CYCLIC UNDRAINED SIMPLE SHEAR STRENGTH OF SANDS AFFECTED BY SPECIMEN PREPARATION METHODS

by

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ABSTRACT

The effects of specimen preparation methods on cyclic undrained simple shear strength were investigated using two kinds of sand. It was found that even for an identical density, cyclic undrained simple shear strengths of the sands are significantly affected by the specimen preparation methods employed in this study. The test results show that the effects are larger for denser sands and also for smaller numbers of loading cycles. It was also found that the effects of specimen preparation methods on cyclic undrained strength are different between for cyclic simple shear tests and for cyclic triaxial tests. Therefore, the relationship between simple shear strength and triaxial strength is affected by the specimen preparation method. This fact seems to indicate that to estimate simple shear strengths from triaxial strengths, the manner in which the sand layer was constituted should be properly taken into account.

INTRODUCTION

It has been planned to construct a highway acrossing Tokyo Bay which consists of those two suspension bridges which will be extented from the both inlands sides. These two bridges will be connected to a submerged tunnel through two huge man-made islands. These man-made islands will be constructed in the central part of Tokyo Bay. It is considered that the islands will be constructed on a thick very soft clay layer of around 30m thick which will be improved by the deep mixing method. In this method, soft clay layers are mixed with some amount of cement. The islands will be around 30m in thickness and 250m × 1,200m at their bottoms and 100m × 500m at their tops. To evaluate the seismic stability of the islands which will be made under water using sand, it is essential to know the cyclic undrained strength of the sand. The sand material will be transported from a nearby inland site using ships and then will be threw away from the ships into water. This sand material will be compacted by the sand compaction pile method (Nakayama, et al. (1973)) or other adequate methods. The sand mass will be compacted so that the sand mass after compaction has an enough resistance against design earthquake loadings.

It is widely considered that a laboratory simple shear simulation is a more appropriate measure of cyclic strength than a triaxial simulation for usual horizontal sand deposits or sand slopes under the plane strain condition. A series of cyclic torsional simple shear test on Sengenyama Sand

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which will be used for contructing the islands has been performed at Institute of Industrial Science, University of Tokyo. A part of the test results has been reported by Muramatsu and Tatsuoka (1981) and Tatsuoka, Muramatsu and Sasaki (1982).

On the other hand, it has been shown that specimen preparation methods have significant effects on the relationship between cyclic undrained triaxial strength and density (or relative density), as typically shown in Fig. 1. However, it is only little known whether specimen preparation methods can significantly affect cyclic undrained torsional simple shear strength of sand. Therefore, it is apparantly necessary to know well how specimen preparation methods affect simple shear undrained strength by laboratory tests to estimate in situ undrained strength in the simple shear condition before the construction. In this investigation, several different specimen preparation methods were employed to reconstitute torsional simple shear specimens. In addition to Sengenyama Sand, Toyoura Sand was also used since other comprehensive cyclic undrained tests on Toyoura Sand have been performed and comparable data of Toyoura Sand were available. It was found that the effects of specimen preparation method is larger for denser specimens and also that the specimen preparation methods affect cyclic undrained torsional simple strength of sands in a quite different manner from the case of cyclic undrained triaxial strength.

TEST PROGRAM

The physical properties of the sands used are listed in Table 1. Four different specimen preparation methods were adopted to prepare torsional simple shear hollow cylindrical specimens (see Table 2). The specimens were 10cm high, 10cm in outer diameter and 6cm in inner diameter.

The air pluviation method consists of pluviating air dry sand into a mold from a tube keeping the height of fall constant. Different density values can be obtained by changing the height of fall. It can be considered that the fabric of a specimen produced by this method is somewhat similar to that in sand deposits formed by free falling of sand particles through air or water.

The wet tamping method is a method of compacting moist coarse grained material in which the material is placed in layers with each layer comacted to a prescribed dry unit weight. In this study, the density of each layer was controlled by adjusting the number of tamping with a constant free fall of 3.5cm. The diameter of the tamping foot was 16.45mm and the weight of the tamper was 189.5g. The number of compaction layers was six for Toyoura Sand and ten for Sengenyama Sand. The water content at tamping was 3% for Toyoura Sand and 8% for Sengenyama Sand. This specimen preparation method was adopted to simulate the field compaction procedure of moist sand layer by vertical tamping on the ground surface.

In the wet vibration method employed in this study, the prescribed amount of Toyoura Sand with a water content of 3% or Sengenyama Sand with a water content of 8% was placed gently in a mold for each layer. Then, a hollow cylindrically shaped weight of 1.43kg was placed on the sand surface. Each layer was compacted by tapping the mold with a wooden hammer uniformly around the mold surface until the height of the layer was reduced to a prescribed value. The number of compaction layers was five or ten for Toyoura Sand and ten for Sengenyama Sand. As will be shown later, no differences in cyclic strength values were found between five-layered specimens and ten-layered specimens for Toyoura Sand. The fabric in test specimens produced by this method may be similar to that formed in field unsaturated sand layers compacted by vibration.

The water-vibration method was adopted only for Sengenyama Sand. The prescribed amount of the sand was poured through water in one layer. After placing the hollow cylindrical shaped weight which was used in the wet vibration method on the sand surface, the specimen was compacted underwater by tapping the mold uniformly with a wooden hammer until the height of the specimen was reduced to a prescribed value. The water vibration method was employed as a simulation of in situ vibrational compaction procedures for submerged sand layers.

In the wet tamping and wet vibration methods, the compacted surface of each layer was scarified before placing the next layer. After being saturated, a test specimen was consolidated isotropically or anisotropically. Most of the specimens of Toyoura Sand were consolidated isotropically to $\sigma'_{vc} = \sigma'_{hc} = 98\ kN/m^2$, where σ'_{vc} and σ'_{hc} are the effective vertical and horizontal stresses at consolidation, respectively. Eleven air-pluviated Toyoura Sand specimens were consolidated with the ratio of σ'_{hc} to σ'_{vc} being equal to the K_0-values. The K_0-values of air-pluviated Toyoura Sand have been estimated to be equal to $0.52e_i$, where e_i is the initial void ratio before consolidation (Oh-kochi, et al. (1981)). The values of σ'_{vc} and σ'_{hc} were adjusted so that the mean principal stress $\sigma'_{mc} = (\sigma'_{vc} + 2\sigma'_{hc})/3$ equaled $98kN/m^2$. All the Sengenyama Sand specimens were firstly consolidated isotropically to $\sigma'_{v} = \sigma'_{hc} = 98\ kN/m^2$ and then, the value of σ'_{v} was increased to $\sigma'_{vc} = 196\ kN/m^2$. Thus, the ratio of σ'_{hc} to σ'_{vc} was 0.5 for any density value. Two triaxial K_0-consolidation tests on saturated air-pluviated Sengenyama Sand were performed using specimens of 7.5cm in diameter and 15cm in height. The K_0 values for specimens of relative density values of 60% and 80% were 0.47 and 0.44, respectively. Therefore, it seems reasonable to consider that the consolidation stress condition of $\sigma'_{hc}/\sigma'_{vc} = 0.5$ is very similar to the K_0-consolidation stress condition.

Except ten specimens, cyclic undrained torsional simple shear tests were performed with allowing the vertical displacement of the specimens to take place freely under a constant value of the total vertical stress for the isotropically consolidated Toyoura Sand specimens. This kind of testing will be called "unclamped" tests. The other ten specimens of air-pluviated Toyoura Sand were tested without allowing vertical displacement in the specimens to know the effects of vertical movement on the cyclic undrained strengths of the isotropically consolidated specimens. This kind of testing will be called "clamped" tests. "Clamped" tests were performed for all of the anisotropically consolidated specimens. It is to be noted that during this kind of test, the cross-sectional area of the specimen is kept constant due to no variations in both its height and volume. This condition can be considered very similar to the plane strain simple shear deformation case. Therefore, this kind of torsional simple shear test can be considered to be one of the best simulations of the stress-strain condition in level ground during earthquakes. All the cyclic torsional simple shear tests were performed with a frequency of 0.5Hz.

TEST RESULTS FOR TOYOURA SAND

In Fig. 2 are shown the relationships between relative density and number of loading cycles where a double amplitude shear strain of 15% was observed for several values of cyclic stress ratio τ_{cy}/σ'_{mc}, where τ_{cy} means the single amplitude cyclic shear stress. These results were obtained from the tests on isotropically consolidated wet vibrated specimens. It can be seen from this figure that the number of compaction layers, five or ten, had negligible effects on the test results. From the relationships shown in Fig. 3, the relationships between stress ratio τ_{cy}/σ'_{mc} and number of loading cycles where 15% double amplitude shear strains were observed were obtained as shown in Fig. 3. Similar relationships for air-pluviated and wet tamped specimens are shown in Figs. 4 and 5. By comparing these figures, it can be clearly seen that the specimen preparation methods employed in this study have significant effects on torsional simple shear strength as on triaxial strengths.

To see the effects of specimen preparation methods on cyclic undrained strength more in detail, strength curves for these specimen preparation methods were compared directly as in Figs. 6 and 7. It can be seen from Fig. 6 that for failure defined for double amplitude shear strain values of 3%, 7.5% and 15% air-pluviated and wet tamped specimens have almost similar strengths, while wet vibrated specimens have considerably larger strengths than the other two kinds of specimens. Similar results for a relative density of 75% are shown in Fig. 7. It can be noted that for this case wet tamped specimens have larger strengths than air-pluviated specimens for the smaller number of cycles. It can be seen from these figures that the effects of specimen preparation methods on cyclic undrained strength are more significant for smaller number of loading cycles, for denser specimens and for larger values of shear strain amplitude.

In Fig. 8 are shown the relationships between cyclic stress ratin and double amplitude shear strain values observed in the tenth cycle. It can be seen that the effects of specimen preparation methods on cyclic undrained strength of Toyoura Sand are more pronounced for larger shear strain values. The test results are further compared in Figs. 9(a) and 9(b), in which are shown the relationships between relative density and cyclic strength defined for a double amplitude shear strain of 15% observed in the tenth cycle or in the twentieth cycle, respectively. It is clearly seen that the differences among the cyclic undrained strengths of Toyoura Sand specimens prepared by the three different methods increase with an increase in density.

It is to be noted that the specimen preparation methods affect the cyclic undrained strength of Toyoura Sand in the torsional simple shear test case in a different manner from in the triaxial test case. For air-pluviated and wet tamped specimens of Toyoura Sand, torsional simple shear strengths are compared with triaxial strengths for failure defined for 15% double amplitude shear strain in the tenth cycle in Fig. 10. It can be seen that for loose to medium dense specimens, the two different specimen preparation methods have negligible effects on torsional simple shear strength, while these have significant effects on triaxial strength. Some quantitative comparisons between torsional simple shear strength and triaxial strength for an identical specimen preparation method will be given later.

TEST RESULTS FOR SENGENYAMA SAND

The test results obtained for the Sengenyama Sand specimens reconstituted by the four different specimen preparation methods are summarized in Figs. 11 through 16 as for the Toyoura Sand specimens. It can also be seen from these figures that the specimen preparation methods have also significant effects on the cyclic undrained shear strength of Sengenyama Sand, especially for denser specimens. Fig. 16 shows the effects of specimen preparation methods on the relationship between stress ratio and double amplitude shear strain induced in the tenth or twentieth cycles. It can be seen that the specimen preparation methods have similar effects on cyclic undrained strength of Sengenyama Sand defined for a wide range of shear strain amplitude. This was not the case for Toyoura Sand of D_r = 75 % as shown in Fig. 8(b). Reasons for this difference are not known to the present authors.

Figs. 17(a) and (b) show the relationships between stress ratio and relative density for a double amplitude shear strain of 15% at N_c = 10 and N_c = 20. It can be clearly seen that the air-pluviation method provides the smallest cyclic undrained simple shear strength among the four specimen preparation methods employed in this study. Therefore, it is likely that the cyclic undrained simple shear strength of air-pluviated specimen reported in this paper is an underestimate for sand deposited densified by some compaction procedures. This situation is schematically illustrated in Fig. 18. Assume that the point A in Fig. 18 represents the condition just after filling by pluviation through water and the curve a-a' is the strength curve for water-pluviated sand. It seems that the cyclic undrained strength of saturated sand may be increased by compaction due to (i) an increase in density, (ii) an increase in K_0-value, and (iii) a change in the fabric. If needed, an increase in strength due to long-term time effects is also to be taken into account. The point B in Fig. 18 represents the condition after compaction. The test results presented in this paper show that there may be an increase in strength by compaction due to other factors than increases in density and K_0-value by compaction. One of these factors may be such a change in the fabric that contacts between sand grains become more stable during compaction.

COMPARISONS OF SIMPLE SHEAR STRENGTH WITH TRIAXIAL STRENGTH

Fig. 10 shows comparisons of torsional simple shear strength by unclamped tests on isotropically consolidated specimens ($K_c = \sigma'_{hc}/\sigma'_{vc}$ = 1.0) with triaxial strengths for two specimen preparation methods. It is clearly seen that the simple shear strength of air-pluviated specimens is larger than the triaxial strength, while the simple shear strength of wet tamped specimens is smaller than the triaxial strength. This fact may indicate that cyclic triaxial test results may overestimate the simple shear strength in some cases and may underestimate the simple shear strength in some cases.

Note that there will be several factors to be taken into account for quantitative comparisons between torsional simple shear strength and triaxial strength. A series of torsional simple shear tests and triaxial tests was performed for air-pluviated Toyoura Sand to find these factors. Fig. 19 shows the effects of consolidation stress condition and strain condition on torsional simple shear strength. Note that for any case shown in Fig. 19 the amplitude cyclic shear stress τ_{cy} is normalized by the mean principal stress at consolidation σ'_{mc}, which is equal to both σ'_{vc} and σ'_{hc} for isotropically consolidated specimens and is equal to $(1 + 2K_0)\sigma'_{vc}/3$ for anisotropically consolidated specimens. It has been shown by Ishihara and Li(1972) that this normalization method gave similar cyclic undrained torsional simple shear strength values irrespectively of the stress ratio values $K_c = \sigma'_{vc}/\sigma'_{hc}$ at consolidation for loose Fuji River Sand of D_r = 55%. This was also the case for loose to medium dense Toyoura Sand in this study. However, it can be clearly seen that the plane strain strengths of dense K_0-consolidated Toyoura Sand specimens are considerably larger than those of isotropically consolidated specimens which were obtained by both "clamped" and "unclamped" tests. Therefore, it seems that the normalization method as τ_{cy}/σ'_{mc} is not be appropriate for dense sands and the equation

$$\left(\frac{\tau_{cy}}{\sigma'_{mc}}\right)_{K_0} > \left(\frac{\tau_{cy}}{\sigma'_{mc}}\right)_{I} \qquad (1)$$

is valid for dense sands. The subscripts K_0 and I means normal K_0-consolidation and isotropical consolidation, respectively.

When the simple shear strength is expressed by the ratio of cyclic shear stress complitude to initial effective vertical stress τ_{cy}/σ'_{vc}, the equations:

$$(\tau_{cy}/\sigma'_{vc})_{K_0} > \frac{1 + 2K_0}{3}\left(\frac{\tau_{cy}}{\sigma'_{vc}}\right)_I \tag{2}$$

and

$$(\tau_{cy}/\sigma'_{vc})_I < \frac{3}{1 + 2K_0}\left(\frac{\tau_{cy}}{\sigma'_{vc}}\right)_{K_0} \tag{3}$$

can be easily derived from Eq. (1). Eq. (2) implies that the strength for normally K_0-consolidated dense specimen $(\tau_{cy}/\sigma'_{vc})_{K_0}$ is underestimated when estimated as $((1 + 2K_0)/3)(\tau_{cy}/\sigma'_{vc})_I$. Therefore, the equation:

$$(\tau_{cy}/\sigma'_{vc})_{K_0} = \frac{1 + 2K_0}{3}\left(\frac{\tau_{cy}}{\sigma'_{vc}}\right)_I \tag{4}$$

can be used for conservative and safe estimation of the value of $(\tau_{cy}/\sigma'_{vc})_{K_0}$. Note that it is experimentally much easier to obtain the value of $(\tau_{cy}/\sigma'_{vc})_I$ than the value of $(\tau_{cy}/\sigma'_{vc})_{K_0}$. It is considered that the coefficient of earth pressure at rest is increased from its original value of K_0 to a larger value of K'_0 by field compaction procedures. It is reasonable to consider that the strength for the value K'_0 is also conservatively and safely estimated by the equation:

$$(\tau_{cy}/\sigma'_{vc})_{K'_0} = \frac{1 + 2K'_0}{3}\left(\frac{\tau_{cy}}{\sigma'_{vc}}\right)_I \tag{5}$$

On the other hand, Eq. (3) suggests that the values of $(\tau_{cy}/\sigma'_{vc})_I$ and $(\tau_{cy}/\sigma'_{vc})_{K'_0}$ are overestimated for dense sands by the equations:

$$(\tau_{cy}/\sigma'_{vc})_I = \frac{3}{1 + 2K_0}\left(\frac{\tau_{cy}}{\sigma'_{vc}}\right)_{K_0} \tag{6}$$

and

$$(\tau_{cy}/\sigma'_{vc})_{K'_0} = \frac{1 + 2K'_0}{1 + 2K_0}\left(\frac{\tau_{cy}}{\sigma'_{vc}}\right)_{K_0} \tag{7}$$

Note that Eqs. (6) and (7) are same when $K'_0 = 1$. It is shown in Fig. 20 that for the case of $K'_0 = 1.0$, the strength estimated by Eq. (6) or Eq. (7) is considerably larger than the strength measured for isotropically consolidated specimens ($K_c = K'_0 = 1.0$), especially for dense specimens.

It has been found by another test program performed in the Geotechnical Laboratory of the Institute of Industrial Science, the University of Tokyo that the cyclic undrained triaxial strength by tests with lubricated ends is larger than that by tests with regular ends of conventional porous stones, especially for dense specimens. A part of these test results is shown in Fig. 21. It can be seen from Fig. 21 that even the cyclic triaxial strength obtained from tests with lubricated ends are considerably less than the cyclic undrained strength by plane strain torsional simple shear tests on K_0-consolidated specimens expressed by the normalized stress ratio τ_{cy}/σ'_{mc}. Thus, the following relationship may be valid for air-pluviated sands:

$$\left(\frac{\tau_{cy}}{\sigma'_{vc}}\right)_{K_0} > \frac{1 + 2K_0}{3}\left(\frac{\sigma_{dp}}{2\sigma'_c}\right)_L > \frac{1 + 2K_0}{3}\left(\frac{\sigma_{dp}}{2\sigma'_c}\right)_R \qquad (8)$$

in which $(\sigma_{dp}/2\sigma'_c)_L$ and $(\sigma_{dp}/2\sigma'_c)_R$ are the cyclic undrained triaxial strengths with lubricated ends and regular ends, respectively. Therefore, it seems that the in situ cyclic undrained strength may be significantly underestimated if estimated as $(1 + 2K_0)/3\cdot(\sigma_{dp}/2\sigma'_c)_R$ for the cases where the plane strain torsional simple shear simulation is appropriate. In particular, a larger underestimate may be obtained for denser sands. For specimens reconstituted by other sample preparation methods, relationships different from those shown in Fig. 21 may be obtained. Further investigations are necessary in this respect.

CONCLUSIONS

On the basis of a limited number of the tests performed in this study, the following conclusions can be derived:

(1) The cyclic undrained simple shear strength can also be significantly affected by specimen preparation methods. Among the different specimen preparation methods employed in this study, the wet vibration method provided the strongest specimens against cyclic undrained loading, while the air-pluviation method provided the weakest specimens. The water-vibration and wet tamping methods provided the specimens which had intermediate strengths.

(2) The effects of specimen preparation methods on cyclic undrained simple shear strength increased with an increase in density and with a decrease in number of loading cycles. For dense Toyoura Sand, the effects increased with an increase in shear strain amplitude.

(3) The effects of specimen preparation methods on cyclic undrained strength in triaxial tests are different from those in torsional simple shear tests. Therefore, the relationship between the triaxial strength and the torsional simple shear strength is affected by specimen preparation methods.

(4) It was also found that to estimate the simple shear strength from the triaxial strength, it is necessary to taken into account those several factors other than the effects of specimen preparation methods; which are the effects of stress ratio $\sigma'_{vc}/\sigma'_{hc}$ during consolidation in torsional simple shear tests and end conditions in triaxial tests (regular or lubricated ends).

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Table 1. Physical Properties of Sands Used

	Sengenyama Sand	Toyoura Sand	Monterey No.0 Sand
Particle Shape	Sub-Angular	Angular	Sub-Round
Specific Gravity, G_s	2.71	2.64	2.65
Maximum Void Ratio, e_{max}*	0.918	0.977	0.847**
Minimum Void Ratio, e_{min}*	0.564	0.605	0.526**
Mean Diameter, D_{50}, in mm	0.23	0.162	0.36
Coefficient of Uniformity, U_c	2.87	1.46	1.5
Fine Content in percent	1.63	0	0

* by the method proposed by the Japanese Society of Soil Mechanics and Foundation Engineerings (1980).

** The values of e_{max} and e_{min} reported by Silver, et al (1976) are 0.85 and 0.56, respectively.

Table 2. List of Cyclic Torsional Simple Shear Tests

Sand	Specimen Preparation Method	σ'_{vc} (kN/m^2)	σ'_{hc} (kN/m^2)	Free Vertical Movement during Cyclic Loading	Number of Specimens Tested	Reference
Toyoura	Air-Pluviation	98	98	yes	30	*
				no	10	
		σ'_{mc} = 98, $\sigma'_{hc}/\sigma'_{vc}$ = $0.52e_i$		no	11	**
	Wet Tamping	98	98	yes	12	
	Wet Vibration				31	This Study
Sengenyama	Air-Pluviation	196	98	no	17	*, **
	Wet Tamping				18	
	Wet Vibration				17	This Study
	Water-Vibration				18	

* Muramatsu and Tatsuoka (1981)

** Tatsuoka, Muramatsu and Sasaki (1982)

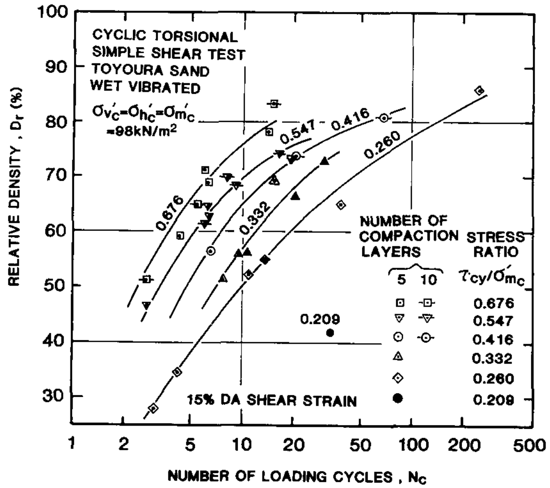


Fig.2 Relationship between Relative Density and Number of Loading Cycles to 15% Double Amplitude Shear Strain for Torsional Simple Shear Tests on Wet Vibrated Toyoura Sand

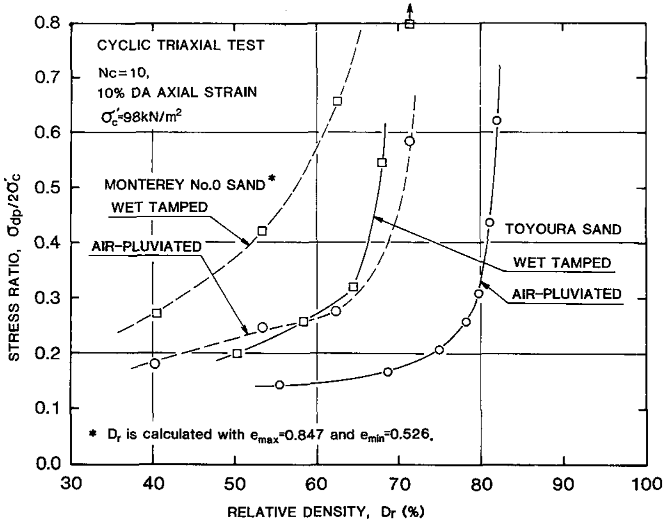
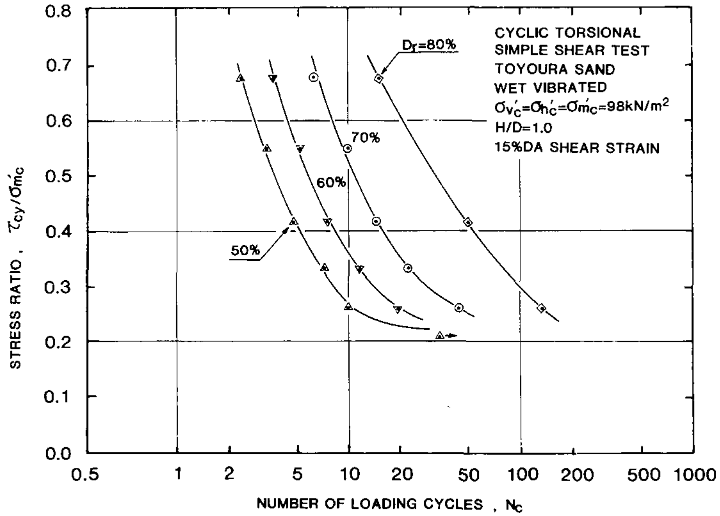
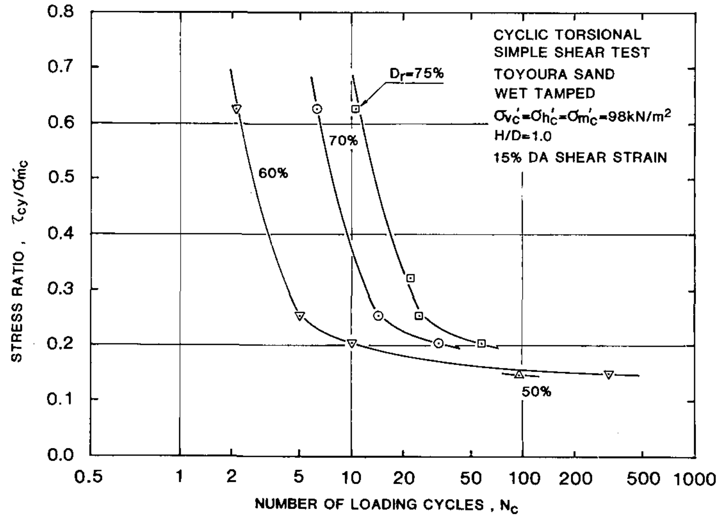


Fig.1 Effect of Specimen Preparation Methods on Cyclic Undrained Triaxial Strength for Toyoura Sand and Monterey No.0 Sand(The test results for Monterey No.0 Sand are from Silver and Tatsuoka(1982)).





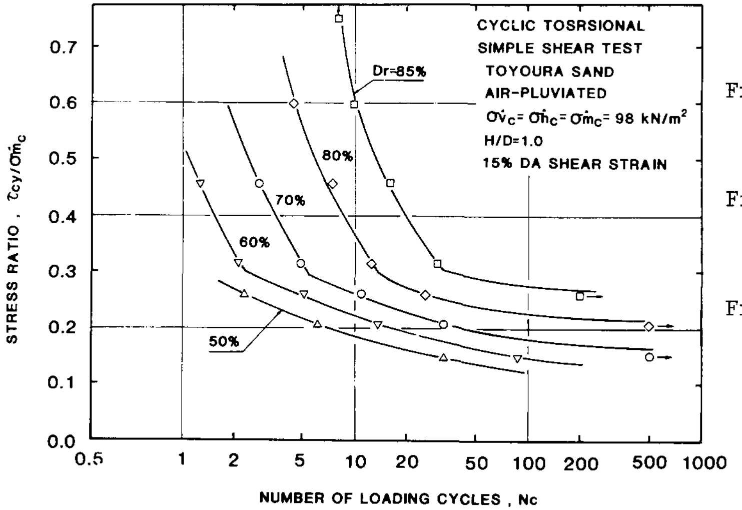
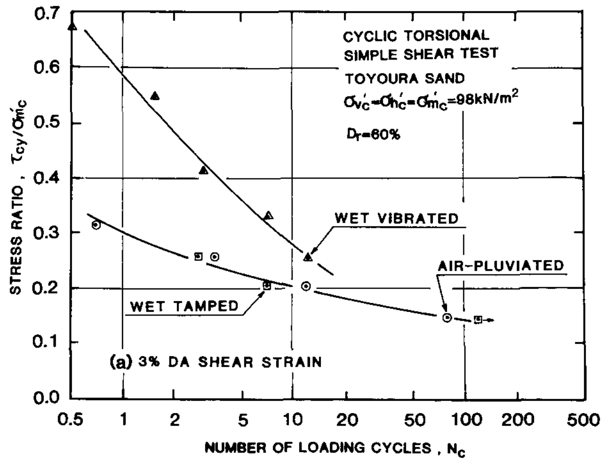
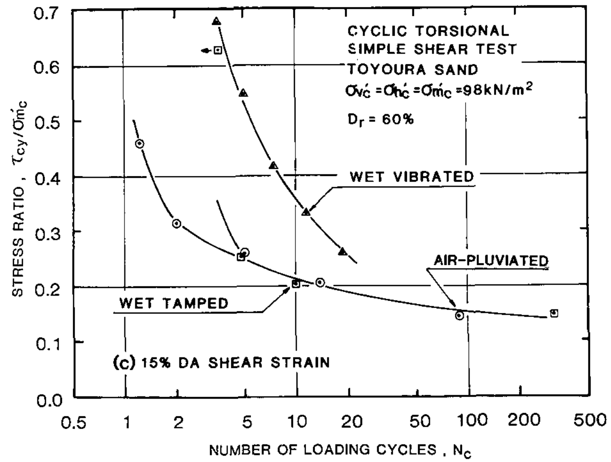


Fig.3(Left Top) Stress Ratio versus Number of Loading Cycles to 15% Double Amplitude Shear Strain for Wet Vibrated Toyoura Sand of D_r=50%,60%, 70% and 80%.

Fig.4(Left Bottom) Stress Ratio versus Number of Loading Cycles to 15% Double Amplitude Shear Strain for Air-Pluviated Toyoura Sand of D_r=50%,60%,70%,80% and 85%.

Fig.5(Right Top) Stress Ratio versus Number of Loading Cycles to 15% Double Amplitude Shear Strain for Wet Tamped Toyoura Sand of D_r=50%, 60%, 70% and 75%.





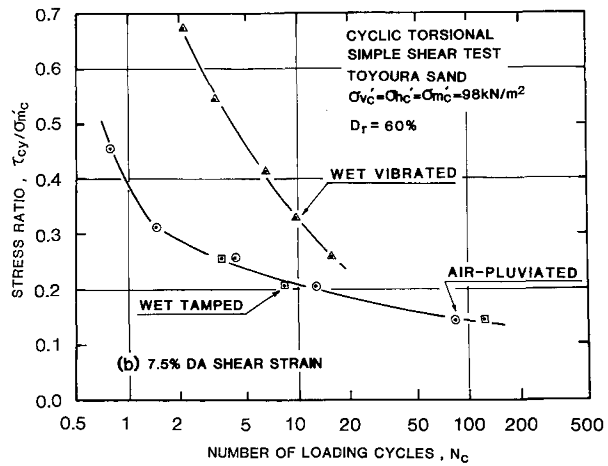
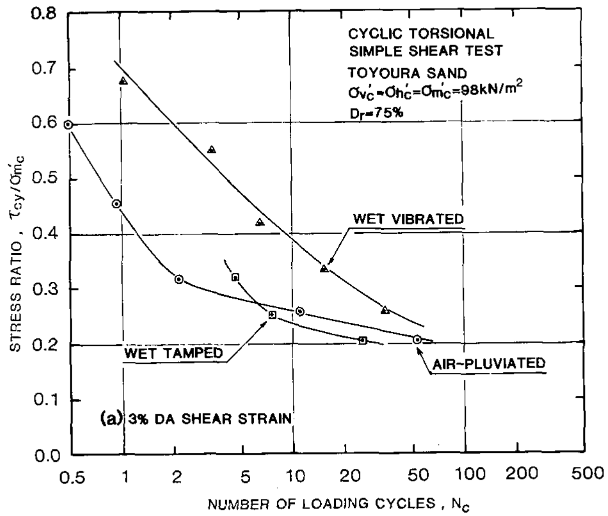
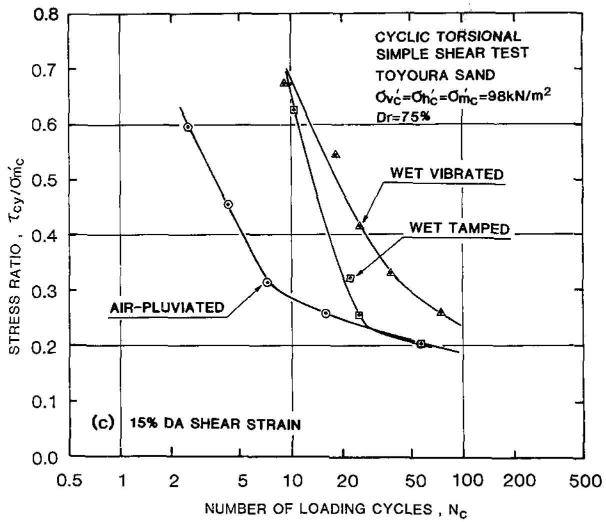


Fig.6 Effects of Specimen Preparation Methods on Cyclic Undrained Torsional Simple Shear Strength of Toyoura Sand for Double Amplitude Shear Strains of (a) 3%, (b) 7.5% and (c) 15% for D_r=60%.





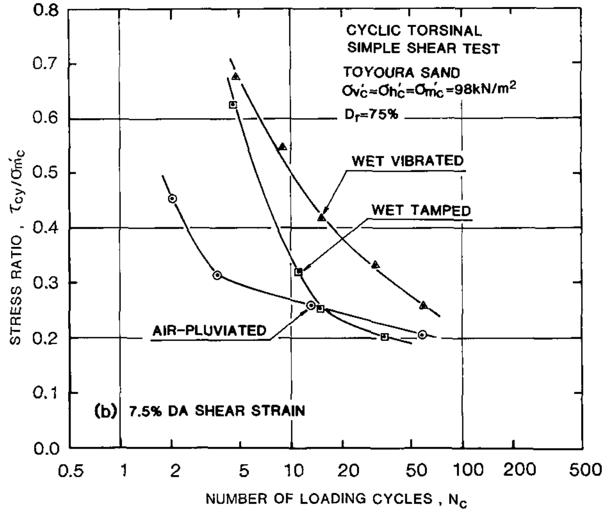


Fig.7 Effects of Specimen Preparation Methods on Cyclic Undrained Tortional Simple Shear Strength of Toyoura Sand for Double Amplitude Shear Strains of (a) 3%, (b) 7.5% and (c) 15% for D_r=75%.

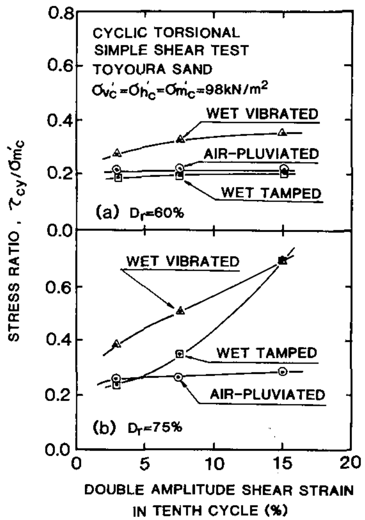


Fig.8 Relationship between Stress Ratio and Double Amplitude Shear Strain in the Tenth Loading Cycle for Air-Pluviated, Wet Tamped and Wet Vibrated Toyoura Sand of (a) D_r=60% and (b) D_r=75%.

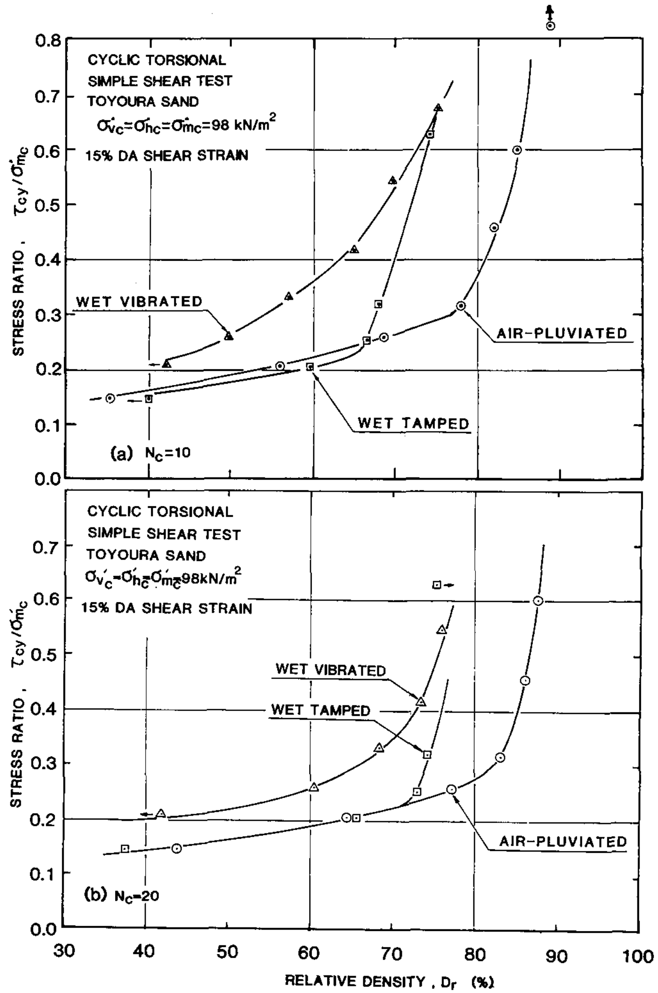


Fig.9 Stress Ratio versus Relative Density of Air-Pluviated, Wet Tamped and Wet Vibrated Toyoura Sand for Failure Defined as 15% Double Amplitude Shear Strain (a) in the Tenth Loading Cycle and (b) in the Twentieth Loading Cycle.

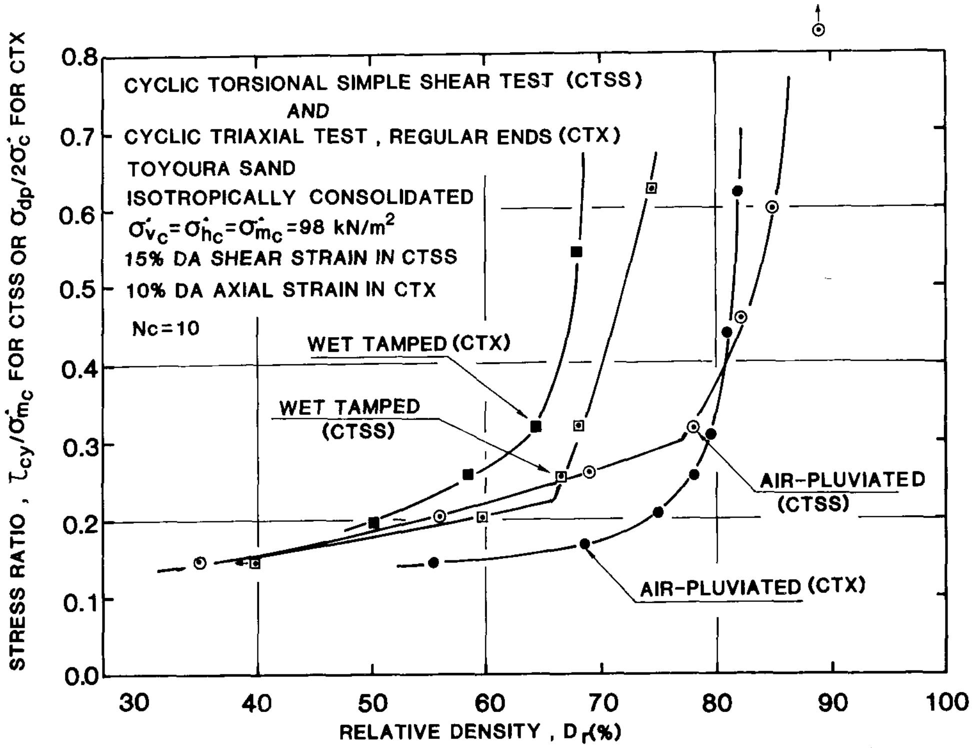


Fig.10. Stress Ratio versus Relative Density for Air-Pluviated and Wet Tamped Toyoura Sand by Torsional Simple Shear Tests and Triaxial Tests(Regular Ends) on Isotropically Consolidated Specimens for Failure Defined as 15% Double Amplitude Shear Strain in the Tenth Cycle.

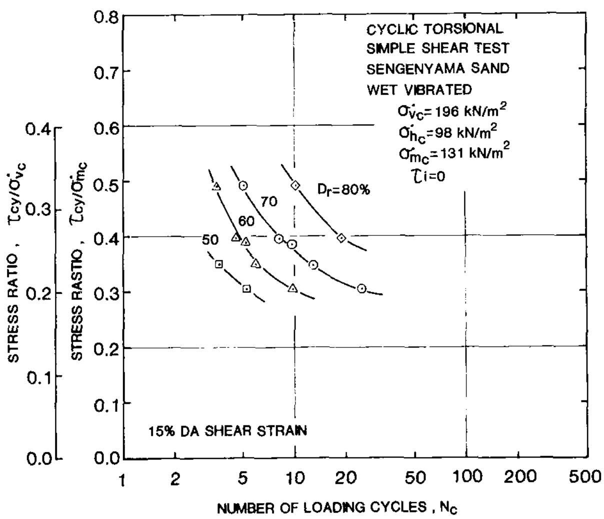
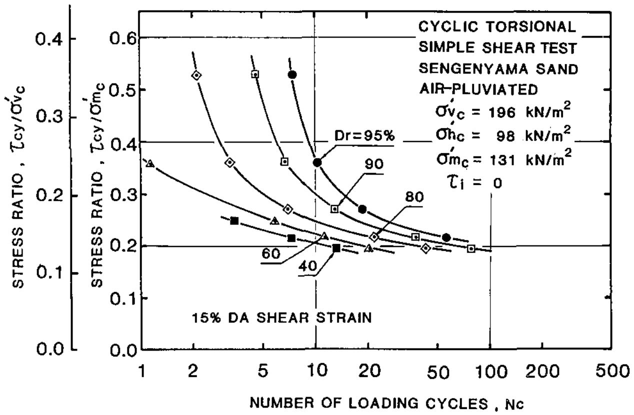
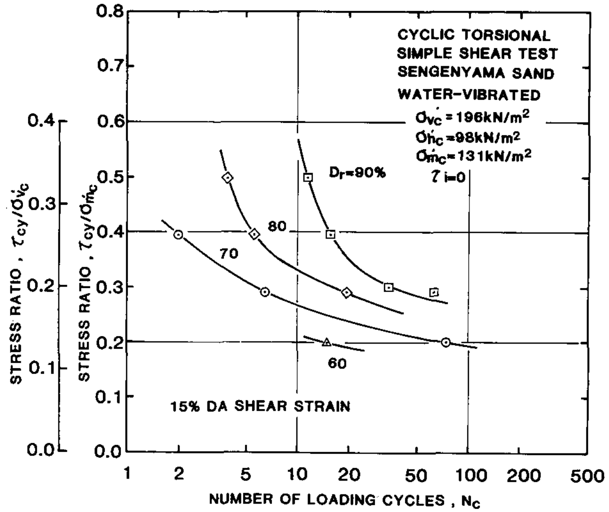


Fig.11 Stress Ratio versus Number of Loading Cycles to 15% Double Amplitude Shear Strain for Wet Vibrated Sengenyama Sand of D_r= 50%, 60%, 70% and 80%.





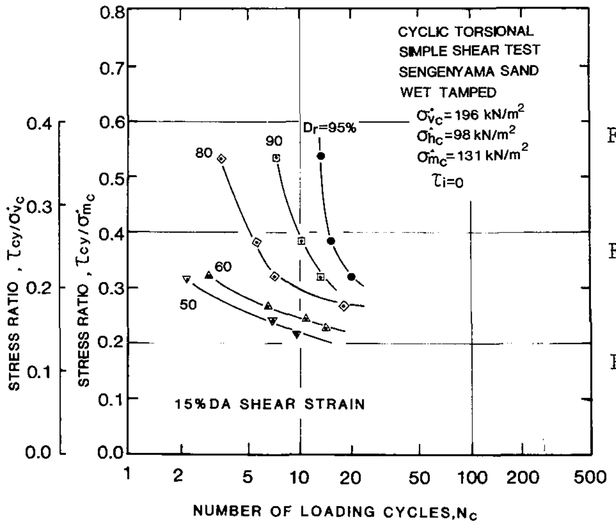


Fig.12.(Left Top) Stress Ratio versus Number of Loading Cycles to 15% Double Amplitude Shear Strain for Air-Pluviated Sengenyama Sand of D_r= 40%, 60%, 80%, 90% and 95%.

Fig.13.(Left Bottom) Stress Ratio versus Number of Loading Cycles to 15% Double Amplitude Shear Strain for Wet Tamped Sengenyama Sand of D_r= 50%, 60%, 80%, 90% and 95%.

Fig.14.(Right Top) Stress Ratio versus Number of Loading Cycles to 15% Double Amplitude Shear Strain for Water-Vibrated Sengenyama Sand of D_r= 60%, 70%, 80% and 90%.

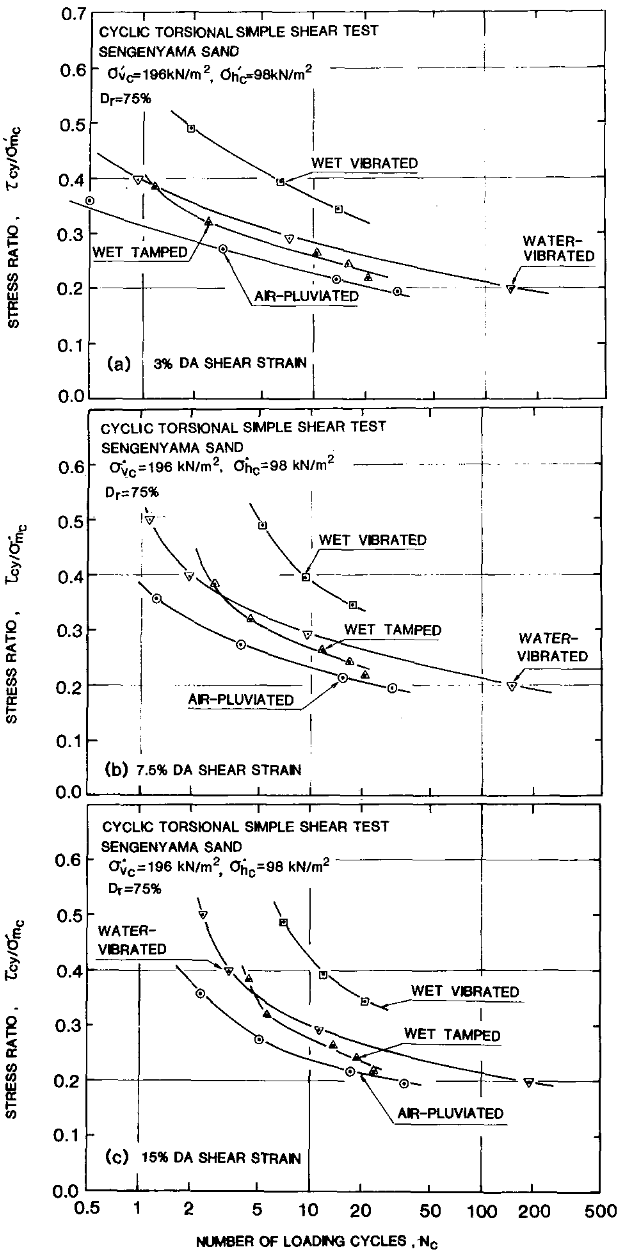


Fig.15 Effects of Specimen Preparation Methods on Cyclic Undrained Torsional Simple Shear Strength of Sengenyama Sand for Double Amplitude Shear Strains of (a) 3%, (b) 7.5% and 15% for D_r= 75%.

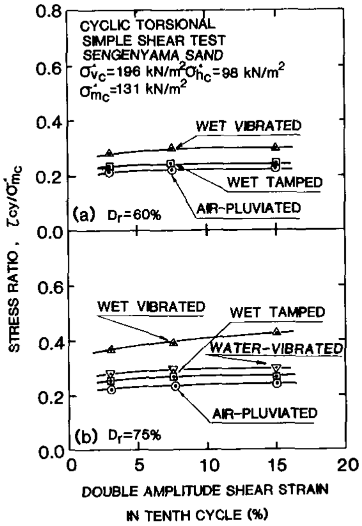
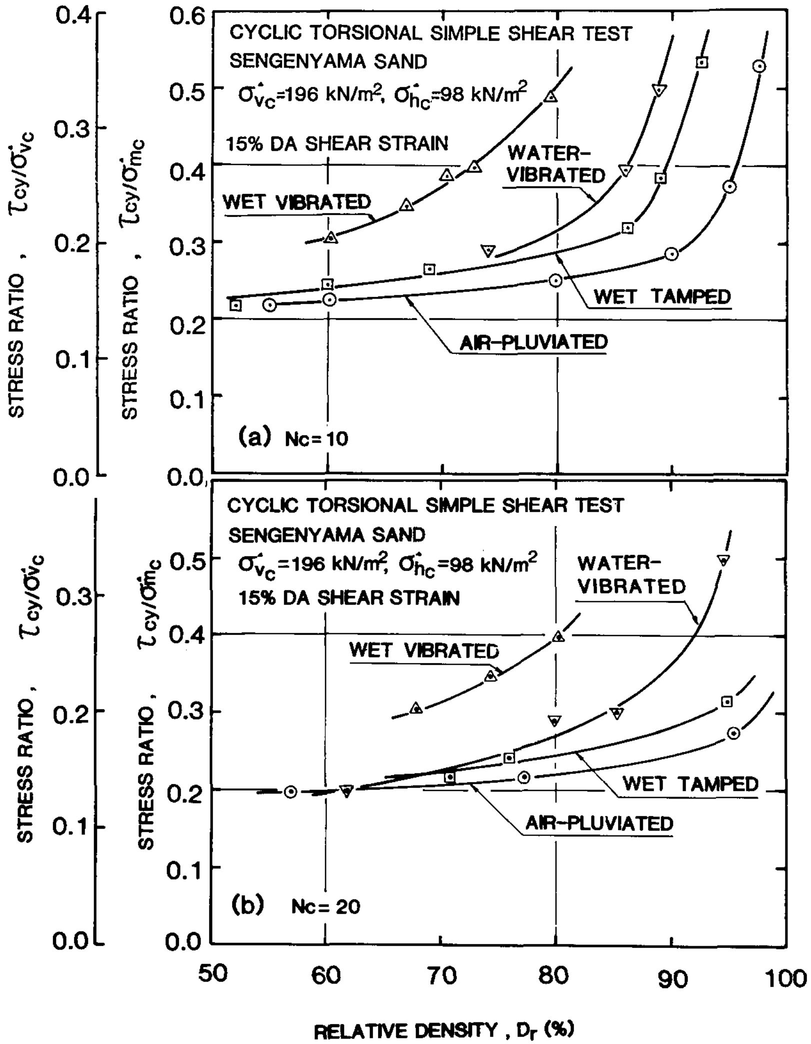


Fig.16 Relationship between Stress Ratio and Double Amplitude Shear Strain in the Tenth Loading Cycle for Air-Pluviated, Wet Tamped, Wet Vibrated and Water-Vibrated Sengenyama Sand of (a) D_r= 60% and (b) 75%.



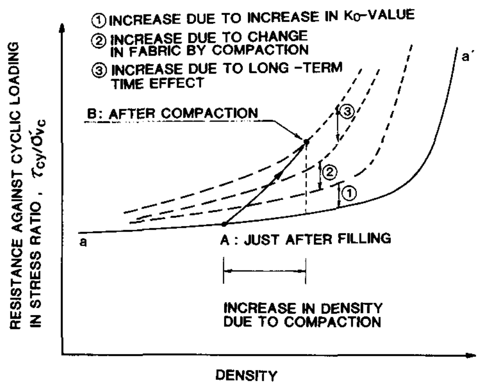
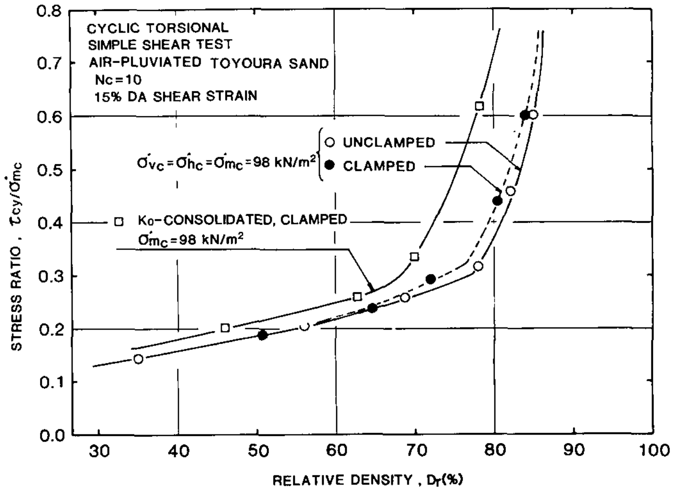
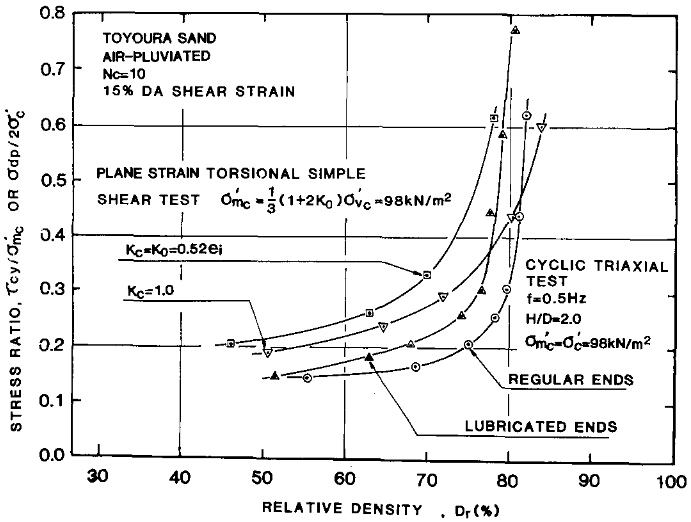


Fig.18 Schematic Diagram Showing Probable Increase in In Situ Cyclic Undrained Strength during Compaction Procedure and Long-Term Consolidation.

Fig.17 Stress Ratio versus Relative Density of Air-Pluviated, Wet Tamped, Wet Vibrated and Water-Vibrated Sengenyama Sand for Failure Defined as 15% Double Amplitude Shear Strain (a) in the Tenth Loading Cycle and (b) in the Twentieth Loading Cycle.





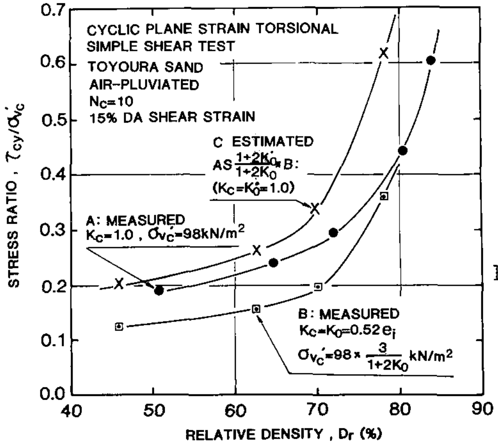


Fig.19. (Left Top) Stress Ratio versus Relative Density of K_0-Consolidated and Isotropically Consolidated Toyoura Sand Prepared by Air-Pluviation for Failure Defined as 15% Double Amplitude Shear Strain in the Tenth Loarding Cycle.

Fig.20. (Left Bottom) Comparison of A: Measured Strength for Isotropically Consolidated Specimens (K_c=1.0) with C: Strength Estimated from B: Measured Strength for Anisotropically Consolidated Specimens (K_c=K_0) in Torsional Simple Shear Tests.

Fig.21. (Right Top) Stress Ratio versus Relative Density for Air-Pluviated Toyoura Sand by Torsional Simple Shear Tests (K_c=K_0 and K_c=1.0) and Triaxial Tests (Regular Ends and Lubricated Ends) for Failure Defined as 15% Double Amplitude Shear Strain in the Tenth Loading Cycle.