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ABSTRACT

A series of undrained cyclic torsional shear tests was conducted to investigate the effects of initial confining stress level on liquefaction resistance of sand. Hollow-cylindrical dense specimens with outer diameter of 10 cm, inner diameter of 6 cm and height of 20 cm are prepared with two kinds of sand. After being saturated, they were isotropically consolidated under an initial confining stress σ_c' of 4.9, 9.8 or 98 kPa, and subjected to undrained cyclic torsional shear while maintaining the axial and lateral stresses constant. The amplitude of the cyclic torsional shear stress τ_{cy} was kept constant with a correction for the effects of membrane force. As a result, for both sands, the cyclic shear stress ratio τ_{cy}/σ_c' to cause liquefaction in a specified number of cycles was found to increase as the initial confining stress σ_c' decreased. This tendency is consistent with the results of previous studies based on undrained cyclic triaxial tests. Such increase in the liquefaction resistance under low confining stress levels should be considered in analyzing relevant model test results. It was also demonstrated that in conducting cyclic torsional shear tests under low confining stresses, correction for the effects of membrane force is indispensable.

KEYWORDS

Liquefaction, Confining stress, Cyclic torsional shear, Hollow-cylindrical specimen, Membrane force

INTRODUCTION

For small-scale model tests conducted under normal gravity, the confining stress in the model ground is lower than that employed in conventional laboratory element tests. Based on undrained cyclic triaxial tests with special attentions to control and measure low confining stress levels accurately, it has been pointed out by Mochizuki and Fukushima (1993), Kanatani et al. (1994) and Amaya et al. (1997) that the liquefaction resistance of Toyoura sand increases when tested under low initial confining stress levels. However, the behavior of level ground subjected to horizontal earthquake motions can be better simulated with cyclic torsional shear tests.

In view of the above, in order to investigate the effects of low initial confining stress levels on the liquefaction characteristics, a series of undrained cyclic torsional shear tests was conducted on hollow cylindrical specimens prepared using two kinds of sands. In the course of the tests, due attentions were paid to control the specified stress states, referring to procedures employed by Tatsuoka et al. (1986a).

APPARATUS

The testing apparatus employed in the present study is based on the one developed by Tatsuoka et al. (1986b) and Pradhan et al. (1988). Major modification with respect to torque loading system was made by Ampadu and Tatsuoka (1993), and minor modification with adding an eletro-magnetic brake for the loading system was made by the authors.

A hollow cylindrical specimen with an outer diameter of 10 cm, inner diameter of 6 cm and a height of 20 cm was set in a pressure cell and was loaded in the torsional and vertical directions independently. The vertical load was applied with a pneumatic cylinder in the tests conducted under a confining stress of 98 kPa, while it was applied with a dead weight in the tests conducted under a confining stress of 4.9 or 9.8 kPa. In the latter tests, to control such low confining stress states, the same amount of pneumatic pressure was applied on two burettes connected to the pressure cell and the specimen, respectively, and the difference in their water heads was carefully adjusted to specified values.

The torque was applied with an AC motor which is connected to the loading shaft through a series of reduction-gears, two sets of electro-magnetic clutch and one eletro-magnetic brake. This device is a displacement-controlled type from a mechanical point of view, whereas cyclic shear tests with keeping a specified stress amplitude could be conducted by using a microcomputer which monitors the outputs from a load cell and controls the device accordingly. The A/D and D/A boards of the microcomputer had a resolution of 16 and 12 bit, respectively.

The load cell, which is capable of measuring deviator load L_c and torque T_c with negligible coupling effect between each other (refer to Tatsuoka et al., 1986b for the details), was set inside the pressure cell in order to eliminate the effects of friction between the loading shaft and the bearing house. The effective axial stress σ_a' and the shear stress $\tau_{a\theta}$ applied on a horizontal plane at the mid-height of the specimen were obtained as:

$$\sigma_a'=\sigma_r'+L_c/A_s-\gamma_w(h_c-h)A_c/A_s+\gamma'(h/2) \quad (1)$$

$$\tau_{a\theta}=3T/\{2\pi(r_o^3-r_i^3)\} \quad (2)$$

$$T=T_c-(2/3)\pi t_m E_m(r_o^3+r_i^3)\theta/h \quad (3)$$

where σ_r' is the effective radial stress measured with a high-capacity differential pressure transducer (HC-DPT); θ is the rotational angle of the top cap measured with a potentio-meter; A_s and A_c are the cross-sectional areas of the specimen and the top cap, respectively; h is the height of the specimen; h_c is the relative height of the cell water level measured from the bottom of the specimen; r_o and r_i are outer and inner diameters of the specimen; γ_w is unit weight of water; γ' is submerged unit weight of the specimen; and t_m and E_m are thickness and Young's modulus, respectively, of the membrane. Note that correction for the effects of membrane force on the σ_a' values was not made, since the axial strain of the specimen accumulated during the undrained cyclic torsional shearing was limited to be about 1 % when the double amplitude shear strain of 1.5 or 7.5 % was attained, which was employed to define the state of liquefaction in the analysis of test results.

Since the outer and the inner cell pressures were kept equal to each other throughout the tests, the effective circumferential stress σ_θ' was the same as the value of σ_r'. In the tests conducted under a confining stress of 98 kPa, a pneumatic regulator that is capable of controlling a pressure between 2 and 1029 kPa was used to control the cell pressure and the back pressure. On the other hand, in the tests conducted under a confining stress of 4.9 or 9.8 kPa, another regulator that is capable of controlling a pressure between 0 and 686 kPa was used. The measurable range of the HC-DPT was also adjusted accordingly.

The axial strain ε_a was obtained from the vertical displacement of the loading shaft that was measured with a displacement transducer. The shear strain $\gamma_{a\theta}$ mobilized on a horizontal plane was obtained from the rotational angle θ of the top cap that was measured with the potentio-meter as:

$$\gamma_{a\theta}=2\theta(r_o^3-r_i^3)/\{3h(r_o^2-r_i^2)\} \quad (4)$$

The volume of water ΔV_w that was expelled from the specimen during its consolidation process was measured with a low-capacity differential pressure transducer. Neglecting the effects of membrane penetration and surface tension of water in the burette on the measured values of ΔV_w, the change in the cross-sectional area A_s of the specimen during the consolidation process was computed based on these values.

TESTING PROCEDURES

Specimens of Kasumigaura sand (G_s=2.795, e_{max}=0.970, e_{min}=0.594, D_{50}=0.27 mm with no fines content under 75 μm) were prepared with putting air-dried sample in a mold and tamping it in ten layers using a cylindrical metal mass to a specified relative density (about 80 %). On the other hand, specimens of Toyoura sand (G_s=2.635, e_{max}=0.966, e_{min}=0.600, D_{50}=0.18 mm with no fines content under 75 μm) were prepared with pluviating air-dried sand particles through air.

Some specimens were saturated at a confining stress of 29 kPa with the double vacuuming method using partial vacuum as both the pore water pressure and the cell pressure, and they were consolidated to a confining stress of 98 kPa. On the other hand, other specimens were saturated at a confining stress of 3.9 and 8.8 kPa, respectively, with pouring carbon dioxide through the void between sand particles and pouring de-aired water, and they were consolidated to a confining stress of 4.9 or 9.8 kPa. Their degree of saturation of these specimens was confirmed with ensuring that the B value prior to isotropic consolidation be not smaller than 0.96.

The initial relative density, D_{ri}, of each specimen was obtained from the specimen dimensions measured under a state immediately before saturation and from its dry weight measured after the tests. It should be noted that, for each sand, the change in the relative density during the consolidation process from a confining stress of 29 kPa to that of 98 kPa, which was evaluated from the amount of water expelled from the specimen, was relatively small compared to the variation in the values D_{ri} among different specimens. Therefore, possible effect of the difference in the confining stress levels at which the initial relative density was measured (i.e., at 3.9, 8.8 and 29 kPa) on the test results was not considered in the present study.

From the specified isotropic stress state, the torsional load was cyclically changed under undrained condition with maintaining a specified single amplitude of the shear stress $\tau_{a\theta}$ that was corrected for the effects of membrane force, while keeping the vertical load constant. The shear strain rate was about 5%/min for specimens of Toyoura sand tested under a confining stress of 98 kPa. For the other specimens, it was reduced to about 0.25 to 0.5 %/min to improve the accuracy in maintaining the constant shear stress amplitude, especially in the beginning of cyclic loading where the shear strain amplitude is small. The cyclic loading was terminated when the double amplitude of the shear strain $\gamma_{a\theta}$ exceeded about 10 % or more.

RESULTS AND DISCUSSIONS

Effects of Membrane Force

Observed stress-strain relationship and effective stress path of Kasumigaura sand that was consolidated to a confining stress σ_c' of 9.8 kPa and subjected to cyclic shear stress with a single amplitude of 3.9 kPa under undrained condition is shown in Fig. 1. In Fig. 1a, shear stresses with/without correction for the membrane force are compared. It is obvious that correction for the membrane force is indispensable in conducting torsional shear tests under low confining stress, similarly to the cases with triaxial tests and plane strain compression tests as pointed out by Fukushima and Tatsuoka (1984), and Tatsuoka et al. (1986c).

Effects of Confining Stress on Stress-Strain Relationship and Effective Stress Path

Typical stress-strain relationship and effective stress path of Kasumigaura sand that was consolidated to a confining stress σ_c' of 98 kPa and 4.9 kPa, respectively, are shown in Figs. 2 and 3. Note that the cyclic stress ratio ($=\tau_d/\sigma_c$', where τ_d is the single amplitude of the shear stress $\tau_{a\theta}$ during cyclic loading) of these tests are 0.4 and equal to that of the aforementioned test at σ_c'=9.8 kPa as shown in Fig. 1. Note also that in these figures the scales for the stresses were adjusted in proportion to the confining stress level.

When the effective stress paths are compared among Figs. 1b, 2b and 3b, it is seen that the reduction of effective mean principal stress p' in the beginning of the first half-cycle, as indicated by broken arrows in the figures, was largest in Fig. 2b that was obtained under the highest value of σ_c'. On the other hand, increase in the value of p' was observed in Fig. 3b that was obtained under the lowest value of σ_c'. The behavior in Fig. 1b obtained under the intermediate value of σ_c' was in between them. These different behaviors demonstrate that the specimen under lower confining stress exhibited more dilative behavior in the beginning of shearing.

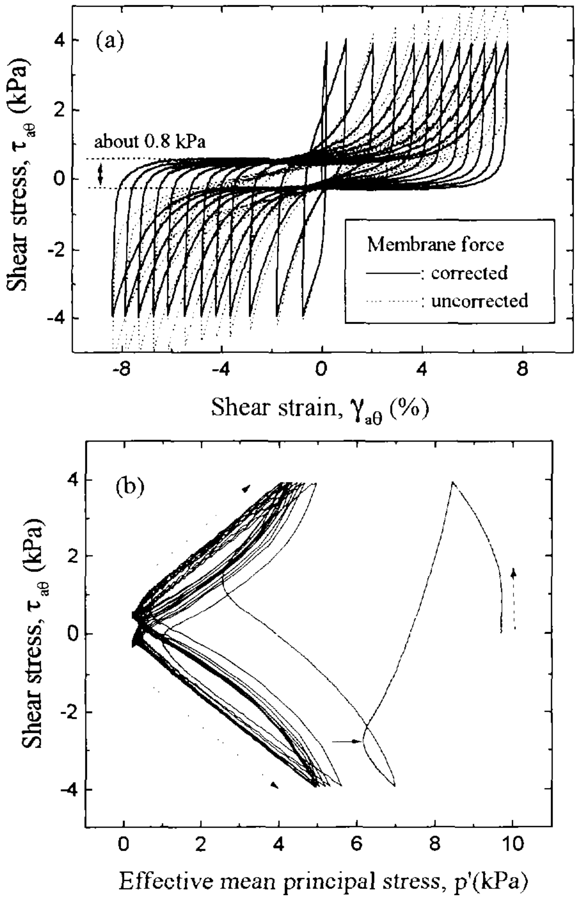

Fig. 1 Test results on Kasumigaura sand at D_{ri}=78%, σ_c'=9.8 kPa and τ_d= 3.9 kPa

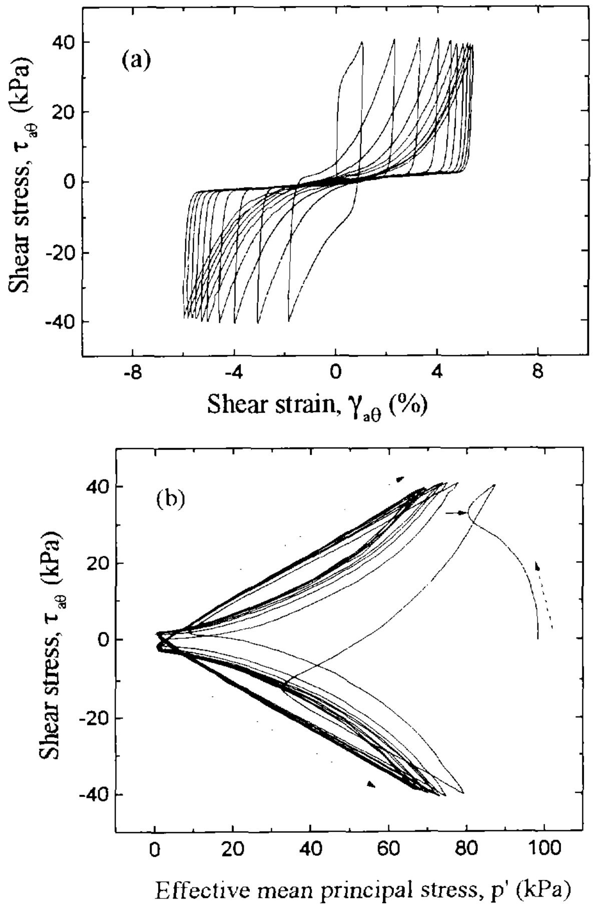

Fig. 2 Test results on Kasumigaura sand at D_{ri}=82%, σ_c'=98 kPa and τ_d= 39 kPa

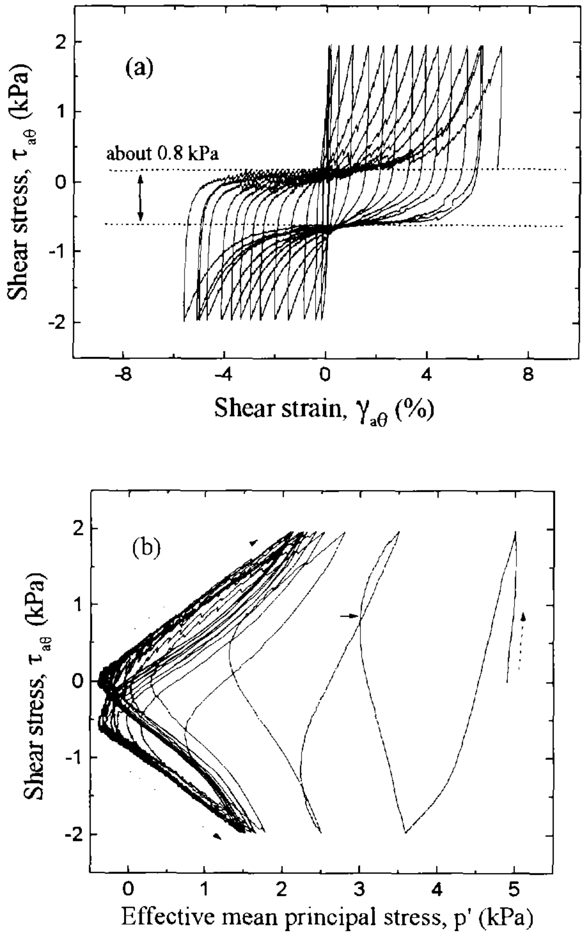

Fig. 3 Test results on Kasumigaura sand at D_{ri}=79%, σ_c'=4.9 kPa and τ_d= 2.0 kPa

It is also seen that the point of phase transformation, as indicated by solid arrows in the figures, appeared in the first half-cycle in Fig. 2b, in the second half-cycle in Fig. 1b, and in the third half-cycle in Fig. 3b. This order is the same as the order of the confining stress level (i.e., σ_c'=98 kPa in Fig. 2b, 9.8 kPa in Fig. 1b, and 4.9 kPa in Fig. 3b), which is consistent with the different dilatancy characteristics as mentioned above.

In addition, when the stress paths in the region of cyclic mobility during reloading, as indicated by dotted lines in the figures, are compared, it is seen that the paths in Figs. 1b and 3b were steeper than the path in Fig. 2b. These different behaviors may reflect different dilatancy characteristics due to shearing, or different volume reduction characteristics due to recovery of effective stress, or both. Further investigation is required on this issue.

When the stress-strain relationships are compared among Figs. 1a, 2a and 3a, it is seen that the test results shown in Figs. 1a and 3a obtained at low confining stress levels exhibited larger area of the stress-strain loop during one cycle loading in the region of cyclic mobility than the result shown in Fig. 2a obtained at higher confining stress. In Fig. 2a, the unloading curves from one direction overlapped with those from the opposite direction when the shear stress level is almost zero. On the other hand, in Figs. 1a and 3a, two groups of unloading curves were located at a distance of about 0.8 kPa, as indicated in these figures. This distance may reflect possible effects of interlocking among soil particles that could be mobilized under extremely low confining stress levels, or effects of the deviation of the deviator stress q (= σ_a'-σ_r') from zero that hindered the stress states from becoming isotropic when $\tau_{a\theta}$ approached zero, or both. Further modification of the apparatus is required to reduce the effects of the latter factor.

Effects of Confining Stress on Liquefaction Resistance

Relationships between the cyclic stress ratio τ_d/σ_c' and the number of cycles N_c to induce a double amplitude shear strain $\gamma_{a\theta}$ of 1.5 % or 7.5 % are shown in Figs. 4 and 5 for Kasumigaura sand and Toyoura sand, respectively. The value of the initial relative density D_{ri} in % for each specimen is indicated in the figures for reference. For both sands, the cyclic resistance increased with the decrease in the value of σ_c', irrespective of the strain level to define the state of liquefaction. Such an effect of the confining stress on the cyclic resistance is consistent with the aforementioned observation that the specimen under lower confining stress exhibited more dilative behavior in the beginning of shearing.

It should be, however, noted that the present results, in particular those conducted under low confining stress, may have been affected by the aforementioned three factors: i.e., 1) friction at the stroke bearing which supported the loading shaft, 2) long-term shift in the output of load cell and 3) distortion of load cell due to errors in the alignment of the specimen with respect to the loading shaft. Due possibly to the factors 2) and 3), the actual shear stress amplitude may not have been the same in the two loading directions, as can be inferred from the stress-strain relationships and the effective stress paths in Figs. 1 and 3.

In spite of all the possible limitations stated above, an attempt was made to compare the undrained cyclic resistance of Toyoura sand obtained in the present study with those obtained by Kanatani et al. (1994). The dependency of the cyclic resistance on the confining stress was compared in terms of the ratio of cyclic resistance, denoted as R_c, which was defined as:

$R_c=(\tau_d/\sigma_c')_{Nc=10}/(\tau_d/\sigma_c')_{Nc=10,\ \sigma c'=9.8kPa}$

in torsional shear tests conducted in the present study

$R_c=(\sigma_d/2\sigma_c')_{Nc=10}/(\sigma_d/2\sigma_c')_{Nc=10,\ \sigma c'=9.8kPa}$

in triaxial tests conducted by Kanatani et al., 1994 (5)

where $(\tau_d/\sigma_c')_{Nc=10}$ and $(\sigma_d/2\sigma_c')_{Nc=10}$ are the cyclic stress ratios to cause a specified state of liquefaction in 10 cycles, while $(\tau_d/\sigma_c')_{Nc=10,\ \sigma c'=9.8kPa}$ and $(\sigma_d/2\sigma_c')_{Nc=10,\ \sigma c'=9.8kPa}$ are the corresponding values obtained under a reference confining stress of 9.8 kPa. Note that σ_d is the single amplitude of the

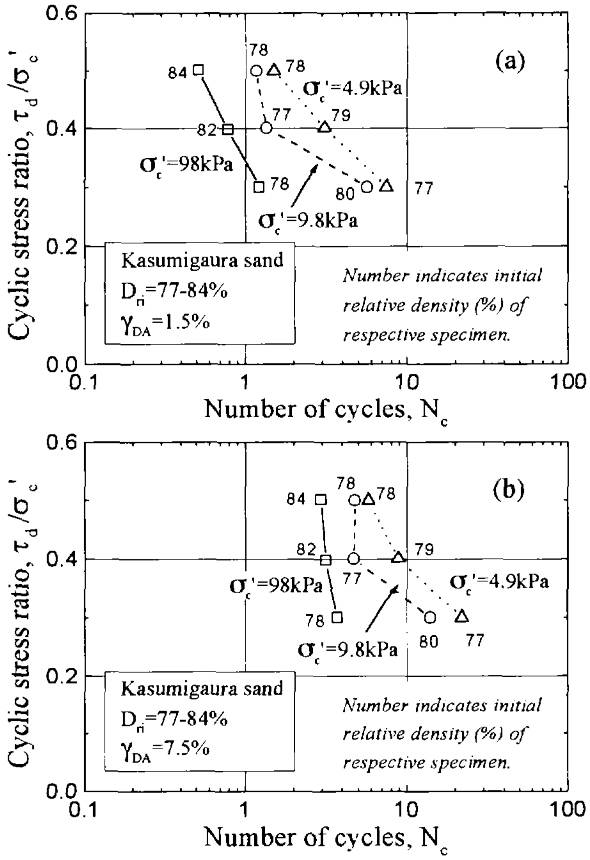

Fig. 4 Liquefaction resistance curves for Kasumigaura sand defined at a double amplitude shear strain of a) 5% and b) 7.5%

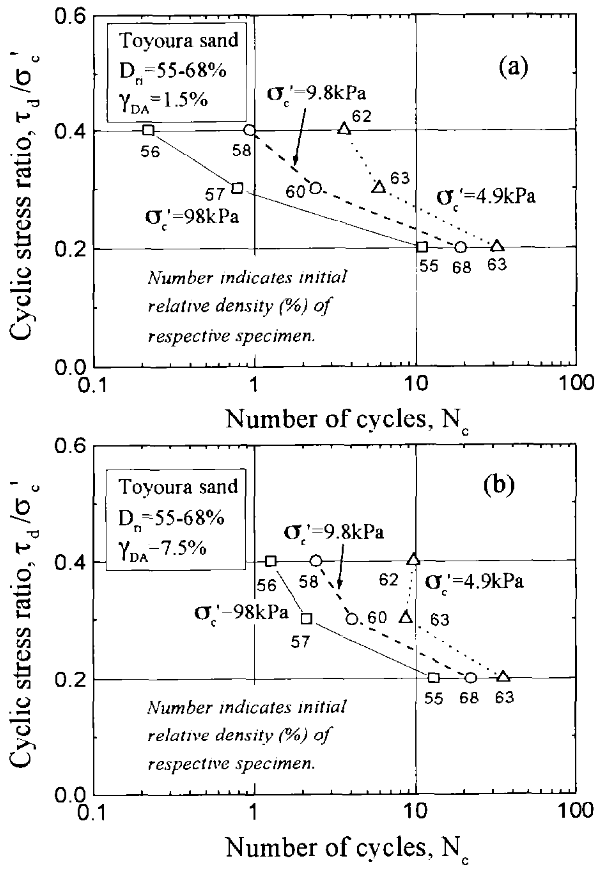

Fig. 5 Liquefaction resistance curves for Toyoura sand defined at a double amplitude shear strain of a) 5% and b) 7.5%

cyclic deviator stress in undrained cyclic triaxial tests. Note also that the specified values of the reference confining stress and the number of cycles were set considering the ranges of the testing conditions and results in the two different tests.

Figure 6 shows the values of R_c for Toyoura sand plotted versus the confining stress σ_c'. The state of liquefaction specified to analyze the results obtained by Kanatani et al. (1994) was initial liquefaction when the excess pore water pressure Δu became equal to the confining stress σ_c', as employed for test results at D_r=50 % and 65 %, or a state when the double amplitude axial strain ε_{DA} reached 1 %, as employed for test results at D_r=90 %. Note that when the state of initial liquefaction was attained in the tests at D_r=50 % and 65 %, the value of ε_{DA} was about 1 %. On the other hand, to analyze the present test results, two levels of the double amplitude shear strain γ_{DA} of 1.5 % and 7.5 % were employed. The former level is equivalent to the state at ε_{DA} of 1 % in the triaxial tests under undrained condition. It is seen from the figure that when compared at similar relative densities (i.e., at D_r about 50 to 70 %), the decrease in the R_c values with the increase in the σ_c' values obtained in the two different tests was comparable to each other. Further, in the present cyclic torsional shear tests, the effects of the strain levels which define the state of liquefaction on the above behavior was almost negligible. However, as demonstrated by Kanatani et al. (1994) through their cyclic triaxial tests, the dependency of the cyclic resistance on the confining stress became larger when tested at higher relative density, as also seen from Fig. 6.

Figure 7 compares the present test results on Kasumigaura sand with those on Toyoura sand. Although the relative density of Kasumigaura sand was higher than that of Toyoura sand, the dependency of their cyclic resistance at low confining stress level was almost similar to each other. It should be noted, however, that neither the cyclic resistance of Kasumigaura sand to cause γ_{DA} of 7.5 % in ten cycles at σ_c' of 98 kPa, nor those to cause γ_{DA} of 1.5 % in ten cycles at σ_c' of 4.9, 9.8 and 98 kPa, could be evaluated from the present test results.

CONCLUSIONS

The results from undrained cyclic torsional shear tests on Kasumigaura sand and Toyoura sand could be summarized as follows.

The cyclic resistance of the tested sands increased with the decrease in the initial confining stress. This tendency was consistent with the undrained cyclic triaxial test results on Toyoura sand at similar relative densities by Kanatani et al. (1994). Such increase in the liquefaction resistance under low confining stress should be properly considered in analyzing relevant model test results.

In the beginning of shearing, the specimen under lower confining stress exhibited more dilative behavior. Further, the slope of the effective stress path in the region of cyclic mobility during reloading was also affected by the level of confining stress.

It was demonstrated that in conducting cyclic torsional shear tests under low confining stresses, correction for the effects of membrane force is indispensable.

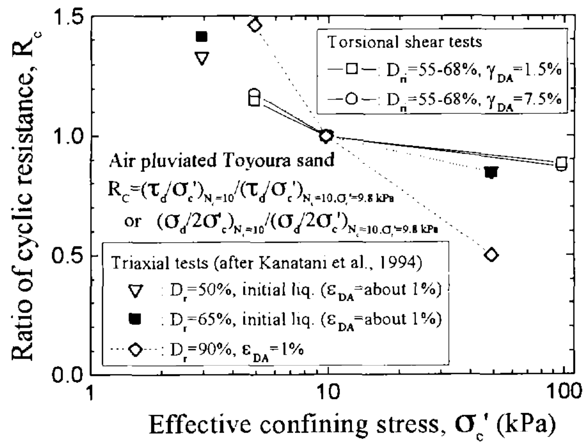

Fig. 6 Relationships between confining stress and ratio of liquefaction resistance for Toyoura sand

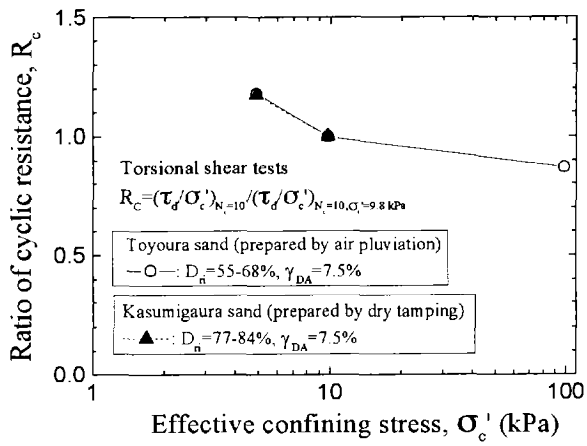

Fig. 7 Comparison of relationships between confining stress and ratio of liquefaction resistance for Toyoura sand and Kasumigaura sand

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