Experiments on Restoring Force Characteristics of Pipe-Liquefied Layer System

著者	MIYAJIMA Masakatsu, Kitaura Masaru
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Experiments on Restoring Force Characteristics of Pipe-Liquefied Layer System

Masakatsu MIYAJIMA* and Masaru KITAURA*

Abstract

The present paper deals with the equivalent soil spring constant in relation to liquefaction process. The equivalent 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, we propose a model of the restoring force characteristics which is represented by two soil spring constants K_1 and K_2. In this paper, K_1 and K_2 are investigated in relation to the effective stress through both static and dynamic loading tests.

Keywords : Liquefaction, model experiment, pipeline, restoring force, soil spring constant.

1. Introduction

Several model experiments have been carried out on the dynamic behavior of buried pipelines in liquefaction processes[1)~5)]. As the results, fundamental characteristics of pipeline response during liquefaction were clarified. Moreover, theoretical and analytical methods have been proposed[6)~9)]. Nevertheless, there still exist certain unresolved problems before earthquake -resistant systems can be designed. One of them is that the equivalent soil spring constant should be estimated more quantitatively in relation to liquefaction process because pipeline response is very sensitive to this constant in the analysis.

Some liquefaction-related experiments dealing with the equivalent soil spring constant revealed the following results. Yasuda et al., after conducting model experiments using sand box and steel pipe, concluded that critical shearing force and equivalent soil spring constant in the liquefied ground became less than 10 percent of those in the non-liquefied ground[10)]. Matsumoto et al. investigated the coefficient of subgrade reaction on pile in liquefied ground. Their findings showed that the coefficiet of subgrade reaction was in direct proportion to the effective overburden pressure and in inverse proportion to the square root of relative displacement[11)]. Yoshida et al. also carried out 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[12)]. Tanabe estimated the equivalent 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[13)].

As mentioned above, some experimental results were revealed. However, accumulation of

* Department of Civil Engineering

experimental data is necessary before appropriate earthquake resistance code for pipelines can be established. In the present paper, model experiments were conducted in order to evaluate the restoring force characteristics of pipe-liquefied layer system.

2. Excitation in the Direction Parallel to the Pipe Axis

2.1 Testing procedures

General view of experimental 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. 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.

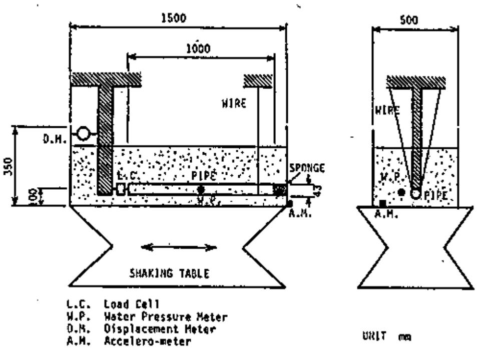

Fig. 1 General view of experimental apparatus.

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

Static loading tests and dynamic loading tests were carried out. In static tests, one cycle of triangular wave with the velocity of 0.1 mm/s was applied to a sand-filled box using the shaking table. Liquefaction of model ground was caused by sinusoidal movement with 5 Hz in the dynamic loading tests.

2.2 Results of static loading tests

Fig. 2 shows the relationship between restoring force and relative displacement, namely, hysteresis curve of the restoring force. 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.

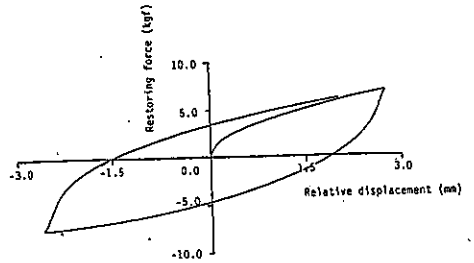

Fig. 2 Hysteresis curve of restoring force (1 kgf=9.8 N).

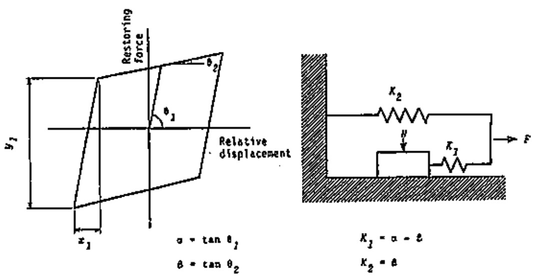

Fig. 3 Model for restoring force characteristics.

Fig. 4 shows the relationship between the frictional coefficient and effective stress. The frictional coefficient was evaluated from the relation between y_1 shown in Fig. 3 and effective stress. This figure suggests that the frictional coefficient is approximately constant with value ranging from 0.18 to 0.25 irrespective of effective stress. Takada indicated that the frictional coefficient was approximately unchangeable, 0.15 to 0.45 in the experiments using dry sand deposit and aluminum pipe[14]. Although the test conditions are different, the tendency of constant value irrespective of effective stress is similar. Fig. 5 indicates the relationship between the relative displacement and effective stress when the slippage between the model pipe and surrounding soil occurs. The relative displacement in that state is assumed to be half of x_1 shown in Fig. 3 in this paper. Fig. 5 suggests that the displacement is in direct proportion to the effective stress. These findings are similar to the previous results indicated by Takada[14].

Figs. 6 and 7 illustrate K_1 and K_2 in relation to the effective stress, respectively. K_1 is approximately a constant value irrespective of the effective stress and K_2 is directly proportional to the effective stress.

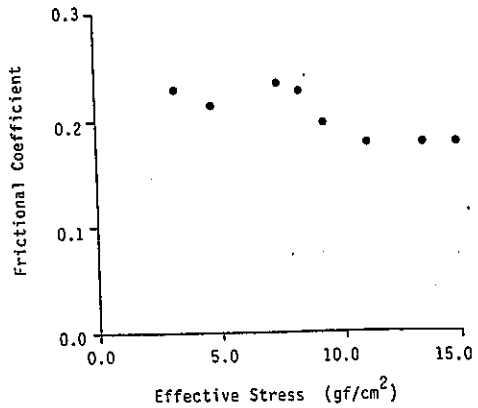

Fig. 4 Frictional coefficient in static loading tests (1 gf/cm^2=98 Pa).

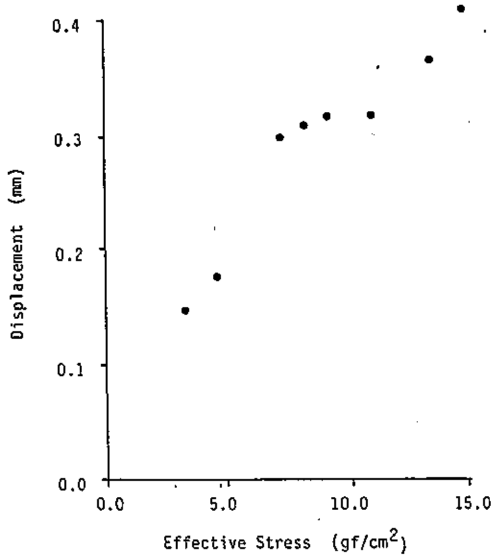

Fig. 5 Relative displacement when slippage occurs (1 gf/ cm^2=98 Pa).

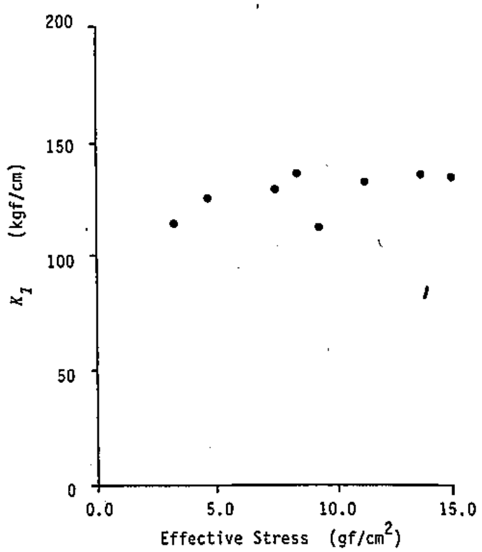

Fig. 6 Relationship between K_1 and effective stress in static loading tests (1 gf/cm^2= 98 Pa).

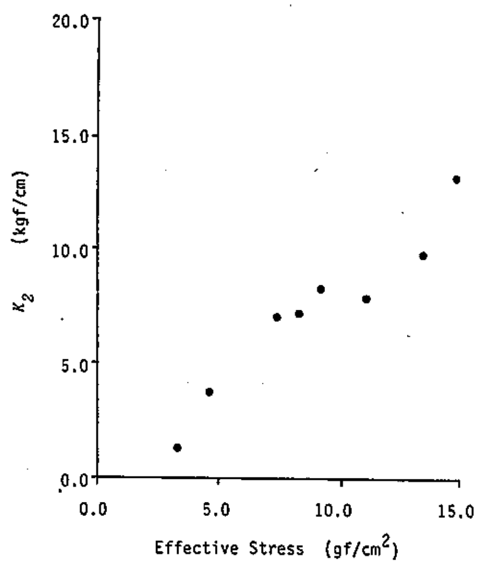

Fig. 7 Relationship between K_2 and effective stress in static loading tests (1 gf/cm^2= 98 Pa).

2.3 Results of dynamic loading tests and discussion

Fig. 8 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 the burial depth of the model pipe was 15

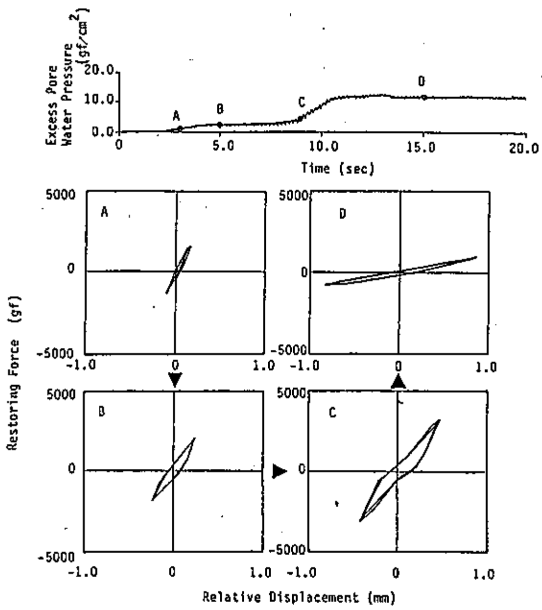

Fig. 8 Time history of excess pore water pressure and hysteresis curves of restoring force (1 gf/cm^2=98 Pa).

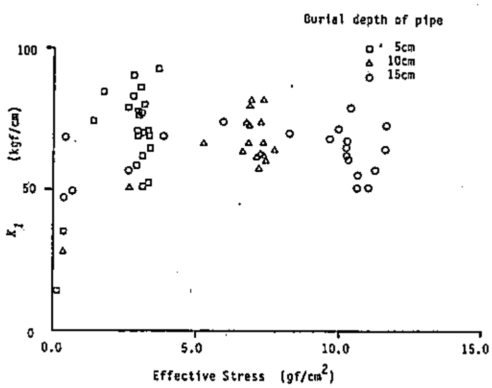

Fig. 9 Relationship between K_1 and effective stress in dynamic loading tests (1 gf/cm^2=98 Pa).

cm, input acceleration was a sinusoidal wave with 5 Hz and the maximum acceleration was 100 gal (1m/s²). This figure indicates that the maximum restoring force decreases with an increase in the excess pore water pressure. K_1 and K_2 in relation to the effective stress were evaluated using the hysteresis curves under several conditions.

Figs. 9 and 10 show K_1 and K_2 in relation to the effective stress, respectively. These figures indicate the results for the burial depth of 5 cm, 10 cm and 15 cm. It can be seen from Fig. 9 that K_1 is almost unchangeable irrespective of the effective stress except for the region less than 1 gf/cm² (98 Pa) of the effective stress, although the data are somewhat scattered. Fig. 10 indicates that K_2 is directly proportional to the effective stress. These tendencies are similar to the results of the static loading tests. However, in quantitative evaluation of K_1 and K_2, it is necessary to clarify the effects of several factors such as magnitude of displacement and loading velocity on the restoring force characteristics.

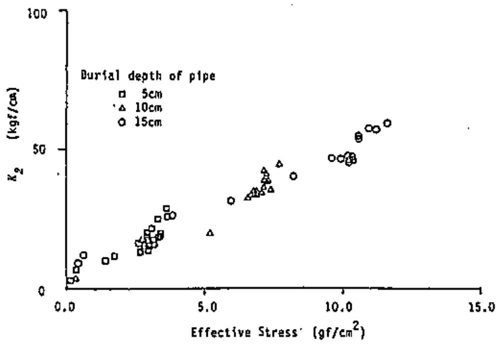

Fig. 10 Relationship between K_2 and effective stress in dynamic loading tests (1 gf/cm² = 98 Pa).

3. Excitation in the Direction Perpendicular to the Pipe Axis

3.1 Testing procedures

Fig. 11 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 chapter 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.

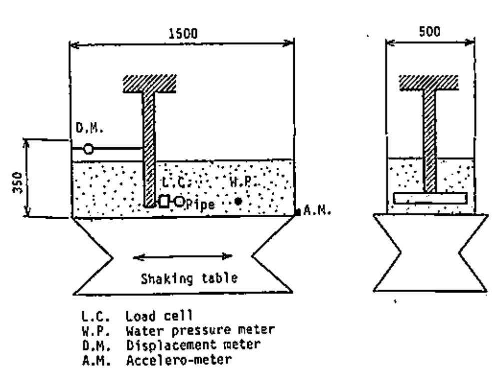

Fig. 11 General view of experimental apparatus.

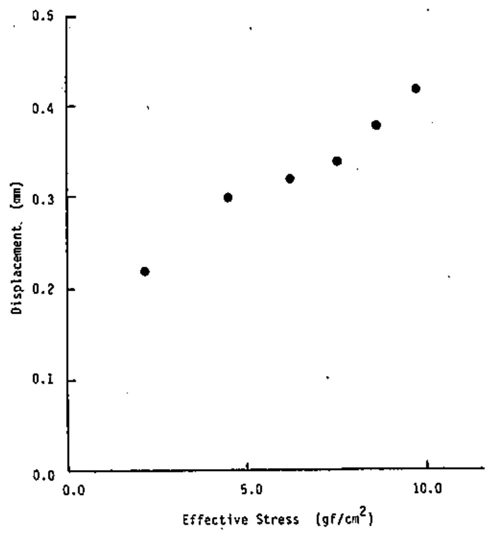

Fig. 12 Relative displacement when slippage occurs (1 gf/cm² = 98 Pa).

3.2 Results of static loading tests

Fig. 12 illustrates the relationship between the relative displacement and effective stress when the slippage between the model pipe and surrounding soil occurs. Fig. 12 suggests that the displacement is directly proportional to the effective stress. Figs. 13 and 14 illustrate K_1 and K_2 in relation to the effective stress, respectively. K_1 is approximately unchangeable irrespective of the effective stress and K_2 is directly proportional to the effective stress. Although these tendencies are similar to the experimental results for excitation in the direction parallel to the pipe, it is conceivable that the restoring force measured in this experiment could include not only the frictional restoring force but also the reaction force from the surrounding soil.

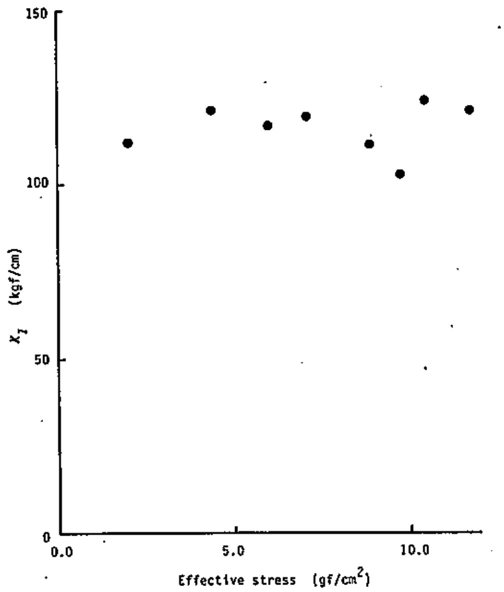

Fig. 13 Relationship between K_1 and effective stress in static loading tests (1 gf/cm^2 = 98 Pa).

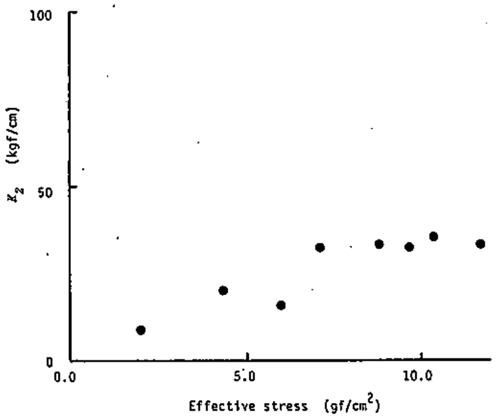

Fig. 14 Relationship between K_2 and effective stress in static loading tests (1 gf/cm^2 = 98 Pa).

3.3 Results of dynamic loading tests and discussion

There was no indication of clear trends between the soil spring constants, namely, K_1 and K_2, and effective stress. Therefore, the restoring force characteristics are investigated using α and β at the first stage. Figs. 15 and 16 display α and β in relation to the effective stress in liquefaction process, respectively. These figures indicate the three groups of burial depth in the region of greater effective stress. Figs. 17 and 18 show α and β for the excess pore water pressure ratio greater than 0.25. These figures suggest that α and β are directly proportional to the effective stress. On the other hand, Figs. 19 and 20 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 bepth are represented by straight line segments. It can be seen from Fig. 19 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 ratio. In Fig. 20, 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, α and β increase.

Next, K_1 and K_2 in relation to the effective stress are investigated for the excess pore water pressure greater than 0.25. This means that the effect of the reaction force is small in these cases. Fig. 21 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. 21 that K_1 is almost unchange-

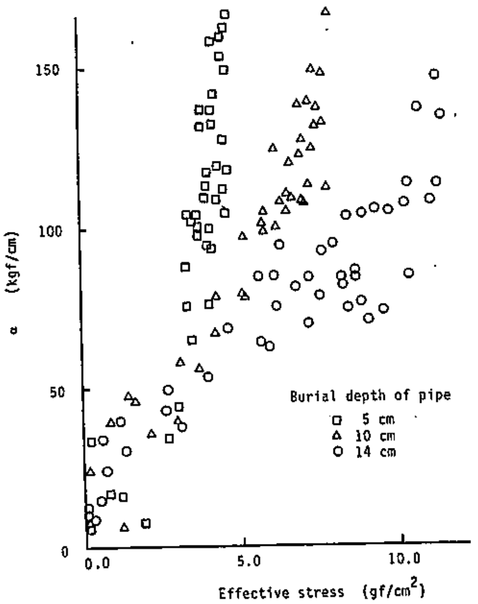

Fig. 15 Relationship between α and effective stress in dynamic loading tests (1 gf/cm^2=98 Pa).

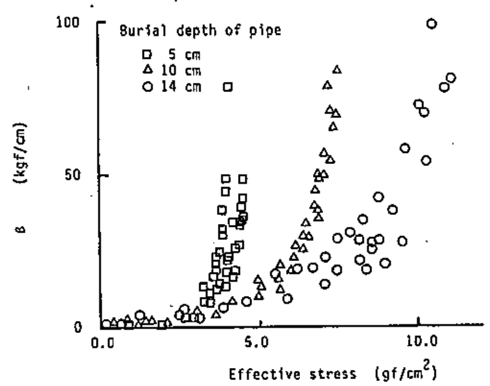

Fig. 16 Relationship between β and effective stress in dynamic loading tests (1 gf/cm^2=98 Pa).

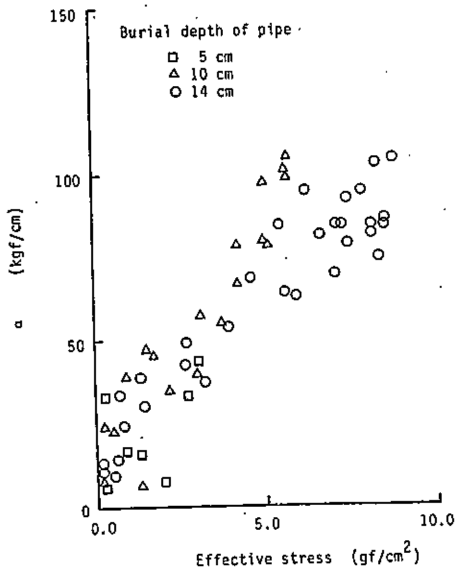

Fig. 17 Relationship between α and effective stress in dynamic loading tests (Excess pore water pressure ratio is greater than 0.25, 1 gf/cm^2=98 Pa).

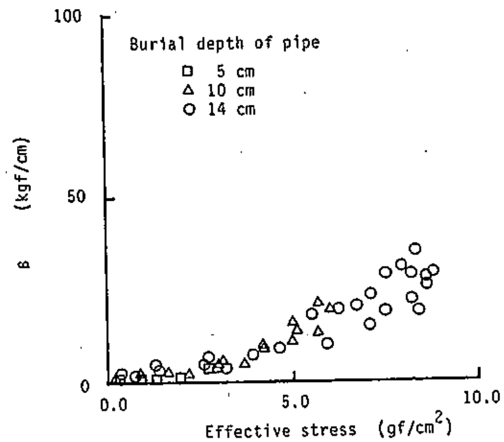

Fig. 18 Relationship between β and effective stress in dynamic loading tests (Excess pore water pressure ratio is greater than 0.25, 1 gf/cm^2=98 Pa).

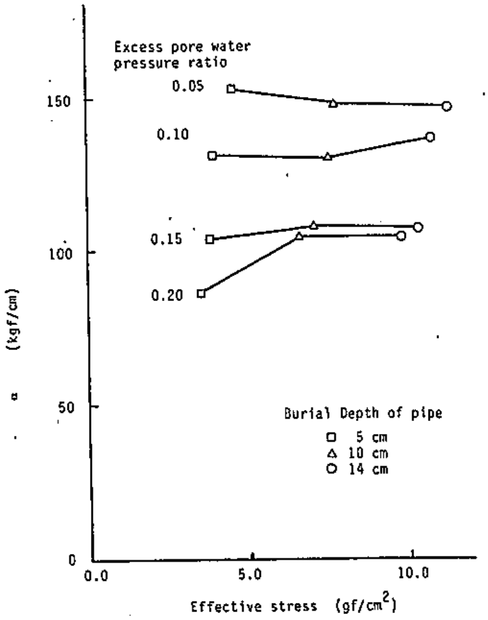

Fig. 19 Relationship between α and effective stress in dynamic loading tests (Excess pore water pressure ratio is less than 0.25, 1 gf/cm^2=98 Pa).

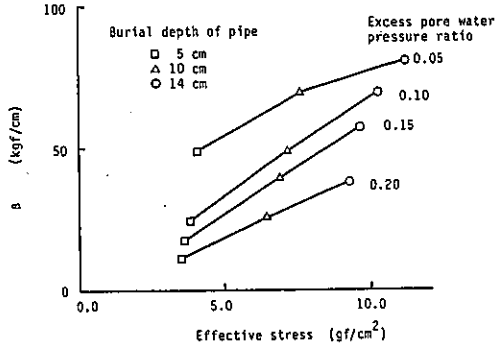

Fig. 20 Relationship between β and effective stress in dynamic loading tests (Excess pore water pressure ratio is less than 0.25, 1 gf/cm^2=98 Pa).

able 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 presented by β, and the effective stress is shown in Fig. 18. It is evident from Fig. 18 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 direction parallel to the pipe axis, 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. However, additional studies are required to clarify the effects of the reaction force from the surrounding soil on the restoring force characteristics.

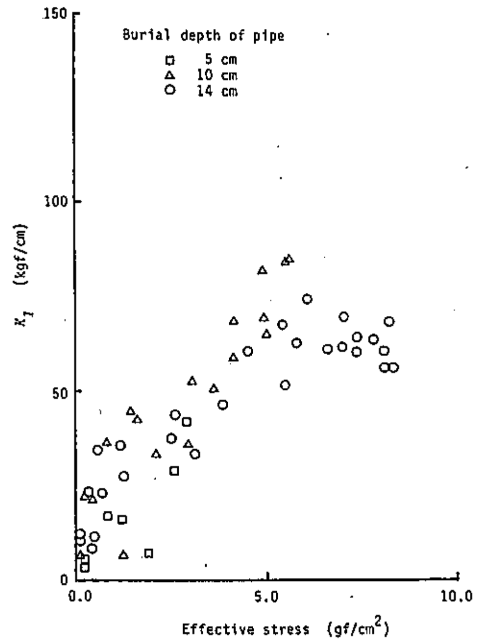

Fig. 21 Relationship between K_1 and effective stress in dynamic loading tests (Excess pore water pressure ratio is greater than 0.25, 1 gf/cm^2=98 Pa).

4. Concluding Remarks

The present paper experimentally investigated restoring force characteristics of pipe-liquefied layer system. We 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 direction perpendicular 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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