QUANTITATIVE ANALYSIS OF SEISMIC DAMAGE TO BURIED UTILITY PIPELINES

by

T. Katayama[I], K. Kubo[II], and N. Sato[III]

SYNOPSIS

Seismic damage to buried utility pipelines caused by past earthquakes was summarized quantitatively. By using the San Fernando data, the relation between damage and severity of ground shaking was discussed. Results of quantitative analysis on the relation between seismic damage to buried water pipes and ground conditions are reported.

INTRODUCTION

In recent years, the seismic problems of utility systems have become to attract the attention of earthquake engineers and researchers (1-3). When compared with earthquake problems of important, independent structures and installations on which most of the previous effort in the field of earthquake engineering has been placed, those of utility systems possess several special characteristics. Seismic behaviors of buried pipelines are dominantly influenced by ground conditions and subsurface strain distribution, but little is known today about the relative-displacement characteristics of surface layers of ground during strong earthquake motions. The earthquake problems of utility systems become increasingly more important in proportion with the level of urbanization because the moderner a city is, the more heavily it depends on utility systems for its day-to-day activities. Since utility systems are networks having sources, transmission lines, storage facilities and distribution systems within themselves, damage to certain locations in a utility network often affects significant portions of the system.

In spite of the fact that seismic damage to utilities in the past was not a major cause of the life and private property loss, it is clear that more effort needs to be directed towards this particular field of earthquake engineering. In addition to understanding the earthquake response of a wide variety of basic elements in utility systems, it is essential to quantitatively review past seismic damages to such systems, to establish performance criteria (2,3), to develop a methodology that will minimize the probability of system breakdown of a network, and to develop rational methods of loss estimates from earthquakes for various utilities. The purpose of the studies reported in this paper is to review in-depth past seismic damages to utility pipelines and to furnish basic information required for the assessment of possible losses in future earthquakes.

PAST DAMAGE STATISTICS

Tables 1 and 2 summarize average numbers of failures in underground water and gas distribution pipelines caused by past earthquakes. (For the references from which the original data are taken, refer to Refs. (5) and (6).) It is seen from these tables that the number of failures of buried water and gas pipes rarely exceeds 2/km during strong seismic motions when averaged over more than 100km or so of pipe length. A large difference is noted for damage rate apparently due to the difference in ground shaking intensity as exemplified in a factor of nearly 8 observed between the water pipe failure rates in Tokyo during the 1923 Kanto earthquake and in Fukui

---

[I]Associate Professor, [II] Professor, and [III]Research Assistant of the Institute of Industrial Science, University of Tokyo.

during the 1948 Fukui earthquake. When intense ground motions are accompanied with ground ruptures (e.g. the zone of surface breakage in the case of the San Fernando earthquake) or by extensive liquefaction (e.g. part of Niigata in the case of the Niigata earthquake), an extremely high damage rate of possibly some 10 failures per km may be expected in localized areas. The high damage rate of gas pipes in Yokohama caused by the Kanto earthquake may be attributable to either or both of the two phenomena. Fig.1 shows the relation between liquefaction and the extent of sewer pipe damage in the city of Niigata caused by the Niigata earthquake. Six sections were chosen where sewer pipes densely existed, and the ratio of the length reconstructed to the length pre-existing was correlated with the ratio of the length in liquefied areas to the total length. It is implied that liquefaction was the determining factor in this particular case.

Because of the rarity of well-documented data, it is difficult to quantitatively discuss the effect of diameter, material, or type of joint on the seismic damage of buried pipes. The data of water pipe failures and of the number of re-calked joints damaged by the Kanto earthquake shows the consistent tendency for damage to decrease with an increase in pipe diameter. Similar trend is also found in the water pipe damage caused by the Managua earthquake. Generally speaking, welded steel pipes behave best while asbestos-cement pipes are most affected. Though both flexibility and strength should be important, the former often seems to play a more dominant role in the seismic behaviors of buried pipes. Examples are the performances of small-sized ductile-iron gas pipes during the Kanto earthquake, clay sewer pipes with flexible joints during the San Fernando earthquake, and PVC water pipes during the Managua earthquake.

DAMAGE AND GROUND SHAKING INTENSITY

Because the San Fernando earthquake had a moderate magnitude of 6.6 with its epicenter lying only about 10km north of the north boundary of Los Angeles, the severity of shaking differed considerably even within the area where buried pipelines suffered serious damage. The damage rate was evaluated for each strip with a north-south width of about 480m. Results are shown in Fig.2, in which damages are correlated with the approximate epicentral distance. The damages of gas service and water service pipes are normalized by the corresponding length of main pipes. High damage rates in the 7th strip from the north are associated with surface breakage of ground reported there. By assuming the maximum horizontal acceleration near the city's north boundary as 500 gal and that at the southmost part of the damaged area as 250 gal, and a linear relationship between the maximum acceleration and the epicentral distance on a log-log paper, the approximate ranges of damage rates for water distribution pipes were correlated in Fig.3 with the estimated maximum acceleration. The value in Strip 7 was discarded in constructing Fig.3, which also shows the average failure ratios obtained in the previous section. Though the maximum acceleration may not be the best measure of the intensity of ground shaking for the analysis of seismic damage to buried pipes, the results in Fig.3 seem to be consistent.

WATER PIPE DAMAGE AND GROUND CONDITION

By using the damage data of water distribution pipes in Tokyo caused by the Kanto earthquake, quantitative analysis was made on the relation between damage and ground condition. There were a total of 381 failures reported including pipe breaks, joint separations and ruptures of hydrants and valves, with their locations plotted on a map. The number of failures was counted for each mesh of 1km×1km, from which the degree of damage of the mesh was evaluated by the damage index ($D.I.$):

$$D.I. = \frac{m}{pA_e} \quad (1)$$

where m is the number of failures in the mesh, p is the ratio of the estimated population density of the mesh to the average population density of the metropolitan area of Tokyo, and A_e is the effective area within the mesh in which water distribution piping was assumed to have existed. The damage index is a measure of damage normalized by the population which can be assumed to be proportional to the length of water distribution pipes. The number of failures, m, varied from 0 to a maximum of 20 for the 96 meshes examined.

Response curves of surface layers at every nodal point of 1km×1km meshes in the metropolitan area of Tokyo had been computed by previous researchers (4) by using the multiple reflection theory. Since these curves often show multiple peaks, the weighted average of predominant frequencies was calculated:

$$\bar{f} = \sum_{i=1}^{k} f_i(a_i-2) \Big/ \sum_{i=1}^{k} (a_i-2) \quad (2)$$

in which a_i and f_i are the i-th peak value and the corresponding frequency, respectively, k is the number of peaks in the response curve, and the constant term "2" stems from the amplification factor at the free surface. The representative frequency of a mesh was evaluated by averaging $\bar{f}$'s at the four corner nodes of the mesh:

$$f_0 = \frac{1}{4}\sum_{i=1}^{4} \bar{f}_i \quad (3)$$

The following value was also calculated for each mesh

$$\sigma_f = \sqrt{\frac{1}{4}\sum_{i=1}^{4} (\bar{f}_i - f_0)^2} \quad (4)$$

which was expected to show the variation of dynamic response properties within the mesh. Though the mesh size of 1km×1km is large, the quantity σ_f should indicate to a certain extent the complexity of surface layer conditions within the mesh. On the whole, the value of f_0 was found to be greater than 3.5Hz in the higher district of Tokyo, and between 1.5Hz and 2.5Hz in the lower district where surface layers are generally thick and soft.

It was found (5,6) that the difference in the degree of damage can be distinguished when the ground condition is classified into the three groups as shown in Fig.4 by using f_0 and σ_f. In Fig.4, the representative value of damage index for the meshes belonging to a certain group of ground condition is evaluated by

$$\overline{D.I.} = \frac{\Sigma m}{\Sigma p A_e} \quad (5)$$

instead of by the simple average of the damage indices of the meshes. It is interesting to note the group corresponding to the highest damage is associated with the meshes in the higher district with old river valleys with higher values of σ_f indicating that the seismic damage to underground pipes is significantly affected by the degree of complexity of ground.

As the second classification of ground condition, the region under consideration was divided into the following four groups mainly according to the composition of surface layers:

(a) Loam or loamy clay & loam with thickness varying from 7m to 15m underlain by compact sand or sand-gravel layers (c_1=1.0),
(b) Soft organic deposits including peat and peaty clay in old river valleys with thickness varying from 5m to 10m (c_2=2.0),
(c) Alluvial layers of mostly loose sand with thickness varying from 10m to 20m (c_3=3.0), and
(d) Soft alluvial layers with thickness greater than 30m, often underlain by soft clay (c_4=4.0).

Most of the higher district of Tokyo is of type (a) or (b), while the lower district is of type (c) or (d). By evaluating the proportion A_i (i=1,2,3 and 4; $A_1+A_2+A_3+A_4=1.0$) of each type of ground in each mesh, the representative ground condition of the mesh was estimated by the following quantity:

$$c_0 = \sum_{i=1}^{4} c_i A_i \qquad (6)$$

Analysis by using this classification showed that the difference in the degree of damage is distinguishable by means of the three groups (c1, c2 and c3) shown in Fig.4.

When the distribution of the 96 meshes was examined by using these two classification methods, there were found some contradictory results. However, general agreement was satisfactory. Hence, it was decided to classify the ground condition into the three groups A, B and C (see Fig.4) by the combination of the two different methods discussed above. The cumulative frequency distributions of *D.I.*'s belonging to these three groups are also shown in Fig.4, which clearly suggests that the degree of seismic damage to water pipes buried in different kinds of ground can be satisfactorily distinguished by means of this classification method. The values of $\overline{D.I.}$ were 9.74 for Group A, 4.18 for Group B, and 2.07 for Group C. If the $\overline{D.I.}$ value of the 96 meshes is taken as unity, the ratios were found to be about 2.0 for Group A, 0.9 for Group B, and 0.4 for Group C. Therefore, the degree of seismic damage to water pipes buried in Group A ground is about twice greater than the average damage in Tokyo, while that in Group C ground is less than half of the average.

REFERENCES

(1) "San Fernando, California, Earthquake of February 9, 1971, Volume II", Utilities, Transportation, and Sociological Aspects, U.S. Dept. of Commerce, 1973. (2) R.V.Whitman, C.A.Cornell and G.Taleb-Agha; "Analysis of Earthquake Risk for Lifeline Systems", Proc. U.S. National Conf. on Earthq. Engg., 1975. (3) C.M.Duke and D.F.Moran; "Guideline for Evolution of Lifeline Earthquake Engineering", Proc. U.S. National Conf. on Earthq. Engg., 1975. (4) H.Kawasumi, Y.Sato and E.Shima; "Dynamic Response of Ground in the Metropolitan Tokyo", Disaster Prevention Committee of Tokyo, 1970.
(5) T.Katayama, K.Kubo and N.Sato; "Earthquake Damage to Water and Gas Distribution Systems", Proc. U.S. National Conf. on Earthquake Engg., 1975.
(6) K.Kubo, T.Katayama and N.Sato; "Quantitative Analysis of Seismic Damage to Buried Pipelines", Proc. 4th Japan Earthq. Engg. Symp., 1975.

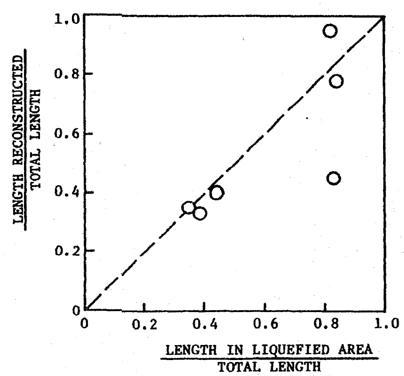


Fig.1. Effect of Liquefaction on Seismic Damage to Sewers in Niigata.

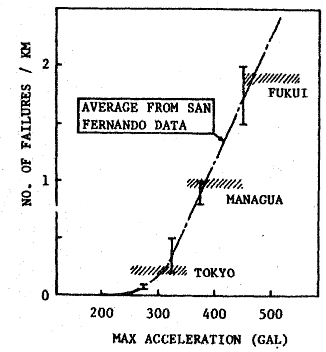


Fig.3. Failure Ratio of Water Pipe and Max Acceleration.

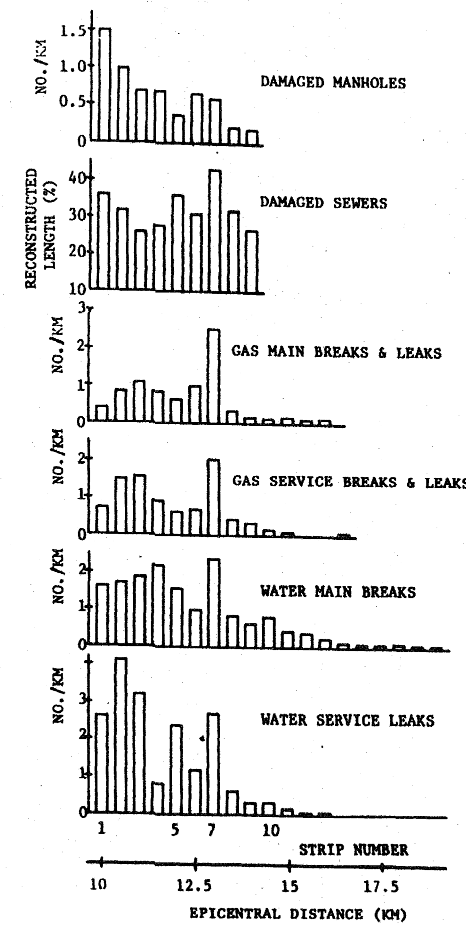
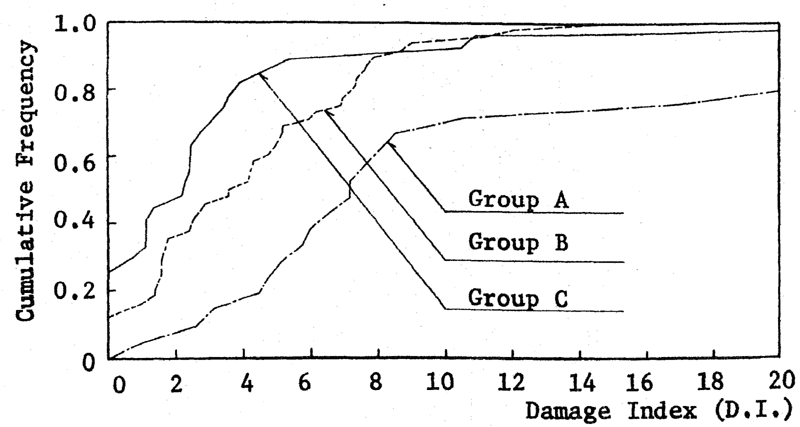


Fig.2. Damages to Buried Utility Pipes Caused by the 1971 San Fernando Earthquake.



CLASSIFICATION BY f_0 & σ_f / CLASSIFICATION BY c_0			f1	f2	f3
			$3.5 \le f_0 < 4.5$ & $\sigma_f \geq 1.15$	$1.5 \le f_0 < 3.5$	$4.5 \le f_0$; $3.5 \le f_0 < 4.5$ & $\sigma_f < 1.15$
		$\overline{D.I.}$	12.74	4.79	2.33
c1	$2.5 \le c_0 < 3.5$	7.58	A	A	B
c2	$1.5 \le c_0 < 2.5$; $3.5 \le c_0 \le 4.0$	4.51	A	B	C
c3	$1.0 \le c_0 < 1.5$	2.73	B	C	C

Fig.4. Classification of Ground Condition, and Cumulative Frequency Distribution of Damage Indices.

Table 1. Damage to Buried Water Pipelines by Past Earthquakes.

EARTHQUAKE	DAMAGED CITY	SEVERITY OF SHAKING	AVERAGE FAILURES PER KM	REMARKS
1923 Kanto	Tokyo	M.M. IX^{-} (300±50 gal)	0.22	Total Length = 980km Diameter = 75-1,100mm Cast Iron Pipes
1948 Fukui	Fukui	M.M. X-XI (500±50 gal)	1.9	Total Length = 80km Diameter = 100-600mm Cast Iron Pipes
1964 Niigata	Niigata	M.M. VIII-IX^{-} (200±50 gal)	0.46	Total Length = 470km Cast Iron Pipes; Effect of Liquefaction Noticeable.
1971 San Fernando	Northern Los Angeles	M.M. VIII-X (200-500 gal)	0.95	Total Length = 493km Diameter ≥ 50mm Cast Iron Pipes
1972 Managua	Managua	M.M. IX (400±50 gal)	0.98	Total Length = 581km Diameter = 25-750mm Cast Iron (122km), Asbestos Cement (330km), PVC (77km) and Galvanized Iron (52km).

Table 2. Damage to Buried Gas Pipelines by Past Earthquakes.

EARTHQUAKE	DAMAGED CITY	SEVERITY OF SHAKING	AVERAGE FAILURES PER KM	REMARKS
1923 Kanto	Tokyo	M.M. IX^{-} (300±50 gal)	Cast Iron Pipe Breaks 0.07 C.I. Joint Damages 2.54 (Separations, Molten Lead Escapes and Loosenings)	L = 1,607km D = 75-1,170mm Breaks occurred only for D ≤ 200mm pipes.
	Yokohama	M.M. IX-X (400±50 gal)	Cast Iron Pipe Breaks 8.98 C.I. Joint Damages 4.30	L = 168km D = 75-350mm
1964 Niigata	Niigata	M.M. VIII-IX^{-} (200±50 gal)	a: C.I. Pipe Breaks 0.61 C.I. Jt. Separations 0.39	L = 131km D = 100-300mm
			b: Welded Steel Pipe, Breakes at Weld 0.76	L = 17km D = 100-200mm
			c: C.I. & W.S. Pipe, Breaks & Separations 7.1	L = 7.4km, D = 150-300mm Main pipes in Liquefied areas.
1968 Tokachi-Oki	Hachinohe, Hakodate, Towada & Muroran	M.M. VIII (150±50 gal)	C.I. and W.S. Pipe, Breaks & Separations 0.05	L = 172km (for 4 cities) D = 50-400mm
1971 San Fernando	Northern Los Angeles	M.M. VIII-X (200-500 gal) Variable According To Epicentral Distance	Mostly W.S. Pipe, Breaks and Leaks: a: All Damaged Areas 0.64	L = 304km D = 50-100mm
			b: Heavily D. Area 0.86	L = 213km
			c: Most H.D. Area 2.6	L = 26km
			d: Estimated Max Accel (gal) 400-500 0.85	L = 125km
			d: Estimated Max Accel (gal) 350-400 0.40	L*= 115km
			d: Estimated Max Accel (gal) 300-350 0.12	L = 90km
			e: Large Diam. Transmission Lines, Max Accel > 400 gal 5.4	L = 11km D = 400-660mm

L = Total Length of Piping, D = Diameter
*Excluding area (c) above.

DISCUSSION

S.K. Guha (India)

Would the author please elucidate if while planning the underground pipe line system, any consideration was given to the type of ground so as to reduce damage in the event of an earthquake ? It would mean that areas having very soft ground i.e. type a or type b are preferably excluded while planning the underground pipe line net works.

Author's Closure

Not received.