Failure envelope of a desiccated, unsaturated silty soil

Enveloppe de glissement d'un sol limoneux desséché, non saturé

T.Nishimura – *Ashikaga Institute of Technology, Tochigi, Japan*
D.G.Fredlund – *University of Saskatchewan, Saskatchewan, Canada*

ABSTRACT: Suction is one of the state variables controlling the shear strength and volume change of unsaturated soils. Extremely high suctions can be produced by evaporation from the ground surface. Considerable research has been done on the relationship between the shear strength of an unsaturated soil and matric suction in the low suction range; however, little research has been done on the shear strength of desiccated, unsaturated soils subjected to extremely high suctions. This study provides an understanding of the shear strength of a desiccated, unsaturated silty soil. The test program involves performing direct shear tests and unconfined compression tests using a silty soil. The modified direct shear apparatus used in this test program can independently control the pore-air and pore-water pressure for unsaturated soil. Unconfined compression tests were conducted on a compacted, unsaturated silty soil subjected to high suctions.

RÉSUMÉ: L'absorption est l'une des variables d'état régulant la résistance au cisaillement et les modifications de volume des sols non saturés. Une absorption particulièrement élevée peut résulter de l'évaporation se produisant à la surface du sol. Des recherches nombreuses ont été effectuées sur les relations entre la résistance au cisaillement d'un sol non saturé et l'absorption métrique dans la gamme des absorptions faibles ; par contre, les recherches sur la résistance au cisaillement des sols asséchés non saturés sujets à une absorption très élevée sont rares. Cette étude est consacrée à la résistance au cisaillement d'un sol asséché non saturé silteux. Le programme des essais inclut des essais de cisaillement direct et des essais de compression unidimensionnelle sur un sol silteux. L'appareil de cisaillement direct modifié utilisé dans ce programme peut indépendament contrôler la pression de l'air et de l'eau interstielles d'un sol non saturé. Les essais de compression unidimensionnelle ont été conduits sur un sol silteux compacté et non saturé sujet à une absorption élevée.

1 INTRODUCTION

Geotechnical engineers encounter slope in stability, lateral earth forces, soil swelling and soil collapse involving unsaturated soils with negative pore-water pressure. The constitutive equations for volume change, shear strength, and flow for unsaturated soils are becoming generally accepted in geotechnical engineering. The soil properties for unsaturated soil prediction models have often been empirical procedures. Experimental studies on unsaturated soil used a conventional triaxial apparatus and a modified direct shear apparatus are generally costly, time-consuming, and difficult to conduct.

The soils above the groundwater table are generally unsaturated and are negative relative to atmospheric conditions. The unsaturated soil profile above the groundwater table can be subdivided into three portions (i.e., dry soil, two phase zone, and capillary fringe). The capillary fringe remains saturated even through the pore-water pressures are negative. The water phase is discontinuous, and air fills most of the voids in the soil. The pore-water pressure near ground surface may undergo dramatic changes due to evaporation and infiltration. If moisture is extracted from the ground surface due to evaporation, the pore-water pressure can become highly negative. Vanapalli et al. (1996) showed the variation of water area for different stages along a soil-water characteristic curve The soil-water characteristic curve assists in understanding the shear strength of an unsaturated soil during the desaturation process.

2 LITERATURE

The shear strength of unsaturated soils has been formulated in terms of two independent stress state variables (i.e., net normal stress, $(\sigma - u_a)$, and the matric suction, $(u_a - u_w)$). The shear strength equation for unsaturated soils proposed by Fredlund et al. (1978) has been accepted widely in geotechnical engineers.

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

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 soil suction.

Fredlund et al (1978) equation is an extended form of the Mohr-Coulomb equation for a planar surface. The reduction in the angle is substantial at high soil suctions.

Gan and Fredlund (1988) showed failure envelopes that were non-liner based on multistage direct shear tests. Fredlund and Rahardjo (1993) 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 to approach an angle of zero degrees (or it may even be negative), as soil suction reaches a value corresponding to residual water content. Escario and 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 zero or negative at high soil suctions.

More recently, several investigators have proposed empirical procedures to estimate the unsaturated soils shear strength using the soil-water characteristic curve (Vanapalli and Fredlund 1999). Vanapalli et al. (1996) proposed a shear strength equation for unsaturated soils as a function of the soil-water characteristic curve. White et al. (1970) presented the concept of different desaturation stages for porous materials; namely, the boundary effect zone, primary transition zone, secondary transition zone and the residual desaturation zone. In the boundary effect stage, the soil pores are filled with water. The water menisci in contact with the soil particles are continuous. After the matric suction reaches the air-entry value, the soil starts to desaturate into the transition stage. In the transition stage, the amount of soil water reduces significantly with increasing suction. Eventually the water menisci area in contact with the soil particles (or aggregates) becomes discontinuous in the residual desaturation zone. Large increases in suction lead to a relatively small change in water content. The soils are essentially dry condition in the residual desaturation zone. The amount of water at the soil particles or aggregate contacts is small.

3 TEST PROCEDURE

A silty soil was used in this test program. This test program includes direct shear tests and unconfined compression tests. A modified direct shear apparatus was used in this test program that was similar in design to that proposed by Gan and Fredlund (1988). The modified direct shear apparatus as shown in Fig. 1. The main addition to the standard apparatus is the air pressure chamber, which completely encloses the direct shear box in order to elevate the ambient air pressure. The direct shear box is modified to allow the independent control or measurement pore-air and pore-water pressures. In this test program a initially slurried silty soil was placed in the shear box. A matric suction was applied to the slurried silty soil by maintaining a constant air pressure in the air pressure chamber, while water was allowed to drain. The applied matric suction was up to 441 kPa. After the soil specimen comes to equilibrium with the applied matric suction, the specimen is subjected to a constant horizontal displacement rate of approximately 0.5 mm/minute. The effective friction angle for the silty soil was established on the basis of saturated direct shear tests.

Unconfined compression tests were also performed on compacted, unsaturated silty soil specimens. All silty soil specimens were placed directly into a temperature and relative humidity controlled chamber in order to apply a high total suction. The selected relative humidities were of 88%, 80%, 70%, 60%, and 50%. Each relative humidity value corresponds to a total suction provided the thermodynamic relationship: 17000 kPa, 30000 kPa, 48000 kPa, 68000 kPa and 94000 kPa (Fredlund and Rahardjo 1988). All compacted silty soil specimens remained in the relative humidity control for a month. The water in the soil pores evaporated into the relative humidity chamber. After the fluid in soil had reached equilibrium with the selected relative humidity, an unconfined compression test was performed on compacted, desiccated silty soil.

The relationship between soil suction and water content for the silty soil was measured for the soil-water characteristic curve over the entire soil suction range.

4 TEST RESULTS

4.1 *Soil water characteristic curve*

The soil-water characteristic curve is shown in Fig. 2. The key futures of the soil-water characteristic curve are the air-entry value and the residual water content. The air-entry value can be estimated by extending the constant slope portion of the soil-water characteristic to intersect the suction axis at saturated conditions. The silty soil had a air-entry value of 10 kPa. The definition of the residual water content, however, is not easy. The residual state of saturation was defined using an empirical graphical procedure corresponding to the point where the line extending from 1,000,000 kPa, intersected the previous tangent line. The silty soil has the residual water content of 2.5 % and a residual suction of 200 kPa using this graphical procedure.

4.2 *Direct shear strength in the low matric suction ranges*

The direct shear envelope with respect to matric suction are presented in Fig. 3. A linear line though saturated shear strength conditions is provided. The slope of the line corresponds to the effective angle of internal friction for the saturated silty soil. In the boundary effect stage, the effect of matric suction on shear strength is similar to that of net normal stress. The direct shear strength envelope is linear until the matric suction equals the air-entry value. After matric suction exceeds the air-entry value, water content decreases with an increase in matric suction. Changes in the shear strength of the unsaturated soil become smaller with an increase in the soil suction. In the transition stage, the effect of matric suction on the shear strength in soil is less than in the boundary effect stage. The strength parameter, ϕ^b , clearly decreases with matric suction during the desaturation processes. The strength envelope is a curvilinear. As the silty soil moves from the transition stage to the residual stage of unsaturation condition due to the application of soil suction, the shear strength increases with slightly suction. Eventually, the strength parameter, ϕ^b , is approximately zero. The failure envelope is composed of a linear segment and a curvilinear segment in the low to intermediate suction range.

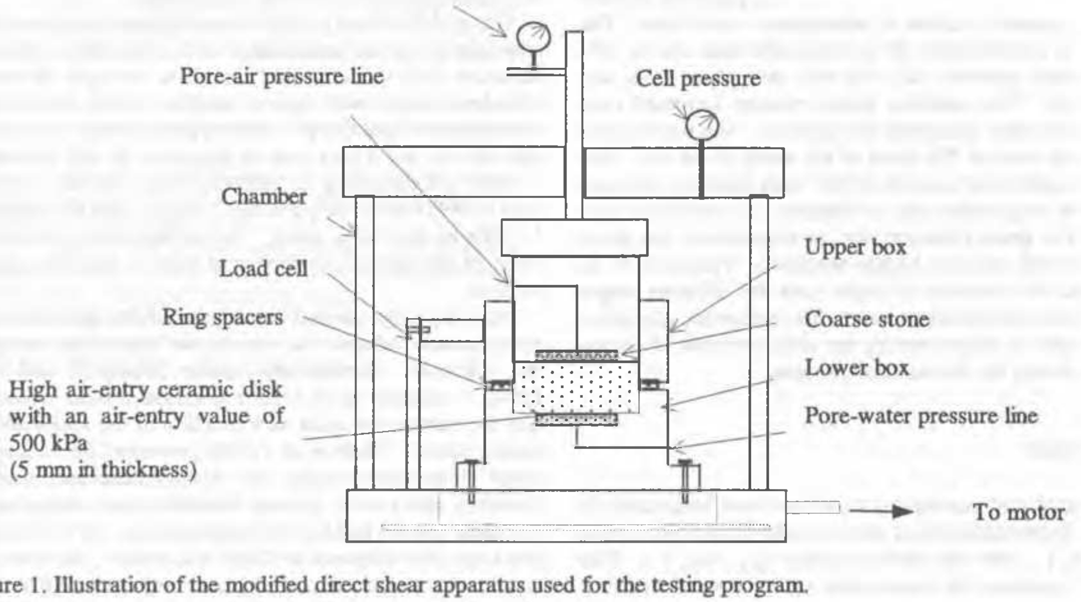

Figure 1. Illustration of the modified direct shear apparatus used for the testing program.

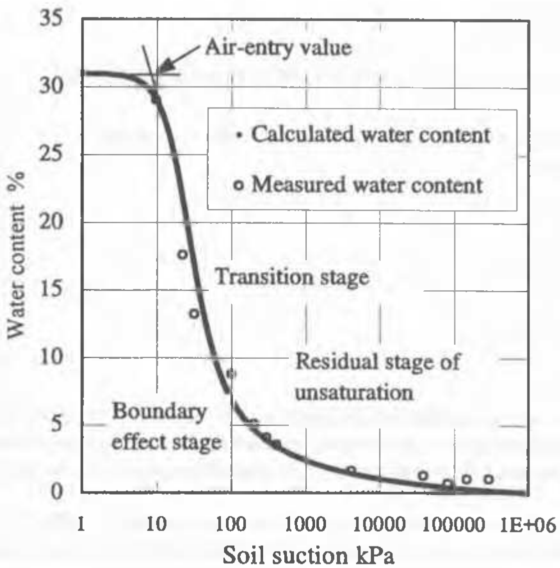

Figure 2. Soil-water characteristics curve for a silty soil.

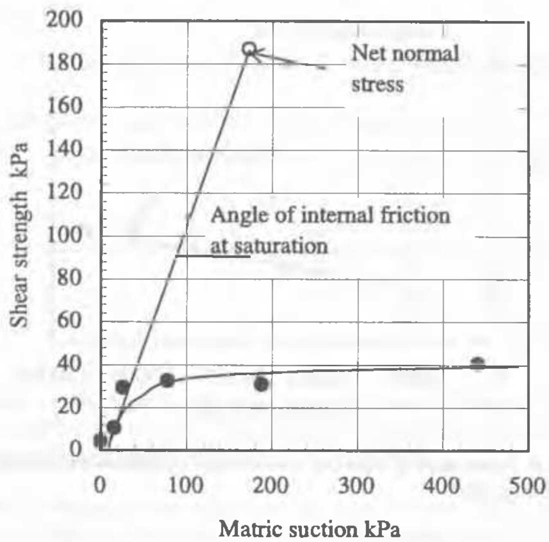

Figure 3. Relationship between shear strength and matric suction.

4.3 *Unconfined compressive strengths at high suctions*

The results of unconfined compression tests on the compacted unsaturated silty soil subjected to high total suction are presented in Fig. 4. The unconfined compressive strength on the ordinate, corresponds to the peak strength of a specimen. The unconfined compressive strength increases slightly with total suction. The failure envelope obtained from the unconfined compression tests is essentially linear with a slope of +0.02 degrees.

The residual suction for the silty soil was approximately 200 kPa from the soil-water characteristic curve (Fig. 2). All compacted silty specimens were prepared at the residual state of unsaturation. The entire failure envelope is composed of three segments as follows: a linear segment at low suctions, a curvilinear segment at intermediate suctions, and horizontal line at high suctions.

5 DISCUSSIONS

The change of shear strength of an unsaturated silty soil is related to the area of contract of water in the soil particles. An unsaturated soil is considered to have four phases: solid, air, water, and contractile skin (the air-water interface). The contractile skin exists like a rubber membrane between soil particles. The surface tension on the contractile skin pulls the particles together providing additional strength to an unsaturated soil. Vanapalli et al (1996) stated that the changing of shear strength in unsaturated soil is related to the area of water. Cui and Delage (1993) emphasized that suction has an important effect on shear strength, stiffening, and softening of the soils. At a high suction the general appearance of the deviator stress versus axial strain curve is quite different with that at low suctions. Vanapalli et al (1996) stated as follows: "The shear strength of an unsaturated soil may remain relatively constant, increase or decrease beyond the residual state. There are no data available to show the soil-water characteristic curve and experimental shear strength data to support and explain the shear strength behavior beyond the residual state of unsaturation".

The non-linear and horizontal envelope obtained from tests can be related to the soil-water characteristic curve. In the boundary effect stage, all soil pores are filled with water. At lower values of matric suction, the pore-water pressure acts directly to increase the effective stress contributing to shear strength. Below the air entry value, the silty soil is saturated and the value of ϕ^b is equal to the value of ϕ'. When the soil starts to desaturate in the transition stage, the amount of water around the soil particle contacts reduces. The discontinuous water menisci area of contact with the soil particles becomes a water menisci area. The amount of water in the soil develops a curved air-water interface in the unsaturated soil. There is a non-linear increase in shear strength in the transition stage. After soil suction exceed the residual suction of the silty soil, the amount of water remaining in the silty soil is very small, and the water phase is also easily disrupted. It can be observed that there is little water remaining in the soil pores when the soil reaches the residual state. In the residual stage, the amount of water is very small and the shear resistances between particles remains at a relatively constant value for a large range of suctions.

6 CONCLUSIONS

The failure shear strength envelope for a silty soil over its entire range of soil suctions is composed of three segments; namely, a linear segment with an angle, ϕ', a curvilinear segment, and horizontal segment. The extent of the contribution of soil suction to shear strength is related to the soil-water characteristic curve. After soil suction exceed the residual suction of the soil, the amount of water remaining is very small. In residual state, even if a high total suction is applied, the shear resistances between the soil particles changes very little. Beyond the residual suction conditions, the shear strength of an unsaturated soil remains relatively constant.

REFERENCES

Cui, Y.T. and Delage, P., 1993, On the elasto-plastic behavior of an unsaturated silt, *In Unsaturated Soils. Edited by Houston, S.L. and Wray, K, New York, NY, American Society of Civil Engineers*, pp. 115-126.

Escario, V. and Juca, J.F.T., 1989, Strength and deformation of partly saturated soils, *Proceedings of the 12th International Conference on Soil Mechanics and Foundation Engineering*, Rio de Janeiro, Vol. 1, pp. 43-46.

Fredlund, D.G., Morgenstern, N.R., and Widger, R.A., 1978, The shear strength of unsaturated soils, *Canadian Geotechnical Journal*, Vol. 15, No. 3, pp. 313-321.

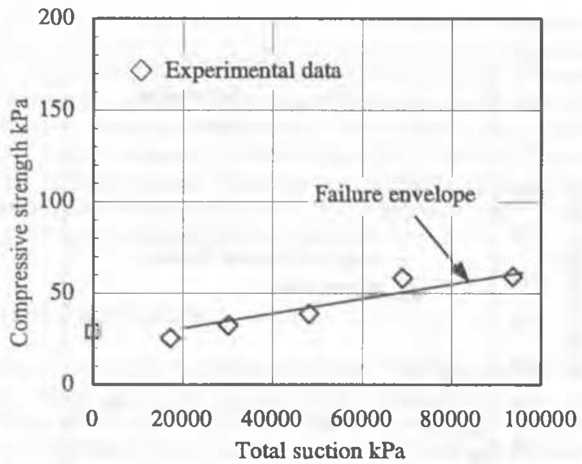

Figure 4. Relationship between unconfined compressive strength and total suction.

Fredlund, D.G. and Rahardjo, H., 1988, State-of-development in the measurement of soil suction, *Proceedings of the International Conference on Engineering Problems of Regional Soils*, Beijing China, pp. 582-588.

Fredlund, D.G. and Rahardjo, H., 1993, An overview of unsaturated soil behaviour, Unsaturated Soils, *Proceedings of sessions sponsored by the Subcommittee on Unsaturated Soils, American Society of Civil Engineers*, pp. 1-31.

Gan, J-K.M. and Fredlund, D.G., 1988, Multistage direct shear testing of unsaturated soils, *American Society of Testing and Materials, Geotechnical Testing Journal, GTJODJ*, Vol. 11, No. 2, pp. 132-138.

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*, 33, pp. 379-392.

Vanapalli, S.K. and Fredlund, D.G., 1999, Empirical procedures to predict the shear strength of unsaturated soils, *Proceedings of the 11th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering*, Seoul Korea, Vol. 1, pp. 93-96.

White, N.F., Duke, H.R., Sunada, D.K., 1970, Physics of desaturation in porous materials, *Journal of the Irrigation and drainage division, Proceedings of the American Society of Civil Engineers*, No. IR2, pp. 165-191.