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Cyclic Undrained Strength of Sand by Simple Shear Test and Triaxial Test Ⅰ (Test Procedures)

単純せん断試験と三軸試験による砂の動的非排水強度（Ⅰ）

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1. INTRODUCTION

At present, the easiest and the most popular method to evaluate undrained cyclic strength of sand is cyclic triaxial test with uniform loading (see Fig. 1 (a)). However, the stress condition of the sand sample in a cyclic triaxial test does not match in situ stress condition of level ground during earthquake motion as closely as does the stress condition in a simple shear test. The stress condition most similar to in situ condition is achieved in cyclic simple shear tests with random loading. Neverthless, this kind of testing is not popular because it is not easy to perform (see Table 1).

Therefore, to use test results by conventional cyclic triaxial test adequately for design purposes, it is first necessary to know the relationship between cyclic strength by cyclic triaxial test with unifrom loading and cyclic strength by cyclic simple shear test with random loading.

So far, several different types of cyclic undrained simple shear tests have been performed (Peacock and Seed (1968), Finn, Pickering and Bransby (1971), DeAlba, Seed and Chan (1976)). The horizontal stress was not measured in any of these tests, nor could it be controlled independently of the vertical stress. Therefore, it was difficult to compare directly the test results by cyclic simple shear tests with those of cyclic triaxial tests.

On the other hand, cyclic undrained torsional simple shear tests in which the horizontal stress could be controlled independently of the vertical stress have been performed by Ishihara and Li (1972) and Ishibashi and Sherif (1974). They used initial liquefaction as a failure eriteria and specimens of only one kind of density were tested. Recently, it has been recognized that initial liquefaction is not neccessarily a good criterion for failure especially for denser sands. Furthermore, methods of preparing samples have significant effects on cyclic undrained triaxial strengths as reported by Ladd (1974) and Mulilis et al. (1977). However, these effects have not been examined for cyclic undrained simple shear tests.

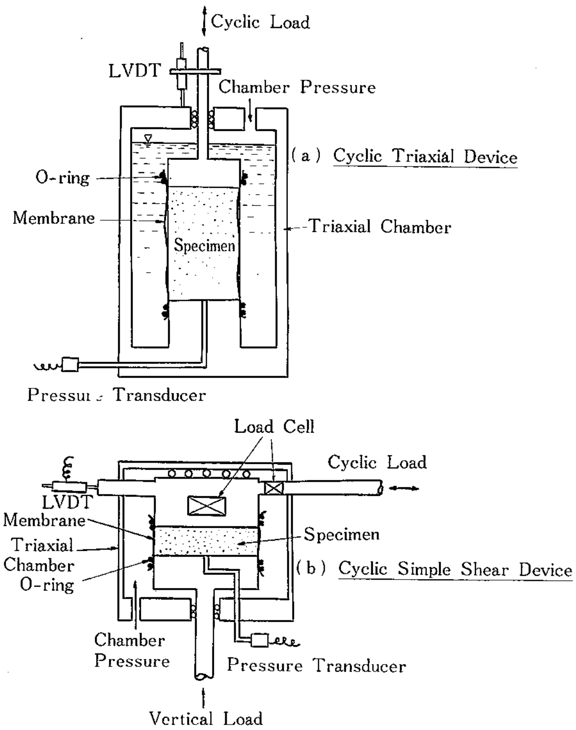

Fig. 1 Schematic Diagrams of Cyclic Triaxial Device and Cyclic Simple Shear Device at UICC.

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Table 1　Comparison among Different Laboratory Tests

	ADVANTAGE	DISADVANTAGE
CYCLIC TRIAXIAL TEST WITH UNIFORM LOADING	The most popular The easiest to perform	Not similar to in situ condition of level ground during earthquake motion
⇕		
CYCLIC SIMPLE SHEAR TEST WITH UNIFORM LOADING		
⇕		
CYCLIC SIMPLE SHEAR TEST WITH RANDOM LOADING	The most similar to in situ condition of level ground during earthquake motion	Not popular Not easy to perform

In this study, cyclic undrained simple shear tests in which the horizontal stress could be controlled independently of the vertical stress and could be measured were performed. In addition, specimens with a wide range of density prepared by two different methods were tested both for cyclic simple shear tests and for cyclic triaxial tests. A failure (liquefaction) criterion defined by double amplitude strain was adopted to analyze test data. It was found that while the effect of sample preparation method on cyclic undrained triaxial strength is significant, this was not the case for cyclic undrained simple shear strength.

2. TEST MATERIAL

Monterey No. 0 sand, a commercially available washed and sieved beach sand, was selected for this study. This is a uniform subround sand which has been widely used for liquefaction studies. The specific gravity of this sand is 2.65, the maximum void ratio is 0.85, the minimum void ratio is 0.56, the mean diameter D_{50} equals 0.36 mm and the coefficient of uniformity is about 1.5.

3. TEST PROGRAM

For cyclic undrained triaxial tests, four different relative densities were selected: 45%, 60%, 70% and 80% (see Table 2). For cyclic simple shear tests, three different relative densities were selected as 45%, 60% and 80%. Each sample was prepared so that the sample had specified relative density after consolidation.

To prepare specimens, two different sample preparation methods were adopted for both triaxial and simple shear tests, namely wet tamping and pluviation through air. The wet tamping method is a method of compacting moist coarse grain material in which the material is placed in layers with each layer compacted to a prescribed dry unit weight. The procedures are described in detail elsewhere (Ladd (1978)). This method was used by Silver et al. (1976) to define the cyclic triaxial strength of Monterey No. 0 sand by a cooperative soil testing program performed by eight organizations. On the other hand, it has been reported by Ladd (1974) and Mulilis et al. (1977) that sample preparation methods have a significant effect on cyclic undrained triaxial strength of sand. For this reason, the other method, pluviation through air was adopted to reconstitute specimens. The procedure consists of pluviating air dry sand into a mold from a tube keeping the height of falling constant. This method is described in detail elesewhere (Mulilis et al. (1977)). In this study, the diameter of the outlet tube was 4.4 cm. Pluviating air dry soil can be considered to be a better simulation of depositing soils in flooding of

Table 2　Test Program

	CYCLIC TRIAXIAL TEST	CYCLIC SIMPLE SHEAR TEST
RELAVIVE DENSITY (%)	45, 60, 70, 80	45, 60, 80
SAMPLE PREPARATION METHOD	WET TAMPING AND PLUVIATION THROUGH AIR	WET TAMPING AND PLUVIATION THROUGH AIR

Table 3　Sample Preparation, Sample Characteristics and Testing Procedure

	Wave form	Frequency in Herz	Loading equipment	Load cell	Piston seal	Stone for drainage	Specimen diameter in mm	Specimen hight in mm	Specimen made on cell	Wet tamping: Compaction layers	Wet tamping: Scarify	Wet tamping: Water content, %	Wet tamping: D tamper / D specimen
Cyclic Triaxial Test	Sine	1	Pneumatic	Outside of the cell	Air	Large Brass	61	153	yes	6	yes	8	0.5
Cyclic Simple Shear Test	Sine	0.5	Pneumatic	Inside of the cell	Bellows	Small Brass	70	20	yes	2	yes	8	0.5

	Membrane number	Membrane thickness in mm	Time to saturate	Back pressure, in kN/m²	Consolidation pressure in kN/m²	B-value
Cyclic Triaxial Test	2	0.30	3 hr	100	Isotropic, $\bar{\sigma}_c=100$	> 0.96
Cyclic Simple Shear Test	1	0.64	2 hr	100 or 200	Anisotropic $\bar{\sigma}_{v_c}=100$ $\bar{\sigma}_{h_c}=40$	> 0.96

rivers or in uncompacted hydraulic filling under water than tamping moist soil. Carbone dioxide was used to achieve high saturation easily for all specimens.

The test procedures for cyclic undrained triaxial tests in this study followed those suggested by Silver et al.(1976) as described in Table 3. The test procedure for cyclic simple shear tests adoped in this study will be described in detail in the next section.

4. CYCLIC UNDRAINED SIMPLE SHEAR TEST

The cyclic simple shear apparatus used in this study can provide a hydrostatic confining pressure to the vertical faces of a circular simple shear specimen by using a pressure chamber (Fig. 1). An unreinforced conventional rubber membrane was used to confiñe a specimen. With this equipment, it is possible to control the total horizontal stress during consolidation. Furthermore, by knowing both total horizontal stress and pore pressure, the effective horizontal stress can be easily calculated. This is a significant advantage over the NGI-type simple shear apparatus in which a reinforced membrane is used to enclose a specimen. A simple shear specimen has dimensions of 70 mm in diameter and 20 mm in height. Grains of Monterey No. 0 sand were glued to the surfaces of the top cap and the pedestal to develop sufficient seating for the sand. Specimen were first consolidated isotropically to $\bar{\sigma}_v=\bar{\sigma}_h\doteqdot 40$ kN/m² ($\bar{\sigma}_v$ is effective vertical stress and $\bar{\sigma}_h$ is effective horizontal stress). Then, effective vertical stress was increased to 100 kN/m². After consolidating a specimen under an anisotropic stress condition for 2 hours, a cyclic undrained test was performed. During a cyclic test, the pedestal was fixed to prevent any movement. Horizontal cyclic load was applied to the top cap which was guided horizontally so that it did not rotate and did not rock. During a cyclic test, total horizontal stress, which was hydrostatic stress, was kept constant. Since there was no vertical deformation in a specimen, total vertical stress was decreasing when the specimen was going to

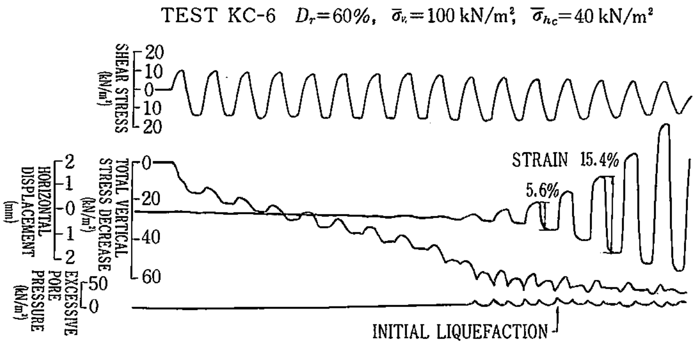

Fig. 2　Recorded Shear Stress, Total Vertical Stress Decrease, Horizontal Displacement, and Excessive Pore Pressure Time History for Wet Tamped Monterey No. 0 Sand (D_r= 60%, $\bar{\sigma}_{v_c}$=100 kN/m², $\bar{\sigma}_{h_c}$=40 kN/m²)

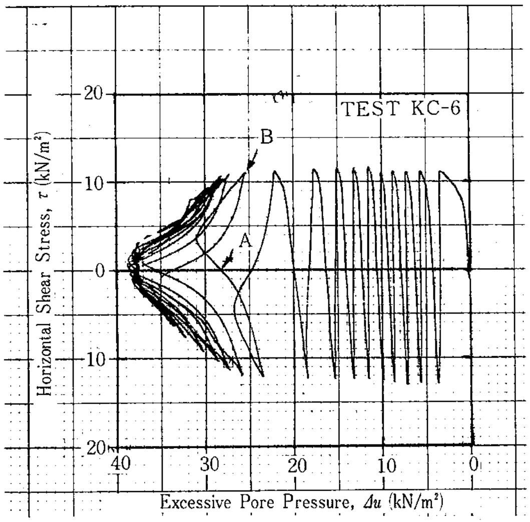

Fig. 3 Recorded Relationship between Shear Stress and Excessive Pore Pressure for Wet Tamped Monterey No. 0 Sand (see Fig. 2)

liquefy. This change in vertical load was measured with a rigid load cell placed just above the top cap. Testing procedures for simple shear testing are listed in Table 3.

During cyclic tests, both vertical strain and volumetic strain were zero. Therefore, horizontal strain can be considered zero during cyclic loading, similarly to in situ condition in level ground subjected to earthquake motion.

A typical time history of shear stress, total vertical stress decrease, horizontal displacement and excessive pore pressure obtained for a wet tamped specimen of $D_r = 60\%$ is shown in Fig. 2. Also the recorded relationshop between shear stress and excessive pore pressure for this test is shown in Fig. 3. It may be seen from Fig. 2 that under a constant horizontal cyclic shear stress, the total vertical stress decreases and the exessive pore pressure increases until cycle 11 where the excessive pore pressure equals the initial effective horizontal stress, namely 40 kN/m^2. In addition, it may be seen that at this moment the summation of excessive pore pressure and total vertical stress decrease equals the initial effective vertical stress, namely 100 kN/m^2, which is defined as initial liquefaction. Furthermore, it may be seen that fluctuation of excessive pore water pressure before initial liquefaction is very small. This phenomenon is very different from that in cyclic triaxial test. It may be also seen from Fig. 2 that very small cyclic deformations were induced in the specimen until approximately cycle 10, after which cyclic deformations were built up until 5.6% double amplitude shear strain was measured in cycle 12 and 15.4% double amplitude shear strain was measured in cycle 14. The form of this trace is typical of the results obtained in this study.

(to be continued)

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REFERENCE

1) DeAlba, P., Seed, H.B. and Chan, C.K. (1976), "Sand Liquefaction in Large-Scale-Simple Shear Tests," Journal of the GE Div., ASCE, Vol. 102, No. GT9, Proc. Paper 12403, Sept., pp. 909–927.
2) Finn, W.D.L., Pickering, D.J. and Bransby, P.L. (1971), "Sand Liquefaction in Triaxial and Simple Shear Tests," Journal of the SMF Div., ASCE, Vol. 97, No. SM4, Proc. Paper 8039, April, pp. 639–659.
3) Ishibashi, I. and Sherif, M.A. (1976), "Soil Liquefaction by Torsional Simple Shear Device," Journal of the GT Div., ASCE, Vol. 100, No. GT8, Proc. Paper 10752, Aug., pp. 871–888.
4) Ishihara, K. and Li, S. (1972), "Liquefaction of Saturated Sand in Triaxial Torsional Shear Test," Japanese Soils and Foundations, Vol. 12, No. 2, June, pp. 19–39.
5) Ishihara, K., Silver, M.L. and Kitagawa, H. (1978), "Cyclic Strength of Undisturbed Sands Obtained by Large Diameter Samplings," Japanese Soils and Foundation, Vol. 18, No. 4, Dec., pp. 61–76.
6) Ladd, R.S. (1974), "Specimen Preparation and Liquefaction of Sands," Journal of the GT Div., ASCE, Vol. 100, No. GT10, Proc. Paper 10857, Oct., pp. 1180–1184.
7) Ladd, R.S. (1978), "Preparing Test Specimens Using Undercompaction," Geotechnical Testing Journal, ASTM, Vol. 1, No. 1, pp. 16–23.
8) Mulilis, J.P., Seed, H.B., Chan, C.K., Mitchell, J. K. and Arulanandan, K. (1977), "Effects of Sample Preparation on Sand Liquefaction," Journal of the GT Div., ASCE, Vol. 103, No. GT2, Feb., pp. 91–108.
9) Peacock, W.H. and Seed, H.B. (1968), "Sand Liquefaction under Cyclic Loading Simple Shear Conditions," Journal of the SMF Div., ASCE, Vol. 94, No. SM3, May, Proc. Paper 5957, pp. 689–708.
10) Tatsuoka, F., Iwasaki, T., Tokida, K., Yasuda, S., Hirose, M., Imai, T. and Kon-no, M. (1978), "A Method for Estimating Undrained Cyclic Strength of Sandy Soils Using Standard Penetration Resistances," Japanese Soils and Foundations, Vol. 18, No. 3, Sept., pp. 43–58.