EFFECTS OF STRESS HISTORY DUE TO UNSATURATION AND DRAINAGE CONDITION ON SHEAR PROPERTIES OF UNSATURATED COHESIVE SOIL

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ABSTRACT

Several studies have concluded that the effect of matric suction on the shear strength of unsaturated soil is very important. However, little attention is given to the stress history due to unsaturation and drainage condition in the arrangement of these experimental results. This paper attempts to show the relationship between shear properties and matric suction under a specified stress history and drainage condition.

In this study, an unsaturated specimen is set up by dehydrating the normally consolidated soil with controlled matric suction to a specified stress history. Triaxial apparatus and hollow cylindrical torsional shear apparatus are employed to examine the effects of stress history and drainage condition, respectively.

Through systematic experiments, the effects of stress history and drainage condition on the stress-strain relationship are clarified. The increase in shear strength by matric suction which is measured at the point of maximum shear stress is observed to be independent of stress history and drainage condition. However, in strain softening behavior it was found that the ultimate strength is independent of matric suction and traces a unique line which is parallel to the critical state line on the $p_{net}-q$ plane.

Key words: cohesive soil, shear strength, stress history, torsional shear, triaxial test, unsaturated soil (IGC: D6)

INTRODUCTION

Mechanical properties of saturated soil are expressed generally by using the principle of effective stress presented by Terzaghi (1936). However, in unsaturated soil there is no firm principle of effective stress because it is difficult to explain the relationship between pore air pressure and pore water pressure in unsaturated soil which is composed of solid, liquid and air.

Bishop (1960) proposed the effective stress equation for unsaturated soils as

\[ \sigma' = \sigma - u_s + \chi(u_s - u_w) \]  

where $\sigma'$ is effective stress, $\sigma$ is total stress, $u_s$ is pore air pressure, $u_w$ is pore water pressure and $\chi$ is a soil parameter which depends on the degree of saturation.

Bishop and Donald (1961) conducted triaxial tests on unsaturated silt to show the effectiveness of Eq. (1). They found that if $(\sigma_1 - u_s)$ and $(u_s - u_w)$ remained constant during the shearing process, there was no effect on the stress-strain relationship; on the other hand, a change in either $(\sigma_1 - u_s)$ or $(u_s - u_w)$ had an effect on the stress-strain relationship. This means that the quantities $(\sigma - u_s)$ and $(u_s - u_w)$, rather than the individual value of $\sigma$, $u_s$ and $u_w$, have effects on the unsaturated soil behavior.

Jennings and Burland (1962) pointed out that an experiment in which $\sigma'$ was kept constant while changing $(\sigma - u_s)$ and $\chi(u_s - u_w)$ was needed to show the validity of Eq. (1). However, they stated that to evaluate the values of $\chi$ without the existence of Eq. (1) is very difficult.

It has been suggested by many researchers (e.g., Coleman, 1962; Matyas and Radhakrishna, 1968) that $(\sigma - u_s)$ and $(u_s - u_w)$ should be treated separately because the two stress components are generated by different mechanisms. Karube et al. (1978) examined the existing effective stress equations using a double-walled triaxial test, but they concluded that the existence of effective stress was subtle.

Escario and Sáez (1986) showed that matric suction had little influence on internal friction angle through experiments which were carried out with statically compacted remoulded samples. Satija and Gulhati (1979) suggested that attention should be paid to the strain rate effect on shear properties of an unsaturated soil when considering drainage condition, e.g., the constant matric suction

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test and constant water content test.

Fredlund et al. (1978) proposed a shear strength equation for unsaturated soil, which was written in terms of two independent stress state variables. This equation is given by

$$\tau = c' + (\sigma - u_s) \tan \phi' + (u_n - u_a) \tan \phi^b$$

(2)

where $\phi^b$ is the friction angle with respect to changes in $(\sigma - u_s)$ when $(\sigma - u_s)$ is held constant. The relationship between shear strength and the matric suction of statically compacted soil with emphasis on $\phi^b$ was examined using direct shear tests by Gan et al. (1988) and Olool and Fredlund (1996). From these test results, an empirical, analytical model was developed to predict the shear strength in terms of soil matric suction (Fredlund et al., 1995; Vanapalli et al., 1996).

Although a great deal of research has been carried out on unsaturated soil to investigate the effect of matric suction on shear strength, little is known about the effects of stress history and drainage condition on shear properties. The purpose of this paper is to examine the strength and deformation characteristics of unsaturated cohesive soil with stress history due to unsaturation. To achieve this objective, a series of triaxial tests was conducted to examine the effect of stress history due to unsaturation and another series of hollow cylindrical torsional shear tests was conducted to examine the effect of drainage condition.

EXPERIMENTS

Triaxial tests were conducted on three types of specimens (see below) to examine the effect of stress history due to unsaturation. Next, torsional shear tests were performed on the A-type specimen to examine the effect of the drainage condition. Though the triaxial tests were conducted under the shear condition wherein $b=0$ (compression), a different shear condition where $b=0.5$ was selected for the torsional shear tests. The parameter $b$ indicates the relative magnitude of the intermediate principal stress $(\sigma_2 - \sigma_3)/(|\sigma_1 - \sigma_3|)$. Furthermore, though it was possible to investigate the effect of the drainage condition also in triaxial tests, torsional shear tests were conducted for comparison purposes.

The following were investigated by these experiments.

2. The effect of drainage condition (torsional shear test).
3. The effect of shear condition (both triaxial and torsional shear tests).

Triaxial Apparatus

A schematic diagram of the triaxial apparatus is represented in Fig. 1. The apparatus is an improved version of the ordinary triaxial apparatus so that experiments with unsaturated soils become possible through the use of a double-walled triaxial cell. The volume change of the unsaturated specimen is measured by the differential pressure transducers (DPT) shown in Fig. 1. This system is similar to that developed by Bishop and Donald (1961) but the mercury in the inner cell is replaced by de-aired water for safety reasons. The reference water table is set up to increase the accuracy and stability of the DPT system by removing the effects of cell pressure and temperature. The size of the specimen is approximately 5 cm in diameter and 12.5 cm in height. Air pressure is applied from the top of the specimen to control the matric suction. A ceramic disk, 2.2 cm in diameter and 0.8 cm in thickness, is installed in the base pedestal using an epoxy resin to prevent air leakage into the water compartment from the area beside the ceramic disk. The air entry value of the saturated ceramic disk is controlled by the pore size of the disk. Figure 2 shows the air passage characteristics of the disk, where matric suction $s(=u_n-u_a)$ is calculated as pore air pressure minus
pore water pressure. The air pressure at which air starts to pass through the disk is referred to as the air entry value (AEV), which equals 380 kPa in this case. The load cell, in which the influence of cell pressure is almost negligible, that is used to measure the axial load is installed inside the triaxial cell to remove the effect of rod friction on the measurement.

**Torsional Shear Apparatus**

A schematic diagram of the hollow cylindrical torsional shear apparatus is represented in Fig. 3. This torsional shear apparatus, which has a double-walled triaxial cell system in the inner and outer cell, was developed for experiments with unsaturated soils. The changes in the inner and outer diameters are calculated through the volume changes, which are measured by differential pressure transducers (DPT) in the hollow cylinder and inner cell, respectively (see Fig. 3). The size of the specimen is approximately 3 cm in inner diameter, 7 cm in outer diameter and 14 cm in height. Air pressure is applied from the top of the specimen to control the matric suction. A ceramic disk, 3.6 cm in inner diameter, 6.4 cm in outer diameter and 0.4 cm in thickness, is installed in the base pedestal using an epoxy resin. Figure 2 shows that the AEV of the disk is equal to 250 kPa. The load cells, in which the influence of cell pressure is almost negligible, that are used to measure the axial load and torque are installed inside the triaxial cell.

**Samples**

The cohesive soil, which is a lateritic soil, was sampled in the Yoneyama area of Niigata Prefecture (Japan). During the air drying process, clay chunks were continuously pounded with a wooden hammer to reduce their size. A soil obtained by sieving out soil particles greater than 840 μm was used in the experiment. The classification of this soil based on the Japanese Unified Soil Classification System (designated as JGS) is MH and is referred to as YONEYAMA sandy silt in this study. The physical properties of the soil are summarized in Table 1 and the grain size distribution is shown in Fig. 4. The drying portion of the moisture characteristic curve (matric suction s versus water content w) obtained from the pressure plate method is shown in Fig. 5.

Before setting in the triaxial cell, two types of test specimens were prepared as follows. One type consisted of soil and de-aired water which were mixed and stirred well to make a slurry. One dimensional pre-consolidation was performed on this slurry under a vertical pressure of 45 kPa in a large size mold. After completion of consolida-

| Table 1. Physical properties of YONEYAMA sandy silt |
|-----------------|-------|-----|-----|-----|-----|
| ρs (g/cm³)      | w₁ (%)| I_p | Clay (%) | Silt (%) | Sand (%) |
| 2.73            | 52.4  | 19.8 | 15.9 | 43.1 | 41.0 |

**Fig. 3. Schematic diagram of hollow cylinder apparatus**

**Fig. 4. Grain size distribution curve of YONEYAMA sandy silt**

**Fig. 5. Moisture characteristic curve of YONEYAMA sandy silt**
tion, the consolidated soil block was taken out from the mold and cut into several pieces. The specimen was made by trimming from each soil piece.

The other type involved distilled water being sprayed on air-dried soil and being mixed well to make a soil with a certain initial water content $w_i$. This moist soil was strewed by hand in a small size mold, the wall of which was coated with Teflon to reduce the friction between the soil and the wall. This moist soil was one dimensionally compressed from both sides (top and bottom) under a vertical pressure of 45 kPa in this small size mold; the resulting specimen is referred to as a statically compacted specimen. The density distributions in the vertical direction of a statically compacted specimen are shown in Fig. 6. It can be seen in the figure that there was a tendency for the density to become smaller the farther it was from the loading place. However, it was clear that a specimen compressed from both sides has a more uniform dry density compared with are compressed from one side only (i.e., with the lower part fixed).

**Triaxial Test Procedure**

A triaxial test in which the axial strain rate is set at 0.02%/min was performed on three types of specimens which were made by the following different processes;

1. A-type specimen
   This specimen made from slurry was saturated ($B$-value greater than 0.95) and consolidated isotropically under 45 kPa in the triaxial cell. After measuring the size of specimen, the specimen was reconsolidated isotropically under a certain confining pressure $p'_c$. Next, the pore water in the specimen was drained through the ceramic disk under a constant $p - u_i (= p'_c)$ by applying a certain $u_i$ from the top of the specimen. This stress history is shown schematically in Fig. 7. In this dehydration process, though water was drained for a long time, the dehydration process was terminated after 3000 minutes. This is because the drained volume of water per unit time became very small and the equilibrium state was achieved at that time (Fig. 8). The time history of the drained volume of water and the distribution of

water content in the specimen after dehydration are shown in Figs. 8 and 9, respectively. It is clear that the drained volume of water became very small after 3000 minutes and the difference in water content in the specimen was less than 0.5%. Triaxial compression tests, with constant lateral stress $\sigma_z$, were carried out under constant water content (CW) condition (the pore air was allowed to drain while the pore water was undrained). The rate of strain was controlled until the failure of the specimen. The test conditions of the specimen are summarized in Table 2.
Table 2. Test conditions of specimens (A, B-type)

<table>
<thead>
<tr>
<th>Type</th>
<th>s (kPa)</th>
<th>$\rho_{\text{tot}}$ (kPa)</th>
<th>$S_i$ (%)</th>
<th>Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100</td>
<td>50</td>
<td>84.9</td>
<td></td>
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<td>200</td>
<td>91.5</td>
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<td>50</td>
<td>81.3</td>
<td></td>
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<td></td>
<td></td>
<td>100</td>
<td>82.2</td>
<td></td>
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<td></td>
<td></td>
<td>200</td>
<td>86.5</td>
<td></td>
</tr>
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Table 3. Test conditions of specimen (C-type)

<table>
<thead>
<tr>
<th>Type</th>
<th>$w_t$ (%)</th>
<th>$\rho_{\text{tot}}$ (kPa)</th>
<th>$S_i$ (%)</th>
<th>Shear</th>
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<td>46.2</td>
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<tr>
<td></td>
<td></td>
<td>200</td>
<td>73.3</td>
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</table>

2. B-type specimen
This specimen made from slurry was saturated ($B$-value greater than 0.95) and consolidated isotropically under 45 kPa in the triaxial cell. After measuring the size of the specimen, the specimen was drained through the ceramic disk under a constant net pressure $p - u_a (= 45$ kPa) with the application of a certain pore air pressure $u_a$ from the top of the specimen. After dehydration for 3000 minutes, the specimen was reconsolidated isotropically under a certain net pressure ($p - u_a$). The reconsolidation time was set at 180 minutes by the application of the $3t$ method (Kame et al., 1987; Oda et al., 1989). This stress history is also shown in Fig. 7. Triaxial compression tests were carried out on the specimen created as mentioned above. The method of triaxial compression tests for the B-type specimen was the same as that for the A-type specimen. The test conditions of this specimen are also summarized in Table 2.

3. C-type specimen
The C-type specimen was made by depositing moist soil with a certain water content. This deposit was very loose because it had already undergone the effect of suction. The suction should be changed for statically one-dimensional compression. The statically compacted specimen was consolidated isotropically under 45 kPa in the triaxial cell. After measuring its size, the specimen was drained through the ceramic disk under a constant $p - u_a (= 45$ kPa) by applying a certain $u_a (= 100$ kPa) from the top of the specimen. In this process, water was drained because the water content was larger than that of the steady state in which a target matric suction was applied. After dehydration for 1000 minutes, the specimen was reconsolidated isotropically under a certain net pressure ($p - u_a$). The $3t$ method defined the reconsolidation time as 2000 minutes for C-type specimen. The stress history of the C-type specimen is not as clear as those of the A and B-type specimens made from slurry. Though the final condition is the same for A, B and C-type specimens, densities are different because of the effect of stress history. Triaxial compression tests were carried out on the C-type specimen using the same method as that for the A-type or B-type specimens. The test conditions of the specimen are summarized in Table 3.

Torsional Shear Test Procedure
A torsional shear test was performed on a specimen made using the same method as for the A-type specimen in the triaxial test, using two different shear conditions, i.e., constant water content (CW) and constant suction (CS) test. Though matric suction varied during shear in the CW test, it was constant during shear in the CS test. The shear strain rates are 0.015%/min and 0.005%/min in the CW and CS tests respectively.

The specimen made from slurry was saturated ($B$-value greater than 0.95) and consolidated isotropically under 45 kPa in the triaxial cell. After measuring the size of the specimen, it was isotropically reconsolidated under a certain confining pressure $p_c'$. Next, the specimen was drained through the ceramic disk for 3000 minutes under a constant $p - u_a (= p_c')$ by applying a certain $u_a$ from the top of the specimen. Torsional shear tests, under a constant $\rho_{\text{tot}}$, $\alpha = 45^\circ$ and $b = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3) = 0.5$, were carried out under constant water content and drained condition with strain control until the failure of the specimen. In the above, $\alpha$ is the direction of the major principal stress relative to the vertical axis. The test conditions of the specimen are summarized in Table 4.

Stress and Strain Parameters
The idealized stress condition in a hollow cylindrical element is illustrated in Fig. 10. The average values of the four stresses and four strains, namely, vertical stress $\sigma_z$, radial stress $\sigma_r$, circumferential stress $\sigma_\theta$, shear stress $\sigma_{\theta z}$, axial strain $\varepsilon_z$, radial strain $\varepsilon_r$, circumferential strain $\varepsilon_\theta$ and shear strain $\gamma_{\theta z} = 2\varepsilon_{\theta z}$ are calculated using the expressions given by Hight et al. (1983). The correction for the membrane forces proposed by Tatsuoka et al. (1986) was introduced in this research.

The stress and strain parameters used in this research
Table 4. Test conditions of specimen (Torsional shear test)

<table>
<thead>
<tr>
<th>Type</th>
<th>$s$ (kPa)</th>
<th>$p_{net}$ (kPa)</th>
<th>$S_i$ (%)</th>
<th>Shear</th>
</tr>
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<tbody>
<tr>
<td>CW</td>
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<td></td>
<td>100</td>
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<td></td>
<td>200</td>
<td>90.4</td>
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<tr>
<td></td>
<td></td>
<td>300</td>
<td>95.9</td>
<td></td>
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<tr>
<td>A</td>
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<td>89.2</td>
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<tr>
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<td>90.0</td>
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Relative magnitude of the intermediate principal stress, $b$:

$$b = \frac{\sigma_2 - \sigma_1}{\sigma_1 - \sigma_3}$$  \hspace{1cm} (8)

Volumetric strain, $\varepsilon_v = 3 \varepsilon_{oct}$:

$$\varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$$  \hspace{1cm} (9)

Shear (Deviator) strain, $\varepsilon_s = (1/\sqrt{2}) \gamma_{oct}$:

$$\varepsilon_s = \frac{\sqrt{2}}{3} \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2}$$  \hspace{1cm} (10)

**EFFECTS OF STRESS PATH**

The effect of stress history due to unsaturation was examined on A, B and C-type specimens through the triaxial tests. The experimental results of consolidation, shear deformation and failure properties are shown and discussed in this section.

**Consolidation Properties before Shear**

Figure 11 illustrates the isotropic consolidation curves for A-type and B-type specimens. It is clear that the void ratios of A-type and B-type specimens are almost coincident during the initial stage ($p_{net} = 50$ kPa) and smaller than that of the saturated specimen because of the additional compression due to matric suction. The reason for this is that the stress history of the A-type specimen is almost the same as that of the B-type specimen because $p'_v$ in Fig. 7 equals 50 kPa. The void ratio of the B-type specimen is larger than that of the A-type specimen at $p_{net} = 100$ and 200 kPa. The reason for this is that the specimen volume change by isotropic consolidation is small because a contact force of the soil particles is generated by applying matric suction. Though the specimen is compressed by an increase in matric suction, compressibility of the specimen against $p_{net}$ becomes small. This means that even if the final stress state is the same, the void ratio varies due to the difference in stress history caused by unsaturation. The slopes of the consolidation curves for A-type and saturated specimens are almost the same because the volume change by the matric suction is nearly equal within the range of net mean stresses $p_{net}$ adopted in the experiments.

Figure 12 illustrates the isotropic consolidation curves for the C-type specimen. The void ratio and the slope of the consolidation curve of this specimen are larger than those of the saturated specimen. This implies that the unsaturated specimen is able to exist in a looser state compared with the saturated specimen.

**Shear Properties**

Figures 13, 14 and 15 show the A-type specimen’s stress-strain, $\varepsilon_s - \varepsilon_v$ and $s - \varepsilon_v$ relationships for respectively. It can be seen that for higher $p_{net}$ and $s$, the shear

$$\alpha = \frac{1}{2} \tan^{-1} \left( \frac{2\sigma_{12}}{\sigma_2 - \sigma_3} \right)$$  \hspace{1cm} (7)
strength is larger. If $p_{cm}=50$ kPa and $s=200$ kPa, strain softening and dilation appear clearly, and the strength approaches the steady state in every case. Matric suction decreases significantly in the initial stage of shear, and its tendency is similar to dilatancy characteristics. Matric suction for the specimen with $p_{cm}=200$ kPa and $s=100$ kPa shows a negative value because the degree of saturation is increased to about 98% during shear.

Figures 16, 17 and 18 show the B-type specimen's stress-strain, $\varepsilon_s-\varepsilon_s$ and $s-\varepsilon_s$ relationships for respectively. Generally the tendencies of shear behavior are similar to those of the A-type specimen. However, the differences in shear behavior between the A-type and B-type specimens are obvious especially for the case of
Fig. 17. $\varepsilon_	ext{s} - \varepsilon_	ext{e}$ relationships for B-type specimen

Fig. 18. $s - \varepsilon_	ext{e}$ relationships for B-type specimen

Fig. 19. Stress-strain relationships for C-type specimen

Fig. 20. $\varepsilon_	ext{s} - \varepsilon_	ext{e}$ relationships for C-type specimen

Fig. 21. $s - \varepsilon_	ext{e}$ relationships for C-type specimen

$P_{\text{int}} = 200\text{ kPa}$ and $s = 200\text{ kPa}$, where the strength is smaller and the decrease of matric suction during shear is larger for the B-type specimen. It is considered that these behaviors are affected by the difference of the initial void ratio (Fig. 11).

Figures 19, 20 and 21 show the C-type specimen's stress-strain, $\varepsilon_	ext{s} - \varepsilon_	ext{e}$, and $s - \varepsilon_	ext{e}$, relationships for respectively. The deviator stress increases and the volume decreases continuously even at 18% shear strain. At a large shear strain level, the slope of the stress-strain curve and the negative dilatancy in the case of $w_i = 28\%$ are larger than those for the case of $w_i = 38\%$. The reason why the behavior is more contractive in the case of $w_i = 28\%$ is because the void ratio before triaxial compression is larger. Matric suction is kept stable in spite of the negative dilation after matric suction decreases significantly in the initial stage of shear.

Final State

The failure points ($p_{\text{int}} - q$ plane) for the A and B-type specimens are plotted in Fig. 22. When a peak does not appear in the stress-strain curve, the state corresponding to $\varepsilon_	ext{s} = 18\%$ is used. The figures beside the plotted point are the values of matric suction at failure. It is seen that when matric suction is large, the failure point is located above the CSL of the saturated soil. The strength and matric suction at failure are different for different stress paths due to unsaturation. Failure lines for constant matric suction are also shown in Fig. 22. This figure shows that failure lines for constant matric suction which are independent of the stress path exist. Figure 23 shows the relationship of $e - p_{\text{int}}$ at failure. All points are plot-
Figure 22. Failure points in $p_{	ext{net}} - q$ plane (A, B-type)

Figure 23. $e - p_{	ext{net}}$ relationship at failure point (A, B-type)

Figure 24. Failure points in $p_{	ext{net}} - q$ plane under triaxial compression test (C-type)

ted near the CSL, and there is a tendency for the points to be plotted a little below the CSL.

Figure 24 shows the failure point for the C-type specimen in $p_{	ext{net}} - q$ plane. Though all points are plotted near the CSL, it is considered that each state should finally reach the failure line of constant matric suction because $q$ continues to increase with $e$ (see Fig. 19), which is indicated by the arrows in Fig. 24. The relationship of $e - p_{	ext{net}}$ at failure for the C-type specimen is shown in Fig. 25. Every point, except for the case of $w_i = 38\%$ and $p_{	ext{net}} = 200$ kPa, is fairly above the CSL because volume change does not converge.

EFFECTS OF DRAINAGE CONDITION

The effect of the drainage condition on the shear process was examined on A-type specimens through torsional shear tests. The experimental results of shear deformation and failure properties are shown and discussed in this section.

Shear Properties

Figures 26, 27 and 28 show the stress-strain, $e_r - e$, and $s - e$, relationships in constant water content tests, respectively. Looking at the stress-strain relationships, there are small peaks and it seems that the ultimate (residual) state is reached at larger strain. The peak appears at a smaller $e$, when $p_{	ext{net}}$ is smaller. Volume change shows a contractive behavior except for the case of $p_{	ext{net}} = 50$ kPa. Matric suction decreases significantly in the initial stage of shear, which is similar to that observed in triaxial compression tests.

Figures 29 and 30 show the stress-strain and $e_r - e$, relationships in consolidated drained (constant suction) tests, respectively. Small peaks also appear and the ultimate (residual) strength is approximately equal for the same $p_{	ext{net}}$. The stress-strain and $e_r - e$, relationships show that the peak in stress-strain relationship tends to appear at smaller $e$, and that the dilation occurs at smaller $p_{	ext{net}}$ and larger $s$. There is a variation in the volume change behavior for the case of $p_{	ext{net}} = 50$ kPa and $s = 100$ kPa because of local failure, which means the appearance of a shear band occurs in the specimen.

Final State

The relationship between $p_{	ext{net}}$ and $q$ corresponding to the maximum strength is shown in Fig. 31. The failure line at constant matric suction is parallel to the CSL of a...
saturated soil and plots higher for a larger matric suction. This means that any increment in strength due to matric suction is constant and independent of $p_{stat}$. Figure 32 shows the $e-p_{stat}$ relationship at maximum strength. The failure line of unsaturated soil is below the CSL and is not affected by matric suction. Moreover, the $p_{stat}-q$ relationship at the ultimate (residual) state is shown as USL (ultimate state line) in Fig. 33. It can be seen that the effect of matric suction does not appear, unlike in the case of the maximum strength state. This line (USL) is a little below the failure line at $s=40$ kPa. This is a boundary which distinguishes strain softening and hardening of the stress-strain curve.

Figure 34 shows the relation between strength incre-
because there is a large difference between the $f_c(s)$ of the triaxial compression test ($\alpha=0^\circ$ and $b=0$) and that of torsional shear test ($\alpha=45^\circ$ and $b=0.5$). However, more experimental data with controlled $\alpha$ and $b$ are necessary to demonstrate and prove the effect of the stress state.

CONCLUSIONS

The effects of stress history and drainage condition on the mechanical properties of unsaturated cohesive soil were examined using triaxial compression and torsional shear tests. The main results are summarized as follows:

1. When arranged through the values at failure of A-type and B-type specimen, there is a strength increment depending on matric suction, which is independent of the stress path due to unsaturation and drainage condition. This means that the failure line at constant matric suction on the $p_m=q$ plane is parallel to the CSL and is independent of the stress path and drainage condition.

2. In the statically compacted unsaturated soil (C-type specimen), the result as mentioned above is not obtained. The reason for this is that in this case, the soil does not reach the final state because of the very loose initial state of the soil.

3. When arranged through the values at ultimate (residual) state after peak, a failure line which is independent of matric suction on the $p_m=q$ plane is obtained. This line is the boundary which distinguishes the strain softening and hardening features of stress-strain curves.

4. The slope of the $f_c(s)-s$ relationship becomes smaller as matric suction increases and is different depending on the experimental condition, i.e., triaxial compression or torsional shear. Hence, there are effects of matric suction and stress state on the strength increment due to matric suction.

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REFERENCES