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Iowa borehole shear testing in unsaturated soil

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ABSTRACT: Research is being conducted at the University of Oklahoma to investigate the influence of matric suction on the soil shear strength parameters determined using the Iowa Borehole Shear Test (BST). This paper presents results of a laboratory study during which the BST was conducted in an unsaturated silty soil compacted within a rigid wall calibration chamber. Results of a field investigation are presented for comparison. Experimental observations indicate that the Mohr-Coulomb strength parameters determined with the BST are greatly affected by the matric suction. The BST friction angle tended to increase with increasing matric suction up to a threshold value, above which the friction angle changed very little. Cohesion intercept values from BSTs, while small, tended to decrease with increasing matric suction.

1 INTRODUCTION

Many parts of the US, and the world in general, consist of arid or semiarid climates where unsaturated soils are predominant. In these areas the application of saturated soil mechanics to the behavior of foundations, slopes or other geotechnical systems will result in unrealistic predictions of behavior. A more realistic approach would be to use a method for predicting expected soil moisture conditions during the design life of a system within the framework of unsaturated soil mechanics. Thus, the moisture dependency of soil properties, such as shear strength and stiffness, is logically incorporated into the design process.

Most of the available methods for approaching unsaturated soil mechanics problems are founded in laboratory determinations of unsaturated soil properties with little emphasis on in situ testing. The complexity involved with constructing equipment and using laboratory testing methods for evaluating unsaturated soil properties, may hinder the use of unsaturated soil strength testing in mainstream geotechical practice. However, the application of unsaturated soil mechanics principles to the interpretation of in situ test methods may have some appeal, since, many of these tests are simple to perform and are becoming more commonplace among consulting firms and other organizations practicing geotechnical engineering.

This paper presents results of research that demonstrate the importance of matric suction on shear strength parameters determined with the BST. A long range goal of this research is to provide a practical framework for interpreting BST results obtained in unsaturated soils, thereby providing a methodology to predict shear strengths under moisture conditions different from those existing at the time of in situ testing.

2 BACKGROUND

2.1 *The Iowa Borehole Shear Test*

The Iowa Borehole Shear Test (BST), developed by Richard Handy and his co-workers (Handy and Fox 1967), can be used in situ to determine the friction angle and cohesion intercept of soil. The BST is the only invasive type in situ test that can produce a Mohr-Coulomb failure envelope by direct determination of forces on the failure plane, and generally, the envelopes are highly linear and reproducible (Lutenegger and Timian 1987).

The BST is a fairly simple test in concept and is analogous to performing a direct shear test on the sidewalls of a borehole. A borehole in which the BST is deployed, is typically 76 mm in diameter and can be readily advanced in most soils using a hand auger, Shelby tube or small solid stem augers, although, minimal disturbance to the borehole wall is desired. Stage testing is conducted by lowering a shear head into the hole and expanding diametrically opposed, curved, serrated shear plates against the borehole wall. During a test, the total normal stress is increased incrementally, and the corresponding shear strength is determined by drawing the shear head upward while measuring the maximum force obtained. The shear and normal stress is calculated using the area of the plates and the shear and normal forces determined during the test. Borehole shear test strength parameters have been found to compare favorably with the results of laboratory determined effective stress-strength parameters for medium to stiff clays below the water table (e.g., Miller and Lutenegger 1994). The test offers considerable advantage over laboratory tests because it can be deployed rapidly. The authors have found that BSTs conducted in unsaturated silt and clay soils, while still producing highly linear and reproducible failure envelopes, have resulted in friction angles and cohesion intercepts that appear to be a function of the matric suction in the soil.

2.2 *Shear Strength of Unsaturated Soil*

According to Fredlund and Rahardjo (1993), unsaturated soil mechanics encompasses soil with negative pore water pressures. The behavior of unsaturated soils depends on the nature of the water and air phases. The air phase can be continuous or can exist as occluded bubbles within the water phase.

It is now widely accepted that the stress state for an unsaturated soil can be adequately described by two independent stress state variables which are the net normal stress and the matric suction. The net normal stress is the difference between the total stress and pore air pressure (σ-u_a) acting in the soil while the matric suction is the difference between the pore air and pore water pressure (u_a-u_w). Two independent stress tensors can be used to fully describe the state of stress at point within a soil mass (Fredlund and Rahardjo 1993). The stress state variables can be used to describe the shear strength of the soil in equation form as follows:

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

where: τ = shear stress at failure on a failure plane, c' = effective cohesion, σ_n = total stress normal to the failure plane, u_a = pore air pressure, ϕ' = angle of internal friction associated with the net normal stress, u_w = pore water pressure, and ϕ^b = angle of internal friction associated with the matric suction. Note, for a saturated soil, u_a = u_w, and c' and ϕ' become effective-stress strength parameters.

Equation (1) describes a plane on a three dimensional plot with shear strength on the vertical axis and matric suction and net normal stress on the horizontal axes. Evidence suggests that this linear representation of shear strength may be applicable over a limited range of suction due to non-linearity in the shear strength-suction relationship (Fredlund and Rahardjo 1993). The evaluation of unsaturated soil shear strength in the laboratory is no trivial matter and requires both control of the pore air and pore water pressures.

Inspection of Eq. (1) reveals that to be able to predict the shear strength, at moisture conditions other than those existing during testing, requires knowledge of the soil-water characteristic behavior, i.e., the relationship between water content and matric suction. It can be seen that for the case where the pore air pressure is zero (atmospheric pressure), an increase in matric suction will result in an increase in the cohesion intercept projected on the net normal stress-shear stress plane; however, the slope of the failure envelope in this same plane remains constant.

2.3 *Calibration Chamber Testing*

Calibration chamber testing involves the creation of soil beds in a laboratory for the purpose of carefully studying soil response to in situ testing or other types of loading. Originally, calibration chambers were developed to calibrate cone penetrometers under simulated field conditions (Holden 1993). The goal of chamber testing is to create consistent, uniform soil beds that can be heavily instrumented to measure soil response to testing under controlled boundary conditions. Calibration chambers offer an excellent way to study the influence of different soil conditions on the test results, because, variables that may otherwise be difficult to determine in situ, such as the state of stress, stress history, or soil homogeneity, are to a large extent under the control of the experimenter. Calibration chambers used to date, incorporate soil test beds with diameters that range from 0.5 to 2 m and heights that range from 0.8 to 2.9 m (Ghionna and Jamiolkowski 1991). The presence of the chamber boundary and the type of boundary have been found to greatly affect in situ test results. Chambers can have rigid or flexible boundaries. Research with sandy and clayey soils indicates that the boundary effects are more severe for rigid, radial boundaries. Ghionna and Jamilokowski (1991) suggest that in silica sand of low to moderate compressibility, a ratio of the chamber to cone penetrometer diameter greater than 30 to 35 is required to avoid boundary effects. Schnaid and Houlsby (1990) found that finite chamber dimensions affected the ultimate cavity pressure determined with a pressuremeter to roughly the same extent that the tip resistance of a cone penetrometer is affected.

While a rigid wall chamber with a diameter of 0.3 m was used in this study, it is believed that the boundary effects were minimal because the BST incorporates a relatively small proportion of soil around the borehole. Furthermore, the stress on the failure plane is known throughout the BST, and the expansion of the shear head results in relatively little lateral deformation.

3.0 RIGID WALL CALIBRATION CHAMBER EXPERIMENTS

3.1 *Experimental Setup*

At the University of Oklahoma, BSTs were conducted in an unsaturated silty soil contained within a rigid wall calibration chamber. Soil beds were prepared by carefully compacting silty soil into 5-cm thick layers to a height of 30 cm. Soil was compacted to a height of 0.3 m using a technique designed to produce a consistent, homogeneous fabric. The target matric suction values were determined from the soil-water characteristic curve. A low plastic silt having a plasticity index of four was selected so that values of matric suction in the soil bed would be within the range that could be measured with a miniature tensiometer inserted near to the test location. To produce a uniform borehole, a 76-mm diameter tube was fixed in the center of the chamber and soil was compacted in the annulus between the center tube and chamber wall.

Following compaction of the soil bed, the bottom of the chamber served as a piston through which a simulated overburden pressure of about 160 kPa was applied via a hydraulic jack. A period of 24 hours was allowed to achieve moisture equilibrium in the soil. Immediately prior to testing, the central tube was carefully removed and the BST was initiated.

3.2 *Experimental Results*

A summary calibration chamber soil data determined for the conditions existing after application of the overburden pressure, just prior to testing is given in Table 1. Borehole Shear Test results are shown in Table 2.

Table 1. Calibration Chamber Soil Test Bed Data.

Test No.	Average Water Content (%)	Void Ratio	Degree of Sat. (%)	Vol. Water Content (%)
1	13.1	0.74	45.1	19.2
2	22.8	0.58	99.8	36.7
3	20.2	0.64	81.2	31.5
4	18.1	0.71	65.2	27.0
5	15.6	0.73	54.9	23.1
6	20.1	0.62	83.0	31.7
7	17.4	0.71	62.8	26.0
8	15.5	0.70	56.8	23.3

Table 2. Borehole Shear Test Results.

Test No.	Matric Suction (kPa)	Friction Angle (deg.)	Cohesion Intercept (kPa)	Coeff. Of Corr., r^2 (%)
1	56	46.0	1.1	0.9994
2	0	32.6	4.6	0.9912
3	10	39.3	6.2	0.9997
4	15	42.8	4.9	0.9991
5	32	44.7	2.3	0.9991
6	*	36.5	3.8	0.9972
7	*	43.8	2.8	0.9965
8	24	43.7	3.6	0.9990

*Tensiometer Failed to Work

In Fig. 1, the BST failure envelopes are plotted. Values of the correlation coefficient, r^2, shown in Table 2, indicate that the envelopes are nearly linear. The data listed in Tables 1 and 2 are shown graphically in Figures 2-4. The soil-water characteristic curve presented in Fig. 2 is typical of silty soil and clearly portrays the dependency of matric suction on the moisture content of the soil.

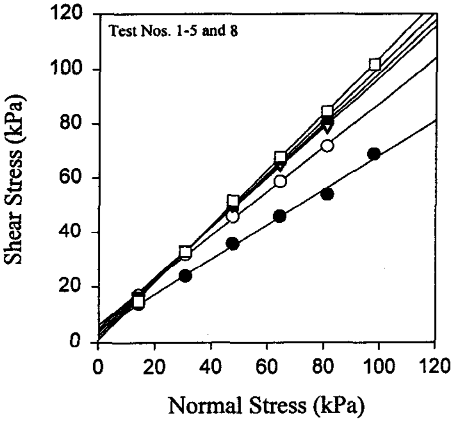

Figure 1. BST Failure Envelopes.

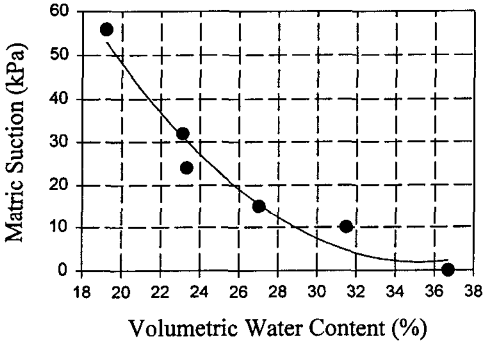

Figure 2. Soil-Water Characteristic Curve.

The relationships between matric suction, volumetric water content, and BST strength parameters are shown in Figs. 3 and 4. Some interesting observations are noted below.

1) The BST friction angle increases rapidly from 33° to 43° as the matric suction increases from zero to 15 kPa. Beyond a matric suction of 15 kPa, the friction angle increases gradually to 46° at a matric suction of 56 kPa. A matric suction of 15 kPa appears to represent a threshold, above which additional increases in matric suction lead to small increases in shear strength.
2) The BST cohesion intercept tends to decrease with increasing matric suction.
3) Both the BST friction angle and cohesion intercept show a significant degree of correlation to the volumetric water content; however, the degree of correlation is greater for the friction angle.

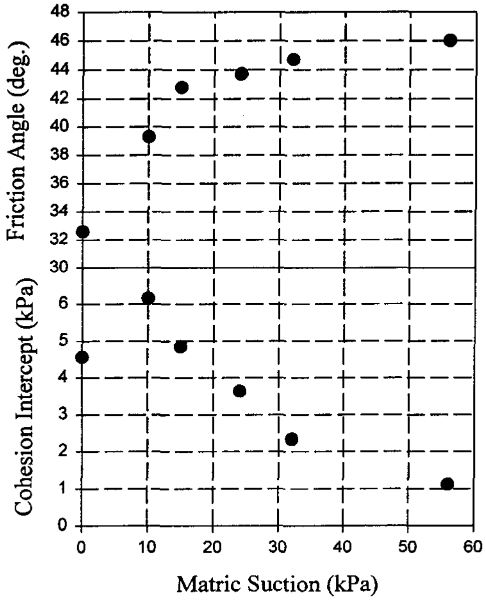

Figure 3. Matric Suction versus BST Strength Parameters.

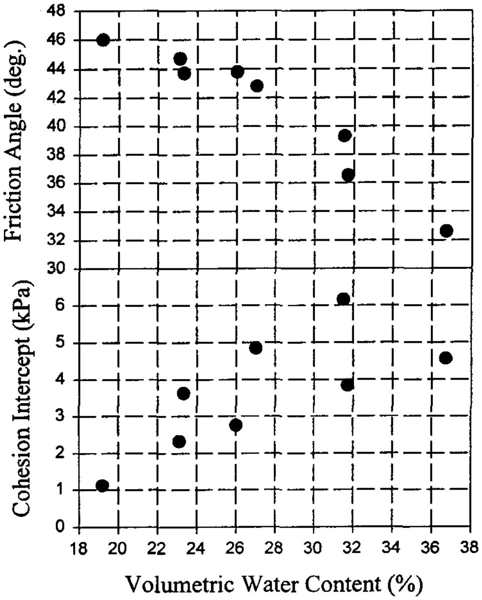

Figure 4. Volumetric Water Content versus BST Strength Parameters.

If the effective stress friction angle and cohesion intercept are assumed to be relatively constant for the range of void ratio investigated, and the pore air pressure is assumed to be equal to atmospheric pressure, then based on Eq. (1), the slope of the BST failure envelopes should be the same, and only the cohesion intercept should increase with increasing matric suction. This is not the case with the data obtained.

The reasons for why the BST friction angle increased as the matric suction increased, are not fully understood, but, possible explanations are offered. First, the effective stress friction angle may have increased as the matric suction increased, due to variations in fabric; however, this seems unlikely given that the void ratio of test beds, shown in Table 1, was higher for higher values of matric suction. Void ratios were higher, for higher values of matric suction, due to the fact that relatively less compression of the test beds occurred under application of the overburden pressure. Second, the matric suction on the failure plane may have changed during application of the normal stress, and/or, during shearing. Thus, the vertical offset of the failure envelope due to the strength contributed by matric suction, may be different for each normal stress increment. Changes in matric suction may have resulted from soil fabric alterations that occurred when the normal stress was increased, or, from volume change tendencies during shearing.

The trend of the friction angle with increasing matric suction shown in Fig. 3 is similar to that seen in the results presented by Mashhour et al. (1996) for triaxial compression tests on highly plastic clayey soil. Under the assumption of constant matric suction during shearing, they offered the following explanation for this phenomena. At low matric suction, water is abundant and acts as a lubricant between soil grains, thus, reducing friction. Drying of the soil has a dual affect on shear strength. It results in an increase of matric suction and an increase of friction due to less lubricant (water) between grains. Hence, the friction angle increases with increasing matric suction. Furthermore, it was suggested that the decrease in the growth rate of the friction angle at higher matric suctions, occurred beyond the residual saturation value. Beyond this value, slight changes in water content result in large changes in matric suction. While this physical explanation, of the phenomena in question, is reasonable, the possibility of other mechanisms such as shear induced changes in matric suction must be explored. For this reason, efforts are currently being made to modify the BST apparatus so that suction can be measured on the face of the shearing plates.

The trend of decreasing BST cohesion intercept with increasing matric suction is opposite to that observed by Mashhour et al. (1996). This result may be due in part to variations in soil fabric, from test to test, that resulted during compaction of the soil under different moisture conditions.

4.0 FIELD OBSERVATIONS

The BST was evaluated for predicting the uplift resistance of four, 80-mm diameter drilled shafts installed in an unsaturated, highly plastic, clayey soil. The prediction method used, was that presented by Lutenegger and Miller (1994). This method incorporates estimates of shear strength parameters from the BST and lateral stresses from the prebored pressuremeter test. Soils at the test site were relatively homogeneous with increasing depth, except with regard to the moisture conditions, which changed from relatively dry to relatively moist with depth. A plot of the water content versus BST strength parameters is shown in Fig. 5. The trend of data is similar to that observed in Fig. 4, where the BST friction angle is seen to decrease and the cohesion intercept is seen to increase, with increasing water content. While the friction angles shown in Fig. 5 are quite high, their use resulted in accurate predictions of the uplift shaft capacity, as shown in Fig. 6. The accuracy of these predictions is likely the result of the fact that the moisture content of the soils, and hence the matric suction, changed very little over the time elapsed between in situ testing and pile load testing.

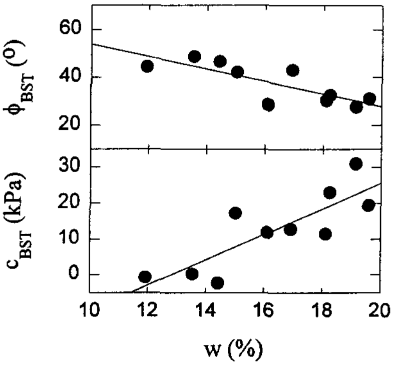

Figure 5. BST Results from the Shaft Uplift Test Research Site.

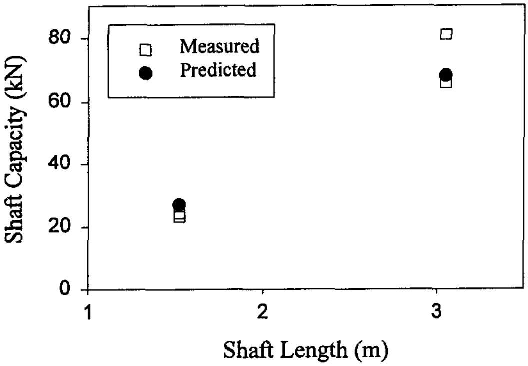

Fig. 6. Uplift Capacity Predictions using BST Results.

The results indicate that the strength parameters determined with the BST, in unsaturated soil, may accurately depict the soil shear strength corresponding to a specific water content.

5 SUMMARY

Results of preliminary calibration chamber studies at the University of Oklahoma indicate that the matric suction has a significant influence on the friction angle and cohesion intercept determined with the BST. The *friction angle tends to increase with* increasing matric suction, while the cohesion intercept tends to decrease. Borehole shear test results from the chamber studies showed strong resemblance to results from actual field tests. Based on limited field testing, the unsaturated, soil strength parameters from the BST appear to be representative of the soil shear strength corresponding to the water content at the time of testing. The relationships between matric suction, volumetric water content, and strength parameters determined with the BST, appear to be predictable, and are similar to those obtained by other researchers using triaxial testing to define the strength.

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