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Volume change and shear strength behavior of an unsaturated soil with high soil suction

Le comportement volumétrique et de résistance en cisaillement d'un sol non saturé à des succions élevées

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ABSTRACT
The shear strength and volume change behavior of an unsaturated non-plastic silty soil is determined with a high suction value using a relative humidity controlled triaxial shear testing apparatus. The design details of this apparatus are briefly presented in this paper. The results of the undertaken study suggest that the Fredlund et al. 1978 equation can be used for interpreting the shear strength behavior of unsaturated soils in the high suction range. In addition, a technique is also presented to determine the volumetric deformation coefficients in loading and unloading stages respectively at high suction values.

RÉSUMÉ
La force de cisaillement et le changement de volume d'un sol limoneux non plastique non saturé à une succion élevée est déterminé grâce à un appareil d'essais triaxial à contrôle de l'humidité relative. Les détails de conception de cet appareil sont présentés. Les résultats de l'étude entreprise suggèrent que l'équation de Fredlund et al. 1978 peut être utilisée pour interpréter le comportement de résistance en cisaillement de sols non saturés pour des valeurs de succion élevées. En plus, une technique visant à déterminer les coefficients de déformation volumétriques pour les stages de chargement et déchargement, respectivement, pour des valeurs de succion élevées est également présentée.

1 INTRODUCTION

The conventional principles of soil mechanics used for saturated soils are generally not found to be applicable for interpreting the engineering behavior of compacted, residual, collapsing, and expansive soils. These soils are referred as problematic soils in the literature and are typically in a state of unsaturated condition. A framework has been put forward to interpret the engineering behavior of unsaturated soils in terms of two stress state variables; namely, net normal stress, $(\sigma - u_a)$ and matric suction, $(u_a - u_w)$ (Fredlund & Morgenstern, 1977). In these variables, the term, σ, is normal or confining stress and u_a and u_w are the pore-air and pore-water pressure respectively.

All soils have a limiting saturation state at zero matric suction. There is also a limiting dry state condition for soils at a total suction value of 1,000,000 kPa. The total suction of a soil is comprised of two components; namely, matric suction, $(u_a - u_w)$ and osmotic suction, π. The changes in soil suctions below 1500 kPa are predominantly associated with the movement of water in the soil in liquid phase and is commonly referred to as matric suction, $(u_a - u_w)$. The change in suction associated with the movement of water in soils in the vapor phase in the suction range which is generally greater than 1500 kPa is called osmotic suction, π. The value of osmotic suction is closer to the total suction value in the high suction range. The distribution of the soil-water-air interphase changes with soil suction over the entire suction range (i.e., 0 to 1,000,000 kPa) and influences the engineering behavior of an unsaturated soil (Vanapalli et al., 1999).

The shear strength of unsaturated soils is conventionally measured using a modified triaxial shear or direct shear testing apparatus in the matric suction range of 0 to 500 kPa by axis translation technique (Hilf 1956). In this paper, design details of a triaxial shear apparatus is presented for measuring the volume change and shear strength behavior of an unsaturated soil in the high suction range. The high soil suction in the soil specimen is achieved by controlling relative humidity using air pressure regulators. In this apparatus, large air pressures are not required for attaining high values of suction in the soil specimens. The use of high air pressures to achieve high suction values extending axis-translation technique can be dangerous in a conventional laboratory testing environment. The relative humidity controlled triaxial shear testing apparatus used in this research program is a safer technique to achieve high soil suctions in the soil specimens. This technique is receiving more attention as it provides a closer reproduction of the natural field conditions of unsaturated soils in comparison to the conventional axis-translation technique (Delage et al., 1992).

2 LITERATURE REVIEW

The Fredlund et al. (1978) shear strength equation proposed in terms net normal stress, $(\sigma - u_a)$ and matric suction, $(u_a - u_w)$ for unsaturated soils is widely used in interpreting the shear strength behavior (Gan et al. 1988, Escario & Juca 1989, Vanapalli et al., 1996). The shear strength of unsaturated soils in the low suction range is conventionally determined using modified direct shear or triaxial shear testing apparatus extending axis translation technique. The assessment of soil shear strength and stiffness behaviour in the high suction range is receiving more attention in recent years to understand the soil behavior over a large suction range to develop models such that time consuming testing techniques can be avoided (Mahaling-Iyer & Williams 1985, Vanapalli and Fredlund 2000, Blatz et al., 2002).

Different types of tests consisting both simple and elaborate techniques were used to interpret strength related properties of unsaturated soils in the high suction range. Cui & Delage (1993) used an osmotic controlled suction apparatus to study the elasto-plastic behavior of a silty soil up to a suction value of 1500 kPa. Other testing techniques include unconfined compression tests and direct shear tests using a modified direct shear apparatus (Nishimura & Fredlund 2001, Vanapalli et al., 2000). Nishimura & Fredlund (2002) reported the influence of the drying and wetting on the unconfined compressive strength of a compacted unsaturated soil subjected to high total suctions. Blatz and Graham (2000) and Blatz et al., (2002) used vapor equilibrium technique in a triaxial testing apparatus to determine the shear strength and stiffness behavior of soils with high suction values. Nishimura & Fredlund (2003) and presented triaxial compression test results for a desiccated soil using a new triaxial compression testing apparatus. Nishimura & Vanapalli (2004) used modified direct shear apparatus to determine the shear strength of an unsaturated soil in low and high suction range under constant volume conditions.

3 TEST PROCEDURE

A new apparatus for measuring volume change and shear strength behavior of unsaturated soils under high soil suctions was developed by modifying a conventional triaxial testing apparatus. Figure 1 shows the cross-section of the triaxial testing apparatus for testing unsaturated soil specimens. This modified apparatus can impose high soil suctions to soil specimens in the triaxial cell using a controlled relative humidity environment by regulating the inflow rate of air (see Chamber 1 in Fig. 1). The flow rate is regulated using a pressure gradient between the upstream pressure applied to Chambers 1 and 2 which is transmitted to top and bottom. The downstream presure outlet is open to atmosphere. The relative humidity of the air passing through the air tube in Chamber 2 is measured using a sensor. Air flow from the bottom to the top of the specimen was acehieved through the use of coarse disks (Fig. 1). Lord Kelvin equation was used to estimate suction value from the measured relative humidity values (Fredlund & Rahardjo, 1993). The confining pressure and the pore-air pressure were controlled to maintain a constant net normal stress, $(\sigma - u_a)$.

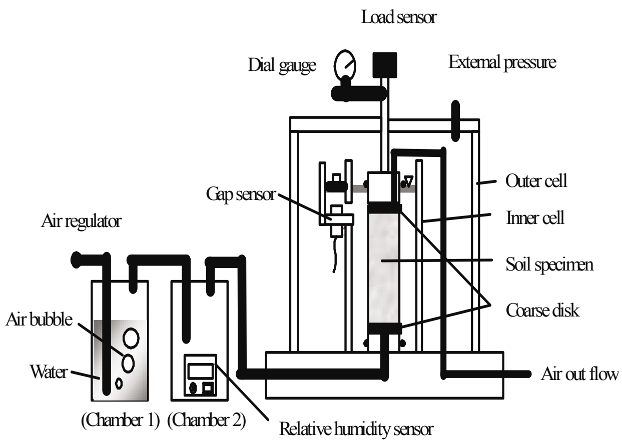

Figure 1. Design details of the triaxial test apparatus.

A non-plastic silty soil which has uniform grain size distribution was used in this test program. Statically compacted soil specimens with an initial water content of 10% representing dry of optimum conditions were used for testing. The specimen size of 50 mm diameter and 100 mm height were used. Isotropic compression and shear strength tests were conducted by controlling the relative humidity conditions as discussed earlier using an air-pressure value equal to 120 kPa under a controlled temperature of 20^{o} C. A relative humidity of 75% was achieved by regulating air pressure at 120 kPa at the upstream inlet to the soil specimen. The acheived soil suction value was equal to 39,000 kPa. The influence of high soil suction on the shear strength of an unsaturated soil was assessed from triaxial compression tests under five different net normal stresses (50 kPa, 100 kPa, 200 kPa, 400 kPa and 600 kPa) along with volume change measurements. Volume change of the soil specimen was measured using a gap displacement sensor installed in the inner triaxial cell (Fig. 1). The sensitivity of volume change measurement was equal to 0.01 cc. In this study, the influence of strain rate on the shear strength behavior was also investigated. Only preliminary test results with respect to shear strength and volume change behavior are presented in this paper.

4 TEST RESULTS

Isotropic compression tests were performed on unsaturated soil specimens with the control of high soil suction. A net normal stress, $(\sigma - u_a)$ of 25 kPa was applied to all soil specimens as initialization stress at the commencement of all the isotropic compression tests. Figure 2 shows the relationship between the void ratio and three different net normal stresses (i.e., 100, 200 and 400 kPa) applied under a constant soil suction of 39,000 kPa. The water content of each soil specimen decreased considerably under the applied soil suction of 39,000 kPa. The reduction of void ratio with respect to the different applied net normal stresses is shown in Fig. 3. The void ratio decreased slightly with the increasing net normal stress. The volumetric deformation coefficients were determined during loading stage

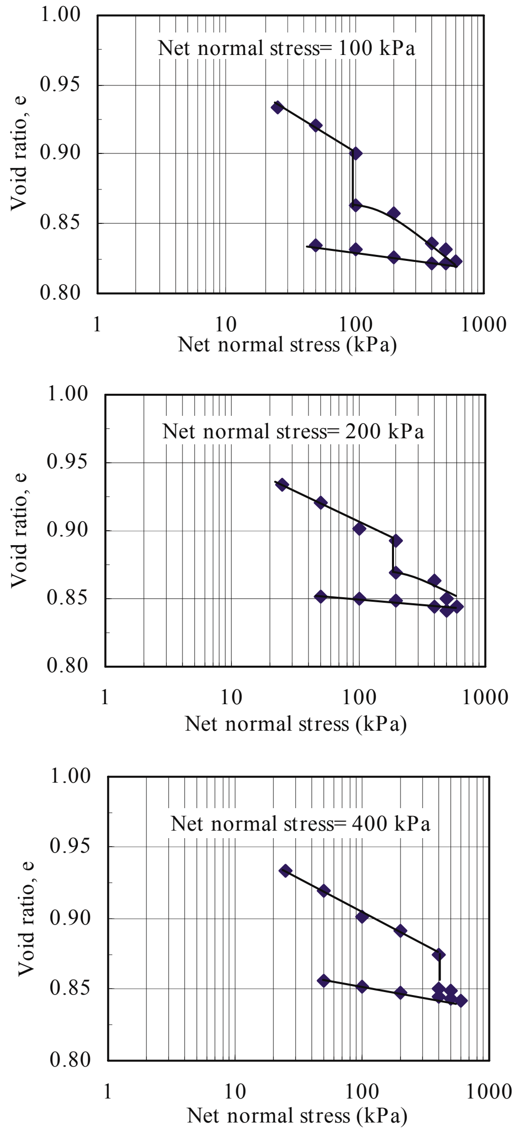

Figure 2. The variation of void ratio and net normal stresses (during loading and unloading).

by increasing the net normal stress value up to 600 kPa (Fig. 4). The volumetric coefficient, a_t decreased slightly with increasing net normal stress. The coefficient of compressibility during isotropic unloading, a_{ts} was also determined. The volumetric deformation surface for unsaturated soils can be developed based on a_t and a_{ts} coefficients (Fredlund & Rahardjo 1993). A linear relationship exists between coefficient a_t and coefficient a_{ts} (Fig. 5). The coefficient for unloading process increased with increasing of the coefficient, a_{ts} . The ratio between a_t and a_{ts} is equal to 1.38.

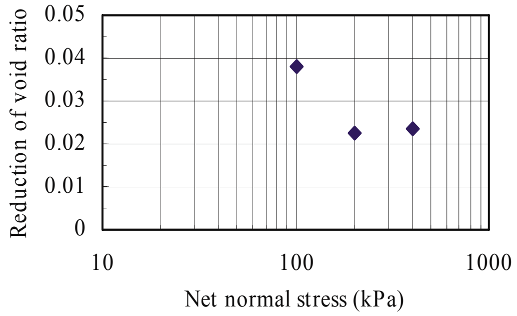

Figure 3. Reduction of void ratio with reduced net normal stress.

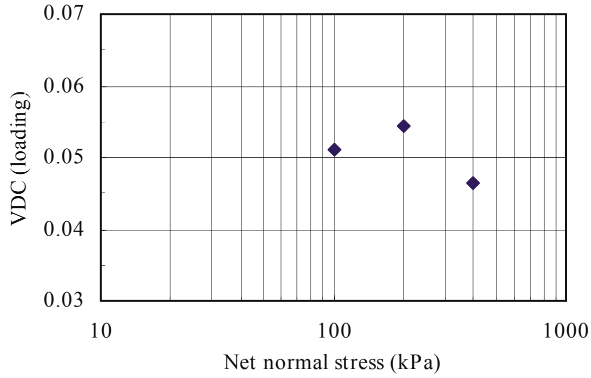

Figure 4. Relationship between the VDC, the volumetric deformation coefficient (loading) and the net normal stress.

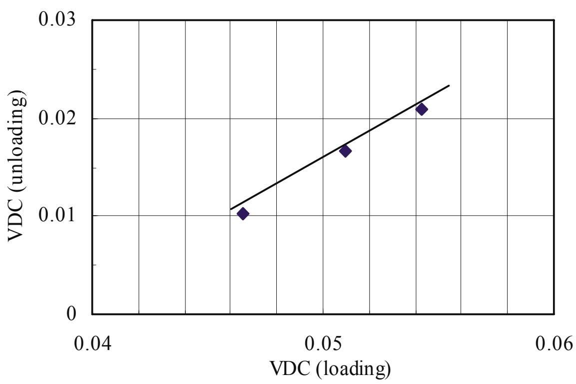

Figure 5. Volumetric deformation coefficients (VDC) during loading and unloading.

The soil specimens compacted with an initial water content of 10% that have a matric suction value of 70 kPa were sheared at different rates of displacements (0.03, 0.3 and 1 %/min.) under a net confining stress of 100 kPa. The results suggest that the shearing rate has practically no influence on the stress versus strain relationships (Fig. 6). However, there is some impact on the stress-strain behavior characteristics of the tested

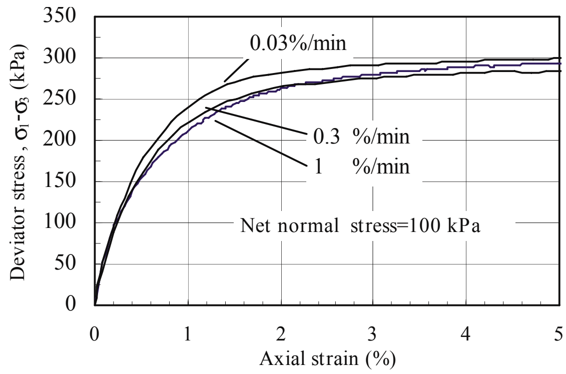

Figure 6. Stress-strain relationships for specimens compacted at a water content of 10%.

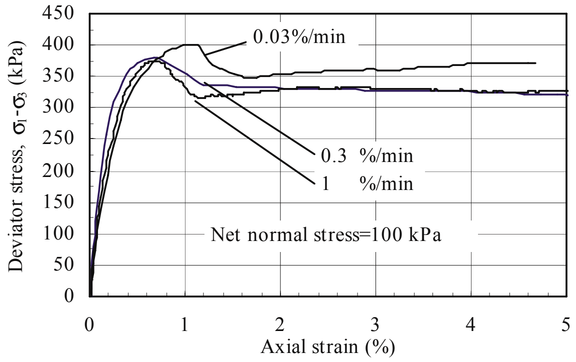

Figure 7. Stress-strain relationships for soil specimens subjected to a suction value of 39,000 kPa.

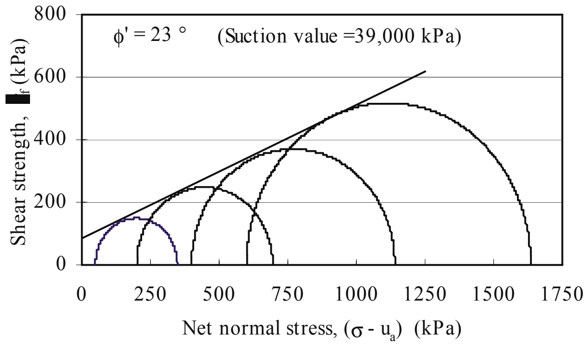

Figure 8. Failure envelope for unsaturated soil specimens (subjected to a suction value of 39,000 kPa).

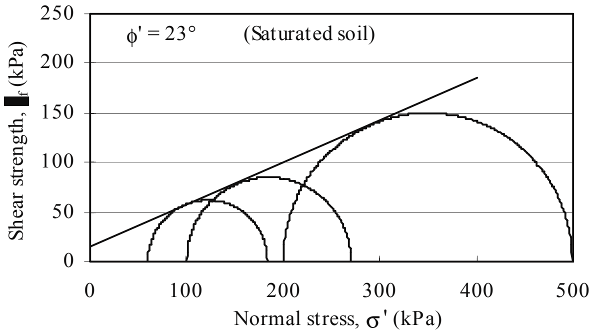

Figure 9. Failure envelope for saturated soil specimens.

unsaturated soil specimens with a high soil suction value of 39,000 kPa tested with a net confining stress of 100 kPa (Fig. 7). The peak values were achieved in the specimens at a relatively low axial strain. The critical state condition followed rapidly after acheiving peak values. The elasto-plastic behavior of the unsaturated soil with high soil suction (Fig. 7) is different compared to soil specimens tested with low suction values

(Fig. 6). The results of Fig. 7 also suggest that there is an increase of stiffness and shear strength due to high soil suction.Triaxial compression shear tests were performed on specimens with a constant soil suction of 39,000 kPa at four different net normal stresses (i.e., 50, 200, 400 and 600 kPa). Figure 8 shows Mohr-Coulomb failure envelope for the tests. The results of this study suggest that the angle of internal friction value, ϕ' is equal to 23°. Figure 9 shows the failure envelope for saturated soils determined from conventional triaxial tests. The angle of internal friction, ϕ' for saturated soils is also equal to 23°. In other words, the angle of internal friction, ϕ' is independent for saturated soil specimens and as well for unsaturated soil specimens with a high suction value. These results are consistent with the Fredlund et al. (1978) shear strength equation. Similar observations were reported by Vanapalli et al., (2000). These studies support the use of the Fredlund et al. (1978) shear strength over the entire suction range.

5 SUMMARY

Limited number of studies are reported in the literature with respect to the volume change and shear strength behavior of unsaturated soils in the high suction range. In this paper, pereliminary test results of shear strength and volume change behavior of an unsaturated silty soil with high suction values are presented using relative humidity controlled triaxial shear testing apparatus. The design details of this apparatus are provided briefly presented in this paper. The relative humidity control technique presented in this paper is a safer, reliable, and reproducible technique to achieve high soil suctions in the soil specimens. This technique also provides a closer reproduction of the natural field conditions of unsaturated soils in comparison to the conventional axis-translation technique. In other words, the modified relative humidity control triaxial compression apparatus is a useful technique that can be used in geotechnical and geoenvironmental engineering applications involving unsaturated soil problems.

The study results show that critical state condition occurs at low axial strains in specimens tested with high suction values. The failure envelope based on Mohr-Coulomb criterion shows that the angle of internal friction, ϕ', is same as for a saturated soil for soil specimens tested with different net normal stresses but at a high soil suction value of 39,000 kPa. Similar results were observed for soil specimens tested with low suction values by other investigators (Escario & Saez 1986 & Vanapalli et al. 1996). The results of the study presented in this paper suggest that the Fredlund et al. 1978 equation can be used for interpreting shear strength behavior of unsaurated soils with high suction values.

Based on the results of this research study, a technique is also presented to determine the volumetric deformation coefficients, a_t and a_{ts} in loading and unloading stages respectively at high suction value. The results suggest that the ratio between the parameters a_t and a_{ts} is a constant value for the soil tested.

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