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Hysteresis effects resulting from drying and wetting under relatively dry conditions

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ABSTRACT: The pore-water pressure near ground surface can undergo dramatic changes in response to evaporation and infiltration. This study reports the influence of the drying process and wetting process on the shear strength of a compacted silty soil and a compacted kaolin subjected to high total suctions. In the drying process, the relative humidity in the soil was decreased from 80% to 40%. The soil specimens remained in the relative humidity chamber for a month. After the soil reached equilibrium with the selected relative humidity, an unconfined compression test was conducted on the desiccated soil. The compressive strength of desiccated soil during wetting was found to be slightly less than that of the desiccated soil during drying. The shear resistance of an unsaturated soil is related to the area of contact of water in the soil and this area is related to the drying and wetting history.

1 INTRODUCTION

1.1 *Background*

Unsaturated compacted soils behavior is important in numerous geotechnical and geo-environmental structures such as earth dams, retaining walls, pavements, liners and waste soil-covers. Fredlund & Morgenstern (1977) used the concept of stress state variables to describe the behavior of an unsaturated soil in the terms of two independent stress variables (i.e. net normal stress and matric suction). Fredlund (2000) stated that two independent stress state variables (i.e. net normal stress and matric suction) are to unsaturated soils, what the effective stress variable is to saturated soils.

Precipitation and evaporation sets up a moisture flux across the ground surface, which directly affect the negative pore-water pressures in an unsaturated soil. Evaporation can induce high soil suctions near the ground surface. On the other hand, precipitation can eliminate the soil suction. The shear strength of a compacted, unsaturated soil is affected by changes in soil suction.

Soil profiles in unsaturated soil regions can be classified as a dry soil, the two-phase zone and the capillary fringe zone. The fundamental theories and concepts are primarily formulated for unsaturated soils in two-phase zone where the air and water phases are continuous (i.e. two-phase zone). Geotechnical engineering has less experimental research for the case where water phase is discontinuous or the residual state of unsaturation defined by the soil–water characteristic curve. Geotechnical engineers are interested in the effect of drying (desiccation) and wetting (swelling) on the shear strength of compacted, unsaturated soils.

1.2 *Purpose of this study*

This study focuses on the influence of the drying process and wetting process on the shear strength of a compacted silty soil and a compacted kaolin subjected to very high soil suctions (i.e. total suctions). This study reports on the effects of hysteresis associated with drying and wetting below the residual water content. Unconfined compression tests were conducted on statically compacted, unsaturated soils under relatively dry conditions. A silty soil and a kaolin were used in this test program. The compacted soils were subjected to high total suctions using a relative humidity equilibrium technique in a temperature and relative humidity controlled chamber. During the drying process, the relative humidity was decreased from 80% to 40% as 10% decrements in relative humidity. A similar test program was conducted for the wetting program. In this case, the relative humidity was increased from 40% to 80% in 10% increments of relative humidity for the wetting process.

2 LITERATURE

2.1 *Shear strength of unsaturated soil*

The shear strength of unsaturated soils can be formulated in terms of two independent stress state variables.

A linear form of the shear strength equation for unsaturated soils was proposed by Fredlund et al. (1978) and is presented in Equation (1):

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

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 to soil suction.

Equation (1) is an extended form of the Mohr–Coulomb equation and represents a planar surface. The angle of internal friction associated with the soil suction variables was originally assumed to be constant soil parameter. Later experimental studies performed over a wider range of soil suction values have shown that the variation of shear strength with respect to soil suction is non-linear. Gan & Fredlund (1988) showed failure envelopes that were non-linear based on multistage direct shear tests. Escario & Juca (1989) tested two clays and a clayey sand for suctions up to 15 MPa as maximum value. Direct shear tests showed that the slope of the failure envelope was essentially zero or negative at high soil suctions. Fredlund & Rahardjo (1993a) stated that the shear strength of unsaturated soils involving a wide range of suctions could be non-linear and it was suggested that the ϕ^b angle appears to approach an angle near zero degree (or it may even be negative), as soil suction exceeded the residual water content. Further laboratory studies over a wide range of soil suctions have revealed that the friction angle should be written as an unsaturated soil property.

The strength parameter, ϕ^b, can be estimated using the soil–water characteristic curve for the soil with the result that the shear strength determines the unsaturated soil property functions. Several mathematical equations have been proposed to describe the soil–water characteristic curve (e.g. Fredlund et al. 1996).

White et al. (1970) proposed the physical properties associated with the desaturation stages for a porous material. Vanapalli et al. (1996) stated that the desaturation stages can be classified along the desorption branch of a soil–water characteristic curve; namely, the boundary effect stage, the transition stage (i.e. with primary and secondary) and the residual stage of unsaturation. Laboratory test to direct measure of the unsaturated soil shear strength function are costly and require a long time to perform. A grain-size distribution can also be used to estimate the soil–water characteristic curve as shown by Fredlund et al. (2000). Nishimura & Fredlund (1999) performed unconfined compression tests on a compacted unsaturated silty soil subjected to high total suctions. The relationship between shear strength and total suction for the compacted unsaturated silty soil was shown as an essentially horizontal failure surface beyond residual conditions. Nishimura & Fredlund (2000) reported the shear strength of a relatively dry kaolin and measured the soil–water characteristic curve over the entire range of soil suctions. A compacted kaolin was subjected to total suctions as high as 124,000 kPa using a relative humidity control technique. The desiccated kaolin showed a very low increase in strength with soil suction (i.e. ϕ^b was estimated at about 0.3 degree).

Mahalinga-Iyer & Williams (1985) conducted unconsolidated undrained triaxial tests on two soils. 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 to 1000 kPa. The ϕ^b angle then decreased slightly in the soil suction range from 1000 to 8000 kPa. Escario & Saez (1987) have observed a slight reduction in shear strength in the soil suction range between 11,000 and 150,000 kPa for a gray clay. It is possible that the non-linear form of the unsaturated shear strength envelope based on the soil–water characteristic curve, can take this form (e.g. Vanapalli & Fredlund 1999). The suggested prediction models for shear strength based on the use of a soil–water characteristic curve are empirical in nature. There is little information on the character of the failure envelope below the residual state of unsaturation.

3 TEST PROCEDURE

3.1 *Description of the soil*

A silty soil and a kaolin were used in this test program. The silty soil is non-plastic soil and the kaolin is a fine-grained cohesive soil. Grain-size distributions for the two soils are shown in Figure 1 using a mathematical form suggested by Fredlund et al. (2000). The silty soil has a relatively uniform grain-size distribution. The kaolin has a larger fines fraction than the silty soil.

3.2 *Test program*

The two soils were compacted statically. Each soil specimen had a height of 100 mm and a diameter of 50 mm. The initial water contents of the silty soil and the kaolin were 9.6% and 31.7%, respectively.

All soil specimens were placed directly into a temperature and relative humidity controlled chamber in order to apply a high total suction. Total suction can be

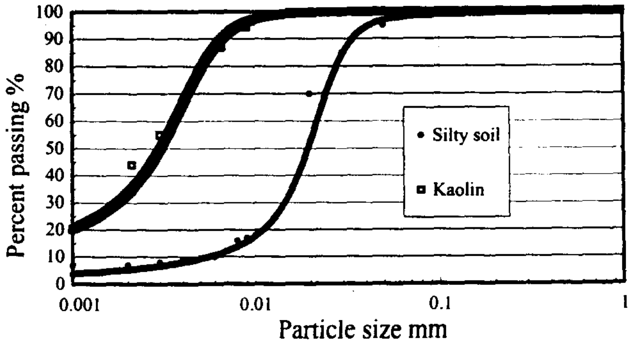

Figure 1. Grain-size distribution for a silty soil and kaolin.

determined by the measurement of the vapor pressure in equilibrium with the soil–water.

The vapor pressure generally is controlled using a dissolved salt solution. The osmotic technique has the advantage of applying a high total suction to the soil–water without the use of the axis-translation technique. The relationship between total suction and relative humidity can be written as

$$\psi = -135.022 \ln\left(\frac{\bar{u}_v}{\bar{u}_{v0}}\right) \qquad (2)$$

where ψ = total suction in kPa, $\bar{u}_v$ = partial pressure of pore-water vapor in kPa, $\bar{u}_{v0}$ = saturation pressure of water vapor in kPa over a flat surface of pure water at the same temperature. The term, $\bar{u}_v/\bar{u}_v\bar{u}_{v0}$, is called relative humidity, RH(%).

This test program consisted of performing unconfined compression tests on dried specimens and then performing unconfined compression tests on specimens that were wetted to equilibrium. The test program selected relative humidities of 80%, 70%, 60%, 50% and 40%. Each soil specimen was subjected to the relative humidity for not less than a month. Desaturation of the soil started as a result of evaporation in the relative humidity chamber.

During the drying process, the relative humidity was decreased from 80% to 40% in decrements of 10%. After the soil specimen had reached equilibrium with the selected relative humidity, an unconfined compression test was conducted at a rate of axial strain of 0.5 mm per minute. The final water content of the soil specimen corresponding to the selected relative humidity was measured at the end of the unconfined compression test. Upon completion of the drying process, the test program continued through a wetting process. In the wetting process, soil specimens are brought to equilibrium starting from a relative humidity of 40%. Specimens were prepared at 10% increments. After the soil reached the selected relative humidity, unconfined compression tests were performed on the soil specimen.

4 TEST RESULT AND DISCUSSIONS

The soil–water characteristic curve (i.e. the relationship between amount of soil–water and soil suction) was evaluated using a pressure plate apparatus, salt solution desiccators and a relative humidity chamber. The soil–water characteristic curves for a silty soil and a kaolin are shown in Figures 2 and 3. The soil–water characteristic curves were best-fit over the entire range of soil suction using the prediction model suggested Fredlund & Xing (1994).

The key features of the soil–water characteristic curve are the air-entry value, the residual water content and the slope of the straight line portion of the desorption branch. The estimated air-entry value for the silty soil and the kaolin are 10 and 100 kPa, respectively. The determination of the residual water content is somewhat difficult to precisely determine, partly due to a scarcity of data at critical points along the curve.

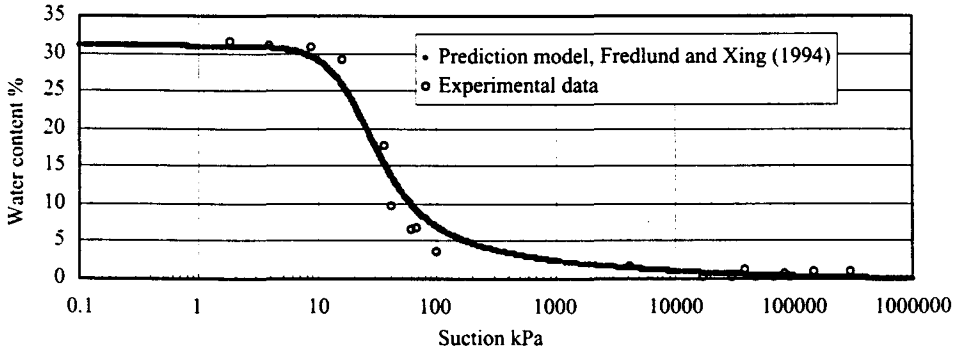

Figure 2. Soil–water characteristic curve for a silty soil.

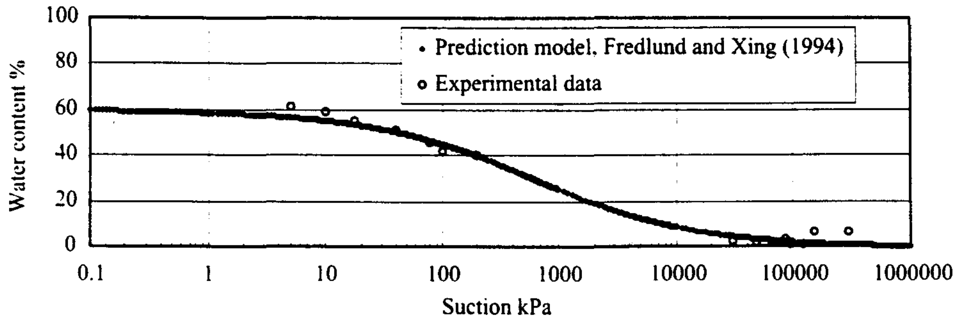

Figure 3. Soil–water characteristic curve for a kaolin.

Both the residual water content and residual soil suction were estimated using an empirical, graphical procedure. The residual state of unsaturation was defined as the point where the line extending from 1,000,000 kPa along the curve intersects the previous tangent line (Vanapalli et al. 1999). The residual state is not defined for the kaolin since there is no distinct breaking point in the high suction range. The silty soil shows a residual water content of 2.5% and a residual suction of 200 kPa. The hysteresis loop in the low suction ranges will be greater than in the high suction ranges (Fredlund 2000). However, it is possible to predict that the hysteresis loops is below the residual state of unsaturation for the wetting curve. The pore-size distribution in the soil remains essentially unchanged during the process of drying and wetting (Fredlund & Rahardjo 1993b).

The relationship between unconfined compressive strength and total suction for the silty soil and the kaolin is presented in Figures 4 and 5. The relative humidities selected in this test program are less than 80%. Soil suctions corresponding to this relative humidity are larger than 30,000 kPa. The soil has a high total suction in the residual state.

The unconfined compression strength corresponding to the "*initial condition*" is plotted on the ordinate axis in Figures 4 and 5. There is a slight increase in the shear strength of the soil related to essentially no change in water content (i.e. no change in wetted area of contact) with increasing soil suction. During the drying process, the shear strength of the desaturated silty soil and kaolin increases slightly with suctions. The angle of friction, $\phi^b_{(drying)}$, with respect to suction was computed from the unconfined compressive shear strength versus soil suction relationship as shown in Figures 4 and 5. The angle of friction, $\phi^b_{(drying)}$, on the drying portion for the silty soil and kaolin are 0.02 and 0.3 degrees, respectively. The angle of friction for the kaolin is slightly larger than that for the silty soil. There is evidence that the failure envelope with respect to soil suction is essentially horizontal in the residual stage of unsaturation.

When soil suction decreases from 124,000 to 94,000 kPa (i.e. starting of the wetting process), a reduction in shear strength occurred for both the desiccated silty soil and the desiccated kaolin. During the wetting process, there is a decrease in the shear strength with decreasing soil suction. The failure envelope on the wetting portion is shown in Figures 4 and 5. The angle of friction, $\phi^b_{(wetting)}$, with respect to suction in the wetting portion was evaluated in a similar manner. The angle of friction, $\phi^b_{(wetting)}$, on the wetting portion for both the desiccated silty soil and the kaolin was 0.01 and 0.05 degrees, respectively.

A summary of the ϕ^b angles associated with the drying and wetting curves is shown in Table 1. The $\phi^b_{(wetting)}$

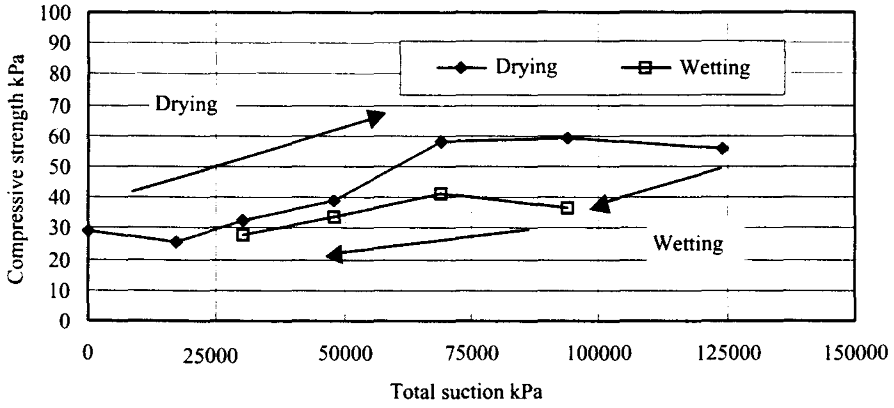

Figure 4. Relationships between compressive strength and total suction for a silty soil.

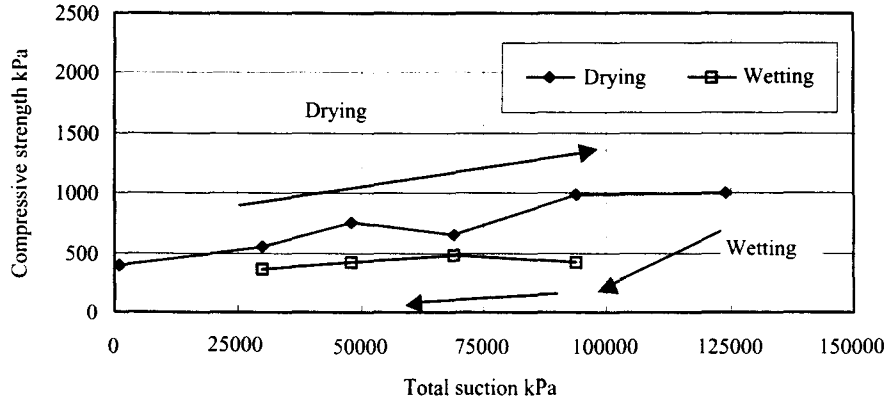

Figure 5. Relationship between compressive strength and total suction for a kaolin.

Table 1. Summary of the angle friction with respect to soil suction.

	$\phi^{b}_{(drying)}$	$\phi^{b}_{(wetting)}$
Silty soil	0.02	0.01
Kaolin	0.3	0.05

is slightly less than the $\phi^{b}_{(drying)}$ for both soils. The failure envelope is, however, essentially a horizontal line in the residual stage of unsaturation in regardless of the drying and wetting history.

There is a slight hysteresis due to drying and wetting in shear strength with soil suction for the silty soil and the kaolin.

5 CONCLUSIONS

This study reported on the results of unconfined compression tests for a compacted, unsaturated soil subjected to high total suction. Changes of the shear strength due to drying and wetting applications were observed. Even if the soil suction is coincident, the shear strength on the drying process is slightly larger than that on wetting process. Consequently, the computed angle of friction, $\phi^{b}_{(drying)}$, is slightly larger than $\phi^{b}_{(wetting)}$. The failure envelope with respect to soil suction is, however, essentially a horizontal line regardless of drying and wetting applications. It is observed that there was a slight hysteresis with respect to shear strength of a compacted, unsaturated soil in the residual suction range.

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