Utility Performance Aspects, Liquefaction Study, Marina and Sullivan Marsh Areas, San Francisco, California

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ABSTRACT

Motivated by water and sewer system failures in the Marina in the 1989 Loma Prieta earthquake, and the recognition that greater damage had occurred in the 1906 earthquake and could be expected again, the city of San Francisco retained an engineering team to estimate the amount and extent of large ground displacements, and their effect on water and sewer utilities. Geotechnical aspects are discussed in an accompanying paper while this paper reviews the utility aspects of the project. The Marina area contains 39,000 ft of potable water (MWSS) pipe, which was estimated to sustain about 80 breaks in an event similar to 1906, while a special aseismic firefighting system (AWSS) is estimated to sustain 11 breaks in 8,150 ft. of pipe. For 62,000 ft of MWSS pipe in the Sullivan Marsh area, 200 breaks are found, while the AWSS is estimated to sustain 84 breaks in 27,000 ft of pipe. Total repair costs for water and sewers are estimated at about $49 million. Geotechnical, structural, operational and systemic mitigation options were developed and prioritized.

INTRODUCTION

This paper summarizes utility aspects of a project performed for the City of San Francisco, concerning estimation of earthquake induced large permanent ground deformations and their effects on underground water supply and sewer utilities. An accompanying paper[1] summarizes geotechnical aspects of the project, while this paper presents the estimation of the effects of the estimated deformations on the underground utilities, and the range of measures considered to mitigate these effects.

The project, termed the *Liquefaction Study*, was motivated by the occurrence of widespread water supply and sewer system damage and failures in the Marina section of San Francisco in the October 17, 1989 Loma Prieta earthquake[2], and the recognition that even greater damage had occurred in the 1906 San Francisco earthquake and could be expected again in a similar event. Further increasing the hazard to San Francisco is the estimation by the U.S. Geological Survey of a 67% probability of a magnitude 7 event in the San Francisco Bay Area in the next 30 years, driven primarily by the high likelihood of a large earthquake on the Hayward fault (note that downtown San Francisco is equidistant from the San Andreas and the Hayward faults, each about 10 miles distant).

The vulnerability of buried water supply pipe due to earthquake is of critical significance, both for post-earthquake fire as well as for continued potable water supply. This criticality was overwhelmingly demonstrated in the 1906 San Francisco and 1923 Tokyo earthquakes and ensuing fires. The 1989 Loma Prieta earthquake damage in the Marina, including a large fire[3], served as a reminder. Beyond the immediate post-earthquake fire problem, continued performance of underground potable water and sewer utilities is vital to urban recovery. Given these needs, the city of San Francisco determined that an examination of the potential performance of these utilities was necessary, and retained an engineering team consisting of: Harding Lawson Associates, Dames & Moore, Kennedy/Jenks/Chilton, and EQE International.

This paper reports on vulnerability measures of underground piping subjected to area-wide deformations, and the spectrum of mitigation measures developed as part of this project. Due to limitations of space, only two of the areas studied, the Marina and Sullivan Marsh areas, are discussed. In order to do this, we next describe the underground utility systems considered as part of this project, summarize our evaluation of utility damage, and review the mitigation options developed for the project.

UNDERGROUND UTILITY SYSTEMS

The project considered two water supply systems dedicated to firefighting: the truck-borne Portable Water Supply System (PWSS), and the underground Auxiliary Water Supply System (AWSS), as well as the potable Municipal Water Supply System (MWSS), and the sewer system.

<u>AWSS</u> The San Francisco AWSS is a water supply system intended solely for adequate water supply for firefighting. It is separate and redundant from the MWSS, and is owned and operated by the SFFD. It was built in the decade following the 1906 San Francisco earthquake and fire, primarily in the north-east quadrant of the city (Figure 1, the urbanized portion of San Francisco in 1906 and still the central business district), and has been

gradually extended into other parts of the city. The AWSS supplies water by a special pipe network with a total length of approximately 129 miles of cast iron and ductile iron pipe serving approximately 1,500 dedicated street large capacity hydrants. The pipe is bell and spigot, originally extra heavy cast iron (e.g., 1" wall thickness for 12" diameter), and extensions are now Schedule 56 ductile iron (e.g., .625" wall thickness for 12" diameter). Restraining rods connect pipe lengths across joints at all turns, tee joints, hills and other points of likely stress. The network as originally designed and constructed was divided into two independent sections, north and south of Market Street, increasing reliability should one section fail. In the 1906 earthquake, San Francisco had sustained major ground failures (leading to water main breaks) in zones generally corresponding to filled-in land and thus fairly well defined. Because it was anticipated these ground failures could occur again, these zones (termed "Infirm Areas") were mapped and the pipe network was specially valved where it entered these Infirm Areas.

PWSS Though the above-ground PWSS was not a subject of analysis in this study, a brief description would be valuable. While the AWSS (described above) provides high assurance of firefighting water supply in the northeast quadrant of San Francisco, major fires can and do occur at large distances from the AWSS pipe network. In recognition of this, and to provide additional flexibility in deployment and to further extend the "reach" of the AWSS, the SFFD has developed in recent years the PWSS. Its basic components are (i) hose tenders with large diameter hose, (ii) hose ramps, (iii) gated inlet wye, (iv) Gleeson valve, a pressure reducing valve, and (v) portable hydrants.

MWSS The San Francisco Water District provides domestic water to the City of San Francisco. Reservoirs serve 23 distinct zones, called pressure districts - only the University Mound District and College Hill District (Figure 2) intersect the study areas. MWSS piping is of diverse vintage, the newest being welded steel pipe; the oldest, cast iron pipe dating back to the late 1850's. In the study areas, the majority of mains are of cast iron segmented bell and spigot lead/oakum-jointed construction, installed in the three decades prior to the turn of the century. Larger, older pipe is of steel. Pre-1930 pipe larger than 24-inch diameter is of riveted steel construction. Longitudinal joints were shop riveted; circumferential joints were riveted in the field. Between about 1930 and 1960, pipe larger than 24-inch diameter was of welded steel construction. Gas welding was used until about 1940, after which arc welding became common. After about 1960, welded steel construction was also used for pipe as small as 20-inch diameter. Joints were bell and spigot, welded outside for 20-inch to 24-inch diameter, and welded inside and outside for 36-inch and larger diameters. Welding for 30 inch diameter mains varied -- sometimes inside and out, sometimes only outside.

The Marina currently contains approximately 40,000 feet of 6 inch to 12 inch diameter mains; 75% is of cast iron construction installed primarily in 1924 and 1925; 3% is of ductile iron with caulked joints, and the remaining 22% is of ductile iron installed primarily in 1990, following the 1989 earthquake.

Sullivan Marsh is estimated to contain approximately 62,300 feet of pipe, of which approximately 44,000 feet is 4 inch to 16 inch diameter cast iron and 13,000 feet of 4 inch to 16 inch ductile iron pipe. Perhaps 3/4 of all MWSS pipe in the study areas was installed between 1860 and 1900. Much of the remainder was installed in the 1930s, although every decade since 1900 saw installation of some length of pipe in the study areas.

Sewer City records indicate that sewers were first constructed in the 1870s in the Sullivan Marsh Study Area. Many of the existing sewers in the Sullivan Marsh area were constructed in the ten-year period following the 1906 earthquake, and many others were built during the 1930s. Records indicate that the sewers in the Marina District Study area were first constructed in the ten-year period preceding the 1915 Exposition.

Based on discussions with Clean Water Program personnel and a review of city records, it was concluded that most city sewers can be divided into the following seven categories:

1. Vitrified Clay Pipe, Old Style VCP - iron or salt glazed pipe with rigid (mortared) joints. This pipe was installed up until about 1945. It is generally very weak structurally. Also included in this category is VCP installed between 1945 and 1960 with rigid joints.

2. Vitrified Clay Pipe, Modern Style VCP - Installed since 1960. This pipe has good structural integrity and has polyethylene gaskets giving it joint flexibility.

3. Brick - This pipe is egg-shaped, with the egg standing on the small end. The predominant size is 3 feet wide by 5 feet high, with a 9-inch wall consisting of two courses of brick with mortared joints. Some are pile-supported.

4. Precast Concrete Pipe, Old Style - Installed between 1900 and 1920 with mortared rigid joints. It is usually less than 24 inches in diameter. This pipe apparently has a low cement content and is not very structurally sound. There is not a significant amount of this type of pipe in the study area.

5. Precast Concrete Pipe, New Style - Installed since 1960 with elastomeric joints. There is very little of this pipe in the study area.

6. Cast-in-Place Concrete Box Structures, Non-Pile-Supported - Includes both modern (excluding the transport system) and old installations.

7. Cast-in-Place Concrete Box Structures, Pile-Supported - Includes both modern (excluding the transport system) and old installations.

UTILITY BREAKS CAUSED BY 1906 AND 1989 EARTHQUAKES

Marina District

Behavior of Marina District soil and utilities in 1906 cannot be discussed, as the Marina District was created by land fill following the 1906 earthquake.

AWSS The AWSS was not structurally damaged in the Marina District during the 1989 Loma Prieta earthquake. Despite the survival of Marina AWSS mains and hydrants, damage elsewhere in the system caused the loss of water pressure in high pressure hydrants, rendering them useless for firefighting immediately after the earthquake.

<u>MWSS</u> Most of the damage sustained by the MWSS in the 1989 earthquake occurred within the Marina Study Area, where approximately 120 main and service breaks were attributed to the earthquake. Approximately two-thirds of these were main breaks. Damage was concentrated in the land filled after 1895. Outside of the Marina District, fewer than 40 breaks were attributed to the earthquake. Figure 2 shows the locations of main and service breaks within the Marina District.

It is worthwhile comparing the performance of AWSS and MWSS pipe breakage in the Marina District during the 1989 earthquake. While MWSS experienced approximately 80 main breaks, AWSS experienced none. This can be explained by comparing three factors of each system: quantity, strength, and location. MWSS is far more extensive than AWSS; approximately 5 times as much MWSS pipe exists in the Marina District as AWSS pipe. AWSS pipe is also stronger and lacks services, and could therefore be expected to experience fewer breaks per length of pipe than MWSS pipe experiencing similar ground deformation. Finally, AWSS pipe in the Marina District is mostly located outside of that region of the Marina District most strongly affected, whereas MWSS pipe exists under every Marina District street.

<u>Sewer</u> Extensive damage resulting from the 1989 Loma Prieta earthquake was incurred by sewers in the Marina District. Most of the damage was incurred by "Old Style VCP," but there was some damage to brick sewers. Considerable damage occurred at the connections between buried sewers and those on pile supports. Minor damage in the form of joint separation was noted for cast-in-place sewers. The Clean Water Program is replacing nearly 6,500 feet of sewers in the Marina at a cost of nearly $1,700,000. Figure 2 shows sewers that were damaged in the Marina in 1989. The criteria used by the City of San Francisco for sewer replacement in the Marina District was to replace the whole run if two or more repairs were required within a single sewer run between manholes, which is a very economical approach.

Sullivan Marsh Area

<u>AWSS</u> SFFD personnel indicate that in the 1989 Loma Prieta earthquake, a 6-inch by 18-inch window break occurred in the 12-inch main on 7th and Natoma streets, apparently caused by settlement of the AWSS onto a sewer line below. Northeast of Sullivan Marsh, a hydrant at Fremont and Mission streets struck by falling masonry from an adjacent building sustained a break at the buried elbow. Similar hydrant elbow breaks occurred at 6th and Bluxome streets, and at 5th Street between Harrison and Bryant streets. The former may have resulted from building collapse (Nielsen, 1991). The latter break has been attributed to settlement of the hydrant branch, which crossed over a pile-supported sewer which did not settle.

The break in the 7th Street main, combined with hydrant branch breaks in the South of Market Area, drained the lower zone within 30 minutes. Following identification and isolation of these breaks, the lower zone was fully pressurized within about four hours of the earthquake.

<u>MWSS</u> At the time of the 1906 earthquake, Spring Valley Water Company owned and operated San Francisco's water system. Three months after the earthquake, Hermann Schussler, SVWC's chief engineer, recorded over 23,000 service breaks and approximately 300 main breaks in MWSS pipe. Schussler considered the damage relatively light, attributing the system's good performance to the high standards he had imposed since the

1860s. He wrote, *"The breaks in the main pipes (considering our great length of distributing system of 441-1/2 miles) were comparatively few, and these were, in the large majority of cases, principally confined to and caused by the sudden sinking of the streets over the old swamps, which movement... tore the pipe over the swamp away from the pipe on terra firma."* (Schussler, 1906).

Approximately 50 of the 300 main breaks were located within the Sullivan Marsh area. These were especially concentrated in the sloping region bounded by Mission, Folsom, 8th and 6th streets, where extensive lateral spreading apparently took place. The record is probably incomplete; the 1906 earthquake reportedly overwhelmed Spring Valley Water's repair crews, and accurate records could not be kept during the months following the earthquake. Breaks discovered in the late summer and fall of 1906 may have gone unreported.

<u>Sewer</u> Initial inspection of the sewers near the Sullivan Marsh Study Area revealed less extensive damage than in the Marina District following the Loma Prieta earthquake. This disparity may be attributed to the smaller inventory of vulnerable rigid joint VCP pipe in Sullivan Marsh. Most of the damage was to this type of pipe, although a 215-foot-long brick sewer on Seventh Street between Mission and Minna streets was damaged just outside the Study Area on 9th Street between Harrison and Division streets. Approximately 900 feet of sewer was initially identified as requiring replacement at a cost of nearly $400,000. More recent TV inspection of sewers in Sullivan Marsh indicates that earthquake damage may have been more extensive than previously thought.

Reports of sewer damage following the 1906 Earthquake are sketchy. ASCE (1907) reports that in areas of significant ground deformation south of Market, sewers were completely destroyed.

EVALUATION OF UTILITY DAMAGE

Water Pipelines

A number of previous studies provide relevant data on the vulnerability of buried water pipelines in earthquakes[5,7]. For this study, past performance of San Francisco water systems in the 1906 and 1989 earthquake was analyzed to develop breakage estimates for AWSS and MWSS water pipe by relating movement (amount of vertical settlement and lateral spreading) and break rate (number of breaks per 1000 feet of pipe), based on pipe material and construction characteristics. Break rates were compared with relevant empirical data found in the literature. Mechanics of materials analyses for pipe damage were considered but not employed, since such analyses required detailed input of ground strain fields, which was beyond the scope of the geotechnical portion of this study.

Breakage in pre-1940 MWSS cast iron pipe was correlated with amount of ground movement. These relationships were then factored to produce damage functions for other classes of pipe. Damage resulting from interaction with other buried facilities was also estimated. Three modes of damage were identified: differential settlement, vertical settlement, and lateral spreading. Differential settlement was particularly associated with pile-supported sewers. Experience in the Loma Prieta Earthquake indicates that high relative settlements can be expected at sewers supported on piles. Pipes crossing over or through these sewers are supported at the sewer and pushed down on either side by surrounding soil settlement. The consequent bending can fracture the pipe. Break rate functions were developed for each material, as a function of permanent ground displacement, shown in Figure 3.

Sewer

Initially, it was hypothesized that the pipe damage rate would show positive correlation with average ground strain, the rate of change of absolute permanent ground deformation. Microzone plots of strain versus damage rates, however, did not verify this. It is assumed, however, that higher damage rates would occur at ground movement interfaces, such as 4th Street and Brannan Street in Sullivan Marsh, as was experienced with water mains in 1906. Next, it was hypothesized that the pipe damage rate would correlate positively with absolute permanent ground deformation. The premise was that local ground strains were much higher than average strains. Local strains would correlate to absolute deformation. Pipe damage rates would then correlate to absolute deformation. The sewer repair and replacement map, Figure 2, was laid over the estimate ground settlement, for the Marina District. Total sewer lengths of repairs and replaced Old Style VCP were measured for each settlement range zone, and damage rates were calculated. A plot of these results is shown on Figure 4.

It is worthwhile to compare the resulting curve with information from another source to assess its validity. In Santa Cruz, the most extensive damage due to the 1989 Loma Prieta Earthquake occurred in liquefiable areas, particularly along the San Lorenzo River. The City of Santa Cruz televised 40,000 feet of sewer pipe in those high water pipe damage areas. Of that total, 5,000 feet were identified as needed to be replaced. Consideration is being given to replacing 10,000 feet to avoid replacing small sections of pipe. The resulting necessary replacement rate is 12.5 percent. Those replacements are plotted on Figure 4, showing similar repair rates to those encountered in the Marina District.

Valuation of Utility Breaks

Using the procedures discussed above, repair and replacement costs were estimated and are detailed in Tables 1 through 4. As a result of the breaks estimated in this study, it was estimated that both AWSS and MWSS (i.e., high and low pressure systems) would lose pressure in the Marina and Sullivan Marsh areas.

MITIGATION OPTIONS

For extended networks, such as San Francisco's water supply or sewer systems, options for the mitigation of earthquake damage or the enhancement of functional reliability can be broadly categorized into four approaches:

- **Geotechnical**, consisting of densification, improvement, replacement or other remediation of the soils,

- **Structural**, consisting of strengthening of the pipe or joints, or other improvements to the connections, such as introduction of special flexible connections, avoidance of contact with neighboring utilities, etc,

- **Systemic**, consisting of changes to the system layout, such as enhanced redundancy via additional piping, avoidance of poor soil areas, etc, and

- **Operational**, whereby the above approaches are not employed in advance of the earthquake but rather the potential for damage is recognized and emergency preparedness measures are put in place whereby system reconfiguration and/or immediate equipment and personnel deployment permit attainment of system functionality.

Each of the above approaches has costs and benefits, including differing levels of reliability and, in some cases, deferment of capital expenditures. In some cases, mitigation options may combine several of these approaches. This section presents a summary of options for reducing improving San Francisco utility performance following a major earthquake.

Water Systems

Table 5 summarizes the above mitigation options for the AWSS. The MWSS pressure district most at risk to liquefaction damage is University Mound. As shown in Figure 5, all University Mound Pressure District feeder mains pass through Mission Creek, Sullivan Marsh, and Embarcadero Study Areas in series. As a consequence, if all mains crossing result any one of these study areas were broken, no University Mound water could be delivered farther north in the pressure district. Though several parallel mains cross through each zone of high liquefaction potential, it is possible that widespread liquefaction in any one of these study areas could damage all feeder mains crossing through it. Each of these study areas, therefore, represent a choke point in the system. Three approaches can mitigate this hazard: (1) Plan to supply water to isolated regions from adjacent, undamaged pressure districts; (2) Reroute feeder mains around these regions of high liquefaction potential; or (3) Strengthen or otherwise reduce the vulnerability of feeder mains passing through regions of high liquefaction potential. Into this last class fall soil remediation, pipe replacement, addition of pipe flexibility, and hydrant replacement. Table 6 summarizes the above mitigation options for the MWSS.

Sewer

<u>**Operational Procedures**</u> In general, sewer pipelines will function to some extent, even though they have been damaged. Some sewers may collapse, causing overflows to the streets. The overflows will travel overland in the streets to the next available operating sewer. However, some ponding will occur due to damaged streets and gutters. Following an earthquake, there is an increased probability of toxic, flammable, and explosive chemical and gasses in sewers. Toxic chemicals may spill as a result of the earthquake and drain into the sewers, such as occurred in the EBMUD system in the Loma Prieta earthquake (according to personal communication with EBMUD staff). If there is blockage or partial blockage of sewers, sewage may become septic, releasing methane and hydrogen sulfide.

In view of these conditions, the following steps could be taken, many of which are normally a part of sewer operations.

a. Sufficient testing equipment should by available, staff should be trained in its use, and it should be used in all instances upon entering any sewer. Portable ventilation equipment and breathing apparatus should also be readily available.

b. Operations should not rely on reduction in sewage flow because of water system failure. Maintain an inventory or access to large capacity portable sewage pumps and hose to bypass collapsed sections of sewers. Maintain an inventory of sewer repair materials, including cement, sand, sand bags, and earth moving equipment.

c. Inventory all pump stations for overflows and add emergency overflows, if they do not currently exist, so that the overflow would be into a storm system or other water body.

Structural Modifications New vitrified clay pipe (VCP) sewers with polyethylene gaskets have performed well to the extent that deformation can be accommodated in the joint. Because of the brittle nature of the VCP, joint restraint of VCP is not feasible. Therefore, in liquefaction areas, where the deformation exceeds VCP capabilities, pipe systems with restrained joints should be considered. The ductile iron pipe systems with restrained joints, discussed for application to the AWSS and MWSS, would be applicable for sewers. The estimated construction costs for ductile iron pipe and VCP are similar, and since sewer corrosion has not been a problem in San Francisco, ductile iron pipe should serve well. Another pipe system alternative recommended for consideration is polyethylene (PE). PE is highly ductile and would move with almost any deformation expected in the liquefaction areas. It has been used extensively for slip-lining of both sewers and natural gas systems, and it has also worked well for sewage forcemains.

A long-term program to replace Old Style VCP and concrete pipe in liquefiable soil areas should be developed. Earthquake vulnerability should be one replacement criteria in the overall pipe replacement program, in addition to considering physical condition, grade, maintenance history, and infiltration factors. Slip-lining with polyethylene pipe should be considered as an alternative to pipeline replacement. Polyethylene sections can be extruded to match nonround cross sections such as the brick sewers, and result in negligible capacity loss. Flexibility should be provided to accommodate differential movement between pile-supported to non-pile-supported pipeline and conduit structures. For small and medium diameter pipelines, this can be accomplished using rubber bellows type, Dresser type, or combination ball joint/expansion sleeve flexible joints. Provide a minimum of two flexible joints in series with a design distance separating them to allow the required design differential movement.

Continue the design of sewage collection systems for grids in selected areas so that if one pipeline fails, sewage backs up and flows through an adjoining drainage basin, rather than onto city streets or into basements.

Rerouting Relocation or paralleling of key interceptors is typically not an alternative because of grade requirement.

CONCLUDING REMARKS

The foregoing summary presents a brief overview of a major study intended to identify critical earthquake-related failures of the water and sewer lifelines in a large city, due to large ground deformations. A number of key issues and research needs emerged from the study, including:

(i) current techniques for the estimation of large permanent ground deformation are geotechnically data-intensive, precluding use of available techniques and resulting in major approximations. Increasing use of GIS-based geotechnical databases may improve this situation.

(ii) current techniques for the estimation of pipe breaks due to large permanent ground deformation are only approximate in nature, with considerable uncertainty. Data collection is vitally needed, of both the pipe performance as well as the associated ground deformations.

(iii) selection of mitigation options is usually conducted within a cost-benefit framework - both aspects require additional work. That is, we found in this study that considerable uncertainty existed regarding the costs of repair, even though recent data was available from the 1989 Loma Prieta earthquake. The benefit aspect was not considered in this study (i.e., the benefits of reduced losses due to disrupted water and sewer service, such as the reduced losses due to fire following earthquake) - considerable data and methodological work is required before this can be cost-effectively incorporated in studies such as this.

(iv) San Francisco is about to acquire a Supervisory Control and Data Acquisition (SCADA) system for the MWSS - use of SCADA systems for rapid damage data collection and reconfiguration should be considered.

(v) the numerous pipe breaks, as well as many service breaks, will clearly lead to rapid loss of pressure at fire hydrants, exacerbating the fire following earthquake problem. Reliable techniques for rapid identification and isolation of damaged areas are needed.

The main finding of the study was that water supply was likely to be disrupted within areas of large permanent ground deformation, and that cost-effective mitigation for existing systems is extremely difficult. The most effective mitigation options for existing systems generally appeared to be those accepting widespread damage, but with plans and preparedness resources to cope with and quickly restore the loss of service. Mitigation of damage for new construction can be much more cost-effectively accomplished.

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Table 1
MARINA BREAK AND DAMAGE ESTIMATE FOR WATER PIPES

Horizontal Ground Displacement Vertical Ground Displacement	6"-12" 6"-12"	3"-6" 3"-6"	0"-3" 0"-3"	Totals
Estimated Ground Displacement (in.)	10.8	5.4	1.8	
Pipe Lengths - Current (feet)				
CI Pre-1940	9,550	6,450	13,650	29,650
CI 1941-1960	0	0	0	0
DI 1961-1988	400	150	800	1,350
DI 1989-1991	4,850	2,500	1,100	8,450
RS/WS Pre-1940	0	0	0	0
WS 1941-1991	0	0	0	0
Total MWSS	14,800	9,100	15,550	39,450
AWSS	2,600	1,100	4,450	8,150
Breakage Estimate				
CI Pre-1940	32	20	15	66
CI 1941-1960	0	0	0	0
DI 1961-1988	0	0	0	1
DI 1989-1991	2	1	0	3
RS/WS Pre-1940	0	0	0	0
WS 1941-1991	0	0	0	0
Total MWSS	34	21	15	70
AWSS	4	2	2	8
Sewer Crossings				
MWSS	12	0	0	12
AWSS	3	0	0	3
Total Breaks				
MWSS	46	21	15	82
AWSS	7	2	2	11
Net Break Rate, Breaks/1000 lf				
MWSS	3.12	2.27	0.98	
AWSS	2.82	1.52	0.54	
Repair/Replace?				
MWSS	Replace	Replace	Repair	
AWSS	Repair	Repair	Repair	
Damage Cost, $1000				
MWSS	$4,400	$2,730	$87	$7,257
AWSS	$733	$167	$242	$1,142

Table 3
SULLIVAN MARSH BREAK AND DAMAGE ESTIMATE FOR WATER PIPES

Horizontal Ground Displacement Vertical Ground Displacement	<2' 2'-5'	6"-2' 1'-2'	<6" 6"-18"	<3" <3"	Totals
Estimated Ground Displacement (in.)	59.4	23.4	12.4	2.1	
Pipe Lengths - Current (feet)					
CI Pre-1940	9,300	4,050	21,500	6,900	41,750
CI 1941-1960	0	1,000	0	1,100	2,100
DI 1961-1988	2,550	1,550	5,300	1,750	11,150
DI 1989-1991	1,300	0	0	900	2,200
RS/WS Pre-1940	0	0	0	0	0
WS 1941-1991	1,600	850	850	1,800	5,100
Total MWSS	14,750	7,450	27,650	12,450	62,300
AWSS	5,600	2,700	14,250	4,450	
Breakage Estimate					
CI Pre-1940	55	16	73	9	153
CI 1941-1960	0	4	0	1	5
DI 1961-1988	4	2	5	1	12
DI 1989-1991	1	0	0	0	1
RS/WS Pre-1940	0	0	0	0	0
WS 1941-1991	1	0	0	0	1
Total MWSS	61	22	78	11	172
AWSS	17	5	24	3	49
Sewer Crossings					
MWSS	10	6	12	2	30
AWSS	8	3	23	1	35
Total Breaks					
MWSS	71	28	90	13	202
AWSS	25	8	47	4	84
Net Break Rate, Breaks/1000 lf					
MWSS	4.84	3.79	3.27	1.06	
AWSS	4.41	3.12	3.32	0.87	
Repair/Replace?					
MWSS	Replace	Replace	Replace	Repair	
AWSS	Repair	Repair	Repair	Repair	
Damage Cost, $1000					
MWSS	$4,425	$2,235	$8,295	$75	$15,030
AWSS	$2,471	$842	$4,735	$385	$8,433

Table 2
DAMAGE ESTIMATES FOR MARINA SEWERS

Ground Displacement and Pipe Type	Replacement Cost/Foot	Pipe Length (feet)	Percent Replacement	Replacement (feet)	Replacement Cost
Zone of Vertical Settlement - Less than 3"					
1.8 inch Displacement:					
VCP - Rigid Joints	$225	7,605	20%	1,521	$342,225
VCP - Elastomeric Joints	$225	2,385	11%	262	59,029
Brick	$700	360	11%	40	27,720
Concrete - Pile Supported	$1,720	333	7%	23	40,093
Concrete - No Pile Supports	$1,170	4,095	7%	287	335,381
TOTAL		14,778		2,133	$804,448
Zone of Vertical Settlement - 3" to 6"					
5.4 Inch Displacement:					
VCP - Rigid Joints	$225	5,436	48%	2,609	$587,088
VCP - Elastomeric Joints	$225	1,332	26%	346	77,922
Brick	$700	0	26%	0	0
Concrete - Pile Supported	$1,720	450	17%	77	131,580
Concrete - No Pile Supports	$1,170	1,665	17%	283	331,169
TOTAL		8,883		3,315	$1,127,759
Zone of Vertical Settlement - 6" to 12"					
10.8 Inch Displacement:					
VCP - Rigid Joints	$225	6,714	91%	6,110	$1,374,692
VCP - Elastomeric Joints	$225	3,843	47%	1,806	406,397
Brick	$700	0	47%	0	0
Concrete - Pile Supported	$1,720	1,260	31%	391	671,832
Concrete - No Pile Supports	$1,170	2,565	31%	795	930,326
TOTAL		14,382		9,102	$3,383,247
				TOTAL DAMAGE	$5,315,454
				SAY	$5,320,000

Table 4
DAMAGE ESTIMATES FOR SULLIVAN MARSH SEWERS

Ground Displacement and Pipe Type	Replacement Cost/Foot	Pipe Length (feet)	Percent Replacement	Replacement (feet)	Replacement Cost
Zone of Vertical Settlement - Less than 3"					
2 inch Displacement:					
VCP - Rigid Joints	$225	143	22%	31	$ 7,079
Brick	$700	1,881	12%	226	158,004
Concrete - Pile Supported	$1,720	1,111	7%	78	133,764
Concrete - No Pile Supports	$1,170	957	7%	67	78,378
TOTAL		4,092		402	$377,225
Zone of Vertical Settlement - 0.5' to 1.5'					
12 Inch Displacement:					
VCP - Rigid Joints	$225	4,917	100%	4,917	$1,106,325
Brick	$700	1,298	52%	675	472,472
Concrete - Pile Supported	$1,720	3,883	35%	1,359	2,337,566
Concrete - No Pile Supports	$1,170	1,518	35%	531	621,621
TOTAL		11,616		7,482	$4,537,984
Zone of Vertical Settlement - 1' to 2'					
24 Inch Displacement:					
VCP - Rigid Joints	$225	0	100%	0	$ 0
Brick	$700	1,705	100%	1,705	1,193,500
Concrete - Pile Supported	$1,720	594	67%	398	684,526
Concrete - No Pile Supports	$1,170	0	67%	0	0
TOTAL		2,299		2,103	$1,878,026
Zone of Vertical Settlement - 2' to 5'					
59 Inch Displacement:					
VCP - Rigid Joints	$225	1,430	100%	1,430	$ 321,750
Brick	$700	209	100%	209	146,300
Concrete - Pile Supported	$1,720	1,815	100%	1,815	3,121,800
Concrete - No Pile Supports	$1,170	1,100	100%	1,100	1,287,000
TOTAL		4,554		4,554	$4,876,850
				TOTAL DAMAGE	$11,670,085
				SAY	$11,670,000

Table 5

MITIGATION OPTIONS, AWSS

	Option	Cost ($ millions)
1	Flexible Joints at Mains Crossing Pile-Supported Sewer	$ 0.5 - 1 *
2	Infirm Area Hydrant Foundation and Connection Improvement	0.2*
3	Subdivide Upper and Lower Zones North/South	0.3**
4	Replace Corroded Tie Rods	?
5	Increase Size of SFFD Portable Water Supply System	2**
6	Fireboat Supply of the AWSS	1**
7	Hardening of Fireboat Manifold Corridors	10**
8	Standing Order to Start Pumps Following Earthquake	-**
9	Designate a Water Supply Officer	-**
10	Automated AWSS Leak Detection and Isolation	2**
11	CI Main Replacement	17*
12	Installation of Flexible Joints at all Hydrant Branches	4*

Table 6

MITIGATION OPTIONS, MWSS

	Option	Cost ($ millions)*
1	Supply Water From Adjacent Pressure Districts	$ 0.1
2	Route University Mound Around Liquefaction Zones	6.7
3	Strengthen Mains in Zones of High Liquefaction Potential	30.0
4	Flexible Joints at Mains Crossing Pile-Supported Sewers	1.0

* Costs indicated for Marina and Sullivan Marsh study areas only
** Costs indicated would benefit all study areas

Figure 1
SAN FRANCISCO AWSS

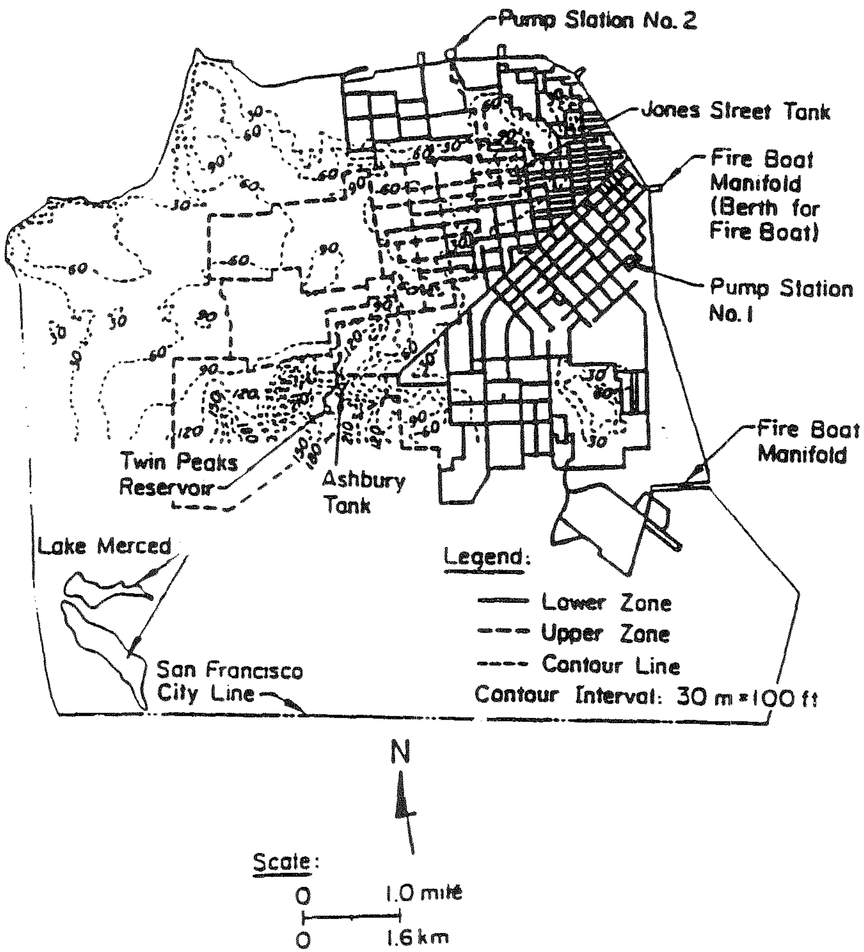

Figure 2
DAMAGED AND REPLACED SEWERS IN THE MARINA FOLLOWING LOMA PRIETA

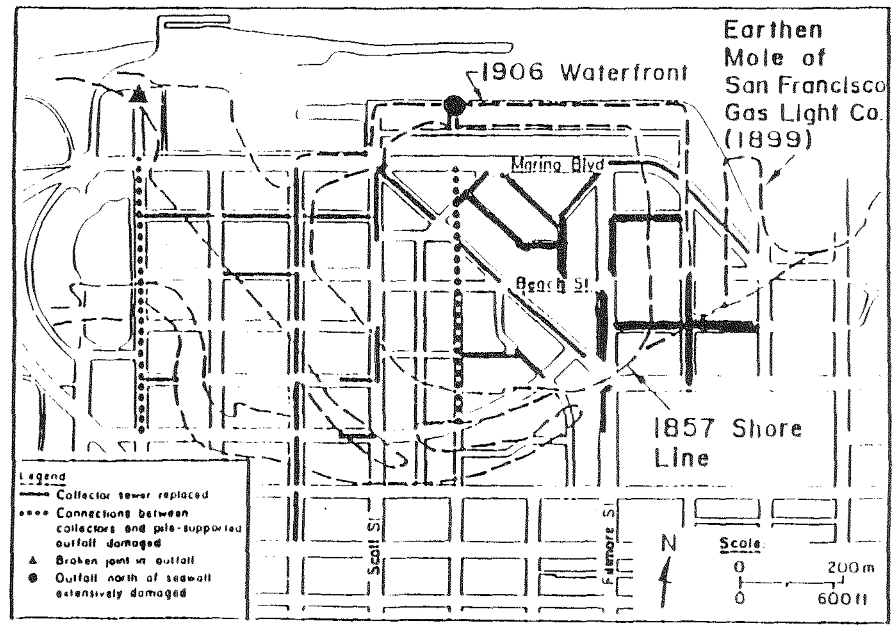

Figure 3
ESTIMATED UNDERGROUND PIPE DAMAGE FUNCTIONS

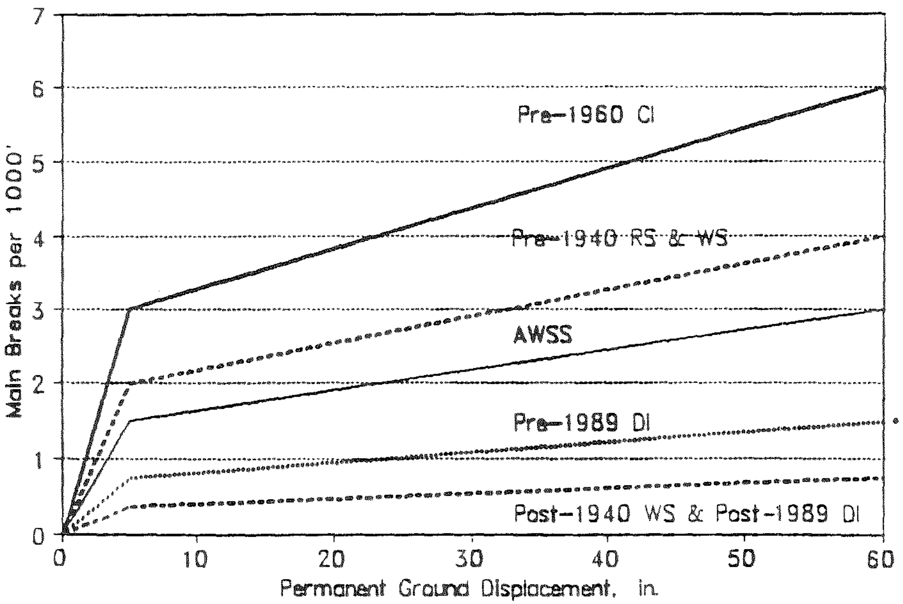

Figure 4
COMPARISON OF MARINA DISTRICT VCP DAMAGE WITH SANTA CRUZ

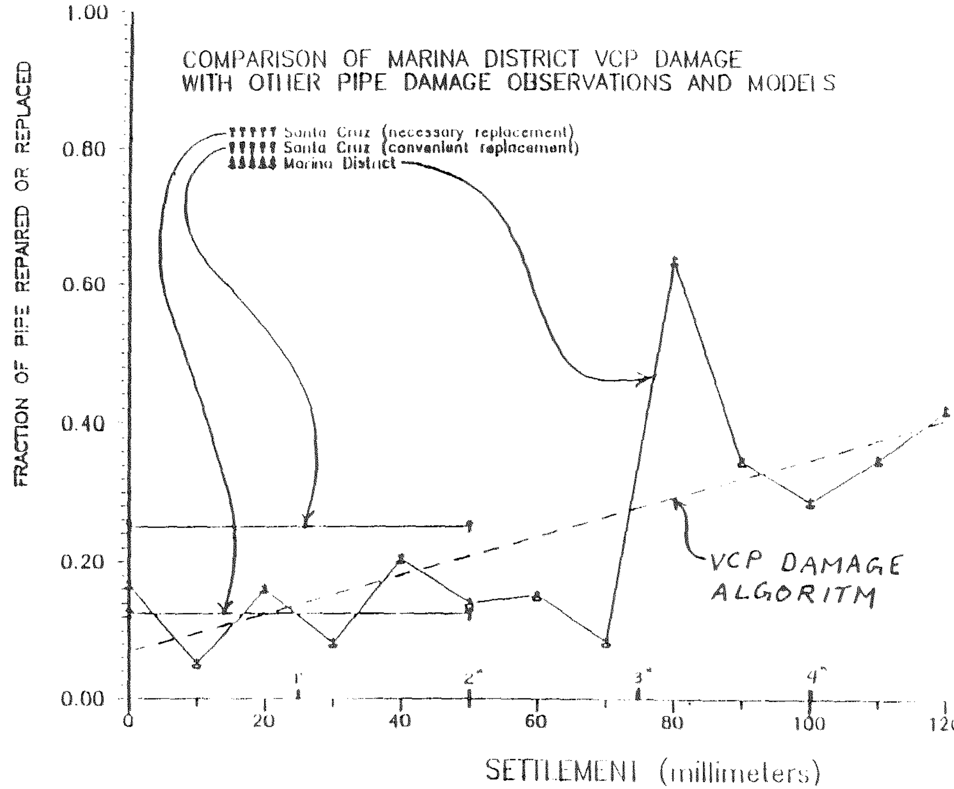

Figure 5
MWSS MITIGATION OPTION 2