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Total stress ratio and shear strength parameters for an unsaturated compacted soil

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ABSTRACT: Unsaturated natural soils and artificially compacted soils near the ground surface are commonly overconsolidated due to environmental changes. Defining the overconsolidation ratio with respect to an unsaturated soil is difficult. In this study, a total stress ratio, *TSR*, is suggested which is the static compaction pressure, divided by the current confining pressure. The laboratory tests were performed on an unsaturated compacted soil using a modified direct shear apparatus. This paper presents data on the shear strength parameters, ϕ', ϕ^b and c' for a compacted unsaturated soil with a total stress ratio, *TSR*, of 1.0. The change in shear strength of an unsaturated soil, due to matric suction can be related to the soil-water characteristic curve. Several models for predicting of the shear strength of an unsaturated soil are proposed in geotechnical literature. Measured shear strength with respect to matric suction was compared with the predicted shear strength by using a soil-water characteristic curve model

1 INTRODUCTION

Geological deposition, erosion, drying and wetting all contributes to the stress history of a soil profile. Unsaturated soils near the ground surface and artificially compacted unsaturated soils are commonly overconsolidated due to changes in the environment. It is necessary for geotechnical engineers to know the stress history of *in situ* soils. The overconsolidation ratio, *OCR*, has been used in geotechnical engineering as an expression of the stress history for saturated soils. It is difficult to find a comparable equation to represent the stress history for natural unsaturated soils and compacted unsaturated soils.

The stress state variables for unsaturated soils consist of the net total stress, $(\sigma - u_a)$, and matric suction, $(u_a - u_w)$, where: σ is the total stress, u_a is the pore-air pressure and u_w is the pore-water pressure. *In situ*, unsaturated soils have a negative pore-water pressure. Compacted soil structures (i.e., embankment) are also in an unsaturated condition with negative pore-water pressures. Changes in negative pore-water pressure are equal to changes in matric suction when the pore-air pressure is atmospheric. The net total stress state, generally remain essentially constant and primarily related to the weight of the overlying soil.

2 PURPOSE OF THIS STUDY

An overconsolidated ratio for compacted, unsaturated soils and natural unsaturated soils has not been clearly established. In this study, a total stress ratio, *TSR*, is suggested to quantify the stress history of a compacted unsaturated soil subjected to a static compaction pressure. The total stress ratio, *TSR*, is defined as:

$$TSR = \frac{P_{comp}}{(\sigma_n - u_a)} \tag{2.1}$$

where: $(\sigma_n - u_a)$ = current confining pressure, P_{comp} = static compaction pressure, σ_n = total stress, and u_a = pore-air pressure.

As the total stress ratio, *TSR*, does not include the matric suction in equation (2.1), the total stress ratio does not completely represent the stress history of a compacted unsaturated soil. The study examines the relationship between matric suction and the direct shear strength of a compacted unsaturated soil with a total stress ratio, *TSR*, equal to 1. Shear tests on a compacted unsaturated soil were performed using a modified direct shear apparatus. The stress history of soil specimens is known by the definition of the total stress ratio, *TSR*.

Soil-water characteristic curve is related to the shear strength of an unsaturated soil through matric suction. An empirical, analytical model from the research literature, is used to predict the shear strength in terms of matric suction. This study measured changes in water content of a compacted soil due to matric suction in order to define the soil-water characteristic curve. The soil-water characteristic curve corresponding to a wide range of matric suctions is used in the proposed empirical model. The results of the predicted the shear strength, using the model based on the soil-water characteristic curve, are compared to the experimental results for a compacted unsaturated soil.

3 SOIL AND TESTING PROGRAM

This test program focuses on direct shear strength data on an unsaturated soil subjected to a static compaction pressure. The soil-water characteristic curve of the soil was measured using both a conventional pressure plate apparatus and vapor equilibrium technique (i.e., desiccation tests).

3.1 *Soil material and apparatus*

A silty soil was used in this test program. The silty soil is non plastic with a relatively uniform grain size distribution. The soil specimens were subjected to a static compaction pressure and each specimen had a diameter of 60 mm and a height of 51.3 mm, as well as a water content of 13 %.

A modified direct shear apparatus was used in the test program. The apparatus was similar in design to that used by

Table 1. Measured shear strength with various stress states

Compaction pressure (kPa)	Confining pressure (kPa)	Measured matric suction at applied compaction pressure (kPa)	Applied matric suction (kPa)	Shear strength (kPa)
30	30	27.1	100	96.5
30	30	27.1	200	160.1
30	30	27.1	300	207.4
30	30	27.1	400	244.5
60	60	28.9	100	108.9
60	60	28.9	200	163.6
60	60	28.9	300	213.8
60	60	28.9	400	265.3
100	100	30.1	100	122
100	100	30.1	200	185
100	100	30.1	300	216
100	100	30.1	400	288
200	200	31.5	100	163.6
200	200	31.5	200	218.9
200	200	31.5	300	285.4
200	200	31.5	400	324.1
300	300	32.1	100	181.1
300	300	32.1	200	249.3
300	300	32.1	300	312.9
400	400	32.7	100	236.4
400	400	32.7	200	273.9

Escario (1980) and Gan and Fredlund (1988). Gan and Fredlund (1988) detailed the design concepts of a modified direct shear apparatus, as well as the necessary modifications for the direct shear apparatus.

The direct shear box was completely enclosed in a pressure chamber in order to elevate the ambient air pressure during the test. The soil specimens installed in the shear box were circular in shape. The independent control of both the pore-air pressure and the pore-water pressure required the use of a high air-entry ceramic disk for the unsaturated soil specimens. The air-entry value of the ceramic disk on the bottom portion of the lower shear box was 500 kPa. The ceramic disk was 5 mm in thickness.

3.2 *Test Procedure*

A static compaction pressure was applied to the soil placed into the direct shear ring. The soil specimen was then placed in the direct shear box. A pore-air pressure and normal pressure was applied until the specimen reached equilibrium in a twenty-four hours. The pore-air pressure was applied to the upper surface of the soil specimen. The pore-water pressure remained at atmospheric conditions through the ceramic base plate.

The static compaction pressure ranged from 30 kPa to 400 kPa. A vertical stress was applied to each specimen. The selected vertical stress was equal to static compaction pressure and therefore the total stress ratio was 1.0. The matric suction in the compacted soil was measured during static compaction of the soil specimen. A designated matric suction was then applied to the soil specimen prior to the application of a shearing force while allowing drainage.

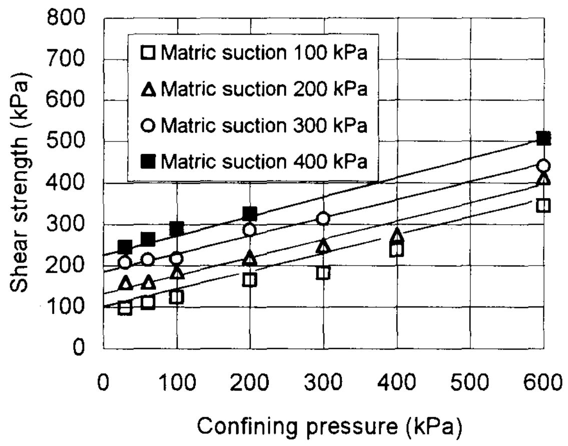

Fig. 1. Relationship between confining pressure and shear strength for the silty soil

4 TEST RESULTS

4.1 *Shear strength and strength parameters*

Direct shear strength data for the compacted unsaturated soil with a total stress ratio, *TSR*, of 1 are shown in Table 1. The relationship between confining pressure and shear strength at various matric suctions is shown in Fig. 1. The shear strength of the compacted soil shows an increase due to an increase in matric suction. The shear strength increases with confining pressure. The failure envelope for an unsaturated soil can be written in a linear form. Fredlund, Morgenstren and Widger (1978) presented the following linear failure equation.

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \qquad (4.1)$$

where: τ = shear strength, c' = effective cohesion intercept, σ_n = total normal stress, ϕ' = effective angle of internal friction with respect to net confining pressure, u_a = pore-air pressure, u_w = pore-water pressure, ϕ^b = angle of internal friction with respect to matric suction, $(\sigma_n - u_a)$= confining pressure, and $(u_a - u_w)$= matric suction.

Net confining pressure and matric suction is required to describe the shear strength for an unsaturated soil. The effective angle of internal friction, ϕ', with respect to net confining pressure can be determined from the failure surface in Fig. 1. The effective angle of internal friction is the tangent to the linear failure surface. The relationship between the computed angle of internal friction and matric suction is shown in Fig. 2. The angle of internal friction of the compacted soil is essentially constant with matric suction. The total cohesion, c, can be computed as the intercept of the failure surface versus net confining pressure. The total cohesion, c, includes the effective cohesion, c', and the matric suction component. The total cohesion, c, is plotted against matric suction in Fig. 3. The total cohesion shows a gradual increase with the matric suction. The relationship between matric suction and total cohesion is non linear. When matric suction is near zero, total cohesion versus matric suction is approximately linear. The estimated effective cohesion, c', from the total cohesion versus matric suction curve is essentially zero. The angle of internal friction, ϕ^b, with respect to matric suction decreases with matric suction. The computed ϕ^b angle is 21.8 degrees for the matric suction range from 300 kPa to 400 kPa. The effective angle of internal friction for the soil, ϕ', is 25 degrees.

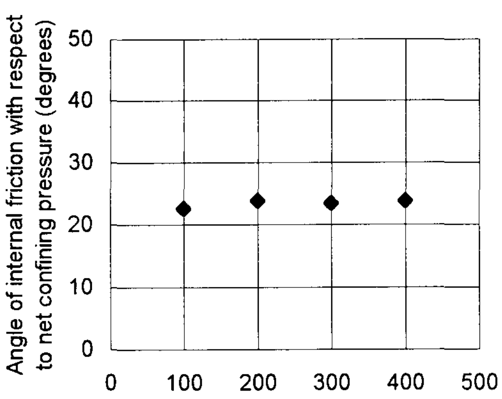

Fig. 2. Relationship between matric suction and the effective angle of internal friction

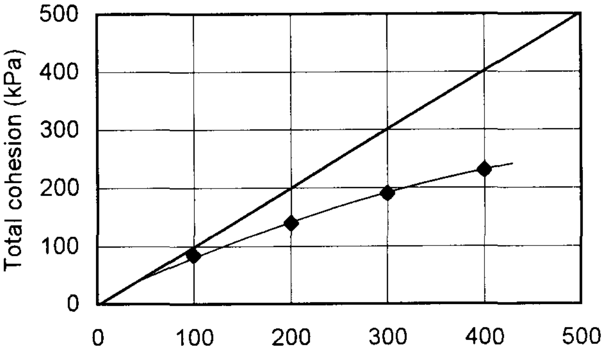

Fig. 3. Relationship between matric suction and total cohesion for the silty soil

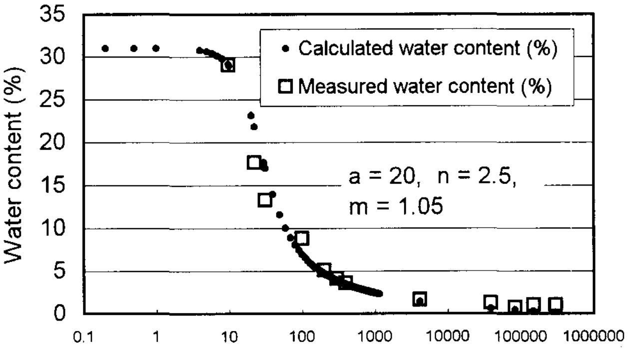

Fig. 4. Soil-water characteristic curve for the silty soil

5 DISCUSSIONS

The constitutive equations for volume change, shear strength and flow for unsaturated soil have been researched in geotechnical literature. Several soil-water characteristic curve models have proposed to empirically predict the permeability function for an unsaturated soil. Fredlund, Xing, Fredlund and Barbour (1996) showed that the soil-water characteristic curve can be empirically related to the shear strength of an unsaturated soil. The proposed model for a reasonable estimate of the soil-water characteristic curve, provided engineers with a means of estimating the shear strength function for an unsaturated soil by using the soil-water characteristic curve and the saturated shear strength parameters. Croney and Coleman (1961) showed that the total suction corresponding to zero water content is slightly below 1,000,000 kPa for all soil types.

Measured water contents are plotted against suction for the silty soil shown in Fig. 4. The soil-water characteristic curve can be described using the equation proposed by Fredlund and Xing (1994).

$$w = w_s \left[1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{1000000}{\psi_r}\right)} \right] \left\{ \frac{1}{\ln\left[e + \left(\frac{\psi}{a}\right)^n \right]} \right\}^m \qquad (5.1)$$

where: ψ is the total soil suction (kPa), e is the natural number, 2.71828, ψ_r is the total suction (kPa) corresponding to the residual water content, a is a soil parameter that is related to the air entry value of the soil (kPa), n is a soil parameter that controls the slope at the inflection point on the soil-water characteristic curve; and m is a soil parameter related to the residual water content of the soil.

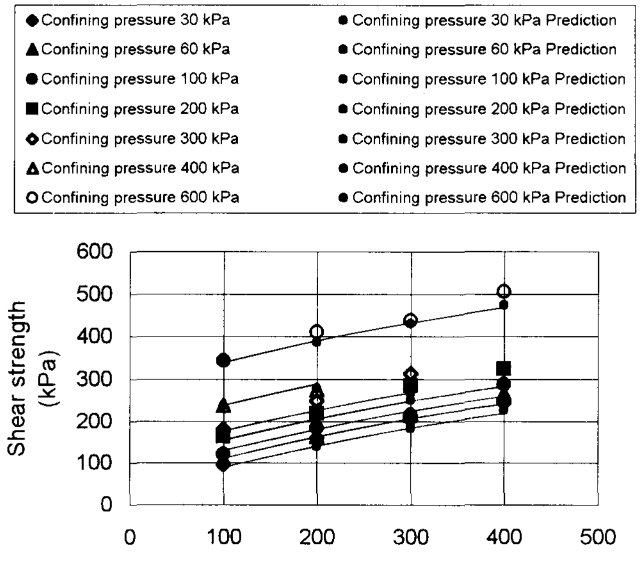

Fig. 5. Comparison of the measured and predicted relationship between matric suction and shear strength

The experimental soil-water characteristic curve data for the compacted, silty soil has a best fit. The soil has an air entry value of 10 kPa, and a suction at residual water content of 500 kPa. Each parameters a , n , and m in equation (5.1) for the soil-water characteristic curve is described in Fig. 4. As the soil is non plastic, the water content beyond the air entry value decreases rapidly with increasing suction.

It is accepted in geotechnical engineering that the shear strength of an unsaturated soil is strongly related to volumetric water content, gravimetric water content or degree of saturation. This study expresses the shear strength of an unsaturated soil due to suction as follows (Fredlund, 1998).

$$\tau_{us} = (u_a - u_w)\Theta^{\kappa} \tan\phi' \qquad (5.2)$$

where: τ_{us} is the shear strength due to the suction, Θ is the normalized volumetric water content, and κ is fitting parameter.

The predicted shear strength with respect to matric suction is shown along with the experimental results in Fig. 5. It can be seen that there is a good correlation between the experimental values for the range of suction and the predicted shear strength when using a value of κ =0.01

CONCLUSIONS

Direct shear tests were performed on a compacted unsaturated soil with a total stress ratio, *TSR* , of 1. Shear strength parameters, ϕ' , ϕ^b and c' were computed. Test results are summarized as follows: The angle of internal friction, ϕ' , is shown to be constant with matric suction. The angle of internal friction, ϕ^b , with respect to matric suction decreases with matric suction. The relationship between total cohesion and matric suction is non linear. I t is shown that the soil-water characteristic curve model can be used to estimate the shear strength function. This paper shows that there is a good correlation between the measure shear strength and predicted shear strength using the proposed model.

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