PERFORMANCE OF WATER SUPPLY PIPELINES IN LIQUEFIED SOIL

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ABSTRACT

Reliable performance of underground water supply pipe in earthquakes is a matter of critical importance, to support immediate firefighting and assure potable water supply. Existing approaches to estimating water pipe breakage, based primarily on estimated MMI, may underestimate major pipe damage concentrated in regions of large liquefaction-induced permanent ground deformations. A recent study (*San Francisco Liquefaction Study*) necessitated estimation of pipe breakage in areas of potential large permanent ground deformations associated with liquefaction and lateral spreading. Data from the 1906 San Francisco and 1989 Loma Prieta earthquakes were used to correlate pipe break as a function of permanent ground deformation. The results tend to agree with previous studies from the 1971 San Fernando and several Japanese earthquakes. The major finding is that normalized pipe break rate is nonlinear with permanent ground displacements. Relatively small displacements cause significant initial pipe breakage; at larger displacements additional breaks occur, but at a relatively smaller rate.

1 INTRODUCTION

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. It has long been recognized that, while earthquakes cause pipe breakage over wide areas, damage is especially concentrated in areas where liquefaction and lateral spreading have produced large permanent ground deformations (Schussler, 1906). A number of studies have examined water supply piping in earthquakes, but most have relied on gross regional performance, producing correlations with seismic intensity measures such as Modified Mercalli Intensity (MMI), or peak ground acceleration (PGA). While these measures may be adequate for overall estimates of regional performance, they tend to underestimate damage concentrated in regions subject to liquefaction and lateral spreading. Other studies have developed analysis techniques that provide failure criteria for pipe subjected to simplified models of ground displacements, well specified with regard to location and dimensions of ground deformation (eg, Eguchi, 1983a; O'Rourke et al, 1985). These

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methods generally cannot yet be used for water system vulnerability assessments, since currently feasible geotechnical engineering methods only permit estimation of area-wide trends of ground settlement or lateral spreading. A need therefore exists, where area-wide quantified trends of ground settlement or lateral spreading is feasible, but vulnerability measures of underground piping subjected to these deformations are lacking.

In an attempt to fill this need, this study addresses the estimation of damage to buried water pipe subjected to estimated (ie, quantified, although imprecisely) permanent ground displacements. This work grew out of a recent study ("San Francisco Liquefaction Study," Harding Lawson et al 1991) which necessitated the development of relationships for the estimation of water pipe damage in regions of potential ground failure. Specifically, this paper describes the development of correlations between gross water pipe break rate and general magnitude of permanent ground displacement, regardless of pipe orientation.

2 LITERATURE REVIEW

This section briefly reviews key literature on water pipe seismic vulnerability, as a function of seismic intensity, fault offset, ground movement and joint type.

2.1 WATER PIPE DAMAGE CORRELATED WITH GROUND SHAKING INTENSITY

Kubo and Isoyama (1980), as well as Katayama, Kubo, and Sato (1975) provided damage rates based on gross regional performance of pipe subjected primarily to JMA V (MMI VII-VIII) ground shaking. In the 1978 Miyagi-Ken-Oki Earthquake, and in the 1923 Kanto and 1968 Tokachi-oki earthquakes, failure ratios in JMA V ground shaking ranged between 0.012 and 0.379 failures per 1000 feet of pipe, depending on material. Cast iron pipe failure ratios ranged between 0.17 and 0.40 breaks per 1000 feet of pipe, not including "joint loosenings," whose definition Katayama et al could only conjecture.

Eguchi (1983b) summarized pipe break rate versus MMI for several United States earthquakes, developing a bilinear semilogarithmic curve for cast iron pipe subject to ground shaking effects only (Figure 1). He found that damage rates increase rapidly with MMI, and then more slowly as MMI exceeds VIII.

2.2 WATER PIPE DAMAGE CORRELATED WITH FAULT OFFSET

Duryea et al (1907) describe damage to cast and riveted iron pipeline crossing fault offsets in the 1906 earthquake. They indicate that cast and riveted iron pipe fractured wherever it crossed a fault offset of several feet. Photographs of the damage indicate that riveted iron pipe fractured at riveted joints, through shear of the rivets.

Eguchi (1981) presents damage to buried cast iron water pipe near faulting during the 1971 San Fernando Earthquake. He correlated damage with fault displacement and distance from the predominant line of fault rupture (Figure 2). Ground shaking effects accounted for relatively little breakage.

Eguchi also evaluated the effect of joint type on break rate in the Sylmar fault area. He found that breaks rates were similar for pipes with caulked joints and pipes with rubber gasket joints, and that the predominant modes of failure for pipe in these areas were joint failure, pipe ruptures, and splits. Cement-caulked joints had a tendency to shatter while pipes with rubber gasket couplings tended to pull apart.

2.3 PIPE DAMAGE CORRELATED WITH LIQUEFACTION-INDUCED GROUND MOVEMENT

Several authors provide data or correlations between pipe breakage and degree of permanent ground deformation. O'Rourke et al (1989) describe ground movement as well as pipe breakage in San Francisco's Sullivan Marsh and Mission Creek in the 1906 San Francisco earthquake. Pipe breakage data is taken from Schussler (1906), who provided a map showing water main breaks identified in the three months following the earthquake (Figure 3). Using photographs and other records, O'Rourke mapped ground movements in the Embarcadero and South of Market (e.g., Figure 4).

In later work, O'Rourke et al (1990) provided ground settlement contours in the Marina District in the 1989 Loma Prieta earthquake, and overlaid pipe breakage records on the settlement map (Figure 5). The data from 1906 San Francisco and 1989 Loma Prieta earthquakes are used in the present paper to develop break rate relations for water pipe in liquefied soil.

Hamada (1989) described Noshiro City gas pipe damage that occurred in liquefied soils in the 1983 Nihonkai-Chubu earthquake. Damage to cast iron gas pipe reached approximately 21 breaks per 1000 feet of pipe, where displacements were on the order of 2 feet.

Eguchi (1983b) provides a constant figure, 1.8 break per 1000 feet for cast iron pipe subjected to landslide, and 1.0 breaks per 1000 feet for cast iron pipe subjected to liquefaction and lurching, regardless of displacement.

2.4 AFFECT OF JOINT TYPE ON PIPE DAMAGEABILITY

Shaoping et al (1983) studied the contribution of joint damage to overall pipe damage. They point out that joints are the weakest points in segmented pipe, and that lead filled joints were superior to cement filled joints, since the latter are brittle and cannot sustain even small deformation. In the Tangshan Earthquake, where break rates in the mezoseismal area reached 10.0 per km (3.0 per 1000 ft), the rate of damaged joints was 79.6%. In Haicheng, approximately 60% of breaks were associated with joints.

3 PIPE TYPES AND BREAK DATA

3.1 SAN FRANCISCO WATER SYSTEMS AND PIPE TYPES

San Francisco possesses three water supply systems: two specifically for firefighting use and one for both fire fighting use and municipal use (potable water). The two firefighting systems are the truck-borne Portable Water Supply System (PWSS), and the underground Auxiliary Water Supply System (AWSS). Both are owned and operated by the San Francisco Fire Department (SFFD). The Municipal Water Supply System (MWSS) is owned and operated by the San Francisco Water Department (SFWD).

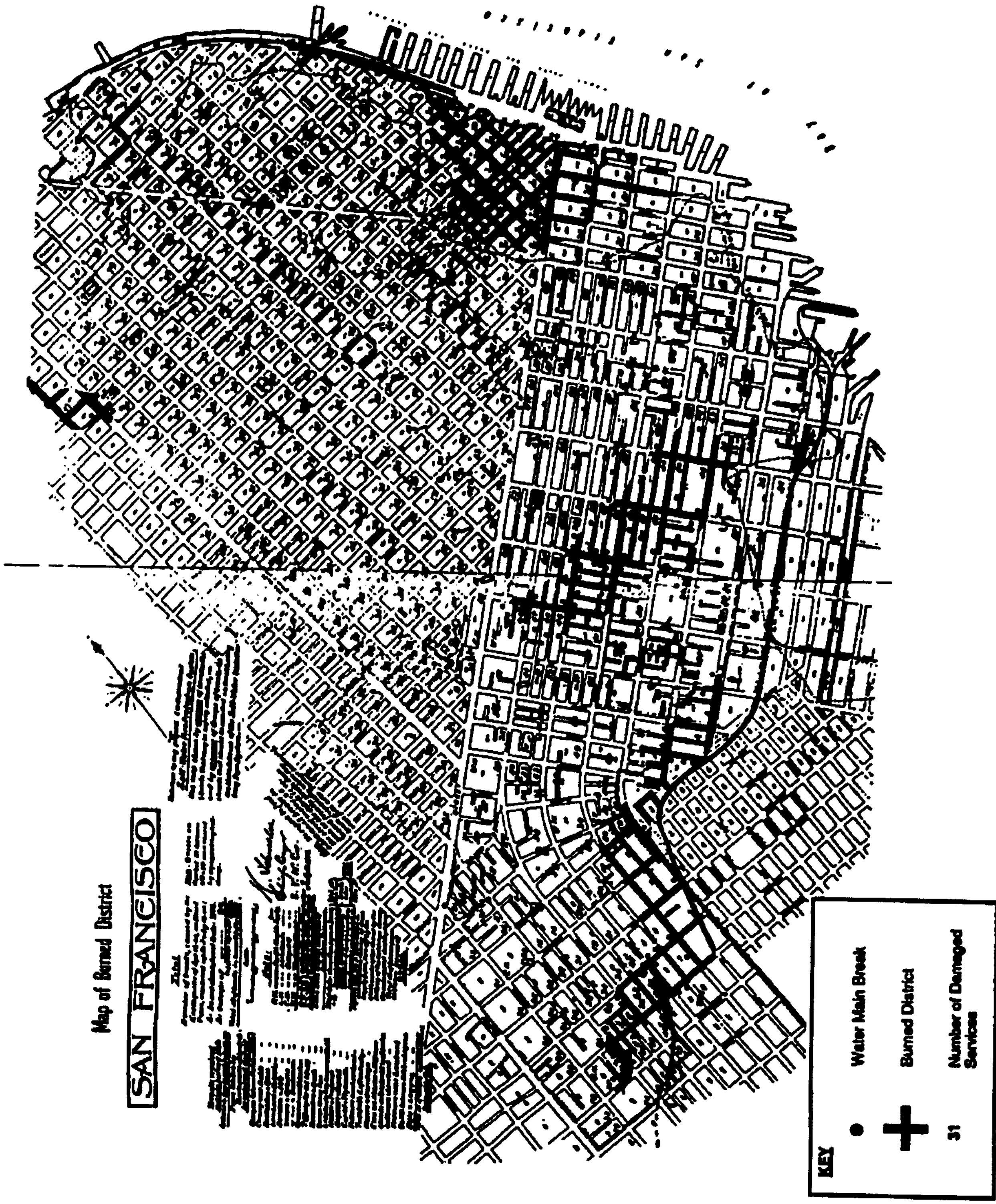

Figure 3: 1906 water main breaks (Schussler, 1906)

The two systems incorporate a variety of pipe materials and construction. The pipe can be roughly classified into 7 types: bell and spigot cast iron, double-spigot cast iron with heavy walls, ductile iron with rigid joints, ductile iron with flexible joints, riveted steel, gas welded steel, and arc welded steel.

Bell and Spigot Cast Iron Pipe

The majority of MWSS water mains are of this type. Until the 1930's, pipe was vertical pit cast iron, 12 feet long, typically exhibiting brittle mechanical properties with tensile strengths on the order of 15 ksi (Ahmed, 1990). Joints were sealed with an oakum gasket and packed with lead caulk. Restraint was typically provided at dead ends and branch installations. After 1930, centrifugally cast iron came into wide use in water systems. Also brittle, this material nonetheless exhibits strengths on the order of 35 ksi. The advantage of stronger material may be offset to some degree by the stiffer joint construction to which SFWD switched at around the same time. Around the 1930s, SFWD began to seal joints with a rubber gasket and dry mortar caulk.

Virtually all the water mains affected in the Marina District by the October 17, 1989 Loma Prieta earthquake were of the pre-1930 construction, as were all mains 24 inches in diameter or smaller in the 1906 San Francisco earthquake.

Double Spigot, Heavy Wall Cast Iron Pipe

This is the type of pipe used for the AWSS. Four characteristics tend to make AWSS cast iron pipe stronger and more flexible than MWSS cast iron pipe: double spigot joints, heavy walls, extra restraint, and fewer lateral connections. Each of these characteristics might be expected to reduce AWSS pipe vulnerability relative to cast iron water pipe described above.

Double spigot joints use cast iron or cast steel sleeves, sealed with lead and oakum, as shown in Figure 6. This type of construction allows twice as much joint rotation as does bell and spigot construction with a similar lead/oakum seal. The Schedule H pipe used in the AWSS has walls typically 60% thicker than those of the MWSS cast iron pipe. Since the AWSS operates at higher pressure than MWSS, extra restraint is employed. Rods connect as many as 10 pipe segments at turns, tee joints, hills and other points of likely stress, as opposed to the restraint of one joint in MWSS tees. Finally, since AWSS contains no service connections (it is a dedicated firefighting only system), laterals occur only at hydrants and branches. Laterals provide restraint and may act as concentrated load points on a water main, potentially resulting in additional pipe damage.

Ductile Iron Pipe with Rigid Joints

After about 1960, ductile iron was used for MWSS pipe of 16 inch or smaller diameter, with geometry and construction similar to the cast iron it replaced, but cast centrifugally in 18 foot lengths. SFWD continued to use gasket and grout joints in new ductile iron pipe construction until 1989.

Ductile Iron Pipe with Flexible Joints

Since 1989, SFWD pipe joints have employed U.S. Pipe's Field Lok Gasket, an elastomeric gasket fitted with mechanical teeth that provide longitudinal restraint (Figure 7). The gasket requires no packing, thereby allowing significant rotational flexibility.

Riveted and Welded Steel

Pre-1930 MWSS pipe larger than 24 inch diameter is of riveted iron or steel construction. Longitudinal joints were shop riveted; circumferential joints were riveted in the field. Gas welding came into use around 1930; during the 1940s, arc welding found widespread use. After about 1960, pipe larger than 20 inch diameter was of welded steel. Joints were bell and spigot with fillet welds at the lap joint. Pipe less than 24 or 30 inches in diameter received a single fillet weld on the outside. Pipe 30 or 36 inches in diameter or larger were welded inside and outside. Weld leg size was equal to pipe thickness.

3.2 1906 PIPE DAMAGE AND GROUND MOVEMENTS

Records of water main damage within San Francisco were not kept during the few months following the 1906 earthquake. The only source of data is a map supplied by Schussler (1906), who recorded 300 main breaks and over 23,000 service breaks by July 1906. Broken mains of all diameters from 2 or 3 inches up are indicated in Schussler's map. As Schussler noted, it is likely that this record is incomplete; many streets were still covered with debris at the time the map was prepared, and no doubt more pipe damage was uncovered as the restoration process continued. Pipe breakage data from the 1906 earthquake therefore must be employed with caution.

Where no breaks or occasional breaks appear on the map, no conclusion can be drawn, since breaks may have remained buried beneath rubble. More confidence may be placed in the completeness of the record for individual blocks that had numerous breaks. One may conclude that on these blocks, breaks were found by restoring service pressure over that block. Restoration of service pressure would have required identification and repair of most or all the breaks.

3.3 1989 PIPE DAMAGE AND GROUND MOVEMENTS

The 1989 Loma Prieta earthquake resulted in over 160 MWSS pipe breaks, approximately 3/4 of which were located in the Marina District. Breaks within the Marina were concentrated in the regions of hydraulic fill created circa 1906-1917. Locations of water main and service breaks are shown in Figure 8, which is based on SFWD records. In the next section, these will be correlated with liquefaction-induced ground settlements. Lateral spreading as large as 7 inches over 100 feet is known to have occurred in the Marina in 1989 (Harding Lawson Associates et al, 1991), but lateral movements have not been mapped.

4 ANALYSIS

4.1 BELL AND SPIGOT CAST IRON PIPE

In order to develop estimates of pipe breakage resulting from area-wide permanent ground deformation, break rates in San Francisco water mains was correlated with amount of ground settlement observed in the Marina in 1989, and lateral spreading observed in Sullivan Marsh and Mission Creek areas in 1906. Marina data was used primarily to develop break rate estimates at low permanent ground displacements; the 1906 data included displacements up to 6 feet.

Because records of settlement are available in the Marina, and records of lateral movement are available in the Sullivan Marsh and Mission Creek, our analysis equates vertical settlement with permanent lateral ground displacement. This was done despite it being generally known that lateral displacements of the same order of magnitude as vertical displacements are known to have occurred in the Marina (good lateral displacement data however are lacking). As a result, our analysis may underestimate total displacements in the Marina.

Low Displacement/1989 Marina Data Analysis

To develop a break rate relationship for low displacements, breaks within the area of the Marina that experienced settlement were aggregated to the nearest street intersection. The number of breaks at each intersection was then divided by the average length of pipe associated with an intersection. No differentiation was made for pipe diameter or pipe orientation relative to ground movement. The resulting break rate and settlement data per intersection were then used to correlate breaks per 1000 linear feet of pipe with permanent ground displacement (ie, settlement).

Large Displacement/1906 Data Analysis

Ground movements as large as nine feet occurred in several parts of San Francisco in the 1906 earthquake, causing widespread damage to pipe of the same construction as existed in the Marina in 1989. Five locations were selected and data taken from Schussler's map and O'Rourke's ground movement records of the 1906 earthquake (O'Rourke et al, 1990). Data were only drawn from locations where both the damage record and ground movement record appear to be complete. It should be noted that the assumptions regarding completeness of the pipe break record (described above) may tend to bias damage data toward atypically high break rates. The potential for this bias cannot be clarified without more complete information on 1906 pipe damage.

Regressions of the data were performed on both sets of data, and a combined set. The best fit was found as follows: (a) the 1989 data was treated as one set, and a regression was performed to fit a line with zero intercept over the domain 0 to 5 inches of displacement; (b) the 1906 data were treated as a separate set, and a regression was performed to produce a best fit line over the domain 5 inches to 9 feet; (c) a bilinear break rate curve resulted, as shown in Figure 9. A null hypothesis test indicates that a correlations exists with at least 95% confidence (Crow et al, 1960). **These correlations and resulting curve apply only to bell and spigot cast iron pipe with lead and oakum joints.**

4.2 VULNERABILITY OF OTHER PIPE TYPES

Detailed damage data is unavailable for the other six classes of pipe. To develop break rates for these other classes, the break rate for bell and spigot cast iron was multiplied by a "relative vulnerability" factor R. Relative vulnerabilities were determined based on a review of the literature, as well as engineering judgment.

4.3 DOUBLE SPIGOT, HEAVY WALL CAST IRON PIPE

Relative vulnerability R for this class of pipe was arrived at by multiplying factors to account for joint rotational capacity (J), wall thickness (W), extra restraint (B for bolts), and laterals (L):

$$R = J * W * B * L$$

The use of double spigot joints doubles joint rotation capacity, so J was assigned a value of 0.5. Since AWSS pipe walls are 8/5 as thick as those of bell and spigot MWSS cast iron, W was assigned a value of 0.625. It is difficult to assess that benefit of added restraint in AWSS pipe. The section properties of restrained joints are only slightly greater than those of unrestrained joints, so bolting is considered to add little overall pipe strength. B was therefore assigned a value of 1.0. L was assigned considering the damage associated with service connections in Marina District MWSS pipe in 1989. Approximately 25% of main breaks in the Marina were associated with services. Since the number of laterals in AWSS pipe is negligible next to that of MWSS, L was assigned a value of 0.75. R is therefore approximately 0.25.

4.4 DUCTILE IRON PIPE WITH RIGID JOINTS

This type of construction was used in San Francisco between about 1960 and 1989. It was assumed to be similar to pipe ductile iron pipe damaged in the in the Miyagi Prefecture in the 1978 Miyagi-Ken-Oki earthquake. The failure ratios reported by Kubo and Isoyama for ductile iron and cast iron water pipe were 0.04 and 0.17 failures per km, respectively. The ratio of these figures equates with R. For simplicity, R has been assigned a value of 0.25.

4.5 DUCTILE IRON PIPE WITH FLEXIBLE JOINTS

Hard data were unavailable on the relative performance of cement caulked joints as compared with lead/oakum joints. The ultimate compressive strength of the two materials is probably comparable, although the strains at ultimate vary greatly. Lead flow plastically while cement mortar will chip out as rotation occurs (ie, brittle failure). It is estimated that Field Lok Gaskets allow joints in bell and spigot ductile iron pipe to rotate approximately twice as much as similar pipe with mortar-caulked joints. Therefore, a value of 0.125 has been assigned to R.

4.6 GAS WELDED STEEL PIPE

Hamada (1983) compared cast iron pipe breakage with steel gas pipe breakage in the 1983 Nihonkai-Chubu earthquake, and concluded that the rate of damage to cast iron pipe was two to three times that in the case of steel pipe. Eguchi describes gas-welded steel pipe in faulting regions as 30% as vulnerable as cast iron. In landslide, the factor is 61%, and in liquefaction and lurching, 70%. Based on these observations, $R = 0.50$ was assigned.

4.7 RIVETED STEEL PIPE

Little data is readily available describing the performance of riveted steel pipe. Judging from photos presented by Duryea, it appears that the failure mode of riveted pipe is shear of the rivets. It is unlikely that significant local deformation can occur around rivet holes because these are most likely fabricated from iron boiler plate. We consider that riveted joints were designed to develop pipe body yield stresses with a marginal safety factor. It was reasoned that riveted steel pipe would perform similarly to pipe construction that immediately succeeded it (ie, gas-welded steel pipe) and therefore the same $R = 0.50$ was assigned.

4.8 ARC WELDED STEEL PIPE

Eguchi describes Grades A and B arc-welded steel gas pipe in fault rupture areas as 5.8% as vulnerable as cast iron. In landslide, the factor is 11%, and in liquefaction and lurching, 15%. The material properties of welded steel water pipe are fairly similar to those of contemporary gas pipe. Using these data, arc-welded steel water pipe was assigned a relative vulnerability $R = 0.125$.

5 DISCUSSION

Break rate functions developed using the methods discussed here are presented in Figure 10. These relationships indicate a trend of break rate increasing from 0 to 6 breaks per 1000 feet of pipe as permanent ground displacement increases from 0 to 6 feet. The trend and order of magnitude of damage tend to agree with Eguchi's data on pipe damage near fault rupture in 1971 San Fernando. In that earthquake, damage ranged from 0.4 to 5 breaks per 1000 feet near fault offsets as fault displacement increased from 3 to 98 inches. The figures developed for the present study are somewhat larger than Eguchi's figures for pipe damage in regions of liquefaction and landslide.

Hamada's data on the 1983 Nihonkai-Chubo earthquake indicate break rates in cast iron gas pipe reach as high as 21 breaks per 1000 feet, but it may be supposed that the higher magnitudes could result from stiffer joint construction. The order of magnitude is also supported by the Tangshan earthquake data presented by Shaoping et al.

The high initial break rate agrees with Miyajima's conclusion that pipe damage can be caused even by an average ground strain of less than 1 percent. Eguchi's relationship between break rate and MMI shows a similar trend, with the logarithm of damage increasing at a slower rate as MMI exceeds VIII.

6 CONCLUDING REMARKS

Damage data from the 1906 San Francisco and 1989 Loma Prieta earthquakes have been used to estimate break rates for cast iron water pipe subjected to permanent ground displacement. A bilinear curve was fitted to the data. The first segment (0 to 5 inches displacement) was based on water pipe damage in the Marina District in the 1989 Loma Prieta earthquake. The second segment (5 inches to 6 feet) was based on records of damage to similar pipes damaged in the 1906 San Francisco earthquake.

Damage rates for other types of water pipe were developed by applying a relative damageability factor, R, to the function developed for cast iron water pipe. The factors were developed for each type of water pipe used by the City of San Francisco for feeder and distribution water mains. Where possible, the factors were based on data presented in the literature. Where such data were unavailable, engineering judgment was employed to estimate relative damageability. As a result, the damage functions for several different types of San Francisco water pipe are similar bilinear curves differing by a factor *R*.

The major observation is that normalized pipe break rate is nonlinear with permanent ground displacements. Relatively small displacements produce initial pipe breakage; at larger displacements, break rates increase at a smaller rate. A possible explanation for the nonlinearity is that damage initiates at low magnitudes of permanent ground displacement, breaking the original pipe network into shorter segments that are relatively free to move with the surrounding soil. Relatively larger displacements are required to cause further breaks in the remaining intact network segments.

Data presented in the literature tend to verify the trend of relatively small displacements causing significant initial pipe breakage, while larger displacements result in additional breaks, but at a relatively smaller rate. The magnitude of break rates developed here tend to lie within the range of break rates recorded for gas and water pipe in other earthquakes under similar conditions.

Additional research is needed on this topic, including for example: (a) careful collection of post-earthquake survey measurements of vertical and lateral displacements in areas of liquefaction and/or high pipe breakage, and (b) small-scale laboratory experimental investigation of pipe break as a function of displacement.

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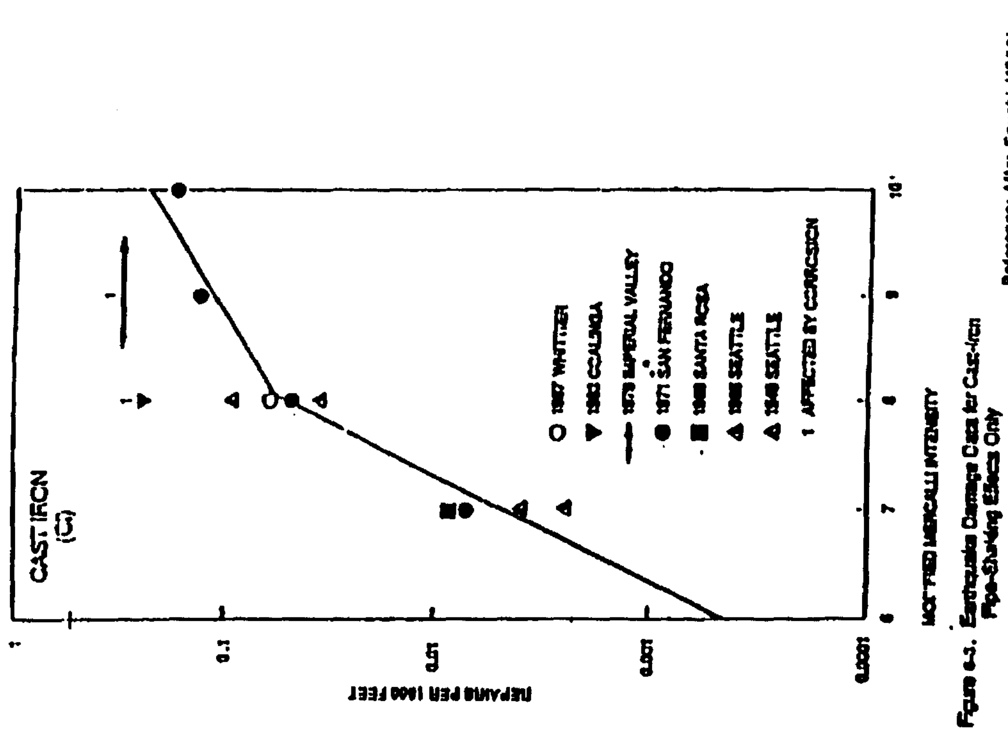


Figure 1: Damage data for shaking effects only
(after Eguchi 1983, appended by Harding Lawson et al, 1991)

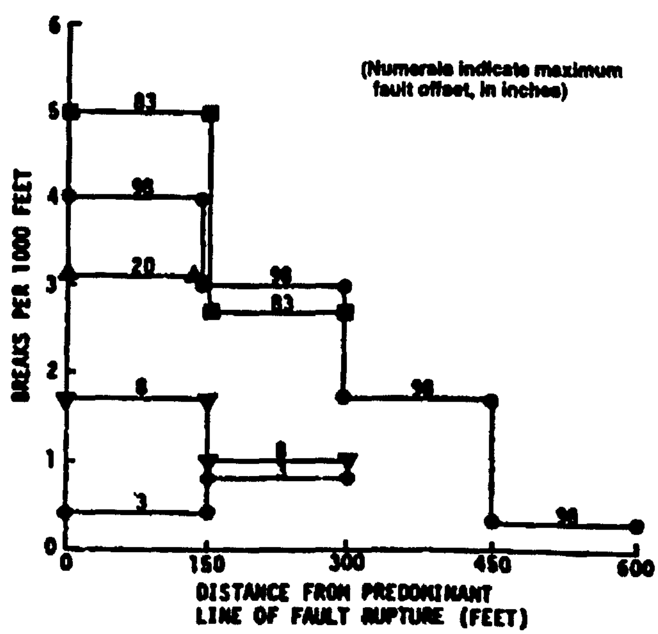
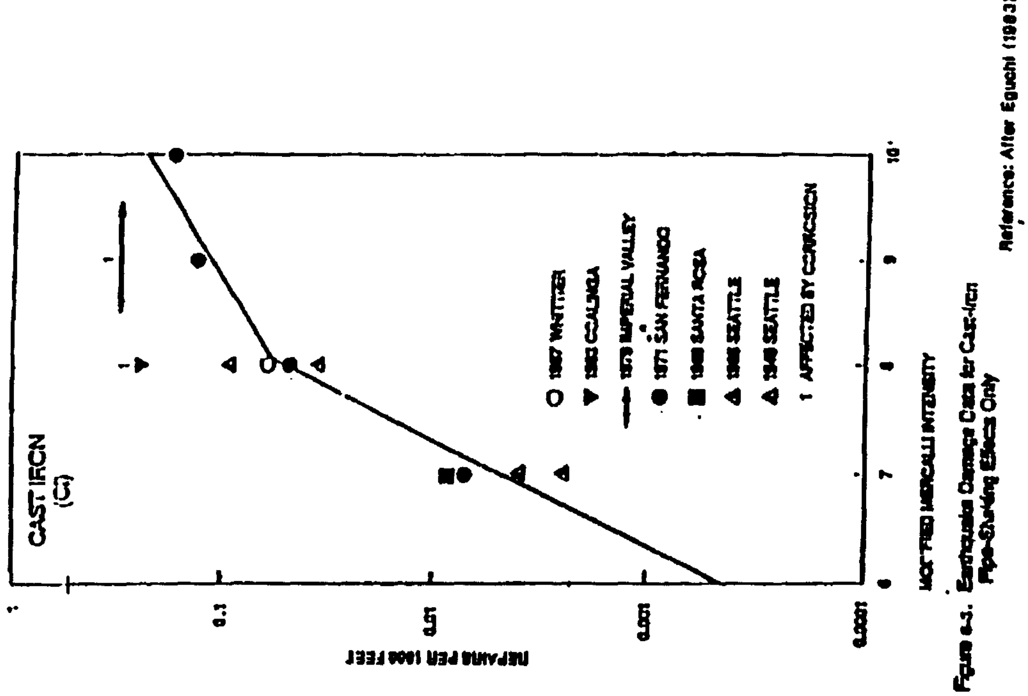


Figure 2: Effect of fault rupture
(Eguchi, 1983)



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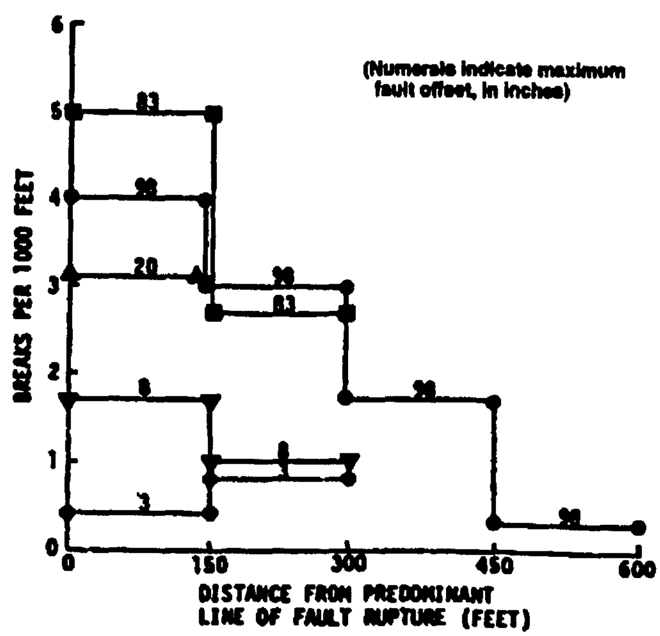

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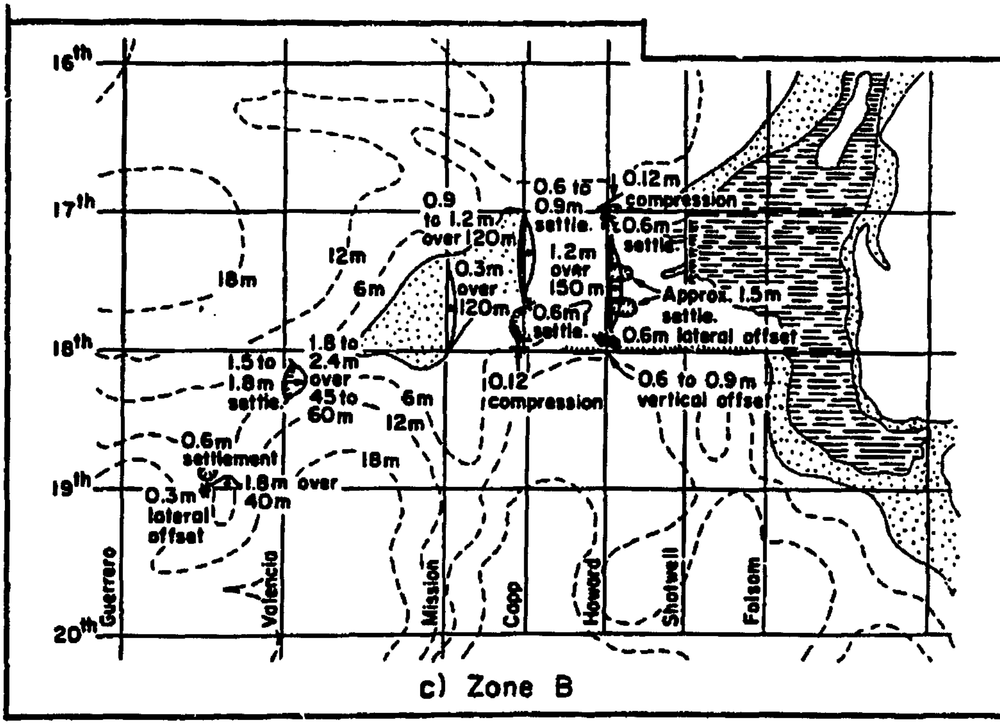

Figure 4: 1906 ground movements in Mission Creek (O'Rourke, 1989)

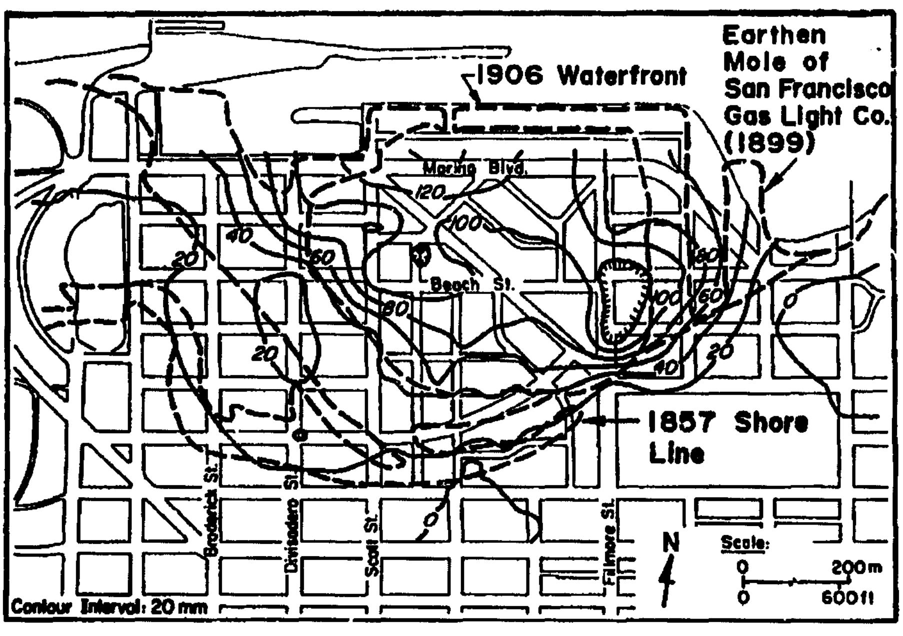

Figure 5: 1989 Marina settlement contours (O'Rourke, 1990)

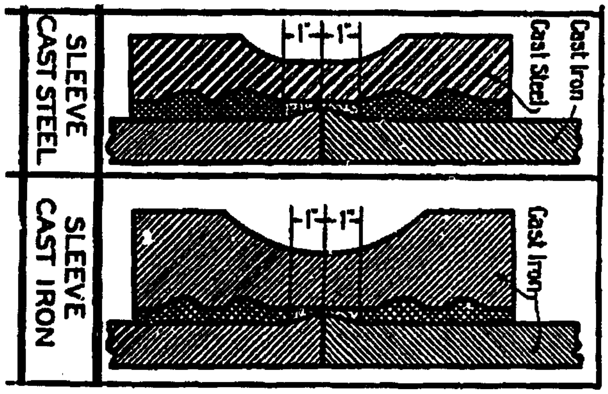

Figure 6: Double spigot joint

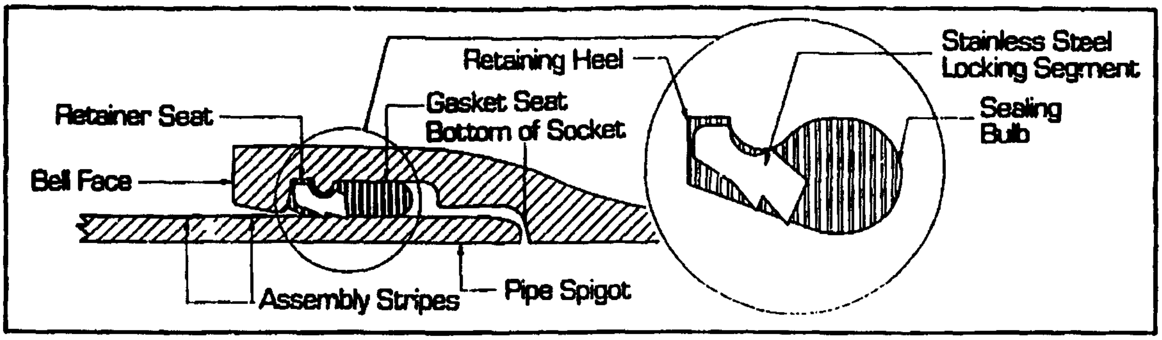

Figure 7: Field Lok Gasket
(U.S. Pipe)

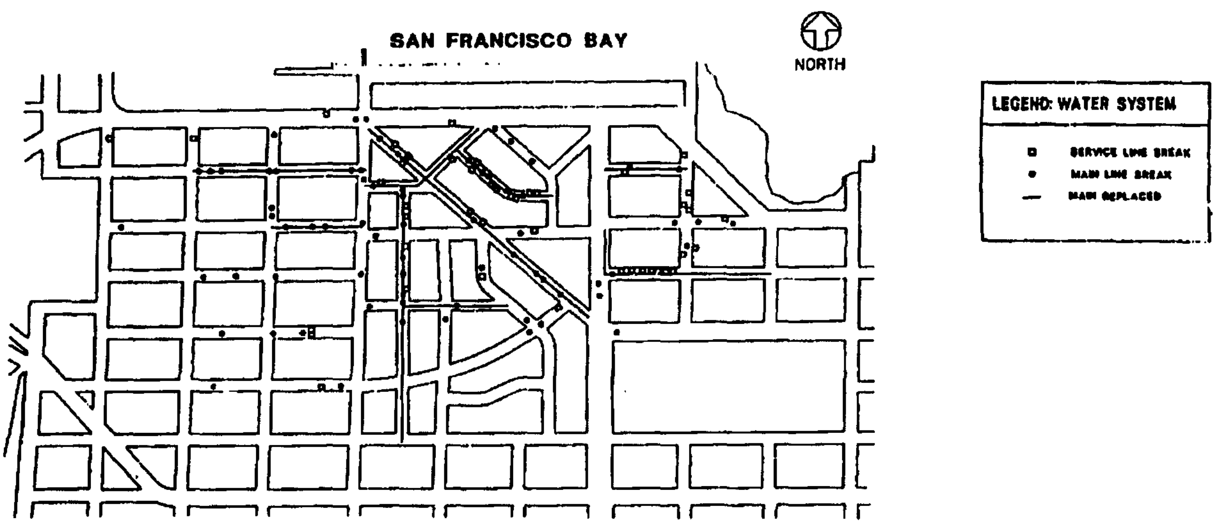

Figure 8: 1989 Marina water system breaks

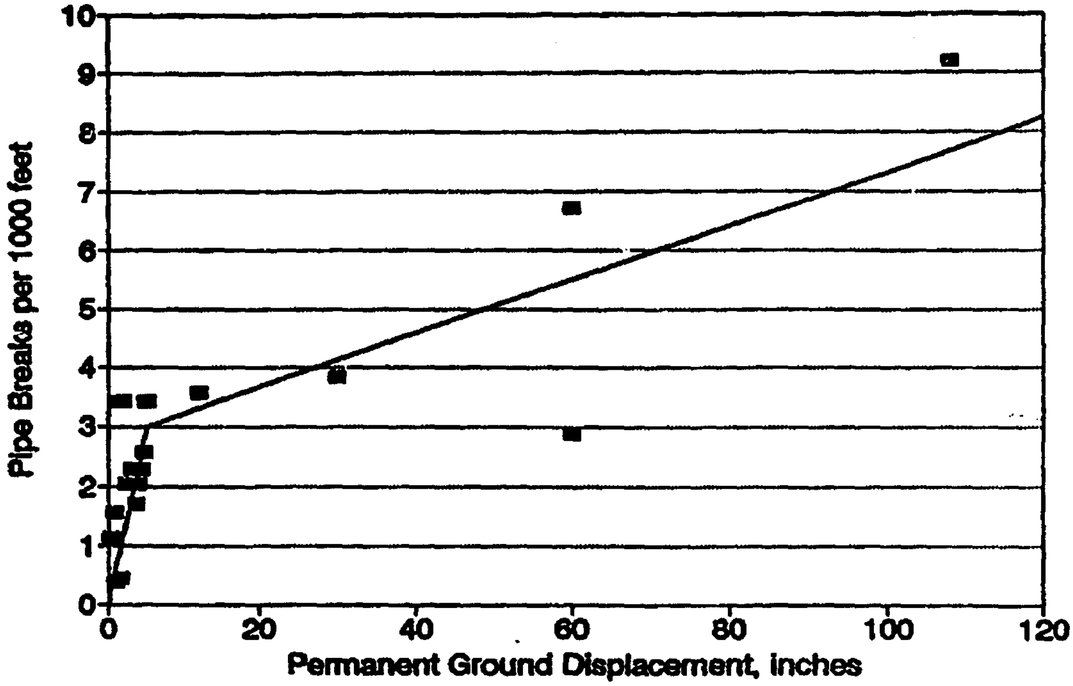

Figure 9: 1906 and 1989 cast iron water pipe damage

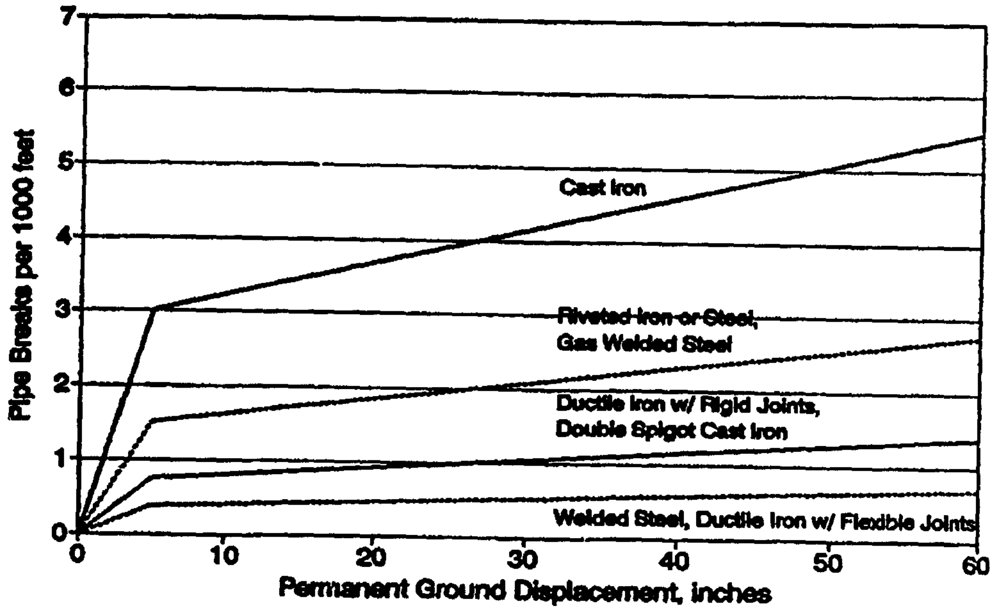

Figure 10: Estimated water supply pipe damage