4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1518

LIQUEFACTION STRENGTH OF COARSE WELL GRADED FILL UNDER TORSIONAL SIMPLE SHEAR

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ABSTRACT

Catastrophic liquefaction failures of many reclaimed man-made islands have occurred during the Great Hanshin-Awaji Earthquake, Kobe, JAPAN, and these failures have necessitated extensive investigations into the liquefaction strength of well graded coarse fill materials that are used for reclaiming these islands. In this study, a large size hollow cylinder torsional testing apparatus was used to examine the liquefaction behavior of such fill materials in order to accommodate such coarse material. The apparatus is capable of correcting the effect of membrane penetration on the liquefaction strength. The objective of such study is to establish a reliable liquefaction strength curve of well graded coarse fill at various relative densities. Based on the test results, the difference in the liquefaction strength curves between clean sand (namely Toyoura Sand) and well graded coarse fill is demonstrated.

Keywords: liquefaction strength, well graded coarse fill, membrane penetration, hollow cylinder test

INTRODUCTION

Liquefaction strength of soil has been studied extensively in the past, but the major thrust of experiments has been mainly for clean sands. But in the Great Hansin-Awaji Earthquake, well graded coarse fill materials at man-made islands near Kobe-port have liquefied extensively causing heavy damages to harbor facilities of Kobe Port, (Tanaka et al. (1986)). Because of such extensive liquefactions of fill materials that contain a large size aggregates and with well graded grain distribution, it became one of the major research items of soil liquefaction to investigate the liquefaction characteristics of well graded coarse fill. This paper deals with the liquefaction strength characteristics of such fill material and the liquefaction strength curves for various relative densities are obtained using a large torsional hollow cylinder test apparatus.

The choice of using a torsional testing device over conventional triaxial testing for the liquefaction strength test was to eliminate the strength conversion problems between two different modes of shearing (i.e., horizontal or 45° inclined). Past studies show that the liquefaction strength conversion between these two modes of shearing is not simple and depends on the soil type (Yamashita and Toki (1991) and Tanaka et al. (2004)). Also in experimenting the undrained behavior of coarse-grained soil, it is very important to consider the membrane penetration (MP) effect. The effect of membrane penetration on the liquefaction strength has been dealt with in the past either by correcting the MP effect during the test or by correcting indirectly by applying a correction factor on the test result that was obtained without MP correction. In this study, a special device was used to correct MP effect during liquefaction test.

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EXPERIMENTAL PROCEDURE

Test Apparatus

Fig. 1 shows a large hollow cylinder test apparatus developed herein. The specimen has outside and inside diameters of 50cm and 30cm respectively, and the height was 60cm. The axial force to specimen is given through the piston via the air cylinder placed above the apparatus, and the torsional force to the specimen is given by two horizontal arms connected to the air cylinders placed at upper edge of outer circular frame. The air pressure to these cylinders was controlled by electro-pneumatic regulators which were in turn operated by personal computer. Measurements of axial and torsional forces on the specimen were made by a two-directional-load-cell that is placed just above the specimen cap, and cell pressure and pore pressure were measured by pressure transducers. Measurements of axial displacement and volume change of the specimen were made by LVDT and load cell to measure the volume of water expelled from the specimen. A membrane penetration correction device is attached at the drainage line from the specimen, and its function will be described in details later.

Test Materials and Sample Preparation

The experimental material was a coarse-grained gravelly sand taken from a construction site at Nishi-

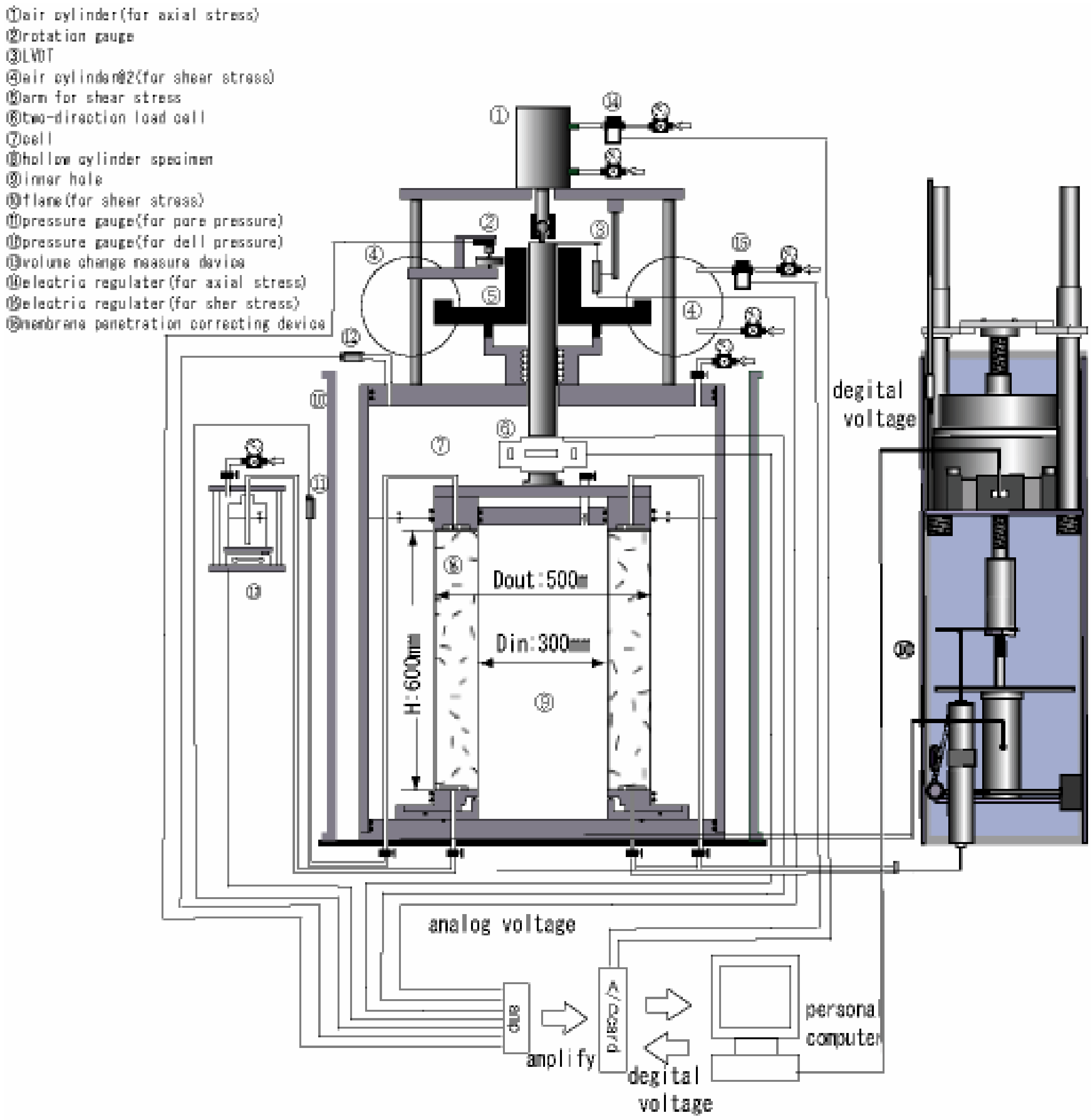

Fig.1 Apparatus for Large Hollow Torsional Shear Test

Ward of Kobe City (hereafter it will be called as Nishi-soil). The maximum grain size of the sample was adjusted to 19mm. The gradation curve is shown in Fig. 2 together with a clean Silica sand, and it is seen that the Nishi-soil is well-graded material. The physical properties of the soil are shown in Table 1.

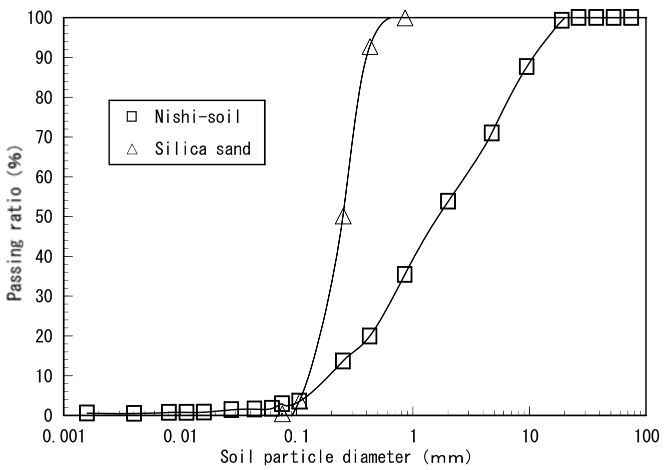

Fig.2 Gradation curve

Table 1: Physical Properties of material

material	Nishi-soil	Silica sand
$\rho_s(t/m^3)$	2.67	2.62
$\rho_{max}(t/m^3)$	1.95	1.57
$\rho_{min}(t/m^3)$	1.54	1.25
D_{max} (mm)	19	0.85
D_{mean} (mm)	1.7	0.22
U_c	15	2.0
U_c'	0.82	1.1

All specimens were prepared by pulverizing soil into a mold and the density of soil was set to three different relative densities of 50%, 60% and 70% by adjusting falling height of air-pulverization. It may be noted that the relative density of coarse soil is defined by using the compaction test results and the maximum density corresponds to the asymptote of density with the increase of compaction energy. For saturating the specimen, a specimen was given an ample amount of CO_2 flow from the bottom, while maintaining a confining pressure of 0.04Mpa to the specimen. Then enough flow of de-aired water was introduced into the specimen, and then a back-pressure of 0.1Mpa was given to the specimen to increase the degree of saturation. Before the test, the measurement of "B" value was made for each specimen, and only those specimens with B value of greater than 0.95 were used for the liquefaction test. It may be noted that all specimens were consolidated to the effective confining pressure of 0.1MPa that was achieved by applying a cell pressure of 0.2MPa with a back pressure of 0.1MPa.

Liquefaction Strength Test

A sinusoidal cyclic of shear stress was applied to the coarse grain soil specimen in undrained condition and cyclic shear stress was applied by giving a rotational twist through a pair of large air cylinders of large torsional hollow cylinder test apparatus, while keeping the isotropic confining stress. The large torsional hollow cylinder test was terminated when the excessive pore pressure exceeds 95% of the confining pressure. The shear stress level was varied from 0.15 to 0.30 in terms of stress ratio for all test cases of three different relative densities. In total, eleven tests have been performed for the specimens having various relative densities and shear stress levels.

During the undrained cyclic shear, the MP correction was applied continuously to the specimen. The MP device used in the large torsional hollow cylinder test is shown in the right hand side of Fig.1 In this device, a minute amount of water is injected in or out of the specimen by horizontal displacement of piston which is generated by rotation of mega-torque motor through a screw gear. The amount of injected water is the product of cylinder's section area and the piston displacement which is measured by LVDT. By applying the measured p' value on the MP correction curve, the amount of water to be injected is calculated and then the MP correction device is operated to give the necessary volume of water.

TEST RESULTS

Undrained Cyclic Behvior

Fig. 3 presents a typical test result obtained from such undrained cyclic torsional test on the Nishi soil. The test data shown in Fig. 3 corresponds to the specimen having Dr=60% and being subjected to a shear stress ratio of 0.20. The following similar trends of test results are observed for all test cases;

1) The shear strain increases gradually as the excess pore water pressure approaches to the initial liquefaction state, and
2) The shear strain develops evenly in both directions of torsional shear.

These observed trends are quite different from those deformation behaviors that a clean sand specimen exhibits during the undrained cyclic triaxial shear. It is well known that a clean sand usually shows a sudden increase of strain as the excess pore pressure approaches the initial liquefactions state, and also that a much larger increase of axial strain usually is observed during a loading in the extension of triaxial testing.

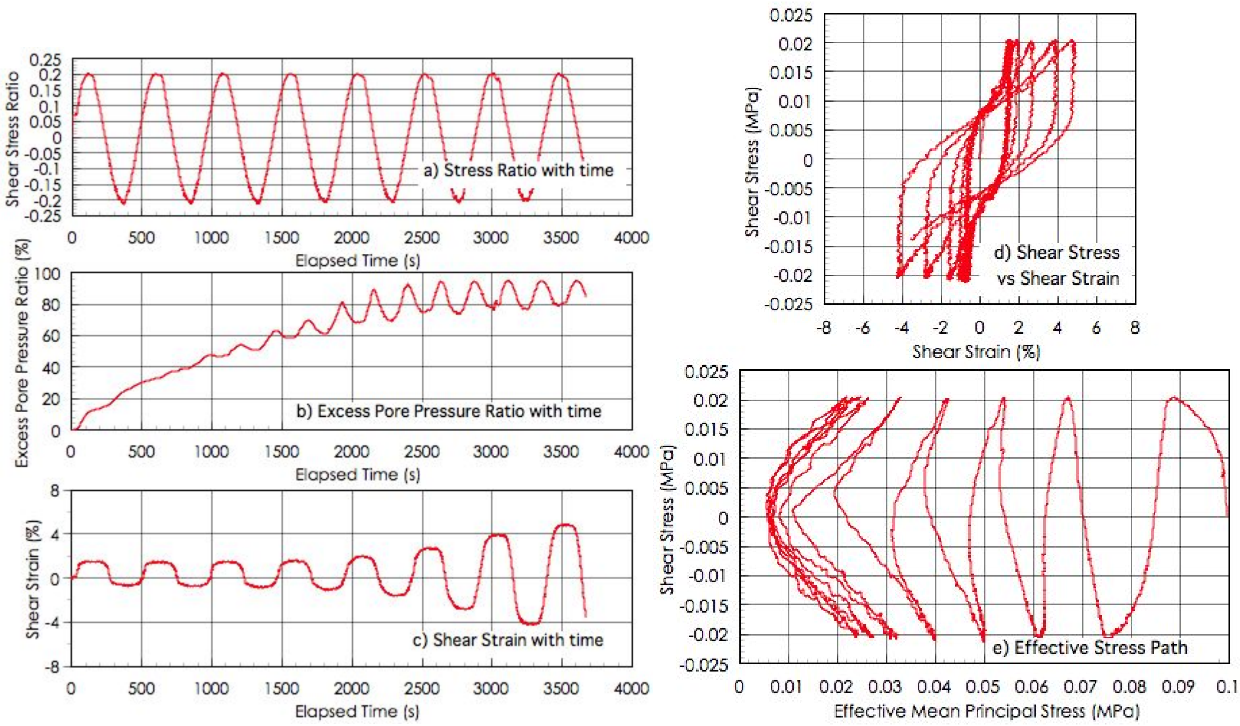

Fig.3 Typical Result of Nishi Soil during Large Hollow Torsional Cyclic Undrained Test (a) Stress ratio, (b) Excess pore pressure ratio, (c) Shear strain, (d) Stress-Strain curve, and (e) Effective stress path

In order to compare the undrained cyclic behaviors between the Nishi Soil (i.e., well graded coarse fill) and a clean sand in the same large hollow torsional test apparatus, a Silica sand of which gradation is shown in Fig. 2 is tested using the same apparatus. Fig. 4 shows the test result obtained for the specimen with relative density of 60% that was subjected to undrained cyclic shear with a stress ratio of 0.125. As can be seen from the figure, the shear strain develops very suddenly when the excess pore pressure approaches the initial liquefaction state. It is also noted that there is an equal increase of shear strain in both directions of shear that indicates the symmetry of soil structure along horizontal plane.

The undrained cyclic behavior of the Nishi Soil under triaxial loading was also examined by subjecting a 100 mm diameter specimen to liquefaction test. The same sample preparation was used and a specimen having relative density of 60% was subjected to a stress ratio of 0.2. Fig. 5 shows the test results in an identical manner to Figs. 3 and 4.

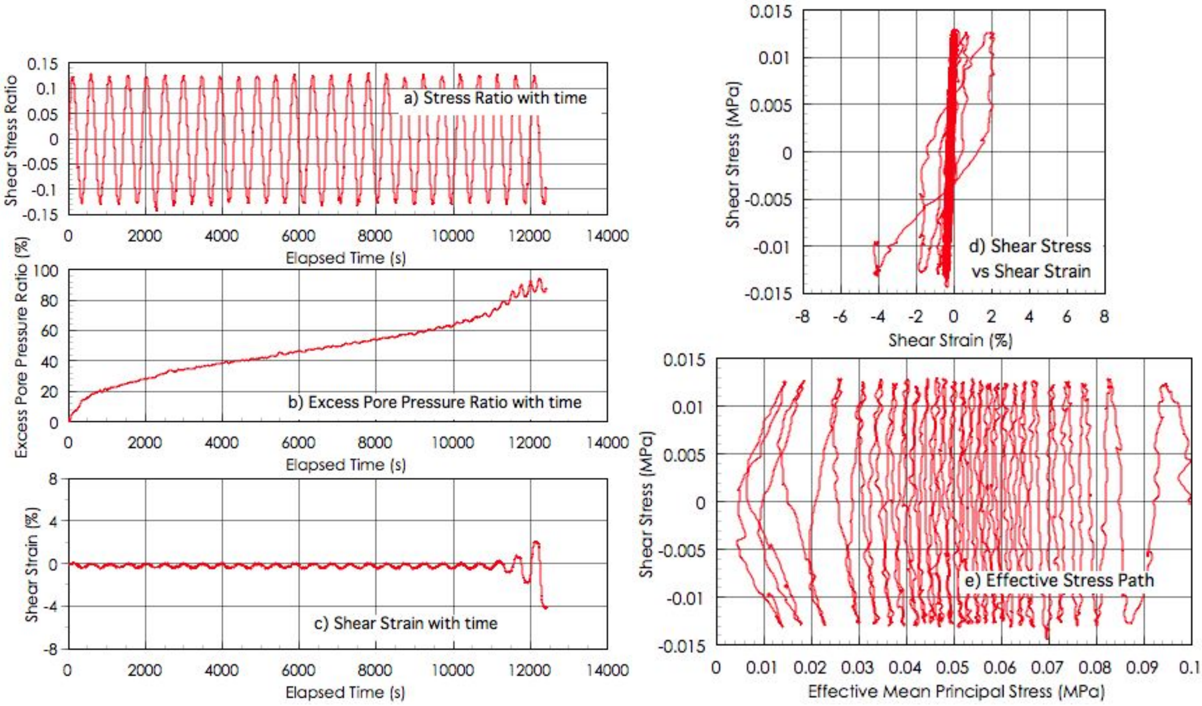

Fig. 4 Typical Result of Silica Sand during Large Hollow Torsional Cyclic Undrained Test (a) Stress ratio, (b) Excess pore pressure ratio, (c) Shear strain, (d) Stress-Strain curve, and (e) Effective stress path

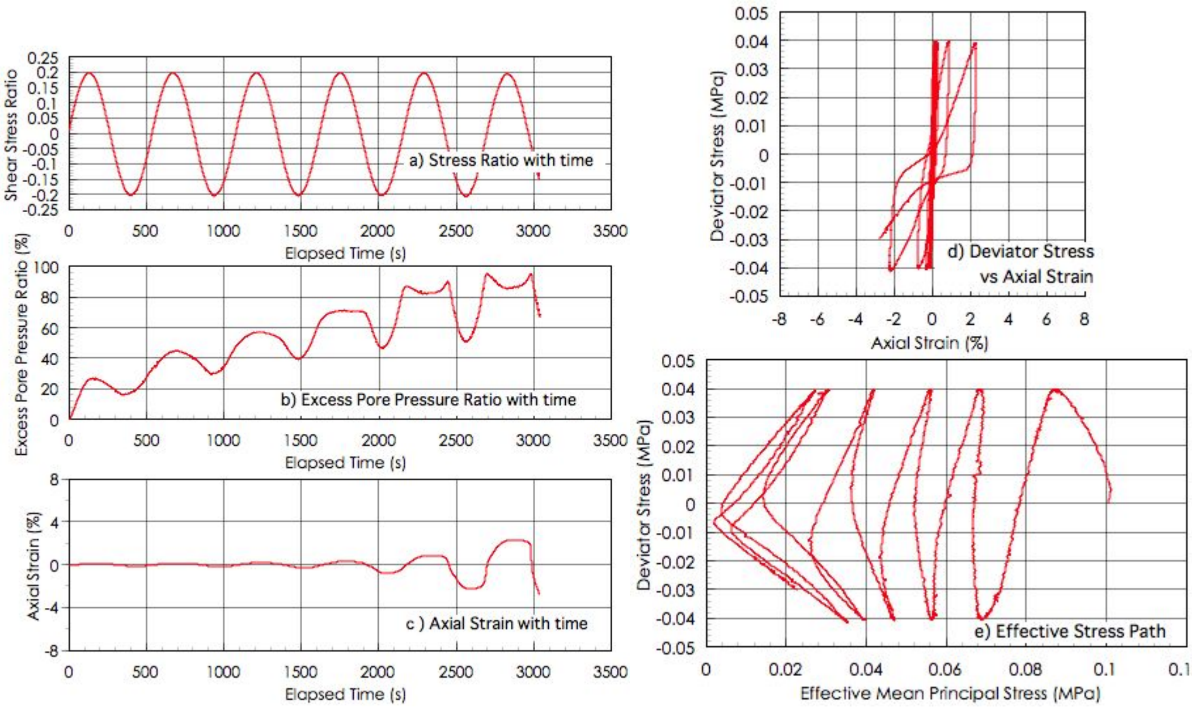

Fig. 5 Typical Result of Nishi Soil during Triaxial Cyclic Undrained Test (a) Stress ratio, (b) Excess pore pressure ratio, (c) Shear strain, (d) Stress-Strain curve, and (e) Effective stress path

As can be seen from Fig.5, the Nishi Soil develops larger shear strains as the initial liquefaction approaches, but the strain increase is very gradual unlike a clean sand, and also the strain is nearly even in both the compression and extension directions. Therefore, the undrained cyclic behavior of well graded coarse fill materials is quite different from that of clean sand.

DISCUSSIONS

Liquefaction Strength Curve

The liquefaction strength of the Nishi Soil was determined by identifying the initial liquefaction state (i.e., the excess pore pressure equals 95% of initial confining pressure). Fig. 6 presents the liquefaction curves for three different relative densities from Dr=50 to 70%. As seen from the figure, the liquefaction strength of the Nishi Soil is not so high. The stress ratio between 0.12 to 0.16 defines the approximate range of liquefaction strength at 20 cycles of loading.

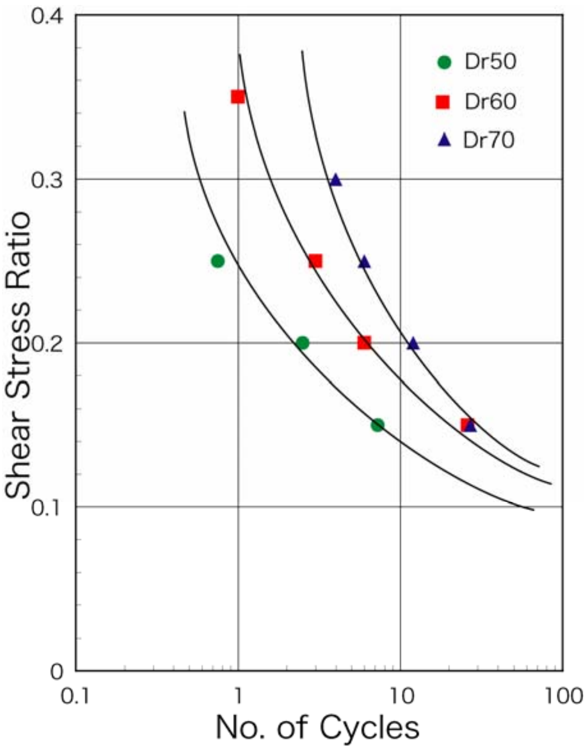

Fig. 6 Liquefaction Strength Curve of Nishi Soil

On the other hand, the liquefaction strength of clean sand may be represented by that of Toyoura Sand that is Japanese standard sand. Fig. 7 shows the variation of liquefaction strength curves for the same three levels of relative density in Fig.6. These curves are drawn by using the following equation which was obtained through various undrained triaxial test results by Matsuo & Higashi (1997).

$$S_R = \frac{C_a}{N} + C_b \quad where$$

$$C_a = DA\left\{0.05\left(\frac{D_r}{100}\right) + 6\left(\frac{D_r}{100}\right)^{15}\right\}$$

$$C_b = 0.21\left(\frac{D_r}{100}\right)$$

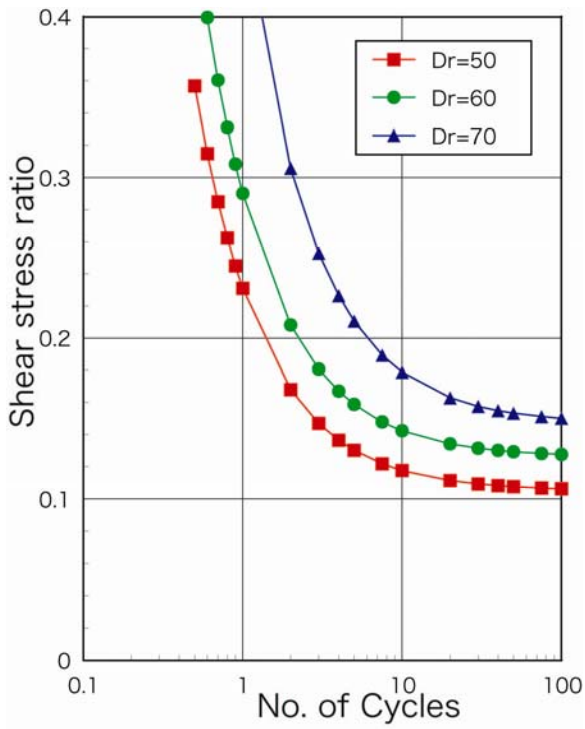

Fig. 7 Liquefaction Strength Curve of Toyoura Sand

By comparing Figs. 6 & 7, it is seen that the Nishi Soil has higher liquefaction strength for higher levels of shear stress at about 0.2 to 0.3. On the other hand, the liquefaction strength is nearly the same or slightly lower for the low shear stress levels.

It may be however noted that there is a difference in the liquefaction strengths obtained from the triaxial and torsional tests for the Nishi Soil. Fig. 8 presents a comparison of test results between the triaxial test and the torsional test for the Nishi Soil at relative density of 60%, Tanaka (2004). It is clear that that the liquefaction strength is higher for the torsional test than for the triaxial test.

Therefore, the difference in the liquefaction strengths between Toyoura Sand and Nishi Soil becomes smaller.

Effect of Relative Density on Liquefaction Strength

The liquefaction strength of well graded coarse fill increased with the increase in the relative density in a similar manner to clean sand. However, it may be noted that we have defined the relative density slightly differently for coarse fill material by relying on the maximum density based on the compaction test result, while the maximum density for clean sands being usually defined by placing a dry soil into a container under horizontal hammering. Such procedure of defining the maximum dry density for coarse well graded fill material became useful after the Great Hanshin-Awaji Earthquake that has resulted in a very large scale liquefaction of man-made islands in Kobe.

Fig. 9 compares the liquefaction strengths of both well graded coarse fill materials including weathered granite, crushed mud stone and Nishi Soil, together with the strength of Toyoura Sand. The Kobe Port Island, which had a largest liquefaction damages during the Earthquake, was built using the weathered granite, and the Rokko Island, which had a slightly less liquefaction damage than the Port Island, was built using the crushed mudstone, Tanaka (1999). It is clearly shown that the increase of liquefaction strengths with the relative density among these materials is in agreement as plotted in Fig.9. Thus a different way of defining the relative density of well graded coarse fill materials is very promising for study of the liquefaction strength for such materials.

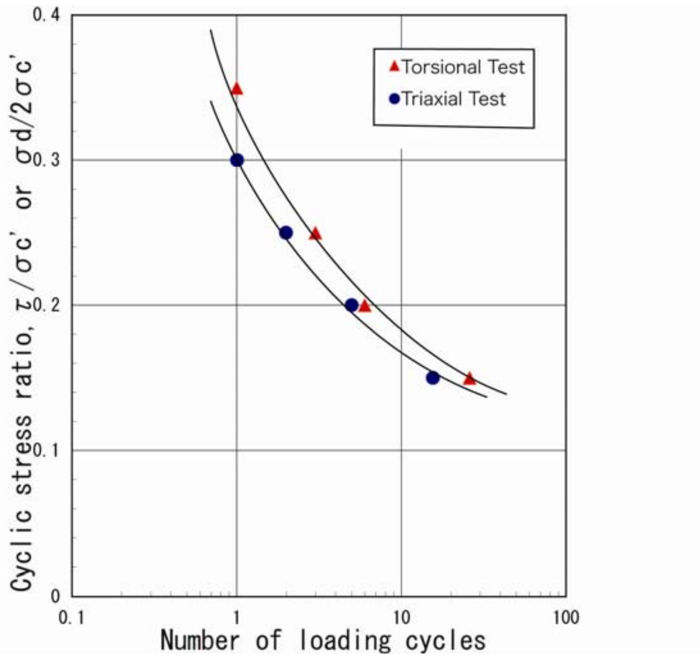

Fig.8 Comparison of liquefaction strength between torsional and triaxial tests for the Nishi Soil

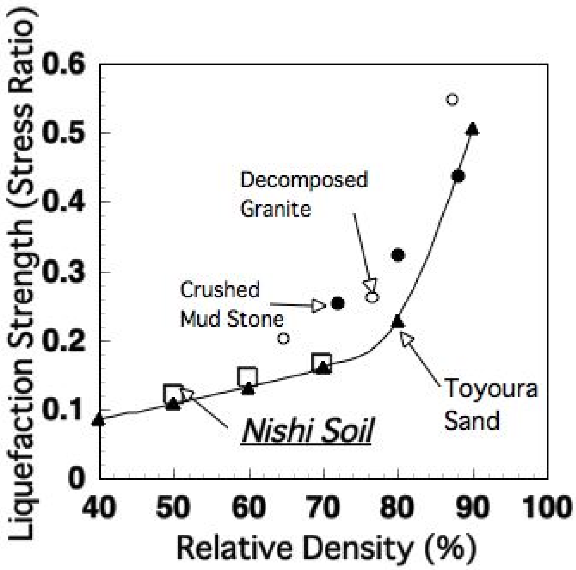

Fig.9 Increase of liquefaction strength with relative density for well graded coarse fill and clean sand.

The mechanism of liquefaction strength increase with increasing the relative density may be observed in Figs. 10 & 11. These two figures show the generation changes of pore water pressure with the application of repeated shear stress, and the changes of the stress-strain relationship for the specimens with the same shear stress ratio of 0.25 and with three states of relative densities, respectively. The specimen with lower relative density naturally shows higher generations of pore water pressure for the same level of shear stress as shown in Fig.10. On the other hand, the stress strain relationship at early stage of shearing does not change very significantly among the specimens with three different relative densities, as shown in Fig.11. Thus the difference of relative density seems to affect more on the compressibility characteristics of coarse soils with well graded characteristics.

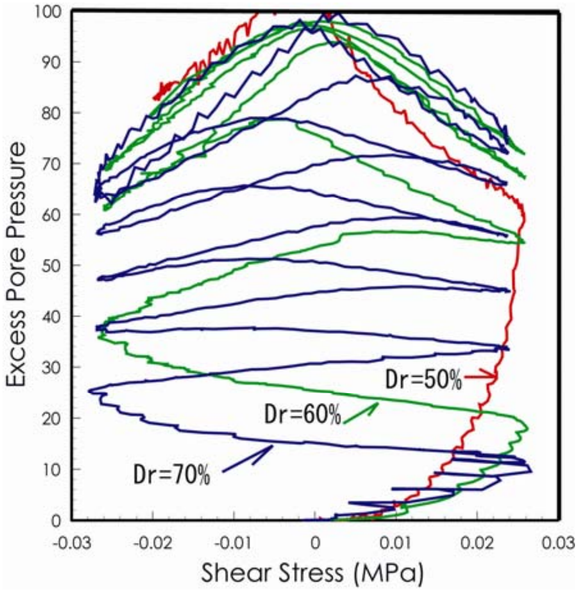

Fig.10 Generation changes of excess pore water pressure for the specimens with three different relative densities

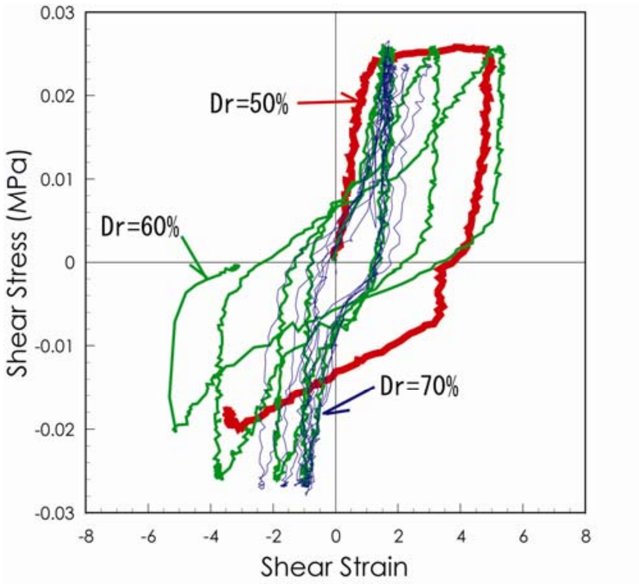

Fig.11 Changes of stress-strain curves for the specimens with three different relative densities

CONCLUSIONS

In this paper, the liquefaction strength curve of well graded coarse fill materials at three different relative densities, namely 50%, 60%, and 70%, have been obtained by performing a series of undrained cyclic shear tests using a large size hollow cylinder torsional test apparatus. The relative density of well graded coarse fill was defined based on the compaction test result. Also a correction of the liquefaction strength considering the effect of membrane penetration was made using a computer controlled device capable of correcting the effect during the test.

The test results indicate that the liquefaction strengths of well graded coarse fill materials are in good agreement with the strengths of Toyoura sand, a representative of clean sand, for the same relative density, provided that the relative density of the former materials be defined according to the method discussed above. There was however a distinctive difference in the deformation characteristics during the undrained cyclic shear and the shape of liquefaction strength curves between the well graded coarse fill materials and the clean sand.

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