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Unconfined compression shear strength of an unsaturated silty soil subjected to high total suctions

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ABSTRACT: There does not appear to be data available that shows the relationship between the soil-water characteristic curve and experimental shear strength beyond the residual state. This paper describes the shear strength of a compacted unsaturated silty soil beyond residual conditions. This study involved performing unconfined compression tests on a compacted unsaturated silty soil subjected to high total suction. The soil-water characteristic curves also measured over a wide range of suctions. The highest total suction was maximum 93,600 kPa corresponding to a relative humidity of 50 %. The relationship between shear strength and total suction for the silty soil shows an essentially horizontal failure surface beyond residual conditions. Prior to the soil reaching residual conditions, the failure envelope is non-linear.

1. INTRODUCTION

Unsaturated natural soils and artificially compacted unsaturated soils near the ground surface can have high negative pore-water pressure due to evaporation. The ground surface is a dynamic boundary, which is controlled largely by the environment or climatic conditions. Geotechnical engineers are well aware that evaporative events can greatly exceed for infiltration events in many regions of the world.

Recent studies have evaluated evaporative rates from soil surfaces. Silvestri, Soulie, Lafleur, Sarkis and Bekkouche (1990) showed that clays were strongly influenced by potential evaporation and result in settlement problems on lightweight structures. Sattler and Fredlund (1989) demonstrated that heave and settlement for expansive clay soils are influenced by evaporation. Barton (1979) suggested that soil evaporation may be estimated on the basis of the humidity and water content of the near surface soil. Granger (1989) stated that evaporation from unsaturated soil surfaces is a function of the actual vapor pressure at the soil surface.

The concept of stress state variables to describe the behavior of unsaturated soils was introduced by Fredlund and Morgenstren (1977). An empirical, analytical model was developed to predict the shear strength in terms of soil suction using a soil-water characteristic curve and saturated shear strength parameter (Vanapalli, et al. (1996)). A typical soil-water characteristic curve has one curve for drying and one curve for the wetting of a soil. Different saturation stages can be defines through the desaturation process due to increasing soil suction. The first future is the air entry value. At large increases in suction, there is a relatively small change of water content at the residual zone stage (i.e., residual water content condition).

Beyond residual soil suction conditions, changes in the shear strength of an unsaturated soil have not been well defined. The change in shear strength beyond residual soil suction conditions (i.e., residual zone stage) may depend on the soil type. Laboratory tests are required in order to estimate the shear strength and beyond residual water content in unsaturated soil mechanics.

2. PURPOSE OF THIS STUDY

Shear strength tests for a soil beyond residual conditions have not been adequately studied. This paper describes the shear strength behavior of a compacted unsaturated silty soil beyond residual water content conditions. Large total suctions were created in a compacted silty soil by controlling the relative humidity in the soil. This was done in a relative humidity chamber. Unconfined compression tests were conducted on unsaturated soil specimens in the residual water content range. The relationship between total suction and shear strength is evident in the total suction range from 41 kPa to 93,600 kPa.

3. TEST PROCEDURE

A silty soil was used in this test program (i.e., a fine-grained cohesionless soil). The statically compacted silty soil specimens had a height of 100 mm and a diameter of 50 mm. Initial physical properties of the silty soil specimens had a water content of 9.6 %, a void ratio of 0.947 and a degree of saturation of 27 %.

All specimens were placed directly into a temperature and relative humidity controlled chamber in order to apply a high total suction. The chamber could control the relative humidity in a range from 20 % to 90 % at a temperature of 30 degrees. There is a relationship between relative humidity and soils suction (i.e., total suction) as shown in Fig. 1. Fig. 1 is plotted using the theoretical model (Fredlund and Rahardjo (1993)). The test program selected relative humidifies of 88 %, 80 %, 70 %, 60 % and 50 %. Each silty soil specimen was subjected to the relative humidity for a long time. Total suction values corresponding to each relative humidity are shown in Table 1.

Soil water leaves the soil surface as result of evaporation. Desaturation of a soil occurs as the dries. When the weight of each soil specimen underwent no further change, it was assume that the soil had come to equilibrium at the selected relative humidity. Each soil specimen was in a residual condition. After soil specimen had reached equilibrium, an unconfined compression test was conducted at residual a rate of axial strain of 0.5 mm/min.

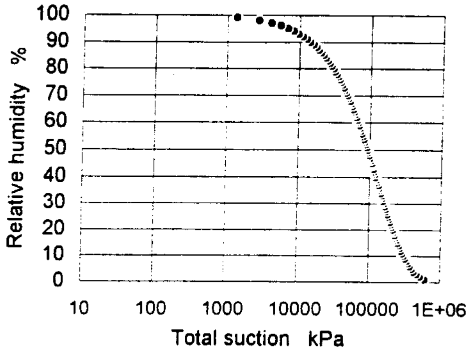

Fig.1 Relative humidity versus total suction relationship

Table 1 Summary of unconfined compression test results

Relative humidity %	Total suction kPa	Unconfined compresive strength kPa	Axial strain at failure %
88	17,260	25.4	0.26
80	30,129	32.4	0.12
70	48,158	38.8	0.19
60	68,972	58.3	0.15
50	93,590	59.2	0.32
Initial condition	41	28.8	0.65

In case of "Initial condition", suction means matric suction.

At the end of the unconfined compression test, the water content of the complete soil specimen was measured in order to evaluate the soil-water characteristic curve. The soil-water characteristic curve is a measure of the available soil water at a particular soil suction.

The soil-water characteristic curve for the silty soil was evaluated using a pressure plate apparatus (i.e., pressure plate method), glass desiccators containing saturated salt solutions (i.e., vapor equilibrium technique) and relative humidity technique over the entire soil suction range. The

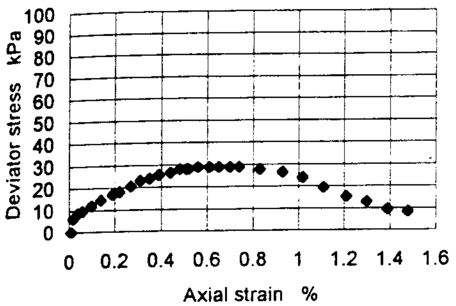

Fig.2 Stress-strain curve for the on unconfined compression test with an Initial matric suction of 41 kPa

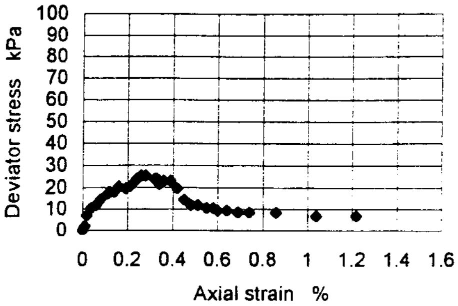

Fig.3 Stress-strain curve for the unconfined compression test at a relative humidity of 88% or a total suction of 17,260 kPa

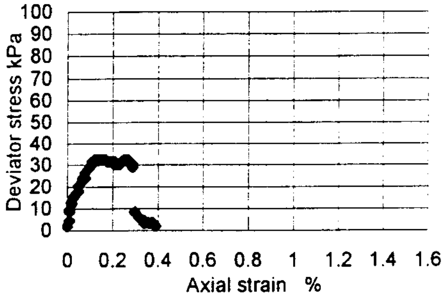

Fig.4 Stress-strain curve for the unconfined compression test at a relative humidity of 80% or a total suction of 30,129 kPa

pressure plate method measures the soil water at a variety of matric suction values. The air pressure in the pressure plate apparatus was increased until a maximum of 182 kPa. The water content corresponding to higher values of total suction was determining using both the vapor equilibrium technique and the relative humidity technique. Small soil samples were placed into each glass desiccators, and water contents were measured corresponding to the total suction established in the desiccators.

4. LABORATORY TEST RESULTS

Geotechnical engineers often required an estimation of the shear strength of soils at low water contents. Previous research work on unsaturated soils has not performed shear strength tests at residual water content conditions. This study reports the results of unconfined compression tests at low water contents on a silty soil. For comparison purpose, the initially compacted silty soil with a matric suction of 41 kPa, was tested in an unconfined compression test.

Stress-strain curves obtained from the unconfined compression tests are shown in Figs. 2,3,4,5,6 and 7. The stress-strain curve for the initial compacted silty soil is shown in Fig. 2. Table 1 provides a summary of the unconfined compression test results. The compacted silty soil indicates a smooth stress-strain curve as shown in Fig. 2. The maximum deviator stress is reached at an axial strain of 0.65 %. The compacted silty soil specimens with a high total suction shows a distinct peak on the stress-stain curve. After reaching the maximum deviator stress, the stress-strain curve decreases rapidly. Failures occur suddenly in the specimens with a high suction. The axial strain at failure for the dried specimens is lower than that of the initially compacted silty soil. The value of the strain at failure varies with the water content condition. The shear strength of a compacted silty soil increases slightly at high total suctions.

5. DISCUSSION OF RESULTS

The shear strength of an unsaturated soil is related to soil-water characteristic curve. The soil-water characteristic curve describes the relationship between available water in the soil and the soil suction, for drying and wetting. The shear

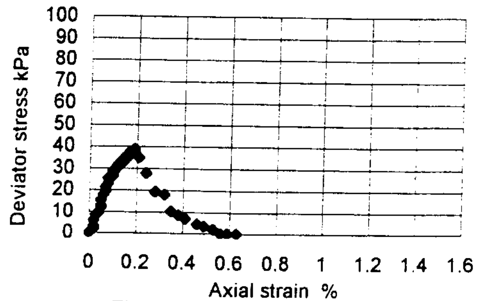

Fig.5 Stress-strain curve for the unconfined compression test at a relative humidity of 70% or a total suction of 48,158 kPa

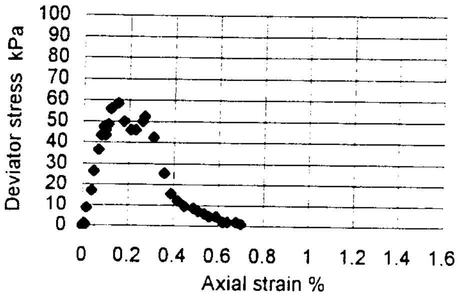

Fig.6 Stress-strain curve for the unconfined compression test at a relative humidity of 60% or a total suction of 68,972 kPa

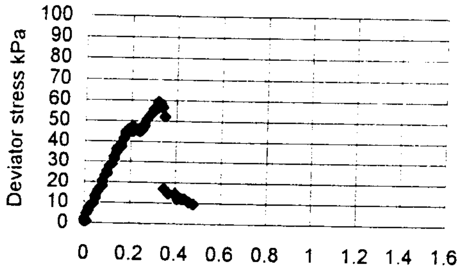

Fig.7 Stress-strain curve for the unconfined compression test at a relative humidity of 50% or a total suction of 93,590 kPa

strength of an unsaturated soil is related to the amount of water in the void of the soil. The soil-water characteristic curve for the silty soil is shown Fig. 8.

Several soil-water characteristic curve models have been proposed to empirically predict the permeability and shear strength function for an unsaturated soil. The soil-water characteristic curve model can be written as an equation as proposed by Fredlund and Xing (1994) (Fig. 8). Model parameters for the best-fit soil-water characteristic curve for the silty soil are shown in Fig. 8. A silty soil has an air entry value of 30 kPa. Beyond a suction of 200 kPa, the soil enters the residual state.

It is well-known that there are different stages of desaturation defined by the soil-water characteristic curve. Vanapalli, et al. (1996) suggested four stages as following: boundary effect stage, primary transition stage, secondary transition stage and residual stage. The soil is essentially saturated in the boundary effect stage. All the soil pores are filled with water. The soil starts to desaturate in the primary transition stage. The water content in the soil reduces significantly with increasing in suction. The air-entry value for the soil lies between the boundary effect stage and the primary transition. In the secondary transition stage, the amount of water between the soil particle or aggregate contacts reduces as desaturation continues. The water meniscus area in contact with the soil particle or aggregates begins to become discontinuous. The rate of decrease in water content, to a change in suction in this stage, is less than that in the primary transition stage. There is little water left in soil pores when the soil reaches the residual state. The water content of the unsaturated soil remains relatively constant in the residual stage. Air almost occupies all the soil pores. The water meniscus in contact with the soil particles is not continuous and may be very small. There is a little water left in soil pores.

Fig. 9 shows the relationship between the shear strength (i.e., unconfined compressive strength) and total suction for the residual condition in the unsaturated silty soil. The shear strength has a slightly increase in strength with increasing of total suction. The ratio of the increase in shear strength to an increase in total suction translates to an angle of 0.02 degrees. There is a negligible increase in shear strength because the amount of water in the soil pores is very small. The effect of total suction on the shear strength is

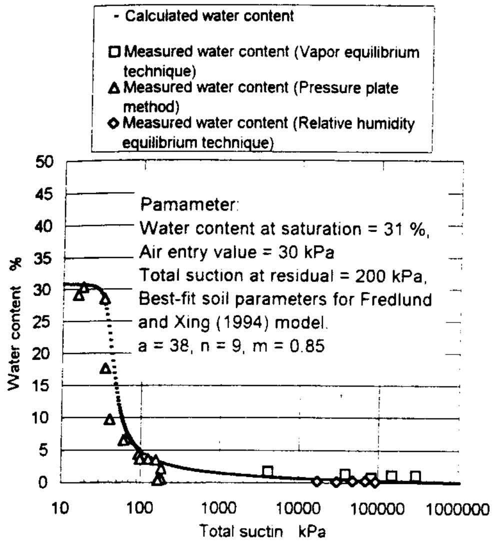

Fig.8 Soil-water characteristic curve for the silty soil

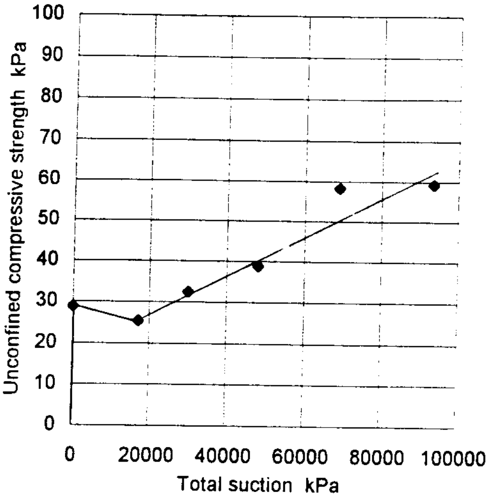

Fig.9 Relationship between unconfined compressive strength and soil suction in the residual state

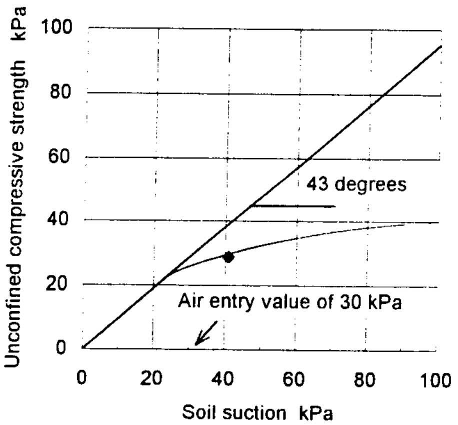

Fig.10 Relationship between unconfined compresive strength and matric suction

negligible. It is concluded that the shear strength for a residual water in the unsaturated silty soil, remain relatively constant.

The shear strength envelope is postulated in Fig. 10 for the initially compacted silty soil at a low matric suction up the 41 kPa. Before the soil suction reaches the air-entry value, the soil is essentially in a saturated state. The failure envelope will be tangent to an angle of internal friction for the saturated silty soil. The angle of internal friction of silty soil used in this study was 43 degrees. Beyond the air-entry values, the effect of soil suction translating to shear strength decreases. A non-linear increase in shear strength is shown in Fig.10. Gan, Fredlund and Rahardjo (1988) observed non-linearly in the failure envelope with respect to matric suction for a compacted glacial till when using multistage direct shear tests. The tangent of the failure envelope decreases significantly at matric suctions in the range of 50-100 kPa. The angle with respect to matric suction reaches a fairly constant value when the matric suction reaches 500 kPa.

Since the shear strength versus total suction relationship was computed as 0.02 degrees in Fig. 9, the failure surface indicates a horizontal relationship with total suction.

6. CONCLUSIONS

This paper presents unconfined compression test results and the measurement of the soil-water characteristic curve for a compacted unsaturated silty soil. Change in shear strength under residual conditions are discussed. The compacted unsaturated silty soil was brought to equilibrium at relative humidities of 88 %, 80 %, 70 %, 60 % and 50 %.

The deviator stress for the soil under residual conditions, reached to maximum value at a low axial strain. After the maximum deviator stress was reached, the strength suddenly decreased. Before the total suction reached its residual state, the silty soil indicated a non-linear failure envelope. The shear strength remained constant under residual conditions.

REFERENCES

Barton, I.J. 1979. A parameterization of the evaporation from non-saturated surface. Journal of Applied Meteorology, Vol.18, pp.43-47.

Fredlund, D.G and Morgenstern, N.R. 1977. Stress state variables for unsaturated soils. Journal of the Geotechnical Engineering Division, ASCE, 103(GT5), pp.447-466.

Fredlund, D.G. and Rahardjo, H. 1993. Soil Mechanics for Unsaturated Soils, JOHN WILEY & SONS, INC. 517pp.

Fredlund, D.G. and Xing, A. 1994. Equation for the soil-water characteristic curve. Canadian Geotechnical Journal, Vol.31, pp.521-532.

Gan, J-K.M., Fredlund, D.G. and Rahardjo, H. 1988. Determination of the shear strength parameters of an unsaturated soil using the direct shear test. Canadian Geotechnical Journal, Vol.25, pp.500-510.

Granger, R.J. 1989. Evaporation from natural non-saturated surface. Journal of Hydrology, Vol.111, pp.21-29.

Satter, P. and Fredlund, D.G. 1989. Use of thermal conductivity sensors to measure matric suction in the laboratory. Canadian Geotechnical Journal, Vol.26, pp.491-498.

Silvestri, V., Soulie, M., Lafleur, J., Sarkis, G. and Bekkouche, N. 1990. Foundation problems in champlain clays during drougts. 1:Rainfall deficits in Montreal (1930-1988). Canadian Geotechnical Journal, Vol.27, pp.285-293.

Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E. and Clifton, A.W. 1996. Model for the prediction of shear strength with respect to soil suction. Canadian Geotechnical Journal, Vol.33, pp.379-392.