AN EXPERIMENTAL STUDY OF EFFECTS OF LATERALLY FLOWING GROUND ON IN-GROUND STRUCTURES

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ABSTRACT

This paper describes an experimental study of effects of laterally flowing ground induced by liquefaction on in-ground structures. In order to investigate the effects, the authors conducted shaking table tests concerning the mechanical properties of liquefied soil.

Generally, there are two kinds of view points for the evaluation of the behavior of liquefied ground. In the first view point, the liquefied ground is assumed to behave as a fluid, and in the second, it is assumed to still behave as a solid with largely reduced stiffness. In this paper, the authors took the first view point based on the findings from the case studies on liquefaction-induced ground displacements during past ten earthquakes.

The following shaking table tests were conducted to investigate the mechanical properties of liquefied soil as a viscous material:

1) Test using a sphere which is drawn up vertically in liquefied soil
2) Test using a pipe which is drawn horizontally in liquefied soil

From the results of both tests, it was recognized that the coefficient of viscosity of liquefied soil, which was calculated from the reactive load acting on the sphere and the pipe, depended on the magnitude of input acceleration and also on the relative density of liquefied soil, namely it depended on the degree of liquefaction severity. In this paper, F_L-value was adopted as an index to estimate the degree of liquefaction severity and the relationship between the coefficients of viscosity and the F_L-values was investigated. From the two kinds of tests it was concluded that the coefficient of viscosity of liquefied soil had a close correlation with the degree of liquefaction severity, and could be estimated quantitatively by F_L-value.

Introduction

At the time of 1983 Nihonkai-Chubu earthquake, liquefaction-induced large ground

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displacements were for the first time measured on aerial photographs which were taken at the pre- and post-earthquake (Hamada et al., 1986). After that, case studies of past ten earthquakes in Japan, U.S. and Philippines have been conducted under a cooperation between Japanese and U.S. researchers (Hamada and O'Rourke, 1992). Based on the results from the case studies, influential factors for the magnitude of liquefaction-induced large ground displacements were examined, and empirical formulae for the prediction of the ground displacements were proposed (Hamada, 1986, Bartlett et al., 1992).

One of research subjects on liquefaction-induced large ground displacements is to investigate the mechanism of the occurrence of the ground displacements with a magnitude of several meters, which were recognized even in almost flat ground with a gradient less than 1 %. Another research subject is to study the effect of large ground displacements on in-ground structures such as foundations and buried pipes.

Generally, there are in principle two kinds of view points to evaluate the behavior of the soil that constitutes liquefied ground which is deforming toward large ground displacement. The first is that the liquefied soil behaves as a fluid. The second is that it still behaves as a solid, but its stiffness is largely reduced due to the liquefaction. As a combination of the two, furthermore, a third view point is possible, where the liquefied soil behaves with dual phases of a liquid and a solid.

Based on the first view point, we conducted experimental studies on the mechanical properties of liquefied soil.

Methods of Laboratory Tests

The following two tests were conducted for the evaluation of the mechanical properties of liquefied soil:

1) Sphere test: Test using a sphere which is drawn up vertically in liquefied soil

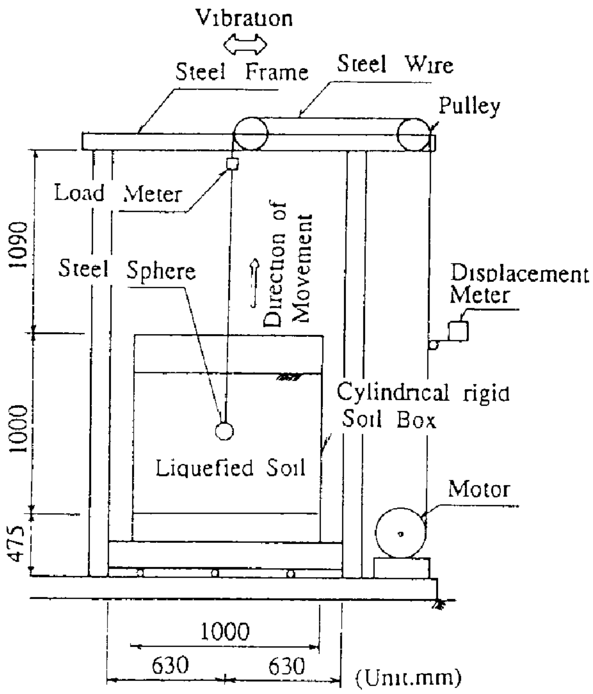
2) Pipe test: Test using a pipe which is drawn horizontally in liquefied soil

Outline of each test is shown in Figures 1 and 2 respectively. The sphere test was conducted with a cylindrical and rigid box with a diameter of 1.0 m and a height of 1.0 m, and Toyoura sand was used. Liquefaction of the soil was induced by sinusoidally shaking the box, and after complete liquefaction, a steel sphere was lifted up in the liquefied soil with a constant velocity, and the reactive load acting on the sphere during the lifting was measured. Sixty cases of tests were conducted with four variable parameters, i.e., diameter of the sphere, input acceleration for shaking table, relative density of the soil and lifting velocity of the sphere, as shown in Table 1.

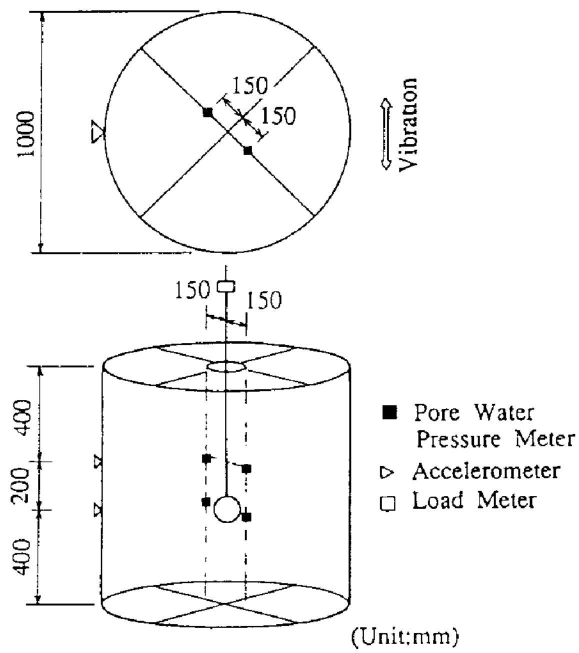
Table 1 Parameters of sphere test.

Diameter of the Sphere (mm)	Input Acceleration for Shaking Table (cm/s^2)	Relative Density of the Soil (%)	Lifting Velocity of the Sphere (cm/s)
30, 50, 100	150, 250, 350	10, 30, 50	1, 3, 6

The pipe test was done in a similar way to the sphere test's. The rigid soil box has a length of 1.8 m, a width of 0.8 m and a height of 1.0 m. An aluminum pipe with a diameter of 5 cm and a length of 70 cm was moved horizontally with a constant velocity

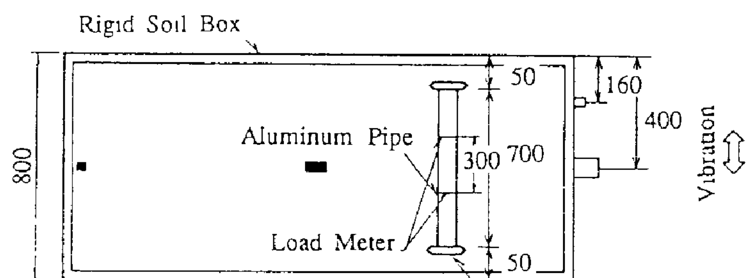


(a) Equipment of sphere test

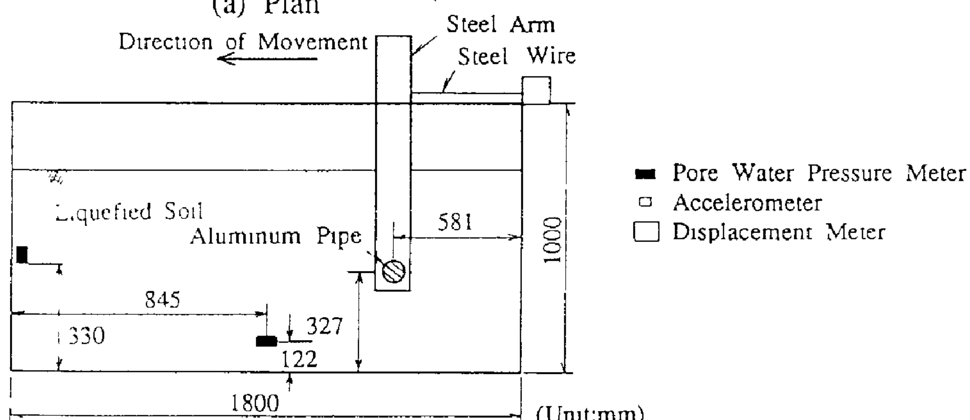


(b) Arrangement of instruments

Figure 1. Outline of sphere test.



(a) Plan



(b) Side view

Figure 2. Outline of pipe test.

after complete liquefaction of Toyoura sand. The soil box was shaken in the direction perpendicular to the direction of pipe movement, so that the effects of the inertia force acting on the pipe could be neglected. The reactive load acting on the pipe during the moving was measured by load meters installed in the pipe. Twenty-three cases of tests were conducted with three variable parameters, i.e., input acceleration for shaking table, relative density of the soil and moving velocity of the pipe, as shown in Table 2.

Table 2. Parameters of pipe test.

Input Acceleration for Shaking Table (cm/s^2)	Relative Density of the Soil (%)	Moving Velocity of the Pipe (cm/s)
80 - 500	25, 35, 45	1, 5

Results of Tests

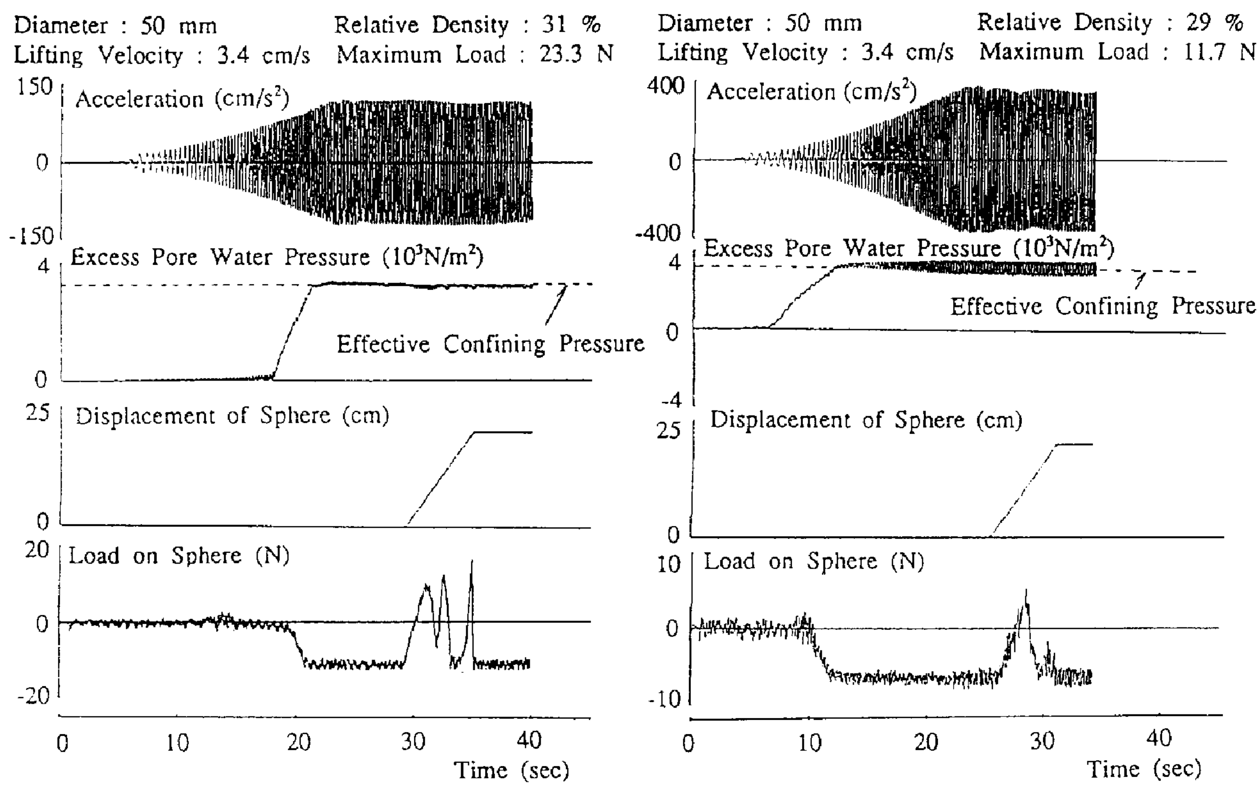
Results of Sphere Tests

Two examples of the results of sphere tests are shown in Figure 3. For both cases, the diameters of spheres are 5 cm, and the relative density and the lifting velocity are almost the same, about 30 % and 3.4 cm/s respectively. However, the input accelerations at the basement of the soil box in each cases are different, 122 cm/s^2 and 379 cm/s^2. The pore water pressure shows that the sand is completely liquefied before and throughout the lifting. The load on the sphere firstly decreases due to the buoyancy of the liquefied soil. The maximum load in the case of larger input acceleration is less than that in the case of smaller input acceleration. Furthermore, according to other tests, while the other three parameters are almost the same, it is also recognized that the maximum load in the case of smaller relative density is less than that in the case of larger relative density.

Figure 4 shows the relationship between the load on the sphere and the excess pore water pressure on the surface of the sphere in preliminary tests. The excess pore water pressure gradually decreases and fluctuates as the sphere is lifted, and this fluctuation coincides well with the load fluctuation. Namely, when the excess pore water pressure has a negative peak, the load has a positive peak, and *vice versa*. The reason is inferred such that the completely liquefied soil around the sphere would recover its stiffness temporarily due to the mobilization induced by the lifting of the sphere and afterwards this incompletely liquefied soil with recovered stiffness would be liquefied again completely by shaking the soil box, and this phenomenon occurs repeatedly around the sphere during the lifting, which can explain the fluctuation of the load in full tests shown in Figure 3.

From above observation, while the soil is completely liquefied in the full tests, the degree of liquefaction severity is greater in the case of larger input acceleration than that in the case of smaller input acceleration, and that is why the load in the case of larger input acceleration is less than that in the case of smaller input acceleration, as shown in Figure 3. In addition, such interpretation might help to explain the difference of the load in the different relative density tests. These results suggest that the mechanical properties of liquefied soil depend on the degree of liquefaction severity, and that the coefficient of viscosity of liquefied soil is governed by the degree of the liquefaction severity.

Therefore, the Factor of Liquefaction Intensity F_L (Iwasaki, et al., 1978) was adopted



(a) Input acceleration : 122 cm/s^2 (b) Input acceleration : 379 cm/s^2

Figure 3. Examples of sphere test results.

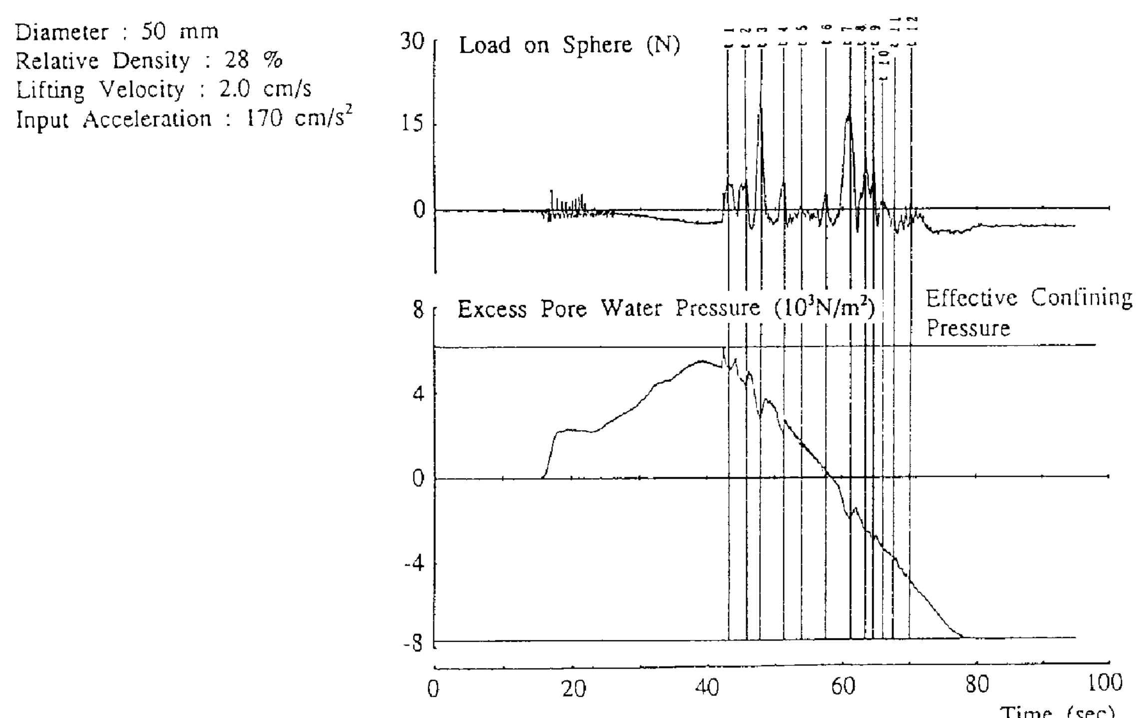


Figure 4. An example of preliminary sphere test results.

as one of the indices to estimate the degree of liquefaction severity. F_L was defined as follows (Japanese Road Association, 1990);

$$F_L = R / L \qquad (1)$$

$$R = 0.0042 D_r \qquad (2)$$

$$L = (\alpha_{max}/g) \cdot (\sigma_v / \sigma_v') \qquad (3)$$

where,

D_r : relative density of the soil

α_{max} : input maximum acceleration of the soil box

σ_v : total overburden pressure

σ_v' : effective overburden pressure

g : gravitational acceleration

The coefficient of viscosity of liquefied soil was estimated with the following formula, because the liquefied soil was assumed as a viscous liquid in this study;

$$\eta = F / 3\pi d V \qquad (4)$$

where,

η : coefficient of viscosity of liquefied soil

F : load on the sphere

d : diameter of sphere

V : lifting velocity of sphere

Figure 5 shows the relationship between the coefficients of viscosity of liquefied soil and the F_L-values. When the F_L-value decreases, namely the degree of liquefaction severity increases, the coefficient of viscosity of liquefied soil decreases, while the coefficient of viscosity becomes a little larger as the diameter of the sphere increases. A parabola line calculated by the method of least squares is drawn as well in Figure 5.

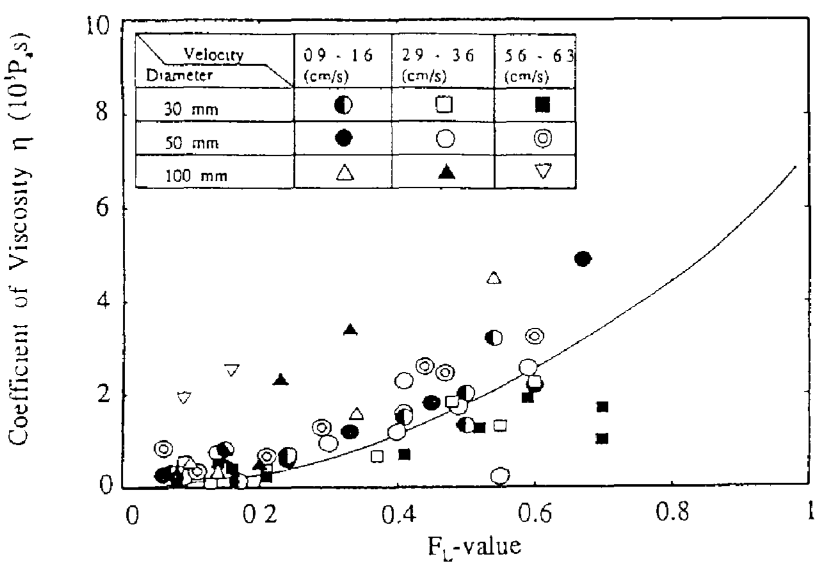


Figure 5. Coefficient of viscosity of liquefied soil in sphere test.

Results of Pipe Tests

Two examples of the results of pipe tests are shown in Figure 6 in a similar way to the sphere test's. For both cases, the relative density and the velocity of the pipe are almost the same, about 34 % and 5.1 cm/s respectively. However, the input acceleration at the basement of the soil box are different, 128 cm/s^2, 255 cm/s^2. As the same as for the sphere tests, the maximum load on the pipe in the case of larger input acceleration is less than that in the case of smaller input acceleration, while the method of the test is different from the sphere test.

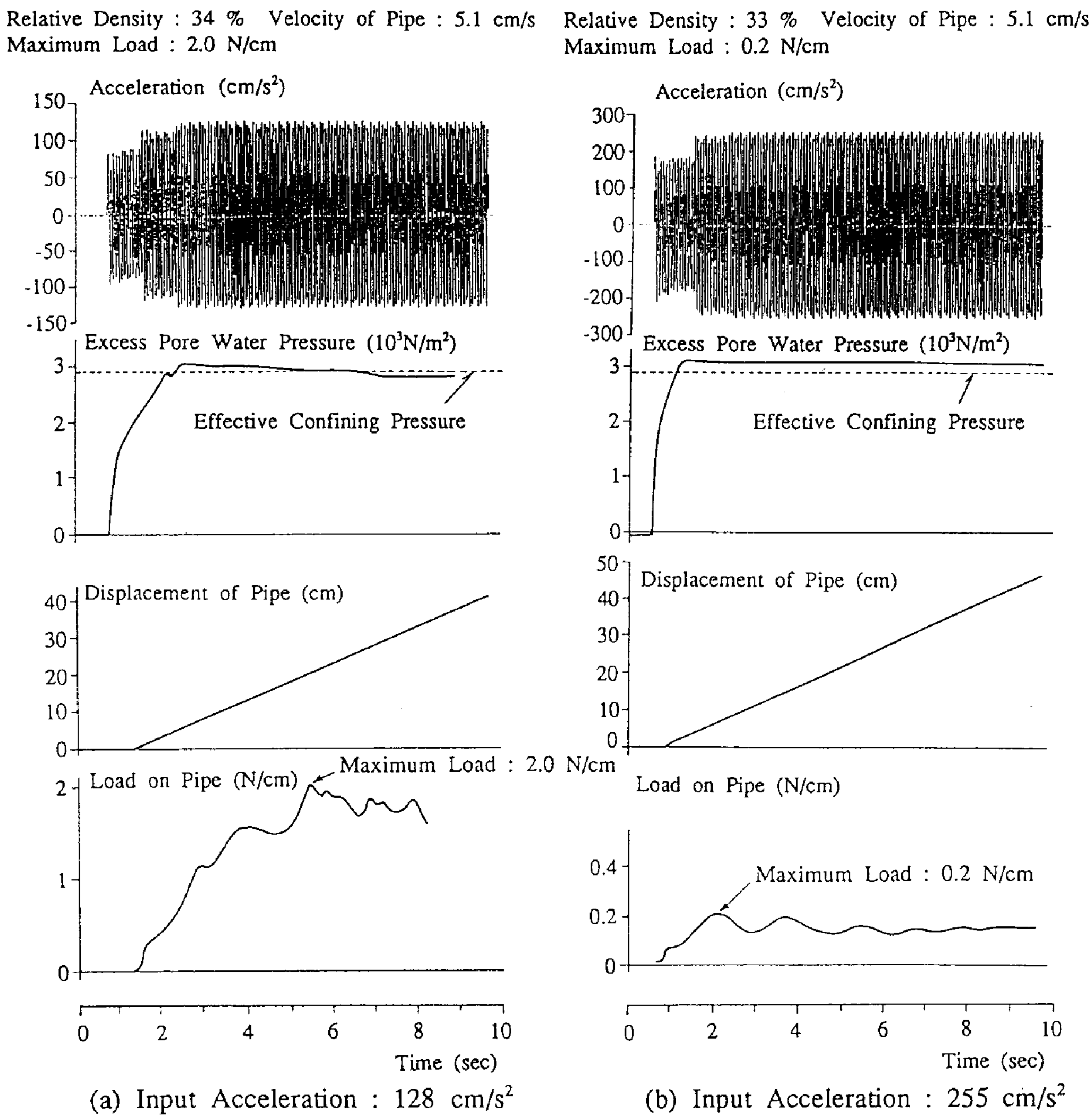


Figure 6. Examples of pipe test results.

The coefficient of viscosity of liquefied soil was calculated with the following formula using the measured load F on the pipe;

$$F = 4\pi\eta V / (2.002 - \log_n Re) \quad (5)$$

where,

η : coefficient of viscosity of liquefied soil
Re: Reynolds Number ($=\rho Vd/\eta$)
V : velocity of pipe
ρ : density of liquefied soil
d : diameter of pipe

Figure 7 shows the coefficient of viscosity estimated from the pipe test, which retains a good correlation with the F_L-value, as the same as for the sphere test.

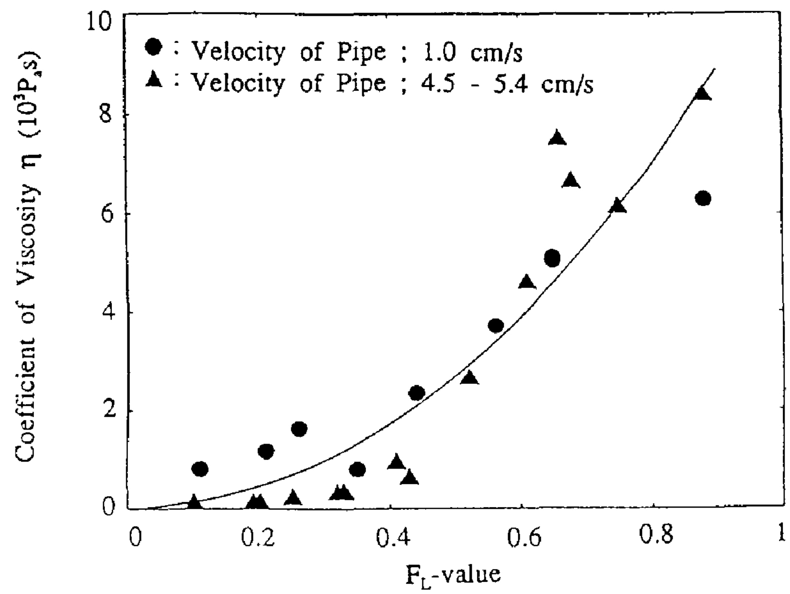


Figure 7. Coefficient of viscosity of liquefied soil in pipe test.

Comparison of Both Tests

Figure 8 shows the results of both kinds of tests. It is notable that the coefficients of viscosity obtained from the pipe tests well coincide with those from the sphere tests, which suggests that it is possible to estimate the coefficient of viscosity quantitatively by F_L-value.

Conclusion

Based on the view point to assume the liquefied soil as a fluid, two kinds of laboratory tests were conducted to evaluate the mechanical properties of liquefied soil, i.e., test using a sphere and test using a pipe. The test results show that the coefficient of viscosity of liquefied soil depends on the degree of liquefaction severity, and that the coefficient can be estimated quantitatively by F_L-value.

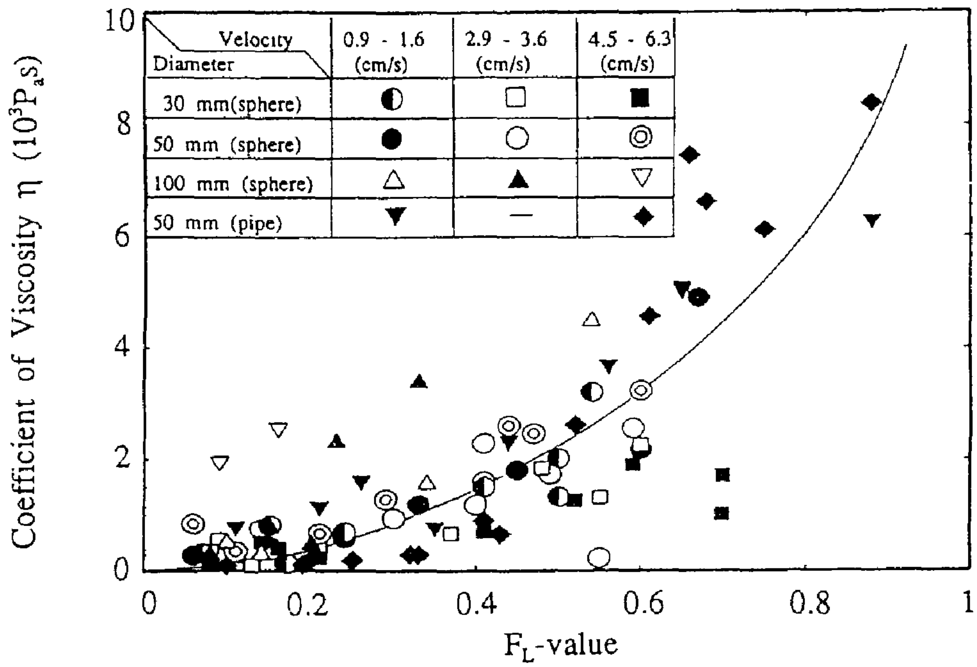


Figure 8. Coefficient of viscosity of liquefied soil in both tests.

In order to prove the proposed assumption that the liquefied ground behaves as a fluid, it is necessary to investigate the behavior of the liquefied soil during ground deformation by experimental studies as well as analytical studies in which the coefficients of viscosity obtained from the sphere test and pipe test are used. Furthermore, it is also necessary to do more research based on the view point to assume the liquefied soil as a solid in order to obtain a rational explanation on the mechanism of the occurrence of large ground displacements.

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