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Assessment of Safety of Pipelines Subjected to Soil Liquefaction

Détermination de la sécurité de conduites dans des sols en liquéfaction

Sicherheit eingebetteter Rohrleitungen bei Erdbeben

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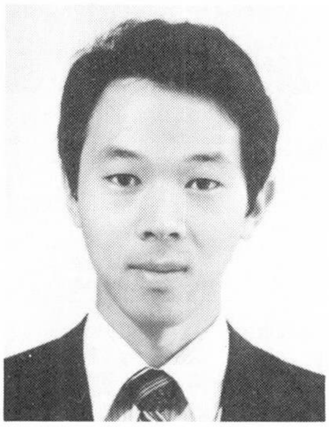

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SUMMARY

Lifeline systems have been frequently damaged by soil liquefaction. The present paper, firstly, describes the example of pipe failure subjected to soil liquefaction and the results of experimental and theoretical studies. Secondly, the factors concerned with pipe failure due to liquefaction and the safety on pipelines are discussed. It became evident from the present study that it was necessary to evaluate not only the liquefaction potential of the construction sites but also that in adjacent areas.

RÉSUMÉ

Les infrastructures subissent fréquemment des dommages lors de liquéfaction des sols. L'article décrit la rupture d'une conduite et les résultats d'études subséquentes, expérimentales et théoriques. Il mentionne les facteurs influençant la rupture de la conduite, lors de liquéfaction du sol, et traite de la sécurité des conduites. Il est nécessaire de considérer la liquéfaction possible du sol non seulement dans la zone de construction, mais aussi dans les zones environnantes.

ZUSAMMENFASSUNG

Der vorliegende Beitrag beschreibt, in welcher Art lebenswichtige Rohrleitungs-Systeme durch erdbebeninduzierte Bodenverflüssigung beschädigt werden können und stellt experimentell und theoretisch gewonnene Ergebnisse vor. Die für das Versagen und die Sicherheit von Rohrleitungen massgebenden Einflussgrössen werden diskutiert. Es ist offensichtlich, dass auch die Eigenschaft des Bodens ausserhalb der eigentlichen Einbettungsstrecke eine wesentliche Rolle spielt.

1. INTRODUCTION

The lifeline systems are becoming increasingly more important in the urban life. It is, however, well kown that the lifeline systems, especially buried pipeline systems, have been frequently damaged by the past earthquakes. For example, the Nipponkai-Chubu Earthquake of May 26, 1983 with magnitude 7.7 on the Japan Meteorological Agency scale caused extensively damage to the buried pipeline systems. A total of about 20 days was required for restoring the water supply and city gas pipelines in Noshiro City where was the middle of the hardest-hit area. It was also reported that the damage to underground pipelines were strongly influenced by soil liquefaction. The earthquake damage to pipelines were caused not only by seismic wave propagation but also by ground failure such as liquefaction, landslide, fault and so on. Dynamic behavior and failure criteria of the underground pipelines during liquefaction, however, have not almost been made clear. The present study deals with behavior of pipelines subjected to soil liquefaction and assessment of safety on the pipelines.

The present paper firstly describes the example of pipe failure subjected to soil liquefaction and the results of the experimental and theoretical studies. Secondly it points out the factors concerned with the pipe failure due to liquefaction and the safety on pipelines is discussed.

2. PIPE BEHAVIOR DUE TO SOIL LIQUEFACTION

2.1 Effects of Liquefaction-induced Lateral Spreading

2.1.1 State of earthquake damage

Permanent ground movement during the 1983 Nipponkai-Chubu Earthquke was measured by aerial photographs taken before and after the earthquke [1] . Figs. 1 and 2 show the permanent ground movement and pipe damage. A, B, C, D and E indicate the failure mode of the pipes in accordance with that

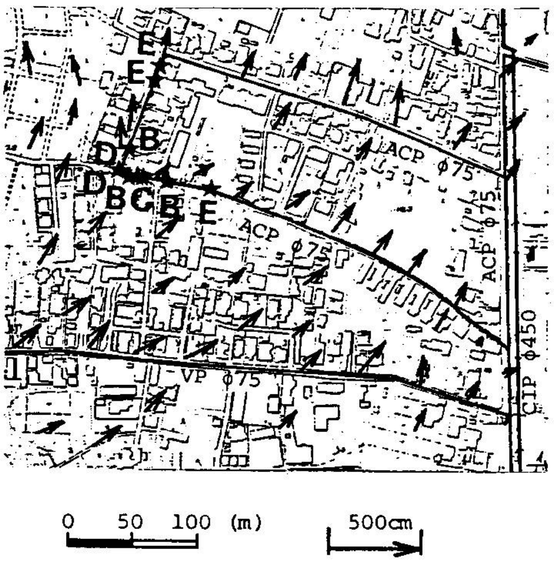

Fig. 1 Lateral spreading and pipe damage (Aoba-cho in Noshiro)

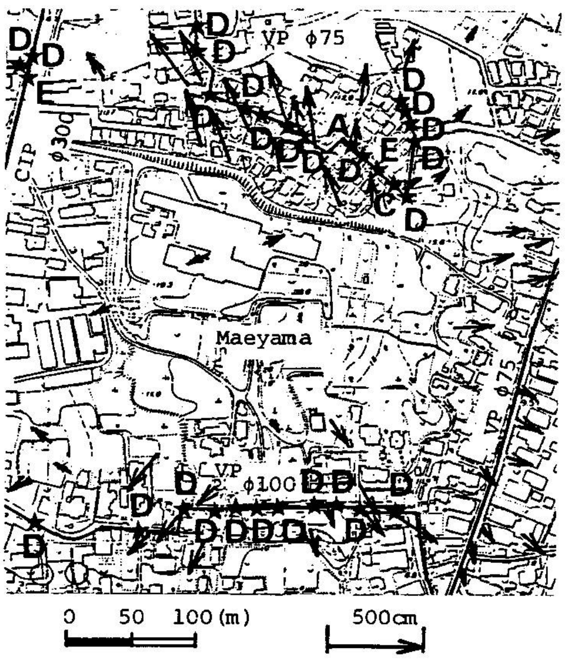

Fig. 2 Lateral spreading and pipe damage (Kawatogawa in Noshiro)

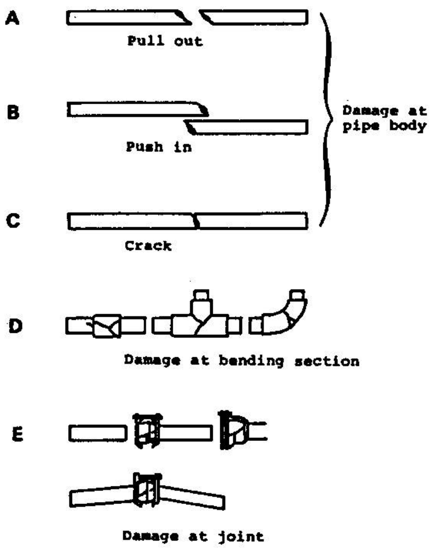

Fig. 3 Failure mode of pipe

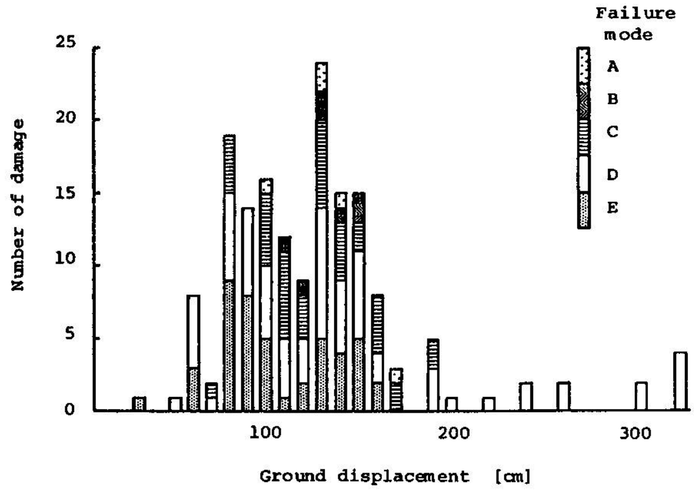

Fig. 4 Relationship between ground displacement and number of pipe damage

shown in Fig. 3 [2] . Length of arrows means the horizontal displacement of the permanent ground movement. Maximum displacement was about 5m in Noshiro City. Fig. 4 shows the relationship between the horizontal ground displacement and number of pipe damage in Noshiro City. This figure suggests that the much damage were caused at the sites where the horizontal ground displacement was greater than about 1m. Most of these areas were reported that the liquefaction occurred [3]. North slope of Maeyama hill in Kawatogawa area in Fig. 2, however, showed little sand volcano in spite that the large ground movement occurred. Based on these investigation data, the liquefaction-induced lateral spreading is classified into two types shown in Fig. 5. Type I is movement of competent surficial soils because of liquefaction of an underlying deposit (see Fig. 5 (a)), and type II is movement of surficial liquefied soils (see Fig. 5 (b)).

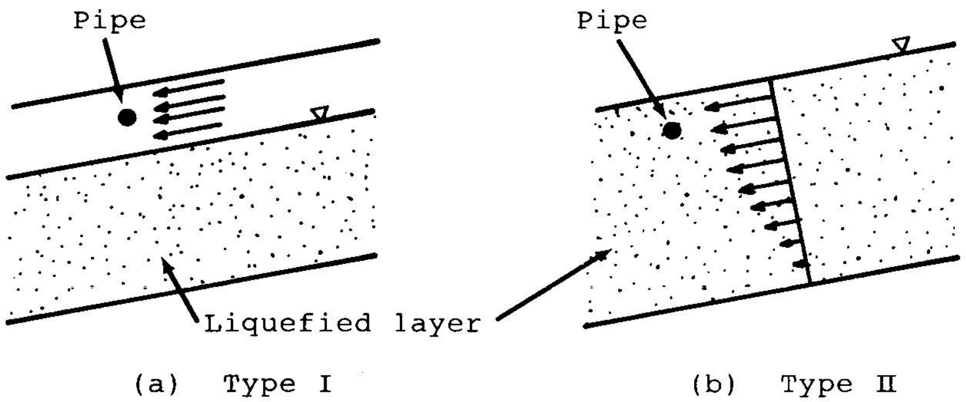

Fig. 5 Types of lateral spreading

2.1.2 Numerical example

An analytical model shown in Fig. 6 is proposed to study the effects of liquefaction-induced lateral spreading on the damage to the pipelines. A pipeline is modeled as a Winkler beam. Shape of horizontal ground displacement is assumed as a sinusoidal curve here and it is transferred to the buried pipeline through the soil spring. The basic differential equations governing the motion of a pipeline can be written for transverse movements:

$$\left.\begin{aligned} EI\frac{d^4v_1}{dx^4} + K_y v_1 &= 0 && x \leq 0 \\ EI\frac{d^4v_2}{dx^4} + k_y v_2 &= k_y\,\delta\,\sin\frac{\pi x}{l} && 0 < x \leq l \\ EI\frac{d^4v_3}{dx^4} + k_y v_3 &= 0 && l < x \end{aligned}\right\}$$

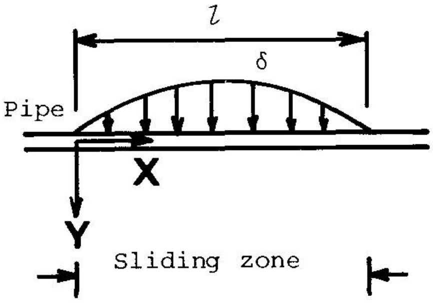

Fig. 6 Analytical model (Plane figure)

where, E is Young's modulus of the pipe material, I is geometrical moment of pipe inertia, δ is maximum displacement of the lateral spreading, K_y is soil spring constant for transverse motion, l is stretch of the liquefied zone and v_1, v_2, v_3 are transverse displacements of the pipe.

Fig. 7 shows the relationship between the maximum bending stress and the soil spring constant. The welded steel pipeline whose nominal diameter is 400mm is analyzed here. Table 1 shows dimensions of the steel pipe which is used in the present study. The maximum displacement, δ , in this case is 1m. Fig. 7 indicates that the maximum bending moment decreases in case that the soil spring constant is less than 17.6 kN/m^3 (1.8 x10^{-3} kgf/cm^3). That is, the horizontal movement of competent soil affects the pipe behavior rather than that of liquefied soil does. It is interesting to note that the smaller the ground stretch of lateral spreading is, the greater the maximum bending moment is. These results suggest the conclusion that the pipe behavior due to liquefaction-induced lateral spreading is strongly influenced by the ground stretch of the lateral spreading and soil spring constant. The numerical example also indicates that the type I mentioned above is more destructive on the pipe than type II in case that the maximum horizontal displacement has the same value.

Table 1 Dimensions of pipe

		Steel pipe
Outside diameter	(cm)	40.64
Thickness	(cm)	0.60
Young's modulus	(MPa)	205.80

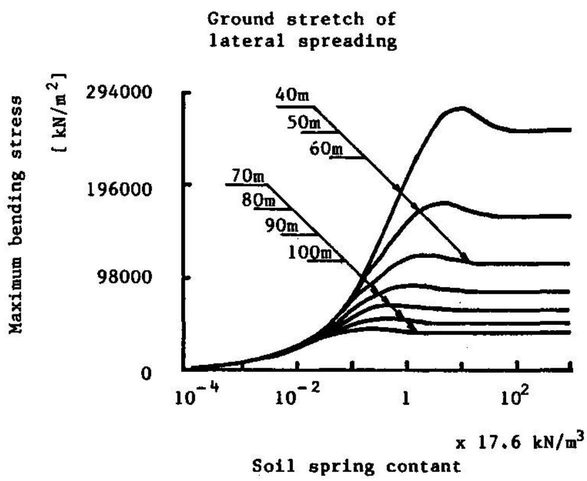

Fig. 7 Relationship between maximum bending stress and soil spring constant

2.2 Effects of Relative Movement Between Liquefied and Non-liquefied Ground

2.2.1 State of earthquke damage

One of the characteristics of the pipe damage due to the 1983 Nipponkai-Chubu Earthquake was that all of the damage to cast iron pipes (CIP) occurred at the liquefied site and most of them occurred at the joints of the pipes with large diameter of 400mm and 450mm. Fig. 8 indicates that such damage was caused at liquefied site near the boundary between the liquefied and non-liquefied sites.

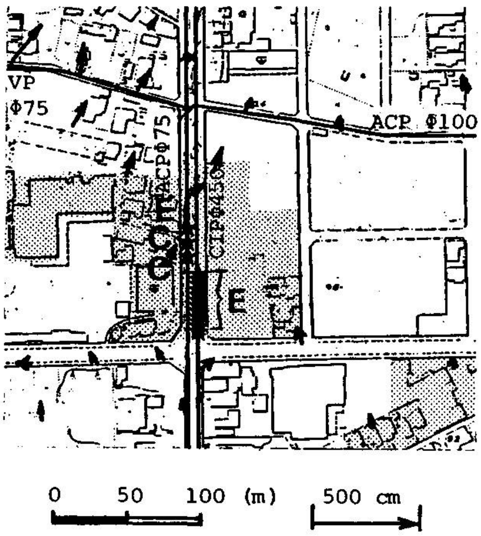

Fig. 8 Liquefied sites and pipe damage (Nagasaki in Noshiro)

Liquefied site

★ Pipe damage

2.2.2 Experimental study

We conducted the experiments employing the model pipe in order to investigate the pipe strain characteristics near the boundary between the liquefied and non-liquefied sites [4]. Fig. 9 shows the general view of experimental apparatus. The buried pipe model was a rubber stick with 20mm diameter and 1000mm in length. Its elastic modulus was 79.4 MPa (810 kgf/cm ^{2}) and its weight per unit volume is 11.2 kN/m^3 (1.14 gf/cm^3). One end of the model pipe was fixed at the rigid arm setting on the sand box. The half of the model ground was very loose and the other was densified by compaction. Exciting frequency was 5Hz. Exciting acceleration was about 200gal and exciting duration time was 30 seconds.

Figs. 10 and 11 show the distribution of the maximum accumulated residual strains of the model pipe and that of mean vibrating strains, respectively. The shaded portion in these figures indicate the non-liquefied area. It can be seen in these figures that both pipe strains express the maximum value in the liquefied ground near the boundary between liquefied and non-liquefied areas. The great similarity can be seen in a comparison of the damage to CIP and the experimental results. It is considered that the follow-ing factors affect the strain characteristics: the buoyancy acting on the pipeline buried in liquefied site, difference of dynamic characteristics between liquefied and non-liquefied ground, ground settlement due to liquefac-tion and so on. It is conceivable that these factors could influence the pipelines near the boundary between liquefied and non-liquefied sites more than those at the liquefied site. Care should be taken of such case.

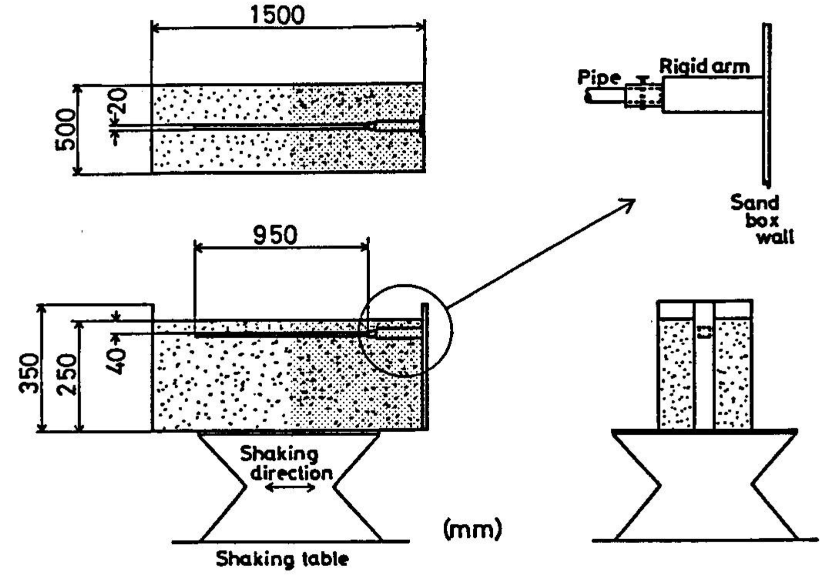

Fig. 9 General view of experimental apparatus

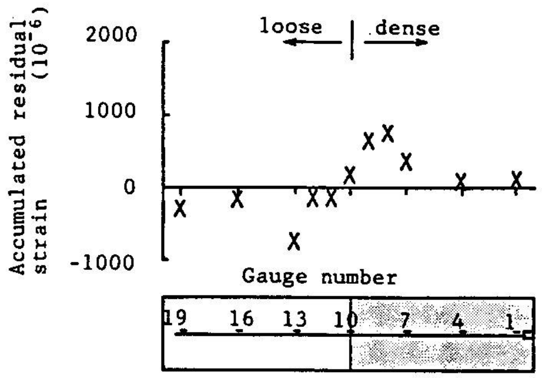

Fig. 10 Distribution of maximum accumurated residual strains of pipe

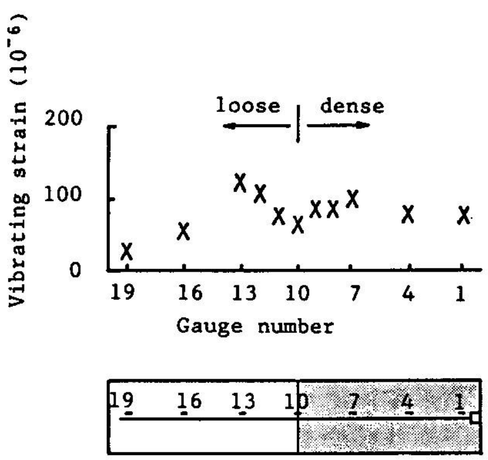

Fig. 11 Distribution of mean vibrating strains of pipe

3. SAFETY ON PIPELINES SUBJECTED TO SOIL LIQUEFACTION

The factors concerned with the failure of buried pipelines subjected to soil liquefaction are considered as follows.
(1) Large dynamic behavior of the ground during incomplete liquefaction.
(2) The forces due to the buoyancy and groundwater flow acting on the pipelines during complete liquefaction.
(3) Relative movement of the ground between the liquefied and non-liquefied ground.
(4) Large ground deformation due to soil liquefaction.
The present study theoretically and experimentally investigated the effects of the factors (3) and (4) based on the field investigation data of the earthquake damage. Factors (1) and (2) infuluence the pipelines at the liquefied sites in the liquefaction process. On the other hand, factor (3) affects the pipelines which go through the boundary ground between the liquefied and non-liquefied sites and as in factor (4), the scale of lateral spreading, that is scale of liuqefaction, influences the behavior of pipelines.

Most of guidlines and technical standards for earthquke-proof design for buried pipelines in Japan indicate how to predict the soil liquefaction. However, they do not predict how severely and how largely the liquefaction occurres, but they only predict whether or not the liquefaction does at a site. Therefore, in order to decide to take countermeasure for factors (3) and (4), it is very important to evaluate not only the liquefaction potential of the construction sites but also that in near areas.

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