Observations from Borehole Shear Testing in Unsaturated Soil

Gerald A. Miller and Charbel N. Khoury

Abstract. The Iowa Borehole Shear Test (BST) is an in situ device to rapidly determine a Mohr-Coulomb failure envelope in a borehole. Under the right conditions in clayey soils, the failure envelope from the BST may yield a friction angle and cohesion intercept in agreement with effective stress strength parameters determined from laboratory tests. Generally, this occurs when the in situ soil is in a nearly saturated condition and where shear-induced excess pore pressures are minimal, such as for stiff clays. For unsaturated soils, the interpretation of BST results is complicated by the presence of, and unknown variations in, soil suction during the test. This paper presents and discusses the results of BSTs and corresponding suction determinations in unsaturated clayey soils at two test sites. Results indicate that soil suction, in addition to other test variables, has a strong influence on failure envelope. Range of normal stress used in the test was also observed to have a strong influence on the resulting Mohr-Coulomb failure envelopes.

Keywords: borehole shear test, shear strength, suction, unsaturated soil.

1 Introduction and Background

The Iowa Borehole Shear Test (BST) is a rapid and simple in situ test to obtain the Mohr-Coulomb shear strength parameters of soil. It simply involves expanding diametrically opposed, curved, serrated shearing plates to engage the sidewalls of a borehole as shown in Fig. 1. The normal force on the plates is applied in increments and the shearing resistance is determined by measuring the maximum force required to move the shearing plates vertically upward. Dividing the normal and shear forces by the area of the plates provides stresses that can be used to construct

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a failure envelope. The BST has been extensively used in many geotechnical engineering investigations such as slope stability analysis associated with landslides (Handy 1986) and prediction of uplift capacity of drilled shafts (Lutenegger & Miller 1994) among others. A preliminary laboratory study of the BST in unsaturated silty soil within a rigid wall calibration chamber was carried out by Miller et al. (1998). More recently, Khoury & Miller (2006) conducted BST field testing on clayey soil to study the influence of borehole flooding (FBST) on the BST results in unsaturated soil.

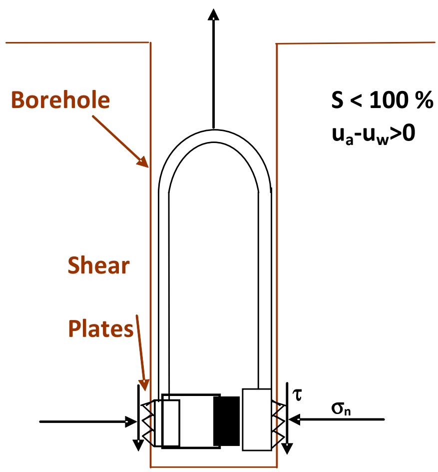

Fig. 1. Schematic of BST.

This paper discusses the effect of initial suction and range of normal stress on the shear strength parameters determined with the BST. In addition to the BSTs, laboratory testing including filter paper and multistage triaxial tests were conducted to determine soil suction and strength parameters, respectively. While this research effort is ongoing, the results presented in this paper have important implications regarding the use and interpretation of the BST strength parameters in stability analyses involving unsaturated soil.

2 Test Sites and Soil Description

Two test sites were chosen for the research located within 10 miles of the University of Oklahoma in the City of Norman; these are the I-35 Interstate Site (I-35), and Westheimer Airport Site (AP). These two sites are relatively close to one another and in the same soil formation. These sites were selected because: 1) they have CH and CL soil layers with relatively uniform composition that allowed for multiple BST tests in each layer, 2) moisture content and suction tends to vary with depth in the profile allowing for BST tests under different conditions, and 3) they were close to campus and have been used in other studies. Characteristic properties of the soil at the I-35 and AP sites are presented in Table 1.

3 Borehole Shear Testing

BST multi-stage tests were conducted in hand-augered boreholes at several depths ranging from 0.46 m (1.5 ft) to 2.29 m (7.5 ft) at an interval of 0.305 m (1 ft). A multi-stage test consists of applying successively higher normal pressures while leaving the shear head in place. This method may produce less accurate strength envelopes if the shear plates are not in good contact with the soil as reported by Handy et al. (1985). However, a number of researchers have observed that the multi-stage BST procedure gives similar results to BST tests involving a “fresh” soil location for each increment of normal stress at a given depth (e.g. Lutenegger & Tierney 1986). Also, Miller et al. (1998) observed that fresh and multistage BST results in unsaturated soil were similar.

4 Results and Discussions

4.1 Suction-Water Content Relationship

In order to assess the BST results, it was first necessary to estimate soil suction present at the time of testing. To accomplish this, thin-walled tube samples were obtained for suction measurement. These tube samples were obtained from boreholes on the same day or within a few days of the borehole shear tests and within several feet of the BST test borings. Soil samples from depths corresponding to the BST test depths were subjected to filter paper testing. The idea was to establish a relationship between the water content of the tube samples and the suction, which could then be used to estimate suction corresponding to water contents of soil samples obtained during the BSTs. This was necessary because water contents in tube samples subjected to filter paper testing were sometimes different than water contents for similar depths during the BSTs.

Data from filter paper tests are presented in Table 1 along with soil properties. The relationship between matric suction and gravimetric water content determined from the filter paper tests showed significant scatter (Fig. 2a). Scatter is attributed to the variation in soil composition at each depth. Thus, a new relationship that incorporates consistency and grain size into the relationship was developed, in which water content values were divided by the Plasticity Index (PI) and the percent passing the number 200 sieve (75 μm openings). The normalized water content shows a strong relationship to matric suction (Fig. 2b). Water content of samples obtained from the borehole immediately prior to a BST were used in conjunction with the best fit equation shown in Fig. 2b to estimate the initial matric suction prior to testing. Values of suction obtained in this way are discussed relative to the results of the BSTs in the following sections.

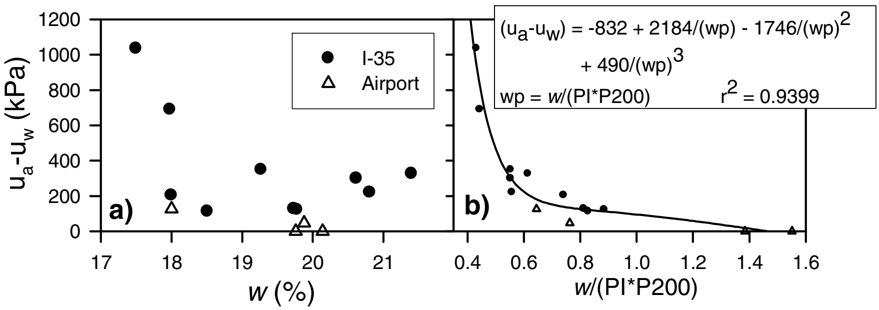

Fig. 2. Suction-water content relationship from Filter Paper Tests: a) Matric Suction versus Gravimetric Water Content and b) Matric Suction versus Water Content Normalized by Plasticity Index and Percent Passing #200 sieve.

Table 1. Filter paper (Suction) test results and soil properties.

Site	Depth (m)	LL (%)	PL (%)	PI (%)	%<2mm (%)	%<#200 P200 (%)	u_a-u_w (kPa)		w (%)	
							B3	B4	B3	B4
	0.76	62	19	43	37	94	1035	689	17.5	18.0
	1.07	56	19	37	38	94	326	348	21.4	19.3
	1.37	56	18	38	42	98	220	298	20.8	20.6
	1.68	40	16	24	41	93	112	121	18.5	19.8
I-35	1.98	41	16	25	47	97	203	126	18.0	19.7
	0.76	52	22	30	39	93	126		18.0	
	1.37	46	15	31	41	98	47		19.9	
	1.98	30	17	13	33	98	0		19.8	
AP	2.29	34	19	15	41	97	0		20.1	

4.2 BST Results for Lower Normal Stress Range

The BST results involving normal stresses in the range of 15 to 100 kPa are presented in Fig. 3. Friction angles (ϕ_{BST}) and cohesion intercepts (c_{BST}) are plotted in this figure against matric suction for both sites. Note that all of the BST tests were of high quality with coefficients of determination (r^2) for the strength envelope close to or greater than 0.99. Some important observations follow from Fig. 3:

1. BST friction angles can be quite high, and were in a range of 17 to 50° for the three sites. Some values are much higher than typical effective stress friction angles from laboratory tests; effective stress friction angles from backpressure saturated triaxial tests at these sites ranged from 17-30°. Some values of BST friction angles that were obtained for lower matric suction are more consistent with drained friction angles.
2. While there is scatter in these plots, there is a clear tendency for increasing BST friction angle with increasing matric suction. This is similar to previous observations by Miller et al. (1998).
3. As shown in Fig. 3, there is a tendency for the BST cohesion intercept to decrease with increasing suction at each site.

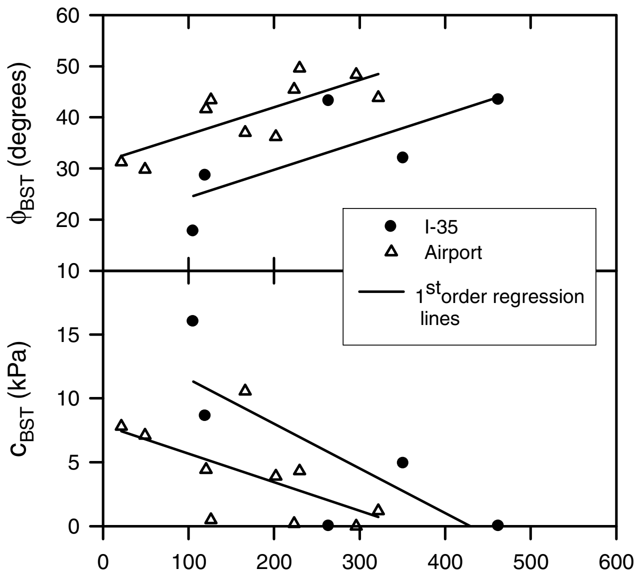

Fig. 3. Strength parameters from BSTs using with normal stresses in the range of 0-120 kPa.

The trend lines in Fig. 3 tend to be different for each site. Other than inaccuracies inherent with using the correlation in Fig. 2b, two factors that may contribute to these differences are the slight disparities in soil properties at each site and variations in suction due to natural wetting and drying cycles at the sites. Some questions naturally arose from the results observed in Fig. 2, which led to research into other factors that may be affecting the BST results from unsaturated soil. Of particular interest was why the BST friction angles were quite large in many cases. Furthermore, the BST results are generally not consistent with unsaturated strength behavior observed during laboratory testing. Laboratory observations from unsaturated strength testing under suction control often show that the friction angle with respect to net normal stress tends to remain constant with increasing suction while the cohesion intercept increases (e.g. Fredlund and Rahardjo 1993). It is not clear why the BST strength parameters vary with suction in the manner observed; however, this may be partly attributed to the fact that suction is not controlled during testing and may actually change during application of net normal stress and shearing. This behavior is the subject of further study.

4.3 BST Results in for Higher Normal Stress Range

Two tests were conducted at the Airport Site (AP) using standard shearing plates with applied normal stresses in the range of 15 to 250 kPa. The standard plates are serrated and have a contact area with the soil of 32.3 cm^2 (5 in^2) per plate. Failure envelopes are presented in Fig. 4. Interestingly, the results obtained showed a nonlinear trend with the failure envelopes becoming flatter at normal stresses above about 75 to 100 kPa. The results were analyzed for the lower and higher stress range using a bilinear failure envelope. The equations are shown in Fig. 4 for the low and high normal stress range. The difference in failure envelopes is significant at lower and higher stress ranges. It may be possible that at higher normal stress levels, the soil in the shearing zone is compressed to such a degree that saturation markedly increases, resulting in a significant decrease in suction. Possibly, this may occur when the preconsolidation stress is exceeded, at which point substantial changes in void ratio and degree of saturation may occur with increasing net normal stress. For comparison, backpressure saturated triaxial compression tests on tube samples obtained at this site between depths of 0.8 and 2 m gave friction angles of 17, 22 and 27 degrees.

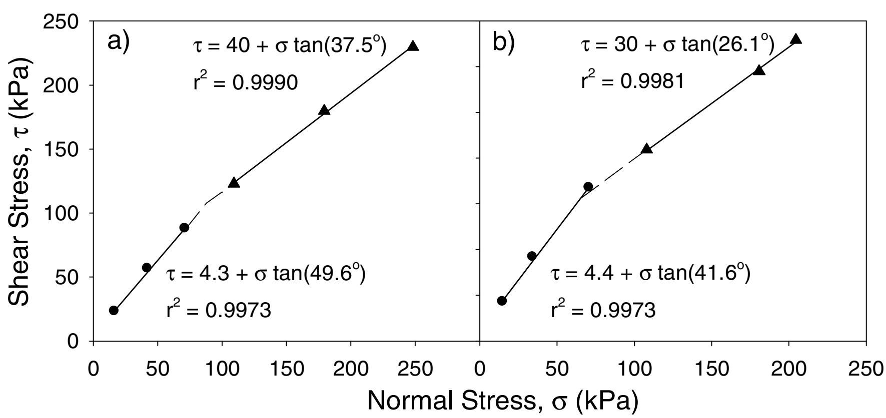

Fig. 4. Results of BSTs at Airport Site Showing Influence of Normal Stress Range at Two Test Depths: a) 0.76 m and b) 1.08 m.

5 Conclusions

The influence of initial suction and normal stress range on Borehole Shear Tests (BST) in unsaturated soil was investigated. Conclusions are summarized as follows:

1. Matric suction can have a significant influence on BST friction angles and cohesion intercepts in unsaturated soil. Generally, the BST friction angle was found to increase and BST cohesion to decrease with increase in suction.
2. For the soils tested in this study, the influence of suction on the BST friction angle was significant when the normal stress during the BST was below 100 kPa. For normal stresses above 100 kPa, the BST friction angles were closer to saturated effective stress strength friction angles determined from backpressure saturated multistage triaxial compression tests. This suggests that BSTs in unsaturated soil should be conducted using a larger range of normal stress in order to estimate effective stress friction angles.

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