UPDATED SEISMIC FRAGILITY FOR WATER AND SEWER PIPELINES

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Abstract: *In 2001, the author led an industry-wide effort to quantify the seismic fragility of water pipes, documented in the report: Seismic Fragility of Water Systems (American Lifeline Alliance, ALA 2001). During the 23 years since that publication, the ALA (2001) report has been used widely in the world to forecast damage to buried water pipelines.*

In the last two decades, there have been a number of earthquakes, and further research into old earthquakes, that have substantially expanded the empirical database as to water pipeline performance. This paper presents updates to fragility models from the ALA (2001) report, as well as to extend the fragility models to cover additional classes of water pipelines that have come into widespread usage since 2001. These updated / new models include: thin-walled riveted steel (wrought iron) pipes (not commonly used for new construction today, but still prevalent in many older water systems); earthquake-resistant ductile iron pipes (such as those manufactured and in widespread use in Japan and becoming more prevalent in usage in the United States), high density polyethylene pipe; and different styles of steel pipe (reflecting different styles of girth joinery, as well as some vintage joinery systems for seam joints).

The paper makes suggestions how one might extend water pipe fragilities for wastewater pipes.

1. Background

The design of continuous water pipes is largely governed by the following two formulae:

$$\sigma = \frac{pr}{t} \text{ (hoop stress) (1)}$$

$$\sigma = \frac{pr}{2t} \text{ (longitudinal stress) (2)}$$

Where σ is stress, p is internal pressure, r is the radius of the pipe and t is the pipe wall thickness. By "continuous", it is mean pipes where each segment is joined with the next, such as welded steel (butt or slip girth joint), riveted steel (riveted girth joint), fusion butt welded high density polyethylene pipe, etc. For segmented pipe (like cast iron, PVC, Ductile Iron, or any other type of pipe that uses rubber gasketed (or similar) joinery between segments, the hoop stress formula is valid, and longitudinal stress is assumed as zero or nearly so. Some segmented pipes use restrained joints (like bars across slip joints) with the restraints designed for forces derived from equation (2).

These formulae have been well established and in use for over 175 years.

But, many types of water pipes have been regularly breaking in earthquakes over these 175 years. This is especially true for older materials (like cast iron and riveted steel that were commonly installed from about

1850 to 1965) as well as for many newer materials (like PVC, asbestos cement, ductile iron pipes that have been commonly installed from about 1955 to the present time).

In recent years (about 1990 to the present time) the newest water pipes (chained ductile iron, HDPE, butt welded steel) been installed in high seismic regions, and so far they have proven to be essentially immune from earthquake damage. But today, less than 10% / 1% of all water pipes in earthquake prone regions of Japan / the United States use these newer types of water pipes.

At the present time, 2024, on the order of 90% (Japan) / 99% (United States) of all water pipes in high seismic regions remain vulnerable. In other high seismic regions, like Peru, Chile, New Zealand, Taiwan, Greece, Italy, Turkey, Mexico and other locales, sometimes up to 100% of existing water pipe inventory remain seismically vulnerable.

Equation (1) remains valid in earthquake prone areas, but should be supplemented by a load case for earthquake-induced hydrodynamic pressure pulses. This supplemental load case may control girth joint design near bends for low pressure pipe. ALA (2005) provides further guidance for this supplemental load case.

Equation (2) is not satisfactory in earthquake prone areas, as it leads to girth joints in PGD zones that cannot sustain high seismic loading. Equation (2) should be supplemented with additional requirements for pipes subject to permanent ground deformations: for continuous and restrained pipe, all girth joints shall be designed to be stronger than the base pipe strength in the longitudinal direction with the intent that PGDs be accommodated by ductile response of the main body of the pipe; for chained pipes, all girth joints shall be designed to be able to resist soil friction forces accumulated over sufficient number of segments of pipe to accommodate the imposed ground deformation. ALA (2005) provides further guidance for girth joint design practices in zones subjected to PGDs.

2. Prior Seismic Fragility Models (ALA 2001)

In 2001, a group of engineers from water utilities, universities and consultants got together to study the seismic fragility of water pipes (ALA 2001). After examining the bulk of the worldwide evidence, they developed statistics of water pipeline damage, and developed water pipe fragility models. Equations (3) and (4) and Table 1 present the fragility models that were then established.

$RR = k_1 * 0.00187 * PGV$ (RR in repairs per 1,000 feet, PGV in inches / sec) (3a)

$RR = k_2 * 1.06 * PGD^{0.319}$ (RR in repairs per 1,000 feet, PGD in inches) (4a)

Or in metric units:

$RR = k_1 * 0.00243 * PGV$ (RR in repairs per km, PGV in cm / sec) (3b)

$RR = k_2 * 2.61 * PGD^{0.319}$ (RR in repairs per km, PGD in cm) (4b)

With the constants k1, k2 set per Table 1, and "small" diameter meaning 4 to 12 inch (100 to 300 mm) and "large" diameter meaning 16 inch (400 mm) and larger. These repair rates include damage to service laterals (up to the utility's meter) and appurtenances on the mains (air releases, blow offs, etc.). ALA (2001) also gives insight for adjustments for soil corrosivity and variations for very small diameter pipes (1 to 4 inch, 25 to 100 mm, these very small pipe diameters are rarely used for mains in modern water systems).

The computation of the seismic hazards PGV (horizontal ground shaking in terms of ground velocity) and PGD (permanent ground deformation) is done using seismic hazard models, which are not discussed in this paper. The final repair rate is taken as the maximum of the two hazards.

The basis of the fragility model and the empirical dataset behind Equations (3) and (4) and Table 1 are presented in ALA (2001), and are not repeated in their entirety here. The fragility model is for median (best estimate) of water pipe damage over reasonably large inventories of pipe (generally 100 miles / 160 km or more), and approaches are given to account for ranges of damage, given randomness and uncertainties in ground motions and pipe performance.

The empirical dataset used in 2001 considered water pipe damage from the following earthquakes:

- 1906 San Francisco (distribution system only); 1933 Long Beach; 1949 Puget Sound; 1965 Puget Sound; 1969 Santa Rosa; 1971 San Fernando; 1979 Imperial Valley; 1983 Coalinga; 1985 Mexico

City; 1987 Whittier; 1989 Tlahuac (Mexico); 1989 Loma Prieta; 1994 Northridge; 1995 Kobe (Japan); 1999 Izmit (Turkey); 1999 Chi-Chi (Taiwan); 2001 Gujarat (India)

Table 1. Pipe Constants for Equations (3) and (4). (per ALA (2001)

Pipe Type, Girth Joints	k1	k2
Cast iron, cemented joints, small diameter	1.0	1.0
Cast iron, rubber gasketed joints	0.8	0.8
Welded steel, lap arc welded joints, small diameter	0.6	
Welded steel, lap arc welded joints, large diameter	0.15	0.15
Welded steel, rubber gasketed joints, small diameter	0.7	0.7
Welded steel, screwed joints, small diameter	1.3	
Welded steel, riveted joints, small diameter	1.3	
Asbestos cement, rubber gasketed joints, small diameter	0.5	0.8
Asbestos cement, cemented joints, small diameter	1.0	1.0
Concrete with steel cylinder, lap welded joints, large diameter	0.7	0.6
Concrete with steel cylinder, cemented joints, large diameter	1.0	1.0
Concrete with steel cylinder, rubber gasketed joints, large diameter	0.8	0.7
PVC, rubber gasketed joints, small diameter	0.5	0.8
Ductile iron, rubber gasketed joints, small diameter	0.5	0.5

3. Fragility Models for Seismic Resistant Pipe

More than two decades have passed since the development of the ALA (2001) fragility models. A number of earthquakes have occurred since then, and more insight has been gained as to water pipe performance. A variety of water system vulnerability studies have been performed since 2001, and many of these studies have used the ALA (2001) fragility models, or some variant, at least as a reference point. Newer seismic-resistant water pipeline materials have been developed and many such pipes have been installed.

What have we learned since then? There have been many additional earthquakes with water pipe damage:

- 2001 M 8.4 Atico, Peru; 2003 M 6.3 San Simeon; 2010 M 6.0 Eureka; 2010 / 2011 M 7.1, M 6.5, M 6.0 Canterbury Christchurch sequence (New Zealand); 2011 M 9.0 Great Tohoku (Japan); 2011 M 8.8 Maule (Chile); 2014 M 6.4 Napa; 2016 M 7.0 Kumamoto (Japan); 2018 M 7.0 Anchorage; 2019 M 6.4, M 7.1 Ridgecrest; 2022 M 6.4 Ferndale.

The above earthquakes were studied by the author and other researchers. In all these events, there was water pipe damage. In all cases, the amount of damage could have been reasonably forecast using the ALA (2001) fragility models (generally within ±60% of actual observed damage). Including the evidence from these more recent earthquakes, should the form of the fragility models (linear vs. PGV for shaking, power rule vs. differential PGDs (liquefaction, landslide, fault offset) be revised? Should the pipe material adjustment factors be updated? The answers to these questions are "no" and "yes", respectively.

How well have the newer water pipe materials performed in these more recent earthquakes?

- HDPE. (High Density Polyethylene Pipe). HDPE has been the water pipe material of choice in some cities in Chile. In the 2011 Maule earthquake, there was a lot of water pipe damage to older cast iron distribution pipe but there was zero damage to HDPE water pipes, many exposed to PGVs of 50 cm/sec, and likely some PGDs.

- HDPE. In the September 2010 Canterbury earthquake, there was a lot of damage to asbestos cement water pipes, especially in zones subject to PGDs. The water utility installed HDPE pipe at locations where the AC pipe failed in the September 2010 event. In the intense shaking in the following February 2011 event (PGV over 100 cm/sec, PGD over 5 cm), none of the recently installed HDPE pipe failed.
- ERDIP (Earthquake Resistant Ductile Iron Pipe). Since the early 1990s, Kubota has developed ERDIP. This is ductile iron pipe with "chained" joints. By "chain", it is meant that every joint can extend / contract around 2 inches (5 cm), and rotate several degrees. If the extension / rotation is exceeded, the joint "locks up", and the force in the joint is transferred to the next "chained" joint. In this way, many chained joints act to accommodate PGDs; and PGVs are accommodated by the small movements at each joint. Just a limited inventory of ERDIP was installed at the time of the 1995 Kobe earthquake: none failed. After the 1995 Kobe earthquake, several (but not all) Japanese water utilities undertook programs to replace older large diameter (generally 300 mm to 600 mm pipe) in zones subject to PGDs or high forecast PGVs; and to install all new 150 to 200 mm distribution pipe with ERDIP. By the time of the 2011 Great Tohoku earthquake, 1000s of km of ERDIP mains were installed and subjected to a wide range of PGVs and PGDs (liquefaction mostly); none failed. This excellent performance was repeated in the 2016 Kumamoto Kyushu and 2018 Hokkaido earthquakes. To date in Japan, the author is aware of only 1 ERDIP pipe failure in any of these earthquakes (according to the manufacturer, the pipe was incorrectly installed); the important point is that the empirical repair rate is nearly zero. The reader is reminded that installing ERDIP for mains does not eliminate damage to service laterals.
- Butt welded heavy wall steel pipe ($D/t \leq 75$, without appurtenances in or near the PGD zones). Butt welded steel pipe with full penetration seam and girth joints, and with D/t ratios (D = diameter) of 50 to 75, have undergone many earthquakes in northern California, with, to date, not a single failure due to ground shaking. At least 6 of these pipes have been exposed to sharp fault offset PGDs on the order of 9 inches to 2 feet; none have leaked (but some yielded). Preliminary data suggest that one 3" diameter pipe leaked in the 2022 Ferndale earthquake; the underlying cause (apparently a few inches of PGD possibly in a high corrosive location) is still being examined.
- Butt welded medium wall steel pipe ($100 < D/t \leq 150$). There have been many failures of large diameter (24 to 48-inches, 600 - 1200 mm) butt welded steel pipe in Concepcion Chile. These were exposed to liquefaction PGDs on the order of 2 to 12 inches (5 to 30 cm) or so. Many welds ripped open. The underlying reason appears to be the use of partial penetration girth welds. Partial penetration welds are good enough to satisfy equation (2), but not good enough to allow the pipes to accommodate PGDs in a ductile manner.
- Slip-jointed large diameter steel pipe. At several locations along a 2-meter diameter steel pipe in the Great Tohoku earthquake, the slip joints blew open. The level of shaking at these locations was modest: on the order of PGV = 20 cm/sec. These slip joints were inserted into the pipe after long lengths (> 1 km) of continuous steel pipe. ALA (2005) provides formulae to calculate the opening movement of slip joints after long lengths of continuous pipe; and this would show the tendency for considerable opening (> 4 inches / 10 cm). Similar failures were observed on riveted wrought iron pipe in the 1906 earthquake, where slip joints opened up. While harnesses are commonly provided to ensure the slip joint does not open up entirely, the forces in these harnesses are often set at levels far lower than what would be needed to mobilize general yielding of the entire pipe; this results in a single slip joint trying to accommodate the entire differential motion cause by wave passage effects.

Table 2 provides pipe constants for these new pipe materials.

Table 2. Pipe Constants for Equations (3) and (4), Seismic Resistant Water Pipes

Pipe Type, Girth Joints	**k1**	**k2**
HDPE, Fusion Butt Welded, diameter up to 24 inches (600 mm)	0.01	0.01
ERDIP, Kubota, diameter up to 72 inches (1800 mm)	0.01	0.01
Welded steel, butt welded joints, all diameters, D/t < 75	0.01	0.01

The following applies for Table 2:

- The values k1, k2 = 0.01 are the same. No distinction is made between the three pipe materials. This reflects that the accumulated empirical evidence is not (yet) so strong as to establish more precise values. At this time all three types of pipes are considered "acceptable" for seismic performance. Any residual damage predicted using k = 0.01 should be accommodated by emergency response capability by the water utility. The values k1, k2 should not be set to zero (even though there could be zero damage in an actual earthquake), reflecting that there may be residual damage due to construction defects or other reasons. Additional damage on service laterals needs to be considered.
- Ductile Iron pipe. Must be provided with corrosion protection (sacrificial anodes, zinc coatings, etc.). Avoid installation in especially corrosive soils, such as those with resistivity < 750 ohm-cm.
- HDPE pipe must not be installed to rest on rigid objects such as other pipes, valves, as these can induce high local stress / strain concentrations, leading to short to moderate term creep-to-failures. This can be generally achieved by maintaining 12 inches (300 mm) spatial separation between HDPE and adjacent pipes. In locations with oil-contaminated soils, HDPE should not be used; or the pipe needs to be protected from exterior attack (for water used for drinking water purposes).
- Butt welded steel. Can be used in any location. Corrosion protection required, particularly for soils with resistivity Rho < 10,000 ohm-cm (and essential where Rho < 1,000 ohm-cm). For intermediate D/t ratios between 75 and 100, k2 increase to 0.02. For D/t ratio 125 to 150, k2 = 0.05. Special care is needed for high D/t pipes located in zones subject to slow moving surface waves (like the lake district in Mexico City), where wall buckling is possible.

Special attention is required for low pressure water pipes (such as steel pipe with D/t > 250). If these are designed using Equations (1) and (2) only, then there can be a very high failure rate at bends in the pipe. This reflects that under high seismic shaking, one can expect earthquake-induced hydrodynamic pressure pulses. ALA (2005) gives some guidance as to how to estimate these hydrodynamic water pulses. In lieu of more detailed evaluations, a fast-traveling water pulse pressure of 60 psi (4 bar) can be assumed under strong shaking (0.2g < PGA < 1.0g). As all water pipe design should includes (at least) a Factor of Safety of 2 on hoop stress (Equation 1), and generally a factor of safety of 3 on longitudinal forces near bends (Equation 2), as long as the pipe is designed for normal pressures between 100 to 150 psi (7 to 10 bar) (common for water systems), the hydrodynamic pressure load case should not control (but could induce some pin-hole failures where there has been accumulated corrosion). However, for low pressure pipes such as those designed for 30 psi (2 bar), a hydrodynamic pressure pulse of 60 psi (4 bar) may grossly overload girth joints near bends, resulting in blow outs / leaks. High failure rates of low pressure water pipes have been observed in the 1906 San Francisco (described in this paper) and 1994 Northridge earthquakes.

4. 1906 Earthquake

ALA (2001) includes pipe damage data that occurred in the 430 miles of (mostly) cast iron water distribution pipe that served 380,000 people in San Francisco, but does not address damage to the 73 miles of (mostly) riveted wrought iron transmission pipes. This section examines the performance of these pipes.

Figure 1 (G&E, 2023) is a map that shows the distribution water pipes in San Francisco, and the red dots show locations of known pipe main damage (258 pipe failures). There were 41 additional pipe main failures, of which 5 are known to be outside any PGD zone; the location of the remaining 36 failures is uncertain. The blue lines show 8-inch (200 mm) diameter and larger water mains. Smaller diameter water mains (some 3 and 4, mostly 6-inch) (75, 100, 150 mm) are not drawn. The yellow zone shows the ultimate burned area of the fire conflagration. The hashed ovals show the major liquefaction zones.

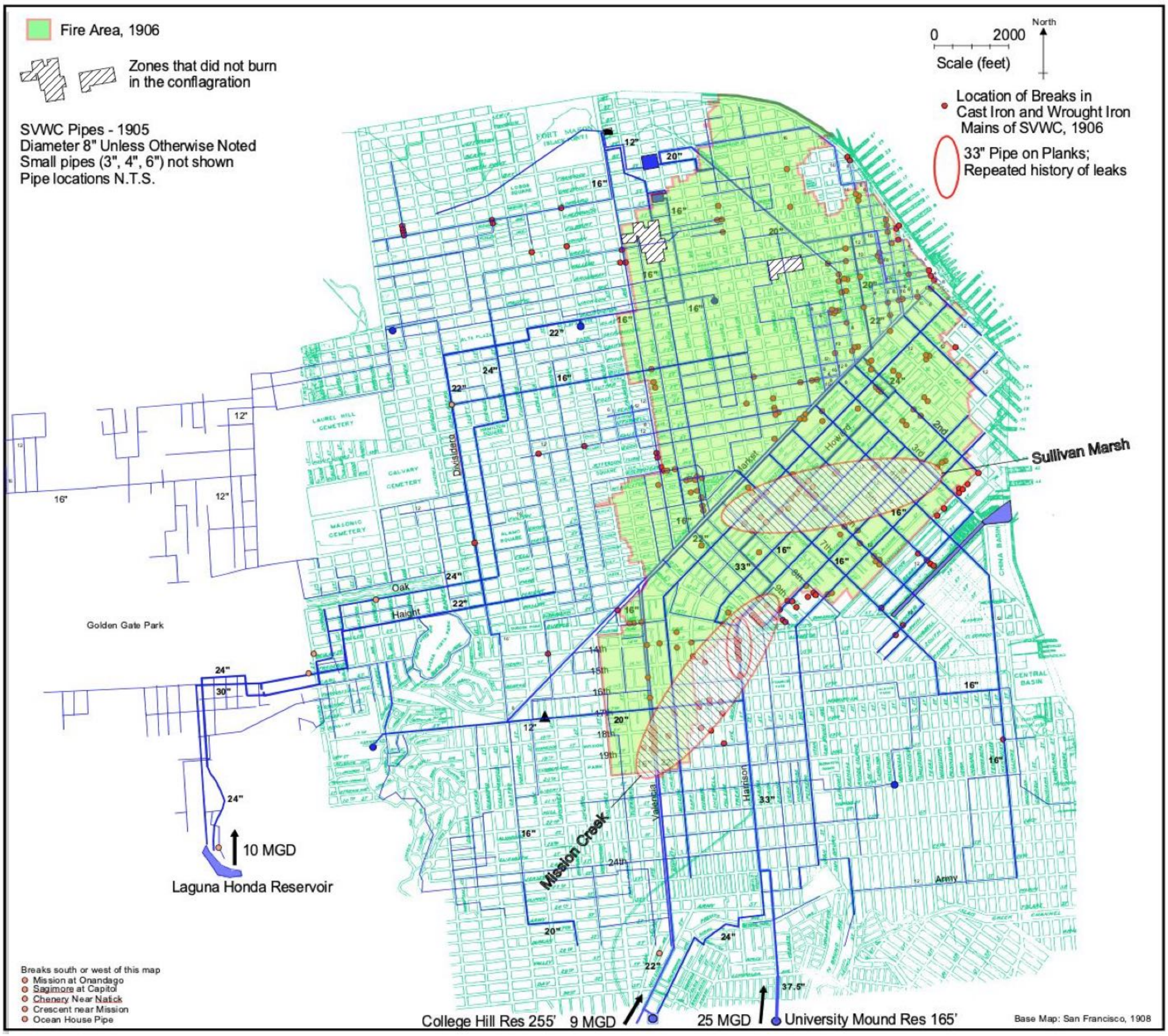

Figure 1. City Distribution System Water Pipes in 1906

Figure 2 (G&E, 2023) is a map showing the 4 transmission water conduits that brought water to San Francisco in 1906. The heavy red dashed line is the location of surface rupture along San Andreas fault in 1906. All 4 conduits sustained damaged (Pilarcitos = purple, San Andreas = red, Crystal Springs = green, and Alameda = blue).

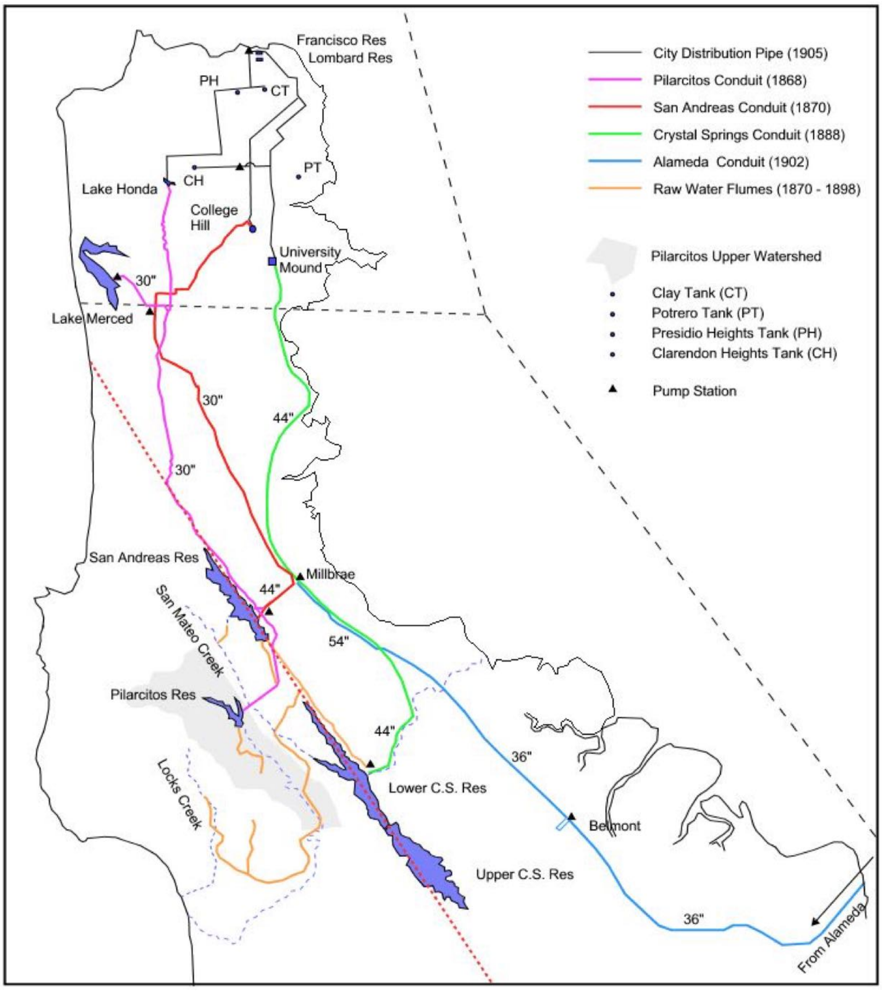

Figure 2. Large Diameter Water Transmission Conduits Serving San Francisco in 1906

Table 3. Number of Pipe Failures in Distribution System, 1906 San Francisco Earthquake

PGD inch: cm:	0 0	1 2	2 5	3 7	4 10	5 12	6 15	8 20	10 25	12 30	16 40	18 45	20 50	24 60	<44 <111
Diameter Inch (mm)															
≤ 2 (≤ 50)	40	5	20	1	3	2	7	3	0	2	0	0	0	0	0
3 - 10 (75 - 250)	34	5	27	11	9	0	4	1	2	4	0	0	0	0	0
12 (300)	7	2	1	0	3	0	0	0	0	8	0	1	0	2	2
16 (400)	8	0	4	0	0	0	2	0	0	0	0	0	0	4	4
22 (560)	2	0	0	0	0	0	0	0	0	0	0	0	0	4	4
33 (840)	1	0	0	0	0	0	1	0	0	4	2	0	2	0	0
37 (940)	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

Table 3 shows the repair rate was about 1.47 repairs per 1,000 feet for pipes in PGD zones that liquefied. The repair rate for large diameter wrought iron pipe is higher than the average, in part that the wrought iron pipe was exposed to particularly high PGDs (often over 2 feet) along Valencia and Harrison.

Table 3 excludes the damage to service laterals, commonly with diameter 1 inch (25 mm) or smaller. Schussler (1906) noted 18,200 damaged service laterals. The vast majority of the damaged service laterals reflect that as structures burned, they destroyed their own service laterals. Some laterals were also damaged due to the impact of fallen brick work from the damaged buildings. The available data is not sufficient to differentiate the damage to service laterals due to PGV / PGD effects from those from fire / fallen debris effects. Generally, laterals would be relatively short, commonly under 20 feet to the meter or under 60 feet to the edge of a structure (6 to 20 meters). Based on ALA (2001), one might suggest that about 60 laterals might have been damaged just due to the effects of ground shaking.

At the time of the 1906 earthquake, the regional supply system consisted of 4 conduits, see Table 4. By "conduit", it is meant a combination of buried pipe, pipe on trestles, flumes and tunnels. Table 5 lists the end-to-end length of each conduit, which is the sum of Pipe + Tunnel + Flume lengths, or 87 miles (140 km). Nearly all pipe was riveted Wrought Iron (WI). The Pilarcitos conduit included short lengths of Cast Iron (CI) pipe. The Alameda Conduit included two sets of parallel cast iron pipe with ball joints (CIB) through two submarine crossings of San Francisco Bay. All tunnels were bored and brick-lined. All trestles were wood. All flumes were wood.

Table 4. Transmission Pipe Inventory (WI = Wrought Iron; CI = Cast Iron; CIB = Cast Iron with Ball joints)

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

Table 5. Length of Transmission Pipe

Conduit	Pipe Length (miles)	Tunnel Length (miles)	Trestle Length (miles)	Flume Length (miles)	Submarine Length (miles)
Pilarcitos	13.08	1.47	0.14	1.39	0.00
San Andreas	13.34	0.53	0.34	0.00	0.00
Crystal Springs	16.58	0.41	1.62	0.00	0.00
Alameda	29.98	2.79	3.12	2.15	5.47
Total (miles)	72.98	5.20	5.21	3.55	5.47
Total (km)	117.40	8.37	8.39	5.71	8.81

Table 6 shows the damage to the Water Transmission System. In Table 6, a pipe break "segment" is the equivalent number of 10-foot (3 meter) long segments that would have to be replaced / re-laid in order to put the pipe back in service. About 2,850 feet (860 meters) of the Crystal Springs 44" (1,100 mm) pipe fell off its support trestles; once the trestles were repaired, the undamaged pipe was replaced atop the wood trestle, and about 14 damaged slip joints repaired; other girth joints showed no distress.

Table 6. Transmission Pipe Damage in the 1906 Earthquake

Conduit	Fault Offset Locations Actual	Collapsed Trestles / Flumes Actual	Pipe Repair Locations Actual	Pipe Break Segments Actual	Pipe Break Segments Forecast	Time to Restore Water Service
Pilarcitos	5	2	31+	~60	33.9	16 hours
San Andreas	0	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	5	5	49	91	73.1	

In Table 6 the term "break" is used to denote a loss of the pressure boundary, requiring the pipe to be shut down. Table 6 excludes damage that did not require repair in order to restore water service in the system. The "Actual" values in Table 6 are based on Schussler's account of the 1906 earthquake (1906).

The "Forecast" values in Table 6 are based on using the "Revised" fragility models in Table 7. To make the forecast, the 1906-era pipe transmission system was digitized, and a forecast of pipe damage was made using modern ground motion attenuation models, and the damage to the pipes was computed using fragility models. Revised fragility models from ALA (2001) are listed in Table 7. For thin-wall Wrought Iron pipe, the k_1 in the analyses was revised from 1.3 to 3.4, to reflect a combination of accumulated corrosion and hydrodynamic loading on the pipe. Table 7 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 (repeat of the 1906 earthquake), the damage due to shaking is increased by 40% to reflect the longer duration of motion (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 7. Updated Fragility Models

Pipe Type	ALA (2001) k1	Revised (2024) k1
Wrought Iron, D/t ≤ 150, Riveted, Asphaltum Lining and Coating, Diam = 30" to 54"	1.3	0.3
Wrought Iron, D/t >180, Riveted, Asphaltum Lining and Coating, Diam = 30"	1.3	3.4
Cast Iron, D = 20" to 24"	0.5	0.5
Cast Iron, D = 16" to 22", Bell joints for submarine pipes	n.a.	0.25
Brick-Lined Tunnels	n.a.	0.03
Wooden Flume (no seismic design loads)	n.a.	1.0

The length of conduit exposed to median horizontal ground motions for the 1906 earthquake, in terms of PGV, are listed in Table 8. (Note: the lengths in Table 8 do not exactly match the total lengths in Table 5 due to the digitization process).

Table 8. Length of Conduit Exposed to Shaking 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

Figures 3 and 4 show the 30" riveted steel pipe of the era. Figure 3 shows that the thin-walled riveted pipe was prone to corrosion failure (this failure, in 1904, when the pipe was 36 years old). Figure 4 shows a section of the Pilarcitos pipe that was relocated in 1907 (note the riveter inside the pipe). The riveted girth joints were about 60% to 75% of the strength of the pipe (per equation 2), and wherever the pipe was exposed to PGDs placing the joint in high tension, the rivets popped or the hole edges ripped open.

Figure 3. Failure of Pilarcitos 30-inch Low Pressure Pipe (WI-Thin), July 28 1904

Figure 4. Installation of Wrought Iron Riveted Pipe, 1907

The Pilarcitos pipeline suffered major damage in the 1906 earthquake. The evidence is that that pipe failed at 31 locations, of which 5 were due to fault offset, 1 was due to the collapse of a wooden trestle bridge, 1 was due to rapid decompression. For the 24 locations where the Pilarcitos pipeline failed, the hazard was due to strong ground shaking; and at every such location, the pipe was thin-walled ($180 < D/t < 310$). The Pilarcitos pipeline had no breaks due to shaking where D/t was < 150. Table 9 provides the breakdown, with each "repair location" denoting a location of failure, which could include the failure of a single girth joint, or the outright collapse of up to 50 feet of pipe. In Table 6, a "break segment" is the number of 10-foot-long equivalent pipe segments that were damaged. This is a puzzling observation, as the general consensus has been that pipe with continuous joints (as was the vast majority of the Pilarcitos pipeline) is almost immune from breakage due to ground shaking.

So, why were there so many failures of the Pilarcitos pipeline? If one adopts the fragility models in ALA (2001), one obtains the following forecast of damage. Assumption. Use k_1 = 1.0 (Cast Iron) and k1 = 1.3 (Riveted). Then using median PGV motions, the forecast would be 5.4 repairs due to shaking over entire pipe length. However, the actual observed damage due to shaking was 24 repairs due to shaking over the entire pipe length.

Therefore, the ALA (2001) fragility model substantially under-predicts the actual damage to the Pilarcitos pipeline, by about a factor of 4. The reasons for under-forecast of damage could be:

- The forecast median level of shaking is too low. But, this is doubtful, as even if one used the 84^{th} PGV motions over the entire pipe length (extremely dubious, but certainly an upper bound), the forecast is 9.5 repairs (still much lower than observed 24).
- There was sympathetic movement of the Serra fault along the pipeline, that might have led to 1, 2 or 3 extra repairs. But modern observations by the author suggest that there was no observable sympathetic offset of the Serra fault in the 1906 event; but it cannot be discounted.
- There were landslides or liquefaction hazards along the Pilarcitos pipe that triggered PGDs that led to the extra damage. This might add 1 or 2 repairs over the length, but today (2024) there is no direct evidence for such PGDs.

The evidence strongly suggests that the k_1 factor for the 30" Pilarcitos pipe (k_1 = 1.3 in ALA 2001) is too low. In ALA (2001), the k_1 factor for riveted steel pipe was set at twice that for small diameter welded steel pipe with single lap girth welds. This was based on limited evidence, as in ALA 2001, there were very few riveted pipes in the empirical dataset, and none were "thin-walled".

Table 9. Length of Pilarcitos Pipeline Exposed to Various Hazards

Seg	Length (feet)	Description	PGV med cm/s	Total Rprs	PGD Rprs	PGV Rprs	Maximum Pressure psi	Pipe t min (inch)
1	1,495	Tunnel	72	0	0	0	5	
2	298	Flume	85	0	0	0	5	
3	3,426	Tunnel	76	0	0	0	5	
4	730	44-inch WI	77	0	0	0	45	0.099
5	2,135	Flume	77	0	0	0	5	
6	2,000	24-inch CI	89	2	1	1	130	0.285
7	13,000	30-inch WI	76	5	0	5	61	0.092
8	10,000	30-inch WI	89	12	4	8	61	0.092
9	5,000	30-inch WI LFC	76	7	2	5	74	0.111
10	10,000	30-inch WI	81	5	0	5	108	0.162
11	10,000	30-inch WI	91	0	0	0	182	0.273
12	10,000	30-inch WI	85	0	0	0	152	0.228
13	7,383	30-inch WI	73	0	0	0	152	0.228
14	5,230	Flume	61	0	0	0	5	
15	940	30" WI	61	0	0	0	17	0.228
16	2,820	Tunnel	53	0	0	0	5	
		Total		31	7	24		

5. Sewer (Wastewater) Pipes

The author has noted that a number of researchers have adopted ALA (2001) water pipe fragilities for the seismic evaluation of sewer (wastewater) pipes. The author notes that the "k1 and k2" constants and the backbone fragility curves (Tables 1, 2, 7, equations 3 and 4) for water pipes were not originally developed for purposes of forecasting sewer pipe damage.

As compared to water pipes, sewer pipes are made from materials that are often much more resilient to interior corrosion, and most sewer pipes operate as gravity flow. Sewer pipe breaks often do not manifest themselves by leaking liquid to street levels. After an earthquake, damaged sewer pipes can be indicated by sudden large increases in flows into wastewater treatment plants due to infiltration, suggesting that sewer pipes have broken; or cut-off of flow to the treatment plants entirely if the damage is severe enough. Sewer pipe breaks can often be found by interior camera inspections.

It is suggested to provisionally use k1 = k2 = 1.0 and equations (3) and (4) for many types of gravity sewer pipes, including cast iron, segmented concrete, vitrified clay, brick. Where rubber gaskets are used for plastic or lined ductile iron pipe, consider k1 = 0.5 and k2 = 0.8. Sewer pipes are often located at much deeper cover depths than water pipes, so PGDs should be computed at the depth of the sewer pipe invert. Additional damage due to sewer pipe / manhole uplift in liquefaction zones should also be estimated. Damage to sewer laterals (customer or utility-owned) should also be estimated.

The importance of seismic upgrades of sewer pipes is very different from water pipes. Repair of sewer pipes can be much more costly (due to much deeper cover) than repair of water pipes. The damage to water pipes can lead to large losses to the community due to fires after earthquakes; fires have been critical impacts after several historical earthquakes. The damage to sewer pipes can lead to environmental impacts to the community (uncontrolled overflows); but such impacts have apparently not had (yet) critical impacts in historical earthquakes.

6. Units, Abbreviations, Credits

All pipe dimensions are listed in inches (1 inch = 25.4 mm). The pipe diameters are nominal, and reflect the common practice in 1906. For pipes with diameter 12 inches and larger, the nominal diameters reflect the wetted inside diameter plus the thickness of the lining (coat tar lining for wrought iron pipes, no lining for cast iron pipes). For pipes under 12 inch diameter, the inside diameter may vary from the nominal value by about 0.25 inches, depending on pressure class. The metric equivalents are listed in millimeters (mm), centimeters (cm) or meters (m), are rounded from the nominal diameter.

Distances are listed in feet or miles (1 mile = 5,280 feet) or kilometers (km) (1 mile = 1.609 km).

CI = Cast Iron. CIB = Cast Iron with Belled ends. WI = Wrought Iron. PVC = Polyvinyl Chloride. AC = Asbestos Cement. HDPE = High Density Polyethylene. PGA = Peak Ground Acceleration. PGV = Peak Ground Velocity (horizontal). PGD = Permanent Ground Deformation. ALA = American Lifelines Alliance. M = Moment Magnitude. ERDIP = Earthquake Resistant Ductile Iron Pipe. cm = centimeters. mm = millimeters. km = kilometers. D = diameter. t = pipe wall thickness. r = radius. g = acceleration of gravity (= 386.4 inches / second / second, = 9.81 meters / second / second). 1 bar = 14.5 pounds per square inch (psi). RR = repair rate.

Credits: Figures 1, 2: Used with permission, G&E Engineering Systems, Inc. Figures 3, 4: Used with permission, City of San Francisco.

7. References

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