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Relationship between Shear Strength and Soil Water Characteristic Curve of an Unsaturated Granitic Residual Soil

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ABSTRACT

The three shear strength parameters that are required to define a failure envelope of an unsaturated soil are c' (apparent cohesion), ϕ' (effective angle of friction), and ϕ^b (shear strength change with change in matric suction). A soil-water characteristic curve (SWCC) that relates the water content of a soil to matric suction is another important relationship in unsaturated soil mechanics. The SWCC essentially shows the ability of an unsaturated soil to retain water under various matric suctions. It has a similar role as the consolidation curve of a saturated soil that relates void ratio or water content to effective stress. The SWCC of a soil dictates the manner by which the permeability, shear strength and volume change of the soil will behave at different matric suctions upon drying and wetting. Since water can only flow through the water-filled pores, the SWCC therefore, essentially indicates the space available for the water to flow through the soil at various matric suctions. This paper describes a study on the shear strength-SWCC relationship that was carried out on an unsaturated granitic residual soil. It is observed that the failure envelope of an unsaturated soil is non-linear due to the non-linear soil water characteristic curve (SWCC). At low matric suctions, where the suction is lower than the air-entry value of the soil, the soil is at or near saturation condition and behave as though it is saturated. Consequently an increase in matric suction produces the same increase in shear strength as does an increase in net normal stress. However, at matric suctions higher than the air-entry value of the soil (> 200 kPa), the soil starts to desaturate. The increase in shear strength with respect to matric suction becomes less than the increase with respect to the net normal stress.

Keywords: Matric suction, shear strength, soil water characteristic curve, unsaturated soil mechanics

INTRODUCTION

The microclimatic conditions in an area are the main factors causing the soils to be unsaturated. Therefore, unsaturated soils or soils with negative pore-water pressures can occur in essentially any geological rock type or climatic environment, such as residual soil, a lacustrine deposit, and soils in arid and semi arid areas with deep ground water table. In Malaysia, residual soil over granite and sedimentary rocks occur extensively, i.e. cover more than 80% of the land area. Yet, not much research work has been carried out on these materials. The situation is even worst in the case of unsaturated residual soils.

Tropical residual soils have some unique characteristics related to their composition and the environment in which they develop. Their strength and permeability are likely to be greater than those of temperate zone soils with comparable liquid limits (Ali and Rahardjo, 2004). Most classical concepts related to soil properties and soil behavior have been developed for temperate zone soils, and there has been difficulty in accurately modeling procedures and conditions to which residual soils are subjected. Engineers appear to be slowly recognizing that residual soils are generally soils with negative in situ pore-water pressures, and that much of the unusual behavior exhibited during laboratory testing is related to a matric suction change in the soil (Fredlund and Rahardjo, 1985, 1993). There is the need for reliable engineering design associated with residual soils (Ali and Rahardjo, 2004).

When the degree of saturation of a soil is greater than about 85%, saturated soil mechanics principles can be applied. However, when the degree of saturation is less than 85%, it becomes necessary to apply unsaturated soil mechanics principles (Fredlund and Rahardjo, 1987). The transfer of theory from saturated soil mechanics to unsaturated soil mechanics and *vice versa* is possible through the use of stress state variables. Stress state variables define the stress condition in a soil and allow the transfer of theory between saturated and unsaturated soil mechanics. The stress state variables for unsaturated soils are net normal stress $(\sigma-u_a)$ and matric suction (u_a-u_w), where s is the total stress, u_a is the pore-air pressure and u_w is the pore-water pressure. The stress state in an unsaturated soil can be represented by two independent stress tensors as (Fredlund and Morgenstern, 1977):

$$\begin{bmatrix} (\sigma_x - u_a) & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & (\sigma_y - u_a) & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & (\sigma_y - u_a) \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} (u_a - u_w) & 0 & 0 \\ 0 & (u_a - u_w) & 0 \\ 0 & 0 & (u_a - u_w) \end{bmatrix} \tag{2}$$

where, σ_x, σ_y, σ_z in Equation 1 are the total normal stresses in the *x*-, *y*-, and *z*-directions, respectively; and τ_{xy}, τ_{yx}, τ_{xz}, τ_{zx}, τ_{zy} and τ_{yz} are the shear stresses.

In term of shear strength, there are three shear strength parameters that are required to define a failure envelope of an unsaturated soil, which is an extended form of the Mohr-Coulomb equation (Fredlund *et al.*, 1978). They are c' (apparent cohesion), ϕ' (effective angle of friction), and ϕ^b (shear strength change with change in matric suction).

A soil-water characteristic curve (SWCC) that relates the water content of a soil to matric suction is another important relationship for unsaturated soil mechanics. The SWCC essentially shows the ability of an unsaturated soil to retain water under various matric suctions. It has a similar role as the consolidation curve of a saturated soil that relates void ratio or water content to effective stress. The SWCC of a soil dictates the manner in which the permeability, shear strength and volume change of the soil will behave at different matric suctions upon drying and wetting (Fredlund and Rahardjo, 1993). Since water can only flow through the water-filled pores, the SWCC therefore, essentially indicates the space available for the water to flow through the soil at various matric suctions.

This paper describes a study on the shear strength-SWCC relationship that has been carried out on an unsaturated granitic residual soil.

TEST EQUIPMENTS AND MODIFICATION

A series of laboratory direct shear test with fixed suction were performed to see if the modified apparatus is suitable for testing the shear strength of unsaturated residual soils; to see if the results obtained comply with the extended Mohr Coulomb failure criterion of Fredlund and Morgenstern (1977), as well as for comparison with the results of other similar studies on unsaturated residual soils.

Fig. 1 shows an ordinary shear box that has been modified to apply matric suction to the soil samples. Suction is applied by controlling the pore air and pore water pressures. The direct shear box is placed in a special fabricated galvanized steel air chamber as shown in *Fig. 1.* A 15 bar high air entry disc is placed at the lower block of the direct shear box. The high air entry disc is used to separate soil samples with the water compartment underneath.

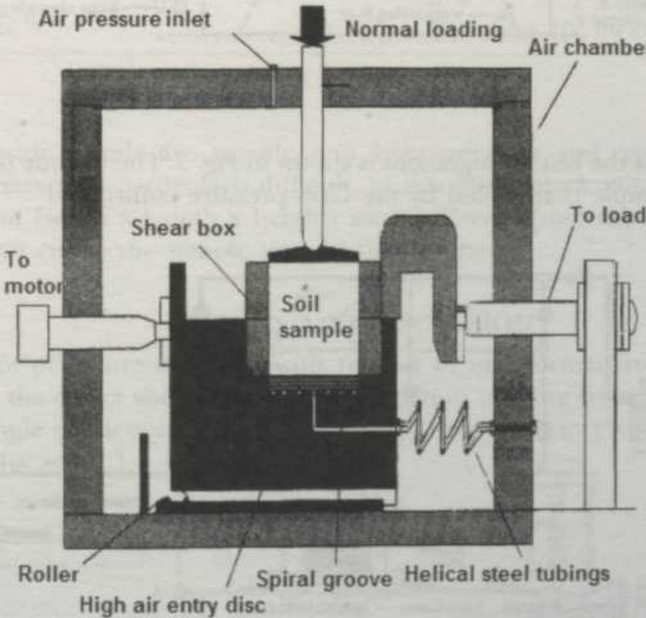

Fig. 1: Modified direct shear apparatus

The total normal stress, σ, is applied vertically to the soil specimen through a loading ram as in the conventional shear box tests. However in this case, the uplift pressure of the air in the air chamber on the loading ram has to be taken into account.

In order to study the soil water characteristic curve of an unsaturated residual soil, the conventional Rowe Cell is modified and used together with the GDS pressure controllers, using the principles of the pressure plate or axis translation technique (Hilf, 1956) for the application of suction. The modification involved removal of the rubber membrane from the cell top, detachment of the side drainage porous layer, blocking of drainage outlet and the fabrication of a completely new base to include the seating for high air-entry ceramic disc and spiral grooved compartment for flushing the diffused air from below the disc, as shown in *Fig. 2.*

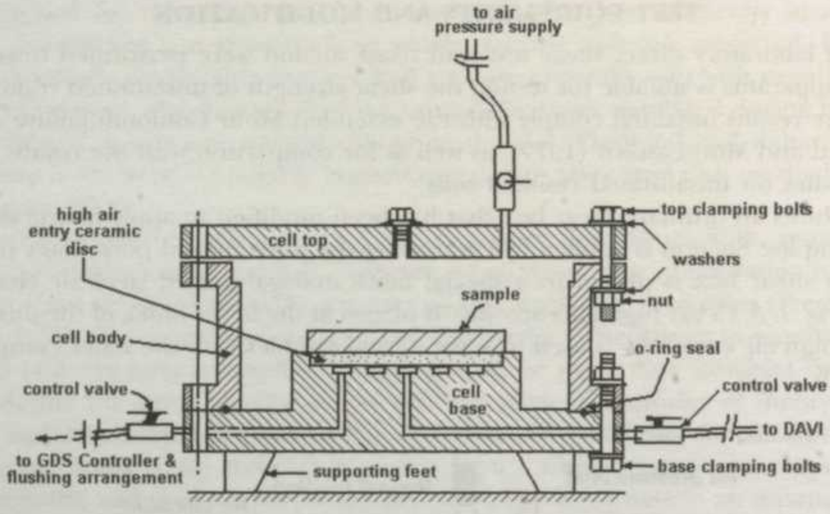

Fig. 2: Modified Rowe cell

The schematic of the test arrangement is shown in *Fig. 3.* The volume of water flowing in or out of the sample is recorded by the GDS pressure controller.

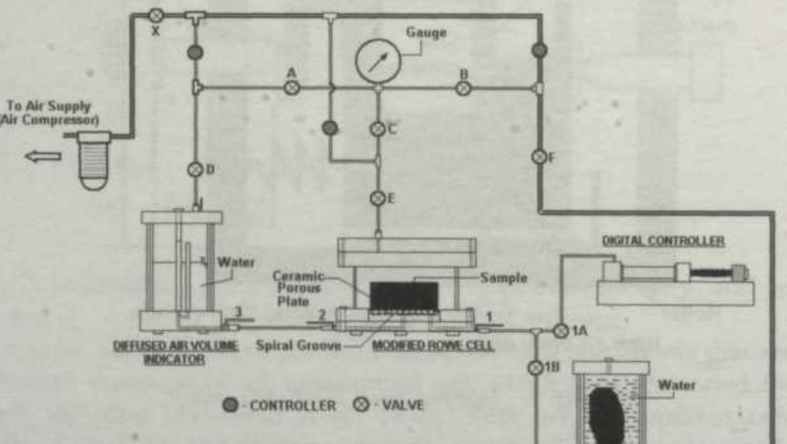

Fig. 3: Schematic arrangement of test setup using modified Rowe cell

SOIL SAMPLE

The soil samples used is this study were obtained from a cut slope at KM 31 of the Kuala Lumpur-Karak Highway. These were residual soils of weathering grade VI, according to the commonly used classification system of Little (1969) that had been formed over porphyritic biotite granite bedrock commonly found in Peninsular Malaysia (Raj, 1985). Table 1 summarizes the basic engineering properties of the soil samples.

TABLE 1
Physical and index properties of the soil sample

Properties	
Weathering grade	VI
Description	Yellowish brown sandy silty clay
Natural water content	22.9 – 27.3%
Liquid limit	95%
Plastic limit	45%
Specific Gravity	2.68
Clay mineral	kaolinite
Particle size distribution:	
Gravel	1.7%
Sand	47%
Silt	11.3%
Clay	40%
Permeability, k	2.5 – 4.1 x 10^8 m/s

Tropical residual soils are usually non homogeneous and anisotrophic, making representative sampling particularly difficult. In this study, block samples measuring 200 x 200 x 200 mm (width x length x height) were collected from the site in metal boxes. These were then cut to the sample sizes in the laboratory.

RESULTS AND DISCUSSION

Fig. 4 show plot of failure envelope with respect to net normal stress plane ($\sigma_n - u_a$) obtained from the direct shear test with fixed suction ranging from 50 to 350 kPa. The soil effective angle of friction ø' is found to range from 20.3° to 29.9° with an average ø' angle of 24.6° (ø' ≈ 25°).

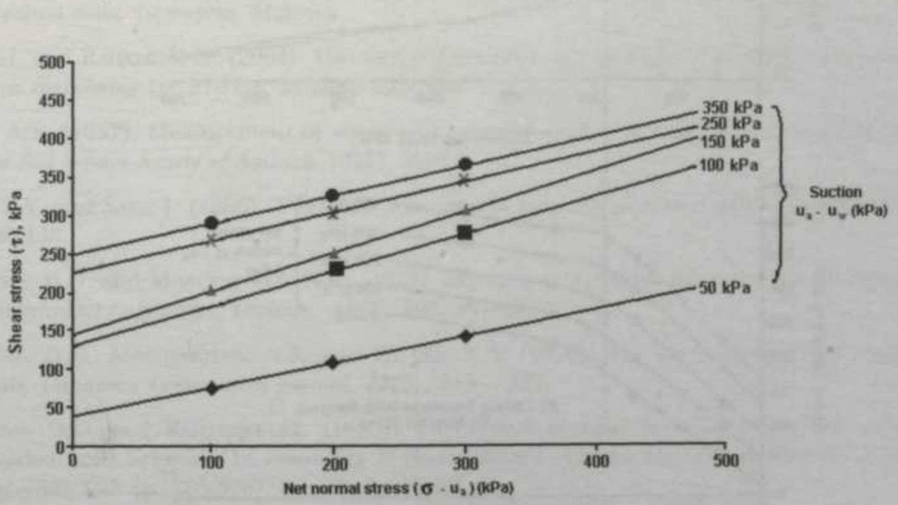

Fig. 4: Failure envelopes with respect to net normal stress, ($\sigma - u_a$) for test with fixed suction

Theoretically ø' should not vary too much (Fredlund *et al.*, 1978). In other words the lines for different values of suction, (u_a-u_w), should be roughly parallel. However, Escario and Saez (1986), Gan and Fredlund (1988) and Abdullah *et al.* (1994) in their research found that the lines showed a tendency for slight divergence at increasing loads, which appears to be in agreement with this study.

This certainly proves that soil suction does play a role towards increasing the shear strength of a soil, and also verifies the unsaturated soil mechanics theory (Fredlund and Morgenstern, 1977; Fredlund *et al.*, 1978: Fredlund and Rahardjo, 1993).

Fig. 5 shows of failure envelope with respect to the matric suction $(u_a - u_w)$ plane. Also plotted is the soil water characteristic curve (SWCC). The non-linearity of the failure envelope of unsaturated soil as reported by earlier studies (Escario and Saez, 1986; Gan and Fredlund, 1988; Abdullah *et al.*, 1994) is evident in this plot. This is due to the non-linear soil water characteristic curve (*Fig. 5a*).

At low matric suctions, where the suction is lower than the air-entry value of the soil, the soil is at or near saturation condition and the air phase consists of a few occluded bubbles (Corey, 1957). The soil would be expected to behave as though it was saturated. In other words the negative pore-water pressure acts throughout the predominantly water filled pores as in the saturated soil condition. Consequently an increase in matric suction produces the same increase in shear strength as does an increase in net normal stress. As a result, the same values are obtained for ϕ' and ϕ^b. ϕ^b is defined as change in shear strength with change in suction, that is the angle of the second portion of the failure envelopes.

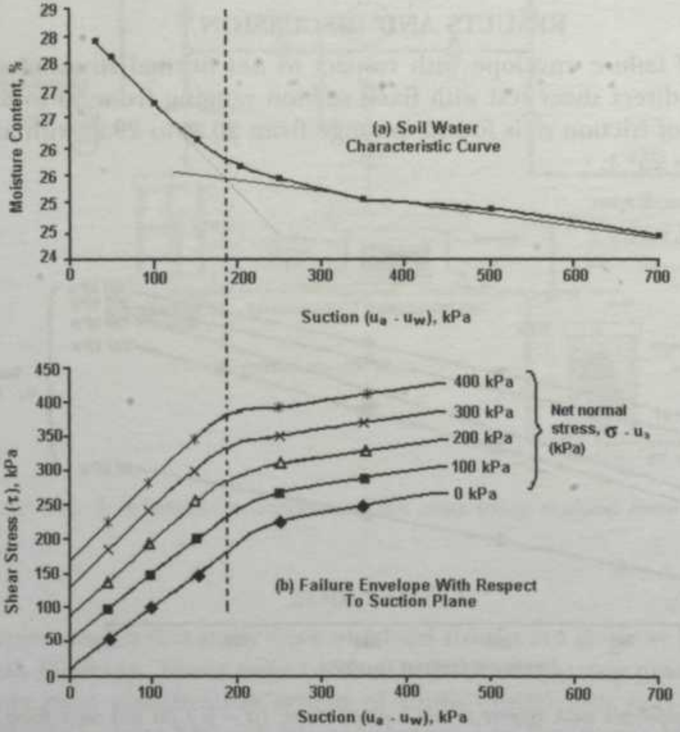

Fig. 5: Relationship between soil-water characteristic curve and shear strength

At matric suctions higher than the air-entry value of the soil (approximately > 200 kPa), the soil starts to desaturate. The negative pore-water pressure does not act throughout the entire pores as in the saturated soil condition. Therefore, the contribution of matric suction towards the strength of the soil is less than the contribution of the net normal stress at the same stress level. In other words the increase in shear strength with respect to matric suction is less than the increase with respect to net normal stress. As a result, the ϕ^b value becomes less than ϕ' at high matric suctions as observed in *Fig. 5.* The value of ϕ^b obtained is the range of 11.6 to 13.1° which an average value of 12, which is much less than the value ϕ' ($\phi' \approx 25°$).

CONCLUSIONS

From the results of this study, the following conclusion can de drawn with regards to the shear strength, matric suction and soil water characteristics curve (SWCC) of unsaturated residual soil.

Soil suction does play a role towards increasing the shear strength of an unsaturated soil.

The non-linearity of the failure envelope of unsaturated soil is due to the due to the non-linear soil water characteristic curve (SWCC).

At low matric suctions, where the suction is lower than the air-entry value of the soil, the soil is at or near saturation condition and behave as though it was saturated. Consequently an increase in matric suction produces the same increase in shear strength as does an increase in net normal stress.

At matric suctions higher than the air-entry value of the soil (> 200 kPa), the soil starts to desaturate. The increase in shear strength with respect to matric suction is then becomes less than the increase with respect to the net normal stress.

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