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Experimental study on underground pipeline stabilizing techniques and their effectiveness during liquefaction

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ABSTRACT: If the ground along an underground pipeline route consists of cohesionless soils likely to liquefy under the influence of seismic shocks, a pipeline buried in such soils may float to the surface of the ground water. In order to investigate four types of underground pipeline stabilizing techniques and their effectiveness during liquefaction, we performed a series of shaking table tests. This paper gives a detailed explanation of the observed data and discusses the effectiveness of stabilizing techniques.

1 INTRODUCTION

If the ground along an underground pipeline route consists of cohesionless soils likely to liquefy under the influence of seismic shocks, it is important to take appropriate stabilization measures. There are two approaches to stabilizing underground pipelines against liquefaction:

1. to improve the ground such that it is not likely to liquefy (see Figure 1 for an example, where two sets of steel sheet pile walls are used to separate the improved and/or replaced ground which is not likely to liquefy, from the original ground, which is likely to liquefy); and
2. to prevent the pipeline from floating to the top of the water table (see for example Figures 2 (a), (b) and (c)).

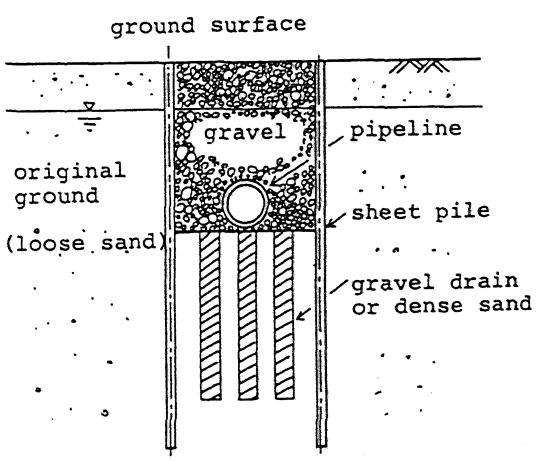


Figure 1. An example of pipeline burying method during liquefaction.

The first strategy may be preferable for very important pipelines; however, it is usually difficult to employ this method for budgetary and other constraints. It seems that the second strategy is more attractive in terms of cost. These stabilizing techniques have been employed in several projects. However, the effectiveness of these methods has not yet been proven in the field. In addition, no appropriate designing procedure is available due to the lack of the experimental and field records.

To study the behavior of underground pipelines during liquefaction, Katada and Hakuno (1981) and Kitaura and Miyajima (1982a, b) performed shaking table tests using model pipes, and found that large strains are observed during the incomplete liquefaction. Following their pioneer work, we performed shaking table tests to: (a) qualitatively evaluate the effectiveness of four types of stabilization techniques illustrated in Figures 1 and 2, and to (b) find out important factors to be considered in the design of stabilizing methods.

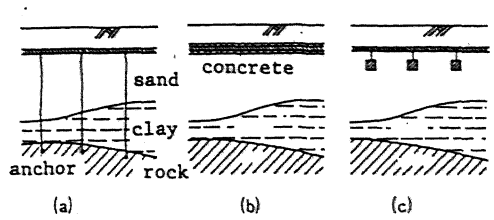


Figure 2. Underground pipelines stabilization techniques during liquefaction.

2 METHODS AND CONDITIONS OF THE TEST

A series of shaking table tests were conducted using model aluminum pipes with an outer diameter of 60 mm, a thickness of 2 mm, and a length of 2,800 mm, buried in sand or gravel layers as shown in Figure 3.

2.1 *Testing methods*

The model grounds were made in a rigid steel box with a length of 3.0 m, width of 1.0 m and height of 0.5 m using the following procedure: (a) fill the steel box with water for industrial use and, (b) put air-dried sand into the steel box. The average density of the saturated model ground was 18.2 kN/m^3, and the relative density, Dr, was 73%. The average diameter, D_{50}, of the sand was 0.6 mm, and the coefficient of uniformity, Uc, was 3.0.

Figure 3 shows the measurement instrumentation. As shown in the figure, accelerometers, ACC1 and ACC2, were located on the steel box, while ACC3 was installed on the model pipe. The pore water pressure meters, PWP1 and PWP2, were located at a depth of 30 cm.

In order to create seismic excitations in the model ground, a one-directional servo type shaking table (3 m x 3 m) was used. In all tests the model grounds were shaken in the direction parallel to the axis of the model pipe, at a frequency of 2 Hz. The magnitude of the displacement amplitude of the shaking table was controlled by hand operation as follows: (a) at the initiation of the excitation, the displacement amplitude was increased gradually, (b) then, the displacement amplitude was kept constant for a while and, (c) after stationary phenomena were observed, the displacement amplitude was decreased gradually.

2.2 *Conditions of the test*

The test conditions are summarized in Figure 4. Case 1 serves as a reference case in which no stabilizing method was introduced. Cases 2 to 4 were conducted to simulate the conditions illustrated in Figures 2 (a), (b) and (c), while Case 5 was intended to simulate the method illustrated in Figure 1. In Case 5, the crushed stones whose diameters ranged from 5 to 13 mm were used to bury the model pipe, and the pore water pressure meter PWP1 was located in the crushed-stone layer.

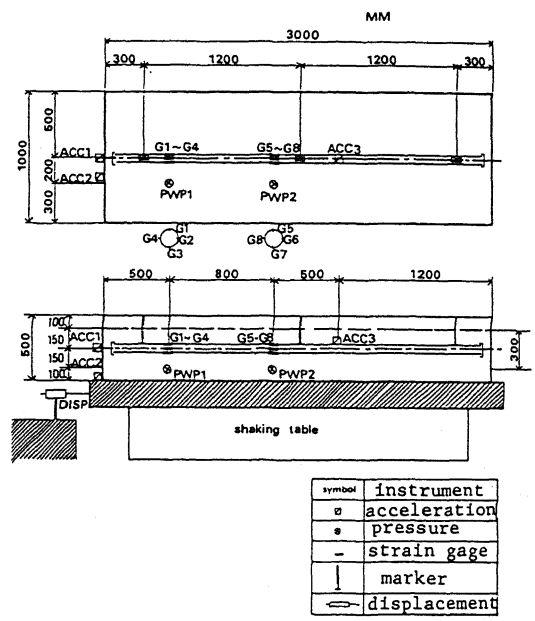


Figure 3. Measurement instrumentation.

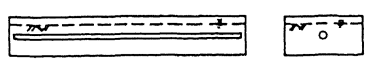
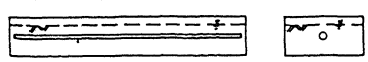
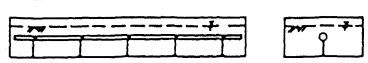
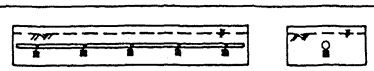
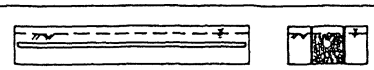
No.	side view of model pipe & ground	stabilizing method
1		without stabilizing method
2		unit weight of pipe is equal to 2.0 gf/cm^3
3		pipe & bottom of shaking box is tied with wire
4		unit weight of pipe & weight system is equal to 2.0 gf/cm^3
5		separate gravel & sand by sheet pile

Figure 4. Test conditions.

3 RESULTS

Figures 6 to 9 show the recorded excess pore water pressures, accelerations and axial strains of model pipes during and after excitation of the shaking table. Shown in Figure 10 are the ground settlements and displacements of model pipes after the excitation. Figures 6 to 9 suggest that the model ground and pipe showed strong non-linear and complex responses during liquefaction. From a close study of these figures, however, it was found that the observed response of the model pipe was consistent with the effective stress state of the surrounding sand. The following classification of the non-stationary process of liquefaction may be useful for understanding the behavior of the model pipes during liquefaction.

3.1 *Classification of liquefaction*

A. Pre-liquefaction: the period from the initiation of the excitation to the time when the excess pore water pressure in the ground started to rise. From a study of recorded accelerations, ACC2 and ACC3, it was found that the model ground and pipe moved in the same manner. It was also found that axial strains of the model pipe were small.

B. Incomplete liquefaction: the period during which the excess pore water pressure was rising from zero to a maximum value which was usually equal to the initial vertical effective stress. In this period, large amplitudes were observed when the surface of the model ground was caused to move. From a study of recorded data shown in Figures 6 to 8, it was found that: (a) the recorded acceleration of the model pipe was greater than that of the steel box, and that (b) the observed dynamic strains (as defined by Kitaura and Miyajima, 1982a) of the model pipe took on maximum values during the incomplete liquefaction. These observations are consistent with those reported by Katada and Hakuno (1981), and Kitaura and Miyajima (1982a).

C. Complete liquefaction/Cyclic mobility: the period after the incomplete liquefaction until the end of the excitation. It may be useful to classify this period more precisely based on the effective stress states in the ground. Figure 5 shows the schematic illustration of the recorded excess pore water pressures, accelerations of the shaking box and model pipes. The figure also shows the effective stress paths and stress-strain relationships estimated based on the observed excess pore water pressures in this test and on the results of the cyclic triaxial test reported by Kokusho et al. (1982). A brief explanation will now be given:

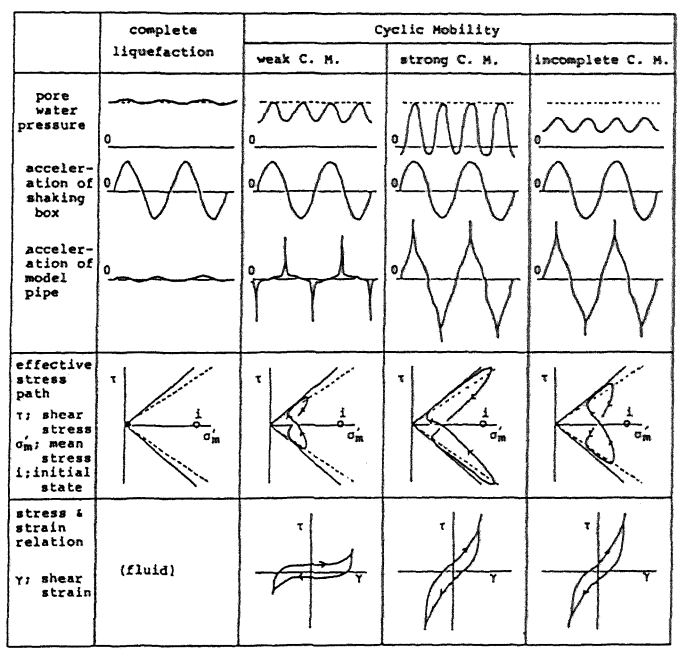


Figure 5. Classification of complete liquefaction and cyclic mobility.

C-a. Complete liquefaction: the state where the effective stress is zero, and the ground behaves as if it were liquid. It was found that the acceleration of the model pipe was less than that of the steel box, and that the recorded axial stress of the model pipe was less than that observed during incomplete liquefaction. These observations are consistent with the fact that shear stress can not be transmitted through liquid. It should be noted that the buoyancy of the model pipe was largest during the complete liquefaction.

C-b. Weak cyclic mobility: one mode of what is called "cyclic mobility," which is observed when the shear stresses transmitted into the soil are relatively small. In this state, it was observed that the acceleration phase of the model pipe was delayed by approximately 90 degrees from that of the steel box. It was also observed that acceleration of the model pipe had strong peaks, as shown in Figure 5. This phenomena may be explained by considering that the soil possesses strain-hardening type stress-strain relationships (see Figure 5), as suggested by Katada and Hakuno (1981). It is noted that the observed axial strains of the model pipes during the "weak cyclic mobility" were smaller than those observed during "incomplete liquefaction."

C-c. Strong cyclic mobility: one mode of "cyclic mobility," where the shear stresses transmitted to the soil are relatively large, as shown in Figure 5. The state was not observed in the test reported in this paper, but observed in tests compiled in Oishi and Sekiguchi (1983a).

C-d. Incomplete cyclic mobility: one mode of "cyclic mobility," in which the effective stress path moves along the phase transformation lines without reaching the zero effective stress state. It was observed that the phase of acceleration of the model ground and pipe was identical, and that the axial stresses of the model pipe were smaller than those during "incomplete liquefaction".

D. After excitation: After excitation was stopped, it was observed that static bending strain of the model pipe increased with a decrease in excess pore water pressure.

3.2 *Observation of each test case*

3.2.1 *Case 1 (Figure 6)*

(a) From 0 to 16 seconds, "pre-liquefaction" may be observed.

(b) From 16 to 20 seconds, "incomplete liquefaction" may be observed.

(c) From 20 to 60 seconds, transition from "weak cyclic mobility" to "incomplete liquefaction" can be observed. The model pipe started to float after 23 seconds, and appeared on the surface of the liquefied ground after 37 seconds, when the observed acceleration of the model pipe was much less than that of the shaking box. After 37 seconds, the observed acceleration of model pipe increased gradually with decrease in excess pore water pressure in the model ground.

3.2.2 *Case 2 (Figure 7)*

(a) From 0 to 7 seconds, "pre-liquefaction" may be observed.

(b) From 7 to 10 seconds, "incomplete liquefaction" may be observed. It should be noted that large dynamic strains are observed during this period.

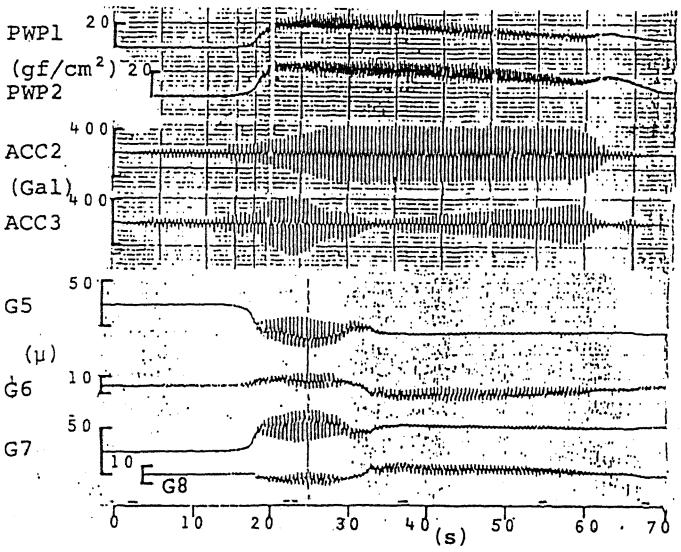


Figure 6. Measured data (Case 1).

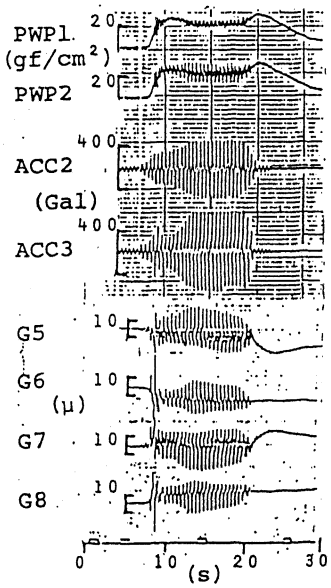


Figure 7. Measured data (Case 2).

(c) From 10 to 11 seconds, "complete liquefaction" may be observed. In this period, the observed acceleration and strains of the model pipe were less than those observed during "incomplete liquefaction", i.e. 7-10 seconds.

(d) From 11 to 20 seconds, "weak cyclic mobility" may be observed. During this period, the phase of the observed acceleration of the model pipe was delayed by 90 degrees from that of the shaking table. The observed axial stresses of the model pipe suggests that the model pipe experienced bending around both the vertical and horizontal axes.

(e) After excitation was completed, it was notable that large static bending strain around the horizontal axis is observed along with the dissipation of excess pore water pressure in the model ground (see G5 and G7 of Figure 7).

3.2.3 *Case 3 (Figure 8) and Case 4*

In Cases 3 and 4, similar observations may be made to that in Case 2 (Figure 7). As shown in Figure 10, it was observed that the stabilized model pipe remained in the original position after excitation. It seems that the effect of the steel wire on the response of the model pipe was negligible, since no significant difference could be observed between the records in Cases 2, 3 and 4.

3.2.4 *Case 5 (Figure 9)*

According to the record of the pore water pressure meter PWP2 located outside the sheet piles, it seems that the sand liquefied for a short period. It is interesting to observe that the excess pore water pressure PWP2 dissipated before the end of excitation. This is probably because the pore water pressures dissipated into the gravel layer through the clearance between the tips of the sheet pile walls and the bottom of the shaking box.

The measured excess pore water pressure PWP1 suggests that the gravel layer did not liquefy. However, it should be noted that the static bending strain of the model pipe is much greater than the dynamic strain (see G5 and G7 in Figure 9). This result suggests that it is important to evaluate the static differential settlement of the ground when developing appropriate stabilization method.

4 DISCUSSION

In this section, the effectiveness of the stabilizing methods will be discussed based on the results of the test described in part 3.

4.1 *Methods which prevent pipes from floating (Figure 2)*

From the test results described in 3.2.2 and 3.2.3, it may be stated that the methods shown in Figures 2(a) to (c) are effective provided that the pipeline is strong enough to survive the incomplete liquefaction and the differential ground settlement. Although it is difficult to quantitatively evaluate ground settlements during earthquakes, work towards this end is in progress (Nishi et al., 1986; Tanabe and Takada, 1988)

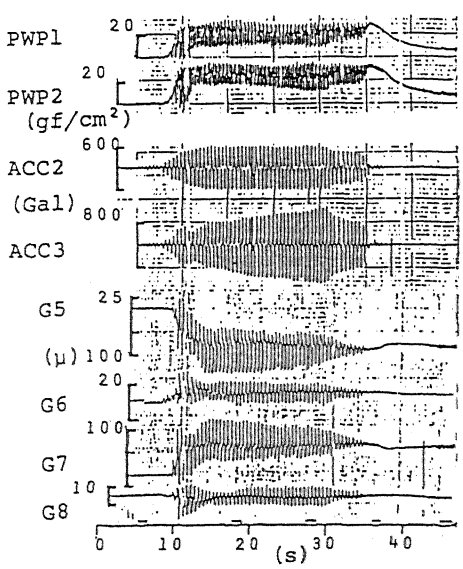


Figure 8. Measured data (Case 3).

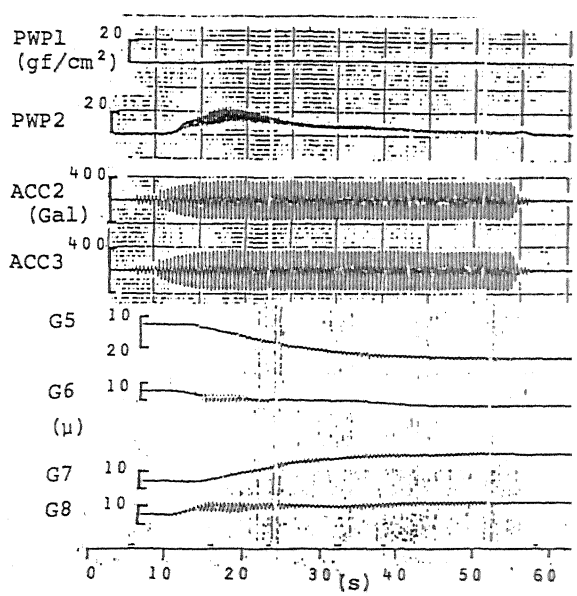


Figure 9. Measured data (Case 5).

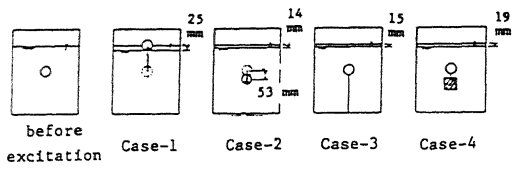


Figure 10. Ground settlement and displacement of model pipe after excitation.

4.2 *Method which uses sheet pile walls and gravel (Figure 1)*

From the observations of the test results described in 3.2.4, it may be stated that this method is promising. When designing this method, it is important to build a structure composed of sheet piles and gravel stable during the probable liquefaction of the surrounding soft sand layers.

5 CONCLUSIONS

In order to study the effectiveness of four types of underground pipeline stabilization techniques during earthquake-induced liquefaction, a series of shaking table tests were performed. Based on the test results, the following conclusions may be drawn:

1. Although the observed response of the model pipe during the liquefaction was very complex, it was consistent with the effective stress state of the surrounding sand.
2. It was generally observed that maximum pipe strains occurred during incomplete liquefaction.
3. It was found that three types of stabilization techniques which prevent a pipeline from floating (Figure 2) were encouraging, provided that the pipeline was strong enough to survive the incomplete liquefaction and differential ground settlements.
4. It was found that the stabilization method using two sets of sheet pile walls and gravel as filling material (Figure 1) was promising.

In this study, attention was given to qualitative evaluation of the effectiveness of underground pipeline stabilizing techniques during liquefaction. It is, however, important to quantitatively evaluate the stress conditions of the pipelines under the effect of buoyancy (Sekiguchi and Oishi, 1987b; Kiyomiya et al., 1988). It is also important to evaluate the influence of a land slide on the safety of underground pipelines when a liquefaction-induced land slide is anticipated (Swanson and Jones, 1982; Hamada et al., 1986).

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