

POSSIBILITY OF UNDRAINED FLOW IN SUCTION-DEVELOPED UNSATURATED SANDY SOILS IN TRIAXIAL TESTS

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ABSTRACT

In examining how far the unsaturated soils located above the groundwater table have a tendency to contribute to flow failures during earthquakes, multiple series of undrained triaxial compression tests were conducted on unsaturated silty sands with the matric suction applied to the soil specimens. The pore air pressure u_a was maintained constant with its valve left opened, while the change in the pore water pressure u_w was monitored with its valve closed, during triaxial compression. The response of matric suction, $u_a - u_w$, and the stress – strain relations are discussed in detail. Based on the outcome of the test results, the residual shear strengths of unsaturated sands are examined with respect to those of fully saturated sands.

Keywords: Flow potential, unsaturated sand, suction, triaxial test

INTRODUCTION

In evaluating the possibility of occurrence of soil liquefaction and associated flow failures during earthquakes with a help of factor of safety, the soil layers located above the groundwater table are assumed as non-liquefiable, and would not contribute to any significant deterioration leading to liquefaction. Located above the groundwater table are basically the unsaturated soil layers, where the field measurements using tensiometers revealed that the negative pore water pressures were observed in many geotechnical engineering applications, (Fredlund and Rahardjo 1993). Herein, in soil mechanics terms, the action of the negative pore water pressure under the atmospheric air pressure within the voids of soil skeletons is measured in terms of matric suction, $u_a - u_w$.

It is known that down to about 5 metres below the groundwater table, there are imperfectly saturated soil layers containing some minute air bubbles. This is evident from the results of velocity logging tests that the velocity of primary wave propagation observed at such layers is equal to $V_p = 500$ to 1000 m/sec, which is well below the value of $V_p = 1600$ m/sec for fully saturated conditions. Since it is primarily at these 5-metre deep partially saturated soil layers that flow failures would be induced during earthquakes, the characteristics of the residual shear strength and flow potential of such partially saturated sands have been recently studied in detail in our research group, (Kamata, et al. 2006). On the other hand, the unsaturated soil layers located above the groundwater table would also be tangled up in the flow failures, though, little is known about the residual strength and flow susceptibility of suction-developed unsaturated soil layers.

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In order to evaluate the overall stability of soil deposits against flow failures during earthquakes, it would be desirable to examine the characteristics of the residual strength of suction-developed unsaturated soils and the conditions leading to flow. In the present study, multiple series of triaxial tests are conducted on suction-applied unsaturated silty sands, and the outcome of the test results are discussed in detail below.

TESTING DETAILS

Soil materials used

Two soil materials are used in the present study, Toyoura sand and Higashi-Takezawa sand. Toyoura sand is a clean sand with no fines content less than 0.075mm, and the physical properties are as follows, $G_s = 2.657$, $D_{50} = 0.18\text{mm}$, $e_{\max} = 0.973$ and $e_{\min} = 0.607$. Higashi-Takezawa sand is a silty sand with non-plastic fines, and was retrieved from one of the sites of landslide in the region of Yamakoshi in Niigata, which occurred in the event of 2004 Niigata-ken Chuetsu Earthquake. The physical properties are as follows, $G_s = 2.64$, $D_{50} = 0.12\text{mm}$, $e_{\max} = 1.429$ and $e_{\min} = 0.810$. The grain size distributions of the soils are shown in Fig. 1.

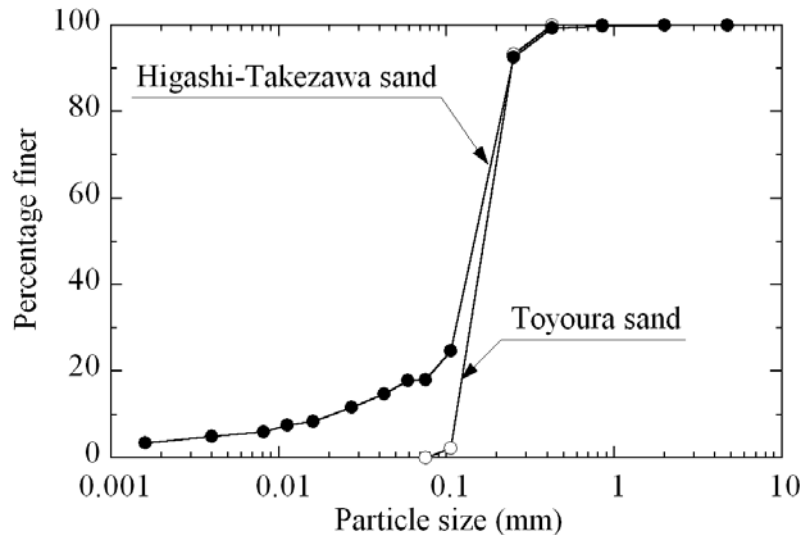


Figure 1. Grain size distributions of soils

Testing apparatus

The testing apparatus and method for triaxial tests on unsaturated soils have been well established ever since the filtering techniques for air and water intrusions were invented using ceramic disks and glass fibre filters. In the present study, the same principle is adopted in controlling the pore air and pore water pressures independently. Another aspect of unsaturated soil testing techniques is the introduction of the axis translation technique, where the application of the matric suction, $u_a - u_w$, under the positive pore water pressure is supposed equivalent to the action of the negative pore water pressure under the atmospheric air pressure, as is the case in any field conditions. The water-saturated ceramic disk with an air entry value of 200 kPa was mounted in the pedestal located at the bottom of soil specimens, and a couple of the glass fibre filters were placed on the surface of the porous stone in the cap located on top of the soil specimens. The pore air pressure, u_a , can therefore be applied from the top of the soil specimens and the pore water pressure, u_w , from the bottom. Since it is known that the matric suction, $u_a - u_w$, is closely associated with the water content according to the water retention characteristics of soils, the measurement of the water content is preferable. The amount of water drained in and out of the soil specimens through the ceramic disk is measured by a combination of a precision scale and a small vessel connected with the pore water tube leading to the ceramic disk.

Testing procedure

In conventional triaxial tests for saturated soils, the effective stress state is given as $\sigma - u_w$, and the cell pressure σ and pore water pressure u_w (back pressure) are controlled separately. However, in determining the stress state in unsaturated soil triaxial tests, two components of stress state variables are necessary. They are net normal stress, $\sigma_{net} = \sigma - u_a$, and matric suction, $u_a - u_w$. In order to provide independent controls on these two stress state variables, the cell pressure σ , pore air pressure u_a and pore water pressure u_w need to be regulated and monitored separately.

The testing procedure consists of two phases. The first phase is the drained isotropic consolidation, in which the valves for pore air and pore water are both left opened. The second phase is the undrained triaxial compression, in which the valve for pore air is left opened and the valve for pore water is closed.

The triaxial specimens with 60 mm in diameter and 120 mm in height were prepared by the method of wet tamping. Upon assembling the cap and pedestal to the soil specimens and making the cell filled with water, the cell pressure σ is first gradually increased to a designed net normal stress σ_{net} . The cell pressure, pore air pressure and pore water pressure are then equally elevated keeping the net normal stress of $\sigma_{net} = \sigma - u_a$ constant and $u_a = u_w$, until the designed level of the pore air pressure u_a is achieved. At the end of the above process, the designed initial matric suction, $s_i = u_a - u_w$, is slowly applied.

Since it is most likely that the pore air and pore water are both entrapped within the unsaturated soil mass during the flow deformation involving unsaturated soil layers, it might be assumed reasonable that during the flow deformation involving unsaturated soil layers, the undrained conditions hold true for pore air as well as pore water. However, in the present study, the valve for the pore air is left opened, while the valve for the pore water is closed. The undrained triaxial compression is then commenced. Therefore, the pore water pressure u_w would respond in an undrained manner while the pore air pressure u_a stays constant during the triaxial compression, leading to the change in the matric suction, $u_a - u_w$. From the reasons described above, further study would be recommended in conducting the other test series adopting the undrained conditions for pore air as well as for pore water.

Test series

The details of the test series conducted in the present study are summarized in Table 1. The net normal stress of $\sigma_{net} = \sigma - u_a = 100$ kPa is applied in all of the tests. More relevant choice of the magnitude of net normal stress might be suggested for further study, since the unsaturated soil layers are expected at shallower depths in the fields where the confining stress is lower than 100 kPa, and the effects of suction might be dependent on the relative magnitude of the net normal stress with respect to suction. The relation between the initial water content w_i and the initial suction s_i reflects the water retention

Table 1. Test series on unsaturated triaxial tests

Soil	$D_r(\%)$	$w_i(\%)$ (Sr(%))	s_i (kPa)	σ (kPa)	u_a (kPa)
Toyoura sand	5-7	5.7 (15.8) 16.1 (44.7)	3.16 1.88	155	55
	25	4.0 (12.1) 22.2 (66.5)	2.44 0.16	150	50
	50-55	5.0 (16.9) 15.2 (51.9)	3.17 1.52		
Higashi-Takezawa sand	15-17	11.5 (21.4) 16.5 (30.9)	28.3 7.0	170	70
	52-54	12.3 (29.5) 16.4 (39.3)	19.5 6.3		

characteristics of soils, where the matric suction reduces with increasing water content. Higashi-Takezawa silty sand appears to exhibit greater initial suction than Toyoura clean sand. This would be related to the tendency of inter-granular suction developing more effectively in miniscule particles such as fines.

TEST RESULTS

Stress – strain and suction behaviour

In conventional saturated soil mechanics, the flow characteristics of saturated sand have been examined in terms of contractive and dilative behaviours, where the sand exhibiting contractive behaviour is more likely to develop flow deformation and vice versa, (Ishihara 1993, and others). It would be most feasible to adopt the same criteria in assessing the possibility of flow in unsaturated sands.

The stress – strain relations of the deviatoric stress, $q = \sigma_1 - \sigma_3$, and axial strain, ϵ_a , for suction-applied unsaturated Toyoura sand are shown in Fig. 2. For comparison purposes, the stress – strain relations for saturated Toyoura sand are also shown in Fig. 3. As shown in Fig. 2, in all of the unsaturated tests, the ductile behaviour is seen to be predominant, implying that the sands are less likely to induce flow deformation in unsaturated conditions. There seem to be not large differences between the tests with the water content less than 10% and those with 15% to 25% water content. However, weaker responses are observed in the tests with the water contents less than 10%. It would imply that there is some value of water content or degree of saturation exhibiting the largest strength, which is similar to the effects of water content on the degree of compaction. The response of suction during undrained compression is plotted against the water content in Fig. 4. The suction seems not to change noticeably,

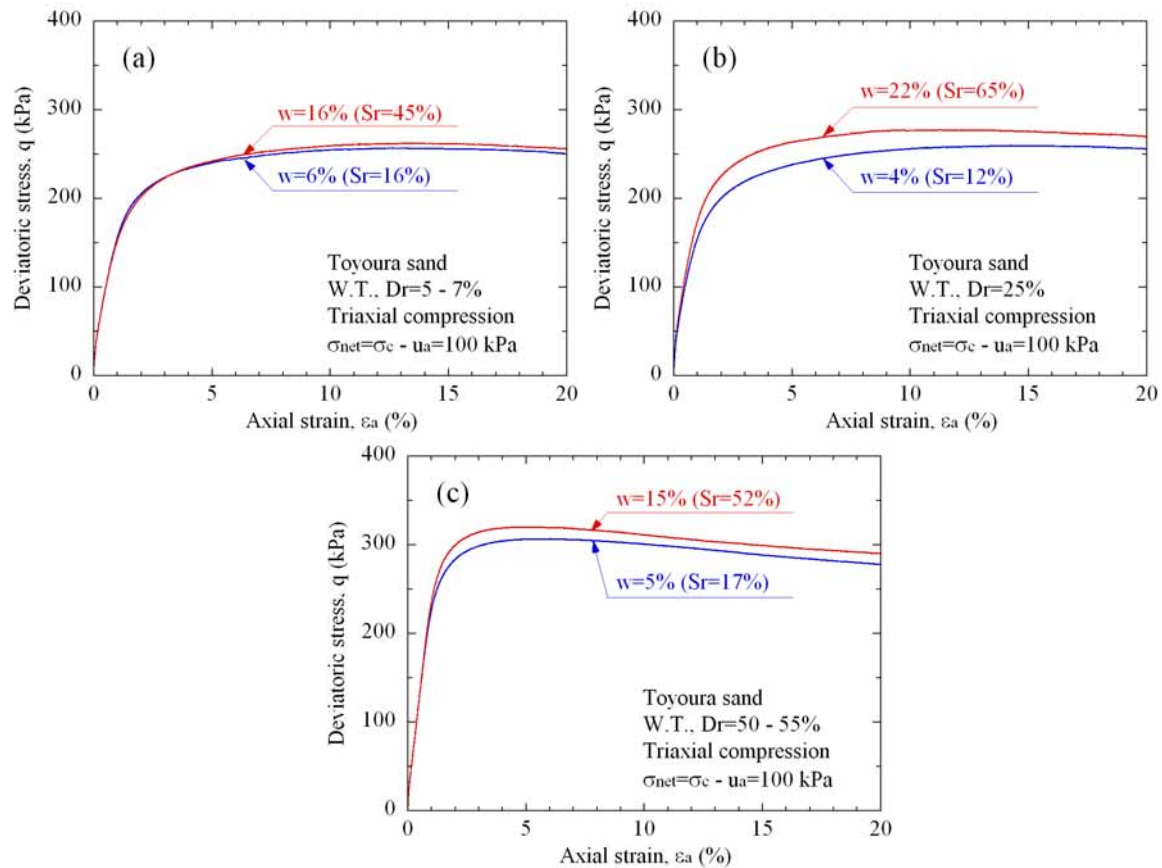


Figure 2. Stress – strain relations for suction-applied unsaturated undrained triaxial compression tests, (Toyoura sand)

except in some tests with higher initial suction and lower water content. It is of interest to notice that the presence of matric suction appears to inhibit the excessive change of the pore water pressure during triaxial compression. It is conceivable that the range of the retentive water content in soils tends to fluctuate with the water retention characteristics. It would therefore be desirable to use the degree of saturation rather than water content in plotting the response of suction, as shown in Fig. 5.

The stress – strain relations for Higashi-Takezawa sand are shown in Fig. 6. Similar to the tests for Toyoura sand, the ductile behaviour is predominant in all of the tests. The response of suction during undrained compression is plotted against the water content and degree of saturation in Figs. 7 and 8, respectively. The matric suction prevailing in the specimens of Higahi-Takezawa silty sand is found to be much greater than Toyoura clean sand.

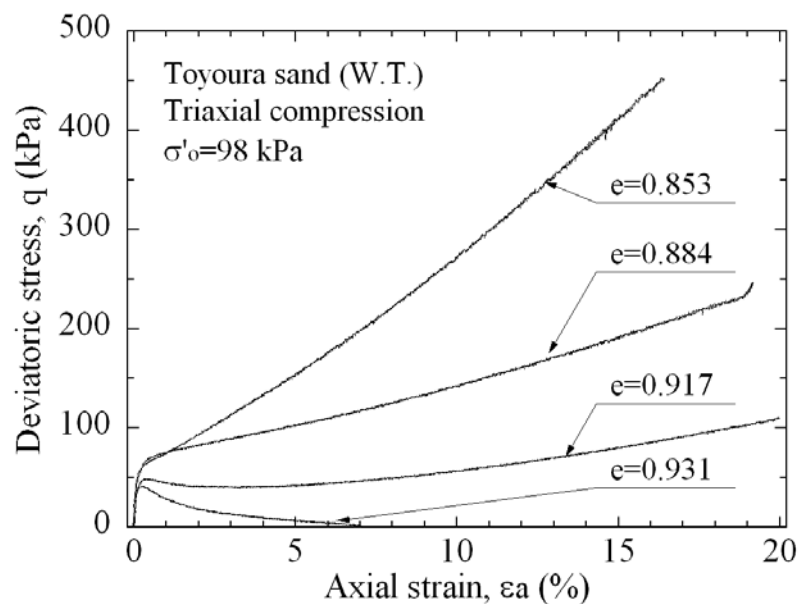


Figure 3. Stress – strain relations for saturated undrained triaxial compression tests, (Toyoura sand)

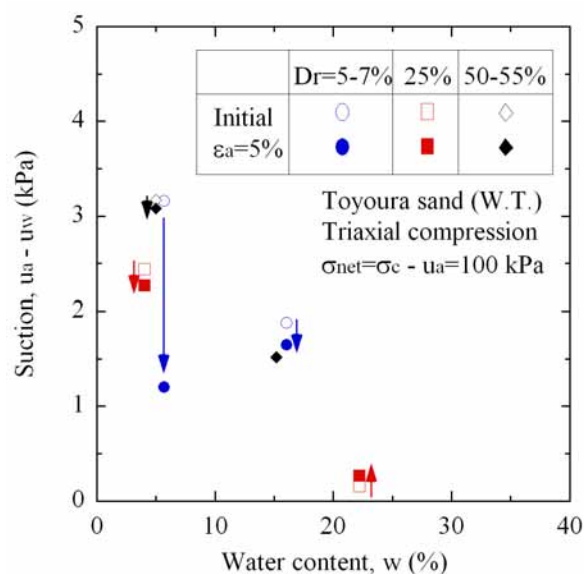


Figure 4. Plots of suction against water content, (Toyoura sand)

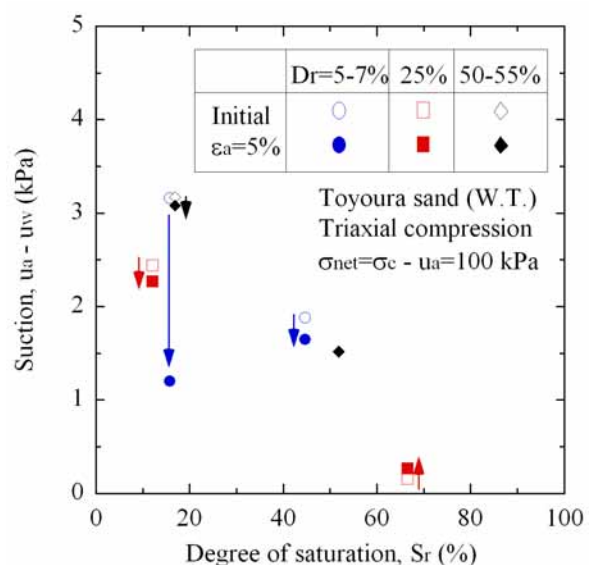


Figure 5. Plots of suction against degree of saturation, (Toyoura sand)

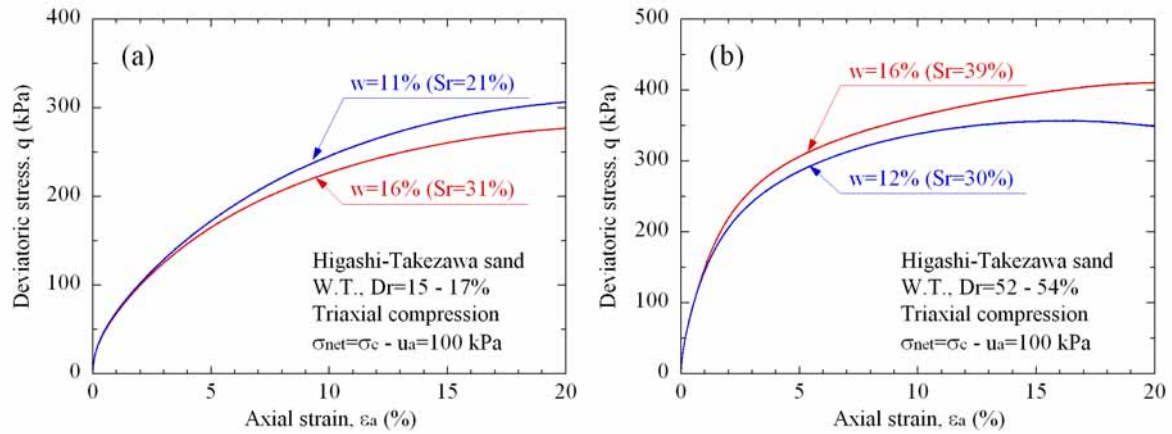


Figure 6. Stress – strain relations for suction-applied unsaturated undrained triaxial compression tests, (Higashi-Takezawa sand)

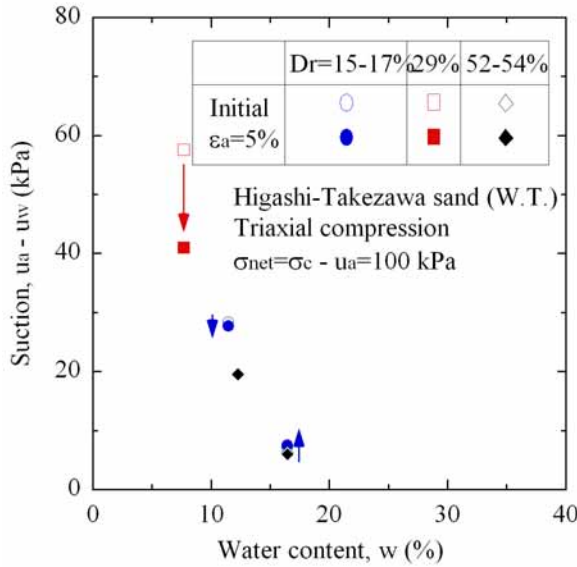


Figure 7. Plots of suction against water content, (Higashi-Takezawa sand)

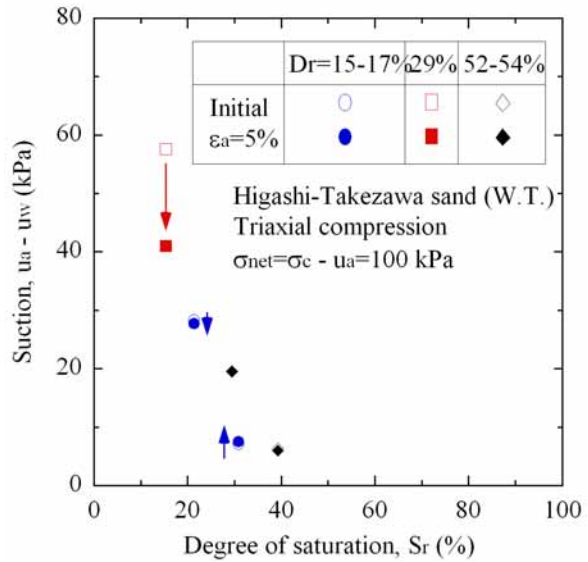


Figure 8. Plots of suction against degree of saturation, (Higashi-Takezawa sand)

Residual shear strength

In examining the residual shear strength of unsaturated soils, it would be preferable to examine how large the residual shear strength becomes in comparison to that of fully saturated soils, since the data on fully saturated soils can be readily available from the conduct of conventional triaxial testing. It has been customary to define the residual shear strength of fully saturated soils at the state of phase transformation (P.T.). The strain levels at which the P.T. states are observed vary with density and confining stress. However, for comparison purposes, the values of the shear stress ratio, $\tau_m/\sigma_{net} = (\sigma_1 - \sigma_3)/(2\sigma_{net})$, observed at the axial strain of $\epsilon_a = 0.5\%$ are read off from the results of unsaturated triaxial tests, and compared with the shear stress ratio, τ_m/σ'_o , observed at P.T. states in fully saturated triaxial tests. Figure 9 shows the results of Toyoura sand in terms of the normalized residual shear strength ratio defined as τ_m/σ_{net} and τ_m/σ'_o plotted against the degree of saturation. The shear strength increase seems to be dependent on the density, however, the residual shear strength of unsaturated sands is found to become 1.5 to 1.8 times that of fully saturated sands. Figure 10 shows the same comparison on the residual shear strength determined at the axial strain of $\epsilon_a = 5\%$. The residual shear strength of

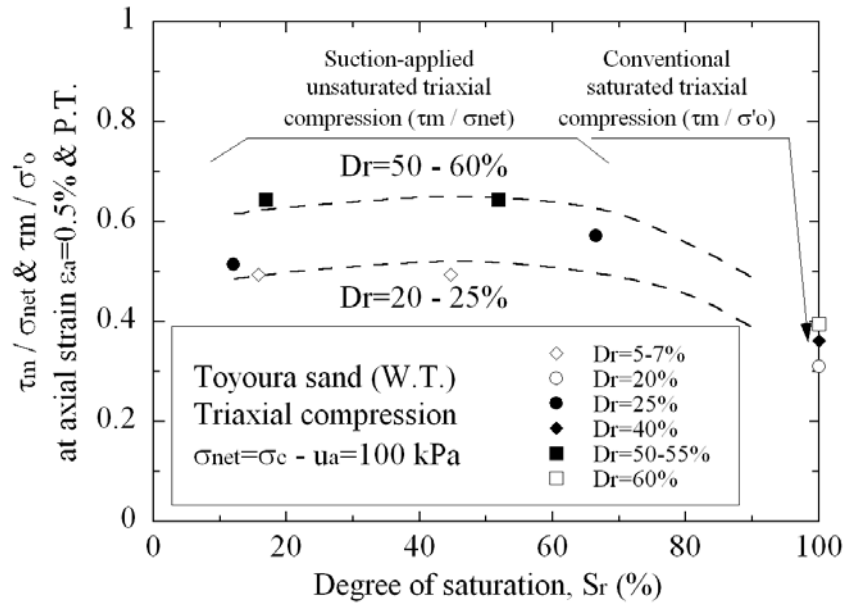


Figure 9. Plots of residual shear strength ratio at P.T. states or $\epsilon_a = 0.5\%$ against degree of saturation, (Toyoura sand)

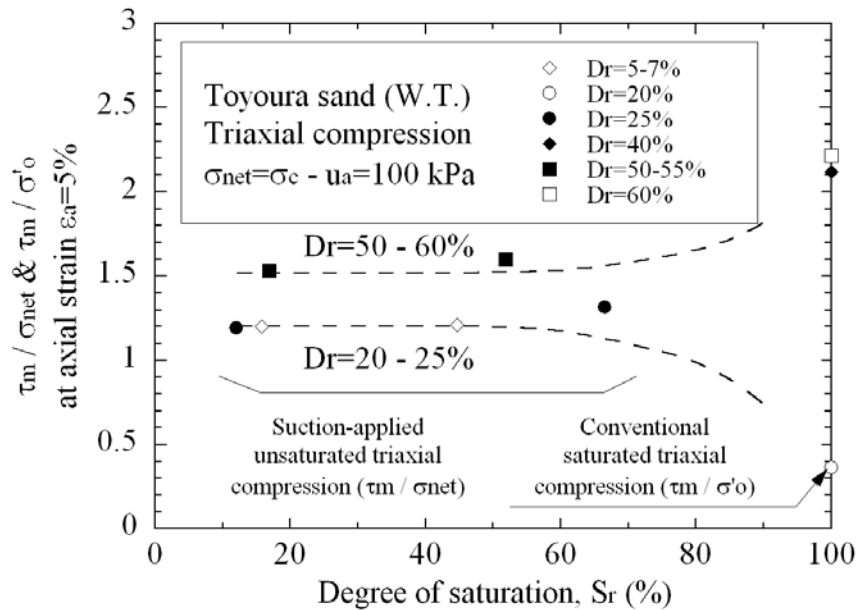


Figure 10. Plots of residual shear strength ratio at $\epsilon_a = 5\%$ against degree of saturation, (Toyoura sand)

saturated medium dense sands is found to become noticeable large due to the ability to induce the large negative pore water pressure. However, the residual shear strength ratio, τ_m / σ_{net} , of unsaturated sands shows the tendency to stay within the values between 1.2 and 1.5.

Figure 11 shows the relations between the residual shear strength ratio and the void ratio. It is seen that in the results of conventional saturated undrained triaxial compression tests, there is a unique relation between them. The threshold value of the residual shear strength dividing the contractive and dilative behaviours can be found as $\tau_m / \sigma'_o = 0.28$. The values of the residual shear strength for unsaturated sand are found to be located above this threshold value, which tended to show ductile behaviours during triaxial compression.

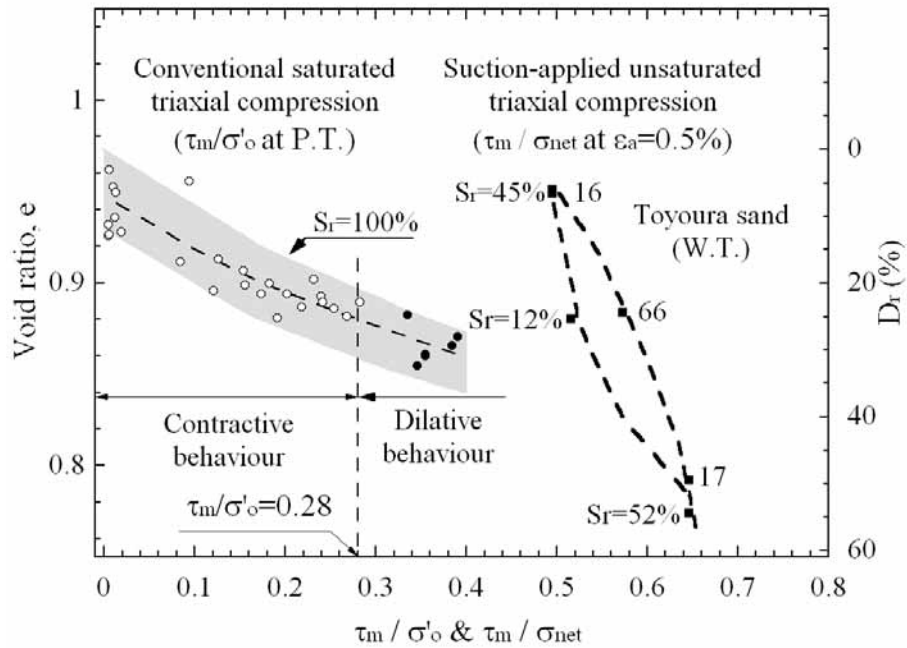


Figure 11. Plots of residual shear strength against void ratio, (Toyoura sand)

CONCLUSIONS

Multiple series of undrained triaxial compression tests were carried out on unsaturated sand specimens. The responses of suction and stress – strain relation were observed. The application of matric suction to the soil specimens was found to inhibit the excessive development of the pore water pressures and the ductile behaviours were observed in all of the tests. The difference in the residual shear strengths of unsaturated sands and fully saturated sands showed complex characteristics, when they were compared at small and large strain levels. However, the residual shear strength of unsaturated sands defined at a small strain level was found to become 1.5 to 1.8 times that of fully saturated sands.

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