Effect of suction stress on strength characteristics of a compacted silty soil under low confining pressure

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ABSTRACT

In order to study the effects of suction stress on undrained shear strength of unsaturated soil under low confining pressure, unconfined compression tests and constant water content shear tests, in which the suction value and the volume change were measured, were carried out using the compacted specimen of a silty soil. The calculated failure stress state parameters were then analyzed with the equivalent confining pressure by taking into account of three kinds of suction stress; one is obtained from the soil water retention curve corresponding to the degree of saturation and the measured suction, and the others are obtained from the soil water retention curve for the water content and suction value, $s^*$ decided by the suction stress - SWRC method (SSM). A unique failure line was obtained for both saturated and unsaturated cases. This verifies the relevance of new suction stress estimation method. In addition, the results also suggests that the unsaturated shear strength can be predicted from uniaxial compression test with specimens at different initial moisture contents if the SWRC for water content is known.

Keywords: unconfined compression test, constant water content shear test, shear strength, suction stress

1 INTRODUCTION

Many researchers have studied the mechanical properties of unsaturated soil by primarily using triaxial tests, in which a high confining pressure more than 100 kPa is applied. The aim of applying a high pressure is to examine the effect of suction on shear strength by removing the effect of cohesion at an overconsolidated state. However, the surface failure in embankments or natural slopes mostly occur at a shallower depth less than 1 m that corresponds to a confining pressure below 10 kPa. Therefore, theoretical results have not been fully confirmed for the low confining pressure condition. In particular, an unconfined compression test is performed under no confining pressure on the specimen during the test, and it can be taken as the most critical condition of a low confining pressure state. There are some studies in the past where the unconfined compression test was carried out to obtain the strength parameters of unsaturated soil (ex, Cunningham et al., 2003). However, the most studies involved the specimens at a high degree of saturation, and studies under low degree of saturation are almost non-existent.

In this paper, in order to examine the effect of suction under low confining pressure, the unconfined compression test and the constant water content test were carried out on the compacted specimen of a silty soil by measuring the suction and the volume change of specimens. The suction value at failure state were estimated using “Suction stress - SWRC Method” (SSM, hereafter), and the derived failure stress states were examined against the equivalent confining stress taking into account of the suction stress given by Karube et al. (1996).

2 SUCTION STRESS AND ITS EFFECT ON THE UNCONFINED COMPRESSIVE STRENGTH OF UNSATURATED SOIL

2.1 EFFECT OF SUCTION STRESS IN TRIAXIAL TEST

Voids in a soil mass exist in various complex shapes and the soil water inside them are taken to be distributed mainly in two forms; the meniscus water that exists at the contact points between soil particles and the bulk water that occupies remaining void space. The soil water introduces the suction in the soil mass. The relationship between the soil water and the suction is called as the Soil Water Retention Curve (SWRC). Bishop (1954) stated that the $\chi$ parameter in his effective stress equation is closely equivalent to the
degree of saturation. This means that both the suction and soil water influence the shear strength property of unsaturated soil.

The internal friction angle and the cohesion are mechanical strength parameters of soils. The past studies on unsaturated soil after Bishop’s study show that the suction and the soil water affect the cohesion only. On the other hand, Karube & Kato (1994) presented a concept of the suction stress in order to evaluate the effect of suction and soil water, which is shown as equation 1 below (Karube et al., 1996).

\[ p_s = \frac{S_r - S_{res}}{100 - S_{res}} \times s \]  

(1)

where \( p_s \) = suction stress, \( S_r \) = degree of saturation, \( S_{res} \) = degree of saturation at residual state, \( s \) = matric suction defined as \( s = u_a - u_w \), and \( u_a, u_w \) = pore air and pore water pressures, respectively.

Karube et al. (1997) carried out triaxial tests on unsaturated clay specimens under constant suction, and examined the stress state at the maximum compression state by using corrected deviator stress for the dilatancy. They showed that the stress state lies around the failure line corresponding to the saturated specimen, and that the critical state exists for unsaturated soil. This shows the applicability of the suction stress on the results obtained from triaxial test.

2.2 EFFECT OF SUCTION STRESS IN TRIAXIAL TEST

Unconfined compression test is performed under no confining pressure on test specimen, and the minimum principal stress for Mohr’s stress circle equals to zero. However, when a negative pressure develops during the dilation of saturated soil, the negative pore water pressure develops for the dilatancy and acts as the minimum principal effective stress, and the Mohr’s stress circle attaches to the failure line for the effective stress. Based on the theoretical result for unsaturated soil, there is a failure plane in stress space of shear stress, net stress and suction as shown in Fig. 1 (Fredlund et al., 1977). The stress circle at failure in unconfined compression test should also attach to the failure plane which has an inclination of \( \phi \) to the suction axis, and also has a cohesion, \( c_{(unsat)} \) along the shear stress axis.

In the unconfined compression test for unsaturated soil, the minimum principal net stress equals to zero because of no confining pressure, and the Mohr’s stress circle attaches to the failure plane on the condition that the suction stress behaves as a confining stress similar to the negative pore water pressure acting in the saturated state (Chae et al., 2010). Figure 2 shows the

![Fig. 1. A failure plane in stress space of shear stress, net stress and suction (Modified for Fredlund et al., 1977)](image1)

![Fig. 2. Mohr’s stress circle for the unconfined compression test and the constant water content test (Modified for Chae et al., 2010)](image2)

Mohr’s stress circle for the unconfined compression test and the constant water content test in this paper, in which the total of the suction stress, \( p_s \) and the minimum principal net stress, \( \sigma_1 \) act as the equivalent confining stress.

In unsaturated soil, the surface of soil water has a property of membrane. Fredlund & Rahardjo (1993) called the surface of soil water as a “contractile skin” and stated four phases of soil, water, air and contractile skin phase that acts as a membrane. When the meniscus forms, the pore water pressure inside the membrane becomes less than the pore air pressure and the soil skeleton is confined by the effect of pore water that induces a suction stress acting as a confining pressure. When a high confining pressure is applied to a soil mass, the suction stress becomes relatively smaller and its effect on soil property diminishes. Therefore, the effect of the suction stress may be only recognized when the confining pressure is small.

2.3 ESTIMATION OF SUCTION AT FAILURE STATE WITH THE SSM

Kim et al. (2010) carried out a series of direct shear tests on unsaturated soil and proposed the suction stress - SWRC method (SSM) to estimate the suction value acting on the failure plane at the failure state. In the direct shear test, the drainage of soil water occurs from a specimen through the gap between the upper and lower shear boxes and it is therefore difficult to control the soil water of the test specimen. This makes the drainage condition of the test unclear. In the SSM, the suction value acting on the failure plane is evaluated from the SWRC and the soil moisture of the specimen.
As shown in Fig. 3, the suction value, \( s^* \), which corresponds to the soil moisture of specimen on SWRC, is given as the suction value acting on the failure plane. They examined the failure stress state taking into account of the suction stress with \( s = s^* \), and showed that failure stress state is arranged uniquely around the failure line for saturated specimen as shown in Fig. 4.

They also examined the triaxial test results for unsaturated soil by Karube et al. (1997) by applying the SSM to derive the suction value at failure stress state. Figure 5 shows the analyzed results, in which the square and the triangle marks show the results of saturated and unsaturated specimen, respectively, and the solid line shows the failure line for saturated specimen. In the paper by Karube et al. (1997), the stress states of unsaturated specimens at failure show a different tendency at the failure line than those by the saturated specimens. However, Figure 5 shows similar tendency for both saturated and unsaturated data referring that SSM is applicable for triaxial test data as well.

The results shown above means that the SSM can be applied not only for direct shear tests but also for triaxial tests. More test results are needed to confirm the applicability to the other soils. However, if the suction value at failure state can be known with the soil moisture and the SWRC, it will add a great convenience for geotechnical engineering practice.

## 3 SAMPLE, TEST APPARATUS AND TEST PROCEDURE

Silty clay which has the soil particle density of 2.64 g/cm³, the liquid limit of N.P., is used for the test. Figure 6 shows its grain size distribution curve. The
water content of the soil sample at a natural dry state was adjusted to 6% and 10%, and were statically compacted with an oil jack. The specimen mold of 50 mm in the diameter and 100 mm in the height was used and the compaction was done in three layers to make a specimen dry density of 1.49 g/cm³ (80% for the maximum dry density obtained from standard compaction test, JIS1210).

Triaxial cells of single cell type and double cell type were used for the test. Figure 7 shows the sketch of test apparatus using a single cell. A ceramic disk (AEV=500kPa) is equipped in the pedestal, and a pore water measuring device is attached to the water line connected to the ceramic disk. The pore air line in the loading cap was released to atmosphere, therefore, the negative pore water value measured with the pore water measuring device was treated as the total suction. In order to measure the volume change of specimen, the displacement of water from the single cell were measured, and were also corrected for the piston penetration to obtain the volume change of specimen.

After the specimen was set inside the cell, the initial suction of the specimen was measured. In case of the unconfined compression test, the shearing process was immediately started. In the case of the constant water content test at different confining condition, the consolidation process was started under undrained condition by applying the cell pressures of 20, 40 and 100 kPa. In both cases of water content of 6% and 10 %, the axial strain was monitored and 3t method was applied to confirm the end of consolidation.

The shearing speed of 0.1% /min was adopted in the shearing process, which is referred in the past study by one of the authors (Kato et al., 2001). The internal friction angle, $\varphi'$ of 32.3 degrees and the cohesion of 4.0 kPa were obtained from the drained triaxial test of the saturated specimen.

## 4 TEST RESULTS AND DISCUSSION

Figure 8 shows the SWRC of water content for the compacted silty specimen. The solid line shows a fitting curve obtained by van Genuchten model (van Genuchten, 1980). It was found that AEV is about 20 kPa, and that the water contents for saturated and residual states are 37% and 3%, respectively. Figures 9, 10, and 11 show the relationships of axial strain against the deviator stress, volume strain and suction for specimens with the water content of 6%, respectively.

In Fig. 9, the deviator stresses increased to the peak values and decreased to the residual state, irrespective of the confining pressure level. In Figure 10, the volumetric strains show a contractive behavior firstly, and then shows a dilative behavior. The dilation value increased with the decrease in confining pressure. In Figure 11, in the case of the unconfined compression test and the constant water content test under low confining pressure, the suction increases corresponding
to the dilative behavior. On the other hands, the suction decreased in the constant water content tests under $\sigma_3=100$ kPa.

The suction stress is given by Eq.(1) which is based on the SWRC for the degree of saturation. The suction value in Eq.(1) is the measured suction, and it can be rewritten as below.

$$p_s = \frac{S_{cal} - S_{res}}{100 - S_{res}} \times s_{mes} \quad (2)$$

where $S_{cal}$ = the current degree of saturation calculated by taking account of the specimen volume change and $s_{mes}$ = the measured matric suction, $S_{res}$ = zero.

As per Bishop (1959), taking account of degree of saturation is adequate to examine the effect of suction on the shear strength parameter. However, the SWRC for other parameters such as, soil moisture, water content and water content by volume are used, especially in agriculture. In practice, the water content is widely used to control the soil state and is easier to measure water content than the degree of saturation. In this study, the suction effect based on SWRC for water content is also examined. Based on similar concept as that of Eq.(1), the suction stress for the suction value based on SWRC for water content can be given by the following equation.

$$p_s = \frac{w_i - w_{res}}{100 - w_{res}} \times s_w^* \quad (3)$$

where $w_i$ = the current water content, $w_{res}$, $w_{sat}$ = water content under residual state and saturated state in SWRC for water content, $s_w^*$ = suction value obtained from the SWRC for water content corresponding to the water content, $w_i$, as shown in Fig. 12.

Here, from the SWRC shown in Fig. 8, $s_w^*$ for $w = 6\%$ and $w=10\%$ are obtained as 119 kPa and 69 kPa, respectively. In this study, the suction stress of intermediate style between Eq.(1) and Eq.(2) is also examined by the following equation.

$$p_s = \frac{S_{cal} - S_{res}}{100 - S_{res}} \times s_w^* \quad (4)$$

where $S_{res}$ = taken as zero as in the case of Eq (2).

Figure 13 shows the failure line obtained from the triaxial test for the saturated specimen. The applicability of Eq.(4) is examined as in the following lines. Figures 14, 15 and 16 show the relationships of the equivalent confining pressure, $(\sigma^* + p_s)$ to the shear stress $\tau^*$ with Eq.(2), Eq.(3) and Eq.(4).
stress, $\tau^*$ based on the failure point, $(\sigma^*,\tau^*)$ on the Mohr’s stress circle for the failure stress state shown in Figure 2. In each figure, the suction stress is obtained with Eqs. (2), (3) and (4), respectively and the solid line shows the failure line for saturated state. From these figures, it was found that the suction stress with Eq.(3) and Eq.(4) related to SWRC for the water content corresponds to the failure state of unsaturated state fairly well, because the data points lie in the vicinity of the saturated failure line. These results shows the applicability of the suction stress obtained with the SSM on the SWRC for water content instead of the suction stress for the degree of saturation. The results also suggests that the unsaturated shear strength can be predicted from the unconfined compression test with specimens at different initial moisture ratios if the SWRC for the water content are known.

5 CONCLUDING REMARKS

In order to examine the unsaturated shear strength under low confining pressure, the unconfined compression test and the constant water content test under low confining pressure were carried out on the compacted silty clay specimens at a constant dry density and varying water contents. The failure stress state obtained from the test data was rearranged by using the equivalent confining stress parameter that took account of the suction stress, $p_s$, calculated from three different methods; i) $p_s$ based on calculated degree of saturation based on the volume change of specimen, the SWRC of the degree of saturation and the measured suction, ii) $p_s$ based on initial water content, the SWRC of water content and the suction given by the SSM on the SWRC, and iii) $p_s$ based on calculated degree of saturation based on the volume change of specimen, the SWRC of the degree of saturation and the suction given by the SSM from the SWRC of the water content. From the rearranged test results, it was found that $p_s$ based on third method explains more clearly the uniqueness of failure stress state for both saturated and unsaturated state. In other words, the result suggests that the unsaturated shear strength can be predicted from the unconfined compression test with specimens at different initial moisture ratios if the SWRC and the water content are known.

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