impelled never to let "that" happen again. But solving "that" had a lot to do with Politics than actual wise engineering. The voters passed a bond issue in 1909 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 the 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.

In 1907, the Board of Supervisors authorized two engineers (Conniuck and Ransom) under the direction of the City Engineer, Marsden Manson, to develop a design and cost estimate for the AWSS. Figure 2 shows their design in 1908, and this was close to what was actually constructed between 1909 and 1912. This design had serious flaws, and was doomed to fail in future earthquakes. The AWSS pipe system was designed in 1908 to operate in three pressure zones:

- Lower Zone (blue pipes in Figure 2). This zone covers the area of the City under 150 foot elevation. The Lower zone is normally controlled hydraulically by the Jones Street Tank. The Lower Zone area (Figure 2) with the 1906 fire bound area (Figure 1) are nearly an exact duplication. Why? The thinking was that a future fire conflagration would be in about the same area as the 1906 conflagration. Of course, this was a dubious assumption, and in the 1989 Loma Prieta earthquake, the major fire was in the Marina district.

- Upper Zone (red pipes in Figure 2). 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.

- Marsden 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 was 3-inch diameter, and the head loss through the hose would be so high as to limit flows beyond ~500 feet practically useless. 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.

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 world;

- "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".

Why did O'Shaughnessy make these statements? Well, after the City had just spent some $6 million to build it, 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 the City and SVWC were then ongoing. The Author is hesitant to describe this boasting as a "lack of honesty" or evidence of "corruption", but the underlying issues point to the fact that the citizens of San Francisco have not been well served over the past 110 years by having a Municipally-owned fire-fighting salt water pipe system that did not work after the 1989 earthquake.

Clearly, O'Shaughnessy was wrong about the ability of cast iron pipes in the AWSS to survive intact after even a modest earthquake (like in 1989); 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, 2023, 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 (SFFD, 1911).

Schussler's 1893 design was for a large reservoir (16-20 MG) at the head of Market Street at 160 feet, and new large diameter pipe down the stable grounds of Market Street. The Market Street reservoir would have been fed from a 500 MG reservoir at 310 feet. This design, had it been built, would have likely saved much of San Francisco in the 1906 fire.

The AWSS design was fatally flawed from the instant it was put on paper. The City's design placed a large reservoir (10.5 MG) at Twin Peaks, and a large pipe down Market Street. This design was logical, and followed Schussler's 1893 concept. The choice of Twin Peaks rather than Market Street was perhaps only slightly unfortunate, in that having the water supply closer to the area to be protected is sound engineering.

The fatal flaw that the City adopted and built by 1912 was to extend the AWSS pipe system throughout the South of Market Street area, right through the liquefaction zones. The City then compounded this error in 1916-1927, by extending the piped water system into the man-made areas of the newly built Marina district on reclaimed land. The City was well aware that the cast iron pipes broke at hundreds of locations in the liquefiable grounds South of Market street in the 1906 earthquake. Schussler's plan avoided these areas entirely. A restrained heavy-walled cast iron pipe system is still seriously seismically vulnerable in areas prone to PGDs much over an inch or so. And these vulnerabilities were exposed in the 1989 Loma Prieta earthquake.

The majority of the 23 cisterns that existed at the time of the 1906 earthquake were located within the ultimate fire boundary, mostly within the areas burned in days 2 and 3 (April 19 and 20). The 11 cisterns in the area burned in Day 1 (essentially the South of Market and the Mission Creek areas) were entirely ineffective in controlling the initial ignition fires and the initial fire spread, even during Day 1, when winds were light.

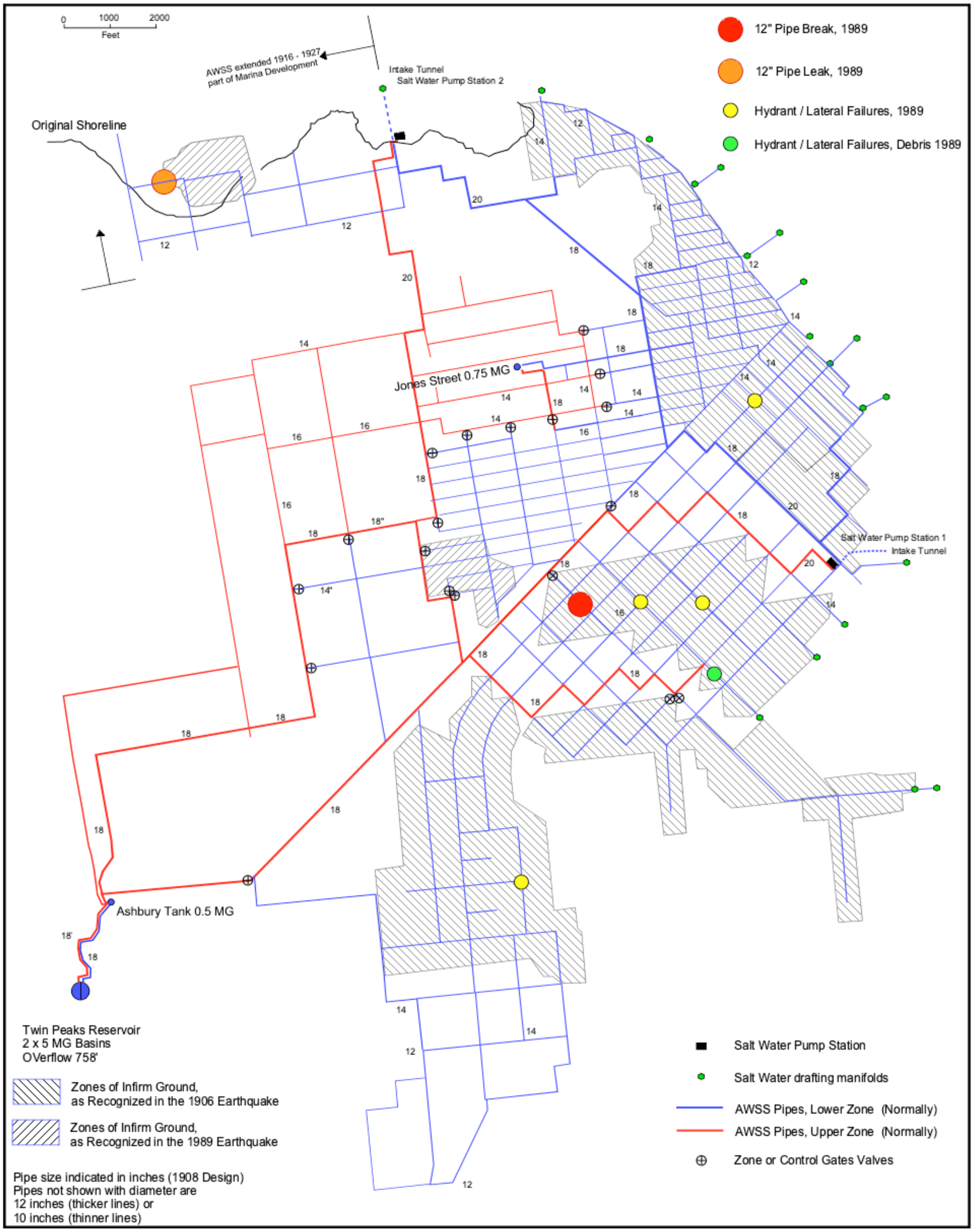

Figure 2. AWSS, 1908, and Marina Extensions, Zones of Infirm Ground, 1989 Damage

It is now (2023) apparent that Schussler's design was better than Grunsky's 1903 or Marsden's 1908 design. Critically, Schussler purposefully omitted the pipe grid that would extend into the infirm ground zones. In contrast, Grunsky, and later Marsden, included a substantial water pipe grid in the infirm ground areas, a serious and fatal flaw of the AWSS pipeline system.

Credit should be given to Grunsky and Marsden for placing the majority of new cisterns in the infirm ground zones. This recognizes that they knew that the SVWC and future AWSS pipe systems 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 nor the 1995 Kobe earthquake-caused fires. 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 1850 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.

In reviewing the 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 very modest levels of shaking and no PGDs; so 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. 7 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, much 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 re-supplied from the salt water pump stations). It is clear that Manson's initial 1909 design was seriously defective, as it assumed zero damage to the AWSS, or that any such damage would "somehow" not cause loss of pressure. Clearly, damaged pipes lead to ongoing 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 valves to isolate the leak will result in zero water 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 District was raging, and the primary 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, with a hydrant immediately adjacent to the large fire in the Marina District, not provide any fire flows? The lower zone could source water either from the Jones Street tank (by gravity flow), or by opening valves the higher elevation Ashbury Tank and Twin Peaks Reservoir (by gravity flow), or either salt water pump station (by pumped flow). The answer lies in several areas:

- One. Gravity flow was not available as the 7 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 San Francisco Fire Department, coupled with all available resources, was not equipped (manpower-wise or technology-wise or training-wise, considering the general difficult conditions after a large earthquake) to both rapidly find the initial pipe leaks in the AWSS and then send crews out there to valve out those leaks (or operate the system's few battery-powered gates valves). Had the leaks been valved out within 5-10 minutes of their occurrence, water from Jones Street tank (or higher Ashbury or Twin Peaks facilities) would have been available by gravity flow to control the large fire in the Marina area.

- Three. Why 5-10 minutes? If a 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.

- Four. Waiting nearly 3 hours for water supply via either the potable water or AWSS piped systems, as was the case in 1989, is not a sound fire-fighting strategy.

- Five. Fortunately, a pumper relay from the cosmetic pool at the nearby Exploratorium, and later via portable hose (5-inch hose) with suction from the nearby Bay, was available, and these modest fire flows were sufficient to control the actual fire in the Marina; "fortunately" as there was no wind.

But, lest the reader think that pumper relays and above ground 5-inch fire hoses are "perfect solutions", consider the following:

- In the 1991 Oakland Hills fire, a 5-inch portable hose system was deployed along Ocean Avenue to draft water from large diameter pipes with nearly inexhaustible supply to control a fire up hill along Ocean Avenue. During this operation, a TV news van drove over the hose, and broke it.

- Subsequently, a 5-inch 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 hypothetical fire ground at Oakland City Hall (about a mile inland, over flat terrain). During this demonstration, an AC Transit 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 about 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, and deploying ramps over the hose to allow cars to safely drive over the hose. During the test, the Author witnessed a car driving over a 5-inch pressurized hose (and fortunately not breaking the hose); but as evidenced by the city bus that pinched and broke a hose against a sidewalk curb with hose failure, and the news van ran over and broke a 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, increasing the chances for hose failures.

On the east side of the Bay, the East Bay Municipal Utilities District (EBMUD) does include Ultra Large Diameter Hose (ULDH, generally 12-inch diameter) as part of their modern (post-2000) 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 of water supply 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 generally feasible.

THE FUTURE OF THE SAN FRANCISCO WATER SYSTEM

In 2023, we know a lot more about earthquakes and the seismic design of water pipes than SVWC's Schussler and the San Francisco Chief Engineers Grunsky and Marsden and O'Shaughnessy knew in the early 1900s. Today, no other city on the West Coast of the USA runs two parallel water systems. Yes, redundancy is good. But, redundant systems that are both vulnerable to earthquakes make little sense.

Our modern design codes for the design of water systems (ALA 2005) provides explicit guidance with regards to redundancy. In a nutshell, ALA says:

- If you build a water system without redundancy, the essential pipes should be built for the highest (2,475-year return period) level of seismic hazard.

- If you build a water system with multiple levels of redundancy, essential pipes can be built for a high (475-year return period) level of seismic hazard.

The present owner and operator of the AWSS is the San Francisco Public Utilities Commission (SFPUC). The SFPUC issued a report in 2021 (SFPUC 2021) which recommends seismic upgrades to the piped AWSS system. These upgrades will cost $6.1 Billion, and be built over 25 years (complete by 2046). Ultimately, this would mean an increased water bill or equivalent in property taxes on the order of about $100 per month, for the average rate / tax payer. This is expensive.

The Author's opinion is that a better strategy would be to upgrade the existing potable water system, at a cost of about $180 million[3]. The strategy would be to replace all larger diameter Cast Iron and Ductile Iron pipe in the mapped liquefaction zones, over a 10-year period. The new pipe could be either Kubota Chained Earthquake Resistant Ductile Iron Pipe (ERDIP), butt-welded heavy wall steel pipe, fusion butt-welded HDPE pipe, or similar seismic-designed pipe. These seismic-designed pipes can readily accommodate up to a few feet of PGDs. There are under 50 miles of such pipe in the most liquefiable areas in San Francisco. At $3 million per mile, including appurtenances, laterals and hydrants, the cost is $150 million; say $180 million with permitting, design, inspection and project management costs. The new pipe could be installed at a rate of 5 miles per year over a ten year period.

The remainder of the ~1,200 miles of existing pipe in the existing potable water system can be replaced with seismic resistant pipe, as that existing pipe grows old and needs to be replaced. A reasonable and cost effective replacement cycle would be about 12 miles per year. These costs can be embedded in the normal capital program for the potable water system, and might not ever require an increase in the monthly water bills or taxes. Once these upgrades are complete, the existing potable water system will become a very formidable and reliable system to deliver water to hydrants after earthquakes. 10 years from now, the City can then abandon the expensive and vulnerable AWSS piped system, saving $6.1 billion at a cost of $180 million.

It can be argued that having more redundancy is a good thing. But, redundancy comes with a price tag. So, consider this:

- Potable Water System. This existing system already delivers water to hydrants on essentially every street in San Francisco. It provides adequate amounts of flow to control fires, as long as the fires are quickly identified and responded to.

- The AWSS pipe system currently services about 10% of the streets in San Francisco. The concept is that if a fire occurs at a point distant from the AWSS hydrant, that long 5-inch

[3] Actual costs may vary, considering competition, inflation, complexity and congestion, permitting, design and other factors. The cost of $3 million per mile of installed water distribution pipe reflects a 50% premium over the average cost to install water distribution pipe circa 2015 in the greater San Francisco Bay Area.

> hose will be connected to the hydrant and water delivered to the distant location. This strategy is clearly inferior to having a hydrant immediately adjacent to a fire, as in the potable water system, as to get water on a fire using AWSS (90% of the time) will require deploying 5-inch hose (allow 10 minutes), watching over the hose that no vehicles drive over the hose and break it. In other words, the AWSS system requires more time to deliver water to fires (90% of the time), and more manpower to deploy that system of hose. These are both serious flaws in the AWSS system, in that rapid response time is of the absolute essence to controlling a fire; and the $6.1 Billion program does not solve this underlying weakness.

CONCLUSIONS

This paper examines why the water pipes broke in the 1906 earthquake. The paper examines the politics of the water system leading up to the 1906 earthquake and fire, and observes that from 1893 to 1905, the City of San Francisco starved funds and otherwise blocked the SVWC from constructing a new parallel water reservoirs and pipes that would deliver vast amounts of water to control fires from spreading into the Central Business District from ignitions that could occur South of Market Street. Had those been built, the great conflagration in 1906 may have been avoided.

Between 1908 and 1912, the City designed and built its own parallel salt water pipe system. It was expanded into the Marina District by 1916. That design was fatally flawed from day 1. That pipe system was put to the test in the 1989 Loma Prieta earthquake, and failed to deliver water to the large fire in the Marina District.

What to do about all this? There can be no doubt that the City of San Francisco violates many modern concepts for fire resistance. Perhaps the most egregious flaw is that a large majority of wooden buildings have been built with no set-backs, meaning that once one building ignites, the fire can rapidly spread to engulf many adjacent buildings. With adverse conditions (loss of water supply, slow fire department response, windy conditions), conflagration can be expected.

The City continues to build cisterns. These have been almost entirely ineffective after large historic earthquakes. To the extent that these are low cost items, then spending more money on building and repairing them, is perhaps of low importance.

The City maintains fire boats and drafting pipes along the water front. This is a proven capable way to fight fires along the waterfront and perhaps a few hundred feet onshore.

The City maintains 5-inch hose. Across the Bay, EBMUD maintains 12-inch hose. Both are tools to move water over distance, but they take manpower to deploy, and are prone to failure if exposed to car or bus traffic. It takes more time to deploy hose than taking water from a nearby hydrant. For water brought in by hose over long distances, the fires are bigger by the time water is applied; and if it is a windy day, there is a greater chance of conflagration than if the water comes from a nearby hydrant. Yes, having hose is a good thing. No, hose is not a complete solution.

The City now owns two piped water systems: the potable water system and AWSS. Both systems are seismically vulnerable. A sound approach would be to upgrade the potable water system by initially installing 50 miles of seismic-resistant pipes in liquefaction zones, costing about $180 million over the next 10 years. An alternate plan, as proposed by the SFPUC, would cost $6.1 Billion over 25 years, would seismically upgrade the AWSS. Upgrading the AWSS system would allow that a portion (perhaps 10% to 25%) of all future fire ignitions will occur within 500 feet of a reliable hydrant. Upgrading the potable water system would result in nearly 100% of fires within 500 feet of a reliable hydrant. Long term, upgrading the potable water system appears to be the better approach.

UNITS AND ABBREVIATIONS

This paper makes use of common English and SI units. No attempt has been made to convert historical common English 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). 1 pound = 4.48 Newtons. psf = pounds per square foot. 1 psf = 47.8803 Newton / square meter. M = moment magnitude. PGD = permanent ground deformation. PGV = peak ground velocity. mph = miles per hour. ADD = Average Day Demand. MGD = million gallons per day. gpm = gallons per minute. 1 gallon (US measure) = 3.7854 liters. Py = yield strength. Pu = ultimate strength. 1 kip = 1,000 pounds. SFPUC = San Francisco Public Utilities Commission. SFFD = San Francisco Fire Department. SVWC = Spring Valley Water Company. EBMUD = East Bay Municipal Utilities District. ULDH = Ultra Large Diameter Hose. HDPE = High Density Polyethylene. NFBU = National Board of Underwriters.

REFERENCES

ALA, Seismic Guidelines for Water Pipelines, American Lifelines Alliance, March 2005, available at: http://www.geEngineeringSystems.com.

Civil Grand Jury, Act Now Before it is Too Late: Aggressively Expand and Enhance Our High-Pressure Emergency Firefighting Water Systems, City and County of San Francisco, 2019.

Eidinger, J. and Hall, N. Timothy, The Great San Francisco 1906 Earthquake: Why Did the Water Transmission Pipes Break at 49 Locations?, available at: http://www.geEngineeringSystems.com, 2023.

Grunsky, C. E., Report of the City Engineer, AWSS Plans, 1903.

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, July 23 1906.

Schussler, H. The Water Supply of San Francisco, Journal of Electricity Power and Gas, Volume XXIII, December 11, 1909.

SFFD, Civil service test, 1911.

SFPUC (2021). Report on AWSS, 25 Year Seismic Upgrade Plan Costing $6.1 Billion.