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CYCLIC UNDRAINED STRESS-STRAIN BEHAVIOR OF DENSE SANDS BY TORSIONAL SIMPLE SHEAR TEST

by

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ABSTRACT

In the first part of the article a review of laboratory cyclic undrained test methods is presented. The features of the cyclic torsional simple shear device which was newly developed to assess the resistance of saturated dense sand against cyclic undrained loading are described. The test results are represented by the relationship between the relative density D_r and the cyclic shear stress amplitude normalized by the effective mean principal stress at consolidation, τ_{cy}/σ_{mc}', for which a certain value of double amplitude shear strain is observed at a certain number of loading cycles. Dense specimens of Toyoura Sand, a clean, uniform, fine sand, prepared by the air pluviation method have an extremely high resistance against cyclic undrained loading, while dense specimens of Sengenyama Sand, a medium fine sand including some fine particles, also prepared by the air pluviation method have a lower resistance as compared with Toyoura Sand. These findings show that the concept that the cyclic undrained strength of sand is proportional to the relative density is not appropriate especially for clean sands.

INTRODUCTION

Needs to evaluate precise cyclic stress strain behavior of saturated dense sand have been increased for seismic designs of critical structures such as nuclear power plants, large storage tanks or high rockfill dams which should be stable even for large earthquake motions. When a design acceleration level is low, it is reasonable to consider that dense sands have enough liquefaction strengths, without having to perform critical evaluations of the liquefaction strengths of dense sands. In past, some considered that strength of sand against liquefaction was proportional to the relative density up to a certain value of relative density, say 80 %. For example, a linear relationship have been proposed as

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$$(\sigma_{dp}/2\sigma_c')_{20} = 0.0042D_r \tag{1}$$

in which $(\sigma_{dp}/2\sigma_c')_{20}$ is the stress ratio in cyclic triaxial tests which induces liquefaction at the number of cycles of 20 and D_r is the relative density of the specimen (Ishihara (1977)). However, it is understood at present that the resistance of denser saturated sand against cyclic undrained loading is higher than evaluated by postulating that the liquefaction strength is proportional to relative density.

Silver and Tatsuoka (1981) performed a series of cyclic triaxial and NGI-type simple shear tests on Monterey No. 0 Sand specimens reconstituted by air-pluviation and wet tamping methods. Fig. 1 is a reproduction from Silver and Tatsuoka (1981). It can be clearly seen from this figure that the relationship is not linear between the relative density and the stress ratio which induces 15 percent shear strain double amplitude at the number of loading cycles of 10. Another important point which can be seen from this figure is that the cyclic undrained triaxial strength of sand prepared by tamping most soil may give an overestimate of the liquefaction strength in horizontal sand deposit for which a laboratory simple shear simulation is an appropriate measure of cyclic strength. It can also be noted that even for the dense sand with a relative density of 80 % prepared by pluviating dry sand, the triaxial strength may be larger than the simple shear strength.

On the other hand, many consider that in the NGI-type simple shear tests, the stress and strain conditions in specimens may be considerably ununiform due to the lack of conpensating shear stresses on the vertical boundaries of specimen. Due to this fact, it can be considered that the ununiform stress and strain conditions may give an underestimate of the cyclic undrained simple shear strength especially for dense sands.

DeAlba, et al. (1975) performed large simple shear tests using very long and shallow test specimens (90 inches long by 40 inches wide by 4 inches deep) which were cyclically excited on a shaking table for evaluating cyclic simple shear strength which are free from the disadvantages inevitable in small simple shear tests. It was shown by DeAlba, et al. (1975) that the shear strain amplitude induced in dense specimens are not unlimited even after considerable number of loading cycles, but the amount of shear strain was limited to a certain value for dense specimens, with limited amount of shear strain being decreased with the increase in density. Since this type of large simple shear test in which a specimen is placed on a shaking table, it is rather difficult to keep the cyclic shear stress amplitude constant in the course of liquefaction because of a large variation of the natural frequency of the specimen due to a large reduction in the rigidity of specimen. Furthermore, due to other two features, very expensive to perform and having a large system compliance, this type of test will not be used as a routine laboratory test to assess liquefaction characteristics.

To overcome the disadvantages inevitable in convensional type of simple shear test which has end boundaries, torsional simple shear devices have been developed in which hollow cylindrical specimens (Fig. 2) are used (Ishihara and Li (1972), Ishihara and Yasuda (1975), Yoshimi and Oh-Oka (1973) and Ishibashi and Sherif (1974)). Since a hollow cylindrical specimen has no end boundaries, the specimen can be considered free from stress concentration problems. Ishihara and Yasuda (1975) showed that the cyclic torsional simple shear strength of a loose sand specimen prepared by pluviating through water is similar to the cyclic triaxial strength when the cyclic shear stress amplitude is normalized by the effective mean principal stress at consolidation.

Presented herein are the cyclic torsional simple shear test results which were performed to assess the liquefaction characteristics of sands having a wide range of density (D_r = 40 % to 100 %). It was found that dense specimens of a clean, uniform fine sand including no fine particles has an extremely large resistance against cyclic undrained loadings, while dense specimens of a medium fine sand having some fine contents do not show such a large resistance.

TEST PROGRAM

Two kinds of sand were selected for this study. The first one is Sengenyama Sand from deposits of diluvial origin, which has been widely used for hydraulic fill reclamation projects in Tokyo Bay area. The physical properties are listed in Table 1. The other sand is Toyoura Sand, a commercially available washed and sieved beach sand. This is a uniform, subangular, fine sand which has been widely used for liquefaction studies in Japan. The physical properties of this sand is listed in Table 1.

To prepare specimens, the air-pluviation method was adopted, which consists of pluviating air dry sand into a mold from a tube keeping the height of fall constant. Densification of the specimens was accomplished by increasing the height of fall. A high degree of saturation was achieved by circulating CO_2 and de-aired water through a specimen and applying a back pressure of 98 kN/m^2 or 196 kN/m^2. The lowest B-value allowed in this test program was 0.96. Most of the measured B-values were larger than 0.98.

A torsional simple shear device (Fig. 3) which was recently developed in the Institute of Industrial Science, the University of Tokyo was used for this investigation. The senior author drew the plans under the supervision of the second author. The stuff members of the workshop in the Institute machined the major parts of the device. A pneumatic cyclic loading system was employed. Cyclic linear motion of the piston of a Bellofram cylinder is converted to cyclic rotational movement of the vertical loading ram through a stretched wire, four pulleys and a wheel (see Photo. 1). The other Bellofram cylinder is placed on the top plate of the device for providing a vertical load to the specimen. A torque pick up is located outside of the cell. It was found that the friction of the air-seal-type piston was negligible. The torque pick up was calibrated by producing a moment force with use of dead weights. For this purpose, a device was developed.

A hydrostatic confining pressure is provided to confine a hollow cylindrical specimen which is enclosed with outside and inside conventional rubber membranes. The hollow cylindrical specimen was 100 mm in outer diameter, 60 mm in inner diameter and 100 mm high. Six 1.5 mm high stainless blades were fixed on the surfaces of porous stone of the top cap and the bottom pedestal to prevent slippage of the sand.

One of the most attractive features of this new apparatus is that the cyclic undrained shear test on saturated specimens in the plane strain condition can be easily performed in a rather simple manner with knowing the effective stress condition throughout consolidation and cyclic loading. With this apparatus, the plane strain condition for undrained saturated specimens is achieved by preventing the axial deformation of specimen by locking vertically the vertical load ram with allowing only its rotational movement. A usual lucid cell is used as in the conventional triaxial test. The adoption of a low friction air sealing for piston makes it possible to place a strain-gauge type load transducer both for torque and axial load out of the cell without involving testing errors due to piston friction. A slender loading ram with a diameter of 20 mm is used in order that the air sealing works satisfactory. In the author's laboratory, same conventional triaxial cells can be used both for triaxial tests and for torsional simple shear tests. For triaxial tests, linear motion bearings are used and these are replaced with stroke bearings for torsional simple shear tests. These arrangements makes the device used in this study much simpler than any of existing other cyclic torsional simple shear devices.

Two different consolidation stress conditions were adopted as:

(1) Specimens of Toyoura Sand were consolidated isotropically to $\sigma_{vc}' = \sigma_{hc}' = 98$ kN/m^2 (σ_{vc}' and σ_{hc}' are the effective vertical and horizontal stresses at consolidation, respectively.), and

(2) Specimens of Toyoura Sand and Sengenyama Sand were consolidated to anisotropic stress conditions. For Toyoura Sand, specimens were consolidated with the ratio of σ_h' to σ_v' being kept equal to measured K_0-values by another test program up to a stress condition where the value of mean principal stress $\sigma_{mc}' = (\sigma_{vc}' + 2\sigma_{hc}')/3$ equaled 98 kN/m^2. The K_0-values used were measured for normally consolidated triaxial specimens by Oh-kochi, et al. (1981) as,

$$K_0 = 0.52\, e_i \tag{2}$$

where e_i is the initial void ratio. Since the K_0-values for Sengenyama Sand were not measured, the following method was adopted. Specimens were first consolidated isotropically to $\sigma_v' = \sigma_h' = 98$ kN/m^2. Then, the σ_v' value was increased to 196 kN/m^2. Thus, the ratio of σ_{hc}' to σ_{vc}' was 0.5 irrespectively of the density of specimen.

After consolidating the specimens under the stress condition as above for 2 hours, a cyclic undrained test was performed. For an isotropically consolidated specimen, the vertical loading ram was free to move vertically during torsional cyclic loading. For an anisotropically consolidated specimen, the height of specimen is kept constant under undrained condition during torsional cyclic loading. During a cyclic test the total horizontal stress, which was the chamber pressure, was kept constant. The total vertical stress, which was measured with a load cell placed above the chamber, decreased when the specimen began to liquefy. Since during the cyclic test both the vertical and volumetric strains were zero, the change in cross area of the specimen was also zero during cyclic loading. It is not unreasonable to assume that the outside and inside diameters were kept constant during cyclic loading. In this case, no change in the cross area results in no horizontal strain. This is similar to the in situ condition in level ground during earthquake shaking. It is to be noted that to maintain constant height is not to produce a constant volume condition, which is achieved by the undrained condition of saturated specimen. Therefore, the degree of effects of system compliance on test results can be considered similar to that in the conventional cyclic triaxial test. It was considered that errors due to membrane penetration effects was not significant due to the small values of D_{50} of sands tested. Furthermore, to reduce system compliance the length of stiff synflex tube with an outer diameter of 3.18 mm and an inner diameter of 1.6 mm was reduced to a minimum value and the number of ball valves was also reduced to only four. Test conditions are listed in Table 2.

TEST RESULTS

A typical time history of shear stress, shear strain and excess pore pressure obtained for an isotropically consolidated Toyoura Sand specimen at a consolidated relative density of 82.3 % is shown in Fig. 4. It can be seen from this figure that the amplitude of cyclic shear stress is maintained constant during cyclic loading without being affected by the development of large shear strain. This fact shows that the pneumatic cyclic loading system worked very satisfactorily. It is very important to maintain a constant cyclic shear stress amplitude especially for liquefaction tests on dense specimens in order that the cyclic shear strength for dense sands can be better defined by cyclic shear strain amplitude values.

Since it was found after several trials that it is not easy to reconstitute a hollow cylindrical specimen at a prescribed density by the air pluviation method. Therefore, several specimens having different arbitary relative density values were tested using an identical cyclic stress ratio. These relative density values ranged from around 40 % to around 90 % for Toyoura Sand and from around 45 % to around 100 % for Sengenyama Sand. For one value of cyclic stress ratio amplitude a relationship was established between the consolidated relative density D_r and the number of loading cycles N_c at which a certain value of shear strain double amplitude γ(DA) was observed (Fig. 5). This procedure was repeated for several different values of cyclic stress ratio. Other figures similar to Fig. 5 were prepared for γ(DA) = 1.5 %, 3 % and 7.5 % and initial liquefaction. From such figures, the relationship as shown in Figs. 6(a) and 6(b) were obtained. In these figures, τ_{cy} means the amplitude of cyclic shear stress and σ_{mc}' is the mean principal stress during consolidation which equals σ_{vc}' or σ_{hc}' for isotropically consolidated specimens. It may be seen from Fig. 6(a) that for D_r = 60 %, relationships between τ_{cy}/σ_{mc}' and N_c are smooth for any values of γ(DA). For D_r = 80 %, as shown in Fig. 6(b), a large increase in τ_{cy}/σ_{mc}' can be seen with the decrease in N_c for N_c less than around 10. Fig.7 shows the relationship between the stress ratio τ_{cy}/σ_{mc}' and the number of loading cycles N_c to 15 % double amplitude shear strain for D_r values of 50 %, 60 %, 70 %, 80 % and 85 %. Inspection of this figure shows that dense Toyoura Sand has significant large resistances against cyclic undrained torsional simple shear loading for smaller numbers of loading cycles. It is also important to note that even for a large number of loading cycles, say larger than 50, dense specimens tested in this study has a resistance much larger than loose specimens. Similar trends, but much less clearly, has been reported for large simple shear tests by DeAlba, et al. (1975). Fig. 8 shows the test results by conventional cyclic triaxial tests with regular porous stone ends on wet tamped Monterey No. 0 Sand with relative density values of 45 %, 60 %, 70 % and 80 %. It may be seen from this figure that the variation in stress ratio by density variation at a number of loading cycles of around 100 is very small as compared with the data shown in Fig. 7. Such small difference may be reflects the redistribution of void during triaxial cyclic loadings in dense specimens, which is ofcouse better to avoid.

The relationships between the stress ratio τ_{cy}/σ_{mc}' and the relative density D_r for failure defined as 3 %, 7.5 % and 15 % double amplitude shear strains in the tenth and twenties loading cycles are shown in Figs. 9(a) and 9(b) respectively. These relationships were determined directly the D_r versus N_c relationships as shown in Fig. 5. It can be clearly seen from these figures that the cyclic undrained strength of Toyoura Sand obtained by this test program is significantly large for a relative density value larger than around 80 %. The relative density from which cyclic undrained strength increases significantly for the further increase in relative density will be defines as critical relative density $(D_r)_{critical}$. The value of $(D_r)_{critical}$ is a function of at least number of loading cycles and shear strain amplitude values. It will be shown later that the value of $(Dr)_{critical}$ is also a function of kind of sand and boundary strain condition. It may be considered that at a relative density which is around 10 % larger than the critical relative density, the sand has an extremely large resistance against cyclic undrained loading. The presence of the critical relative density as defined above can also be seen in Fig. 1 for wet tamped and air pluviated Monterey No. 0 Sand in the case of cyclic triaxial tests. However, the values of $(Dr)_{critical}$ can not be determined in Fig. 1 as clearly as in Fig. 9(a) and 9(b) due to the limited numbers of relative density examined. On the other hand, the critical relative density can not be seen in Fig. 1 in the case of cyclic simple shear tests. This may be due to the underestimate of cyclic undrained strength of dense sand in the case of cyclic simple shear tests which have some inevitable detects decribed before.

Figs. 10(a) through 10(c) show typical time histories of shear stress, shear strain, excess pore pressure and total vertical stress decrease obtained for loose, medium and dense Sengenyama Sand by cyclic torsional simple shear tests under the plane strain condition. The relationship between the double amplitude shear strain, γ(DA), and the number of loading cycles, N_c, obtained from the data in Figs. 10(a) through 10(c) are replotted in Figs. 11(a) through 11(c). The number of loading cycles where a certain value of γ(DA) was attained was determined as shown in Figs. 11(a) through 11(c) for any test result in this investigation. Figs. 12(a) through 12(c) give the time history values of σ_v' and σ_h' calculated from the traces in Figs. 10(a) through 10(c) taken when the cyclic horizontal stresses were zero. The method of calculating the values of σ_v' and σ_h' from measured values are illustrated in Fig. 13.

Effective stress paths constructed from the values shown in Figs. 12(a) through 12(c) are shown in Figs. 14(a) through 14(c). Smooth curves seen in these figures, which are very similar to the K_0-rebound curves by conventional K_0-tests, may indicate that the arrangements provided for the cyclic plane strain tests worked very satisfactorily. Similar test results were obtained by plane strain undrained cyclic torsional simple shear tests on K_0-consolidated Toyoura Sand specimens, while the data are not shown here due to the limited space.

Test results for Sengenyama Sand are summarized in Fig. 15 as the relationship between the relative density and the number of loading cycles where 15 % double amplitude shear strains were attained for several values of τ_{cy}/σ_{mc}', in which $\sigma_{mc}' = (\sigma_{vc}' + 2\sigma_{hc}')/3$ is the mean effective principal stress during consolidation. Figures for double amplitude sbear strains of 1.5 %, 3 % and 7.5 % similar to Fig. 15 were also prepared. The relationships between the stress ratio τ_{cy}/σ_{mc}' or τ_{cy}/σ_{vc}' and the number of loading cycles N_c for relative density values of 60 % and 95 % are shown in Figs. 16(a) and 16(b). It may be seen in Fig. 16(a) that the strength defined for 15 % double amplitude shear strain increases with decreasing N_c for N_c

less than around 10 in the case of D_r = 95 %. Fig. 17 shows the relationship between the stress ratio and the number of loading cycles where 15 % double amplitude shear strain was observed for relative density values of 40 %, 60 %, 80 %, 90 % and 95 %. It is important to note that the rate of the increase in strength for larger relative densities is not as significant as in the case of Toyoura Sand.

Stress ratio values for 15 % double amplitude shear strain at the number of loading cycles of 10 for anisotropically consolidated specimens of Sengenyama Sand and Toyoura Sand were compared with those for isotropically consolidated Toyoura Sand specimens as in Fig. 18. Note that the amplitude of cyclic shear stress for anisotropically consolidated specimens are normalized by the mean principal stress at consolidation σ_{mc}'. It is seen from Fig. 18 that a clear critical relative density may also be defined for anisotropically consolidated Toyoura Sand. However, for Sengenyama Sand, the value of the critical relative density is much larger than for Toyoura Sand. This difference between Sengenyama Sand and Toyoura Sand may be due to its difference in fine content. Sengenyama Sand contains fine particles to some extent which may somewhat prevent larger particles to locate in more stable positions when pluviated through air. On the other hand, Toyoura Sand is a clean uniform sand which does not involve any fine particle. Therefore, particles of Toyoura Sand may be easier than Sengenyama Sand to locate in stable positions when pluviated through air. These facts also show that cyclic undrained stress-strain relationship depends on not only relative density but also other factors. Further researches are necessary to clarify these unknown factors.

CONCLUSIONS

On the basis of the limited number of tests reported in this paper on the cyclic undrained strength of dense sands by cyclic torsional simple shear tests, the followings were found:

(1) Cyclic undrained torsional simple shear tests under the plane strain condition on anisotropically consolidated specimen can be easily performed with knowing effective stress conditions throughout tests by using the newly developed device in which a pneumatic cyclic loading system, an air-sealing for piston and a locking device for the vertical loading ram are provided.

(2) Cyclic undrained strength of Toyoura Sand, a clean, uniform, fine sand, is extremely high for a smaller number of loading cycles when 7.5 % or 15 % double amplitude shear strain are used as failure criteria, while Sengenyama Sand, a medium fine sand including some fine particles, does not have such an extremely high strength as for Toyoura Sand.

(3) The concept that the cyclic undrained strength of sands is proportional to relative density may gives an underestimated value for dense clean sands.

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Table 1. Physical Properties of Sands Tested

	Sengenyama Sand	Toyoura Sand
Particle Shape	Subangular	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	0.23	0.14
Coefficient of Uniformity	2.87	2.64
Fine Content in percent	1.63	0

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

The values of e_{max} and e_{min} by the method proposed by Yoshimi and Toh-no(1972) were as follows.

$$\left.\begin{aligned} e_{max} &= 0.96 \\ e_{min} &= 0.64 \end{aligned}\right\} \text{ for Toyoura Sand}$$

Table 2. Testing Procedure

Wave Form	Sine(0.5Hz)
Loading Equipment	Pneumatic
Torque pick up	Outside of the cell
Piston seal	No seal
Specimen outer diameter in mm	100
Specimen inner diameter in mm	60
Specimen hight in mm	100
Specimen made on cell	yes
Time to saturate	2hr
Back pressure in kN/m^2	98 or 196
Consolidation pressure	$\sigma_{vc}'=\sigma_{hc}'=98kN/m^2$ or $\sigma_{hc}'/\sigma_{vc}'=K_0$ and $\sigma_{mc}'=(\sigma_{vc}'+2\sigma_{hc}')/3$ $=98kN/m^2$ for Toyoura Sand, and $\sigma_{vc}'=196kN/m^2$ and $\sigma_{hc}'=98kN/m^2$ for Sengenyama Sand
B-value	0.96 or more

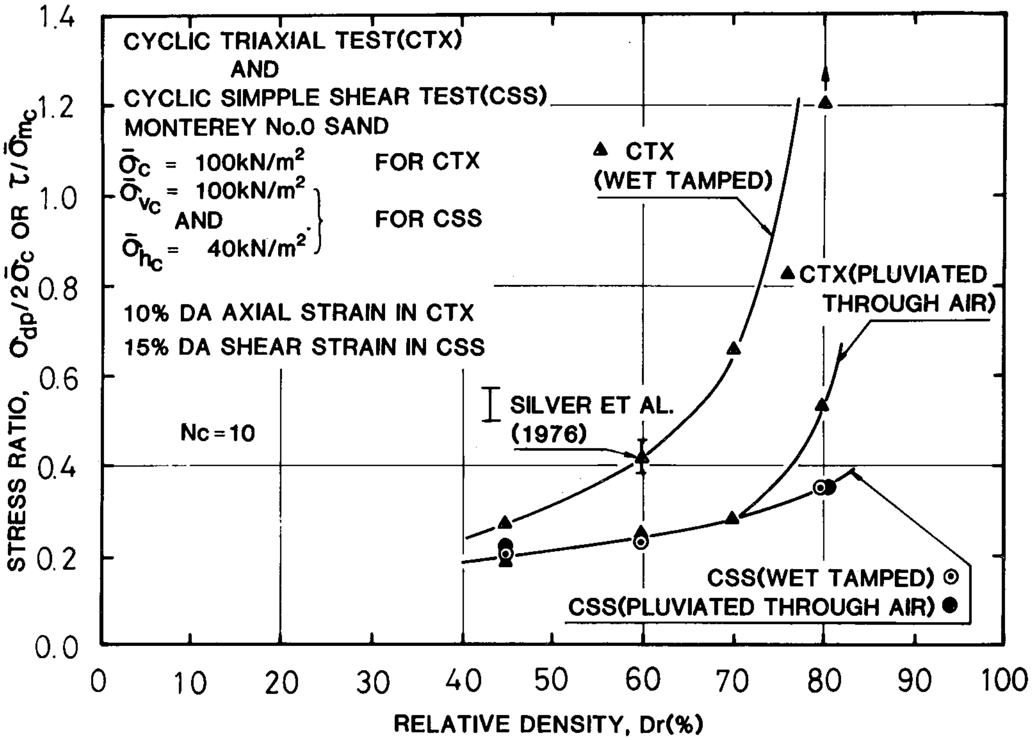


Fig. 1. Effect of Relative Density on Cyclic Strength for Cyclic Triaxial and Cyclic Simple Shear Tests for Failure Defined as 15 % Double Amplitude Shear Strain in the Tenth Loading Cycle for Wet Tamped and Air-Pluviated Monterey No. 0 Sand (Reproduction from Silver and Tatsuoka (1981)).

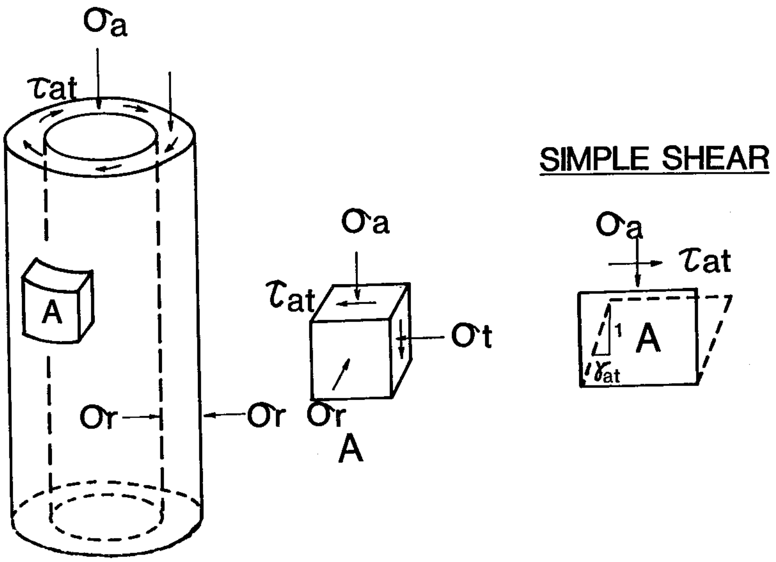


Fig. 2. Stress-Strain Condition in Hollow Cylindrical Specimen in Torsion.

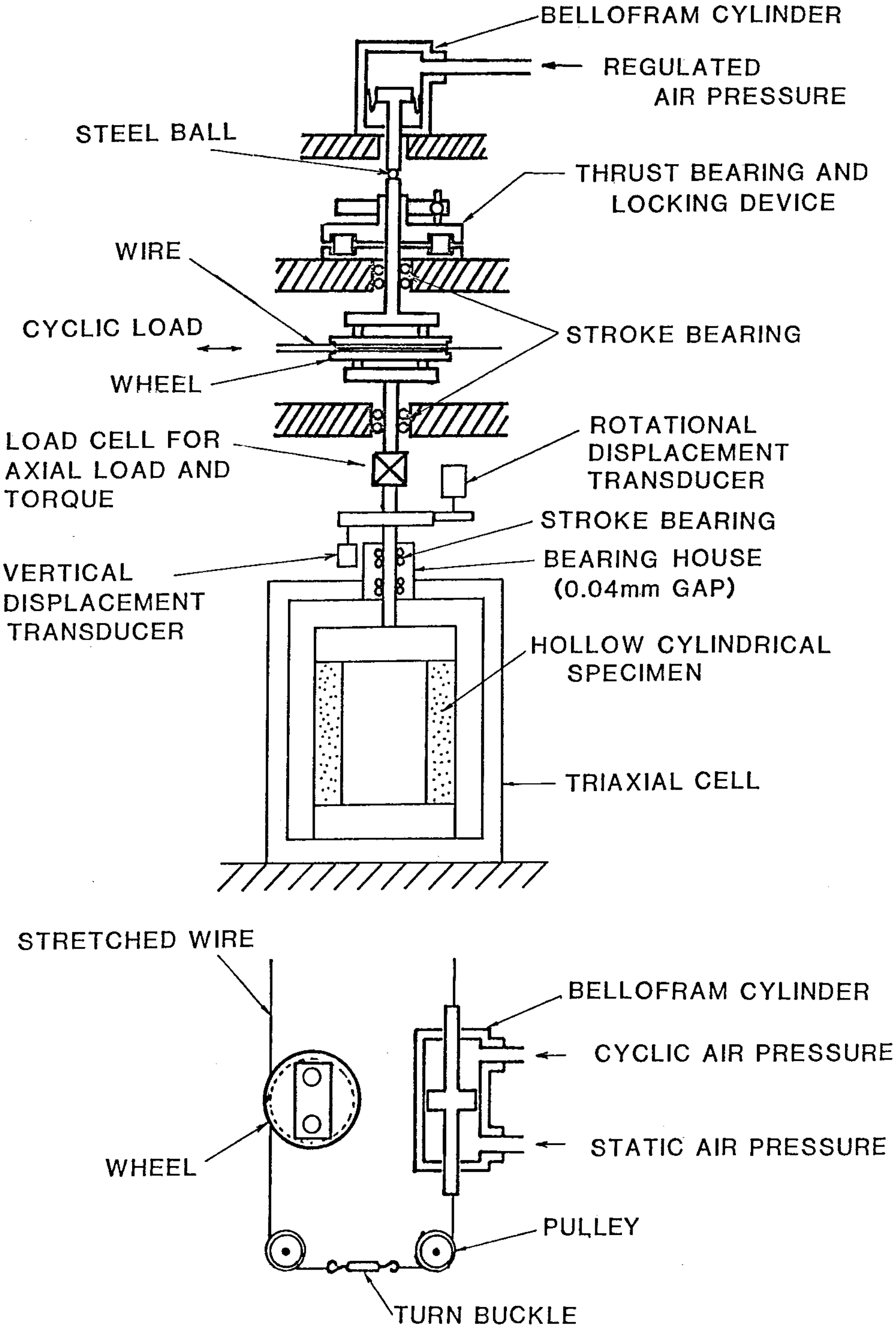


Fig. 3. Schematic Diagram of Cyclic Torsional Simple Shear Apparatus

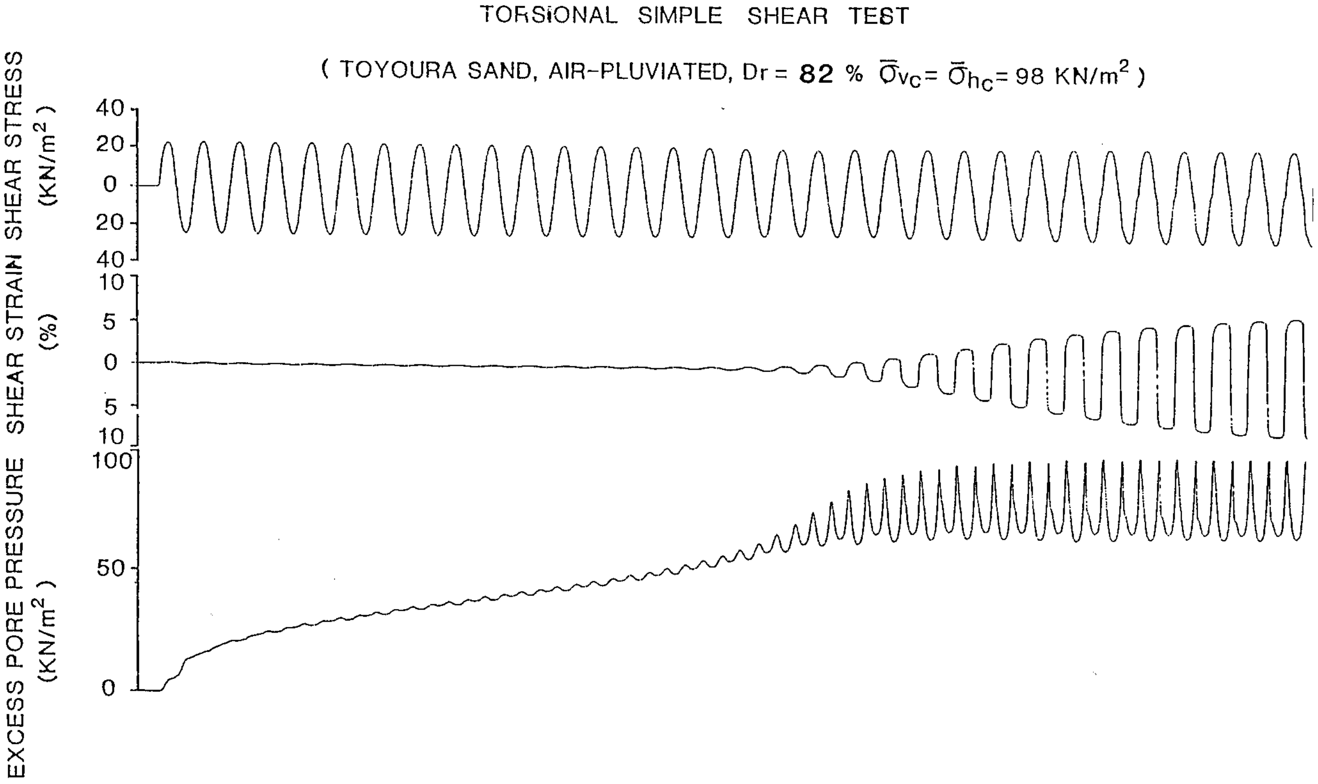


Fig. 4, Time History of Shear Stress, Shear Strain and Excess Pore Pressure for Isotropically Consolidated Air-Pluviated Toyoura Sand

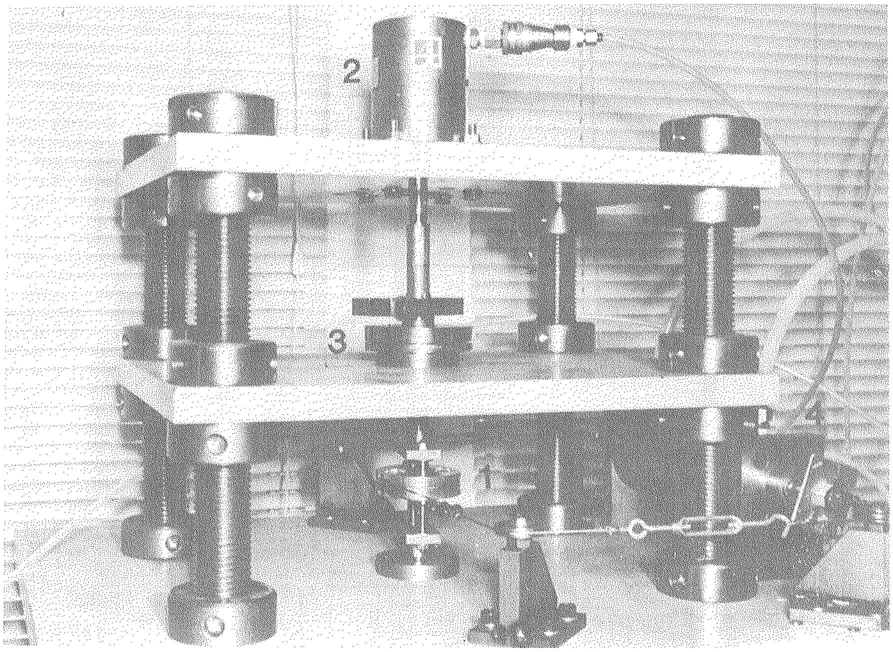


Photo. 1. Top Portion of Torsional Simple Shear Device, 1: Wheel for Converting Linear Motion to Rotational Motion, 2: Bellofram Cylinder for Providing Vertical Load, 3: Locking Device for Vertical Movement, 4: Bellofram Cylinder for Providing Cyclic Load.

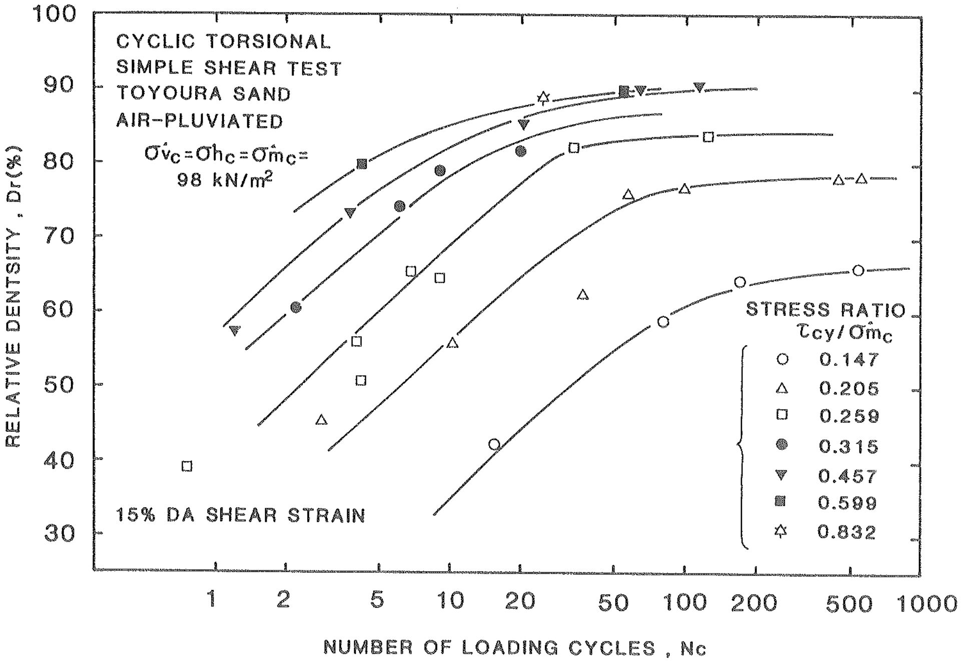


Fig. 5. Relationship between Relative Density and Number of Loading Cycles where 15 % Double Amplitude Shear Strain was Observed for Isotropically Consolidated Air-Pluviated Toyoura Sand.

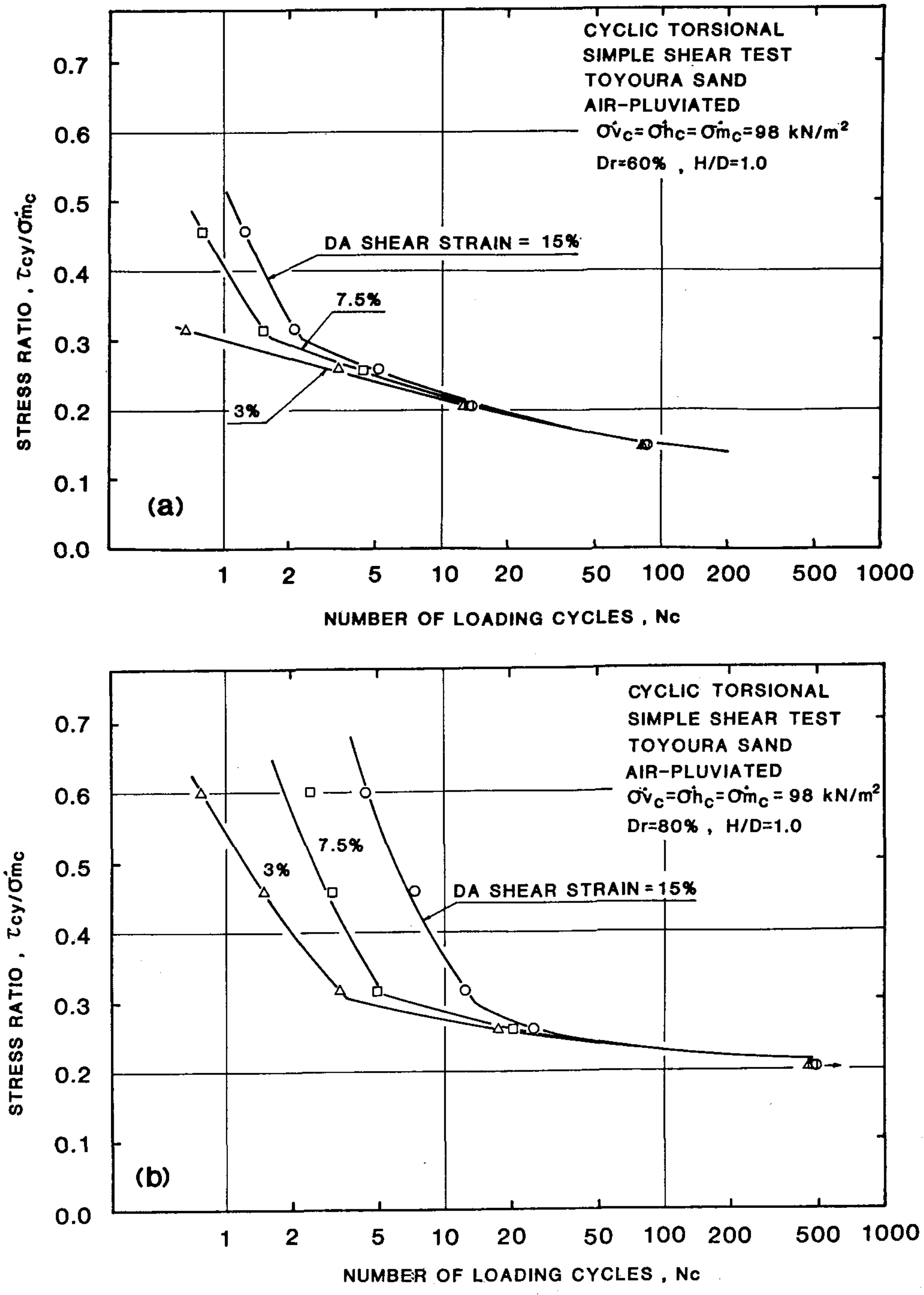


Fig. 6(a) and (b). Stress Ratio Versus Number of Loading Cycles to 3 %, 7.5 % and 15 % Double Amplitude Shear Strain for Isotropically Consolidated Air-Pluviated Toyoura Sand ((a) D_r = 60 %, (b) D_r = 80 %).

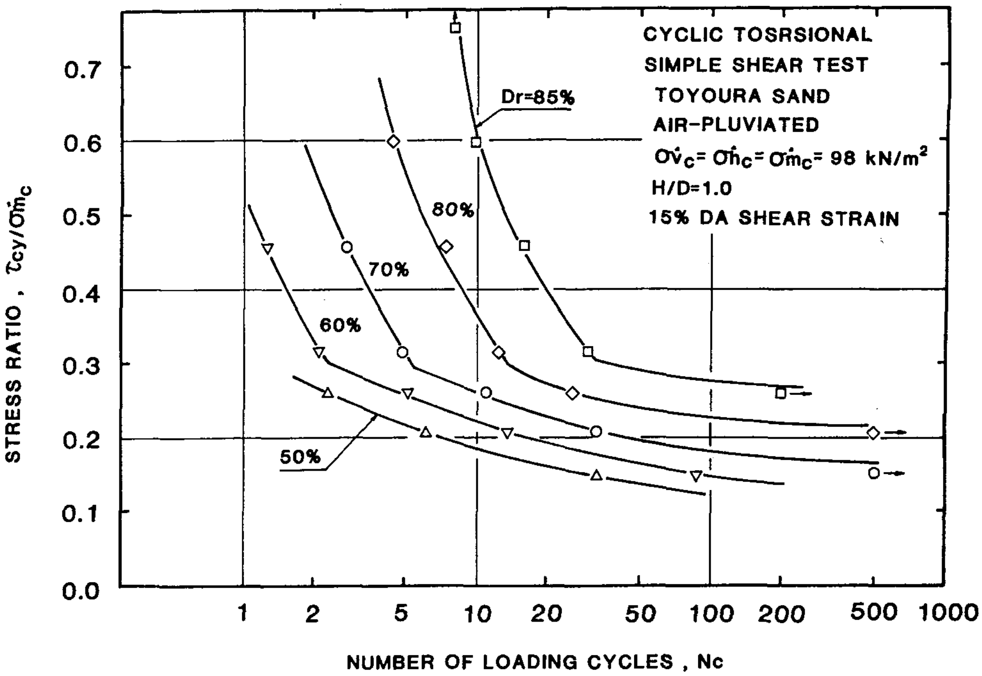


Fig. 7. Stress Ratio Versus Number of Loading Cycles to 15 % Double Amplitude Shear Strain for Isotropically Consolidated Toyoura Sand of D_r = 50 %, 60 %, 70 %, 80 % and 85 %.

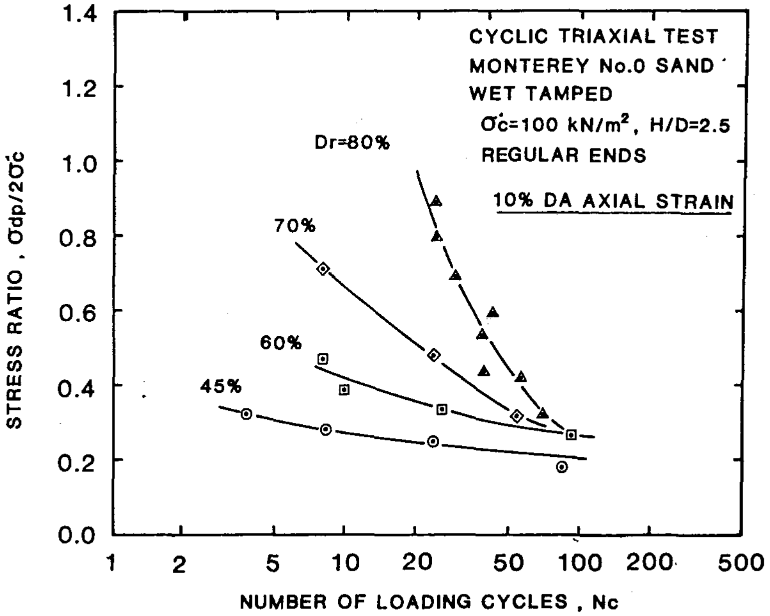


Fig. 8. Stress Ratio Versus Number of Loading Cycles by Conventional Cyclic Triaxial Test for Wet Tamped Monterey No. 0 Sand of D_r = 45 %, 60 %, 70 % and 80 % (Reproduction from Silver and Tatsuoka (1981)).

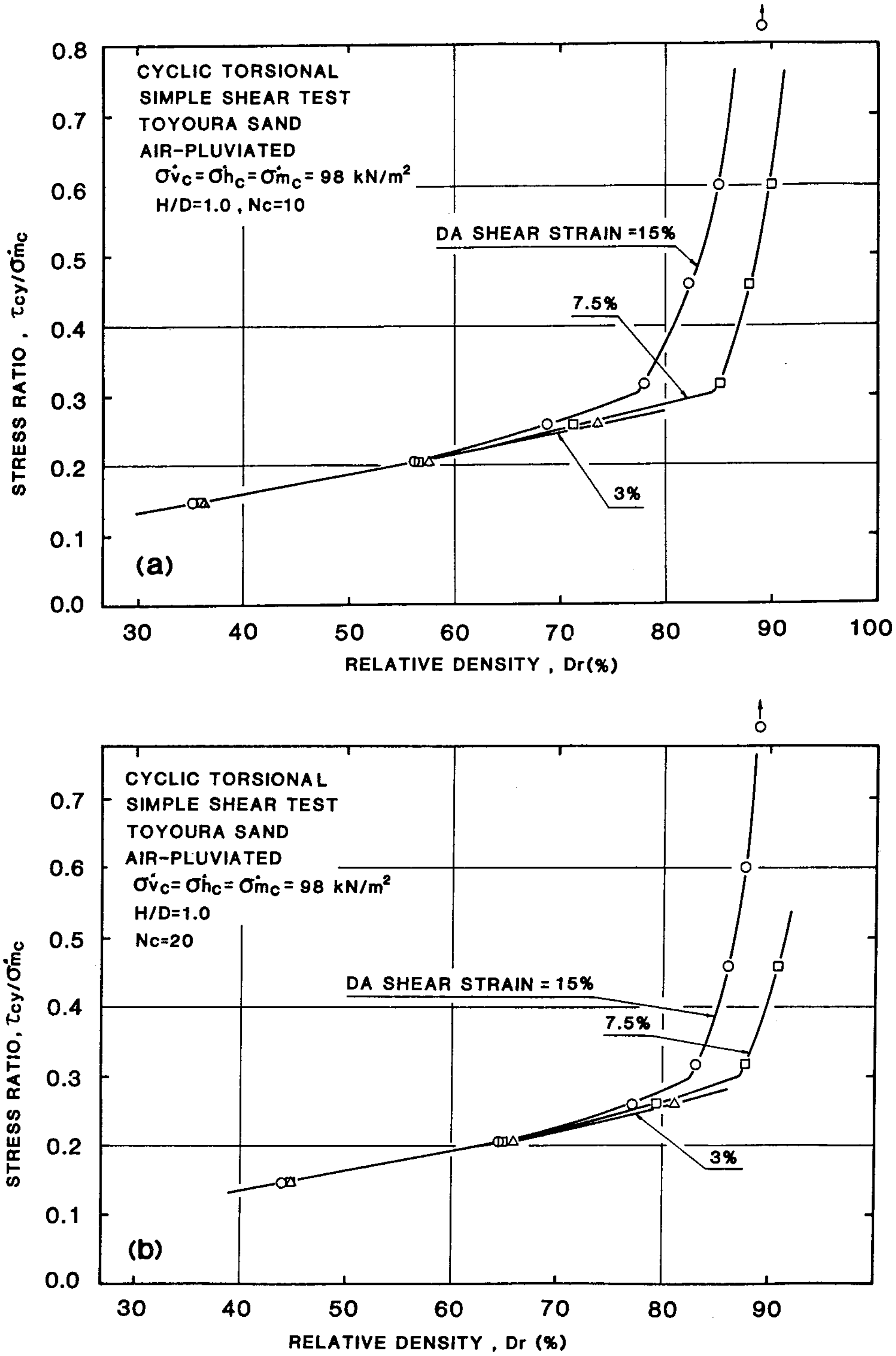


Fig. 9(a) and (b). Effect of Relative Density on Cyclic Strength by Cyclic Torsional Simple Shear Test for Failure Defined for 3 %, 7.5 % and 15 % Double Amplitude Shear Strain (a) in the Tenth and (b) in the Twentith Loading Cycles for Isotropically Consolidated Air-Pluviated Toyoura Sand.

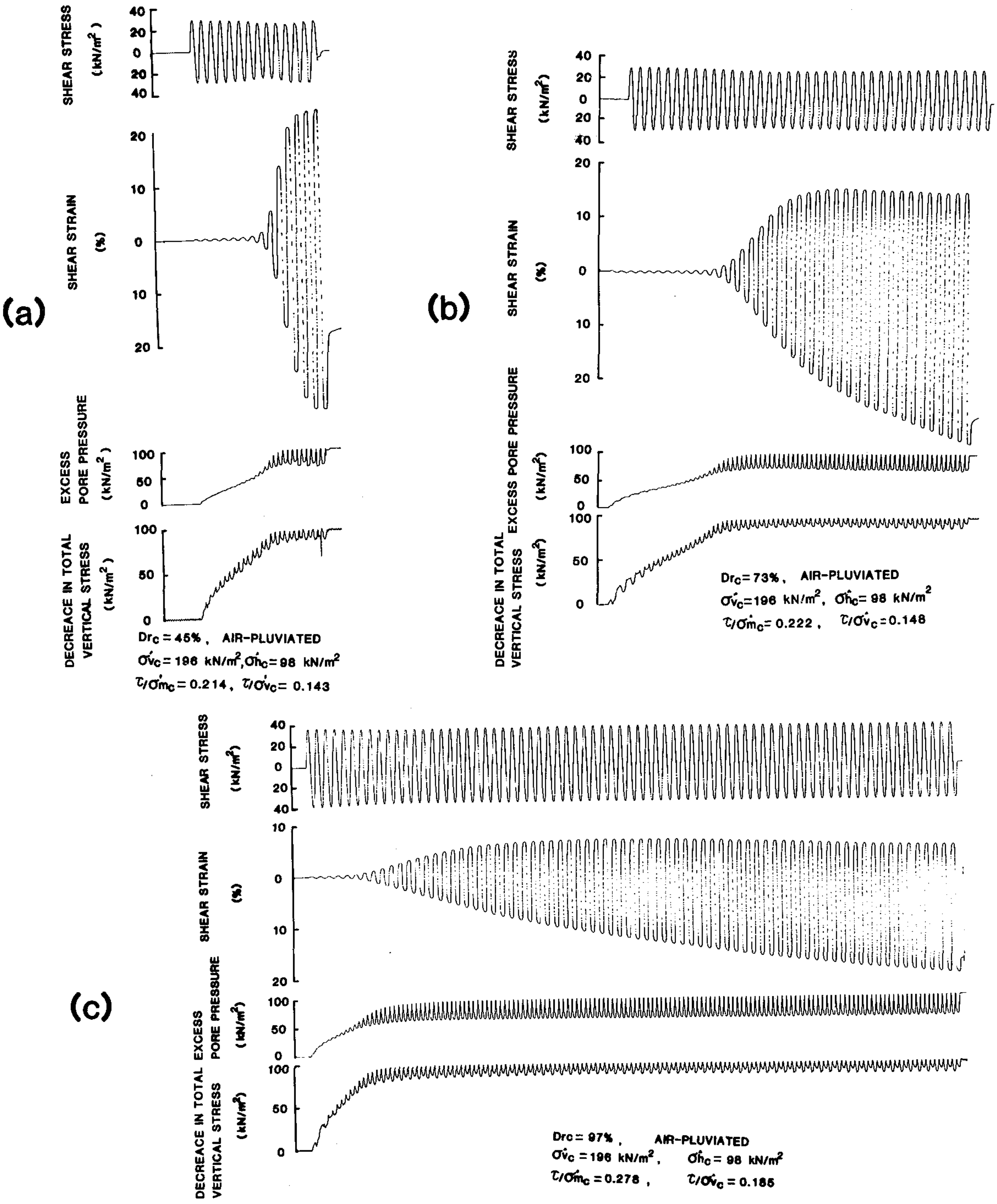


Fig. 10(a), (b) and (c). Time Histories of Shear Stress, Shear Strain, Total Vertical Stress Decrease and Excess Pore Pressure by Plane Strain Cyclic Undrained Torsional Simple Shear Tests for (a) Loose, (b) Medium Dense and (c) Dense Air-Pluviated Sengenyama Sand (σ_{vc}' = 196 kN/m^2 and σ_{hc}' = 98 kN/m^2).

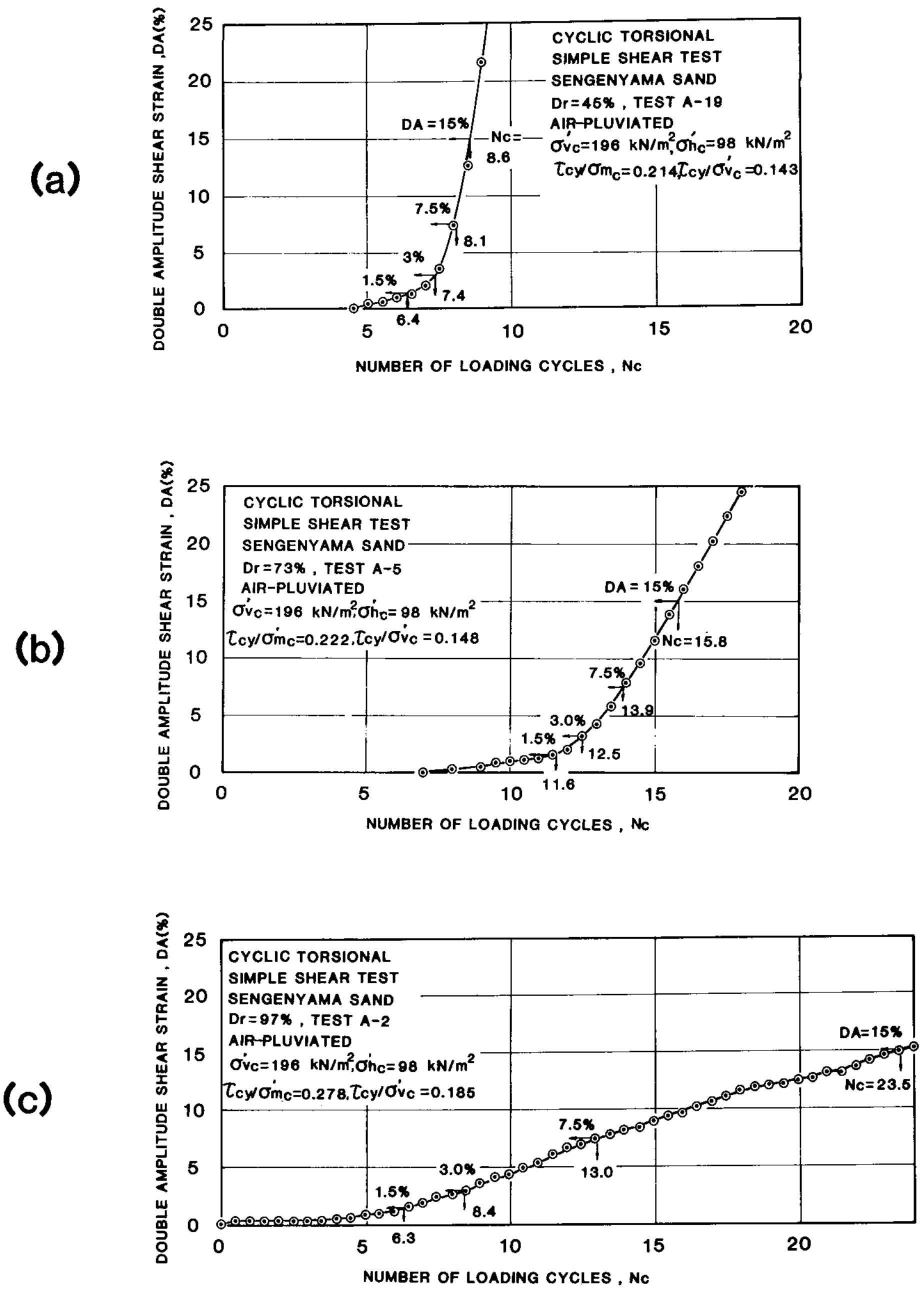


Fig. 11(a), (b) and (c). Relationships between Double Amplitude Shear Strain and Number of Loading Cycles for (a) Loose, (b) Medium and (c) Dense Air-Pluviated Sengenyama Sand.

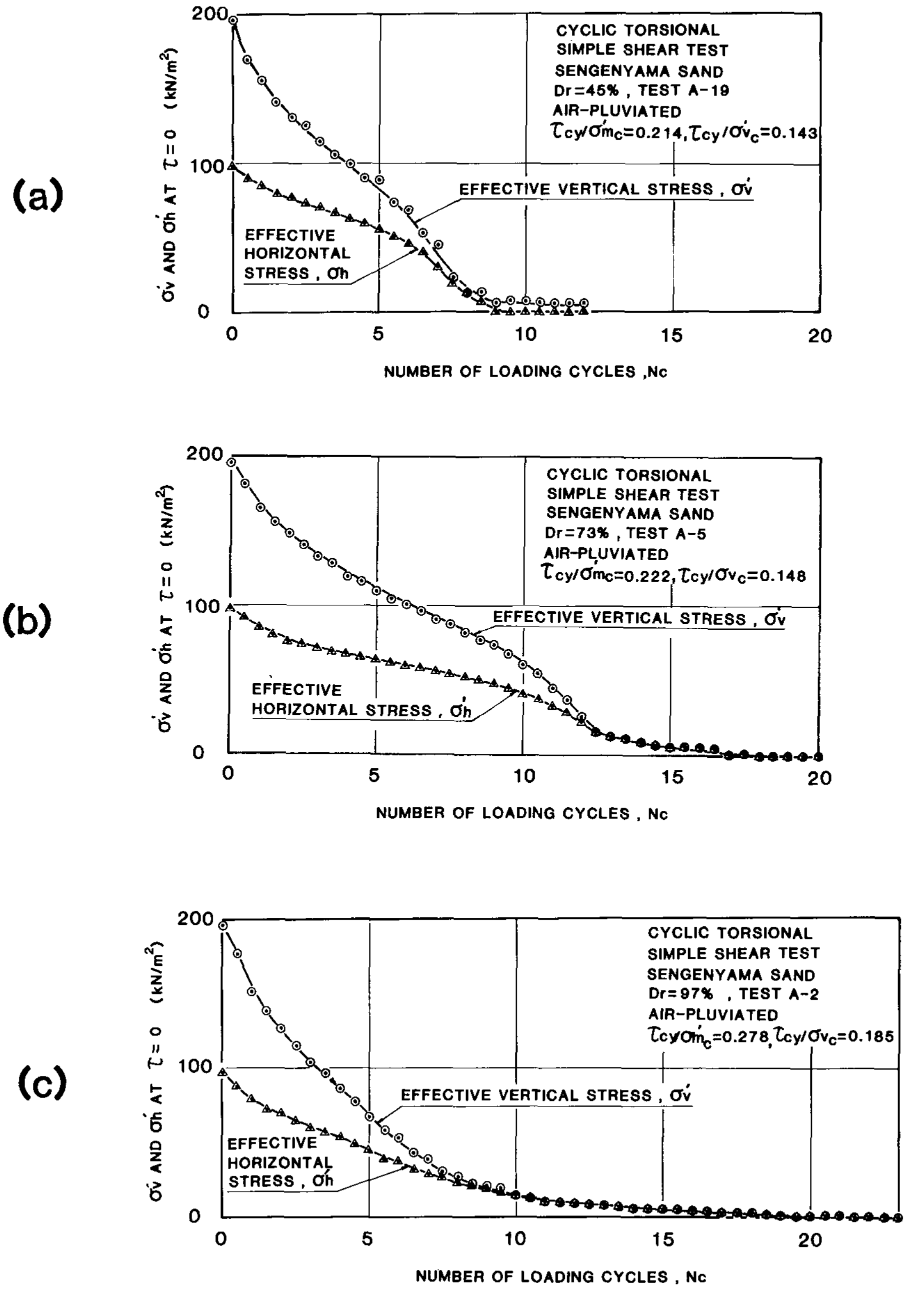
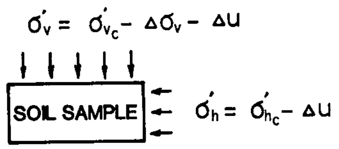
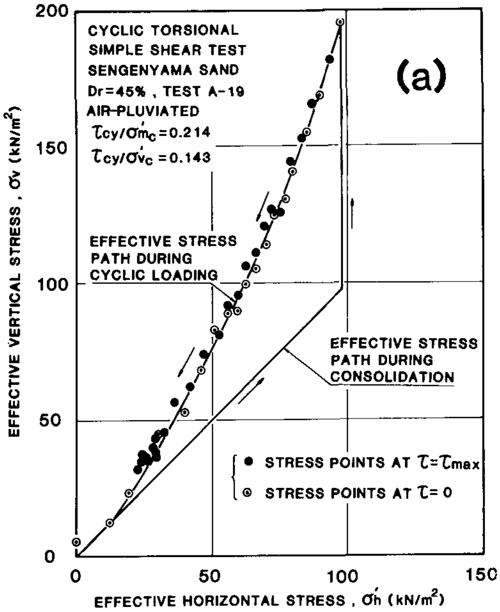


Fig. 12(a), (b) and (c). Relationships between Effective Vertical Stress, Effective Horizontal Stress and Number of Loading Cycles for (a) Loose, (b) Medium and (c) Dense Air-Pluviated Sengenyama Sand.



σ'_v : EFFECTIVE VERTICAL STRESS DURING CYCLIC LOADING
σ'_{v_c} : INITIAL EFFECTIVE VERTICAL STRESS DURING CONSOLIDATION
$\Delta\sigma_v$: DECREACE IN TOTAL VERTICAL STRESS DURING CYCLIC LOADING
σ'_h : EFFECTIVE HORIZONTAL STRESS DURING CYCLIC LOADING
σ'_{h_c} : INITIAL EFFECTIVE HORIZONTAL STRESS DURING CONSOLIDATION
Δu : EXCESS PORE PRESSURE DEVELOPED DURING CYCLIC LOADING

Fig. 13. State of Effective Stress during Cyclic Loading of Simple Shear Specimens.



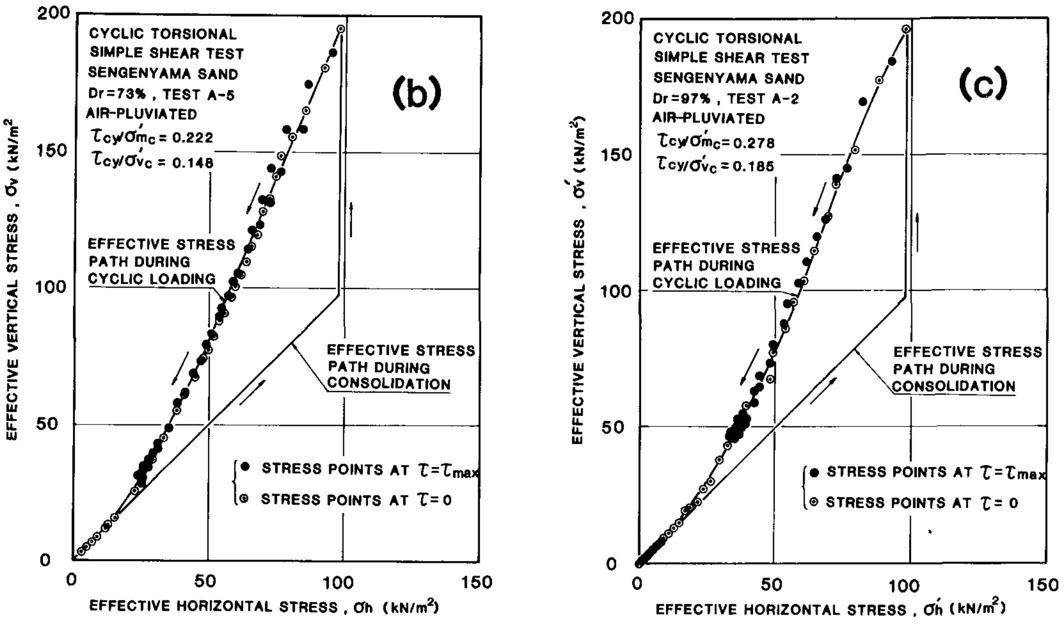


Fig. 14(a), (b) and (c). Effective Stress Paths for (a) Loose, (b) Medium and (c) Dense Air-Pluviated Sengenyama Sand by Plane Strain Cyclic Undrained Torsional Simple Shear Tests.

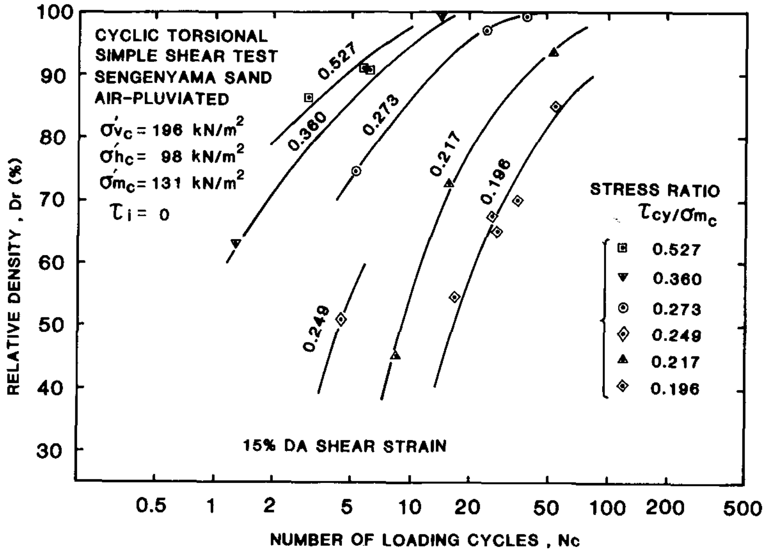


Fig. 15. Relationship between Relative Density and Number of Cyclic Loading Cycles where 15 % Double Amplitude Shear Strain was Observed for Anisotropically Consolidated Air-Pluviated Sengenyama Sand.

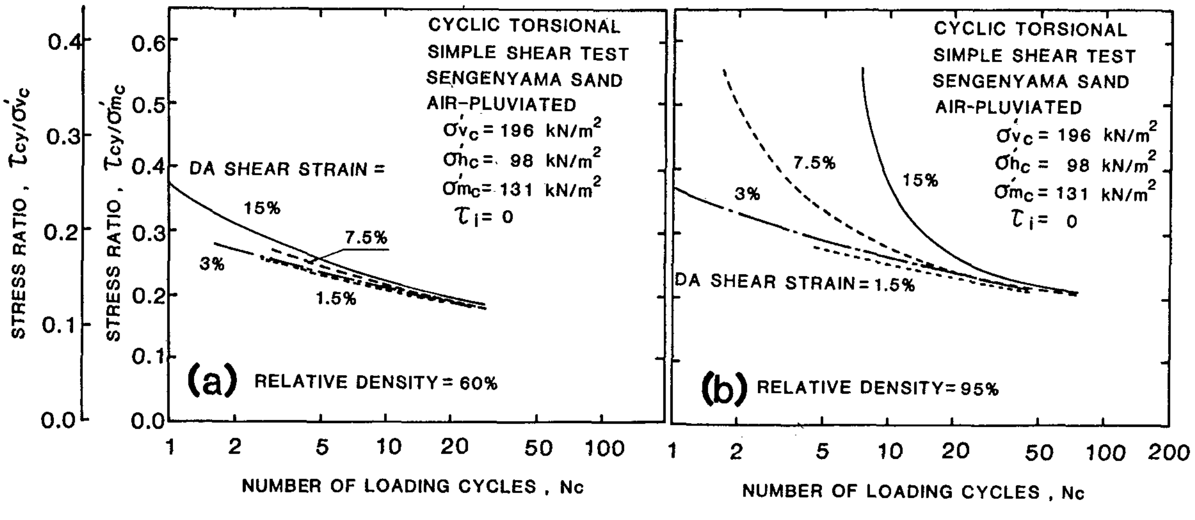


Fig. 16(a) and (b). Relationships between Stress Ratio and Number of Loading Cycles where 3 %, 7.5 % and 15 % Double Amplitude Shear Strain were Observed for Anisotropically Consolidated Air-Pluviated Sengenyama Sand ((a) D_r = 60 % and (b) D_r = 80 %).

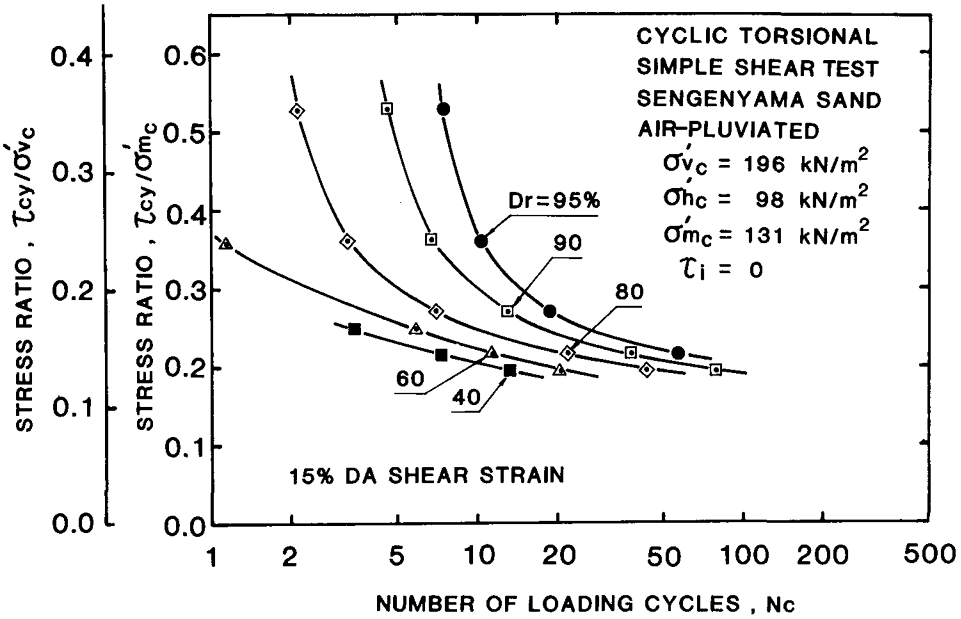


Fig. 17. Relationship between Stress Ratio and Number of Loading Cycles where 15 % Double Amplitude Shear Strain was Observed for Anisotropically Consolidated Air-Pluviated Sengenyama Sand for D_r = 40 %, 60 %, 80 %, 90 % and 95 %.

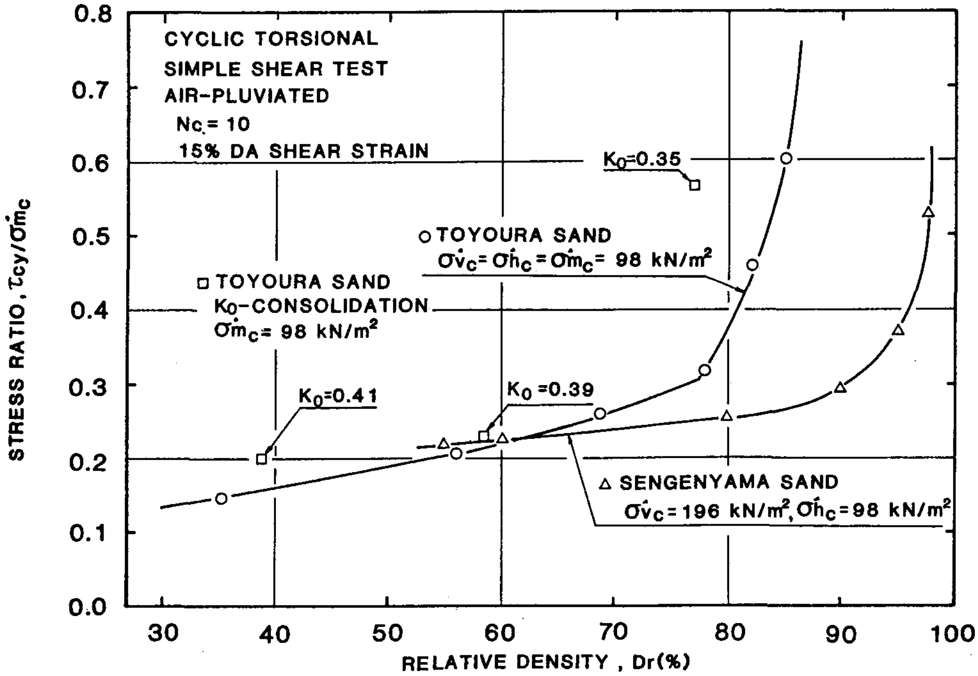


Fig. 18. Effect of Relative Density on Cyclic Strength for Failure Defined as 15 % Double Amplitude Shear Strain in the Tenth Cyclic Loading for Isotropically Consolidated and K_0-Consolidated Toyoura Sand and Anisotropically Consolidated Sengenyama Sand.