A new triaxial apparatus for high total suction using relative humidity control

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12th Asian Regional Conference on
"Soil Mechanics and Geotechnical Engineering"
Aug. 4-8, 2003, Singapore

Abstract: Shear strength theory for unsaturated soils have been widely accepted in geotechnical engineering. The analysis of shear strength. volume change and seepage involving unsaturated soil required the soil-water characteristic curve as key soil information. Several models are proposed using a soil-water characteristic curve with the experimental researches. The procedures being proposed are approximate but are satisfactory for analyzing many unsaturated soil mechanics problems. Particularly, these functions are available until matric suction is below the residual suction (i.e., below about 1500 kPa). This study presents the triaxial compression test results for the desiccated soil subjected to high soil suction using a new unsaturated soil triaxial compression apparatus. Consequently, the shrinkage of unsaturated soil proceeds due to applying of high soil suction, and the slope of failure envelope to the net normal stress is similar to the saturated soil or unsaturated soil with low matric suction.

1 INTRODUCTION

All soils in a limiting saturated state condition at zero matric suction and in a total dry condition at a total suction of 1,000,000 kPa. The distribution of soil-water-air inter phase relationships also change. which have a significant influence on the engineering behavior of unsaturated soil. Recent work by Vanapalli, Sillers and Fredlund (1998) insisted that the residual state as one point along soil-water characteristic curve is important with respect to the shear strength behavior and hydraulic properties. The common definition is that the water phase is discontinuous and isolated with thin films of water surrounding the soil and air. The soils at residual state condition have considerable high total suction or highly negative pore-water pressure. It is hard to measure the high total suction. The shear strength of unsaturated soils has been investigated using a conventional triaxial apparatus and a conventional direct shear apparatus in the laboratory. Most of unsaturated soils testing have been performed with the help of any air entry value ceramic porous stone as pressure plate method. The method consists in applying of air-pressure like external load. The limitation of pressure plate technique depends on the air entry value as usual. Many traditional unsaturated soil triaxial apparatus was originated from the triaxial equipment proposed by Bishop and Donald (1961).

2 PURPOSE OF THIS STUDY

In this paper. a newly triaxial apparatus developed high soil suction and relative humidity vapor controllable triaxial apparatus for studying isotropic and shear behavior of unsaturated soils introduced and described. It is based on vapor pressure technique. High total suction was produced due to control relative humidity in the pore air. The application of the apparatus is illustrated by measuring water content of specimen subjected to high total suction. An advantage of the new apparatus is tion. An advantage of the new apparatus is without large air pressure and ensures safety. By using new apparatus, volume change with external stress can be measured during drying.

3 LITERATURE

3.1 *Soil suction*

The total suction of a soil is comprised of two primary components; namely, matric suction and osmotic suction. Soil suction below about 1500 kPa are matric suction while suctions above about 1500 kPa are soil suction or total suction. In generally, 1500 kPa has formed an approximate dividing line between matric suction applied in the laboratory. It is surprising that matric suction and soil suction are generally plotted on the same graph as a soil-water characteristic curve. Matric suction has been shown to dominate the lower suction portion while osmotic suction dominates the high suction portion. In other words, capillary effects dominate in the low suction range and salt concentration dominates in the high suction range.

Capillary effects related to the amount of liquid water in the soil. At the amount of water in a soil decrease, the salt concentration increase resulting in an increase in osmotic suction. Barbour (1999) described how osmotic suction theoretically increases as the water content of a soil decreased. The osmotic suctions appear to increase toward 1,000,000 kPa as the water content of the soil goes towards zero. Osmotic suction began to dominate the behavior of the soil. Liquid flow appears to stop and vapor flow dominates.

3.2 *Shear strength of unsaturated soils*

The shear strength of unsaturated soils has been formulated in terms of two independent stress state variables (i.e., net normal stress and matric suction). The shear equation for unsaturated soils proposed by Fredlund, Morgenstern and Widger (1978) has been accepted widely in geotechnical engineers.

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\ \tan\phi^b \qquad (1)$$

where, τ = shear strength, c' = effective cohesion intercept, σ = total normal vertical stress, ϕ' = effective angle of internal friction with respect to net normal stress, u_a = pore-air pressure, u_w = pore-water pressure, ϕ^b = angle of internal friction with respect soil suction.

There are several experimental researches for understanding of two strength parameters (ϕ' and ϕ^b). Gan and Fredlund (1988) showed failure envelopes that non-linear based on multistage direct shear test. Escario and Juca (1989) tested two clays and a clayey and for suction up to 15 MPa as maximum value. Direct shear tests showed that the slope of the failure envelope was zero or negative at high soil suction. Mahaling-Iyer and Williams (1985) conducted unconsolidated undrained triaxial tests. The results showed that the slope, ϕ^b , of the failure surface with respect to the matric suction decreased sharply in the matric suction ranges from 0 kPa to 1,000,000 kPa. The ϕ' angle then decreased slightly in the soil suction range from 1,000 kPa to 8,000 kPa. Fredlund and Rahardjo (1993a) stated that the shear strength of unsaturated soils involving a wide range of suctions could be non-linear. It was suggested that the ϕ^b angle appears approach an angle of zero degrees (or it may even be negative). Nishimura and Fredlund (1999) mentioned that the relationship between shear strength and total suction for the compacted unsaturated silty soil described an essentially horizontal failure surface beyond residual conditions. Nishimura and Fredlund (2001) conducted out both unconfined compression test for an unsaturated silty soil subjected to high suctions and the direct shear test using a modified direct shear apparatus. Beyond the residual suction conditions, the shear strength of an unsaturated soil remains relatively constant. Nishimura and Fredlund (2002) reported the influence of the drying process and wetting process on the unconfined compressive strength of a compacted unsaturated soil subjected high total suctions. Changes of the shear strength due to drying and wetting applications were recognized. It was observed that there was a slight hysteresis with respect to unconfined compressive strength of a compacted, unsaturated soil in the residual suction ranges. Relative little experimental data for shear behavior (or shear strength) have been reported in literature respect to unsaturated soil with high soil suction.

4 TEST PROCEDURE

4.1 Equipment design

Many traditional methods for measuring shear strength of unsaturated soil using a conventional unsaturated triaxial compression apparatus suggested by Bishop and Donald (1961). The triaxial compression tests are performed in various countries of the world through of use of a pressure plate technique as standard procedure for unsaturated soil. The conventional unsaturated triaxial equipment design has the limitations of controlling matric suction ranges. Matric suctions are applied to the soil through use of a high air entry disk (or a cellulose membrane), up to a maximum value of about 1500 kPa.

An apparatus for measuring isotropic mechanics stresses and shear stresses of unsaturated soil with high soil suction was developed by modifying a conventional unsaturated soil triaxial apparatus. Figure 1 shows the cross-section of a new triaxial apparatus for unsaturated soils. This newly apparatus is advancing to impose high soil suction for soil specimen in the triaxial cell. It is able to measure the volume change in addition to the applying of net normal stress. High soil suctions are provided through a controlled relative humidity environment. The relative humidity environment can be converted to a total suction. generally greater 1500 kPa, through use of the Lord Kelvin equation (Fredlund and Rahardjo, 1993b).

The confining pressure, σ , and pore-air pressure, u_a , are separate acting on the soil specimen. For the prior an inflow of air to soil specimen, the relative humidity of the fluid air was controlled. The air regulator maintains the magnitude of the pore-air pressure. A point of air tube is inserted in the water. So many air bubbles occurred in the Chamber I as shown in Fig. 1. The amount of air bubbles is depended on the magnitude of pore-air pressure. The relative humidity of air in the empty space in Chamber I has been increasing with greater occurrence of air bubbles. In other words, the relative humidity of fluid air is controlled satisfactory due to be regulation of the air pressure.

This study measured the relative humidity of the fluid air through the air tube in the Chamber II for remaining at constant of relative humidity. Before the inflow of air to the soil specimen, the relative humidity was checked by the sensor, and was adjusted to the required the relative humidity.

The confining pressure and the pore-air pressure have to adjusting simultaneously for remaining a constant of net normal stress. The fluid air flows through the soil specimen from bottom of specimen to top of specimen. A coarse disk was installed into the pedestal and cap for making smoothly the flow of air. As the relative humidity create a highly soil suction, the water content of the soil specimen decreased considerable after the soil pore equilibrium with the relative humidity. During applying of both isotropic stress and deviator stress to the soil, the volume change was measured using a gap sensor installed in the inner cell.

4.2 Test program

A silty soil was used in this test program. The silty soil was formulated as the soil specimen for the triaxial test. Isotropic compression test and shear test were conducted in the newly triaxial compression apparatus with controlling relative humidity above mentioned. The relative humidity of 75 % was applied to the soil specimen in the triaxial cell with a constant pore-air pressure of 120 kPa. The relative humidity of 75 % create the highly soil suction of 39,000 kPa. The net normal stress was applied to the soil specimen from 25 kPa to 400 kPa in ranges.

5 TEST RESULT

5.1 Isotropic compression test

Isotropic compression tests were often preformed on unsaturated soil with controlling of matric suction. Measurement of volume change is effort for establishing of elasto-plastic constitutive model of unsaturated soil. Net normal stresses were loaded to soil specimen with a constant water content (i.e., no applying of high soil suction). The void ratio is plotted with net normal stress on the logarithm scale as shown in Fig. 2. The results presented a compression curve. The slope of the compression curve in a constant water content was calculated 0.07 as a compression index.

This study attempted to appear the isotropic compression behavior of the unsaturated soil with highly soil suction. Isotropic loaded soil specimen at the net normal stress of 25 kPa was imposed in the relative humidity of 75 % environment when the net normal stress of 25 kPa remained with the pore-air pressure of 120 kPa. The void ratio decreased due to applying of highly soil suction as shown in Fig. 2. The water content of the soil specimen with equilibrium at the relative humidity of 75 % was 0.25 %. The water content decreased considerable. Decreasing of void ratio due to applying of soil suction is similar to the test results presented by Yong, Japp and How (1971). Yong, Japp and How (1971) applied soil suction of about 10,000 kPa to slurry from kaolin, and measured volume change. It is indicated that decreasing of void ratio remained in high soil suction rages. Thomas (1993) developed a constitutive model based on thermodynamic analysis involving a continuous transition from saturated to unsaturated conditions. Thomas (1993) described the volume change and water content when water content was below shrinkage limits. It is appeared that void ratio decrease with increasing of external load. The result obtained from this isotropic compression test is similar to several researches in literature.

Isotropic compression loading was preceded for the desiccated soil specimen until the net normal stress was 400 kPa. Calculated compression index for the desiccated soil was 0.107. It is found that the compression index of the desiccated soil is larger compared to the soil with no apply high soil suction. The acting of high soil suction make effort to isotropic volume change behavior. After net normal stress reached to 400 kPa, unloading process began until net normal stress was 50 kPa. The loading process was repeated.

5.2 Shear strength and volume change

Triaxial compression test was performed at five different net normal stress (25, 50, 100, 200 and 300 kPa) with measuring of the volume change due to shear force. Highly soil suction was a constant of 38,000 kPa corresponded the relative humidity of 75 %. The shear rate was selected as 0.1 % over a minute. The deviator stress is plotted with axial strain as a stress-strain curve under a constant soil suction of 39,000 kPa in Fig. 3.

Classically, both shear strength and compressive tendency increase with the net normal stress. After the deviator stress reached a peak, the deviator stress remains steady. The residual state or critical state seem to be reached rapidly with the exception of the net normal stress of 300 kPa. Small hardening behavior was observed under the net normal stress of 300 kPa, corresponding to a more pronounced compressive tendency. The stiffening of the desiccated soil due to net normal stress is observed when considering the initial portion of the stress-strain curve. The shear strength is higher with a higher net normal stress. For five different net normal stress, the existence of maximum deviator stress and no softening at low net normal stress are important concerns.

Figure 4 shows the effect of the net normal stress on volume change during shearing. A clear shear plane was not observed at all values of net normal stress. For the net normal stress of 200 kPa and 300 kPa, compressive dilation completely progressed. Maximum negative volume strain was exhibited at the net normal stress of 300 kPa. In case of the net normal stress less than 200 kPa, expansive volume strain occurred with the progress of shearing. The dilation behavior of the net normal stress of 50 kPa was similar to the 100 kPa. Figure 4 describes important the effort of net normal stress to volume change for the desiccated soil.

Shear strength is plotted with net normal stress in Fig. 5. Shear strength means maximum shear stress during test. Shear strength has been increased with net normal stress. It is predicted that the effort of friction soil particles together remained regardless of the net normal stress. The failure envelope was developed as a straight line. The role of net normal stress is important to the shear strength for the unsaturated soil in highly soil suction ranges. The slope of failure envelope corresponds similar to the angle of internal friction with respect to net normal stress. Calculated angle was 66.0 degrees. The vertical axis indicated a cohesion of 140 kPa when net normal stress was zero value (i.e., cohesion is calculated as 140 kPa).

6 DISCUSSION

Volume change for the soil with high soil suction was appeared to conduct in isotropic mechanical stress. This test result obvious that the compression index was larger due to be imposed highly soil suction. There are several experimental researches with respect to elasto-plastic volume change for unsaturated soil in low soil suction. Alonso, Gen and Josa (1990) presented a constitutive model include hardening plasticity. The proposed that the compression index decreased with increasing in matric suction. Sivakuma and Wheeler (1993) performed controlled suction isotropic compression test for compacted kaolin in order to propose the elasto-plastic framework. Sivakuma and Wheeler (1993) indicated that the slope of isotropic compression curve showed relatively little variation with matric suction. The relationship between slope of isotropic compression curve and matric suction had a non-linear. After matric suction was over 200 kPa, the slope decreased with matric suction. Above mentioned that it is difficult to establish the relationship between a compression index and matric suction correctly.

The shear strength equation suggested by Fredlund, Morgenstern and Widger (1978) useful for analyzing of geotechnical problems. The equation includes three strength parameters, c', ϕ', ϕ^b. It is knowledge that ϕ^b closely related to the soil suction. When matric suction is less than the air entry value, ϕ^b coincident with ϕ'. After matric suction is over than air-entry value, ϕ^b decreased. In residual state of unsaturation, ϕ^b shows a essentially zero. In case of sandy soil, for example, ϕ^b go toward to negative in highly suction ranges.

There is interest in the influence of highly soil suction to the angle of internal friction respect to net normal stress. Triaxial test was performed for saturated soil and the unsaturated soil with matric suction. Applied matric suction were 300 kPa and 400 kPa in the conventional triaxial cell. Relationship between shear strength and net normal stress with various matric suction is shown in Fig. 6. Saturated condition means no capillary effort or no matric suction in the soil pore. For all matric suction, shear strength increases with net normal stress. Three failure envelope is identified as a straight line. The slope of failure envelope is coincident together. The slope of failure envelope for various matric suctions agrees with that of the desiccated soil. This test result agrees with the concept of shear strength equation theory mentioned by Fredlund, Morgenstern and Widger (1978). Fredlund, Morgenstern and Widger (1978) had an assumption that the angle of internal friction with net normal stress, ϕ' independent on the soil suction. This study proves that the assumption of the angle of internal friction with net normal stress, ϕ' for unsaturated soil could be available the entire soil suction ranges.

6 CONCLUSIONS

There is an increasing demand to understand the mechanical behavior of unsaturated soils with high total suction for predicting the behavior of unsaturated engineered soil barriers for unclear waste disposal. Most of experimental researches for the shear strength of unsaturated soil using a conventional triaxial apparatus discussed as long as the matric suction is less than 1500 kPa. This study improves to utilize an existing the conventional unsaturated triaxial compression equipment for understanding of desiccated soil. A new triaxial apparatus is introduced in this paper. During a test, both isotropic mechanical stresses and high soil suction can be applied using vapor pressure technique and volume changes of a compacted unsaturated silty soil can be measured.

High soil suction is created in equilibrium with relative humidity environment. Liquid flow alters to vapor flow according to increasing in soil suction. Vapor flow dominates in the soil. The water content decreased considerably with decreasing of void ratio. A compression index is larger than that of soil no subjected high soil suction.

The advantages to this paper are having the changes in shear strength in highly soil suction rages. The shear strength for desiccated soil has important effort of net normal stress. The failure envelope with net normal stress exhibits the angle of internal friction similar to both saturated soil and the soil with matric suction.

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