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RESPONSE ANALYSIS OF BURIED PIPELINES SUBJECTED TO PERMANENT GROUND MOVEMENT INDUCED BY SOIL LIQUEFACTION

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SUMMARY

The purposes of the present paper are to analyze the response of pipelines subjected to liquefaction-induced permanent ground displacement and to discuss the subsequent failure of pipelines. Response simulations of the buried pipelines, continuous welded steel pipelines and jointed ductile iron pipelines, are conducted. The results of simulations are in accordance with the failure mechanism of the buried pipelines subjected to permanent ground displacement.

INTRODUCTION

Permanent ground displacement induced by soil liquefaction is one of the most serious liquefaction hazards. Using aerial photographs taken before and just after the earthquakes, Hamada et al. measured the permanent ground displacement following the 1964 Niigata Earthquake and the 1983 Nipponkai-Chubu Earthquake (Ref. 1). According to their findings, the maximum detected permanent ground displacement was more than 8 m along the Shinano river in Niigata City and more than 5 m in Noshiro City. We investigated the relationship between permanent ground displacement and pipeline damage following the 1983 Nipponkai-Chubu Earthquake. The results indicated that buried pipelines were vulnerable to permanent ground deformation (Ref. 2). Little work has been done on the response of pipelines subjected to permanent ground deformation so far, however.

In the present paper, response simulations are performed by using a modified transfer matrix method and the failures of pipelines due to liquefaction-induced permanent ground deformation are discussed. The results obtained from the present study can give us a useful piece of information for determining whether or not countermeasures for the pipeline buried in the ground with high liquefaction potential should be taken, and what countermeasures should be done.

SIMULATION OF PIPELINES' RESPONSE DUE TO PERMANENT GROUND DISPLACEMENT INDUCED BY SOIL LIQUEFACTION

<u>Analytical Models</u> The shape of distribution of the permanent ground displacement is assumed to be a sinusoidal curve shown in Fig. 1 (Ref. 3). W and δ in this figure indicate the ground width of the permanent ground displacement along the pipe axis and the maximum ground displacement, respectively. K_1 and K_2 denote equivalent soil spring constants at each zone, in which non-linear characteristics are taken into consideration. The basic differential equations governing the mo-

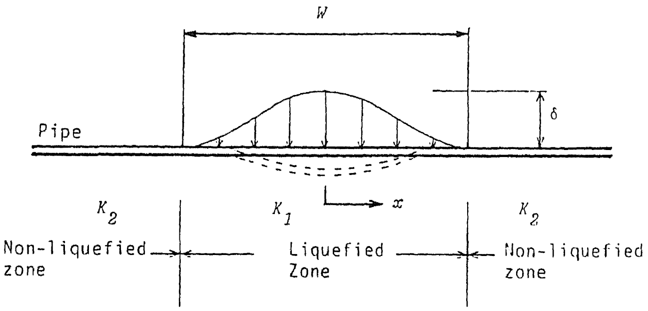

Fig. 1 Analytical model for permanent ground displacement (plane figure).

Table 1 Dimensions of pipelines.

		DCIP	SP
Outer diameter	(mm)	425.6	406.4
Thickness	(mm)	8.5	6.0
Young's modulus	(kgf/cm^2)	1.6 x10^6	2.1 x10^6
Specific gravity		7.15	7.85

DCIP : Ductile cast iron pipe
SP : Steel pipe (1kgf/cm^2 = 98kPa)

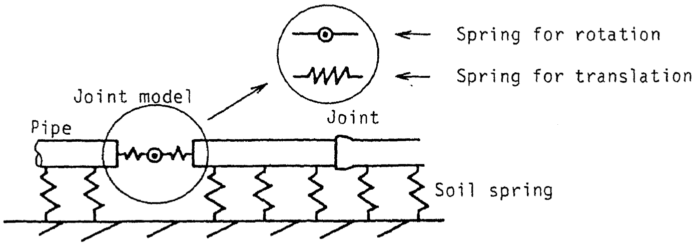

Fig. 2 Analytical model for jointed pipelines.

tions of a buried pipeline in the transverse direction can be established as follows:

$$0 \le x < \frac{W}{2};\quad EI\frac{d^4 v_1}{dx^4} + K_1 v_1 = K_1\delta\left(1 - \sin\frac{\pi x}{W} \right) \qquad \frac{W}{2} \le x;\quad EI\frac{d^4 v_2}{dx^4} + K_2 v_2 = 0$$

where v = transverse displacement of the pipe, E = Young's modulus of the pipe material, A = cross-sectional area of the pipe, I = area moment of inertia of the pipe, K = equivalent soil spring constant for the transverse motion, respectively. Subscripts 1 and 2 respectively correspond to the two sections shown in Fig. 1. The response of continuous welded steel pipelines and jointed ductile iron pipelines are simulated herein. Table 1 illustrates the dimensions of the pipes used in the simulations. Fig. 2 shows the analytical model of jointed pipelines used in the present study. The jointed pipelines are assumed here to be connected by springs for rotational and translational movements at the joints.

Application of Simulation Models to Continuous Welded Steel Pipelines Figs. 3 and 4 show the results of the response simulations. These figures display the relationship between the maximum bending stress and the width of the liquefied

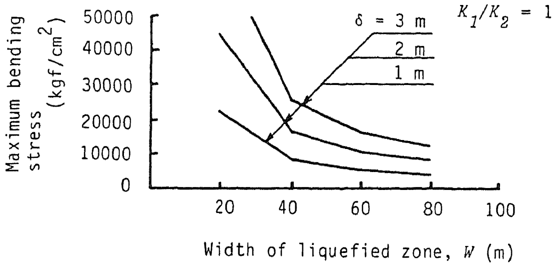

Fig. 3 Relationship between width of liquefied zone and maximum bending stress (K_1/K_2 = 1).

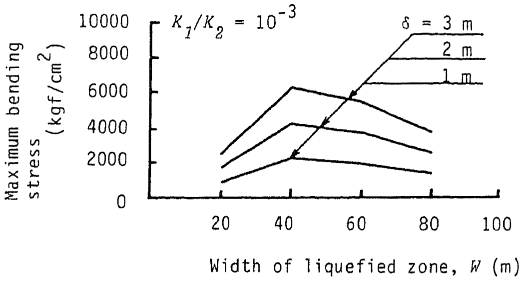

Fig. 4 Relationship between width of liquefied zone and maximum bending stress ($K_1/K_2 = 10^{-3}$).

zone. Fig. 3 expresses the results for the non-liquefied superficial layer deformation, that is, $K_1/K_2 = 1.0$. It can be seen from Fig. 3 that the maximum bending stress increases with a decrease in the width of the deformed ground. These values are much greater than the bending strength of 4200 kgf/cm^2. Therefore the probability of failure is very high in this case. Fig. 4 shows the results for 10^{-3} of the ratio of the equivalent soil spring constant, K_1/K_2. According to the experimental results presented by Takada et al. (Ref. 4), this value of 10^{-3} seems to be an appropriate value adopted for the design of buried pipelines subjected to liquefaction. Therefore, Fig. 4 expresses the response of pipelines due to deformation of completely liquefied ground. The maximum bending stress is smaller than that in Fig. 3 and the tendency of lesser pipe response with increasing width of deformed ground as shown in Fig. 3 dose not appear in Fig. 4. In other words, the maximum bending stress for the width of liquefaction zone of 20 m is smaller than that for 40 m. This can be explained in terms of the slippage between the pipelines and liquefied sand.

Figs. 5 and 6 express the relationships between the maximum bending stress and the ratio of the equivalent soil spring constant. Fig. 5 shows the response of pipelines for 1 m of the maximum magnitude of the permanent ground displacement and Fig. 6 reflects that for 40 m of the width of deformed ground. It can be seen from these figures that the maximum bending stress increases with an increase in the ratio of the equivalent soil spring constant, that is, a decrease in the degree of liquefaction. In other words, the probability of pipe failure is high for the deformation of the non-liquefied superficial layer above the liquefied layer. Generally speaking, the greater the degree of liquefaction is, the greater the magnitude of permanent ground displacement. Therefore, the failure of pipes could occur with even a relatively small ratio of the equivalent soil spring constant, that is, with great degree of liquefaction.

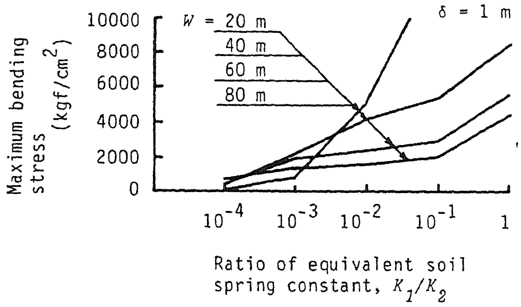

Fig. 5 Relationship between ratio of equivalent soil spring constant and maximum bending stress (δ = 1 m).

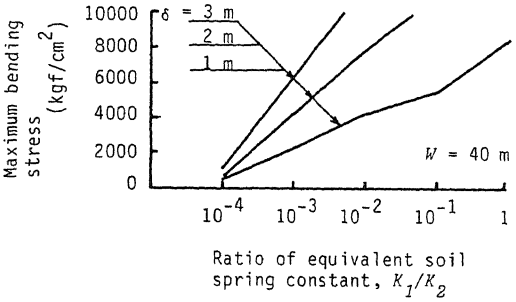

Fig. 6 Relationship between ratio of equivalent soil spring constant and maximum bending stress (W = 40 m).

Application of Simulation Models to Jointed Ductile Iron Pipelines Figs. 7 and 8 show the results of the response simulations. These figures display the relationships between the maximum displacement angle at a joint and the width of the liquefied zone. Fig. 7 expresses the results for the non-liquefied superficial layer deformation, that is, K_1/K_2 = 1.0. It can be seen from Fig. 7 that the maximum displacement angle at a joint increases with a decrease in the width of the deformed ground. This tendency is identical to the results as shown in Fig. 3. Since the allowable value for displacement angle at a joint is 7°, failure at a joint can be caused by greater than 3 m permanent ground displacement in a width of the liquefied zone less than 80 m. Pipe failure could also be caused by permanent ground displacement less than 1 m in a width of liquefied zone less than 20 m. Fig. 8 shows the results for 10^{-3} of the ratio of the equivalent soil spring constant. The maximum displacement angle at a joint is smaller than that in Fig. 7, however, the tendency of lesser pipe response with increasing width of deformed ground is similar.

Figs. 9 and 10 express the relationships between the maximum displacement angle at a joint and the ratio of the equivalent soil spring constant. Fig. 9 shows the response of pipelines for 1 m of the maximum magnitude of permanent ground displacement and Fig. 10 reflects that for 40 m of the width of deformed ground. It can be seen from these figures that the maximum displacement angle at a joint decreases with a decrease in the ratio of the equivalent soil spring constant, that is, with an increase of the degree of liquefaction. The failure of pipes at a joint could occur with even a relatively small ratio of the equivalent soil spring constant, that is, with great degree of liquefaction because of great permanent ground displacement.

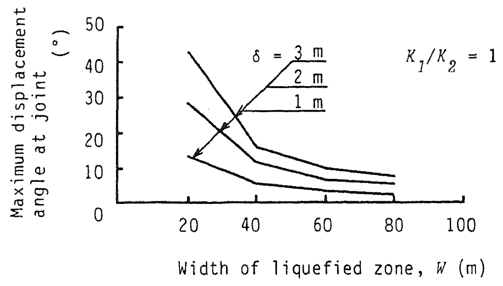

Fig. 7 Relationship between width of liquefied zone and maximum displacement angle at joint (K_1/K_2 = 1).

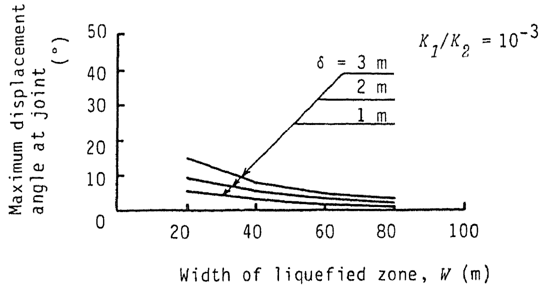

Fig. 8 Relationship between width of liquefied zone and maximum displacement angle at joint ($K_1/K_2 = 10^{-3}$).

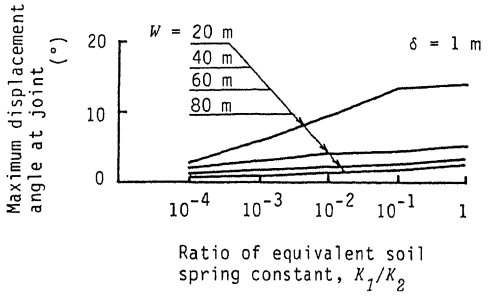

Fig. 9 Relationship between ratio of equivalent soil spring constant and maximum displacement angle at joint (δ = 1 m).

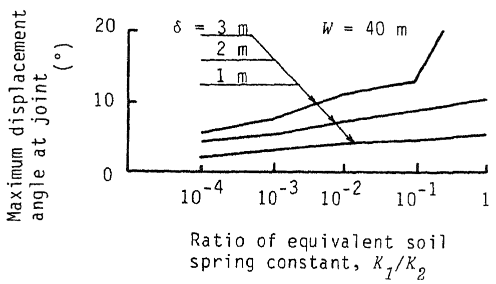

Fig. 10 Relationship between ratio of equivalent soil spring constant and maximum displacement angle at joint (W = 40 m).

The above results obtained by the response simulation seem to show that the probability of failure is high for a relatively narrow width of the deformed non-liquefied superficial layer above the liquefied ground. However, we do not take into consideration the relationship between the magnitude of the maximum ground displacement and the width of deformed ground in these examples. It is a crucial point to clarify the relationship between the magnitude of permanent ground displacement, the degree of liquefaction and the width of deformed ground quantitatively in the future.

CONCLUDING REMARKS

The following conclusions have been derived:

(1) The maximum bending stress of continuous steel pipelines subjected to permanent ground displacement increases with a decrease in the width of the deformed ground, however, the slippage between the pipelines and liquefied soil reduces the bending stress.

(2) The results of the response simulation for jointed pipelines suggest that the probability of failure at a joint is high in areas where the deformed non-liquefied superficial layer above liquefied ground is less than 80 m in width for the maximum permanent displacement greater than 1 m.

(3) The relationship between the magnitude of permanent ground displacement, the degree of liquefaction and the width of deformed ground is one of the crucial points for evaluating the failure of pipelines subjected to permanent ground displacement.

(4) It is crucial to predict liquefaction potential and generation of ground deformation in an extent smaller than 100 m for evaluating the pipelines' failure induced by permanent ground displacement.

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