Direct shear and compression behaviors for an unsaturated compacted soil with water content and matric suction measurement

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ABSTRACT: One of the most problematic unsaturated soils is the collapsible soil. Owing to their high void-ratio characteristics, these soils exhibit significant strength and low compressibility at in-situ water content. They also collapse significantly under constant load when wetted. Damages to constructions often result from the differential deformations which have been neglected in the design process. Therefore, the identification of collapsible soils or estimation of the collapse potential and shear strength become major aspects in the design of structures in moisture-sensitive soil sites. A laboratory test is commonly used for the identification of collapsible soils. The aim of the work presented in the paper was to obtain a quantitative estimate of collapse potential for estimating potential settlements of a structure and soil shear strength. The shear strength parameters for an unsaturated soil were then measured using a modified direct shear apparatus with the facility to control matric suction. The water content was also measured. Both collapse potential and shear strength are strongly related to the loading history and soaking history.

I. INTRODUCTION

The safety factor of residual or compacted soil slopes with a deep groundwater table depends, among other factors, on the magnitude of the negative pore-water pressure above the groundwater table which contributes to additional shear strength of the soil (Fredlund and Rahardjo, 1993). With precipitation, the pore-water pressure becomes less negative or even positive. As a result, the shear strength of the soil decreases and this may trigger landslides. Thus, it is important to understand the characteristics of pore-water pressure changes in soils due to water infiltration in order to predict the extent of reduction in shear strength under a certain rainfall condition.

The objective of the study presented in this paper was to investigate the strength and deformation characteristics of the compacted soil during infiltration accounting for the effects of loading history and shear level upon soaking. The loading history of the compacted soil is represented by the compaction pressure, the vertical pressure, and the matric suction. Shear tests on a compacted soil were conducted using a modified direct shear apparatus. The influence of loading history and shear level at wetting on shear strength and deformation are presented and discussed.

1.1 Collapsible soil

Collapsible soil is a common geotechnical concern in arid regions. Despite relatively high void-ratio, it exhibits high shear strength and low compressibility at field water content. A combination of reduction in soil suction and weakening of bonds that are associated with accidental or intentional wetting could trigger soil collapse. The problems encountered in collapsible soils are always associated with changes in groundwater regime or influx at the ground surface.

Geotechnical and geological engineers are confronted with (1) identification of collapsible soils, (2) estimation of the extent of the future wetting causing the collapse. However, the greatest problems with collapsible soils arise when the existence and extent of the collapse potential are not recognized prior to the construction. If the differential deformations and slope stability effects have been neglected in the design and construction processes, they could cause damage to constructions. Therefore, the identification
of collapsible soils with estimation of the collapse potential and shear strength become major components in appropriate engineering design involving these moisture-sensitive soils.

1.2 Collapsibility

The collapsibility is the decreasing in height of a confined soil upon wetting under the application of a constant vertical stress. In another word, a collapsible soil may withstand a relatively large applied vertical stress with small settlement at low water content. However, it will exhibit settlement after wetting with no additional increase in total stress.

The collapsibility can be described by equation (1). It can be calculated from the collapse index ($I_c$) or collapsed potential ($I_2$) from the double consolidation testing. Note that the definition of collapse index and collapsed potential used is from ASTM D 5333-92, which defines the relative magnitude of collapsibility of a confined soil. It is defined for wetted soil at an applied vertical stress of 200 kPa and at any values of constant vertical stress.

$$I_c = \frac{100 \Delta e}{1 + e_0} = \frac{100 \Delta H}{H_0}$$

where $\Delta e$ and $\Delta H$ are the change in void ratio and sample height due to the inundation at the same confining pressure. Also, $e_0$ and $H_0$ are the initial void ratio and initial sample height. In addition, the classification of the degree of collapsibility of soil can be found in Table 1.

1.3 Shear strength of unsaturated soils

Shear strength of saturated soil depends on the effective stress, $\sigma'$, which is defined as $(\sigma - u_w)$. Where $\sigma$ is the total stress and $u_w$ is the pore-water pressure. Typical values of the pore-water pressures in saturated soils are positive number or zero. While, negative value of pore water pressure are typically found in unsaturated soil. The difference between the pore-air pressure, $u_a$ and pore-water pressure, $u_w$, can be referred to as matric suction ($u_a - u_w$). Unlike saturated soils, the mechanical behavior of unsaturated soils depends on stress tensor, $(\sigma - u_a)$, which is referred to as the net normal stress, and the matric suction $(u_a - u_w)$ (Fredlund and Rahardjo, 1993). Note that the soil behavior is independent of the individual values of $u_a$, $u_w$, or the total stress, $\sigma$, as long as the stress-state variables, $(\sigma - u_a)$ and $(u_a - u_w)$, are invariant. Fredlund et al. (1978) proposed the equation of shear strength for unsaturated soil, $\tau_f$, as following:

$$\tau_f = c' + (u_a - u_w)\tan \phi' + (\sigma - u_a)\tan \phi$$

(2)

Here, $c'$ is the intercept of the "extended" Mohr-Coulomb failure envelope on the shear stress axis where net normal stress and the matric suction at failure are equal to zero. It can also be referred to as "the effective cohesion". The variables $(u_a - u_w)$ and $(\sigma - u_a)$ are the matric suction and net normal stress on the failure plane, respectively. $\phi'$ is the angle controlling the increase in shear strength associated with matric suction. Finally, $\phi'$ is an angle of internal friction associated with the net normal stress.

The testing procedure must accommodate independent measurement (or control) of the pore-air pressure, $u_a$, and the pore-water pressure, $u_w$. Therefore, conventional triaxial and direct shear equipment used to measure the shear strength of saturated soils needs to be modified and this will be discussed in detail in this paper.

1.4 Measures of stress history

The overconsolidation ratio (OCR) has been used in geotechnical engineering as an expression of the stress history for saturated soils. However, an OCR for unsaturated, compacted soils and unsaturated natural soils has not been clearly established. Fredlund and Rahardjo (1993) have been suggested that the situ state of stress in an unsaturated soil can be translated into the total stress plane (the swelling pressure). However, a careful study of the procedure that can be used to define the overconsolidation ratio this particular soil is needed. Nishimura et al., (1998) have been taken the independent effects of confining pressure and matric suction into account.

In this study, a total stress ratio, TSR, is defined for the loading history of a compacted soil:

$$TSR = \frac{P_{\text{comp}}}{\sigma - u_a}$$

(3)

where $P_{\text{comp}}$ is the compaction pressure.

The total stress ratio is written in terms of the applied total stress, and no attempt is made to represent the pore-water pressures. Even though, the pore-water pressures can be determined during the compaction and the testing process, when there are two independent stress state variables, the overconsolidation ratio can
not clearly defined. It should be noted here that the total stress ratio simply provides a ratio of the total vertical stress and historical stress applied to the soil since it has been compacted.

2 METHODOLOGY

Two major purposes of the testing program are to define the shear strength of compacted specimens and to study the effects of shear level infiltration. The specimens with 65% relative density at different net normal stress under constant water content were used in this testing program.

2.1 Description of the soil

The non-plastic volcanic sandy soil named "Shirasu" (particle size less than 0.85 mm) has been used in this study. To determine the collapsibility and shear strength parameters in the laboratory, all of the soil specimens are prepared with the same relative density and initial water content. The diameter, height and spacing of the specimen are 60 mm, 21 mm, and 1 mm, respectively. The properties of Shirasu soil are shown in Table 2.

2.2 Modified direct shear apparatus

This research deals with the collapsible unsaturated soil, emphasizing on the study of the collapsibility and shear strength properties. These are the problem for this type of soil with low confining pressure encountered in shallow excavations for waste containment. The direct shear testing is suitable to be used for double consolidation test and to study the effect inundation on the shear strength. According to some of the disadvantages of conventional direct shear box, the direct shear box apparatus need to be modified for measuring the water content and matric suction during soaking. The electrical sensors for water content measurement made by Theta probes are installed on the upper half of shear box near the shear plane. The detail of this apparatus has been reported by Horndee et al. (2005). Measurement of the matric suction, \( (u_g - u_r) \) requires making use of a high air entry ceramic disk for the water phase and a coarse disk for the air phase. Since the constant water content condition is believed to be more appropriate to simulate the field condition when loading the unsaturated soils (Habibagahi and Mokhberi 1998).

Table 2  Index properties of volcanic ash sandy "Shirasu" soil.

<table>
<thead>
<tr>
<th>Property</th>
<th>Shirasu soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>2.54</td>
</tr>
<tr>
<td>Grain size distribution</td>
<td>85:13:2</td>
</tr>
<tr>
<td>Air dried water content</td>
<td>0.6–1.2 %</td>
</tr>
<tr>
<td>OMC</td>
<td>8.1 %</td>
</tr>
<tr>
<td>Maximum dry density</td>
<td>1.44 g/cm³</td>
</tr>
<tr>
<td>( \gamma_{min} )</td>
<td>0.954 g/cm³</td>
</tr>
<tr>
<td>( \gamma_{max} )</td>
<td>1.297 g/cm³</td>
</tr>
</tbody>
</table>

Figure 1. The modified direct shear box test setup.
An innovative adaptation to the direct shear apparatus is shown in Fig. 1. Shear forces were induced by displacing the upper portion of the shear box. They were measured by a load cell installed on the lateral surface of the upper portion of the shear box. Note that these processes were done at a constant vertical pressure applied by the air cylinder. It should be mentioned here that the response of the upper load cell reduces the applied confining pressure to the specimen due to the effect of side friction in consolidation process. In addition, Japanese Geotechnical Society code JGS 0661-2000 also suggests that the net normal stress applied on the shear plane should be measured on the upper half of specimen.

To determine the changing in water content during testing, Theta probes have been installed, located on the upper half of the shear box near the shearing zone as shown in Fig. 2. These probes consist of four stainless shafts. One of them sends the signal from the others to transducer. It senses the volumetric water content ($\theta_w$) by means of evaluating the changing of apparent dielectric constant ($e$). The $\theta_w$ is represented as the ratio of volume of water ($V_w$) to the total volume ($V$). For a completely dry sample $\theta_w$ is 0 and $\theta_w$ is equal to 1.0 for pure water.

Measurement of matric suction requires a high air entry ceramic disk for the water phase and a coarse disk for the air phase. The ceramic disk thickness is 5 mm with the air entry value (AEV) of 150 kPa. It is fixed in place by epoxy placed around its perimeter at the lower pedestal.

In the case of direct shear box testing, the maximum or peak shear stress is defined as the failure criterion. If the shear stress versus horizontal shear displacement curves did not exhibit any peak stress, the shear stress at a set arbitrary horizontal shear displacement value of 7 mm will be selected.

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2.3 Testing procedure

The purpose of the testing program conducted at Kyushu University is to study the relationship between loading history and the shear strength of a compacted soil. A one-dimensional, static compaction was applied to the soil specimens with the initial water content of air-dry water content of about 1% or 8%. The soil was then compacted in the direct shear box to obtain a

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Figure 3. Steps of test program.
relative density of 65%. Pore air pressure, pore-water pressure, and normal stress were applied to the soil specimens for a period of time to allow it to reach an equilibrium state. The entire specimen has been tested at constant net vertical stress of 20, 80 or 160 kPa. The pore-air pressure was connected to atmospheric at the upper surface of the soil specimen. It was maintained at atmospheric conditions through the ceramic base plate. The pore water was allowed to drain or enter the specimen. During the shearing of the specimen, the pore-air pressure, pore-water pressure, and vertical stress were maintained at constant level. The shear rate in this test was 0.2 mm/min. The testing procedure is shown in Fig. 3. Note that the dry and saturated condition are shear under constant water content and shearing infiltration conditions for the testing program no.1 and no.2 respectively.

3 RESULTS AND DISCUSSIONS

The properties of the soil that will be discussed in this section are: 1) the shear strength at different net normal stress under constant water content and 2) the effects of shear level for infiltration.

The identical specimen can be prepared using the e-log p curve as shown in Fig. 4. The stress history of specimen can then be identified as yield stress. As discussed by Hormdee et al. (2004), the curves of air-dry and saturated condition indicate the boundary for predicting the collapse potential of each condition. The e-log p curves for any water content will be located inside the boundary. In addition, the maximum of collapse potential occurs near the maximum stress history. As can be seen from the maximum stress history in Fig. 4, the compaction pressure is about 80 kPa in the case of air dry water content.

![Figure 4](image-url)  
**Figure 4.** e-log p curve of various water content conditions.

3.1 Results of shearing under constant water content

Figure 5 illustrated the relationship between the shear stress, the vertical displacement and the horizontal shear displacement curves for the compacted soils. The shear stress increases gradually with horizontal shear displacement. It also increases in strength due to the confining pressure. The shear strength of the saturated soil is less than that of unsaturated soils at the same confining pressure. This is due to the matric suction gaining more strength in soils as shown in Eq.2. Owing to an angle of internal friction of 40.6°, the value of matric suction about 2–10 kPa in this testing has no significant effect on the value of shear strength in Eq. 2. Therefore, the magnitude of the shear strength of the saturated soil is not much different from that of the unsaturated soils shown in Fig. 6.

One reason that sample having initial water content of 8% gains more shear strength is the energy being used to compact the sample with Dr = 65% is higher than that of the 1% initial water content as shown in Fig. 4. Even the relative density of initial specimen is same, but the energy to compact is higher than in the case of starting with air dry water content then adding water to 8%.

Fig. 5 also shows that dilatancy could be reduced by higher confining pressures. However, this results in an increase in the maximum shear strength. From these results, the relationship between the normalized peak shear stress can be determined by the net normal stress and the dilatancy index (−Δv/Δh) which is the straight line in Fig. 7. It should be emphasized here that although each different factor (i.e., initial water content, net normal stress) produces different shear strength (as shown in Fig. 5), the dilatancy index only depends on the normalized peak shear strength with irrespective of each factors on peak shear strength itself. This relationship should be useful for further evaluating of the shear strength for the same type of soil. That is the effect of different water content on the shear strength directly reflect the changing of the dilatancy. So it can say that such unique relationship is effective and essential not only in the case of saturation but also in the case of unsaturation.

3.2 Results of shearing infiltration

As discussed in the previous section, the shear strength of the saturated condition is lower than that of the unsaturated condition, especially when the matric suction is high. Therefore, the effect of shear level upon soaking must be accounted for in design involving in-situ conditions.

Figure 8 shows the results from shearing infiltration test on the soils after confining pressure of 80 kPa. The shearing infiltration tests have been conducted in order to observe the strength of a soil when
Figure 5. Effects of net normal stress.

Figure 6. Relationship between net normal pressure and shear strength for compacted specimens with Dr = 65%.

Figure 7. Relationship between dilatancy index and normalized of peak shear strength.

Figure 8. Effects of shear level of infiltration process.
Collapsibility is the decrease in height of a confined soil following wetting at a constant applied vertical stress. However, when soaked under shearing, it motivates horizontal movement which increases with shearing infiltration (as shown in Fig. 8). In addition, Fig. 9 illustrates that increasing in the shear infiltration level causes reduction in settlement that also occur during shearing process. For the soaking process, the degree of saturation slowly changes in the first stage with the rapid settlement because the water content measuring equipment is located near the middle of the specimen. On the other hand, the collapse occurs whenever the water comes to some part of soil even without reaching the sensor. Therefore, the relationship on first part of $\Delta v - \Delta S$, curve depends on the void ratio, pressure of water for infiltration and the location of the water content sensor.

4 CONCLUSIONS

To learn about soil response upon wetting, testing of a collapsible sandy soil at low confining pressure is inevitable. However, testing cannot be carried out with a conventional shear box apparatus. It has to be modified in order to be able to measure the water content and matric suction close to shear zone. As detailed in this work, the relationship between dilatancy index and normalized of shear stress is quite unique. They are not depending on the net normal stress and initial water content. This means that the effect of different water content on the shear strength directly reflect the changing of the dilatancy. It is also found that even the collapsibility is more without shearing and the horizontal movement causes higher shear for soaking. Therefore, we can conclude that more attention should be paid in designing with the collapsibility under shear stress.

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