CYCLIC UNDRAINED STRENGTH OF SAND BY TRIAXIAL TEST AND SIMPLE SHEAR TEST

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SUMMARY

This paper describes the results of cyclic triaxial tests and cyclic simple shear tests performed on the same sand at the same initial conditions to compare the liquefaction behavior of sand tested using two different laboratory test procedures. The cyclic simple shear test equipment used in this study confined the specimen in a pressure chamber and thus the specimen could be back pressure saturated, pore pressure buildup could be measured, and the effective stress path could be calculated for any stage of the test. It was found that the cyclic strength of loose to medium dense simple shear and triaxial cohesionless specimens prepared by pluviation agreed well together when test results were normalized based on the mean effective consolidation stress and shear strain value. Unlike cyclic triaxial test results, different specimen preparation techniques had almost no effect on cyclic strength values from cyclic simple shear tests. Further, cyclic strength of specimens prepared by wet tamping methods was higher for triaxial tests than for simple shear tests even when compared at equivalent normalized stress and strain values.

INTRODUCTION

At present, the easiest and the most popular method used to evaluate the undrained cyclic strength of sand is the cyclic triaxial test with uniform periodic loading. However, the laboratory stress condition in a cyclic triaxial test does not match the in situ stress condition in level ground during earthquake motion. A better stress representation of in situ conditions is achieved in the laboratory cyclic simple shear test and 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). However, the horizontal stresses were not measured in any of these tests, nor could they be controlled independently of the vertical stress. Therefore, it has been difficult to compare directly test results obtained from cyclic simple shear tests with test results obtained from 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 criteria and specimens of one density value were tested. Such limited data makes a detailed comparison of cyclic triaxial and cyclic simple shear data difficult.

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Recently, moreover it has been recognized that initial liquefaction is not necessarily a good criterion for failure especially for denser sands. Furthermore, methods used to prepare samples have a significant effect on cyclic undrained triaxial strength as reported by Ladd (1974) and Mulilis, et al. (1977). However, these specimen preparation effects have not been examined for cyclic undrained simple shear tests.

In this study, cyclic undrained simple shear tests were performed in which the horizontal stress could be controlled independently of the vertical stress. In addition, specimens with a wide range of density values prepared by two different specimen preparation methods were tested to determine both cyclic simple shear strength and cyclic triaxial strength. A failure (liquefaction) criteria defined in terms of double amplitude strain was adopted to analyze the test data. The results of these tests are described in the following paragraphs.

TEST PROGRAM

Monterey No. 0 sand, a commercially available washed and sieved beach sand, was selected for this study. This is a uniform subrounded 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} is 0.36mm and the coefficient of uniformity is about 1.5.

For cyclic undrained triaxial tests, four different relative density values were selected: 45%, 60%, 70% and 80%. For cyclic simple shear tests, three different relative density values were selected: 45%, 60% and 80%. Each sample was prepared so that the sample had the specified relative density value after consolidation. To prepare specimens, two different sample preparation methods were adopted for both triaxial and simple shear tests: 1) wet tamping and 2) pluviation through air. The wet tamping method is a method of compacting moist coarse grained 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 by Ladd (1978). This metbod was used by Silver et al. (1976) to define the cyclic triaxial strength of Monterey No. 0 sand through a cooperative soil testing program performed by eight organizations. Because 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, the second preparation method, pluviation through air was also adopted to reconstitute specimens. The procedure consists of pluviating air dry sand into a mold from a tube keeping the height of fall constant. This method is described in detail by Mulilis, et al. (1977). Many consider that pluviation of sand through air or through water gives a better representation than wet tamping of the in situ soil fabric obtained by natural sand deposition such as from fluviation or from underwater hydraulic filling.

The cyclic simple shear apparatus used in this study provides a hydrostatic confining pressure to the vertical face of a circular simple shear specimen using a pressure chamber (Fig. 1). An unreinforced conventional rubber membrane was used to confine the specimen. With this equipment, it was possible to control the total horizontal stress during consolidation. Furthermore, by knowing both the total horizontal stress and the pore pressure, the effective horizontal stress could be easily calculated at any time during the test. This is a significant advantage over the NGI-type simple shear apparatus in which a reinforced membrane is used to enclose the specimen. The simple shear specimen was 70mm in diameter and 20mm high. Grains of Monterey No. 0 sand were glued to the surfaces of the top cap and to the bottom pedestal to prevent slippage of the sand.

Specimens were first consolidated isotropically to $\bar{\sigma}_v=\bar{\sigma}_h=40kN/m^2$ ($\bar{\sigma}_v$ is the effective vertical stress and $\bar{\sigma}_h$ is the effective horizontal stress). Then, the effective vertical stress was increased to $100kN/m^2$. After consolidating the specimen under this anisotropic stress condition for 2 hours, a cyclic undrained test was performed. During a cyclic test, the bottom pedestal was fixed so that it could not move vertically and horizontally, or rotate. Horizontal cyclic loads were applied to the top cap which was guided horizontally so that it did not rotate or rock. During a cyclic test, the total horizontal stress, which was the hydrostatic stress, was kept constant. Since no vertical deformation was possible, total vertical stress decreased when the specimen began to liquefy. This change in vertical load was measured with a rigid load cell placed just above the top cap. Since during the cyclic test, both the vertical strain and the volumetic strain were zero, the horizontal strain was also zero during cyclic loading. This is similar to the in situ condition in level ground during earthquake shaking.

Conventional laboratory test equipment was used for the cyclic triaxial tests described in this paper and generally accepted procedures were adopted for the test program (Silver, et al., 1976). Simple shear and triaxial test conditions are compared in Table 1.

SIMPLE SHEAR TEST RESULT

A typical time history of shear stress, total vertical stress decrease, horizontal displacement and excess pore pressure obtained for a wet tamped specimen at a relative density of 60% is shown in Fig. 2. For this test the initial effective vertical confining pressure, $\bar{\sigma}_{vc}$, was $100kN/m^2$ and the peak horizontal shear stress, τ, was $12.4kN/m^2$ giving a simple shear stress ratio, $\tau/\bar{\sigma}_{vc}$ of 0.124. It may be seen that under a constant periodic horizontal cyclic shear stress, the total vertical stress decreased and the excess pore pressure increased until cycle 11 where the excess pore pressure equaled the initial effective horizontal stress of $40kN/m^2$. In addition, it may be seen that in this cycle, the summation of the excess pore pressure and the total vertical stress decrease equaled the initial effective vertical stress ($100kN/m^2$). This state is defined as initial liquefaction. It may be also seen from Fig. 2 that very small cyclic deformations were induced in the specimen until approximately cyclc 10, after which cyclic deformations built up until 5.6% double amplitude shear strain was measured in cyclc 12 and 15.4% double amplitude shear strain was measured in cyclc 14. The form of this time history trace is typical of the other results obtained in this study.

The effective horizontal stress, $\bar{\sigma}_h$, during the cyclic undrained test equaled the constant cell pressure value minus the excess porepressure value. The value of effective vertical stress, $\bar{\sigma}_v$, during a test was obtained by subtracting both the excess porepressure and the total vertical stress decrease value from the initial effective vertical stress value, $\bar{\sigma}_{vc}$. Fig. 3 gives the time history of $\bar{\sigma}_v$ and $\bar{\sigma}_h$ calculated from the trace in Fig. 2 taken when the cyclic horizontal shear stress was zero (at the zero stress crossing). In Fig. 4 is shown the effective stress path in the terms of $\bar{\sigma}_v$ and $\bar{\sigma}_c$ when the cyclic horizontal shear stresses were zero and a maximum value. It can been seen from this figure that there is a unique effective stress path for simple shear loading irrespective of the value of shear stress. It can also be seen from this figure that this effective stress path is very similar to that obtained from a K_0 rebound test in which horizontal strain is zero while vertical stress decreases. The relationship between double amplitude shear strain, DA, in percent and the loading cycle, N_c, obtained from the data in Fig. 2 for $\tau/\bar{\sigma}_{vc}$=0.124 is replotted in Fig. 5. Noted on the figure are the numbers of cycles required to reach double amplitude strain values of 1.5%, 3%, 7.5% and 15%. It may be seen from the figure that strain buildup was rapid after some number of loading cycles. Similar plots for other data from tests performed at different test conditions were also obtained.

COMPARISON OF SIMPLE SHEAR AND TRIAXIAL TEST RESULTS

Test results obtained from undrained triaxial tests and simple shear tests both for wet tamped specimens and for pluviated specimens were compared at equivalent stress values and at equivalent strain values in the following way. Cyclic triaxial test results were normalized using the conventional stress ratio $\sigma_{dp}/2\bar{\sigma}_c$ in which σ_{dp} is the maximum single amplitude axial stress and $\bar{\sigma}_c$ is the initial effective isotropic consolidation stress. Cyclic simple shear test results were normalized using the stress ratio $\tau/\bar{\sigma}_{mc}$, in which τ is the maximum single amplitude horizontal shear stress and $\bar{\sigma}_{mc}$ is the initial mean consolidation principal stress which equals $(\bar{\sigma}_{vc}+2\bar{\sigma}_{hc})/3$. This simple shear normalization was suggested by Ishihara and Li (1972) and by Ishibashi and Sherif (1974). It is important to note that $\sigma_{dp}/2$ and τ are the maximum cyclic shear stress values induced in the specimens for cyclic triaxial tests and for cyclic simple shear tests, respectively. In addition, $\bar{\sigma}_c$ and $\bar{\sigma}_{mc}=(\bar{\sigma}_{vc}+2\bar{\sigma}_{hc})/3$ are the mean principal stress values during consolidation for cyclic triaxial tests and for cyclic simple shear tests respectively. It can be shown that shear strain values are 1.5 times axial strain values in cyclic undrained triaxial tests. Therefore, the number of loading cycles for a specified double amplitude axial strain in a cyclic triaxial test were compared with the number of loading cycles for 1.5 times the measured double amplitude shear strain in a cyclic simple shear test (ie, 10% double amplitude strain in cyclic triaxial tests was equivalent to 15% double amplitude strain in cyclic simple shear tests).

Cyclic triaxial and cyclic simple shear test results for specimens compacted to a relative density of 60% are summarized in Fig. 6 for a double amplitude shear strain of 15% in simple shear tests and for a double amplitude axial strain of 10% in triaxial shear tests. It can be seen in both figures that the cyclic triaxial undrained strength obtained for wet tamped specimens was significantly larger than the strength obtained for specimens which were prepared by pluviating through air. It can also be seen that there was no significant difference in cyclic undrained simple shear strength between wet tamped specimens and pluviated specimens. Since the number of different sample preparation methods examined was rather limited, a general conclusion about the effect of sample preparation on cyclic undrained simple shear strength can not be derived from the test results reported in this paper. However, it seems apparent that the effect of sample preparation on cyclic undrained simple shear strength is less than the effects of sample preparation on cyclic undrained triaxial strength. Finally, it can be seen from these figures that there was not a significant difference between cyclic undrained simple shear strength of wet tamped and pluviated specimens in terms of the simple shear stress ratio $\tau/\bar{\sigma}_{mc}$ and the cyclic undrained triaxial strength of pluviated specimen in terms of the triaxial stress ratio $\sigma_{dp}/2\overline{\sigma}_c$.

Fig. 7 shows the relationship for simple shear and triaxial cyclic strength versus relative density for failure defined as 15% double amplitude shear strain in the tenth loading cycle. It is clear in the figure that the ratio of cyclic triaxial strength for wet tamped specimens and for air-pluviated specimens increases with an increase in relative density. It can further be seen that the difference in cyclic undrained simple shear strength between wet tamped specimens and air-pluviated specimens is negligible for relative density values ranging from 45% to 80%. It is further shown in Fig. 7 that, except for relative densities greater than D_r=80%, the difference between cyclic triaxial strength and cyclic simple shear strength is not significant for pluviated specimens.

The data obtained from this study shows that the relationship between cyclic undrained triaxial strength and cyclic undrained simple shear strength may not be as simple as suggested in previous papers (Peacock and Seed, 1968; Finn, et al., 1970; Ishihara and Li, 1972; Seed and Peacock, 1971, and Seed, 1979). The relationship between cyclic triaxial and simple shear strength is apparently a function of sample preparation method, density, failure definition, the number of loading cycles and probably other factors.

CONCLUSIONS

The following conclusions were drawn from the results of this test program:

1) In triaxial tests, specimens prepared by compacting moist sand showed significantly greater resistance to cyclic undrained shear than specimens prepared by air pluviation. However, in simple shear tests, specimens prepared by wet tamping and air pluviation showed negligible strength differences. Therefore, the ratio of cyclic undrained strength under simple shear test conditions to cyclic undrained strength under triaxial test conditions is significantly affected by the sample preparation method.

2) It was also found that for loose to medium specimens prepared by air pluviation, cyclic undrained simple shear strength values were almost identical to cyclic undrained triaxial strength values when strength comparisons were made using a stress ratio defined as the maximum cyclic shear stress devided by the mean effective principal stress at consolidation.

3) These results showed that the cyclic undrained triaxial strength of sand prepared by tamping moist soil may give an overestimate of the liquefaction strength in horizontal sand deposits for which a laboratory simple shear simulation is an appropriate measure of cyclic strength.

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Table 1. Sample Preparation, Sample Characteristics and Testing Procedure for Cyclic Triaxial and Cyclic Simple Shear Tests

	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
CYCLIC TRIAXIAL TEST (CTX)	Sine	1	Pneumatic	Outside the cell	Air	Large Brass	61	153	yes
CYCLIC SIMPLE SHEAR TEST(CSS)	Sine	0.5	Pneumatic	Inside the cell	Bellofram	Small Brass	70	20	yes

	Wet tamping				Membrane, number	Membrane total thickness in mm	Time to saturate	Back pressure, in kN/m^2	Consolidation pressure, in kN/m^2	B-value
	Compaction layers	Scanfy	Water content, %	D tamper / D specimen						
CTX	6	yes	8	0.5	2	0.61	3hr	100	isotropic, $\bar{\sigma}_c$=100	>0.96
CSS	2	yes	8	0.5	1	0.64	2hr	100 or 200	anisotropic $\bar{\sigma}_{vc}$=100 $\bar{\sigma}_{hc}$= 40	>0.96

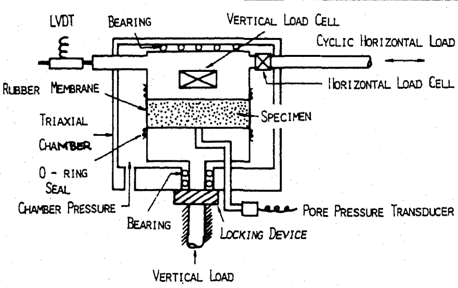

Fig. 1 Schematic Diagram of Cyclic Simple Shear Device

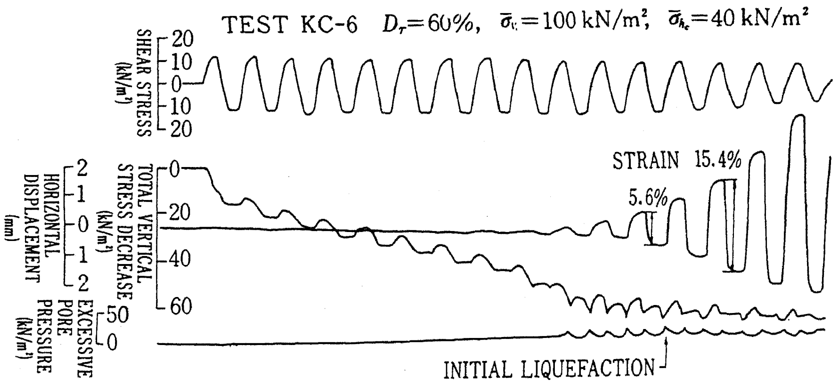

Fig. 2 Time History of Shear Stress, Total Vertical Stress Decrease, Horizontal Displacement, and Excess Pore Pressure for Wet Tamped Monterey No. 0 Sand (D_r=60%, $\overline{\sigma}_{vc}$=100kN/m^2, $\overline{\sigma}_{hc}$=40kN/m^2)

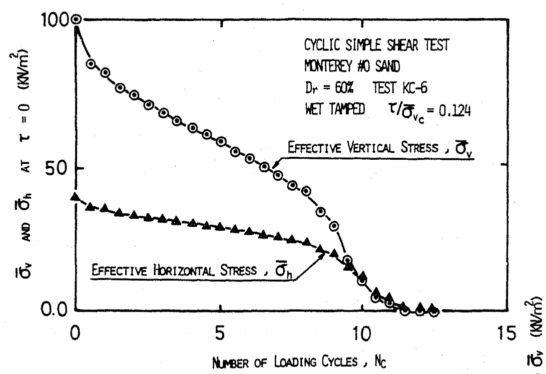

Fig. 3 Relationships between Effective Vertical Stress $\overline{\sigma}_{vc}$, Effective Horizontal Stress $\overline{\sigma}_{hc}$, and Number of Loading Cycles for Wet Tamped Monterey No. 0 Sand at D_r=60%

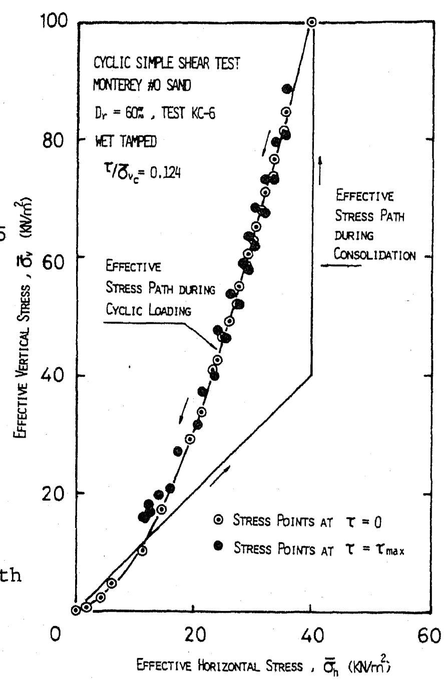

Fig. 4 Effective Stress Path for Wet Tamped Monterey No. 0 Sand at D_r=60%

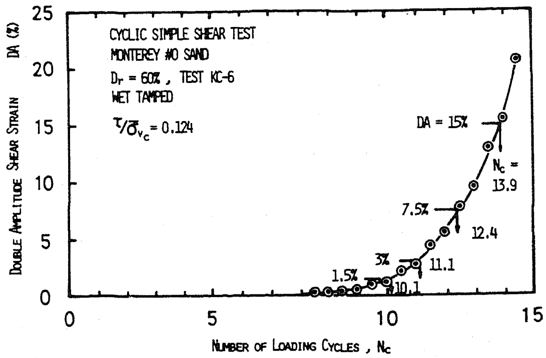

Fig. 5 Relationship between Double Amplitude Shear Strain and Number of Loading Cycles for Wet Tamped Monterey No. 0 Sand at D_r=60%

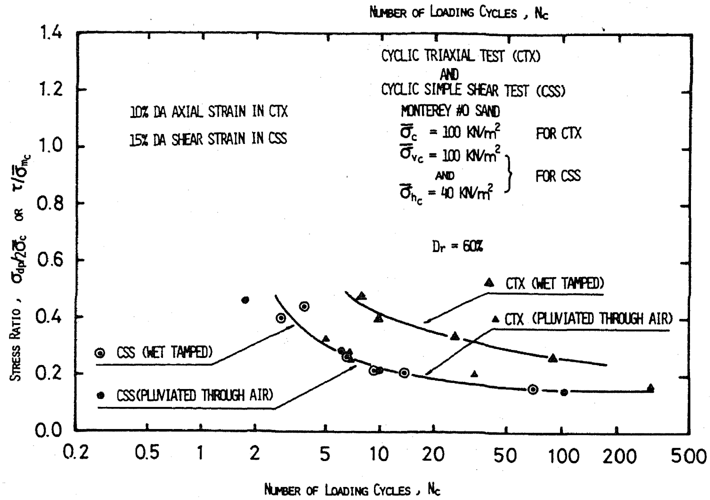

Fig. 6 Stress Ratio Versus Number of Loading Cycles to 15% Double Amplitude Strain for Wet Tamped and Air-Pluviated Monterey No. 0 Sand at D_r=60%

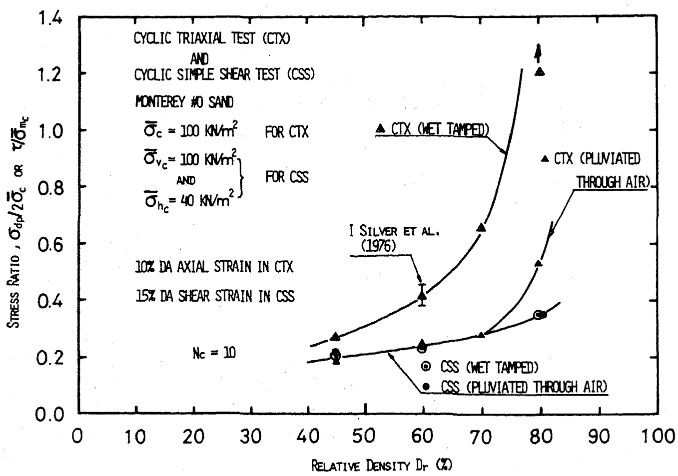

Fig. 7 Stress Ratio Versus Relative Density for Failure Defined as 15% Double Amplitude Shear Strain in the Tenth Loading Cycle for Wet Tamped and Air-Pluviated Monterey No. 0 Sand