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<td><strong>Author(s)</strong></td>
<td>Nyunt, T. T.; Leong, Eng Choon; Rahardjo, Harianto</td>
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Stress-strain behavior and shear strength of unsaturated residual soil from triaxial tests

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ABSTRACT: Multi-stage triaxial compression tests were performed on undisturbed samples of residual soils from Bukit Timah Granite formation in Singapore. Tests were carried out under two conditions, namely, consolidated undrained test (CU) (i.e. both pore-air and pore-water pressure were not allowed to drain during shearing) and constant water content test (CW) (i.e. drained pore-air but undrained pore-water condition during shearing). Stress-strain relationships and shear strength of unsaturated soils were studied at different initial matric suctions of 50 kPa, 100 kPa, 200 kPa, and 400 kPa, by performing CU and CW tests. The variations of matric suction during shearing at two different test conditions (CU and CW tests) are also presented. From the experiments, it was observed that the stress-strain relationship from CU test is less stiff than that from CW test. A single relationship of total cohesion intercept with matric suction was obtained from CU and CW tests.

KEYWORDS: stress-strain behavior; shear strength; unsaturated residual soil; matric suction

1 INTRODUCTION

Residual soils cover about the two-thirds of the land area of Singapore. The groundwater tables in these residual soils are well below the ground surface and thus the bulk of the residual soils are unsaturated (Leong et al. 2003). The residual soils are derived from the two formations, namely: Bukit Timah Granite residual soils and Jurong Formation sedimentary residual soils. Figure 1 depicts the geological map of Singapore. The Bukit Timah Granite is one of the oldest formations in Singapore and was formed approximately 200 to 250 million years ago. The heavily weathered residual soils were formed in the top portions of the Bukit Timah Granite up to depth of 60 m. Generally, residual soils from Bukit Timah Granite consist of reddish to yellow brown clayey soils. The Jurong formation was formed about 100 to 200 million years ago. The upper portions of the Jurong Formation were heavily weathered and the residual soils are found approximately up to depth of 30 m. The residuals soils of Jurong Formation consist mainly of silty clays. In this paper, the stress-strain relationship and shear strength of unsaturated undisturbed residual soils from Bukit Timah Granite formation are presented. The location of the sampling site is indicated in Figure 1.

Shear strength parameters for unsaturated soils can be obtained by performing triaxial tests, namely: consolidated drained test (CD), constant water content test (CW), consolidated undrained test with pore pressures measurement (CU) and unconfined compression test (UC) (Fredlund and Rahardjo 1993). In this study, CU (i.e. undrained pore-air and pore-water pressure condition) and CW (i.e. drained pore-air pressure and undrained pore-water pressure condition) triaxial tests were performed to investigate the stress-strain relationship and shear strength of undisturbed residual soils under different drainage conditions in terms of pore-air phase.
2 SHEAR STRENGTH THEORY FOR UNSATURATED SOILS

Fredlund et al. (1978) proposed an extended Mohr-Coulomb failure envelope for unsaturated soil as follows:

\[
\tau_f = c' + (\sigma - u_a)\tan \phi' + (u_a - u_w)\tan \phi_b
\]  

(1)

where \(\tau_f\) is shear stress at failure, \(c'\) and \(\phi'\) are effective stress shear strength parameters obtained from saturated test, \((\sigma - u_a)\) is net normal stress at failure, \((u_a - u_w)\) is matric suction at failure and \(\phi_b\) is angle describing increase in shear strength with matric suction. Equation 1 can be written in two-dimensional representation as:

\[
\tau_f = c + (\sigma - u_a)\tan \phi'
\]  

(2)

where, \(c = c' + (u_a - u_w)\tan \phi_b\)

(3)

3 TEST SET-UP

A modified triaxial apparatus was used to study the stress-strain relationship and shear strength of unsaturated residual soil. The triaxial apparatus is equipped with a 3 kN submersible load cell, an external linear variable differential transformer (LVDT), a submersible LVDT, and a pair of local displacement transducers (LDT) for axial strain measurement at different strain levels, a pair of proximity transducers for radial strain measurement and pressure transducers for pore-air and pore-water pressure measurements. A 5-bar high air entry ceramic disk was fixed in the bottom pedestal using epoxy for unsaturated soils testing. Figure 2 shows the modified triaxial apparatus used in this study.

4 TEST PROCEDURE

Soil specimens of 50 mm diameter and 100 mm height were trimmed from 70 mm diameter undisturbed residual soil samples. The undisturbed residual soil samples were obtained using Mazier sampling. The residual soil specimens used for CU and CW tests were from depths of 2 to 3 m. Table 1 summarizes the basic properties of the residual soils. The average initial water content and the average initial degree of saturation of the undisturbed residual soil sample were 43% and 90%, respectively. The soil specimens were saturated in the triaxial cell prior to consolidation to ensure identical initial water content in the specimens. The pore-water parameter B obtained was greater than 0.96 for the soil specimens during saturation. Near or full saturation was assumed when pore-water pressure parameter B was greater than 0.96 (Head 1980).

After saturation, the soil specimens were isotropically consolidated to the in situ effective confining pressure and subsequently at the required net confining pressure \((\sigma_3 - u_a)\) and matric suction \((u_a - u_w)\) via the axis-translation technique (Hilf 1956). For the application of matric suction, a constant air pressure of 450 kPa was supplied at the top of the soil specimen through a porous disk and water pressure was controlled via a digital pressure volume controller (DPVC) through a 5-bar high air entry ceramic disk. The amount of water flowing out of the soil specimen during matric suction equalization was monitored via DPVC. The matric suction equalization was assumed to have been completed when the amount of water flowing out of the soil specimen had leveled off.

Multi-stage shearing was adopted to study the stress-strain behavior and shear strength of the undisturbed residual soil at different initial matric suction. Shearing was carried out in four stages at initial matric suction of 50 kPa, 100 kPa, 200 kPa and 400 kPa under net confining pressure of 50 kPa and constant air pressure of 450 kPa. At the end of each matric suction equalization stage, the specimen was sheared until failure was imminent and unloaded before imposing the next required matric suction.

The soil specimens were tested under two different test conditions: consolidated undrained test (CU) and constant water content test (CW). A constant strain rate of 0.5 mm/min was used for both CU and CW tests. In CU test, both pore-air and pore-water pressure were not allowed to drain during shearing and in CW test, air was allowed to flow freely, however, pore-water pressure was undrained during shearing. The variations of pore-air and pore-water pressure during shearing were recorded. At the end
of the test, water content was measured to obtain the variation of water content with respect to the imposed matric suction.

5 RESULTS AND DISCUSSIONS

Stress strain relationship and shear strength of the undisturbed residual soil specimens from CU and CW tests are presented. The stress-strain relationship at initial matric suctions, \((u_a - u_w)_{i}\), of 50 kPa, 100 kPa, 200 kPa and 400 kPa for CU and CW tests are shown in Figure 3. Peak deviator stress increases with initial matric suction for both CU and CW tests. The strain at which the soil specimen reaches the peak deviator stress decreases with initial matric suction for both CU and CW tests.

The stress-strain relationships obtained for CU test exhibit less stiff behavior as compared with that for CW test. Moreover, the values of peak deviator stress obtained from CU tests are lower than the corresponding values from CW tests. The differences become more significant with higher initial matric suctions. This behavior can be explained by differences in drainage condition of pore-air phase during shearing. In CU test, excess pore-air pressure was undrained during shearing resulting in higher void ratio at failure under lower \(\sigma_3\) compared with the corresponding CW test where pore-air pressure was drained and thus, the stress-strain relationship for CU test was less stiff. In addition, the resulting higher void ratio at failure due to excess pore-air pressure that developed in the CU test may have influenced the decrease in peak deviator stress compared with the corresponding CW test.

The variations of matric suction with axial strain for CU and CW tests at different initial matric suctions are plotted in Figure 4. Table 2 summarizes the values of peak deviator stress, pore-air pressure, pore-water pressure, and matric suction at failure for CU and CW tests. The excess pore-water pressures at failure were very close for both CU and CW tests with the same initial matric suction. In addition, the excess pore-air pressures at failure in CU tests at different initial matric suction were observed to be similar as shown in Table 2. Therefore, matric suction at failure, \((u_a - u_w)_{f}\), for CU test was higher than that for the corresponding CW tests. Similarly, net confining pressure at failure, \(\sigma_3\), in CU test was lower than that for the corresponding CW test.

The effective shear strength parameters \(c'\) and \(\phi'\) for the saturated residual soils are \(c' = 22\) kPa and \(\phi' = 33^\circ\) obtained in another study. The extended Mohr-Coulomb failure envelopes for the CU and CW tests were plotted using Equation 2 by drawing the tangent line to the Mohr circles of the
unsaturated soil specimens at different initial matric suctions with slope of $\phi'$. Peak deviator stress was used to plot the Mohr circle to obtain the extended failure envelopes for unsaturated soils. Figure 5 shows the Mohr circles with total cohesion intercepts for CU and CW tests. The values of total cohesion intercept increase non-linearly with matric suction. Similar non-linear behavior of total cohesion intercept with matric suction has been reported by Gan et al. (1988) and Thu et al. (2006).

The $\phi^b$ angle for CU and CW tests were obtained by plotting the total cohesion intercept with matric suction at failure as shown in Figure 6. The values of $\phi^b$ angle obtained from CU test are close to the

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\( \phi^b \) values obtained from CW tests. For non-linear variation of \( \phi^b \) angle with matric suction, Equation 3 can be written as:

\[
c = c' + \int_{0}^{f} (u_a - u_w) \tan \phi^b d(u_a - u_w)_{f} (4)
\]

where

\[
\tan \phi^b = f \left[ (u_a - u_w)_{f} \right] (5)
\]

Figure 6 shows the calculated and measured total cohesion intercept with matric suction for CU and CW tests. Figure 6 also shows that the total cohesion intercept with matric suction relationship from CU and CW tests can be represented by a single curve. The initial \( \phi^b \) angle obtained is 33° same as \( \phi' \) and approaches 0 at high matric suction. The \( \phi^b \) angle was normalized with \( \phi' \) and compared with the normalized water content, \( w/w_o \) (where \( w_o \) is the water content at low matric suction) obtained from the experiments as shown in Figure 7. It was observed that the ratio of \( \phi^b / \phi' \) with matric suction relationship has similar trend as the normalized water content (i.e. \( w/w_o \)) with matric suction relationship.

6 CONCLUSION

Stress-strain relationship and shear strength of unsaturated undisturbed residual soil from Bukit Timah Granite formation were studied by performing CU and CW tests. From the experimental results, it was observed that the stress-strain relationship from CU test showed less stiff behavior than the corresponding CW test. A single curve can be used to represent the relationship of total cohesion intercept with matric suction for CU and CW tests. Non-linear relationship of \( \phi^b \) angle with matric suction was observed and it has similar trend as the water content with matric suction relationship.

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