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EFFECT OF SAMPLE PREPARATION METHOD
ON
CYCLIC UNDRAINED STRENGTH OF SAND
IN
TRIAXIAL AND TORSIONAL SHEAR TESTS

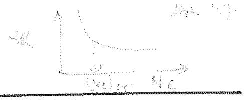
by

Fumio TATSUOKA[I), Kenzo OCHI[II) and Shinji FUJII[III)

ABSTRACT

The effects of sample preparation methods on the cyclic undrained strength of two kinds of sand were investigated using two kinds of laboratory cyclic testing methods; the triaxial and torsional shear tests. Clean sand and sand with fines were used. Four different methods of sample preparation were adopted; namely, the air-pluviation method, the wet-tamping method, the wet-vibration method and the water-pluviation and vibration method. The density of sample was varied from a very loose one to a very dense one. The total number of tests was more than 500. It was found that the effects of sample preparation methods on cyclic undrained strength defined as cyclic stress ratio required to cause a certain value of strain at a certain number of loading cycles are significant, the density of sample being the same, for both kinds of sand in both kinds of testing methods. The test results show that the effects on the cyclic stress ratio values are larger either in denser sand, or in smaller numbers of loading cycles where liquefaction strengths are defined, or in larger strain amplitude values for which liquefaction strengths are defined. Furthermore, the effects of sample preparation methods for the same kind of sand were not consistant between the triaxial test and the torsional shear test. Therefore, the ratio of cyclic undrained strength between the triaxial test and the torsional shear test for the same kind of sand was not the same among the different sample preparation methods employed. Furthermore, it was found that the effects of sample preparation methods were not totally the same between two kinds of sand. These findings show that the estimation of cyclic undrained simple shear strength as measured by torsional shear tests from triaxial strengths is not as simple as has been considered.

In addition, it was found that the cyclic undrained strength characteristics are better represented by the critical number of loading cycles than the conventional strength index such as the cyclic stress ratio. The critical number of loading cycles is defined as the number of loading cycles at the maximum curvature in the curve of the relationship between the cyclic stress ratio and the logarithm of the number of loading cycles where a certain value of strain is observed.



I) Associate Professor, Institute of Industrial Science, University of Tokyo. II) Research Engineer, Technological Research Institute, Tokyu Construction Co., Ltd. III) Research Engineer, Technical Research Institute, Sato Kogyo Co., Ltd. II) and III) Formerly Visiting Research Personnels of University of Tokyo.

INTRODUCTION

To evaluate the liquefaction strength of a presently existing ground by performing laboratory cyclic undrained tests, it is crucial to obtain very high-quality undisturbed samples, which are now considered very difficult to obtain by existing tube sampling methods especially for dense sands. On the other hand, laboratory cyclic undrained tests on reconstituted samples are still useful where information is required concerning the as-placed liquefaction strength of sand in grounds which will be artificially made in future. Furthermore, it is often required in such a case as above to determine in advance the design compaction density of these artificial grounds so that these grounds will have an enough resistance against design earthquake loadings.

It is widely considered that a laboratory simple shear simulation is a more appropriate measure of cyclic undrained strength than a triaxial simulation for usual horizontal sand deposits or sand slopes under the plane strain condition. However, the triaxial apparatus is still much more popular and much easier to operate than the simple shear apparatus. Therefore, even from now triaxial tests will be performed on undisturbed samples in routine laboratory tests. However, only a limited number of literature is available concerning the relationship between the triaxial and simple shear strengths and also the test conditions employed in these investigations were rather limited (Ishihara and Yasuda, 1975, Silver et al, 1980).

Related to the earthquake-resistant design of two huge man-made islands mainly made of sand which will be a part of a 15km-long highway crossing the Tokyo bay, a series of cyclic undrained tests has been performed for these five years at the Geotechnical Engineering Laboratory, the Institute of Industrial Science, the University of Tokyo. A part of the results has been reported elsewhere (Muramatsu and Tatsuoka, 1981, Tatsuoka et al, 1982a and Tatsuoka et al, 1983a). It has been required to determine the compaction criteria in advance for a given kind of sand, Sengenyama Sand, which will be used to make the man-made islands. The islands will be around 30m thick and around 250m × 1,200m wide at their bottoms and around 100m × 500m wide at their tops and the major part of the islands will be submerged. The islands will connect two bridges extending from both inland areas with a submerged tunnel which will be located between the islands. Since the construction sites are located in one of the areas having the highest seismicity in Japan, the islands should have a high resistance against cyclic undrained loading.

In an attempt to evaluate the as-placed liquefaction strength of artificially compacted deposits of Sengenyama Sand, it was considered that the increase in strength by compaction would be caused by at least the following three factors (see Fig.1); ① the increase in density by compaction, ② the increase in K_0-value by compaction and ③ the change in the fabric of sand by compaction. Suppose that in Fig.1 the point designated by the letter A represents the condition just after filling by pluviation through water and the curve a-a' is the strength curve for the water-pluviated sand. The point designated by the letter B represents the condition after compaction. In this study, the effect of the change in the fabric of sand was mainly investigated and the effect of K_0-value was investigated only to a limited extent. The effect of long-term time consolidation is beyond the scope of this study.

In addition to Sengenyama Sand, Toyoura Sand was also used because Toyoura Sand has been widely used in Japan for the study on sand liquefaction and a large amount of the comparable data are available. The torsional shear test on a hollow cylindrical sample was employed to perform a simple shear test because accurate torsional shear tests are much easier to perform than accurate conventional simple shear tests on disk-type samples.

Presented herein are the summarized results of this research program. It was found that the effect of sample preparation on cyclic undrained strength in any test condition employed was significant, especially in dense sand at a smaller number of cycles. However, the manner of the effect was not totally the same either between the triaxial and torsional shear tests or between two kinds of sand. Therefore, the relationship between the triaxial and torsional shear strengths was found to be a function of at least the sample preparation method and the kind of sand.

Some of the figures which have been shown elsewhere will be very slightly modified in this paper besed on the additional data obtained afterwards.

TEST PROGRAM

The physical properties of the test materials used are shown in Fig.2 and Table 1 (a part of the physical properties of Sengenyama Sand reported previosly was incorrect and should be corrected). While Toyoura Sand has no fine contents, Sengenyama Sand has 2.4% fine contents. To confirm the consistency of the properties of these sands during the period of this study, check cyclic undrained triaxial and torsional shear tests under the same condition were performed occasionally and it was confirmed that the variation in the results during this test program be negligible in both test materials.

In Fig.3 are shown the stress conditions during consolidation and cyclic loading employed in this study. For a cyclic triaxial test (this will be abbreviated as CTX in the following part), a sample was isotropically consolidated to an effective confining pressure σ_c of 1 kgf/cm^2 (98 kN/m^2) for Toyoura Sand or 1.333 kgf/cm^2 (130.6 kN/m^2) for Sengenyama Sand, either value of which was equal to the mean effective principal stress at consolidation in the torsional shear test on the same kind of sand. A triaxial sample was 15cm long and 7.5cm in diameter with porous stones at both ends. In this test program, 0.3mm-thick latex rubber membranes were used in both triaxial and torsional shear tests. The frequency of cyclic loading was 0.5Hz in the early stage of this investigation and has been changed to 0.1Hz in the later stage in order to record the outputs of test more accurately. No effects of this change of frequency on the test results were found. In any test, the constant amplitude of cyclic load and the symmetry of the amplitude of cyclic load between the triaxial compression and extension conditions were carefully achieved (Fig.4). Stress ratio shown in Fig.4 is defined as (deviator axial load)/(cross-sectional area of sample at consolidation)/(2 times effective confining pressure at consolidation). Axial strain is the axial displacement divided by the sample length at consolidation.

$\{\sigma_d/2\sigma_c\}$

Two kinds of cyclic torsional shear tests were performed, where a sample was either isotropically consolidated for Toyoura Sand or anisotropically consolidated for both kinds of sand. A torsional shear test sample was 10cm long, 10cm in outer-diameter and 6cm in inner-diameter. A sample of Toyoura Sand consolidated isotropically to $\sigma_c'=1$ kgf/cm^2 (98 kN/m^2) was cyclically loaded with a frequency of 0.5Hz or 0.1Hz. This kind of test will be called CTS-I (abbreviation of Cyclic undrained Torsional Shear test on Isotropically consolidated sample) in the following part. No effect of this change of frequency was found in the torsional shear tests either. In most of the cyclic undrained loading in CTS-I, the height was free to change. In some tests on air-pluviated samples, the height of sample was kept constant by clamping the loading ram vertically, but only a very small increase in strength was induced by this clamping (see Fig.14, Tatsuoka et al, 1982a). The data reported herein are those by the tests without this kind of clamping. For preventing slippage at the top and bottom ends of sample, six 1.5mm-high stainless blades were fixed on each of the top and bottom surfaces of porous stone in the early stage of this investigation. However, it was found meanwhile that in the tests where these blades were not used and the top and bottom surfaces of sample were in contact with porous stones no slippage was observed as well and the results were very similar to those obtained by the tests using these blades. Therefore, most of the data reported herein were obtained by the tests without these blades.

In the other kind of torsional shear test(CTS-A), samples were anisotropically consolidated with the ratio of effective vertical stress to effective horizontal stress $K=\sigma'_{h_c}/\sigma'_{v_c}$ being 0.5 for Sengenyama Sand and $0.52e_i$ for Toyoura Sand, where e_i is the initial void ratio of sample. The value $K=0.52e_i$ was the K_0-values measured on air-pluviated triaxial samples of Toyoura Sand (Okochi and Tatsuoka, 1984). K=0.5 for Sengenyama Sand is close to the measured K_0-values for air-pluviated Sengenyama Sand, which are 0.44 for $D_r=80\%$ and 0.47 for $D_r=60\%$ (Tatsuoka et al, 1984). The procedure of anisotropic consolidation is described in detail elsewhere (Tatsuoka et al, 1982 and 1983). The mean effective principal stress at consolidation $\sigma'_{m_c}=(\sigma'_{v_c}+2\sigma'_{h_c})/3$ was equal to the value of σ'_c in the corresponding triaxial test. The height of sample was kept constant during cyclic undrained loading to maintain the cross-sectional area of sample to be constant. This condition can be considered similar to that for an element of saturated sand in an level ground in situ during earthquake motions. This kind of test will be called CTS-A (abbreviation of Cyclic undrained Torsional Shear test on Anisotropically consolidated sample) in the following part.

The methods of maintaining the sample height to be constant in CTS-A and of appling the rotational movement to the loading ram were modified after this method was reported for the first time elsewhere (Muramatsu and Tatsuoka, 1981, Tatsuoka et al, 1982a and Tatsuoka et al, 1983b). The following two parts were mainly modified (see Fig.5 and Photo.1 a and b). First, the clamping device was moved to the level below the device in which the cyclic linear movement of wire is transformed to the rotational movement of the loading ram. Secondly, the method of this transformation had been achieved with a somewhat complicated device in the previous version, but this was modified to be simpler by using a ball spline bushing and its loading shaft which are commercially available. It was found after these modifications that the vertical movement of loading shaft under the action of its rotational mevement became smoother in CTS-I and the vertical settlement of the top of specimen caused by its liquefaction in CTS-A was decreased significantly from an order of 0.1mm in the old version to an order of 0.01mm, which should be zero in the ideal condition.

The following four kinds of sample preparation methods were employed (see Fig.6 and Table 2).

The air-pluviation method(AP) 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 producd by this method is somewhat similar to that of sand deposits formed by free falling of sand particles through air or water. Note that even a void ratio close to the minimum void ratio can be achieved by this method.

The wet-tamping method(WT) 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. 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 for torsional tests and 3.7cm for triaxial tests and the weight of the tamper was 189.5g in both kinds of tests. 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 method was adopted as a simulation of field compaction of moist sand in layers by vertical tamping on the ground surface.

In the wet-vibration method(WV) a prescribed amount of moist Toyoura Sand with a water content of 3% or moist Sengenyama Sand with a water content of 8% was placed gently in a mold for each compaction layer. Then, either a cylindreally shaped weight for triaxial tests or a hollow cylindrically shaped weight for torsional shear tests was placed on the present sample surface, the mean vertical stress being 0.0286 kgf/cm^2 (2.80 kN/m^2). 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. No differences in cyclic strength values were found between five-layered specimens and ten-layered specimens of Toyoura Sand. The fabric of a test specimen produced by this method may be similar to that formed in field moist sand layers compacted by a vibrational method.

In the water-vibration method(WAV), a prescribed amount of air-dry sand was poured either through water for Toyoura Sand or through air for Sengenyama Sand in one layer. For Sengenyama Sand, sand was pluviated through air and then saturated to avoid segregation. After placing the weight as used in the wet-vibration method on the top surface of sample, the specimen was compacted underwater by tapping the mold uniformly with a wooden hammer until the total height of the specimen was reduced to a prescribed value. This method was employed as a simulation of in situ vibrational compaction procedures for submerged sand layers.

In the wet-tamping method and the wet-vibration method, the compacted surface of each layer was scarified before placing the next layer. After being saturated, a test specimen was consolidated isotropically or anisotropically. It was confirmed that a Skempton's B-value be 0.98 or higher.

Cyclic triaxial test results were normalized using the conventional stress ratio $SR=\sigma_{dp}/2\sigma'_c$ in which σ_{dp} is the maximum single amplitude of cyclic deviator stress and σ'_c is the effective isotropic consolidation stress. Note that σ_{dp} is defined as the single amplitude cyclic axial load divided by the cross-sectional area of sample at consolidation. Therefore, the true maximum deviator stress after the sample deforms is either smaller in triaxial compression than or larger in triaxial extension than σ_{dp}. Cyclic torsional shear test results were normalized using the stress ratio $SR=\tau_{cy}/\sigma'_{m_c}$ where τ_{cy} is the maximum single amplitude of horizontal cyclic shear stress and σ'_{m_c} is the effective mean principal stress at consolidation which equals σ'_c in CTS-I or $(\sigma'_{v_c}+2\sigma'_{h_c})/3$ in CTS-A. This normalization method was suggested by Ishihara and Li (1972) and Ishihara and Takatsu (1979) either to relate the triaxial strength with the torsional shear strength or to relate the torsional shear strength for a given value of $K=\sigma'_{h_c}/\sigma'_{v_c}$ to that for another value of K. It will be shown, however, that this normalization method is effective only in a limited condition. Cyclic undrained triaxial strength was defined for 2%, 5% and 10% double amplitude axial strain values. On the other hand, it can be shown that the maximum shear strain values defined as the differences

DA (Ca) = 1%

$\gamma = \varepsilon_a - \varepsilon_r = 1.5 \varepsilon_a$

between the major and minor principal strains are 1.5 times axial strain values in undrained saturated triaxial samples. Therefore, for the purpose of comparing the triaxial strength with the torsional shear strength, the cyclic undrained torsional shear strength should be defined for 3%, 7.5% and 15% double amplitude maximum shear strain values. The shear strain values γ obtained by dividing the average horizontal displacement on the top of sample by the initial height of sample is not the same with the maximum shear strain value when the height of sample and/or the thickness of cylinder wall changes during shearing as in CTS-I. However, it was confirmed that the difference between these two kinds of shear strain values be negligible for the purpose of this study. Therefore, the torsional shear strengths were defined for double amplitude values of γ of 3%, 7.5% and 15%.

The results by each kind of cyclic test were summarized in such a form as shown in Fig.7. In this figure, D_r is the relative density value obtained after consolidation and N_c is the number of loading cycle where a double amplitude shear strain DA of 15% is observed. For a value of N_c less than 10, this value was obtained down to one tenth's place of decimal by such an interpolation as follows. Suppose that DA was 8% at $N_c=7$ and DA=14% at $N_c=8$. Then, N_c for DA=10% was obtained as $7+(10-8)/(14-8)=7.3$. Since a series of tests was performed for a similar cyclic stress ratio changing density purposely, a relationship between D_r and N_c could be defined for a given value of cyclic stress ratio SR as shown in Fig.7. Using this relationship, the value of N_c or D_r can be determined from given values of the other variable (D_r or N_c) and SR. The values of D_r and N_c reported in the followings were obtained as above. The results shown in Fig.7 indicate negligible effects of the number of compaction layers on the results of wet-vibrated Toyoura Sand samples.

TEST RESULTS OF TOYOURA SAND

In Figs. 8(a) through 8(d) are shown the relationships between the cyclic stress ratio and the number of loading cycles where a 10% double amplitude axial strain was observed for different consolidated relative density values for four different sample preparation methods. It may be noted by comparing these figures that the effect of sample preparation methods is significant as has been reported by Mulilis et al (1977). Furthermore, it may be noted in Figs. 8(a) through 8(d) that in each figure or for each sample preparation method the strength curves for different values of D_r have a similar shape having the maximum curvature at a stress ratio of around 0.23. For the range of stress ratio less than this value these curves have a small slope, while for the range of stress ratio larger than this value these curves have a large slope. Thus, this kind of stress ratio will be called the critical stress ratio SR_{cr} which was found to be rather unique both in the cyclic triaxial tests performed in this study ($\sigma_{dp}/2\sigma_c' = 0.23$) and in the cyclic torsional tests (CTS-I and CTS-A) performed in this study ($\tau_{cy}/\sigma_{m_c}' = 0.3$). These features may have an implication as follows. When the stress ratio of a given sinusoidal loading is larger than the critical stress ratio, whether cyclic undrained failure is induced or not in a given sand having a given density by this given sinusoidal loading depends mainly on its number of loading cycles and is less insensitive of the stress ratio value. On the other hand, when the stress ratio is less than the critical stress ratio, whether cyclic undrained failure is induced or not in a given sand by a given sinusoidal loading depends mainly on the stress ratio and its number of loading cycles has a secondary meaning. Accordingly, it seems that the number of loading cycles corresponding to the critical stress ratio for a given strength curve may better represent the features of the strength curve than other conventional strength indices such as the stress ratio for which a given strain value is induced at a given number of cycles, for example 10 or 20. This kind of the number of loading cycles will be called the critical number of loading cycles; $(N_c)_{cr}$. This point will be discussed again in the later part.

To see the effects of sample preparation method more clearly, Figs.9 (a) through (c) were prepared where for D_r=75% the strength curves for four sample preparation methods are directly compared for double amplitude axial strains of (a)2%, (b)5% and (c)10%. It may be seen that, the other factors being equal, the air-pluviated samples are the weakest, the water-vibrated samples are intermediate and the wet-tamped samples and the wet-vibrated samples have a similar strength and have the largest strength among these kinds of samples. Furthermore, in Figs.10 (a) and (b) are shown the relationships between the cyclic stress ratio and the consolidated relative density for a double amplitude axial strain of 10% in (a) the tenth cycle or (b) the twentieth cycle. A very clear effect of sample preparation method on the results may be seen in these figures.

Similar results by the torsional shear tests on isotropically consolidated samples(CTS-I) and anisotropically consolidated samples(CTS-A) are shown in Figs. 11 through 16. It may be seen that in the torsional shear tests the effects of sample preparation method on cyclic undrained strength are significant as well as in the triaxial tests. It may be seen that also in the torsional shear tests the air-pluviated samples are the weakest, the water-vibrated samples have an intermediate strength and the wet-vibrated samples are the strongest as in the triaxial tests. However, the test results show that the wet-tamped samples are not necessarily the strongest in the torsional shear tests. These results show that the sample preparation method may affect the cyclic undrained strength in a somewhat different manner between in the triaxial tests and in the torsional shear tests. This point will be discussed again in the later part.

TEST RESULTS OF SENGENYAMA SAND

The results of the triaxial tests and the torsional shear tests(CTS-A) of Sengenyama Sand are summarized in Figs. 17 through 22. It may be seen from these figures that also for Sengenyama Sand the effects of sample preparation method is significant as well as in the case of Toyoura Sand. In general, the air-pluviated samples of Sengenyama Sand are the weakest and the wet-vibrated samples are the strongest, the other parameters being equal. However, several different features than those for Toyoura Sand may be seen in these figures. First, for an identical relative density value, the strength of Sengenyama Sand is generally smaller than that of Toyoura Sand for any sample preparation method in both triaxial and torsional shear tests. This point is clearly seen in Figs.23 (a) through (d) and Figs.24 (a) through (d). It would appear from these results that relative density value used in this study is not a good index to represent the density condition of different kinds of sand with respect to cyclic undrained strength. The values of e_{max} and e_{min} used in calculating relative density values were obtained under no vertical stress using air-dry sand. e_{max} was obtained by gently pouring air-dry sand into a stainless-steel mold and e_{min} was obtained by tapping a mold in which air-dry sand has been placed by spooning in 10 layers. The mold has an inner-dimension of 6cm in diameter and 4cm in height. However, the value of e used in calculating relative density values were those measured after consolidation for test samples prepared by the methods which are different from that used in obtaining the values of e_{max} and e_{min}. Therefore, is reasonable to consider that if more appropriate values of e_{max} and e_{min} which were obtained under the similar condition as for cyclic test samples in calculating the values of D_r or another density index, the differences both between two kinds of sand and between different sample preparation methods are reduced to a smaller amount. This point is beyond the scope of this paper and will be discussed in detail elsewhere by the authors.

COMPARISONS BETWEEN TRIAXIAL AND TORSIONAL SHEAR STRENGTHS BASED ON STRESS RATIO VALUES

Ishihara and his colleagues (Ishihara and Li, 1972, Ishihara and Yasuda, 1975 and Ishihara and Takatsu, 1979) showed that for a loose sample (D_r=55%) of Fuji river Sand made by the method similar to the water-vibration method used in this study, the triaxial strength and the torsional shear strength of isotropically consolidated samples with $K=\sigma'_{h_c}/\sigma'_{v_c}=1.0$ and that of anisotropically consolidated samples with K= of 0.5 and 1.5 are related to each other as

$$(\sigma_{dp}/2\sigma'_c)_{CTX}=(\tau_{cy}/\sigma'_{m_c})_{CTS\text{-}I}=(\tau_{cy}/\sigma'_{m_c})_{CTS\text{-}A} \qquad (1)$$

in which $(\sigma_{dp}/2\sigma'_c)_{CTX}$, $(\tau_{cy}/\sigma'_{m_c})_{CTS\text{-}I}$ and $(\tau_{cy}/\sigma'_{m_c})_{CTS\text{-}A}$ are the stress ratioes at which initial liquefaction was observed in the twentieth cycle in the triaxial tests, the torsional shear tests on isotropically or anisotropically consolidated samples repectively and $\sigma'_{m_c}=(\sigma'_{v_c}+2\sigma'_{h_c})/3$. Following this suggestion, the stress ratio $\sigma_{dp}/2\sigma'_c$ for the triaxial tests or τ_{cy}/σ'_{m_c} for the torsional shear tests at which a double amplitude shear strain of 15% (or axial strain of 10%) was observed in the twentieth cycle were plotted against consolidated ralative density values in Figs.25(a) through 26(d), in each of which the data for the same kind of sand and the same kind of sample preparation method have been plotted. Therefore, the difference seen in each of these figures should be attributed to different test methods. It may be clearly seen that Eq.(1) is valid only in a limited condition for the results obtained this investigation.

First, the effect of $K=\sigma'_{h_c}/\sigma'_{v_c}$ in the torsional shear test results of Toyoura Sand will be discussed. It may be seen in Figs.25 (a) through (d) that these two kinds of strength are quite similar in the samples prepared either by the wet-vibration method or by the water-vibration method for a wide range of density, It may also be seen that these two kinds of strength are similar in loose samples prepared by the air-pluviation and wet-tamping methods. This finding is well in accordance with the suggestion by Ishihara and his collegues. However, in the cases of dense air-pluviated or wet-tamped samples of Toyoura Sand, this normalization method seems invalid. In these cases, when the strength of anisotropically consolidated sample is estimated from that of isotropically consolidated sample as

$$(\tau_{cy}/\sigma'_{m_c})_{CTS\text{-}A}=(\tau_{cy}/\sigma'_{m_c})_{CTS\text{-}I} \qquad (2)$$

this strength value $(\tau_{cy}/\sigma'_{m_c})_{CTS\text{-}A}$ is underestimated. When the stress ratio is expressed as $(\tau_{cy}/\sigma'_{v_c})_{CTS\text{-}A}$, or $(\tau_{cy}/\sigma'_{v_c})_{CTS\text{-}I}$ using the effective vertical stress at consolidation σ'_{v_c}, then the results except for dense air-pluviated and wet-tamped samples can be related as

$$(\tau_{cy}/\sigma'_{v_c})_{CTS\text{-}A} \fallingdotseq (1+2K_0/3)\cdot(\tau_{cy}/\sigma'_{v_c})_{CTS\text{-}I} \qquad (3)$$

in which K_0 is the K_0-value of a normaly consolidated Toyoura Sand sample for CTS-A. However, for dense air-pluviated and wet-tamped samples, the following equation should be used

$$(\tau_{cy}/\sigma'_{v_c})_{CTS\text{-}A} > (1+2K_0/3) \cdot (\tau_{cy}/\sigma'_{v_c})_{CTS\text{-}I} \qquad (4)$$

The reason why Eq.(3) is not valid for dense air-pluviated and wet-tamped Toyoura sand is not known yet. Further researches will be needed.

The relationship between the triaxial strength and the torsional shear strength by CTS-A is also important from the practical point of view. It may be seen in Figs. 25(a) through 26(d) that the relationships obtained by this investigation were not so simple as expressed by Eq.(1). For Toyoura Sand, Eq.(1) is valid in relating the triaxial strength and the strength by CTS-A only for the wet-tamped samples for a wide range of density. For Sengenyama Sand, the strength curves of the triaxial test and the torsional shear test have generally different shapes and it may be seen that these two kinds of strength may be the same only at a very limited range of relative density value of around 90% where two strength curves cross each other. It may also be seen that except for the wet-tamped samples Toyoura Sand has a lower triaxial strength than a torsional shear strength by CTS-A, and that for Sengenyama Sand a sample looser than around D_r=90% has a lower triaxial strength than a torsional shear strength by CTS-A also.

To see more clearly the difference between these two kinds of strengths, Figs. 27 and 28 were prepared. Four curves shown in each of Figs.27 (a) and (b) are representing the relationships between the triaxial strength $(\sigma_{dp}/2\sigma'_c)_{CTX}$ and the torsional shear strength by CTS-A, $(\tau_{cy}/\sigma_{m_c})_{CTS\text{-}A}$, for the different sample preparation methods where strength values are defined for a double amplitude shear strain of 15% (or axial strain of 10%) in the twentieth cycle. It can be shown that if Eq.(1) is valid, all these four curves should collapse into a single line having a slope of 45% from the origin. However it may be seen that this was not the case for the test results obtained by this investigation.

The torsional shear strength by CTS-A is often estimated from the triaxial strength by using the equation

$$(\tau_{cy}/\sigma'_{v_c})_{CTS\text{-}A} = c_l\,(\sigma_{dp}/2\sigma'_c)_{CTX} \qquad (5)$$

where $(\tau_{cy}/\sigma'_{v_c})_{CTS\text{-}A}$ and $(\sigma_{dp}/2\sigma'_c)_{CTX}$ are the cyclic undrained strengths by these two kinds of tests defined for a cetain strain value in a certain number of loading cycles and c_l is the correction factor. In this study, the consolidation stress ratio $K=\sigma'_{h_c}/\sigma'_{v_c}$ was similar to the K_0-value of normally consolidated sample of the test material. Then, it can be shown that when Eq.(1) is valid for the test results obtained by this investigation the correction factor c_l equals (1+2K)/3 which is very close to $(1+2K_0)/3$. On the other hand, a value of 0.57 has been proposed for c_l by De Alba et al.(1976) and Seed(1976) based on their large-scale simple shear tests and triaxial tests on Monteley No.0 Sand. When K_0=0.4, $c_l=(1+2K_0)/3=0.6$ which is very close to 0.57.

In Figs.28 (a) and (b) are shown the values of c_l obtained as $c_l=(\tau_{cy}/\sigma'_{v_c})_{CTS\text{-}A}/(\sigma_{dp}/2\sigma'_c)_{CTX}$ plotted against consolidated relative density for failure defined for a double amplitude shear strain of 15% (or axial strain of 10%) in the twentieth cycle. These test results show that the value of c_l is generally higher than $(1+2K_0)/3$. In particular, the value of c_l is considerably larger than 1.0 for loose Sengenyama Sand. This implies that in such a case if a correction factor of $c_l=(1+2K_0)/3$ is used in Eq.(5), the torsional shear strength by CTS-A or the simple shear strength is largely underestimated. For Sengenyama Sand, the relation; $c_l=(1+2K_0)/3$, is approximately valid only in dense samples. Accordingly, it can be concluded that the estimation of the simple shear strength from the triaxial strength for a given sand element is not as simple as suggested previonsly by Seed sand his colleagues and Ishihara and his colleagues.

Probably, the estimation of the torsional shear strength or the simple shear strength using Eq.(5) with a unique correction factor as $c_1=(1+2K_0)/3$ or as $c_1=0.6$ can be allowed only in a very limited condition. It seems that this estimation is in general quite difficult. A more fundamental research will be needed to relate the triaxial strength and the torsional shear or simple shear strength for a given sand element. Furthermore, it would appear that for estimating the simple shear strength a torsional shear or simple shear test should be performed in place of a triaxial test if possible.

CRITICAL NUMBER OF LOADING CYCLES

Cyclic undrained strength has been represented conventionally using a stress ratio value for which initial liquefaction or a certain value of strain is observed at a certain number of loading cycles. However, this method is sometimes quite misleading. For example, the points designated by the letters A, B and C in Fig.8(a) correspond to the cyclic stress ratio values at which a double amplitude axial strain of 10% was observed at the fifteenth cycle in cyclic triaxial tests on the air-pluviated Toyoura Sand samples having relative density values of 85%, 80% and 60%. These stress ratio values will be denoted as SR_A, SR_B and SR_C. It may be seen that the differende between SR_A and SR_B is as large as around 0.5, while the difference in the general features between these two strength curves for D_r=80% and 85% is not so large. In contrast, it may also be seen in Fig.8(a) that the difference between SR_B and SR_C is as small as around 0.15, but the difference in the general features between these two strength curves for D_r=60% and 80% is not so small. It may be seen in Figs.10 (a) and (b) and in similar other figures (Figs.13, 16, 19 and 22) that when sand is loose, stress ratio increases at a very small rate along a strength curve as relative density increases, while when sand is dense, stress ratio increases at a very large rate as relative density increases. It is clear that the change of the locations of such strength curves of the relationships between the stress ratio and the logarithm of the number of loading cycles with the change of density as shown in Figs.8 (a) through (d) is much smoother than the change of the stress ratio with the change of density in the relationships as shown in Figs.10 (a) and (b). This kind of discussion is also valid for the torsional shear tests, CTS-I and CTS-A. In particular, it may be seen in the data obtained by this study that when the stress ratio value $\sigma_{dp}/2\sigma_c'$ is larger than around 0.23 in the triaxial tests or when the stress ratio value τ_{cy}/σ_{m_c}' is larger than around 0.3 in the torsional shear tests, the change of stress ratio either by a small change of relative density at a given number of loading cycles or by a small change of the number of loading cycles for a given density value can be very large. Therefore, the comparison of stress ratiovalues larger than these critical values shown above can be too sensitive to test variables and cannot be very accurate. Therefore, a critical analysis of the correction factor c_1 for dense sand seems rather difficult.

In view of the above, the critical number of loading cycles $(N_c)_{cr}$ were obtained for each test case. $(N_c)_{cr}$ is defined as the number of loading cycles N_c at which a certain value of strain is observed for a stress ratio $\sigma_{dp}/2\sigma_c'$ of 0.23 in a triaxial test or for a stress ratio τ_{cy}/σ_{m_c}' of 0.3 in a torsional shear test. These stress ratio values are defined as the critical stress ratioes SR_{cr}. In Figs. 29 and 30 are shown the averaged relationships between $(N_c)_{cr}$ and D_r for double amplitude shear strains (or axial strains) of (a) 3%(2%) or (b) 7.5%(5%) or (c) 15%(10%), both for Toyoura Sand and for Sengenyama Sand. It may be seen in each of these figures that the relationship is much smoother than that between the stress ratio and D_r for the similar failure criterion. A response of a sand element against a random cyclic loading can be considered to be reflecting the whole features of the strength curve of a such relationship between the stress ratio and the number of loading cycles as shown in Figs.8 (a) through (d). Thus, it can be expected that the response of a given sand element against a given random cyclic loading can be well related to $(N_c)_{cr}$. In fact, it has been found that the undrained response of a given saturated sample of Toyoura Sand against a given random loading changes smoothly with the change of density in a similar manner with $(N_c)_{cr}$ (Tatsuoka et al, 1983). Accordingly, $(N_c)_{cr}$ can be considered to be a better index than the conventional stress ratio value for the cyclic undrained strength against general random loadings of dense sand. This will be reported in more detail elsewhere by the authors.

It was also found that such relationships between the stress ratio and the number of loading cycle as shown in Figs.8 (a) through (d) collapse into a single curve for the same sample preparation method in the same test method irrespectively of both the kinds of sand used in this study and the relative density value when a normalization method as $N_c/(N_c)_{cr}$ is used (see Figs.31 (a) through (d)). Thus, combining the relationship between $(N_c)_{cr}$ and D_r and that between SR and $N_c/(N_c)_{cr}$ shown in these figures (Figs. 29 through 31), the relationship between the stress ratio SR and the number of loading cycle N_c for a given test condition can be readily obtained for a given value of D_r. Such relationships as shown in Figs. 29 through 31 can be used effectively in the analyses of the relationship between the cyclic undrained strength for sinusoidal loading and that for random loading. This will also be reported in detail elsewhere by the authors.

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 torsional shear strengths were also strongly affected by sample preparation methods as well as the cyclic undrained triaxial strength. Among the four different sample preparation methods employed, the wet-vibration method generally provided the strongest samples and the air-pluviation method generally provided the weakest samples and the other two methods, the wet-tamping method and the water-vibration method, provided the strongest samples in some cases or the weakest samples in other cases or the samples having an intermediate strength in other cases.

(2) The manners of the effects of sample preparation methods on cyclic undrained strength were not necessarily the same both for two kinds of sand tested and for two kinds of tests; the triaxial and torsional shear tests. Accordingly, the ratio of strength represented by stress ratio value between the triaxial test and the torsional shear test was found not to be unique, but a complicated function of many factors; the kind of sand, the sample preparation method, the relative density, the strain value for which failure was defined and so on. Therefore, it can be concluded that the accurate estimation of simple shear strength from triaxial strength is in general rather difficult and that to estimate a simple shear strength, it is better to perform a torsional shear test on a K_0-consolidated sample(CTS-A) or another kind of simple shear test in place of a conventional cyclic triaxial test if possible.

When the strength is expressed using τ_{cy}/σ'_{m_c}, the strength by the torsional shear test on an isotropically consolidated sample was generally similar to that on an anisotropically consolidated sample for Toyoura Sand, except for dense samples prepared either by the air-pluviation method or by the wet-tamping method.

(4) To represent the whole features of the strength curve of the relationship between the stress ratio SR and the number of loading cycles N_c at which a certain strain value is observed, the critical number of loading cycles $(N_c)_{cr}$ was found to be better than the conventional stress ratio index defined as the stress ratio for which liquefaction is induced at a certain number of loading cycles. $(N_c)_{cr}$ is defined in this study as the value of N_c at which a certain strain value is observed for the critical stress ratio $(SR)_{cr}$. $(SR)_{cr}$ is defined as the stress ratio at which the slope of the strength curve of the SR-logN_c relation has the largest curvature, which were found in this study to be $\sigma_{dp}/2\sigma_c$ =0.23 in the triaxial tests and τ_{cy}/σ'_{m_c}=0.3 in the torsional shear tests on both anisotropically and isotropically consolidated samples(CTS-I and CTS-A).

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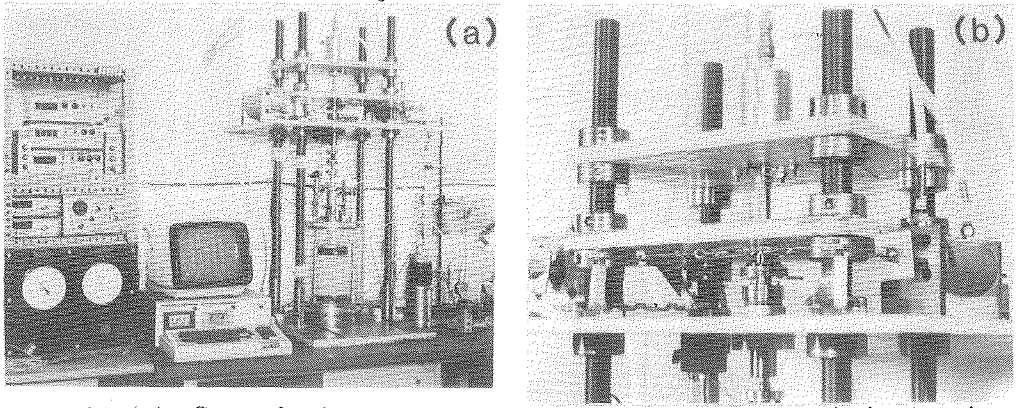


Photo.1. (a) General view and (b) force transmission part of the torsional shear apparatus.

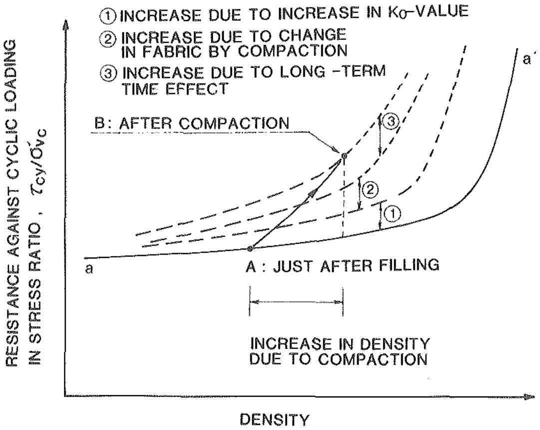


Fig.1. Schematic diagram showing probable increase in in situ cyclic undrained strength by compaction procedure.

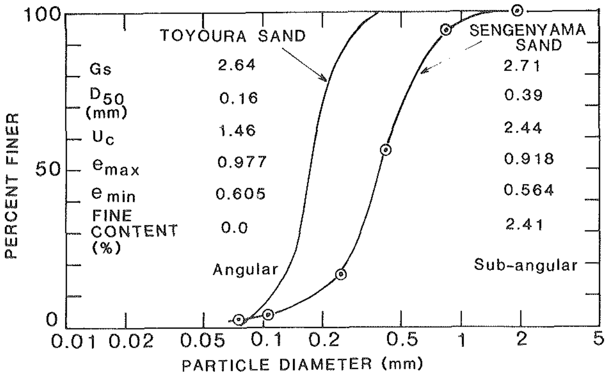
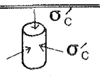
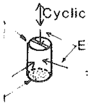
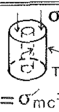
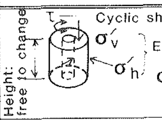
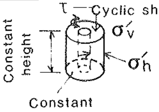


Fig.2. Grading curves of test materials.

Table 1. Physical Properties of Test Materials

	Sengenyama Sand	Toyoura Sand
Particle Shape	Sub-angular	Angular
Specific Gravity	2.71	2.64
Maximum Void Ratio*	0.918	0.977
Minimum Void Ratio*	0.564	0.605
Mean Diameter in mm	0.39	0.162
Coefficient of Uniformity	2.44	1.46
Fine Content in percent	2.41	0

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

	Consolidation	Cyclic Undrained Test
Cyclic Triaxial (CTX)	 σ'_c σ'_c T $\sigma_c' = \sigma'_{mc} = 1.0\mathrm{kgf/cm^2}$ S $\sigma_c = \sigma'_{mc} = 1.333\mathrm{kgf/cm^2}$	 Cyclic deviator stress:single amplitude= σ_{dp} Effective confining stress $= \sigma'_c - \Delta u$, Δu Excess pore pressure Porous stone
Cyclic Torsional on Isotropically Consolidated Sample(CTS-I)	 $\sigma'_{vc} = \sigma'_c$ $\sigma'_{hc} = \sigma'_c$ Toyoura Sand $\sigma'_c = \sigma'_{mc} = 1.0\mathrm{kgf/cm^2}$	 Height: free to change Cyclic shear stress:single amplitude $= \tau_{cy}$ σ'_v σ'_h Effective stress $\sigma'_v = \sigma'_h = \sigma'_c - \Delta u$
Cyclic Torsional on Anisotropically Consolidated Sample(CTS-A)	 σ'_{vc} $\sigma'_{hc} = K\sigma'_{vc}$ T $\begin{cases} K = K_o = 0.52c_i \\ \sigma'_{mc} = 1.0\mathrm{kgf/cm^2} \end{cases}$ S $\begin{cases} K = 0.5 \\ \sigma'_{mc} = 1.333\mathrm{kgf/cm^2} \end{cases}$	 Constant height Cyclic shear stress:single amplitude $= \tau_{cy}$ σ'_v σ'_h Constant cross-sectional area $\begin{cases} \sigma'_v = \sigma'_{vc} - \Delta\sigma'_v - \Delta u \\ \sigma'_h = \sigma'_{hc} - \Delta u \end{cases}$ $\Delta\sigma'_v$:decrease in total vertical stress

NOTE: (1) T:Toyoura Sand S:Sengenyama Sand
(2) $1\mathrm{kgf/cm^2} = 98\mathrm{kN/m^2}$
(3) Mean effective principal stress$((\sigma'_1+\sigma'_2+\sigma'_3)/3)$ at consolidation
(4) Consolidation time:1hr for Toyoura Sand and until the end of primary consolidation (less than 2hrs) for Sengenyama Sand

Fig.3. Stress conditions during test.

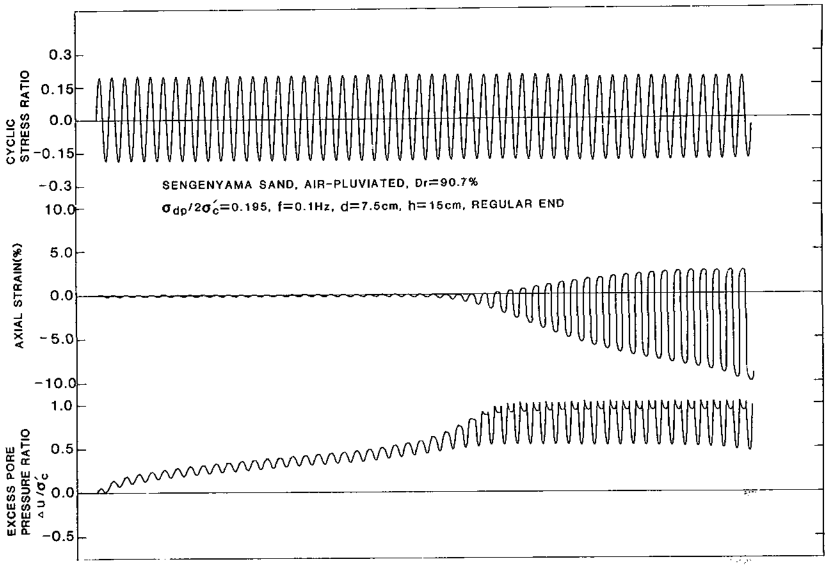


Fig.4. Typical record of cyclic triaxial test.

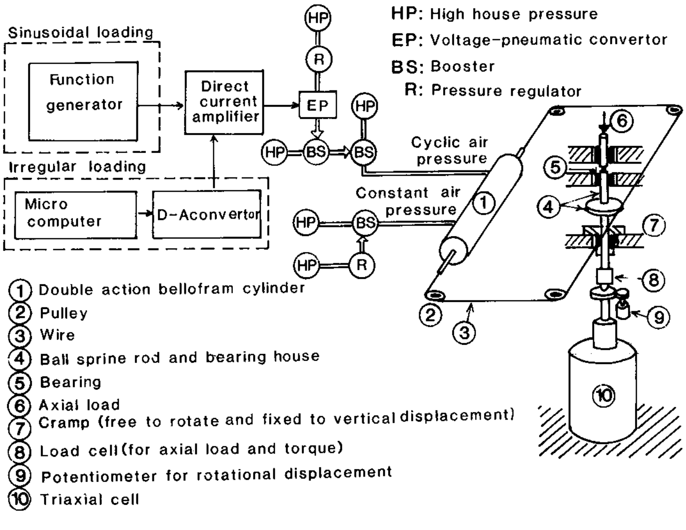


Fig.5. Schematic diagram of the modified torsional shear apparatus.

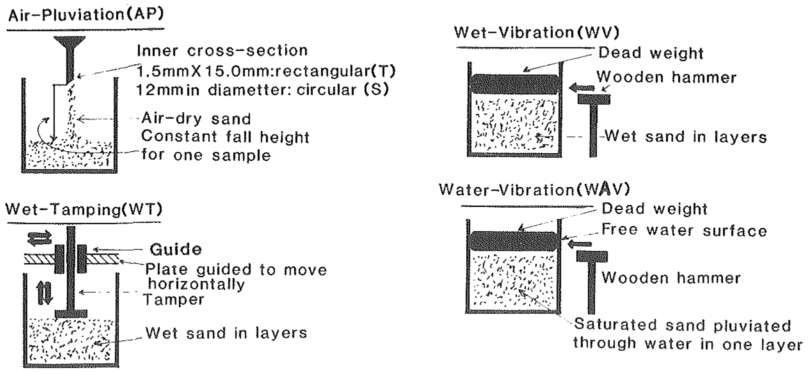


Fig.6. Schematic diagrams of four sample preparation methods.

Table 2. Details of Sample Preparation Methods

		Wet-Tamping(WT)					Wet-Vibration(WV)			Water-Vibration(WAV)		
		Tamper		Free fall height (cm)	Number of layers*	Water content of sand (%)	Dead weight in averaged stress (kgf/cm^2)	Number of layers*	Water content of sand (%)	Dead weight in averaged stress (kgf/cm^2)	Number of layers	Sand
		Footing (cm)	Weight (g)									
Toyoura Sand	CTX	3.70	185.9	3.5	6	3	0.0286	10	3	0.0286	1	Saturated
	CTS	1.645	185.9	3.5	6	3	0.0286	(5)+ 10	3	0.0286	1	Saturated
Sengenyama Sand	CTX	3.70	185.9	3.5	10	8	0.0286	10	8	0.0286	1	Saturated
	CTS	1.645	185.9	3.5	10	8	0.0286	10	8	0.0286	1	Saturated

NOTE: * The compacted surface of each layer was scarified.
+Only in some samples. Effects of number of layers 5 or 10 were found negligible.

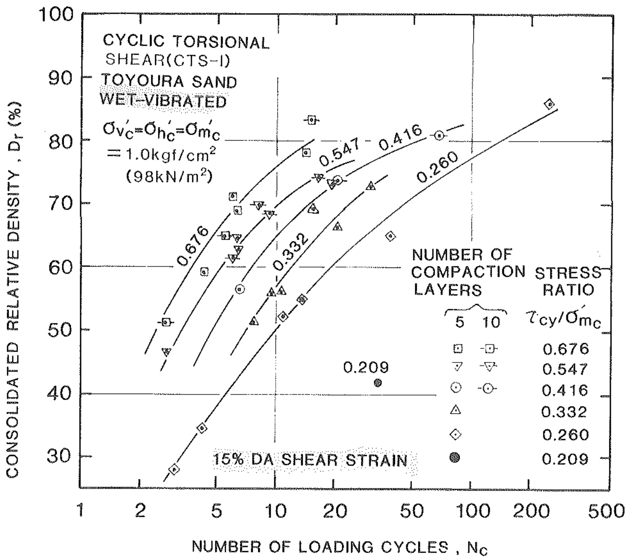


Fig.7. Typical relationships between consolidated relative density and number of loading cycles to 15% double amplitude shear strain by torsional shear tests (CTS-I) on wet-vibrated Toyoura Sand.

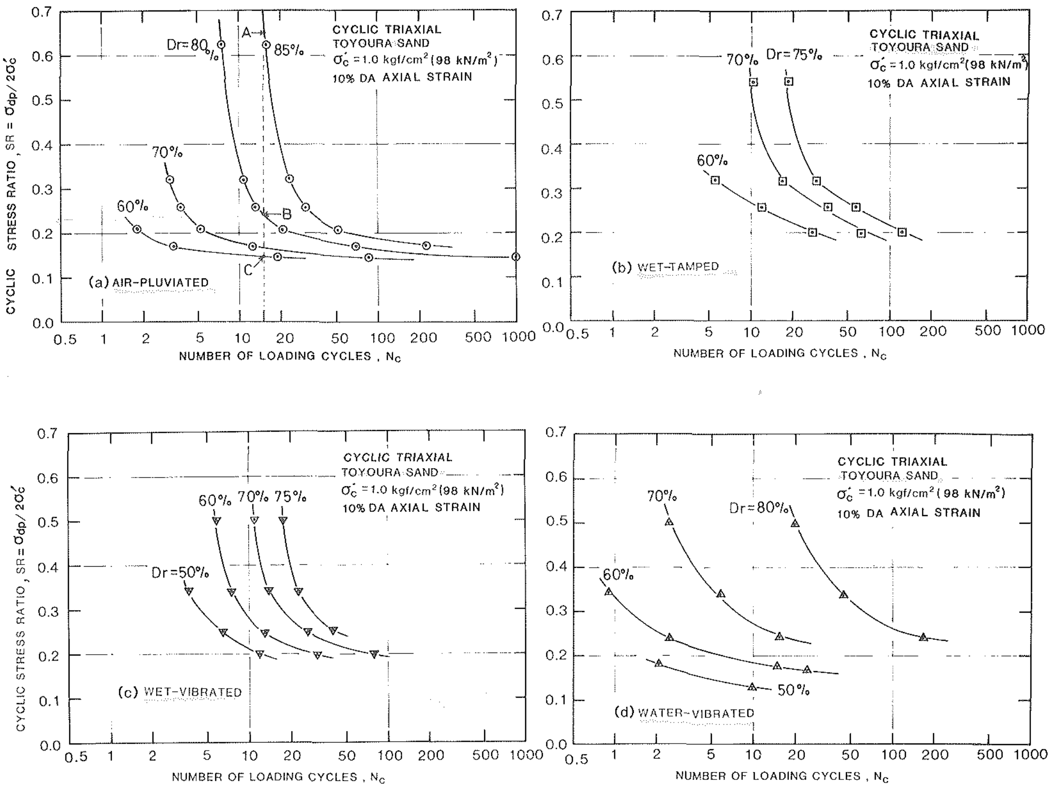


Fig.8. Relationships between stress ratio and number of loading cycles to 10% double amplitude axial strain by triaxial tests on (a) air-pluviated, (b) wet-tamped, (c) wet-vibrated and (d) water-vibrated Toyoura Sand.

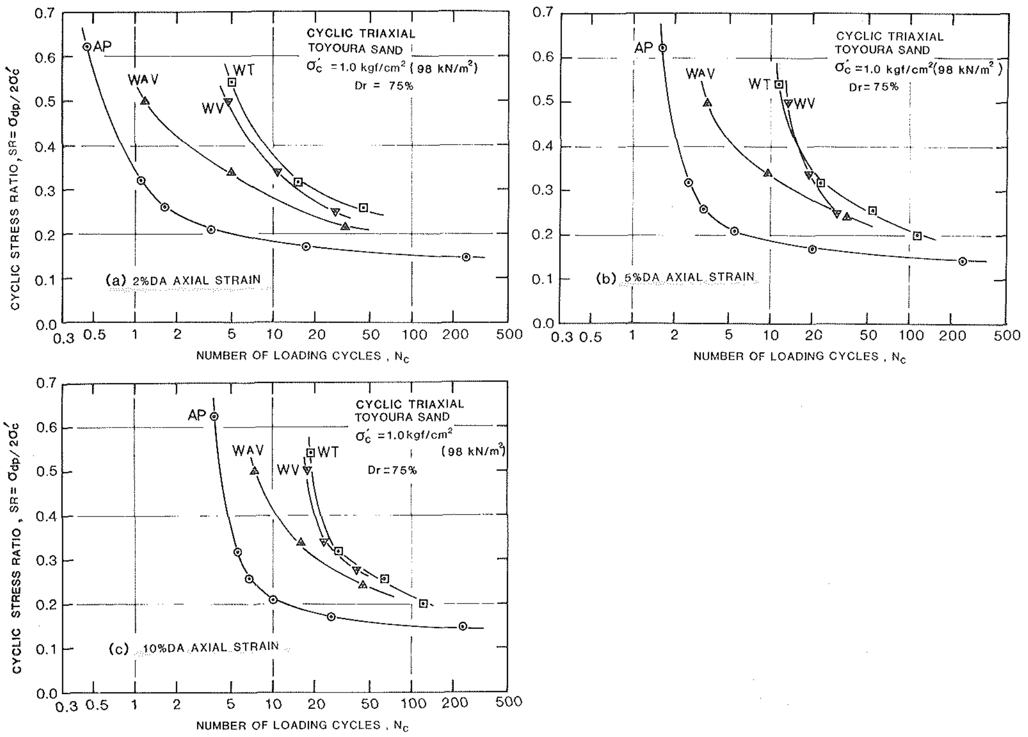


Fig.9. Relationships between stress ratio and number of loading cycles to (a) 2%, (b) 5% and (c) 10% double amplitude axial strains by triaxial tests on Toyoura Sand samples of D_r=75% prepared by four mehtods.

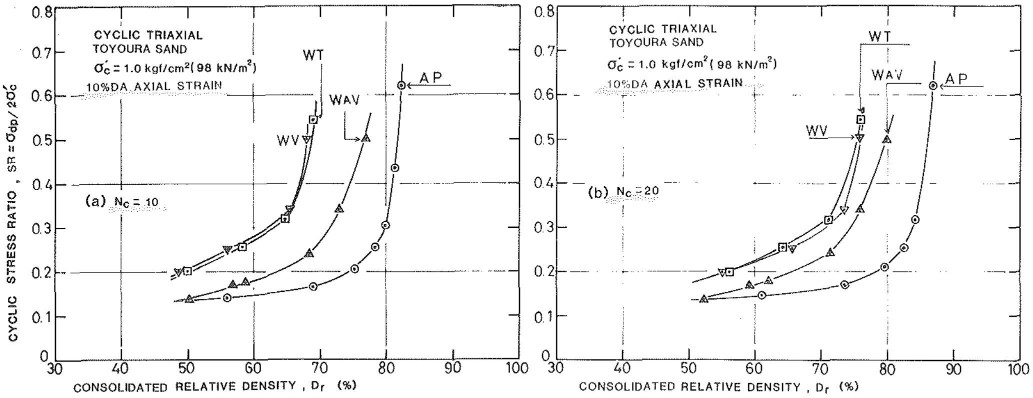


Fig.10. Relationships between stress ratio and consolidated relative density for 10% double amplitude axial strain at (a) 10th and (b) 20th cycle by triaxial tests on Toyoura Sand samples prepared by four methods.

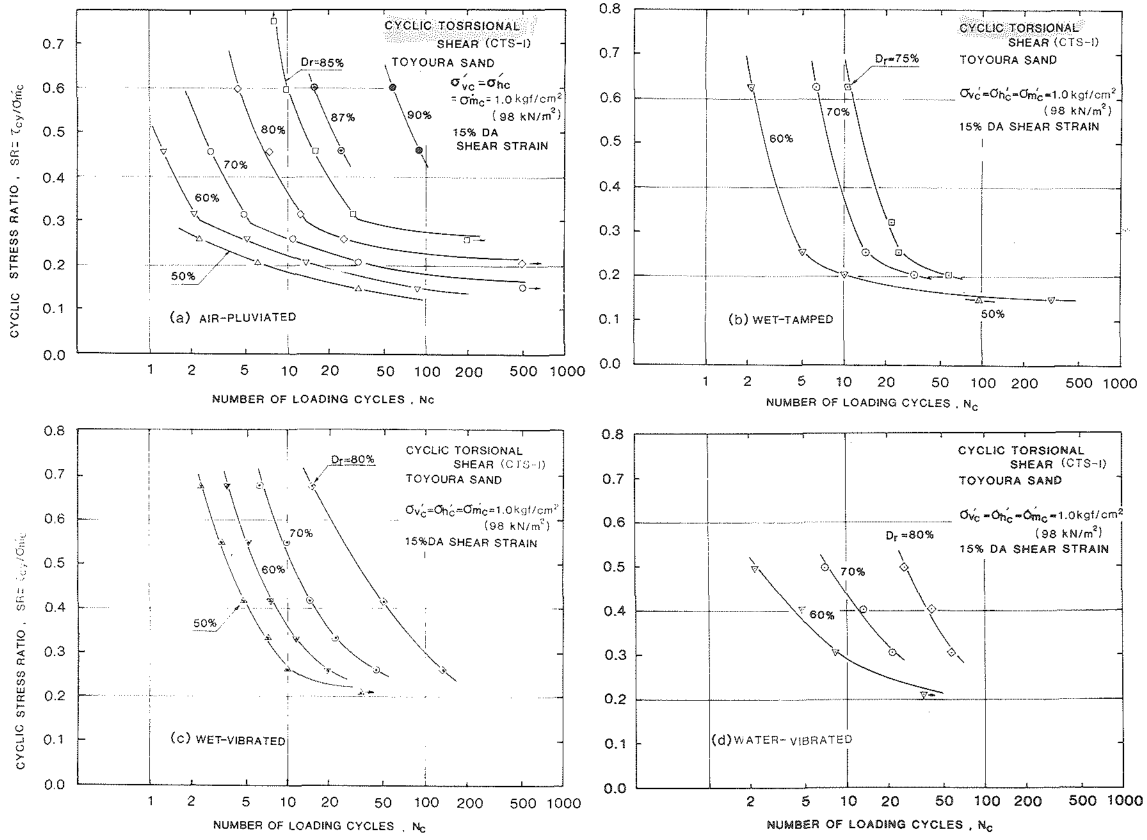


Fig.11. Relationships between stress ratio and number of loading cycles to 15% double amplitude shear strain by torsional shear tests (CTS-I) on (a) air-pluviated, (b) wet-tamped, (c) wet-vibrated and (d) water-vibrated Toyoura Sand.

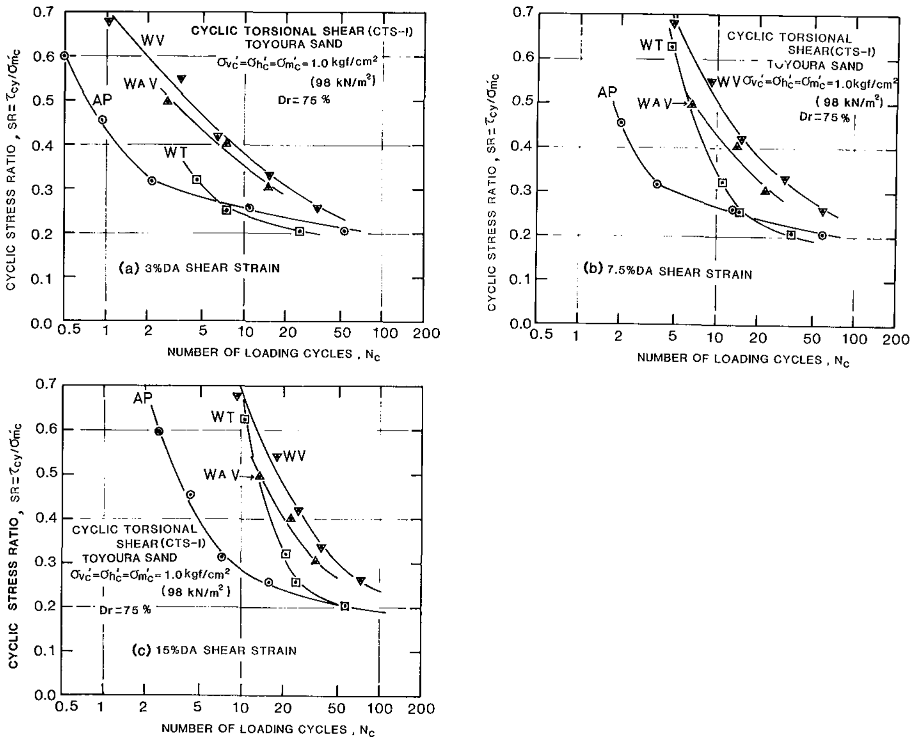


Fig.12. Relationships between stress ratio and number of loading cycles to (a) 3%, (b) 7.5% and (c) 15% double amplitude shear strains by torsional shear tests(CTS-I) on Toyoura Sand samples of D_r=75% prepared by four methods.

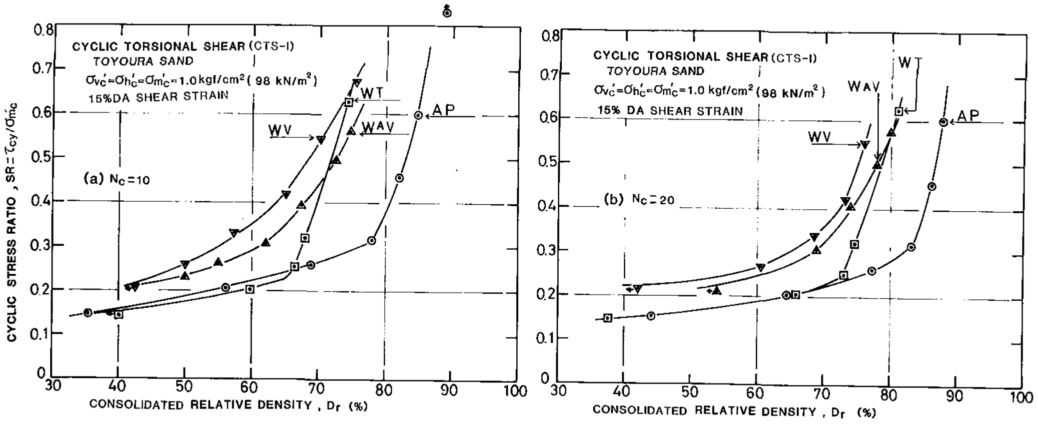


Fig.13. Relationships between stress ratio and consolidated relative density for 15% double amplitude shear strain at (a) 10th and (b) 20th cycle by torsional shear tests(CTS-I) on Toyoura Sand samples prepared by four methods.

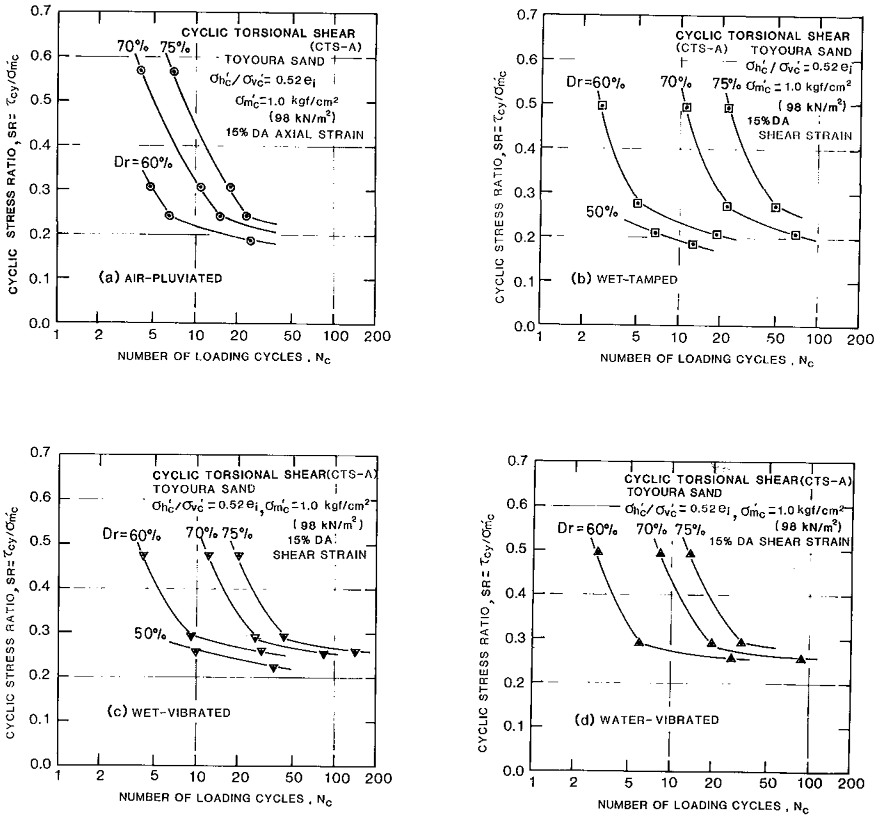


Fig.14. Relationships between stress ratio and number of loading cycles to 15% double amplitude shear strain by torsional shear tests(CTS-A) on (a) air-pluviated, (b) wet-tamped, (c) wet -vibrated and (d) water-vibrated Toyoura Sand.

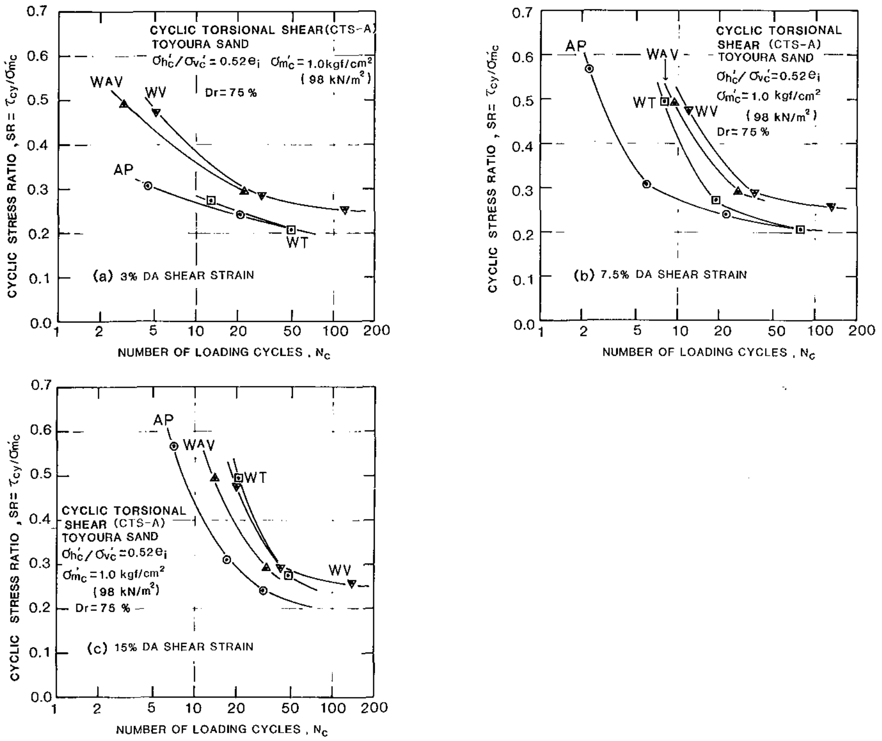


Fig. 15. Relationships between stress ratio and number of loading cycles to (a) 3%, (b) 7.5%, (c) 15% double amplitude shear strains by torsional shear tests (CTS-A) on Toyoura Sand samples of D_r=75% prepared by four methods.

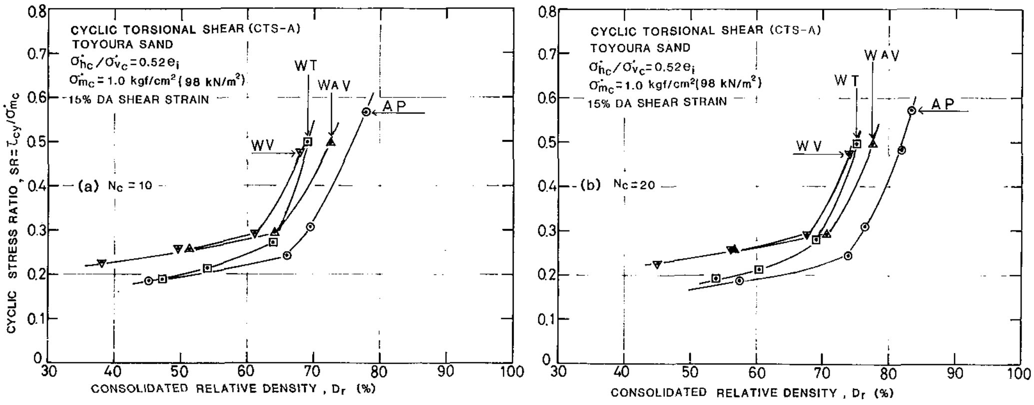


Fig. 16. Relationships between stress ratio and consolidated relative density for 15% double amplitude shear strain of (a) 10th and (b) 20th cycles by torsional shear tests (CTS-A) on Toyoura Sand samples prepared by four methods.

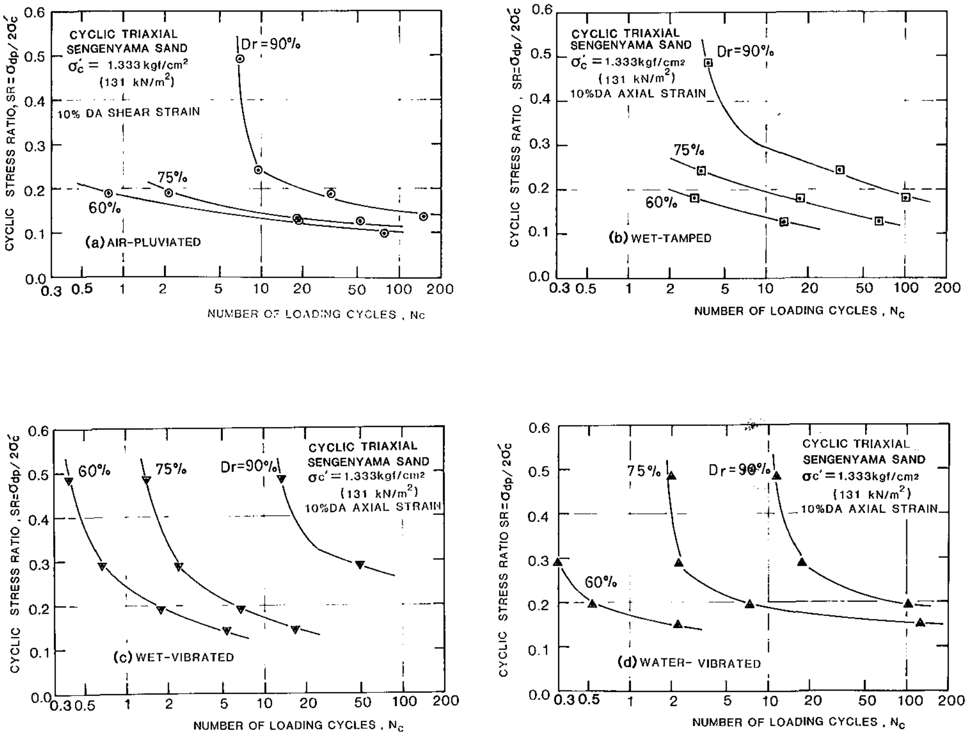


Fig.17. Relationships between stress ratio and number of loading cycles to 10% double amplitude axial strain by triaxial tests on (a) air-pluviated, (b) wet-tamped, (c) wet-vibrated and (d) water-vibrated Sengenyama Sand.

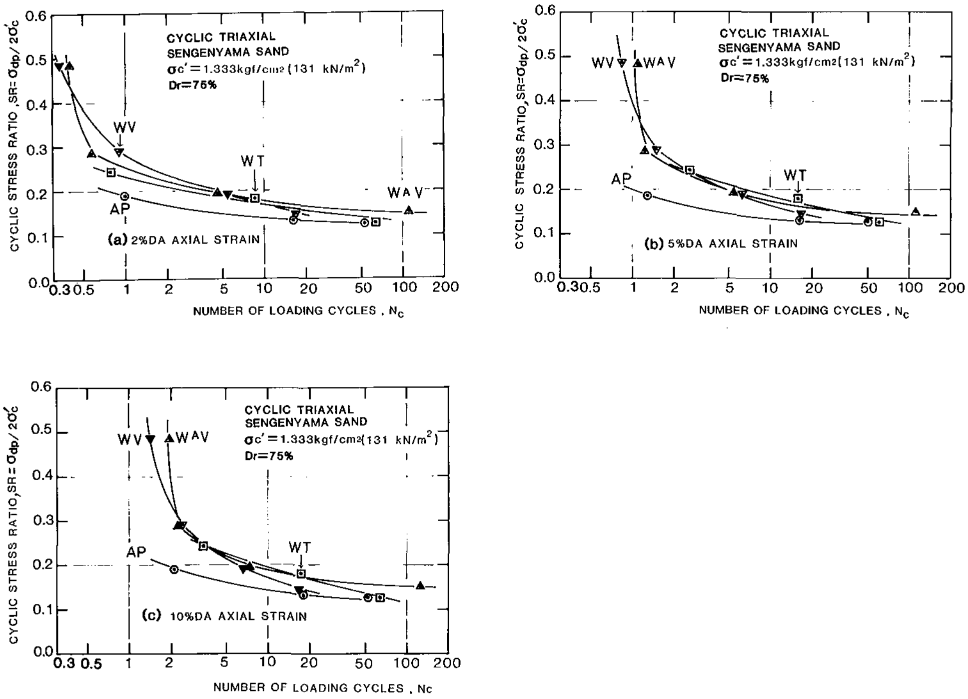


Fig.18. Relationships between stress ratio and number of loading cycles to (a) 2%, (b) 5% and (c) 10% double amplitude axial strains by triaxial tests on Sengenyama Sand samples of D_r=75% prepared by four methods.

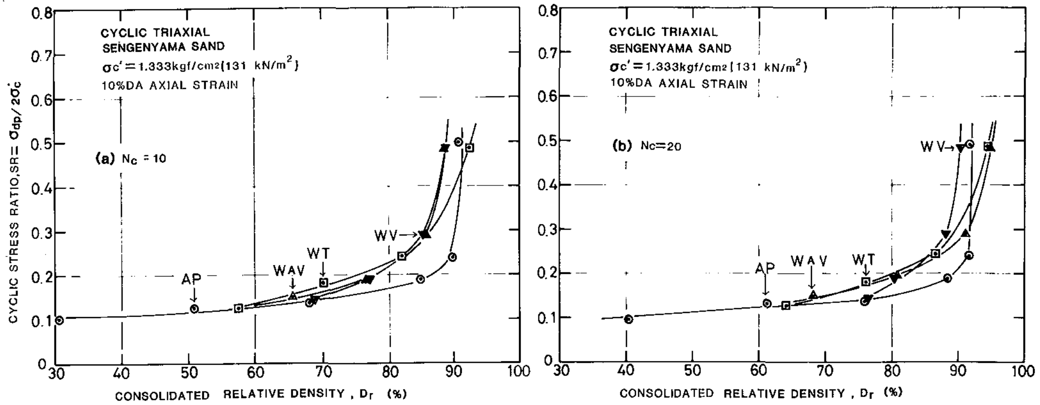


Fig.19. Relationships between stress ratio and consolidated relative density for 10% double amplitude axial strain at (a) 10th and (b) 20th cycles by triaxial tests on Sengenyama Sand samples prepared by four methods.

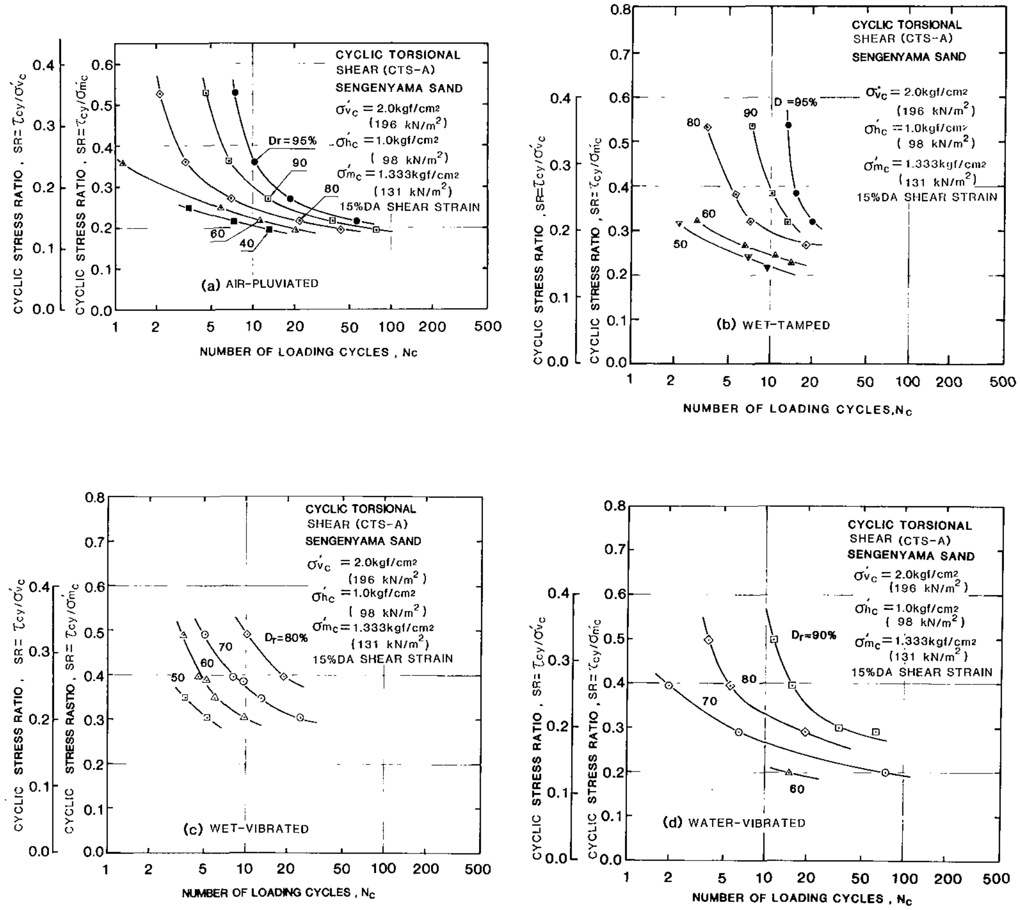


Fig.20. Relationships between stress ratio and number of loading cycles to 15% double amplitude shear strain by torsional shear tests(CTS-A) on (a) air-pluviated, (b) wet-tamped, (c) wet-vibrated and (d) water-vibrated Sengenyama Sand.

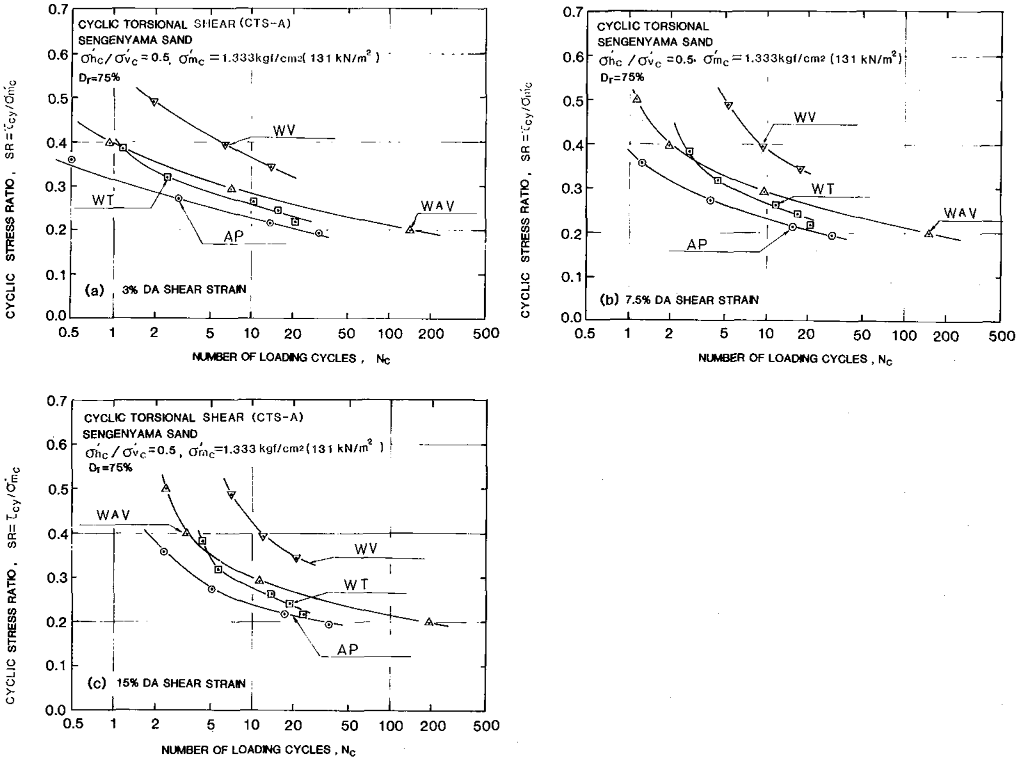


Fig.21. Realtionships between stress ratio and number of loading cycles to (a) 3%, (b) 7.5% and (c) 15% double amplitude shear strains by torsional shear tests on Sengenyama Sand samples of D_r=75% prepared by four methods.

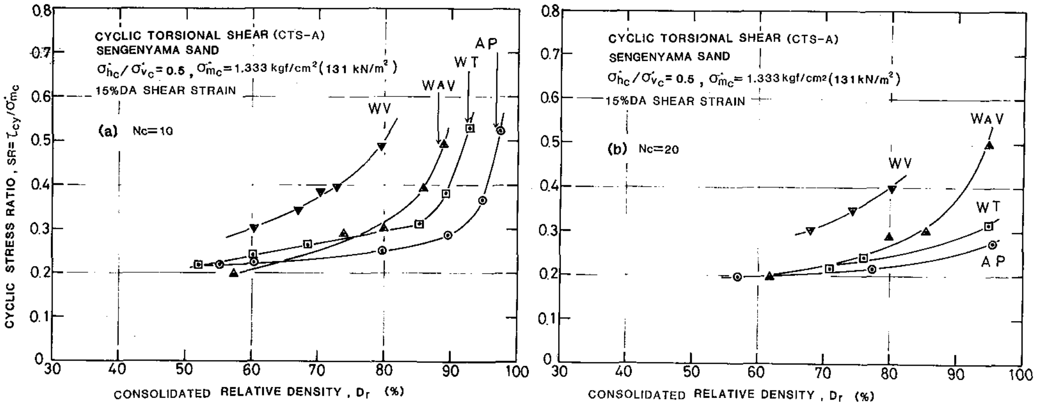


Fig.22. Relationships between stress ratio and consolidated relative density for 15% double amplitude shear strain at (a) 10th and (b) 20th cycles by torsional shear tests(CTS-A) on Sengenyama 10th and prepared by four methods.

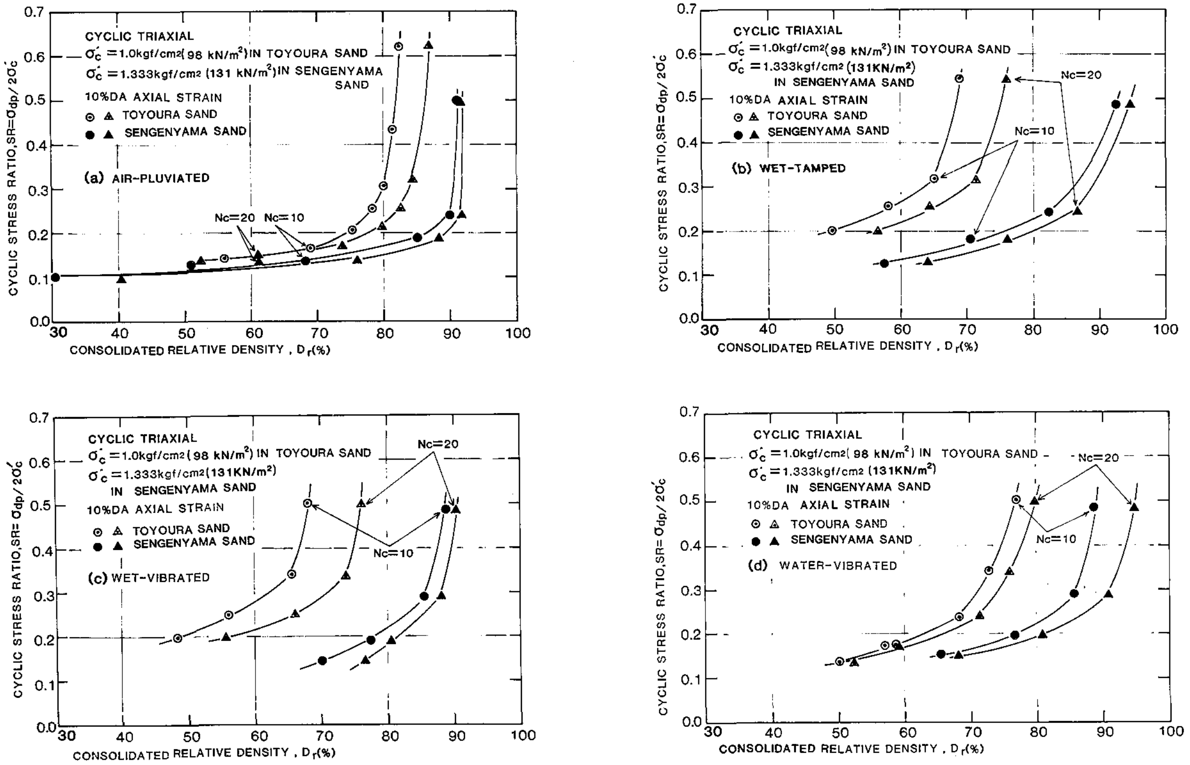


Fig.23. Comparisons of triaxial strength (stress ratio for 10% double amplitude axial strain in 10th or 20th cycles) between two test materials for (a) air-pluviated, (b) wet-tamped, (c) wet-vibrated and (d) water-vibrated samples.

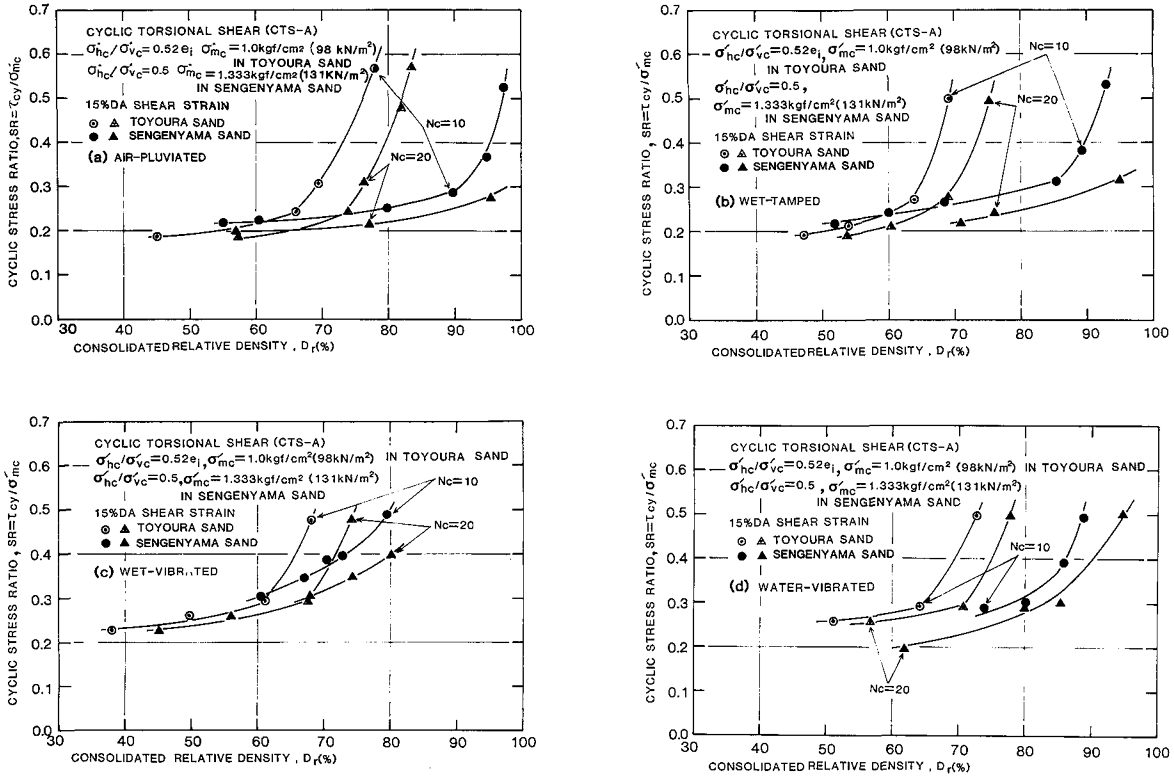


Fig.24. Comparisons of torsional shear strength by CTS-A (stress ratio for 15% double amplitude shear strain in 10th or 20th cycles) between two test materials for (a) air-pluviated, (b) wet-tamped, (c) wet-vibrated and (d) water-vibrated samples.

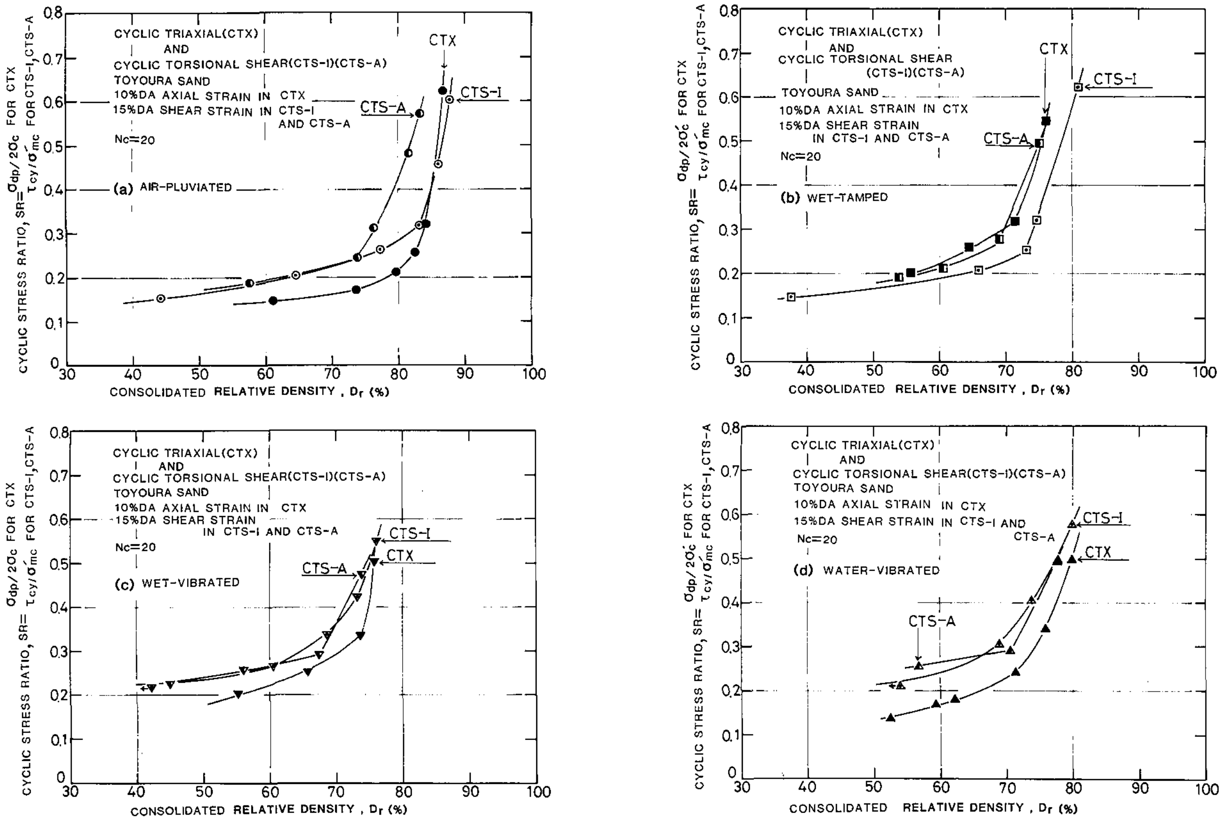


Fig.25. Comparisons between triaxial strength and torsional shear strengths by CTS-I and CTS-A for (a) air-pluviated, (b) wet-tamped, (c) wet-vibrated and (d) water-pluviated Toyoura Sand for 15% double amplitude shear strain in 20th cycle.

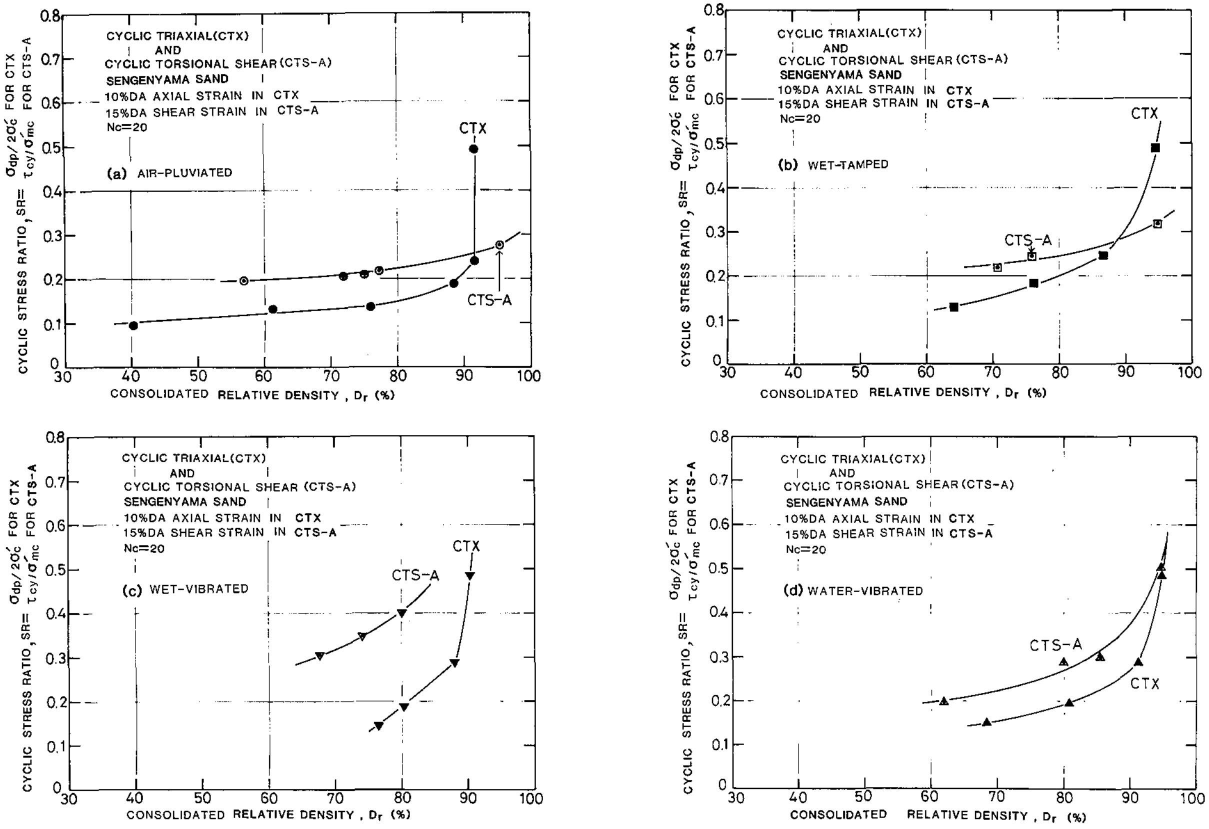


Fig.26. Comparisons between triaxial and torsional shear strength strength by CTS-A for (a) air-pluviated, (b) wet-tamped, (c) wet-vibrated and (d) water-vibrated Sengenyama Sand for 15% double amplitude shear strain in 20th cycle.

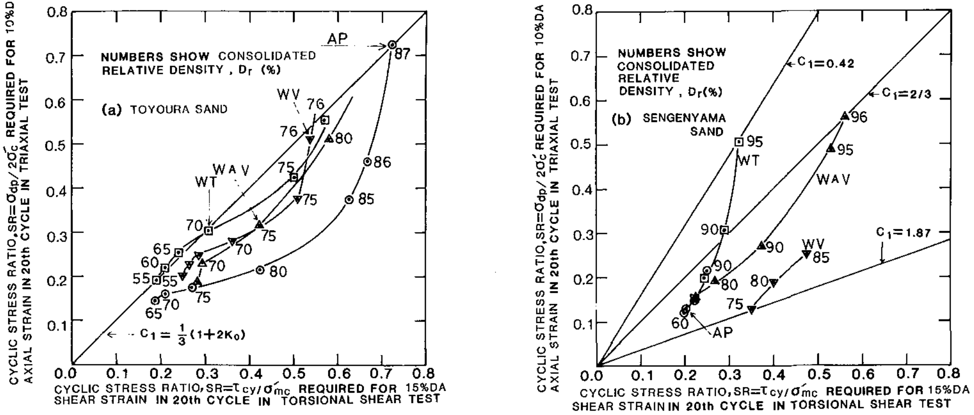


Fig.27. Comparison between triaxial and torsional shear CTS-A for failure defined as 15% double amplitude shear strain in 20th cycle for samples of Toyoura Sand and (b) Sengenyama Sand samples prepared by four methods.

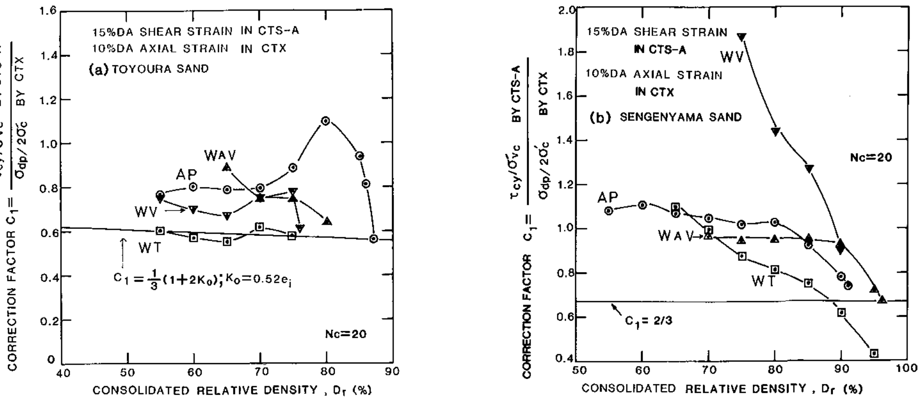


Fig.28. Correction factor c_l versus consolidated relative density obtained by this study for failure defined as 15% double amplitude shear strain in 20th cycle for samples of (a) Toyoura Sand and (b) Sengenyama Sand prepared by four methods.

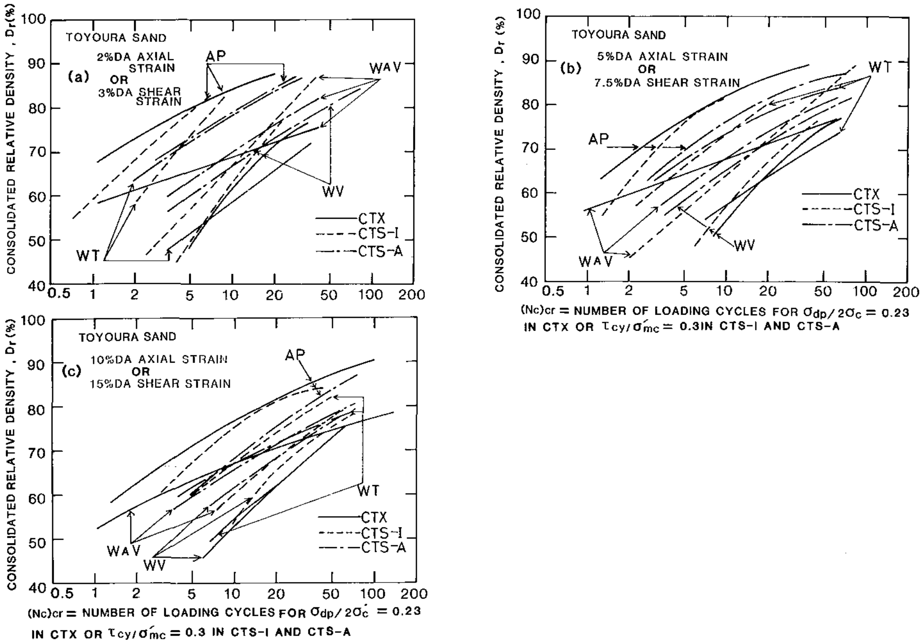


Fig.29. Relationships between the critical number of loading cycles and consolidated relative density for failure defined as (a) 3%, (b) 7.5% and (c) 15% double amplitude shear strains for Toyoura Sand.

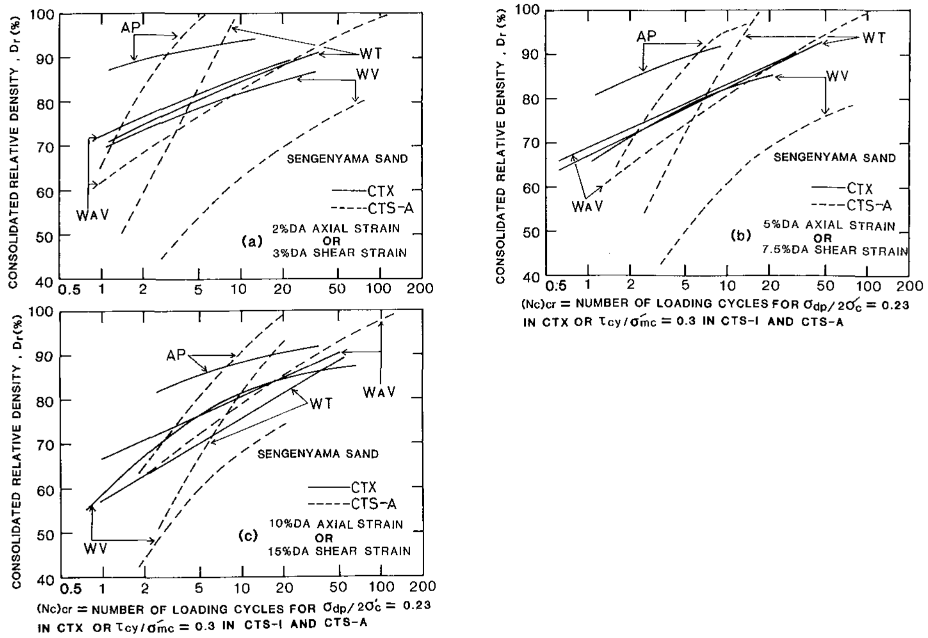


Fig.30. Relationships between the critical number of loading cycles and consolidated relative density for failure defined as (a) 3%, (b) 7.5% and (c) 15% double amplitude shear strains for Sengenyama Sand.

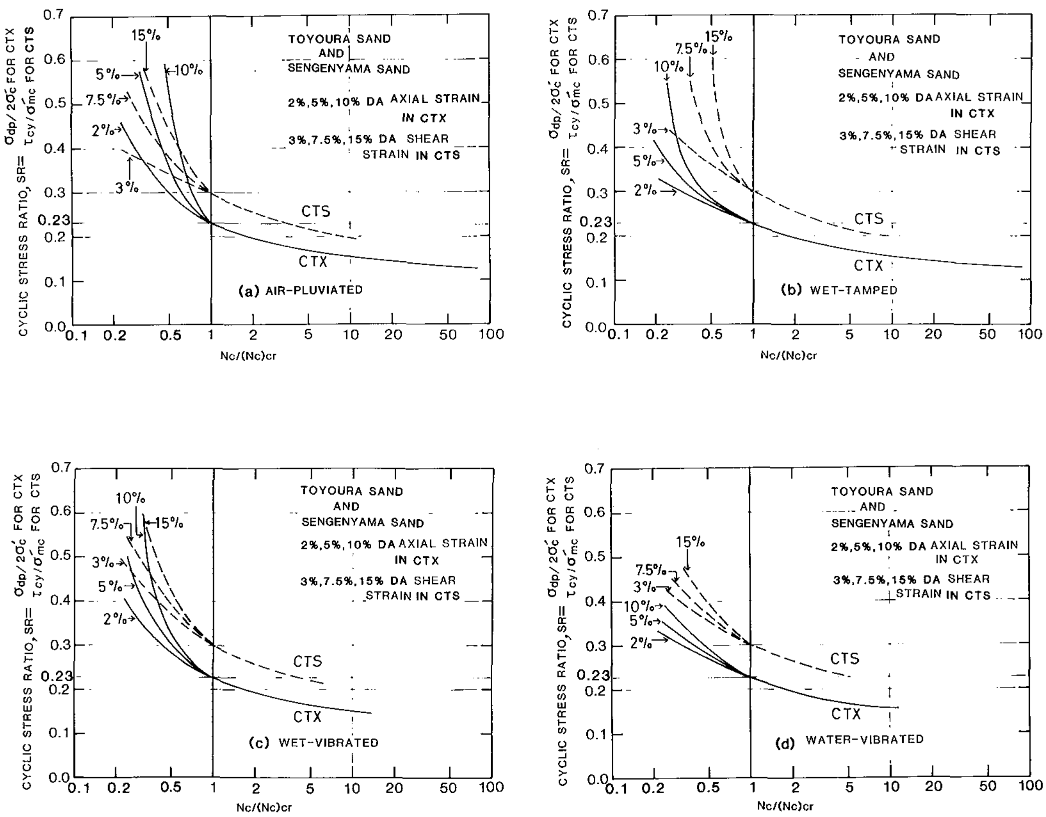


Fig.31. Relationships between stress ratio and normalized number of loading cycles for 3%, 7.5% and 15% double amplitude shear strains obtained by triaxial and torsional shear tests (CTS-I and CTS-A) on samples of two test materials prepared by (a) air-pluviation, (b) wet-tamping, (c) wet-vibration and (d) water-vibration.