Experimental Evaluation of Viscid Properties of Liquefied Sand

Jun Kawamura, Kenji Hattori and Hirokazu Akagi

ABSTRACT

Earthquakes cause liquefaction of saturated loose sand. In the great Hanshin-Awaji earthquake of 1995, many revetments and foundations of structures were seriously collapsed by liquefaction in seaside reclaimed ground, and lateral flow damaged buried pipelines of lifeline and foundation piles. Therefore, studies on predicting lateral flow are vital for geotechnical engineering. Recently, the results of model tests are employed to point out that liquefied sand behaves like a viscous fluid. The purpose of this study is to evaluate the physical properties of liquefied sand through changes in the apparent coefficient of viscosity of liquefied sand. The shear resistance of liquefied sand was measured with a hollow cylindrical torsion shear test.

Key Words: Fully saturated sand, liquefaction, torsion, pore pressure, lateral flow

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INTRODUCTION

Earthquakes cause liquefaction of saturated loose sand and lateral flow of liquefied sand. Because of the ground vibration of an earthquake, floating particles of sand in the pore water become like slurry, causing “liquefaction”. Lateral flow implies the soil movement due to even slight inclinations in ground, composed of loose sand that has become liquefied. Hence, liquefaction is often followed by lateral flow, or the phenomenon of ground displacement in a horizontal direction on the order of a meter. The average shear strain of the liquefied layer falls into the several tens to hundreds percentage range. After a seismic vibration, a great displacement is induced that differs from the phenomenon of slope failure in that even the ground beneath a surface that can almost be thought to be horizontal from the engineering view point (1 to 2% or less). Because this great displacement in the ground takes place, many revetments and foundations of structures can be seriously collapsed by liquefaction in seaside reclaimed ground, while lateral flow can damage buried pipelines of lifeline and foundation piles. Because most of the great cities exist on loosely deposited ground, which can easily be liquefied, damage to urban structures by lateral flow is immeasurable. Japan suffers tremendous damage from liquefaction and lateral flow due to her many earthquakes. Therefore, studies on how to predict lateral flow followed by liquefaction are necessary for geotechnical engineering.

Investigating the mechanisms by which lateral displacement of ground by liquefaction occur and finding a way to predict it must begin with the results of case analyses of actual earthquake events, flow tests of model ground, and studies of the engineering properties of liquefied sand (Hamada et al. 2000[1]) . Although the results of ground model tests depend on the velocity and liquefied ground resistance, it has been shown that liquefied sand itself behaves like a viscous fluid. The shear resistance of liquefied sand is measured by performing hollow cylindrical torsion shear testing. Assuming that liquefied sand was a viscous fluid, the viscid properties of liquefied sand were quantitatively evaluated by determining a coefficient of viscosity.

OUTLINE OF TEST

Sample and Testing Apparatus

Toyoura fine sand was used for the samples. Each specimen was a hollow cylinder with a height of 100mm height, an inner diameter of 30mm, and an outer diameter of 70mm. Physical properties of the sample are given in Table.1. In order to reduce friction between the rubber membrane and the specimen, a smooth membrane-sheet 1μm thick was employed to cover around the specimen.

Table.1 Physical properties of sample

Sample	Toyoura fine sand
Density of soil	2.639 g/cm^3
sand	94.80%
silt	1.82%
clay	3.38%
Max grain size	0.85mm
Max density	1.646 g/cm^3
Min density	1.353g/cm^3

One problem of the hollow torsion shear test is that the tension of the rubber membrane influences the testing data. As a new method of compensating for the rubber membrane tension, the circumference part of the pedestal rotates as well as the top cap simultaneously. Then, the device was improved so that the test might be done without the rubber membrane being twisted. The structure of this device, including the rotating pedestal, is shown in Fig.1.

Axial pressure, axial displacement, torque, rotational displacement, lateral pressure and pore water pressure were measured during the undrained shear test by a digital dynamic strain meter. The measured data were recorded directly into the mobile computer directly. The test apparatus is given in Fig.2

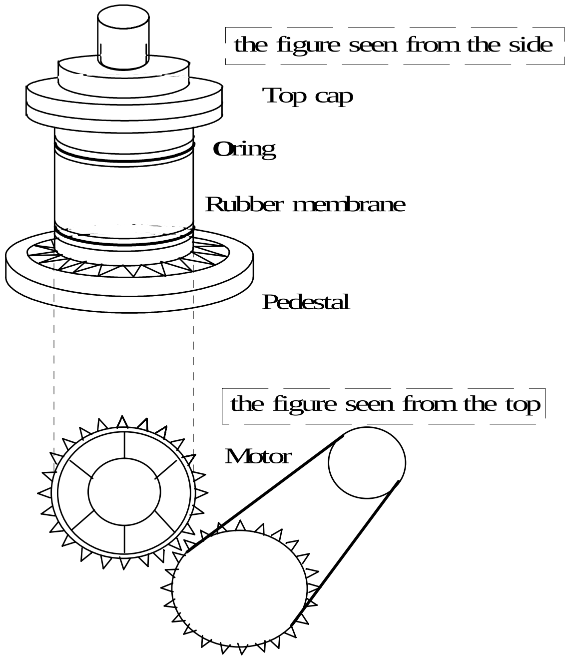

Fig.1 The structure of pedestal

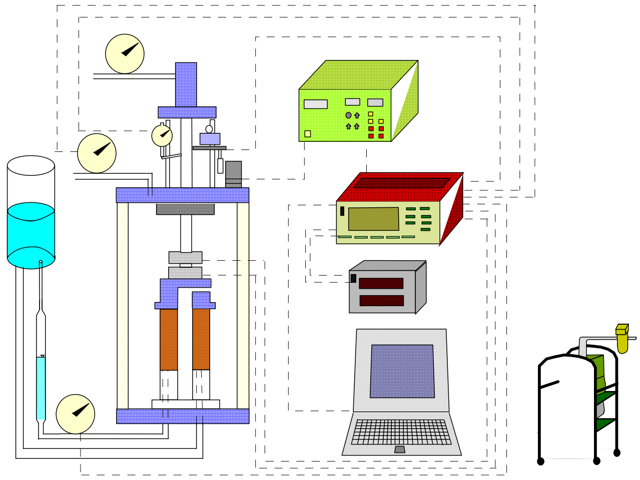

Fig.2 The system of test apparatus

Test Procedure

Specimens were created using the air pluviation method with a relative density of 40%, permeated by water, and frozen in the freezer. After freezing, each specimen was set on the pedestal base and melted in negative pressure. After melting, negative pressure was changed into confining pressure, and the void of the specimen was filled with carbon dioxide. Then, the specimen was permeated by de-aired water and was saturated by using backpressure of 0.2 MPa. The target value of B was over 0.95.

The specimen was consolidated isotropically under constant confining stress. Axial displacement and change in volume of specimen were measured.

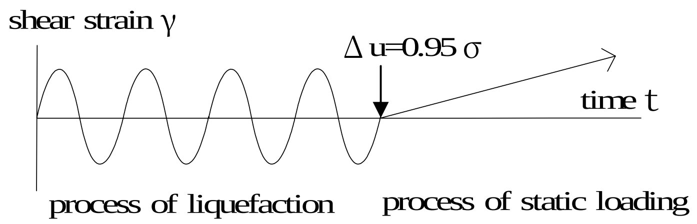

Fig.3 The process of loading

After completion, an undrained cyclic torsion shear test was performed. When excess pore water pressure became 95% of the confining pressure, the specimen was considered to be liquefied, and the cyclic shear test was ended. Then, undrained static torsion shear test was conducted to measure the shear resistance of liquefied sand. The data were analyzed after the undrained static shear test was performed. Each datum had been recorded in the personal computer.

The loading process of the test at this procedure is shown in Fig.3, and a flow chart of the test procedure is shown in Fig.4. The test was performed with the above process; the coefficient of viscosity of the liquefaction of sand was calculated from the experimental data mentioned above.

Start
⇩
Form of frozen specimen
⇩
Defrost of specimen
⇩
saturation
⇩
Consolidation
⇩
Undrained cyclic torsion shear test
⇩
Undrained static torsion shear test
⇩
Estimate coefficient of viscosity
⇩
End

Fig.4 Test procedure

Testing Conditions

Shear strain rate and confining pressure were used as the variable testing conditions. In addition, to evaluate the effect of rubber membrane tension, the tests without pedestal rotation and the blank tests with and without dummy rubber specimen were carried out. The condition of 40% relative density of the specimen was used in all the experiments. Table 2 summarizes the test conditions. The tests were performed several times under each condition to confirm the results.

Table.2 Test condition

Sample	Confining pressure (Mpa)	Strain rate (%/min)	Rotation
Toyoura fine sand	0.05	10	○
	0.1	20	
	0.2	30	
	0.1	30	×
Water	×	30	×
Dammy	0.1	30	×
	0.1	30	○
Only dammy	×	30	×

The rubber membrane filled with the de-aired water was used for the specimen in one of the test conditions in Table 2, indicated by “water”. The dummy specimen is made of rubber, whose dimensions are the same as the sand specimen. Except for the cyclic loading torsion shear for liquefaction, the torsion shear test was performed by the same process as when a sand sample was used. Just the dummy specimen was used in the test, where torsion shear was done without attaching rubber membrane and membrane sheet. Because confining pressure could not be loaded in this case, it is shown with an × in Table 2.

The cases in which rubber membrane tension was compensated by rotation of the pedestal circumference are shown with ○ in the column of Table 2.

The confining pressures used were 0.05, 0.1, or 0.2 MPa, and the strain rates used were 10, 20, or 30% per min. There were a total of nine testing conditions for sand specimens.

RESULTS AND DISCUSSIONS

Rubber membrane tension effects in the pedestal circumference rotation

As shown in Fig. 5, the difference between each value of shear stress and shear strain with the dummy specimen and the dummy specimen without rotation of the pedestal circumference was measured. This figure depicts the magnitude of tension of the rubber membrane during torsion shear. From the figure, it becomes clear that shear stress is in proportion to shear strain in tension state of rubber membrane.

The results from the dummy specimen with pedestal rotation are shown in Fig.6. They were compared with the results for the blank test using the dummy specimen without pedestal rotation. It was found that the shear stress approached a value that was the same for both. Rotation of the circumference part of pedestal eliminated the influence of the tension of rubber membrane.

The effect of the pedestal circumference rotation under identical conditions of confining pressure 0.1MPa and a strain rate of 30% per min is demonstrated in Fig.7. That figure shows the relations between pore water pressure and shear strain from tests with and without rotation. There was no difference seen between the shear stress and strain relation. However, in tests for which a saturated sand sample was used, considerable differences appeared in the results. With the pedestal rotation, pore

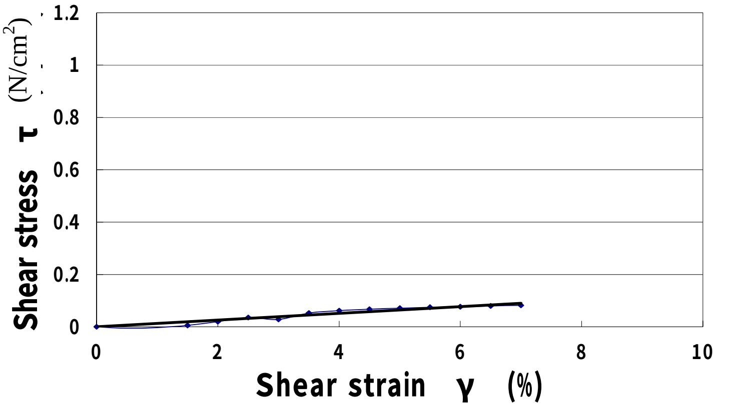

Fig.5 Tension of the rubber membrane by the test of dummy specimen

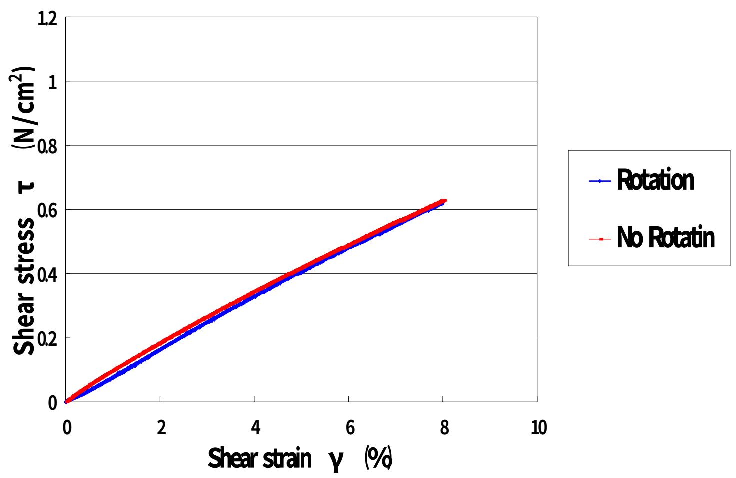

Fig.6 The comparison between the results from the dummy specimen with and without pedestal rotation

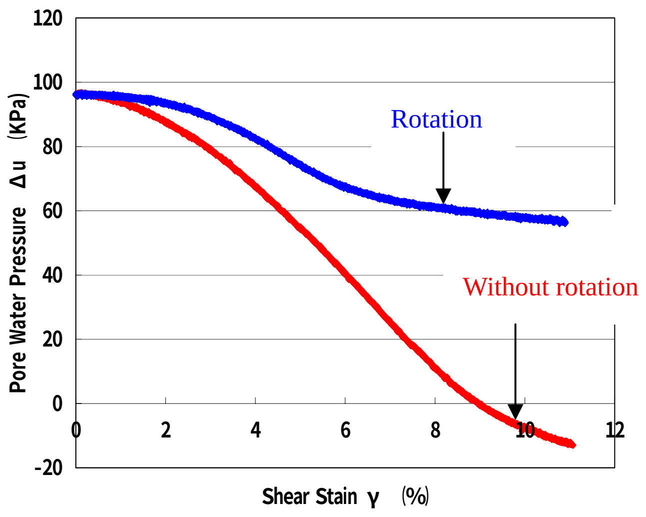

Fig.7 The relations between shear strain and pore water pressure

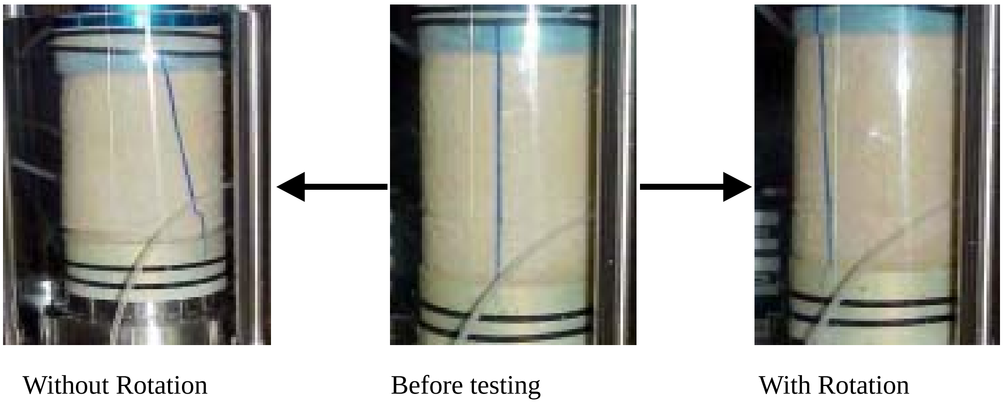

Fig.8 The comparison of the specimens after testing

water pressure remained at nearly constant value and decreased gradually from the middle. Without the pedestal rotation, it decreased rapidly the moment shear began and ultimately reached a negative value. From the past published experimental results, the shear resistance of liquefied sand shows minute resistance at first; when it is beyond a certain strain, rigidity is recovered, and resistance increases. It is highly unlikely that pore water pressure falls so rapidly at the early stages of shear and that pore water pressure so easily becomes a negative value, suggesting that the result with the pedestal rotation is more appropriate.

What causes the differences that emerge in test results due to the existence of the rotation? When the deformation state of the specimen after test is observed as shown in Fig.8, a change in appearance is hardly seen in cases with the pedestal rotation. But in cases without rotational, the twisting of the rubber membrane clearly transforms the specimen on the side. It can be assumed that deformation due to the twist of the membrane has brought about the change in pore water pressure inside the specimen. Once again, it can be said that results of test performed with the rotation of the pedestal circumference are more accurate or appropriate.

Discussions of Coefficient of Viscosity for Liquefied Sand

The relation between shear stress and shear strain rate was prepared from the experimental results. The apparent coefficient of viscosity for liquefied sand was obtained by the inclination of that relation, as shown in Fig.9. Under the condition of pedestal rotation, the tension of rubber membrane was corrected for, as mentioned before.

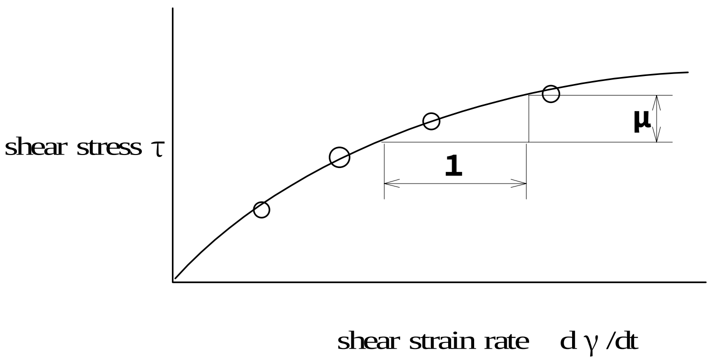

Fig.9 Model of coefficient of viscosity

The following process determined the coefficient of viscosity. When time (1, 3 or 5 sec) passed from the static shear start, the shear stress obtained from the static shear test was plotted on the coordinates (Fig.10). The inclination of this plot represents the apparent coefficient of viscosity of liquefied sand. Table 3 shows the obtained coefficient of viscosity for each confining pressure.

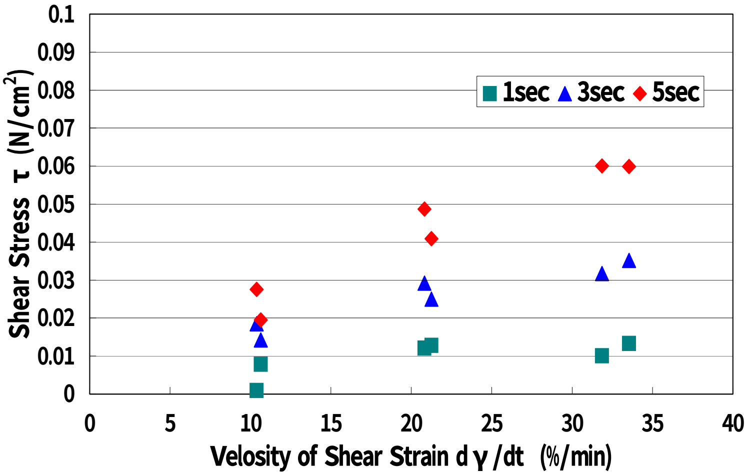

Fig.10 The relationships between shear stress and shear strain rate at the specified elapsed time

In the results of model ground test, it is reported that the coefficient of viscosity of liquefied sand depends on confining pressure. The relationship between the coefficient of viscosity and confining pressure is shown in Fig.11. When confining pressure increased, the coefficient of viscosity was found to increase, as well. The relations shown with log-log plots can be connected with a straight line; the value of the inclination is 0.5 or 0.6.

Table.3 Coefficient of viscosity

Confining pressure (Mpa)	Coefficient of viscosity (N·sec/cm³)		
	1sec	3sec	5sec
0.05	1.8	4.8	9.6
0.1	2.4	9.0	18.0
0.2	3.6	11.4	21.6

In addition, the coefficient of viscosity increases with time after liquefaction (Fig. 12). As for the

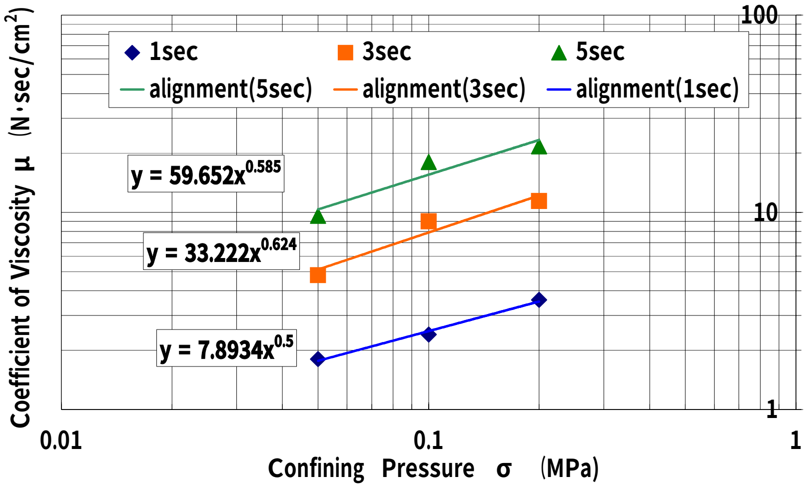

Fig.11 Relations between the coefficient of viscosity and confining pressure

value of inclination as well, it was found that the coefficient of viscosity became greater, as the elapsed time after liquefaction became longer and the confining pressure became larger.

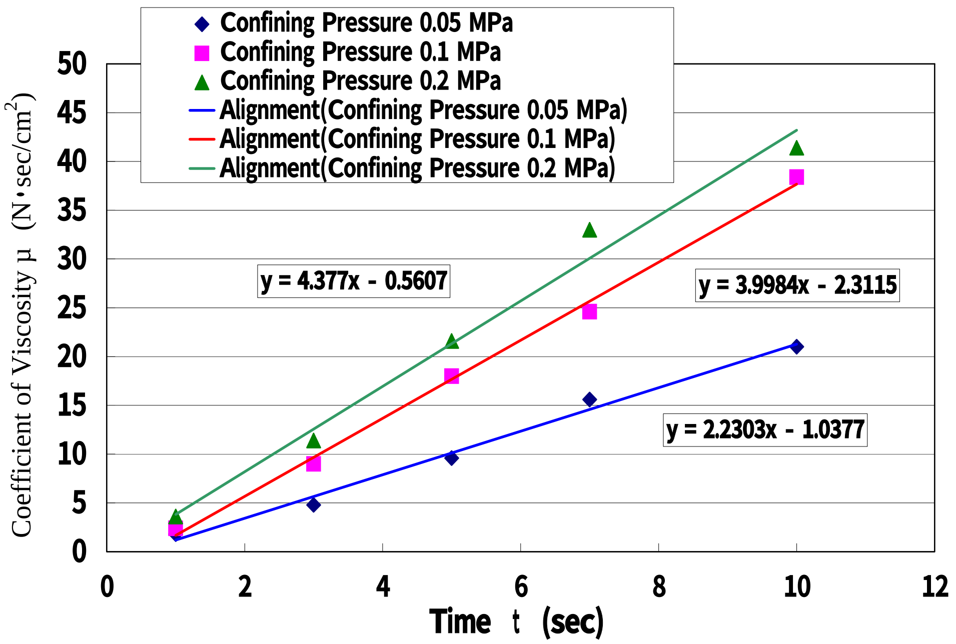

Fig.12 The relationship between the coefficient of viscosity and elapsed time

CONCLUSIONS

1) In the hollow cylindrical torsion test, the tension compensation of the rubber membrane due to the rotation of the part pedestal circumference yields more accurate results than the blank test.

2) The apparent coefficient of viscosity of liquefied sand depends on confining pressure.

3) The apparent coefficient of viscosity of liquefied sand is proportion to the time after liquefaction.

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[1] Masanori Hamada, A. Kono, T. Nasu and K. Yanase: The mechanism of lateral flow of inclined ground and displacement prediction. Proc.2nd Symposium on “Enhancement of Earthquake Performance of Infrastructures Based on Investigation into Fracturing Process”, pp.235-240, March 2000, JSCE