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Experiments on Soil Spring Constants During Liquefaction

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SYNOPSIS: The present paper deals with the soil spring constant on pipeline in relation to liquefaction process. The soil spring constant is one of the most influential factors in evaluation of the pipeline failure induced by soil liquefaction. Laboratory tests were conducted using a steel pipe in order to obtain the hysteresis curve of pipe-soil layer system. Based on the experimental results, the authors propose a model of the restoring force characteristics which is represented by two soil spring constants K_1 and K_2. Furthermore, the authors investigated K_1 and K_2 in relation to the effective stress through dynamic loading tests.

INTRODUCTION

The large ground deformation induced by soil liquefaction is one of the most serious causes of pipeline failures during earthquake. Rational design of pipelines under such condition requires knowledge of the soil forces resulting from relative soil-pipeline displacement. In other words, the response of pipelines due to liquefaction is very sensitive to the soil spring constant, which is defined as the soil forces divided by relative soil-pipeline displacement. Therefore, the soil spring constant should be estimated more quantitatively in relation to liquefaction process in order to establish the earthquake-resistant system of pipelines.

Some liquefaction-related experiments dealing with the soil spring constant revealed the following results. Yoshida and Uematsu (1978) conducted experiments using a model pile in the liquefied ground. Their experimental results indicated that the coefficient of subgrade reaction on pile decreased to 1 percent or more of that in the non-liquefied ground. Matsumoto et al. (1987) investigated the coefficient of subgrade reaction was in direct proportion to the effective overburden pressure and in inverse proportion to the square root of relative displacement. Yasuda et al. (1987), after conducting model experiments using sand box and steel pipe, concluded that critical shearing force and soil spring constant in the liquefied ground became less than 10 percent of those in the non-liquefied ground. Tanabe (1988) estimated the soil spring constant based on the experiments using model pipe in the liquefied ground. The soil spring constant on pipeline in liquefied ground decreased to 1/32 for settlement and to 1/40 - 1/50 for lateral spreading.

As mentioned above, some experimental results were revealed. However, accumulation of experimental data is necessary before appropriate earthquake resistance code for pipelines can be established. In the present paper, model tests were conducted in order to obtain the hysteresis curve of pipe-soil layer system in liquefaction processes and discussed the soil spring constant in relation to the effective stress.

SOIL SPRING CONSTANT IN THE AXIAL DIRECTION

TEST PROCEDURE

General view of test apparatus is shown in Fig. 1. The size of sand box was 500 mm in width, 1500 mm in length and 350 mm in height. Sand deposit was made from loose sand and physical properties of the sand are shown in Table 1. The model pipe used was a steel tube with 47 mm in diameter and 1000 mm in length. One end of the model pipe was connected to the load cell fixed at rigid wall. Therefore, the relative displacement between the model pipe and surrounding soil was caused by movement of the sand-filled box on the shaking table.

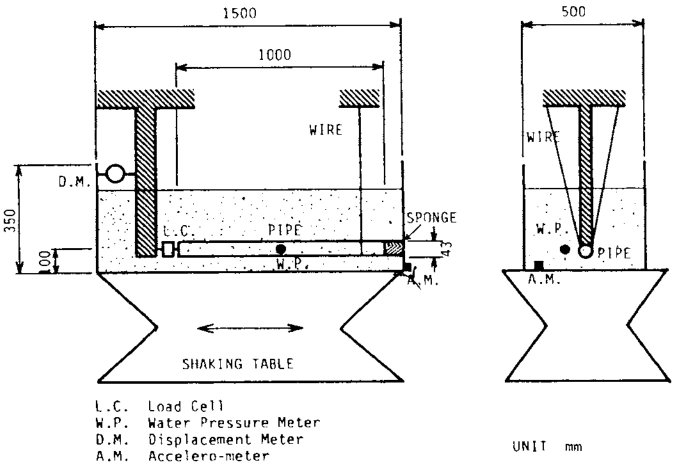

Fig. 1 General view of experimental apparatus.

Table 1 Physical properties of sand.

Specific gravity	2.67
Uniformity coefficient	2.96
Maximum void ratio (e_{max})	0.982
Minimum void ratio (e_{min})	0.717
Coefficient of permeability for e_{min}	0.0157
(cm/s) for e_{max}	0.0176

Displacement meter was installed between the wall of sand box and rigid wall in order to measure the relative displacement. The sponge was attached between another end of the pipe and the wall of the sand box in order to reduce the effects of the soil surrounding the pipe end on the restoring force characteristics. Moreover, pore water transducer was buried in the same depth of the model pipe to measure the excess pore water pressure in the liquefaction process. Liquefaction of model ground was caused by sinusoidal movement with 5 Hz in the dynamic loading tests.

TEST RESULTS AND DISCUSSION

Fig. 2 displays the time history of excess pore water pressure and hysteresis curves at each stage. A, B, C and D shown in the hysteresis curves correspond to each stage shown in the time histories of excess pore water pressure. In this case burial depth of the model pipe was 15 cm, input acceleration was a sinusoidal wave with 5 Hz and the maximum acceleration was 100 gal (1 m/s^2). This figure indicates that the maximum restoring force decreases with an increase in the excess pore water pressure.

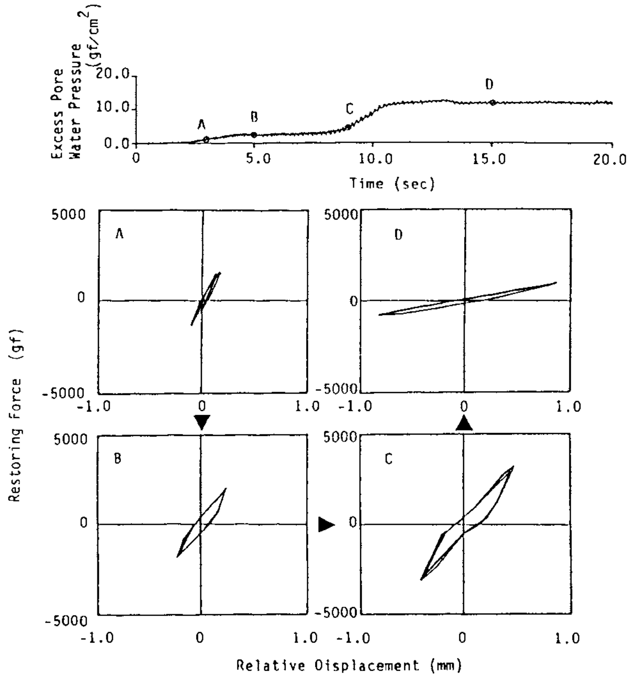

Fig. 2 Time history of excess pore water pressure and hysteresis curves of restoring force (1 gf/cm2 = 98 Pa).

A bi-linear model, shown in Fig. 3, is used to approximate the restoring force characteristics. Soil spring constants K_1 and K_2 express the restoring force characteristics in this model. Therefore, K_1 and K_2 in relation to the effective stress were evaluated using the hysteresis curves under several conditions. Figs. 4 and 5 show K_1 and K_2 in relation to the effective stress, respectively. These figures indicate

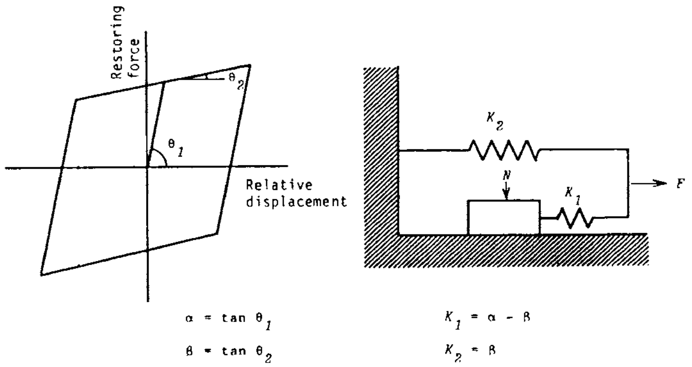

Fig. 3 Model for restoring force characteristics.

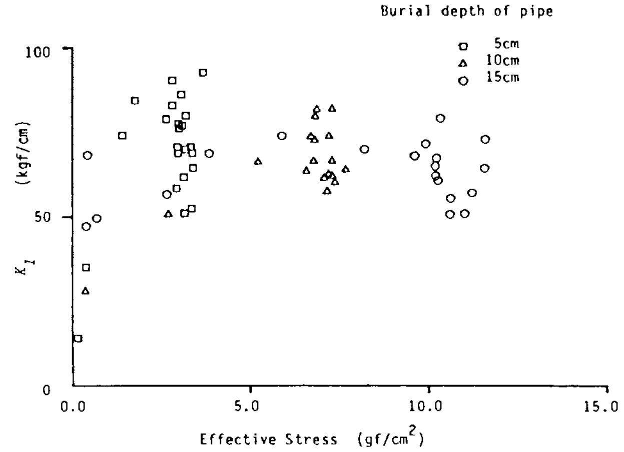

Fig. 4 Relationship between K_1 and effective stress (1 gf/cm2 = 98 Pa).

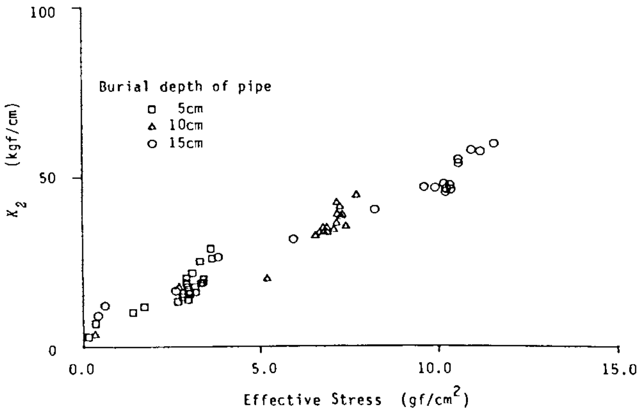

Fig. 5 Relationship between K_2 and effective stress (1 gf/cm2 = 98 Pa).

the results for burial depth of 5 cm, 10 cm and 15 cm. It can be seen from Fig. 4 that K_1 is almost unchangeable irrespective of the effective stress except for the region less than 1 gf/cm^2 (98 Pa) of the effective stress, although the data are somewhat scattered. Fig. 5 indicates that K_2 is directly proportional to the effective stress. These tendencies are similar to the results of the static loading tests (Miyajima and Kitaura, 1989).

SOIL SPRING CONSTANT IN THE TRANSVERSE DIRECTION

TEST PROCEDURE

Fig. 6 shows general view of experimental apparatus. The same shaking table and model sand deposit were also used in this chapter. The model pipe was the same type as that used in the previous tests and the length of the pipe was 405 mm. The center of the model pipe was connected to the load cell attached at rigid wall. Other experimental conditions were the same as those in the previous chapter.

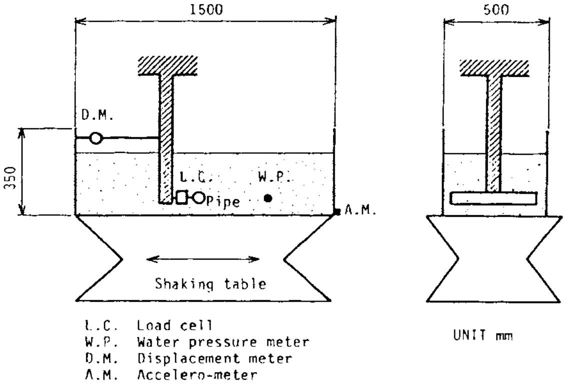

Fig. 6 General view of experimental apparatus.

TEST RESULTS AND DISCUSSION

K_1 and K_2 in relation to the effective stress are investigated for the excess pore water pressure. Fig. 7 illustrates the relationship between K_1 and the effective stress for the excess pore water pressure ratio greater than 0.25. It can be seen from Fig. 7 that K_1 is almost unchangeable irrespective of the effective stress in the region of the effective stress greater than 4 gf/cm^2 (392 Pa) and K_1 is directly proportional to the effective stress in the region less than 4 gf/cm^2 (392 Pa). The relationship between K_2 and the effective stress is shown in Fig. 8 for the excess pore water pressure greater than 0.25. It is evident from Fig. 8 that K_2 is directly proportional to the effective stress. It is very interesting to note that these tendencies are similar to the experimental results of excitation in the axial direction, although the effective stress at which K_1 changes is different. These findings suggest that the restoring force characteristics is well explained in terms of K_1 and K_2, that is, the model proposed in the present paper is useful for evaluation of restoring force characteristics of pipe-liquefied layer system.

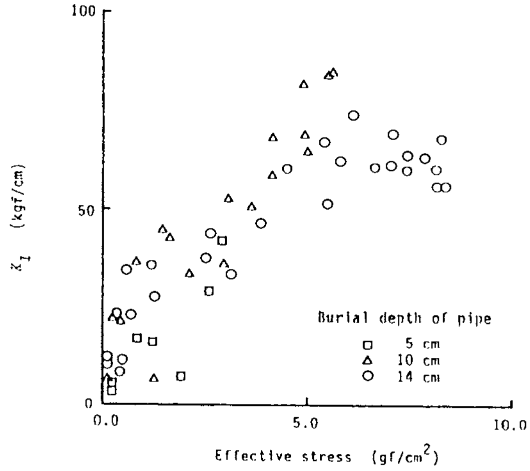

Fig. 7 Relationship between K_1 and effective stress (Excess pore water pressure ratio is greater than 0.25, 1 gf/cm2 = 98 Pa).

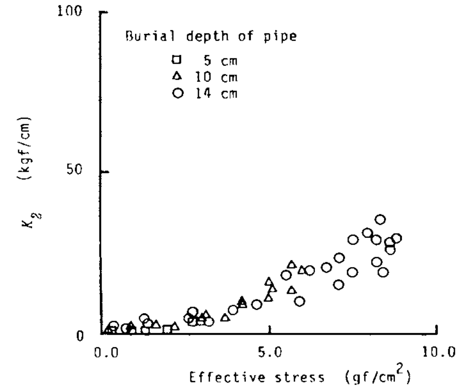

Fig. 8 Relationship between K_2 and effective stress (Excess pore water pressure ratio is greater than 0.25, 1 gf/cm2 = 98 Pa).

However, there was no indication of clear trends between the soil spring constants, namely, K_1 and K_2, and effective stress for the excess pore water pressure ratio less than 0.25. Therefore, the restoring force characteristics are investigated using α and β shown in Fig. 3. Figs. 9 and 10 illustrate α and β for the excess pore water pressure less than 0.25. In these figures, the values in the same excess pore water pressure ratio for each burial depth are represented by straight line segments. It can be seen from Fig. 9 that α in the same excess pore water pressure ratio remains almost unchangeable with the effective stress but varies with the excess pore water pressure

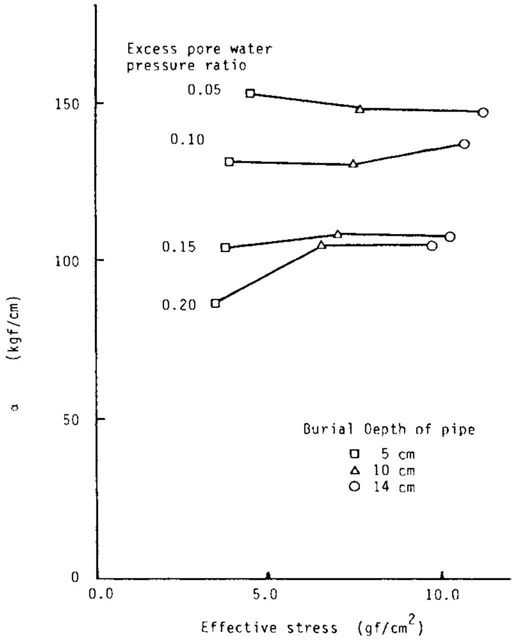

Fig. 9 Relationship between α and effective stress in dynamic loading tests (Excess pore water pressure ratio is less than 0.25, 1 gf/cm2 = 98 Pa).

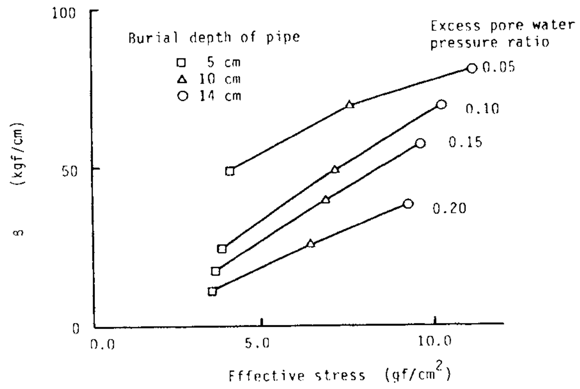

Fig. 10 Relationship between β and effective stress in dynamic loading tests (Excess pore water pressure ratio is less than 0.25, 1 gf/cm2 = 98 Pa).

ratio. In Fig. 10, β is proportional to the effective stress. Moreover α and β decrease with an increase in the excess pore water pressure ratio. This is explained in terms of the effects of the reaction force from the surrounding soil. That is, the reaction force increases with a decrease in the excess pore water pressure ratio. Therefore, additional studies are required to clarify the effects of the reaction force from the surrounding soil on the restoring force characteristics in the transverse direction shaking tests.

CONCLUDING REMARKS

The present paper experimentally investigated restoring force characteristics of pipe-liquefied layer system. The authors proposed a model of restoring force characteristics, which was represented by K_1 and K_2 of soil spring constants. It became evident from the dynamic loading tests that K_1 is almost unchangeable in the region of greater effective stress and K_2 is directly proportional to the effective stress. These experimental results suggest that the modeling done is good enough to evaluate the restoring force characteristics of pipe-liquefied layer system. In the experiments of excitation in the transverse direction to the pipe axis, the effects of the reaction force from the surrounding soil was included in the restoring force characteristics, particularly in the excess pore water pressure ratio less than 0.25 in these experiments. Therefore, additional experiments are needed in order to clarify the effects of the reaction force and other factors such as vibration frequency, relative displacement, etc.

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