The 1906 Earthquake Impacts on the San Francisco and Santa Clara Water Systems - What We Learned, and What We are Doing About It

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This paper describes what happened to San Francisco's water transmission and the City of Santa Clara water distribution systems in the 1906 and the more recent 1989 earthquakes. The 1906 and 1989 earthquakes showed that many of our existing transmission and distribution pipelines are susceptible to damage, and some of our older water treatment plants, tanks, pump stations need to be upgraded. Accordingly, seismic upgrade programs are being undertaken to reduce the vulnerability of the regional water transmission and distribution systems. In developing a cost effective seismic upgrade program, both the transmission system operator and distribution system operator (if different) must consider what the weaknesses are of both systems, so that the maximum amount of seismic upgrade can be achieved at the lowest overall cost.

INTRODUCTION

For the purpose of discussion, it is often convenient to distinguish between the transmission system, that delivers water to a jurisdiction, and the distribution system, that distributes water locally within the jurisdiction. In the 1906 earthquake, significant damage to both the San Francisco distribution and transmission systems was a factor that led to the largest urban fire loss in US history. In the months after the 1906 earthquake, the then-chief engineer Mr. Schussler embarked on a campaign to convince the City Fathers that something had to be done to prevent a re-occurrence of this disaster. As usual, politics, money and a desire to do what was right all played roles in what actually happened.

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Ultimately, through Mr. Schussler's efforts, and in conjunction with the Fire Department, a second (auxiliary) water system was built in San Francisco beginning in 1908. Unfortunately, even the best intentions could not live up to incomplete understanding of earthquake phenomena, and a single pipe failure coupled with slow emergency response prevented the auxiliary system from delivering water for fire flows in the 1989 Loma Prieta earthquake. Only a third system, using fire boats and flex hose, helped control fires in the Marina District in the 1989 earthquake.

While much attention has been placed on the development and performance of the San Francisco water system, it is instructive to also study other systems in similar circumstances. Today the City of San Francisco represents just 11% of the population in the greater San Francisco Bay Area. The current San Francisco Public Utilities Commission (SFPUC) water transmission system wholesales water to another 24% of the population of the bay area, for 29 water systems. In this paper, we also review seismic issues for one of these systems, the City of Santa Clara. The importance of the City of Santa Clara cannot be underestimated. It is located in the heart of Silicon Valley, and many vital companies, such as Intel, have large offices, research, development and manufacturing facilities there. With a population of about 100,000 people, and a gross regional product over $40 billion per year, the City of Santa Clara is one of the most economically vital cities in the nation, on a per capita basis.

This paper examines the water system improvements that the cities of San Francisco and Santa Clara have undertaken over the past 100 years and highlights further improvements that will be taken over the next decade to get ready for the next "Big One". A lot was learned from the 1906 and 1989 earthquakes. In the period from 1923 to 1965, the SFPUC built many redundant pipelines to meet the growing need for water. When building those pipelines, the SFPUC was careful to avoid, whenever possible, the liquefaction and fault crossing zones that devastated the 1906 system. Even so, not all of those pipelines avoided all the hazards, and the job today (2005) remains incomplete. Similarly, in preparation for future events, cities like Santa Clara have built many storage tanks between the mid-1950s and mid-1980s, to the then prevailing codes and standards. However, the 1989 earthquake showed that many older codes do not always provide the level of protection that is desirable.

The 1989 Loma Prieta earthquake was a big wake up call for the San Francisco Bay Area. In addition, the 1994 Northridge and 1995 Kobe earthquakes convinced the SFPUC and the City of Santa Clara that more work needed to get done. In the 1990 to 2018 period, the SFPUC and Santa Clara and other San Francisco Bay Area water utilities have and will take many more steps to secure a safe and reliable water supply. From 1990 to 2005, more than $300 million was spent to seismically upgrade water systems in the San Francisco Bay Area. From 2006 to 2018, another $1.7 billion or so will be spent.

The issues created by the 1906 earthquake damage to the City of San Francisco distribution system and subsequent fires are covered in detail in a companion paper in this volume (Scawthorn et al 2006).

DESCRIPTION OF THE TRANSMISSION SYSTEM THEN AND NOW

The SFPUC Hetch Hetchy water transmission system was first put into service in 1934, and has continuously undergone improvements ever since. The modern Hetch Hetchy system includes components inherited by the SFPUC from the Spring Valley Water Company. Today, the system includes a 167-mile long gravity-driven network of dams, reservoirs, tunnels, pump stations, aqueducts and pipelines that collect Tuolumne River runoff near Yosemite, as well as in local Bay Area watersheds in Alameda and San Mateo counties. In recent years, the SFPUC delivered an average of nearly 260 million gallons per day (MGD) to end users in the City of San Francisco and to 29 wholesalers / retailers (cities, water districts, public utilities and other institutions) in Alameda, Santa Clara and San Mateo counties.

Figure 1 shows a map of the current water transmission system in the local San Francisco Bay Area. In Sunol Valley, water from Yosemite is blended with water from the Sunol Valley Water Treatment Plant (WTP), and then heads westward. All of the SFPUC's seven major pipelines in Sunol Valley cross the Calaveras fault; some with multiple crossings. Then, the water is split into four pipelines, called the Bay Division Pipelines (BDPL) 1, 2, 3 and 4. BDPL 1 and 2 pipelines head westward, where they cross the Hayward fault, and then the Dumbarton Strait. BDPL 3 and 4 pipelines head southwards, around the San Francisco Bay, crossing through the cities of Fremont, Milpitas, San Jose, Santa Clara, Sunnyvale, Mountain View, Palo alto and Redwood City, where they joint up with BDPL 1 and 2 at the Pulgas tunnel. Some of this water is diverted into the Crystal Springs and San Andreas reservoirs, where it is treated and re-introduced into the potable water system via the Harry Tracy WTP. Most of the water continues north via several pipelines, where it ends at the University and Sunset potable reservoirs. North of the University and Sunset reservoirs, the water is delivered to the 800,000 people of the City of San Francisco via the city's distribution system.

Figure 1 shows the major pipelines and tunnels in the SFPUC regional transmission system. Figure 1 also shows areas as having "very high", "high" or "moderate" risk of liquefaction as mapped by Knudson (2000). A zone mapped as having a very high susceptibility of liquefaction means that about 25% to 100% of the area will liquefy, given a nearby major earthquake that produces PGA at that area of 0.2g or more. Similarly, a zone mapped as having a high or moderate susceptibility of liquefaction means that about 5% to 25% (high) or 1% to 5% (moderate) of the areas will liquefy, respectively, under similar earthquake conditions.

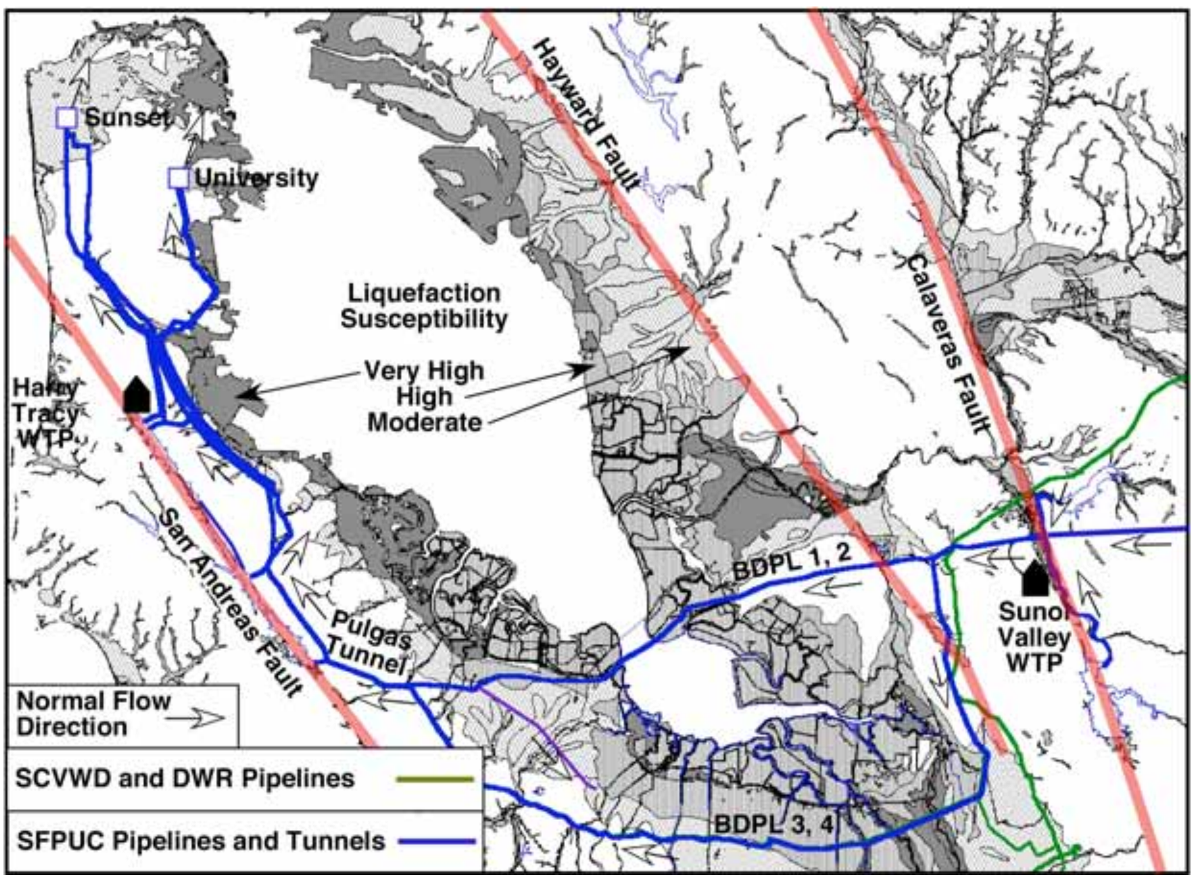

Figure 1. SFPUC Transmission System (2005) and Geologic Hazards (Knudson et al 2000)

Before the transmission system ends at the University Mound and Sunset reservoirs, about two-thirds of all the water is sold under wholesale agreements to 29 cities serving about 1,700,000 people along the route of the pipelines. When considering the seismic and reliability improvements for the transmission system, it is vital to consider these wholesale customers, along with how their own water distribution systems are configured with respect to seismic reliability.

Figure 2 shows the same system in Figure 1 as a hydraulic profile. The dotted lines highlight all the transmission pipelines that were in service in 1906. The 1906-era pipelines are listed as serving the "High", "Middle" or "Low" pressure zones of the City, corresponding to the higher, moderate or lower elevations of the city. All of the 1906-era transmission pipelines were damaged to varying degrees in the 1906 earthquake. The map in Figure 3 shows the location of the 1906 damage. The cumulative damage to the 1906 transmission pipelines led to a 100% disruption of water supply to the City of San Francisco. It took 62 hours to restore some transmission supply to the City. This disruption meant that the only water available to fight fires had to come from local City reservoirs and tanks. While the San Francisco distribution reservoirs and tanks largely remained functional, concurrent severe damage to the local distribution pipe network led to the rapid exhaustion of all water supply within most parts of the City, greatly hampering fire fighting activities and helping the ultimate spread of fire.

DAMAGE TO THE WATER TRANSMISSION SYSTEM IN THE 1906 EARTHQUAKE

The M 7.8 earthquake of April 18, 1906 occurred at 5:12 am Pacific Standard Time. The causative fault was the San Andreas fault. Fault rupture occurred from just north of San Juan Batista (west of Hollister) to Cape Mendocino in the north, a distance of about 270 miles. The duration of strong ground shaking was about 45 to 60 seconds.

At the time of the earthquake, the waterworks for San Francisco was owned and operated by the Spring Valley Water Company (SVWC). Some parts of the 1906 water system performed very well in the earthquake, but other parts suffered a range of damage from minor to catastrophic.

Major components that were damaged or had good performance of the SVWC system as reported by Schussler (1906) and mapped in Figure 3 and are described in the following sections. In hindsight, if one were aided by the geologic hazard maps now available and a modern understanding of earthquake vulnerability of water components, one could have forecasted some (but probably not all) of the damage that actually occurred. If one were to try to pinpoint the most important items of damage that led to the loss of water supply for fire fighting in San Francisco, the answer would be the simultaneous failure of all three supply pipelines: Pilarcitos pipeline (due to multiple failures due to fault offset and a few inertial overloads on weakly installed wood trestles at canyon crossings), San Andreas pipeline (due to inertial overload of a weakly installed pipe on a short bridge over Colma Creek), and Crystal Springs pipeline (due to landslide-induced pipe failures along San Mateo Creek and three inertial-induced wood trestle failures at crossings over three long "swamps" (now called very high liquefaction zones). Most of the other transmission system damage had little or no effect on transmission of water for fire flows, but impacted only longer timer water supply. It could be argued now that had any of these three transmission pipelines survived intact, then the resulting spread of fire within the City of San Francisco could have been somewhat reduced, possibly by a third or so (?[4]). However, the primary reasons for fire ignitions and fire spread had more to do with the damage to structures, wind, failure of the local distribution pipe system and hampered fire department response, so even had the transmission system remained completely intact, fire losses in the City would still have been great. Recognizing that an intact transmission system does not entirely solve seismic vulnerability or even eliminate the bulk of the risk of fire spread, this paper also deals with what the City of Santa Clara (one of the SFPUC's wholesale customers) is doing to upgrade its own water distribution system.

[4] ? Possibly had the San Andreas pipeline not been broken, there would have been water available to rapidly control fires that initiated in higher elevation parts of the City some time after the earthquake, and their resulting spread. However, the fires that burned down all of the South-of-Market area were immediately isolated from water supply due to the gross failure of many distribution pipes that supply and traverse the Sullivan marsh to reach that low-elevation area.

The Sunol Collectors. These are a set of diversion works to collect water from Alameda Creek, behind the Sunol dam. No damage in the earthquake. These remain irregularly in current use as a source of raw water to the Sunol Valley WTP.

The Sunol Aqueduct. This aqueduct (concrete tunnel and heavy timber flume) ran along the south side of Niles canyon, bringing water from Sunol dam to (then) Centerville (now Fremont). No damage in the earthquake. This alignment has, over the years, been subject to landslide damage. Examination of the landslide hazard about 1980 showed them to be difficult (or too costly) to mitigate; the aqueduct has since been abandoned, with portions removed.

The Niles Aqueduct. This aqueduct ran along the north side of Niles canyon, bringing water from Niles dam to (then) Centerville (now Fremont). No damage in the earthquake. This alignment has been abandoned.

Alameda Pipeline. A 36-inch diameter pipeline traversing from Centerville, through Newark, to Dumbarton point. Includes 7,000 feet of wood trestle supported pipeline. No damage in the earthquake. Not in current use, but in the same alignment as the current wood trestle supported BDPL 1 and 2. **Dumbarton Crossing**. Four submarine pipelines that were part of the Alameda Pipeline, traversing the bay, including two 16" diameter pipes (built 1887) and two 22" diameter pipes (built 1901), at two locations (Newark Slough and San Francisco Bay crossings). No damage to main pipes under the water in the earthquake; slip joint pulled apart a few inches at the east side shoreline approach; two 8-inch blow-offs were damaged on the west side shoreline approach. This damage was quickly repaired and water was flowing from along the Alameda pipeline at 14.5 MGD soon after the earthquake. The above ground and submarine pipelines were removed during the construction of BDPL 2. These pipes were generally within 100 feet and parallel to modern BDPL 1 and 2 Dumbarton crossing. **Ravenswood to Belmont Pump Station Pipeline**. A 36" diameter pipeline traversing from Ravenswood to Belmont. Includes 2,000 of trestle-supported pipeline. No pipe breaks in the earthquake. The Belmont pump station no longer exists. Since BDPL 1 and 2 pipelines traverse the same alignment as the older Alameda pipeline, through 5 miles of soils mapped as having high or very high liquefaction susceptibility, the SFPUC has conducted detailed investigations of BDPL 1 and 2 in this area as summarized as follows: the actual soils through Dumbarton Strait are mostly not liquefiable; in contrast to the map in Figure 1; the timber-supported BDPL 1 and 2 pipelines were over-designed in 1923, and remain adequate for high seismic loads; the steel truss bridge that supports a portion of BDPL 1 and 2 has some seismic weaknesses; the SFPUC plans to mitigate these weaknesses.

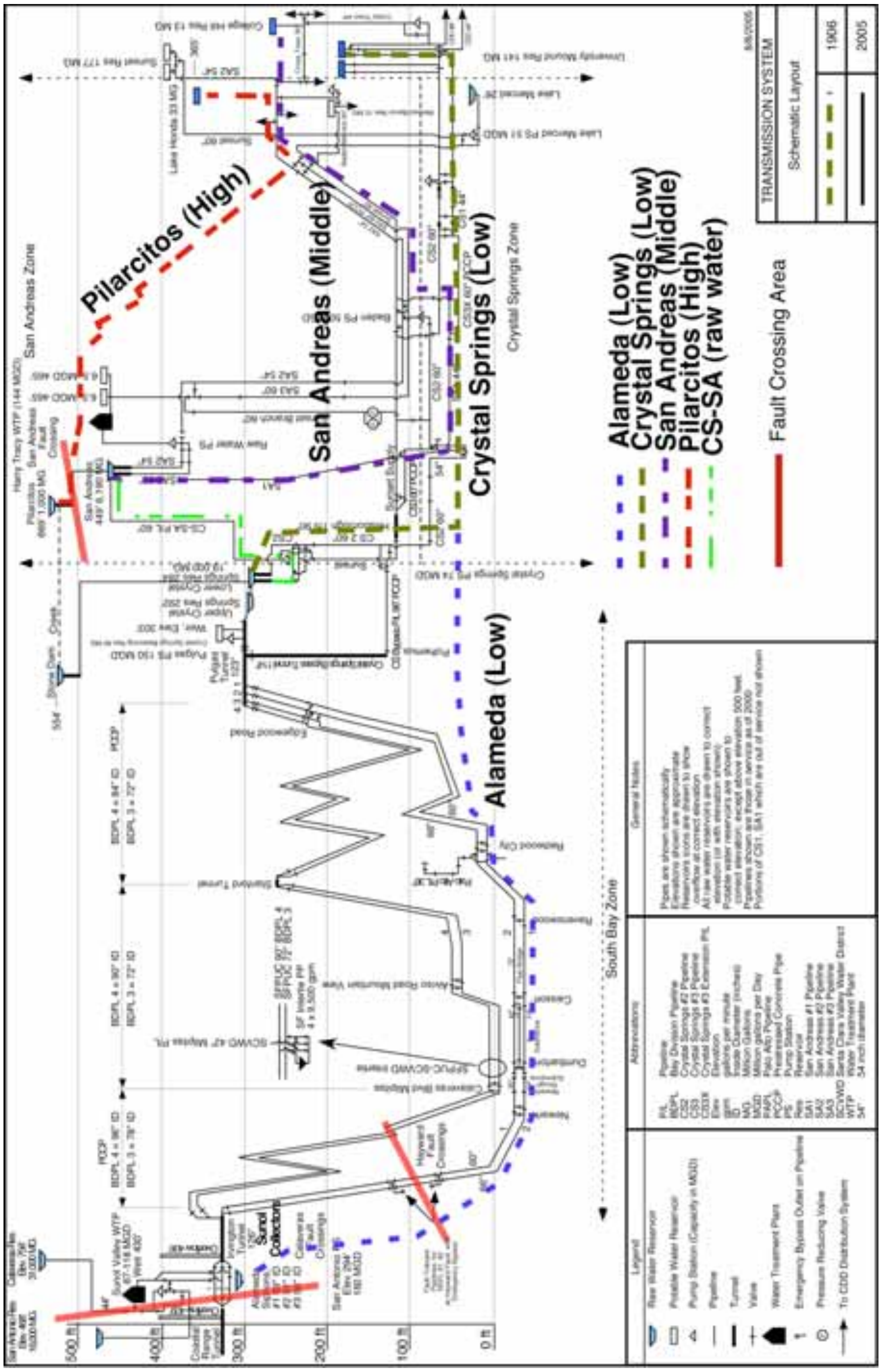

Figure 2. SFPUC Transmission System – 1906 and 2005

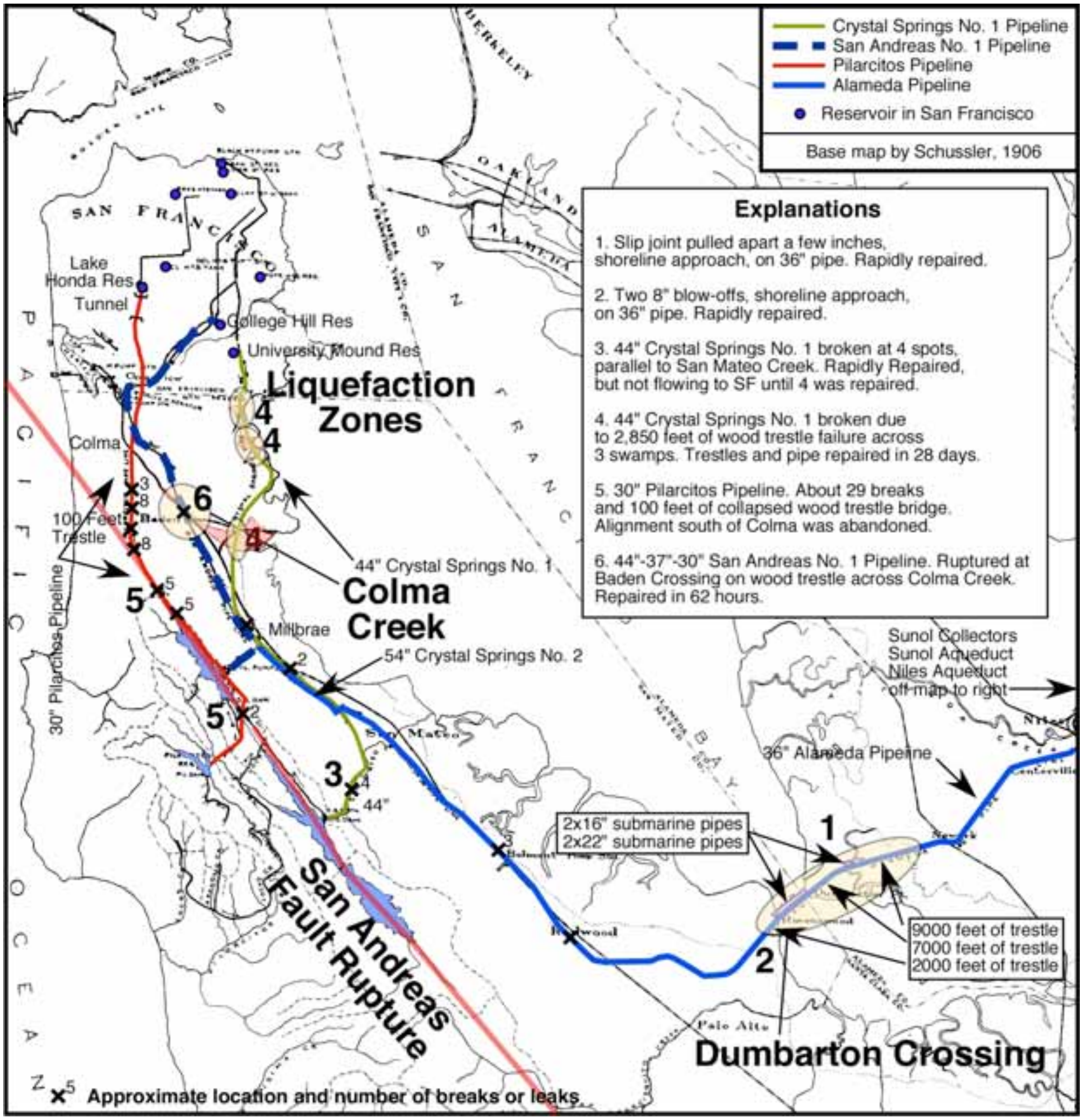

Figure 3. Damage to SFPUC (then SVWC) Transmission System, 1906 Earthquake

Crystal Springs Dam. Concrete Gravity Dam. Same dam as in current service. No damage in the earthquake. No damage to the reservoir outlet works, consisting of a tower and lateral intake pipes.

Upper Crystal Springs Dam (Now Highway 92 between upper and lower Crystal Springs Reservoirs). Apparently suffered some damage, but was considered not important, as failure of the dam would just result in the combining of the upper and lower Crystal

Springs reservoirs. This dam has been modified since 1906 with the construction of Highway 92.

Crystal Springs Pump Station. A smaller version of the current pump station with the same name. Located at the base of the Crystal Springs Dam. Remained intact in the 1906 earthquake; but the modern pump station in still considered vulnerable has is planned to be upgraded.

Crystal Springs Pipeline to Burlingame. A 44" diameter riveted steel pipeline from the Crystal Springs Pump Station, from the dam to Burlingame. For more than half its length, this pipeline follows the San Mateo Creek alignment. This pipe broke in several locations. This section of pipeline has since been abandoned, and two newer welded steel parallel pipes have been installed more or less along the same alignment.

Crystal Springs No. 2 Pipeline from Burlingame to Millbrae. 54" diameter wrought iron pipe. The alignment parallels the modern (2005) alignments for Crystal Springs 3 and Sunset Supply pipelines, each being on adjacent parallel streets. No reported damage to this pipeline. A pump station at Millbrae was then in use; it was not damaged by the earthquake; the pump station was abandoned more than 30 years ago.

Pilarcitos Dam. Same dam as in current service. No damage in the earthquake.

Locks Creek Line. This aqueduct was one of the main feeders of raw water from the west into San Andreas reservoir. It diverted water from San Mateo Creek. Damaged due to landslides and repaired. It no longer exists.

Crystal Springs Flume and Pipeline to San Andreas Reservoir. The flume portion of this conduit, located near the east abutment of the San Andreas dam, completely collapsed where it crossed the fault. This flume no longer exists. The pipeline portion was replaced; and is schedule to be replaced again in order to increase the hydraulic capacity of moving water from Crystal Springs reservoir to San Andreas reservoir.

San Andreas Dam. Located within 10s of feet of the fault offset. The Dam, built from selected clay and with a puddle core, was left uninjured, only showing a few small cracks in the macadam pavement on the top of the dam and above the puddle core. A brick outlet tunnel was offset by the fault, but not so severely that water could not continue to flow.

Fissures in the brick lining were repaired with cement. Another brick-lined tunnel was sharply offset by the fault and was cut in two. The heavy timber chute connected to this tunnel was partly destroyed.

San Andreas Pipeline. A 44" diameter pipeline from the Pilarcitos pumps east to the Millbrae pump station, then north to Baden pump station, then northwest as a 30" diameter pipeline to Lake Merced pump station. Portions of this pipeline are still in use in 2005. The 44", 37" and 30" San Andreas No. 1 pipeline was badly ruptured at one location near Baden Pump Station, and suffered some other minor damage at other locations. The damage near Baden pump station consisted of four large lugs being torn off the pipe near an expansion joint on the pipe bridge at Baden. The repair of this break was high priority, with a temporary repair being made in about 2 days (Figure 4). By the 7 pm on April 20, 1906, 62 hours after the earthquake, water from San Andreas reservoir was again being delivered via San Andreas No. 1 pipeline to College Hill reservoir in San Francisco at an 8 MGD rate.

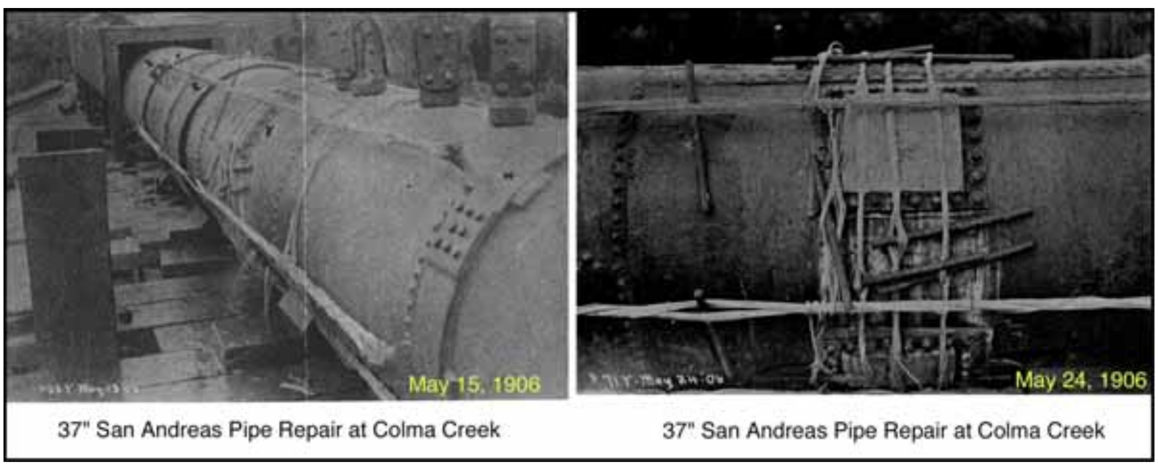

Figure 4. Damage to San Andreas Pipeline

The cause of the damage appears to be the above-ground trestle-supported pipeline crossing near Baden pump station through a "swamp" (zone mapped in Figure 1 as having a very high liquefaction susceptibility). This demonstrates the vulnerability of above-ground pipes with dresser-type couplings and harnesses, if not properly designed for seismic forces.

Crystal Springs Pipeline from Millbrae to University Mound reservoir. The Crystal Springs 44" No. 1 pipeline (laminated wrought iron, t=1/4", girth joints made from a single line of 0.5" diameter rivets) was ruptured in seven places between the Crystal Springs concrete dam outlet works and the (modern) Millbrae valve lot. Several miles north, the pipe was also severely damaged where it was supported on substantial wooden trestles across the "swamps" or "marshes" across three valleys: San Bruno Valley (Colma Creek, Figure 5); Guadalupe Valley (near City Hall location of modern Brisbane) and Visitacion Valley; the wooden bridges failed, and in locations the pipeline was thrown off the trestle.

The several damage points on the pipeline between the dam and Millbrae were rapidly repaired. However, since the downstream pipeline was still damaged, no water from Crystal Springs reservoir was then available to San Francisco.

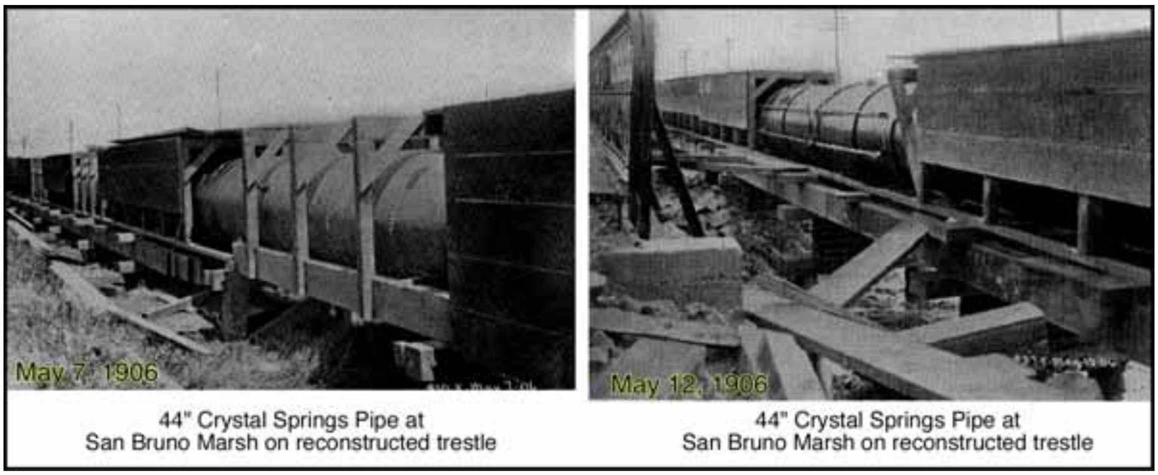

Figure 5. Damage to Crystal Springs Pipeline

The repair of the three trestles took substantial time. Once the trestles were repaired, the original pipeline was jacked back into place, various joints were repaired, and the pipe was put into service on May 16, 1906 (28 days after the earthquake).

The wooden trestles at these three crossings were overloaded due to strong horizontal and vertical inertial loading of the pipe, possibly aggravated by longer duration shaking due to localized deeper soft soil profiles. The modern CS-No. 1 pipeline still traverses these three valleys along the same alignment, but is now a buried pipeline (i.e., no more wooden trestles). Between Crystal Springs concrete dam and Millbrae, the original 44" pipeline has been abandoned in place; the reasons for the damage might have been a combination of strong ground shaking, coupled with some hillside movements.

Pilarcitos Pipeline from Pilarcitos reservoir to Lake Honda. The upper elevation reaches of this conduit (southern portion) was a 30" diameter riveted steel pipeline (laminated wrought iron, t=3/16", girth joints made from a single line of rivets) that paralleled the San Andreas fault from the north end of San Andreas reservoir. This pipe was torn and telescoped at several places (Figure 6) and practically destroyed. Initial estimates suggested it would take many months to repair and put this pipeline back in service. Ultimately, the pipe was not repaired, and it was removed from service. The northern portion of the 30" pipeline, from about the modern location of the San Pedro valve lot to Lake Honda, was only slightly damaged, and was quickly (16 hours) restored to service, drawing water from the Lake Merced pumps and delivering water at a 6 to 7 MGD rate to Lake Honda and beyond. This water, coupled with local storage in Lake Honda, helped control the spread of the conflagration within the City of San Francisco.

30" Pilarcitos Pipe pulled apart 2 feet | 30" Pilarcitos Pipe telescoped | 30" Pilarcitos Pipe pulled apart 3 feet

Figure 6. Damage to Pilarcitos Pipeline

The cause of the damage to the southern part of the Pilarcitos conduit included fault offset at several places, and inertial overload of the 100-foot long wooden trestle bridge supporting the pipe across Frawley Canyon. The southern alignment is no longer part of the modern SFPUC system. The northern alignment of the pipeline is also no longer in service, but roughly parallels the modern San Andreas No. 2 pipeline east of Lake Merced.

City Distribution System. The earthquake caused about 52 fire ignitions within the City of San Francisco. The bulk of these initial ignitions were rapidly controlled; however a few of the ignitions spread, in part due to inadequate fire department response, high winds and lack of water, and these fires ultimately burned down a major portion of the City. The earthquake caused at least 300 broken distribution mains and about 23,200 broken service laterals. The Lake Honda reservoir suffered cracked walls with large fissures. Two wood roof structures over storage tanks burned. Fire following earthquake issues are further described in (Eidinger 2004).

TRANSMISSION SYSTEM PERFORMANCE – 1989 LOMA PRIETA EARTHQUAKE

The SFPUC transmission system was exposed to the magnitude 7 Loma Prieta earthquake on October 17, 1989 at 5:04 pm PDT. The epicenter was located 16 km northeast of Santa Cruz and 100 km south of San Francisco. This event killed 63 people, injured 3,757 people, destroyed 366 businesses, damaged 3,550 businesses and left more than 12,000 people temporarily displaced. The strong shaking lasted less than 15 seconds (less then 10 seconds in most places) and is estimated to have caused more than $7 billion in damage, not including economic losses.

This earthquake caused significant damage to various water systems in the greater San Francisco Bay area and the Santa Cruz area. A survey was conducted of more than 25 water agencies. Of the agencies that participated in the survey, there were 862 recorded buried pipeline failures. By including the non-participating agencies, probably more than 1,000 pipe failures occurred.

Figure 7 shows a regional map with the bulk (but not all) of recorded water pipeline breaks and leaks. Figure 8 shows a close up of water distribution system pipe damage in the City of Santa Clara. Unlike the damage pattern to the San Francisco distribution pipes in 1906, almost all of the damage in the City of Santa Clara in 1989 occurred at locations mapped as having essentially no liquefaction susceptibility; further, in portions of the City of Santa Clara that are mapped as having high liquefaction susceptibility, where the predominant type of pipeline is asbestos cement, essentially no damage occurred.

One known damage point to the SFPUC system in the 1989 earthquake was the failure of a blow off (air valve?) on the BDPL 3 and 4 alignment immediately adjacent to the Bear Gulch reservoir. This damage led to leakage of water from the BDPL pipeline into the lake. The BDPL pipelines were not shutdown due to this damage, but were kept in operation until repairs could be made.

An inspection of BDPL 2 (concrete portion near the Irvington Tunnel) in 1995 revealed three WEKO seals on consecutive joints that had been installed in the spring of 1990. It was reported that a leak had developed in the pipeline in 1990 shortly after the Loma Prieta earthquake.

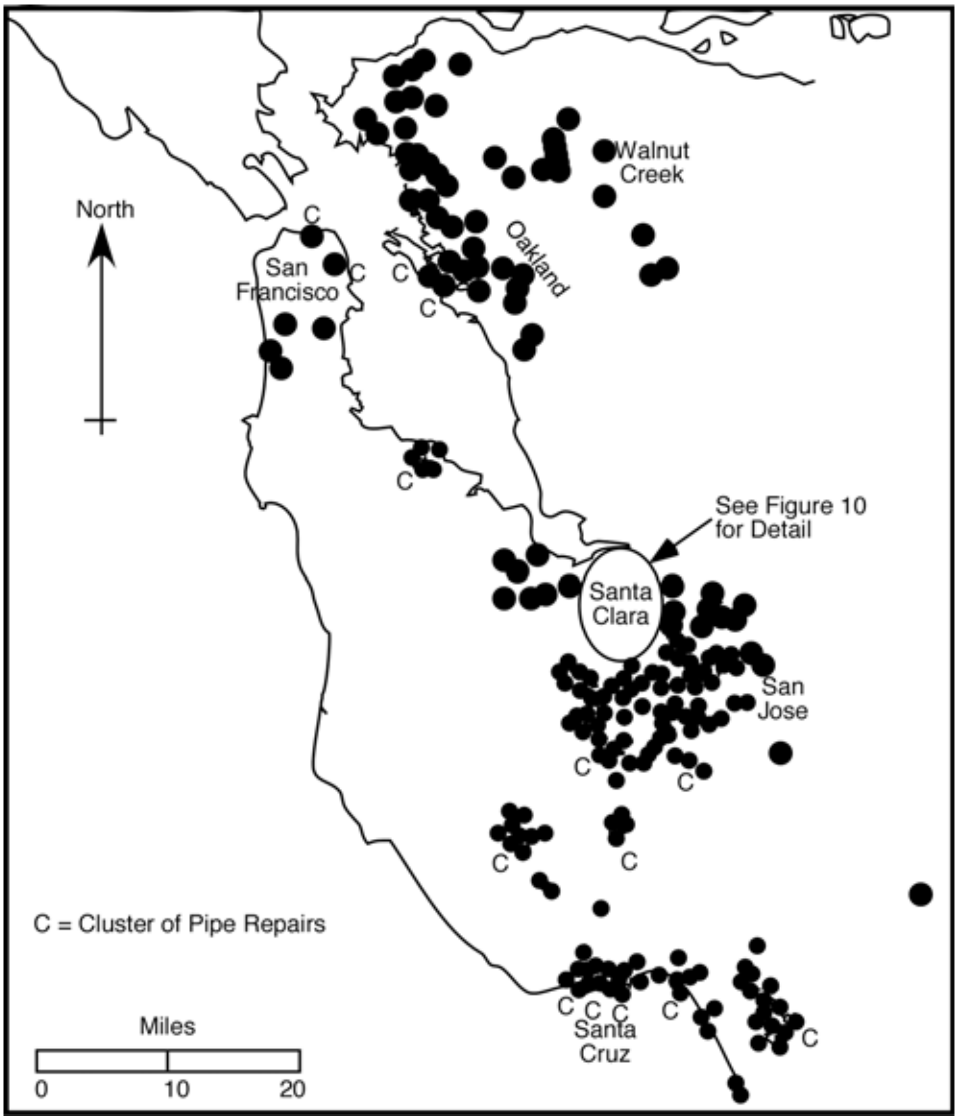

Figure 7. 1989 Loma Prieta Earthquake – Locations of Pipe Damage

PERFORMANCE OF THE LOCAL SYSTEM OF THE CITY OF SANTA CLARA – 1906 AND 1989 EARTHQUAKES

The City of Santa Clara is located near the southern end of the San Francisco Bay Area, see Figure 7. The water system in Santa Clara was damaged in both the 1906 and 1989 earthquakes.

The 1906 earthquake exposed the then considerably smaller City of Santa Clara water system to moderate to strong ground shaking. Recorded damage to the Santa Clara water system included the collapse of its water tanks. Figure 8 shows the four elevated wood tanks then in use in the City (pre-earthquake). Figure 9 show the same tank structure, collapsed by ground shaking in the 1906 earthquake.

Figure 8. Santa Clara Waterworks and Gas Plant (c. 1905)

Figure 9. Collapsed Water Tanks in Santa Clara (c. April 1906)

The 1989 Loma Prieta earthquake again damaged tanks and pipelines in the City of Santa Clara. The left side of Figure 10 maps the location of distribution system damage in Santa Clara in the 1989 earthquake; the right side shows the geologic hazards for the city. Three of the six 4 MG unanchored steel tanks in the City suffered roof damage, likely due to wall uplift. The three remaining tanks did not suffer damage; but were located in the northern parts of the city where ground motions were lower.

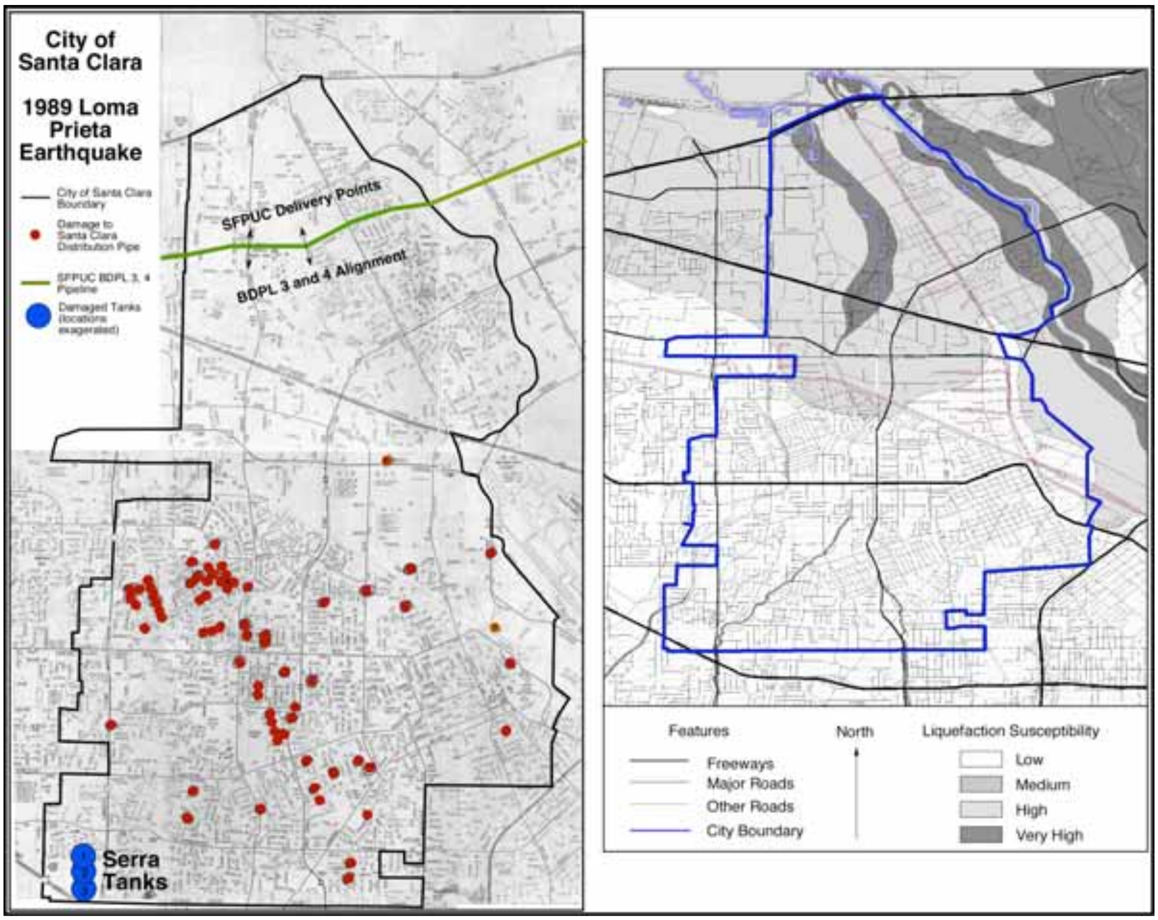

Figure 10. 1989 Loma Prieta Earthquake – Locations of Pipe Damage in Santa Clara

Figure 11 shows one of the three damaged tanks. This tank is located at a site in the southwest corner of the city, where there are 3 similarly-built tanks; each suffered similar damage. This view shows the southern face of the tank. The damage seen reflects the lateral buckling of the roof rafters which in turn caused the buckling of portions of the roof and knuckle shell (the scaffolding seen is part of the repair effort).

Figure 12 shows the roof lines of Serra Tanks 1 (background) and 2 (foreground). At the time this photo was taken, the roof for Tank No. 2 was already repaired (November 1991); Tank 1 had not been repaired. A large buckle can be seen in the roof of Tank No. 3, indicative of the damage to the roof beams below.

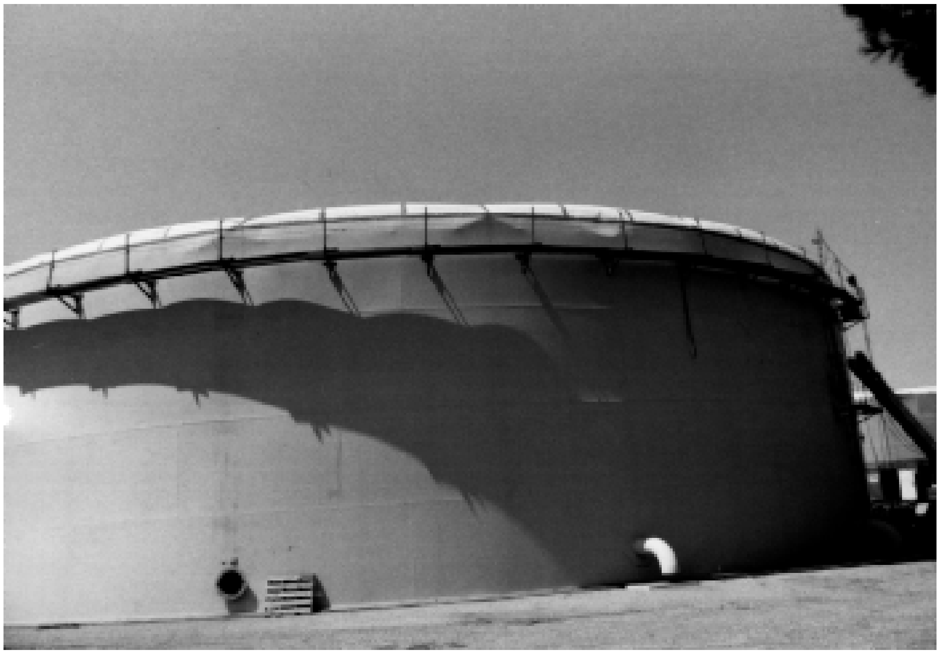

Figure 11. Damage to Serra Tank No. 3

Figure 12. Damage to Serra Tank No. 1 (Background)

Figure 13 shows the damaged roof rafters of Tank No. 1. At the time this photo was taken, the tank had been drained and the damaged roof plate had been removed. The photo is taken looking up at the damaged roof rafters and knuckle. Lateral buckling of the roof rafters is readily observed.

Figure 13. Damaged Roof Rafters

The three damaged tanks are all welded steel tanks resting on concrete ring beam foundations. All the tanks were unanchored, with side entry pipes. At the time of the earthquake, there was more than 10 feet of freeboard above the water line to the roof rafters. Nearest strong ground motion instruments suggest that the tanks experienced about PGA = 0.30 to 0.35g shaking. The damage to all three tanks was nearly identical in terms of location, suggesting that the damage was due to incipient wall uplift, and not water sloshing. Very similar damage has since been seen in Paso Robles at similar sized unanchored welded steel tanks in the 2003 San Simeon earthquake. While the roof damage did not cause loss of water contents for fire fighting purposes, it was expensive to fix. More troubling is the fact that the tanks could be exposed to considerably higher levels of shaking in a future earthquake on the nearby San Andreas fault, and the resulting uplift would damage the inlet-outlet pipes, as well as damage (again) the roof. The modern AWWA code for steel tank design remain deficient in providing guidance as to avoiding this type of damage, and similar types of damage can be expected for unanchored steel tanks that are constructed to code minimums, should they experience an earthquake that causes wall uplift.

The 1989 earthquake also caused pipeline damage in the distribution system. A study was performed based on time card data for repair crew staff, for the period from 5 pm October 17, 1989 (the time of the earthquake) through November 17, 1989. Figure 14 shows the daily breakdown of the total repair effort. The bulk of the intense pipe effort started at 5:04 pm October 17, continuing through October 24, 1989. Key statistics are as follows:

- A total of 66 pipe repairs were made in the period Oct 17 to Nov 17 1989. The "normal" number of pipe repairs in the City are about 1 or 2 per week, which would be about 6 or so for this same time period had there been no earthquake.
- The bulk of the pipe repairs were made from Oct 17 1989 to Oct 24 1989. In this time period, there were 45 pipe repairs made. During this time period, the average effort was 32 manhours per repair, with most repairs made to 6" mains and service lines up to the meter.
- The bulk of the repair work was for leaking pipes. By "leaking", it is meant to say that the pipe suffered a pin hole leak, a slight opening of the joint, or a failure of the service connection. By service connection, it is meant that the repair was made up to the water utility's side of the meter; and not damage to the customer's service pipe.
- In only a few cases were repairs made to "broken" pipes, where "broken" means total loss of flow capability. For example, the pipe may have pulled apart completely, or suffered a large split.

Figure 10 shows a map of the 66 pipe repairs (left side) and liquefaction susceptibility (right side). Some key observations:

- 64 of the 66 repairs were to Cast Iron (CI) pipe or the service connections attached to CI pipe. All of these repairs were located south of the Central Expressway.
- 1 (or 2) of the 66 repairs were to Asbestos Cement (AC) pipes (the repair location near the Downtown tank might have been to other than a AC pipe). One of these repairs was located south of the Central Expressway.

- Essentially none of the pipe damage occurred in zones mapped as having either high or very high liquefaction susceptibility. This is the opposite of what happened in the 1906 earthquake in the City of San Francisco distribution system.
- There are about 295 miles of pipe in the Santa Clara water system. South of the Central Expressway, where the bulk of the pipeline damage occurred, about 90% are cast iron.

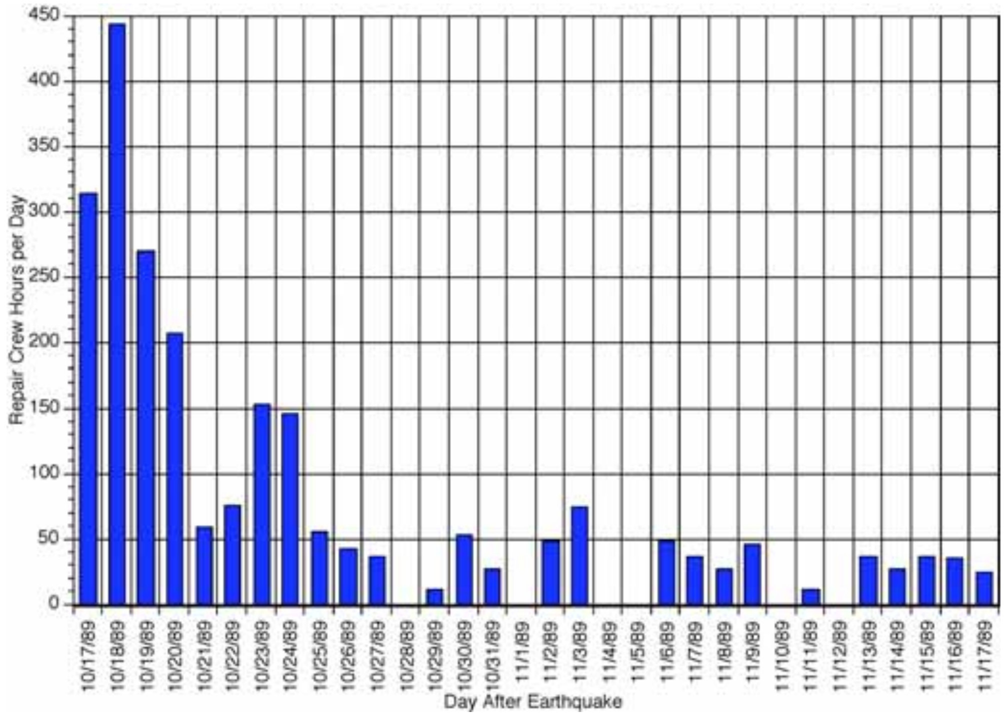

Figure 14. Pipe Repair Effort, October 17, 1989 through November 17, 1989

For the City of Santa Clara, the 1989 Loma Prieta earthquake caused no observed surface level evidence of liquefaction, in the entire built area with pipelines. Therefore, the pipe damage is due to ground shaking entirely. The following repair rates (RR) (Oct 17 – Nov 17 1989) were observed (inclusive of service laterals):

- RR = 0.0423 per 1,000 feet, system-wide
- RR = 0.062 per 1,000 feet, cast iron pipe, system wide
- RR = 0.008 per 1,000 feet, asbestos cement pipe, system wide
- RR = 0.065 per 1,000 feet, cast iron pipe, south of Central Expressway
- RR = 0, all other pipes, all locations

The observed repair rates confirm fragility data in Eidinger (2001) that AC pipe has superior seismic capability versus CI pipe, when exposed to ground shaking alone.

The actual pattern of damage in Figure 10 shows a concentration along a northwest trending alignment. The damage rate within this 0.75 mile wide by 3.5 mile band was much higher than outside this band. This suggests that the actual highest levels of ground motions in the City of Santa Clara were concentrated along this narrow alignment., but this unusual band of damage might also be attributed to any of the following reasons:

- Directivity effects of the earthquake. So called "directivity" effects may have created higher levels of shaking in Santa Clara along this zone.
- Basin effects of the earthquake. Basin effects may have focused higher levels of shaking in Santa Clara along this zone, or a different soil profile could have cuased higher amplifications. However, this banded zone follows, more or less, constant surface elevate contours as well as constant elevation contours of bedrock at depth. This would create a uniform soil amplification rate along the corridor, as well as a uniform effect due to wave focusing.
- Corrosive soils. While it is generally assumed that soils south of the Central Expressway have low-corrosive potential for metal pipe, it might be that along this zone that there has been more corrosive actions.
- Quality of installations. The bulk of the pipeline damage was to cast iron pipes installed from 1954 to 1959. It could be that during this vintage that the quality of construction was poorer than in more recent times. For example, bedding, service line connections and other factors may have changed since that time.
- Local soil conditions. Unconsolidated soils in and near creeks can contribute to various kinds of soil failures, leading to pipeline damage. The actual current creek alignments in the City of Santa Clara run more-or-less south to north. The liquefaction susceptibility map in Figure 8 (same as Figure 1, at larger scale) does not explain the observed northwest pipe damage trend.

The combined damage to the Santa Clara tanks and distribution tanks did not lead to a long water outage for the city. In part, this good performance reflects that the damaged pipes were put back into service within three days, there were no fire ignitions / spread, and Santa Clara's three water supplies (SFPUC, SCVWD and local wells) were not disrupted. So, the 1989 earthquake could be considered a moderately strong test of the water system, but not necessarily the worst that could happen in a repeat of the 1906 San Andreas earthquake.

CURRENT SEISMIC UPGRADE EFFORTS

Given the damage in the 1906 and 1989 earthquakes, coupled with compelling evidence of damage to other water systems, such as the 1995 Kobe earthquake, the San Francisco and Santa Clara water utilities have embarked on seismic upgrade programs.

The SFPUC has budgeted a $4 billion seismic and reliability upgrade program. Generally, seismic upgrades are made to the latest seismic criteria, with ground fault offset set at (about) the 84^{th} percentile not-to-exceed motions given maximum earthquakes on either the San Andreas, Hayward or Calaveras faults, and ground shaking levels set at 975 years return period (important items with some redundancy) or 2,475 years (essential items with no redundancy). Items without critical post-earthquake service requirements but with some life-safety component are designed for ground shaking levels set at 475-years.

More than 35 separate programmatic elements are included as part of the SFPUC seismic and reliability upgrade program, of which 24 have at least some bearing on improving local- or system-wide seismic performance, costing $1.7 billion. Many of the projects factor in non-seismic issues as well, such as improving reliability for drought, water quality, as well as providing additional operations and maintenance flexibility. As of late 2005, the main seismic upgrade projects include the following (before the entire effort is complete, it is possible that some of these program elements might change):

- Procuring spare pipe and supplies, supplemented by mutual aid agreements, so that major transmission pipe repairs can be made as quickly as feasible in a post-earthquake environment.
- Installing reliable backup power supplies at key locations in the system, so that water treatment plants and isolation valves that are critical to rapid post-earthquake service restoration can be operated during the time frame when there will be a (likely) regional power blackout.

- Seismic hardening of the Sunset and University Mound reservoir roofs. This will assure that the roofs do not collapse in future earthquakes.
- BDPL 1 and 2. In 2003, the SFPUC replaced BDPL 1 and 2 pipelines where they cross the Hayward fault. The replaced pipelines include new isolation valves either side of the fault, and new fault tolerant pipelines capable of withstanding from 5 to 10 feet of fault offset, emergency bypass manifolds, pressure, flow and ground motion instruments, telemetry to offsite operations site, and permanent on-side back up power supplies.
- BDPL 3 and 4. By 2013, the SFPUC will upgrade these two pipelines where they cross the Hayward fault, similar to that already used for BDPL 1 and 2.
- BDPL 5. A new BDPL 5 pipeline / tunnel system will be constructed to parallel BDPL 1 and 2. This new 5^{th} pipeline will provide additional hydraulic capacity as well as redundancy to the system, considering that BDPL 1 and 2 pipelines were built in 1923 to 1933, and might now be susceptible to age-related failures. BDPL 5 will be built as a tunnel under San Francisco Bay, to bypass the soils mapped as having high liquefaction susceptibility in Figure 1, and to avoid environmental restrictions building near the shorelines of San Francisco Bay.
- BDPL 3 and 4 Crossovers. A series of valve vaults will be built along the BDPL 3 and 4 alignments to allow shorter lengths of each pipeline to be taken out of service for maintenance purposes, as well as to increase seismic reliability. By "crossover", it is meant that water from BDPL 3 can be moved into BDPL 4, or vice versa, given an outage (earthquake damage or otherwise) forcing a segment of pipeline out of service.
- Crystal Springs Bypass Pipeline and Tunnel 2. A second bypass tunnel / pipeline system will be built to transport potable water parallel to Crystal Springs reservoir. In this way, should the existing pipeline/tunnel system be damaged (a large landslide threatened the existing bypass pipeline during a heavy rain winter), then the new bypass will provide continued flow while repairs are made.

- Water Treatment Plant upgrades. Both of SFPUC's water treatment plants will be hardened to withstand ground motions on the order of PGA = 0.6g.
- Calaveras Fault Crossings. A new pipeline will be built to move Hetch Hetchy water through Sunol Valley, even with a large offset of the Calaveras fault. Selected portions of the existing pipelines that cross the Calaveras fault will also be upgraded to be somewhat fault tolerant, or to constrain damage such that the remaining pipelines will continue to function uninterrupted, and maintain at least winter time water flows.
- BDPL 1 and 2 at Dumbarton Crossing. Seismic upgrades for the older BPDL 1 and 2 pipelines at the Dumbarton Crossing are planned to make them reliable for earthquakes that might likely occur within their remaining design life (about PGA = 0.30 g).
- BDPL 4. BDPL 4 is the primary source of supply of water to many cities in the South Bay. Portions of BDPL 4 are prestressed concrete cylinder pipe. This type of pipe is susceptible to corrosion-induced failure as the pipes age; and the pipe is not particularly well suited to take permanent ground deformations (there is also some debate as to how much ground shaking it can take). Some portions might be slip-lined with a new welded steel pipe on the interior. Many of the cities in the South Bay are able to get water from either this pipeline, or from the SCVWD, or from wells. Should this pipeline not be upgraded, the wholesale customers supplied by this pipeline will still be able to rely on the local groundwater basin available in the South Bay for a portion of their post-earthquake water supply while repairs are made to this SFPUC as well as other SCVWD transmission pipelines that might be simultaneously damaged.
- Irvington Tunnel. A parallel tunnel will be built next to the existing 1923-vintage Irvington tunnel. While there are no significant active faults that cross the existing tunnel, the need for the new tunnel also reflects that the existing tunnel cannot be shut down for any type of significant maintenance purposes; so the new tunnel will provide both seismic and operation reliability improvements.

The City of Santa Clara will upgrade its six largest water tanks (all unanchored steel tanks) with flexible couplings, to prevent pipe failures due to tank wall uplift possible under very large earthquakes; anchor one of the tanks; and anchor various pieces of electrical and mechanical equipment at its various pumps stations. The cost of this upgrade program is envisioned to be less than $2,000,000. The City has already installed many local wells, some with permanent backup power supplies, so that it can provide winter time flows to the community even with complete disruption of supply from its two surface water suppliers, the SFPUC and SCVWD. Once these upgrades are complete, the City should have higher reliability of providing fire flows to the community in the first hours after any large earthquake, even if there is a service disruption from wholesale supplies from the SFPUC or SCVWD; and be able to provide sufficient water to the community to sustain rapid economic restoration, while repairs are made to the City's distribution pipelines, as well as SFPUC's and SCVWD's transmission pipelines and tunnels.

UPDATE ON OTHER BAY AREA DISTRIBUTION SYSTEMS

The SFPUC delivers water to the Cities of San Francisco and Santa Clara, as well as 28 other cities and agencies in the greater San Francisco Bay Area. When developing its seismic upgrade program, the SFPUC considered that its upgrades should address all of its 29 customers. Similarly, the City of Santa Clara considered what might be happening to its neighboring cities (including San Jose and Sunnyvale) in major earthquakes. Cumulatively, these other 28 agencies are undertaking seismic upgrades that will cumulatively cost in the range of $50 million.

CONCLUSIONS

The SFPUC and the City of Santa Clara operate two different water systems. Over the past few years, each utility has identified its own unique seismic vulnerabilities, and developed a seismic upgrade program tailored to its needs.

Both water utilities have experienced damage in the prior 1906 and 1989 earthquakes. Both utilities recognize that the loss of water supply can have major impacts to their communities, considering both the fire following and economic disruption threats.

The Cities of San Francisco and Santa Clara are not alone in dealing with seismic vulnerabilities to water systems in the greater San Francisco Bay Area. There are more than 60 other water utilities serving the 7 million people in the 10 county San Francisco Bay Area. A workshop sponsored by EERI was held in October 2004 (EERI, 2004) dealing only with seismic issues for water utilities; more than 25 utilities attended. It is evident that many Bay Area water utilities are being pro-active in establishing their own system-unique vulnerabilities, figuring out what can be done, finding the financial resources to fund improvements, and then implementing the upgrades. Not all the water utilities are taking the same approaches; some have been very aggressive and others are taking more limited approaches. It will probably take another decade or longer before the bulk of this work is complete.

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