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QUANTITATIVE EVALUATION OF DAMAGE TO BURIED PIPELINES INDUCED BY SOIL LIQUEFACTION

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SUMMARY

The purposes of the present paper are to analyze earthquake damage to pipelines quantitatively using a statistical method and to clarify failure modes of pipelines based on field investigation data in Niigata City during the 1964 Niigata Earthquake and in Noshiro City during the 1983 Nipponkai-Chubu Earthquake. The results of a multivariate analysis suggest that liquefaction is more important variable than individual item of the ground characteristics such as SPT blow count, ground water table, etc. in order to establish an equation for prediction of the pipe damage during an earthquake.

INTRODUCTION

Buried pipeline systems have been damaged extensively by soil liquefaction during severe earthquakes in recent days, for example, the 1971 San Fernando Earthquake in USA, the 1964 Niigata Earthquake and 1983 Nipponkai-Chubu Earthquake in Japan. After the 1964 Niigata Earthquake and the 1964 Alaska Earthquake in USA, many studies on soil liquefaction have been performed actively. The mechanism of liquefaction has become to be known and some evaluation methods of liquefaction potential were proposed from the results of these studies. Despite the achievements in the studies on liquefaction, there still remain several major problems to be solved in the field of the lifeline engineering. One of those is the effects of soil liquefaction on the pipeline damage.

First, the relationship between pipeline damage and several influential factors including liquefaction effects is described using field investigation data in Niigata City during the 1964 Niigata Earthquake, and in Noshiro City during the 1983 Nipponkai-Chubu Earthquake. Secondly, a multivariate analysis is conducted and liquefaction effects to pipelines' damage is discussed. In this paper, a "damage" refers to one specific site of damage in a pipeline. Therefore, "number of damages" refers to the number of sites of damage in the piping under discussion.

EFFECTS OF SOIL CONDITIONS ON PIPELINES' DAMAGE

State of Earthquake Damage to Pipelines The length of pipelines, and number of damage for each type and diameter of pipe were measured in each cell based on the pipe-laying maps. In the present study, cell size is approximately 500 m x 500 m, one of 400 equal cells on a topographical map with a scale of 1:25,000. Figs. 1

and 2 indicate the relationship between pipe diameter and damage ratio in Niigata City and Noshiro City, respectively. The damage ratio is defined as the number of pipe damage divided by the total length of a pipeline in the present study, following the method of Kubo and Katayama et al. (Ref. 1). The number of pipe damage includes damage to pipe body (breakage, bursting, cracking and thrusting), and damage to joint (breakage, pull-out, and looseness). It can be seen from these figures that markedly high damage ratios are obtained for the cast iron pipes (CIP) with 400 mm and 450 mm diameter. Moreover, all of these damages occurred at joints and such damages were caused at liquefied sites near the boundary between the liquefied and non-liquefied sites according to the pipe-laying maps. The causes of those pipe damages could be explained in terms of variable ground movements due to sharp change of the ground characteristics and buoyancy effect at the liquefied site (Ref. 2). Given the fact that the pipes with relatively small diameter of 50 mm to 150 mm were severely damaged, a great similarity can be seen in a comparison of past earthquake damage to the pipelines in which liquefaction was not present. The correlation between the damage ratio and factors regarding ground characteristics such as SPT blow count and ground water table was not clear. It suggests that the damage to the pipelines is affected by various interrelated factors of ground characteristics.

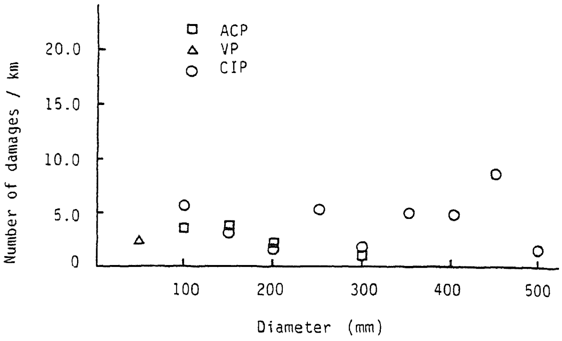

Fig. 1 Relationship between damage ratio of pipelines, diameter and pipe type (Niigata City).

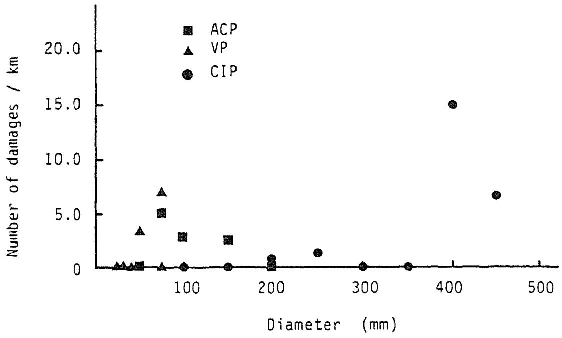

Fig. 2 Relationship between damage ratio of pipelines, diameter and pipe type (Noshiro City).

Influence of Liquefaction Liquefied areas in Noshiro City during the 1983 Nipponkai-Chubu Earthquake were identified by some researchers. Based on liquefaction maps indicated by Tohno and Shamoto (Ref. 3), we indicate the number of pipe damage in liquefied areas and that in non-liquefied areas in Fig. 3. This figure also shows the failure modes of the pipelines in accordance with those illustrated in Fig. 4, which are taken from Noshiro City Gas and Waterworks Bureau (Ref. 4). Since the data in this figure are not taken from the pipe-laying maps but from reference 4, the damage to ductile iron pipes (DCIP) is also shown. It is evident from Fig. 3 that roughly half of the damage to asbestos cement pipes (ACP) and polyvinyl chloride pipes (VP) were caused in the liquefied areas irrespective of the failure modes. Furthermore, it is very interesting to note that almost all of the damage to cast iron pipes (CIP) and ductile iron pipes (DCIP) were caused at joints of a pipe in the liquefied areas. These facts suggest that earthquake damage to the pipelines is strongly related to soil liquefaction.

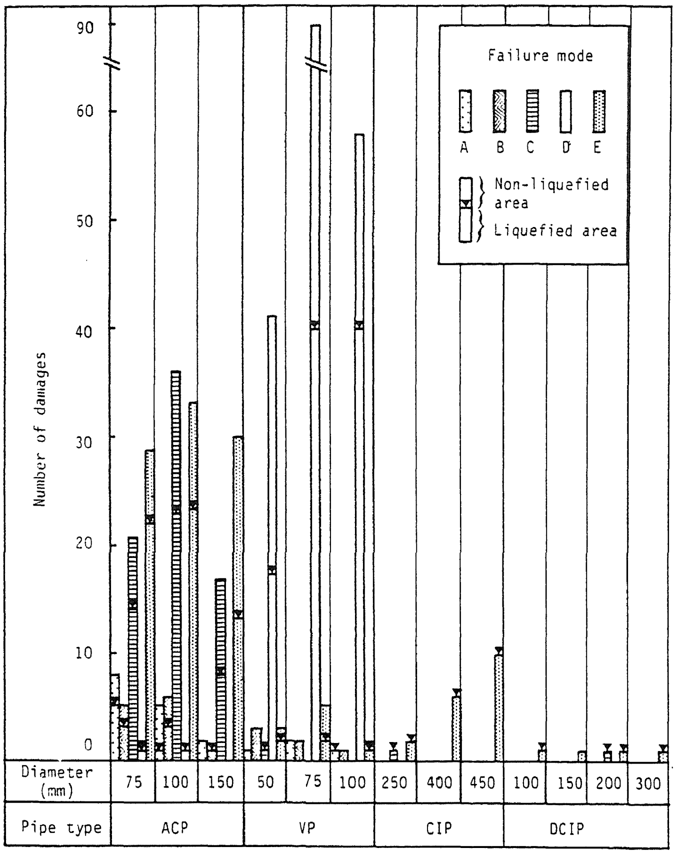

Fig. 3 Relationship between number of damages, ground condition, pipe type and failure mode during the 1983 Nipponkai-Chubu Earthquake.

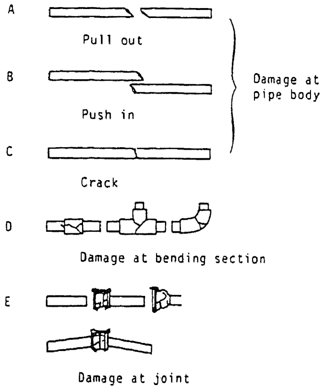

Fig. 4 Failure modes of pipeline(from Noshiro City Gas and Waterworks Bureau, 1983).

Influence of Permanent Ground Displacement Induced by Soil Liquefaction

Fig. 5 indicates the relationship between horizontal permanent ground displacement and number of pipe damages. This figure suggests that many damages were caused at sites where permanent ground displacement was greater than about 1 m. However, in order to discuss a relationship between pipe damage and permanent ground displace-

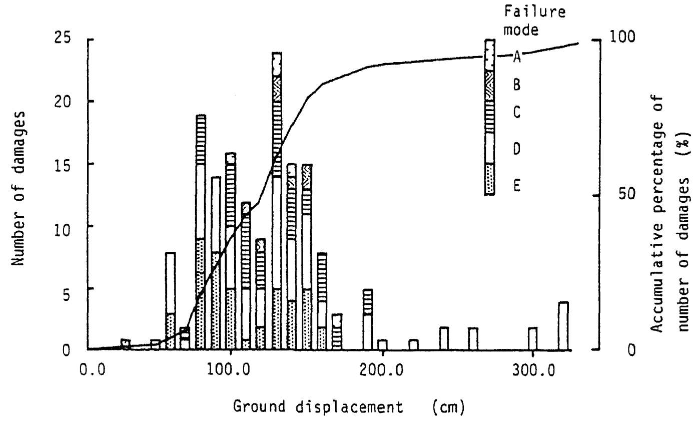

Fig. 5 Relationship between number of damages and permanent ground displacement.

ment, it is more pertinent to observe ground strain around the buried pipelines than to observe absolute displacement. Therefore, the average ground strains for longitudinal directions of a pipe axis are evaluated using two vectors of the permanent ground displacements near the site of pipe damage. Fig. 6 displays the relationship between number of damages and average ground strain. It can be seen from Fig. 6 that the pipe damages could be caused by an average ground strain as low as 1 percent or less. However, it is insufficient to merely observe the residual ground deformation after an earthquake in order to discuss a relationship between the pipe damage and ground strains because the ground movement during an earthquake is variable.

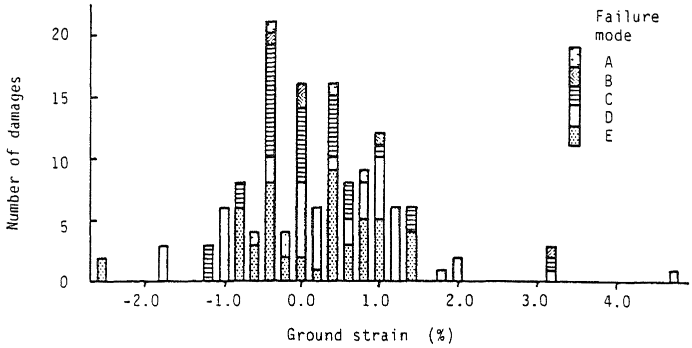

Fig. 6 Relationship between number of damages and average ground strain in longitudinal direction to the pipe axis (in Noshiro City).

MULTIVARIATE ANALYSIS INCLUDING LIQUEFACTION EFFECTS

The results mentioned above revealed that the pipe damage was much influenced by liquefaction and permanent ground displacement due to liquefaction. In this chapter, a multivariate analysis known as the "Quantification Theory I" was conducted. The item of liquefaction is classified into three classes: none, light and heavy, which are determined by the size of a liquefied area in a cell based on the liquefaction map indicated by Tohno and Shamoto (Ref. 3). Similarly, permanent ground displacement is classified into four categories based on the distribution map of the permanent ground displacement indicated by Hamada et al. (Ref. 5).

Table 1 indicates the results of the multivariate

Table 1 Number of damages due to permanent ground displacement in Noshiro City.

Item	Category	Num.	Category weight	Partial correlation coefficient
Pipe type	A C P	56	0.563	0.278
	V P	27	1.295	
	C I P	29	-2.294	
Diameter (ϕ) mm	$\phi \leq 50$	17	-0.790	0.269
	$50 < \phi \leq 100$	48	-0.017	
	$100 < \phi \leq 200$	29	-1.093	
	$200 < \phi \leq 300$	10	0.384	
	$300 < \phi \leq 400$	4	3.290	
	$400 < \phi$	4	7.237	
SPT blow count up to a depth of 5m (N)	$0 \leq N \leq 9$	15	1.185	0.427
	$9 < N \leq 11$	48	3.453	
	$11 < N \leq 13$	16	-5.671	
	$13 < N$	33	-2.862	
Soil type	Silt	3	-1.306	0.289
	Fine sand	45	1.866	
	Medium sand	46	-0.953	
	Coarse sand	11	-2.722	
	Clay	7	-0.893	
Ground water table (H) m	$0 \geq H \geq -2.0$	25	-0.254	0.385
	$-2.0 > H \geq -2.5$	22	3.638	
	$-2.5 > H \geq -3.0$	22	3.251	
	$-3.0 > H \geq -4.5$	22	-2.158	
	$-4.5 > H$	21	-4.654	
Total length in a mesh (l) km	$0 < l \leq 0.1$	23	-1.322	0.150
	$0.1 < l \leq 0.3$	33	0.621	
	$0.3 < l \leq 0.5$	26	0.810	
	$0.5 < l$	30	-0.371	

Multiple correletion coefficient 0.56

analysis using some ground characteristics such as SPT blow count, ground water table, etc. Table 2 shows the results of second multivariate analysis including the liquefaction effects. The multiple correlation coefficients in these analyses are 0.56. In general, the multiple correlation coefficient decreases with a decrease in the number of items. However Table 2 indicates no decrease in the multiple correlation coefficient in comparison with Table 1. This suggests that the pipe damages are explained by liquefaction effects rather than some items of ground characteristics: SPT blow count, ground water table, etc. Moreover, the partial correlation coefficients for liquefaction and permanent ground displacement are higher in this analysis. Since the correlations for two items of liquefaction and permanent ground displacement are high, third multivariate analysis is carried out using only the item of liquefaction and eliminating permanent ground displacement as an item. The results are shown in Table 3. Since the number of items is further decreased, the multiple correlation coefficient decreases to 0.43. The partial correlation coefficient of liquefaction is the highest of all the items, in this result.

The above results show that liquefaction is the most influential factor in pipe damage. Although the multiple correlation coefficients of the analyses are too low to establish an equation for prediction of earthquake damage to the pipelines, the results suggest that liquefaction is more important item for evaluating the pipe damage than individual item of the ground characteristics such as SPT blow count, ground water table, etc. It is, therefore, a crucial point in establishing a prediction equation to determine the extent of liquefaction more precisely.

Table 2 Results of multivariate analysis including liquefaction and permanent ground displacement in Noshiro City.

Item	Category	Num.	Category Weight	Partial correlation coefficient
Pipe type	A C P	46	0.024	0.155
	V P	18	-1.804	
	C I P	22	1.426	
Diameter (ϕ) mm	$\phi \le 50$	13	1.113	0.173
	$50 < \phi \le 75$	20	1.260	
	$75 < \phi \le 100$	14	-0.906	
	$100 < \phi \le 200$	22	-0.111	
	$200 < \phi \le 300$	9	-2.985	
	$300 < \phi$	8	0.290	
Liquefaction	None	28	-2.871	0.475
	Light	27	-1.897	
	Hard	31	4.245	
Permanent ground displacement	None	16	-0.049	0.410
	Small	18	-1.049	
	Medium	22	4.340	
	Large	30	-2.568	
Total length in a mesh (l) km	$0 < l \le 0.1$	17	-2.923	0.269
	$0.1 < l \le 0.3$	22	1.595	
	$0.3 < l \le 0.5$	20	0.284	
	$0.5 < l \le 0.7$	5	0.948	
	$0.7 < l \le 0.9$	7	-1.226	
	$0.9 < l$	15	0.850	

Multiple correlation coefficient 0.56

Table 3 Results of multivariate analysis including liquefaction in Noshiro City.

Item	Category	Num.	Category Weight	Partial correlation coefficient
Pipe type	A C P	46	0.358	0.116
	V P	18	-1.487	
	C I P	22	0.468	
Diameter (ϕ) mm	$\phi \le 50$	13	0.970	0.198
	$50 < \phi \le 75$	20	1.354	
	$75 < \phi \le 100$	14	-0.672	
	$100 < \phi \le 200$	22	-0.615	
	$200 < \phi \le 300$	9	-3.169	
	$300 < \phi$	8	1.473	
Liquefaction	None	28	-1.661	0.318
	Light	27	-1.393	
	Hard	31	2.713	
Total length in a mesh (l) km	$0 < l \le 0.1$	17	-2.386	0.205
	$0.1 < l \le 0.3$	22	1.194	
	$0.3 < l \le 0.5$	20	0.487	
	$0.5 < l \le 0.7$	5	1.258	
	$0.7 < l \le 0.9$	7	0.742	
	$0.9 < l$	15	-0.462	

Multiple correlation coefficient 0.43

CONCLUSIONS

Conclusions obtained from this study are summarized as follows:

(1) It is interesting to note that markedly high damage ratios of piping with a large diameter of 400 mm and 450 mm are present, and these pipes are located at liquefied sites near the boundary between the liquefied and non-liquefied sites. This could be explained in terms of variable ground motion due to sharp change of the ground characteristics and buoyancy effects at the liquefied sites.

(2) Many pipe damages occurs at sites where the permanent ground displacement is greater than 1 m. Moreover, the pipe damage could be caused even by an average ground strain of less than 1 percent.

(3) The tensile and compressive failure modes of the pipelines at joints do not always agree with the direction of the permanent ground displacement. Since the ground movement during an earthquake is variable, it is insufficient to merely observe the residual ground deformation after an earthquake in order to assess pipe damage.

(4) Liquefaction is the most influential factor to the pipe damage. Although the multiple correlation coefficients in the analyses are too low to establish an equation for prediction of earthquake damage to pipelines, the results suggest that liquefaction is more significant in evaluating pipe damage than such ground characteristics as SPT blow count, ground water table, etc.

Although the authors have collected extensive soil profiles data and pipelaying maps plotting the sites of pipe damage from Niigata City Waterworks Bureau and Noshiro City Gas and Waterworks Bureau, an equation for prediction of earthquake damage to pipelines is not established because of an insufficient amount of data. It is necessary to accumulate more detailed data of earthquake damage to pipelines and ground conditions.

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