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Determination of the shear strength of unsaturated soils using the multistage direct shear test

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ABSTRACT

The determination of the shear strength of unsaturated soils is generally more complicated, time consuming and expensive compared to the determination of the shear strength of saturated soils. Although much research has been done on unsaturated soil testing methods, there is still a strong need to translate these studies into practice. Further studies are needed on practical testing methods that can reduce both the cost of and time associated with shear strength testing of unsaturated soils. This paper presents a comprehensive evaluation of the validity of using the multistage direct shear test as a rapid and practical method to determine the shear strength of unsaturated soils. The laboratory tests were performed using a newly-constructed modified direct shear test apparatus that allows independent control of matric suction, referred to as a suction-controlled multistage direct shear test. Unsaturated shear strength was established using multistage loading over a range of net normal stresses and matric suction values. Shear strength parameters obtained from the multistage tests are compared with those from conventional direct shear tests using multiple soil specimens. Recommendations are given on how to carry out multistage direct shear tests to ensure reliable unsaturated shear strength measurements. The tests were performed on undisturbed soil samples obtained from the riverbank of the lower Roanoke River in eastern North Carolina, USA.

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1. Introduction

A number of studies have been conducted on the experimental determination of shear strength of unsaturated soils (e.g., Fredlund et al., 1978; Escario and Saez, 1986; Rahardjo et al., 1995; Feuerharmel et al., 2005). The fundamental goal of these experimental methods is to establish the shear strength characteristics of unsaturated soils in terms of net normal stress and matric suction. Matric suction is an important parameter that affects the shear strength of unsaturated soils, and is considered to be a component of cohesion in unsaturated soil shear strength (Lu and Likos, 2004). Numerous experimental techniques creating a suction-controlled environment have been proposed to control the effective stress state the test sample is subjected to. For example, osmotic and vapor equilibrium techniques have proven successful to control suction and determine the shear strength of unsaturated soils (e.g., Cui and Delage, 1996; Blatz and Graham, 2000; Boso et al., 2005; Delage and Cui, 2008; Sheng et al., 2009). More widely, the axis translation technique has been successfully employed to control suction as well (e.g., Hilf, 1956; Matyas and Radhakrishna, 1968; Fredlund and Morgenstern, 1977; Aversa and Nicotera, 2002; Sedano et al., 2007). This technique has been applied to the conventional direct shear test, ring shear test, triaxial tests, resonant column test, and true triaxial tests (Ho and Fredlund, 1982; Gan et al., 1988; Hormdee et al., 2005; Cabarkapa and Cuccovillo, 2006; Feuerharmel et al., 2006; Vassallo et al., 2007; Hoyos et al., 2008, 2010).

In addition to the direct determination of the unsaturated shear strength, techniques that relate unsaturated shear strength to the saturated shear strength and the soil–water characteristic curve (SWCC) have also been proposed (e.g., Vanapalli et al., 1996; Vanapalli and Fredlund, 2000). However, in itself, the determination of the SWCC is a time consuming process. Finally, empirical models are also available to estimate unsaturated shear strength (e.g., Fredlund et al., 1996, 1997; Vanapalli and Fredlund, 2000; Vilar, 2006).

The main challenges to the experimental determination of the shear strength of unsaturated soils regardless of the testing technique are: 1) the large number of tests required in establishing the variation of shear strength with matric suction, and 2) the long testing times needed to establish suction equilibrium in soil samples before they can be sheared. Methods for unsaturated shear testing are generally more complicated, more time consuming and more expensive when compared to conventional test methods for saturated soils. Although interest in evaluating unsaturated soil characteristics has increased, more studies are required to generalize the application of each method. As a result, further studies are needed on practical testing

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methods that can reduce the cost and time associated with shear strength testing of unsaturated soils. The multistage direct shear test is a promising laboratory technique that can reduce the time and cost required to determine the shear strength of saturated soils. However, the applicability of the multistage direct shear test for unsaturated soils has not been fully and critically evaluated.

The main objective of the research presented in this paper is to investigate the validity of the multistage direct shear test for saturated and unsaturated soils. This is done by critically evaluating the effects of different tests conditions on the measured shear strength. Experimental data from multistage tests are compared with those obtained from conventional direct shear tests using multiple soil specimens. Based on these comparisons, recommendations are provided for carrying out multistage direct shear tests to ensure reliable shear strength data for unsaturated soils. The study is conducted using undisturbed soils from riverbank soil deposits along the Lower Roanoke River near Scotland Neck, North Carolina, USA. The experimental data are interpreted using the most widely available theories and models for the shear strength of unsaturated soils.

2. Shear strength of unsaturated soils

There are several formulations for quantifying the effects of matric suction on the shear strength of unsaturated soils (Vanapalli and Fredlund, 2000). Most originate from the following effective stress equation for unsaturated soils derived by Bishop (1959):

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \tag{1}$$

where σ = total stress, u_a = pore air pressure, u_w = pore water pressure, and χ = parameter related to matric suction with a value of $\chi = 0$ for dry soils and $\chi = 1$ for saturated soils. This is an extension of Terzaghi's (1943) effective stress equation and accounts for the presence of both gaseous and liquid phases in the voids of the soil. The term $(\sigma - u_a)$ is the net total stress, and $(u_a - u_w) = \psi$ is the matric suction, which is negative since $u_a < u_w$. Although the value of χ is known to be affected by the soil structure, stress changes, and cycles of wetting and drying (Bishop, 1961), the degree of saturation is the dominant factor in determining the matric suction ψ, and ultimately, the effective stress. Suction increases the effective stress, and in turn, the shear strength of unsaturated soils.

Substituting Eq. (1) in the Mohr–Coulomb failure criterion for frictional-cohesive soil:

$$\tau = c' + \sigma_n' \tan\phi' \tag{2}$$

yields:

$$\tau = c' + [(\sigma_n - u_a) + \chi(u_a - u_w)] \tan\phi' \tag{3}$$

where τ = shear strength of unsaturated soil, ϕ' = effective friction angle, and c' = effective cohesion.

Several researchers have shown the difficulty of quantifying the value of χ in Eq. (3) both theoretically and experimentally (Jennings and Burland, 1962; Burland, 1965; Matyas and Radhakrishna, 1968; Fredlund and Morgenstern, 1977). To circumvent this difficulty, Fredlund et al. (1978) proposed a shear strength equation for unsaturated soils with two independent strength parameters corresponding to $(u_a - u_w)$ and $(\sigma_n - u_a)$:

$$\tau = c' + (u_a - u_w) \tan\phi^b + (\sigma_n - u_a) \tan\phi' \tag{4}$$

where ϕ^b= angle of shearing resistance with respect to matric suction.

When a soil is fully saturated, the pore air pressure becomes equal to the pore water pressure, and the matric suction component is eliminated. Then, Eq. (4) reduces to the conventional Mohr–Coulomb shear strength equation for saturated soils (Eq. (2)). For an unsaturated soil, the matric suction ψ and angle ϕ^b are additional parameters that increase the shear strength compared to Eq. (2). Thus, the shear strength of an unsaturated soil can be determined by the parameters ψ and ϕ^b in addition to the saturated shear strength parameters.

The shear strength of an unsaturated soil as function of matric suction ψ can be estimated experimentally. The effective friction angle ϕ' and cohesion c' are determined by conventional direct shear or triaxial tests on saturated soil specimens. Specimens at different degrees of saturation are then tested, and the shear strength determined from each specimen is plotted against matric suction. The slope of the shear strength vs. matric suction failure envelope is the angle of shearing resistance with respect to matric suction ϕ^b. In early studies, the angle ϕ^b was assumed to be constant resulting in a linear variation of shear strength with matric suction. A simple approximation is $\phi^b = \phi'$ (Fredlund and Rahardjo, 1993). However, subsequent experimental studies have shown that $\phi^b \neq \phi'$ for many soils and ϕ^b is not constant but varies nonlinearly with suction i.e., $\phi^b = \phi^b(\psi)$, and, thus, shear strength varies nonlinearly with respect to soil suction (Escario and Saez, 1986; Fredlund et al., 1987; Gan et al., 1988; Wheeler, 1991; Ridley, 1995; Rohm and Vilar, 1995; Feuerharmel et al., 2005). It has been suggested that ϕ' may also be affected by suction changes (Abramento and Carvalho, 1989; Rohm and Vilar, 1995).

One simplifying assumption that has been made is that the unsaturated shear strength vs. matric suction relationship changes bilinearly. That is, ϕ^b is equal to the friction angle ϕ' for matric suction values lower than the air entry value (AEV) of the soil and decreases for matric suction values above the AEV. However, there are also cases where the ϕ^b is larger than ϕ'. While simple, the bilinear relationship does not accurately represent the shear strength vs. matric suction relationship of unsaturated soils.

3. Experimental procedures

The unsaturated shear strength characteristics of riverbank soils as function of the degree of saturation were studied in the laboratory using the multistage direct shear test. The laboratory tests used a newly-constructed modified direct shear test apparatus that allows independent control of matric suction, referred to as a suction-controlled multistage direct shear test. The shear strength was established using multistage loading over a range of net normal stresses and matric suction values.

3.1. Construction of suction-controlled direct shear test equipment

To investigate the relationship between matric suction and shear strength of unsaturated soils, a new direct shear box placed inside a pressure chamber was constructed as shown in Fig. 1. The pressure chamber allows for the control of matric suction over a wide range of values during testing. The pressure chamber is 190 mm wide, 190 mm long and 150 mm high, and the shear box is 90 mm wide, 90 mm long and 55 mm high. The shear box holds a disc-shaped soil specimen with a 63.5 mm diameter and 25 mm thickness. A high air entry ceramic disc (HAECD) with an AEV of either 100 kPa or 300 kPa, manufactured by Soilmoisture Equipment Corp., is placed at the bottom of the soil specimen to provide continuity of the water phase in the soil with the atmosphere. A grooved channel is constructed beneath the HAECD for drainage from the soil sample and to remove diffused air below the HAECD. Both ends of the channel are open to the atmosphere, which makes the pore water pressure of the soil equal to atmospheric pressure without being influenced by the applied air pressure. This setup is also used for injecting water to remove air bubbles. The bottom shear box is seated on a frictionless

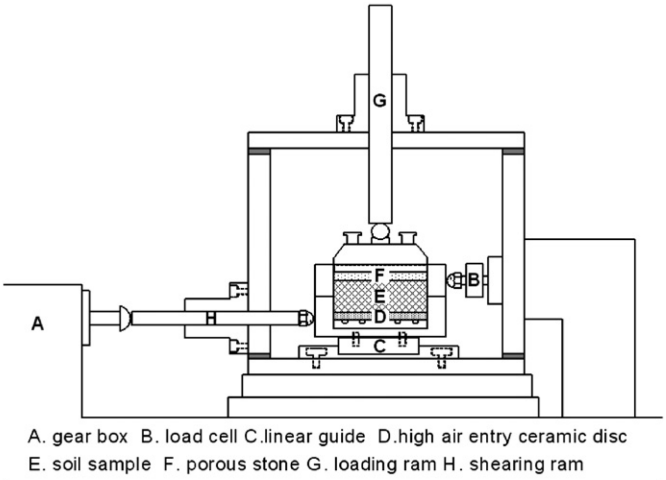

Fig. 1. Schematic diagram of the modified suction-controlled direct shear test apparatus.

linear guide for horizontal shearing, and the top shear box is in contact with a load cell to measure the shear load. Loading and shearing rams are connected through the pressure chamber with O-rings and linear bearings to prevent air from leaking. A pressure transducer and a low profile load cell are placed in the chamber to monitor pressure changes and shear load, respectively (Figure 2). The top plate of the pressure chamber is made of transparent polycarbonate to provide a view into the chamber. The new pressure chamber with the modified shear box can be used in conjunction with a conventional direct shear loading frame with sample height adjustment for shearing ram alignment.

3.2. Multistage direct shear test

Unlike conventional shear strength tests for soils that use several soil specimens, a multistage test uses a single soil specimen and shears the sample in stages with increasing confining stresses. The multistage test is not an ASTM standard method for obtaining total or effective stress parameters, but has been widely used in practice. The multistage test has been adapted to both triaxial and direct shear tests, especially when there are difficulties in sampling and sample preparation. It has been applied to rocks (Kim and Ko, 1979; Tisa and Kovári, 1984), undisturbed submarine soils (Nambiar et al., 1985), undisturbed silty sand (Saeedy and Mollah, 1988), and undisturbed residual soils (Gan et al., 1988). The benefits of the multistage tests are: 1) the effects of sample variability are eliminated, 2) the time required for sample preparation and testing is minimized, and 3) the overall cost for the tests is reduced. As a single sample is used during testing, it is important that the sample be representative of the site of interest.

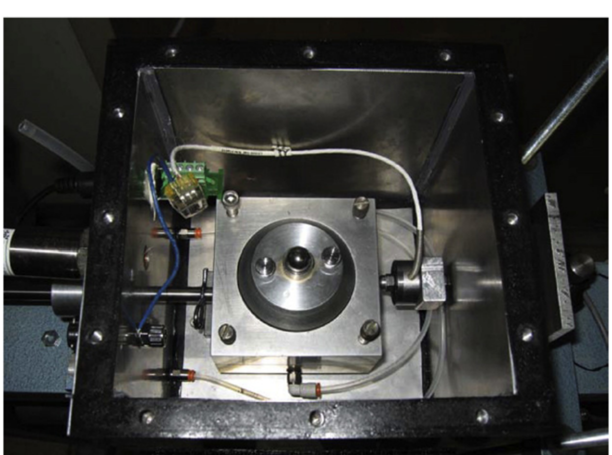

Fig. 2. Details of the modified direct shear test apparatus in a pressure chamber.

Multistage tests were first introduced by Taylor (1951) to measure the shear strength of undisturbed, partially saturated silty clay using both consolidated and unconsolidated, undrained triaxial tests with pore pressure measurements. At each stage, a single soil sample was sheared until failure, followed by an increase in the confining pressure leading to the next stage of shearing. The results were considered satisfactory. However, Taylor noted that multistage tests should be limited to soils that are not sensitive to changes in structure. Kenney and Watson (1961) performed consolidated drained triaxial tests and consolidated undrained triaxial tests with pore pressure measurements on both undisturbed and remolded soils. Their conclusions also supported the benefits and reliability of multistage tests, but did not recommend it for drained compression tests on sensitive soils. Lumb (1964) emphasized the benefits of using multistage triaxial tests on undisturbed residual soils in Hong Kong, mainly decomposed rhyolite and decomposed granite, which have great variation in their properties. He also concluded that the results are practically indistinguishable from conventional tests. Parry and Nadarajah (1973) also performed consolidated undrained multistage triaxial tests for remolded and undisturbed clays, and provided the same conclusion that the errors in results from multistage tests are practically negligible compared to those from single stage tests using multiple specimens. Soranzo (1988) used the multistage unconsolidated undrained and isotropically consolidated undrained triaxial compression tests on natural complex clayey soils, and concluded that the multistage test results are highly comparable to those of conventional triaxial tests.

The multistage loading method is ideally suited for unsaturated soil testing where each single stage requires increased testing time due to the long equilibrium period (Gan and Fredlund, 1988; Huat et al., 2005a; Futai et al., 2006). Ho and Fredlund (1982) measured the shear strength of unsaturated residual soils in Hong Kong with modified triaxial test equipment. The modified equipment was able to control matric suction up to 500 kPa using the axis translation technique. Ho and Fredlund (1982) suggested that the samples should not be sheared excessively during the early stage of loading. The shear strength increased linearly with matric suction, although the measured strength at the last stage was smaller than the projected value determined by the results at lower suctions. It was interpreted as a possible reduction in shear strength due to the multistage test. However, the reduced shear strength was later attributed to the nonlinear matric suction vs. shear strength relationship. A number of studies have shown the feasibility of using multistage tests with triaxial test equipment modified for unsaturated soil tests (Drumright and Nelson, 1995; Rahardjo et al., 1995; Aversa and Nicotera, 2002; Futai and Almeida, 2005; Cabarkapa and Cuccovillo, 2006; Lu and Wu, 2006).

Although the triaxial test is generally more advanced and versatile for research purposes, including being adapted for multistage tests, the direct shear test is preferred for unsaturated soil testing as the drainage path of soil samples in the direct shear test is much shorter than that of the triaxial test, especially for soils with low permeability (Gan et al., 1988). Several researchers have also adapted the direct shear test to unsaturated soils (Escario and Saez, 1986; De Campos and Carrillo, 1995; Boso et al., 2005; Feuerharmel et al., 2005; Hormdee et al., 2005). However, there have been few investigations of the application of the multistage shearing technique to the direct shear test for unsaturated soils (Gan and Fredlund, 1988; Huat et al., 2005b).

4. Experiments

The validity of suction-controlled multistage direct shear test procedures to determine the unsaturated shear strength of riverbank soils is investigated using undisturbed soil samples obtained from the riverbank of the Lower Roanoke River near Scotland Neck, North Carolina in the eastern U.S. The surface soil consists of Quaternary alluvium deposits up to a depth of 7.6 m and Upper Cretaceous sedimentary materials underlying the alluvium soil layer (Weems et al., 2009). This location has been exposed to frequent changes of water surface elevation due to an upstream hydropower dam. It has also undergone extensive levels of riverbank erosion and failure as documented by Hupp et al. (2009).

4.1. Soil samples and physical properties

Undisturbed soil samples for direct shear tests were extruded from Shelby tubes and block soil samples obtained from the study site. Disturbed soil samples were also collected and tested for grain size distribution, Atterberg limits, specific gravity, and classification by the United Soil Classification System (USCS). A representative soil profile of the riverbank, where the soil samples were collected, consists of: silty sand SM (0–0.6 m), low plasticity clay CL (0.6–2.5 m), high plasticity silt MH (2.5–3.8 m), and low plasticity clay CL (3.8–4.5 m). In this study, the upper and lower clays are called as CL1 and CL2 respectively for the classification. Tables 1 and 2 summarize the physical properties of the soil samples used in the study. The SWCCs of the four soil types, shown in Fig. 3, were originally obtained by Nam et al. (2010), and were established using the pressure plate test, dew point potentiameter, vapor equilibrium technique, osmotic method, Tempe cell test and filter paper test. The AEVs were determined from the curves.

4.2. Laboratory tests

The conventional direct shear test procedures followed ASTM D 3080 (2004), except in the case of the multistage tests. The multistage direct shear tests were performed for both saturated and unsaturated tests. A single specimen was used for each multistage test, and the shear stress vs. shear displacement response was continuously monitored during the test. When the slope of the shear stress vs. shear displacement curve approached zero, the test at the present stage was terminated and taken to the next stage. Typically, the shear stress vs. shear displacement curve became almost flat after 1 to 2 mm of shear displacement. In the final stage, the sample was sheared until strain softening was observed at a shear displacement of about 5 mm. For unsaturated samples, instead of increasing a normal stress, the matric suction was increased for the next stage. When the air pressure was increased for the matric suction at the present stage, an additional vertical load was applied to counteract the increased air pressure, keeping the net normal stress ($\sigma_n - u_a$) constant throughout the unsaturated test. The soil sample was sheared at a rate of 0.005 mm/min for silt (MH) and clay (CL), and 0.008 mm/min for silty sand (SM).

Table 1
Soil properties of the site.

Soil properties	Units	Soil type			
		SM	CL1	MH	CL2
Depth, D	m	0–0.6	0.6–2.5	2.5–3.8	3.8–4.5
Specific gravity, G_s	–	2.69	2.72	2.73	2.72
Liquid Limits, LL	%	N.P.	39–48	50–57	37–43
Plasticity Index, I_p	%		16–25	18–24	15–20
Sand content	%	68–71	4–24	5–14	4–18
Silt content	%	20–24	28–58	41–48	50–66
Clay content	%	8–9	30–48	42–50	23–43

Table 2
Average soil properties and results of multistage direct shear tests.

Soil condition	Soil property	Soil type				Remark
		SM	CL1	MH	CL2	
Saturated conditions	w_{ini}, %	9.7	34.3	30.7	30.5	Measured before saturation
	$\gamma_{t\ ini}$, g/cm^3	1.67	1.79	1.82	1.78	
	e_{ini}	0.82	1.04	0.96	1.01	
	ϕ', °	35	32.4	32	28.4	
	c', kPa	4.3	5.0	15.8	22.5	
Unsaturated condition	w_{ini}, %	10.6	36.4	29.0	29.4	
	$\gamma_{t\ ini}$, g/cm^3	1.59	1.79	1.85	1.74	
	e_{ini}	0.83	1.06	0.91	1.02	
	ψ_a, kPa	60	180	280	200	Air entry value (AEV)
	α, kPa	50	50	50	100	Inflection point
	$\sigma_n - u_a$, kPa	43	43	43*	43	
	ϕ^b, ° ($\psi_M < \alpha$)	38.7	46.6	44.9*	16.0	
	ϕ^b, ° ($\psi_M > \alpha$)	13.3	10.2	14.7*	9.0	
	τ_{sat}, kPa	36.3	33.6	42.3	39.7	
	a	4.68	10.18	8.13	12.34	$\tau = a\psi^b + \tau_{sat}$
	b	0.54	0.39	0.46	0.35	
	R^2	1.00	0.96	1.00	1.00	
	a	5.64	5.84	6.45	5.84	When b is fixed at 0.5
	R^2	1.00	0.90	1.00	0.96	

* Estimated from measurements from 21 and 68 kPa of matric suction.

Special procedures were followed to control the matric suction when testing unsaturated soils. The high air entry ceramic disc (HAECD) fixed in the shear box was saturated before testing. It was kept in a saturation chamber, which was filled with water and maintained at 60 kPa of vacuum pressure during the saturation process. Before setting a soil sample, the shear box with the flooded HAECD was checked for any leakage with high air pressure. Then the soil sample was placed in the shear box and moved to the saturation chamber for another 7 to 14 days for saturation. A porous stone was placed on top of the soil specimen and additional weight was placed above the shear box. The additional weight was not applied on the soil directly and thus did not compress the sample, but served to restrict and minimize the volume change of the sample during the saturation. The samples did not exhibit noticeable volume change during consolidation. After the saturation process, the shear box was moved into the pressure chamber and the sample was consolidated. After the consolidation process, a designated air pressure was applied to create the suction-controlled environment. The loading steps of the matric suction for the multistage tests were 25, 50, 100, 200, and 290 kPa. Under higher pressures, typically above 200 kPa, water in the grooved channel and connecting tubes was flushed every 8 to 12 h

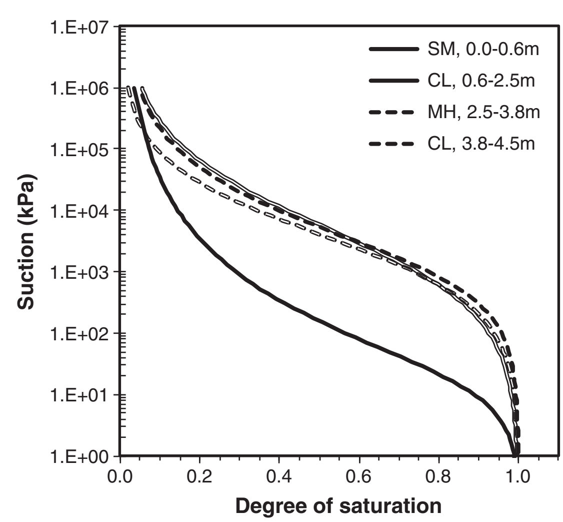

Fig. 3. Soil–water characterisitics curves (SWCCs) for the four soil types (Nam et al., 2010).

to remove air bubbles from the system. The weight of drained water was monitored to determine if the sample has reached equilibrium. The equilibrium period is known to differ with applied pressure, soil type, void ratio and other soil properties. A typical equilibrium period was 1 to 3 days for air pressures less than 100 kPa, and 5 to 12 days for higher air pressures. As the system was not equipped with a diffused air volume measurement system, the weight of water was measured for 3 h after each flushing to minimize the error caused by the diffused air in the channel and tubes. Following the equilibrium period, the soil samples were sheared.

5. Results and discussion

Multistage direct shear tests for saturated and unsaturated soils were successfully performed for the three different soil types: silty sand (SM), high plasticity silt (MH), and low plasticity clay (CL). Results are presented for: (1) validation of the multistage technique, (2) shear strength of saturated soils by consolidated drained direct shear tests, and (3) shear strength of unsaturated soils by suction-controlled consolidated drained direct shear tests. The experimentally determined shear strengths of unsaturated soils were compared to those estimated from the SWCC and the saturated shear strength.

5.1. Validation of the multistage direct shear test

Fig. 4 shows typical results from a multistage direct shear test on a saturated sample of the MH soil. The normal stress was increased from 43 to 164 kPa in 5 shearing stages. Shearing at each loading stage was stopped when the change in shear stress became almost minimal with an increase in shear displacement. The sample was then unloaded to zero shear stress and the normal stress was increased to the next level. Once the sample had been consolidated under the new effective normal stress level, it was then re-sheared until the shear stress vs. shear displacement curve again became almost horizontal. For unsaturated soils, the matric suction was increased instead of the normal stress while maintaining a constant net normal stress during a multistage test, and the sample was sheared after it reached equilibrium under the new matric suction level.

The most important requirement for the multistage test is that the loading at each stage should never extend beyond the peak shear stress into the strain softening regime. Fig. 5 shows typical examples of multistage tests for saturated and unsaturated soils that did not comply with this requirement. In Fig. 5a, a saturated sample was subjected to a large shear displacement beyond the peak shear stress, sheared in the opposite direction, and returned to zero shear displacement. The normal stress was then increased from 71 to 96 kPa and allowed to consolidate before the sample was re-sheared. As can be seen, despite the increase in the normal stress, the shear stress did not increase and the response followed essentially the same shear stress vs. displacement curve from the prior shearing at the normal stress of 71 kPa. Fig. 5b shows the response of a highly strain softening unsaturated sample, where strain softening suddenly occurred before the slope of the shear stress vs. shear displacement curve approached zero. The sample was re-sheared after the matric suction was increased in two stages from the initial value of 60 kPa to 87 kPa then 106 kPa. Although the increase in matric suction is expected to increase the shear strength, no such gain in shear strength was observed. Fig. 5a and b emphasize that multistage shearing should be monitored to guarantee that the peak strength is not surpassed, and to proceed to the next stage before strain softening occurs to ensure correct results.

To investigate the validity of the multistage direct shear tests, test results were compared to those from single stage loading and the virgin stage shearing of soil samples. The single stage test is a conventional direct shear test using one soil sample per normal stress. The virgin stage is the first stage of a multistage test before the sample has been subjected to any re-shearing. Fig. 6 shows an example of this

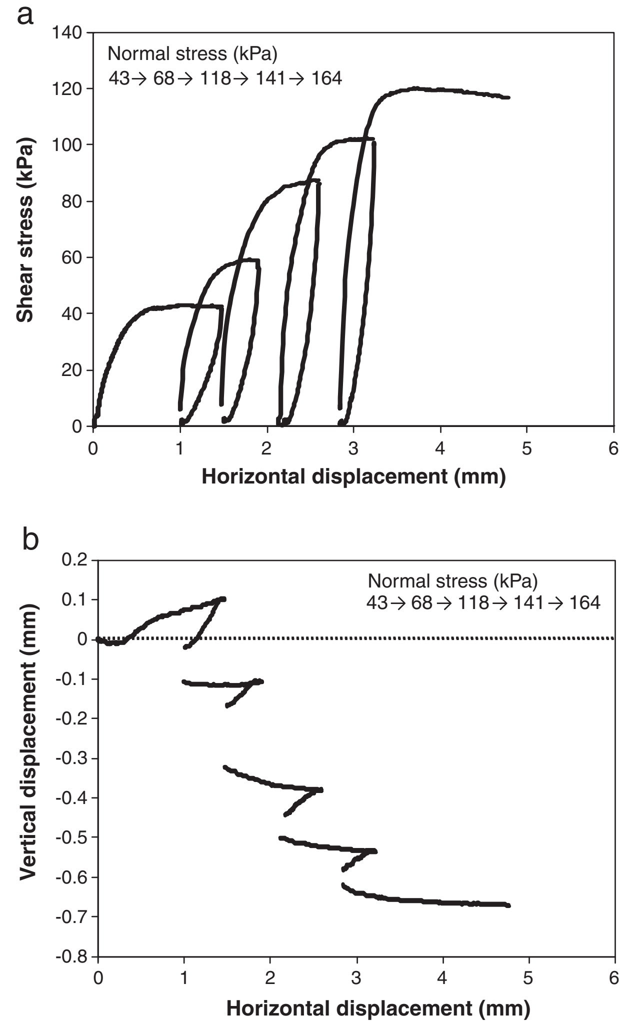

Fig. 4. Results of multistage direct shear test for saturated MH soil. Negative volumetric strain indicates dilation.

comparison for the MH soil. The failure envelope determined from the combined results of the single stage and virgin stage direct shear tests is shown as a dotted line, while the failure envelope determined from the multistage tests is shown as a solid line. As can be seen, the friction angle of $\phi = 32°$ from the multistage test is slightly lower than that from the single and virgin loading tests of $\phi = 33.6°$. On the other hand, the cohesion of $c = 15.8$ kPa for the multistage test is higher than the cohesion of $c = 12.3$ kPa for the single and virgin loading tests. The differences are, however, small and may be due to sample variability. Thus, it is deemed that the multistage test can yield results that are reasonably accurate for use in practice. Similar results were obtained for the tests on the upper clay (CL1).

As noted previously, it is very important not to exceed the complete shear failure of the soil sample during a multistage direct shear test. Each shearing stage was terminated when the shear stress had almost reached the maximum stress and stabilized. This shear stress is defined as the "failure shear stress" in this study. As shown in Fig. 7, the failure shear stress from each stage of loading was determined at a shear displacement of about 1.5 mm from the start of the re-shearing. To determine how close this failure shear stress is to the true peak shear stress, samples were sheared until strain softening occurred in the final stage of shearing. Fig. 7 illustrates typical behavior of two samples of the upper clay from the same Shelby tube, where the samples were subjected to large shear displacements at the last stage of shearing. One sample was sheared in four stages while the other was sheared in five

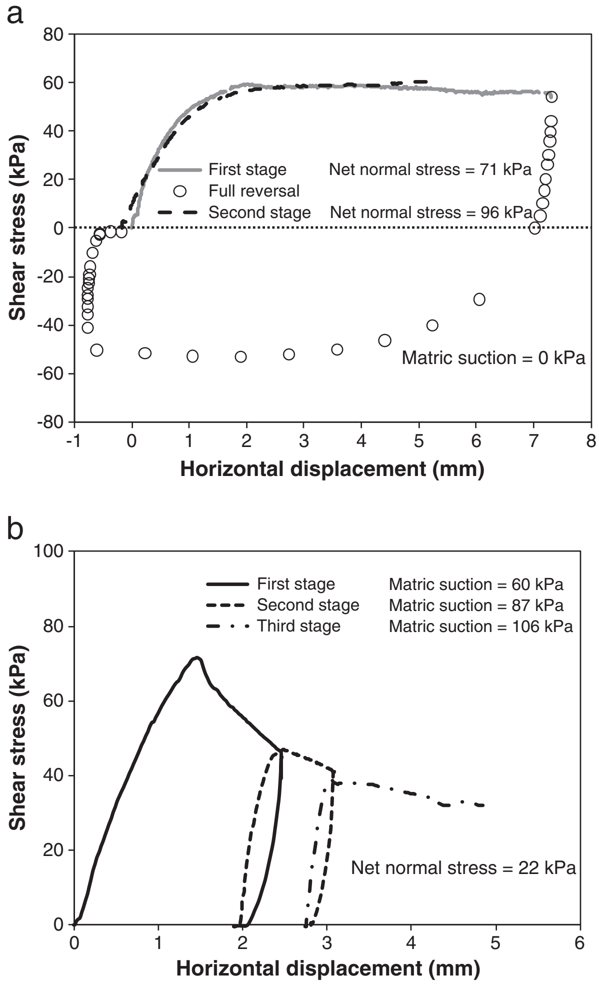

Fig. 5. Examples of incorrect multistage test results. (a) Multistage test with full and reverse shearing under different normal stresses (saturated), and (b) multistage test with different matric suctions applied after the peak stress.

stages. The shear stresses at 1.5 mm shear displacement and the true peak shear stress are indicated by circles in the final stages. As highlighted by the second circles, the peak shear stresses occurred at shear displacements larger than 1.5 mm. However, the failure shear stresses corresponding to 1.5 mm of shear displacement were only 3% lower than the true peak shear stress. Similar results were also observed

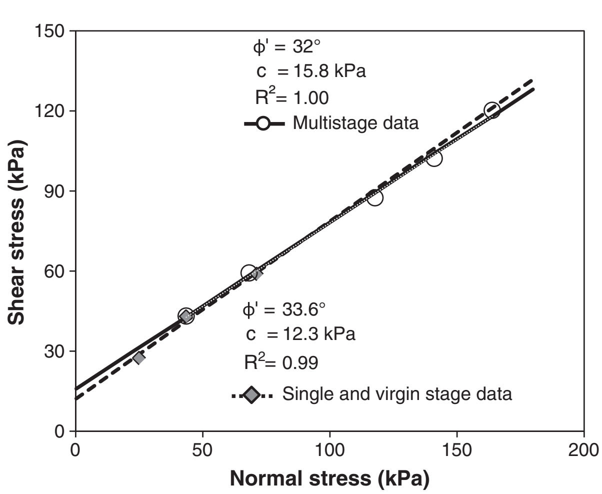

Fig. 6. Validation of results from the multistage direct shear tests for saturated MH.

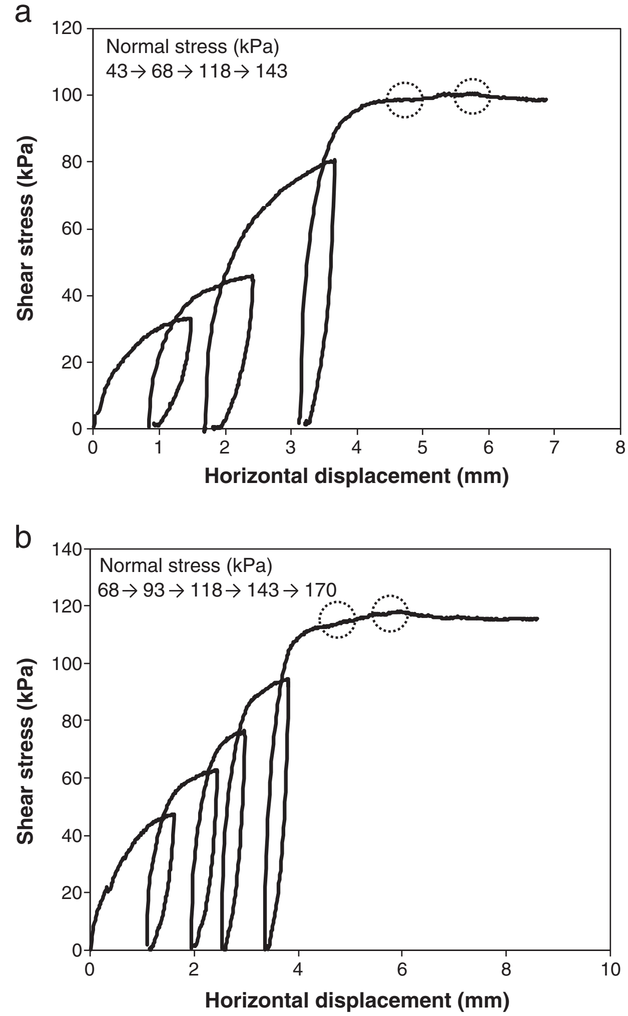

Fig. 7. Repeatability of the multistage direct shear test for saturated CL1. (a) Multistage test with four stages, and (b) multistage test with five stages.

in the other soils. Thus, the error from determining the failure friction angle and cohesion from the shear stresses at an earlier stage of displacement appears to be minimal. Fig. 7 illustrates the importance of carrying out the last stage of shearing under large shear deformation to check the validity of selecting the failure shear stress at a smaller shear displacement.

Another crucial factor in determining the validity of the multistage direct shear test is the repeatability of the test. This is demonstrated using the tests given in Fig. 8 constructed from the results in Fig. 7. As described, two samples from the same Shelby tube were sheared in four and five stages under different normal stress histories as shown in Fig. 7. The failure envelopes obtained from the two tests, summarized in Fig. 8, are nearly identical despite the fact that the two samples have undergone different loading histories. The results shown in Fig. 8 indicate that the multistage loading test provides results that are consistent and repeatable. The results also demonstrate that the multistage test can be carried out using up to five loading stages and still yield results that can be relied upon in engineering practice.

5.2. Shear strength of saturated soil samples

The failure envelopes, cohesion and friction angle of the saturated soils for the four soil types, all determined using the multistage direct shear test, are summarized in Fig. 9, and in Table 2. The results appear

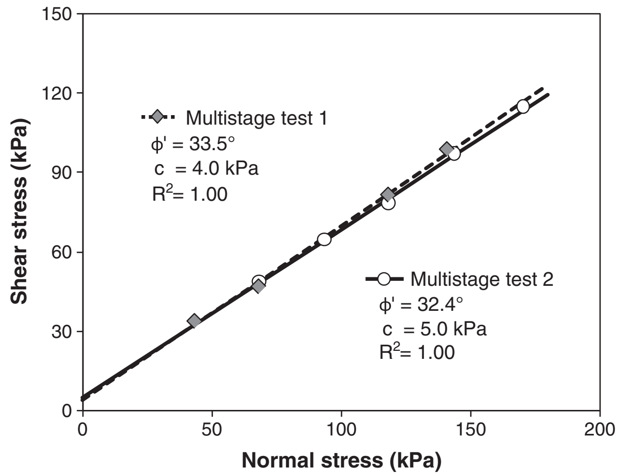

Fig. 8. Results of two multistage direct shear tests on samples of CL1 soil with different loading histories.

to be consistent, and linear failure envelopes fit the data well for the range of effective normal stresses used in the tests. The friction angle appears to decrease with increasing depth of the sample, while cohesion increases with increasing sample depth. Surprisingly, the friction angle of the upper clay CL1 was relatively high and the cohesion was low when compared to those of the much stiffer lower clay CL2. These shear strength values for CL1 were closer to those of the MH soil than CL2, although the CL1 and CL2 have comparable index properties.

5.3. Shear strength of unsaturated soil samples

The relationship between shear strength and matric suction for the unsaturated soil sample was obtained from suction-controlled multistage direct shear tests. The testing procedures were similar to those with the saturated samples except that the matric suction was changed instead of the normal stress. While maintaining a constant net normal stress, the first stage of matric suction generally began with 25 kPa. The suction was doubled at each stage until reaching 200 kPa, and in the final stage the suction was raised to the limit of the HAECD, which was 290 kPa.

Typical results of the multistage direct shear test using increasing magnitudes of matric suction are illustrated in Fig. 10 for the SM soil.

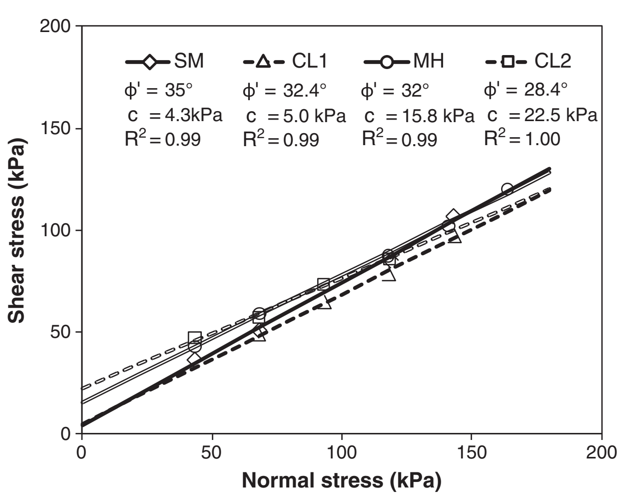

Fig. 9. Failure envelopes determined from the multistage direct shear tests on saturated soil samples from the four soil types.

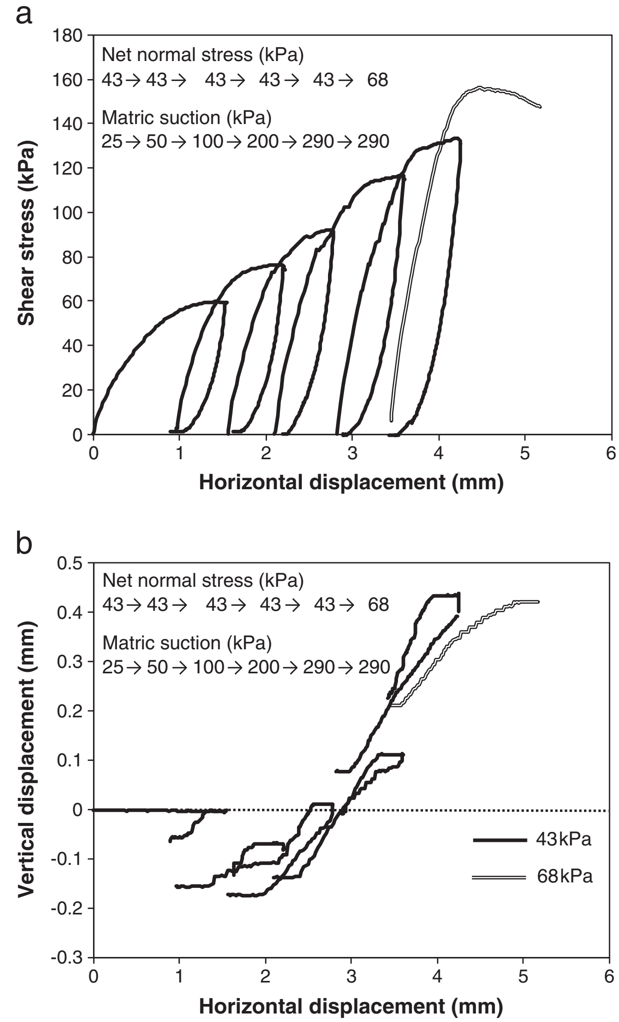

Fig. 10. Multistage direct shear test results for unsaturated SM soil under different suction values. (a) Shear stress vs. horizontal displacement, and (b) vertical displacement vs. horizontal displacement.

The solid lines represent the results from the multistage tests at a constant net normal stress $(\sigma_n - u_a)$ of 43.3 kPa, while the hollow lines represent the results at the last loading stage that were tested at a matric suction ψ of 290 kPa and an increased net normal stress of 68 kPa. The volume changes during the suction-controlled tests were different from those in the saturated direct shear tests. The samples typically contracted during shearing in the saturated soil samples, whereas the samples seemed to be initially contracted then dilated under unsaturated conditions regardless of the soil type.

Fig. 11 shows the effect of matric suction on the shear strength of unsaturated soils. The shear strengths shown are for a constant net normal stress of 43.3 kPa. Consistent with the observations of many researchers, the shear strength increased nonlinearly with increasing matric suction. Fredlund et al. (1987) suggested the use of a bilinear failure envelope to model the effect of matric suction on the shear strength of unsaturated soils. The bilinear criterion assumes that the slope of the τ vs. ψ failure envelope ϕ^b is equal to ϕ' when the suction is lower than the AEV, whereas the slope is smaller when suction is larger than the AEV. Thus, ϕ' and ϕ^b are the upper and lower bound values, respectively, of the matric suction dependent friction angle of unsaturated soils. Assuming a constant ϕ^b above the AEV results in a linear failure envelope and smaller, but conservative, unsaturated shear strengths.

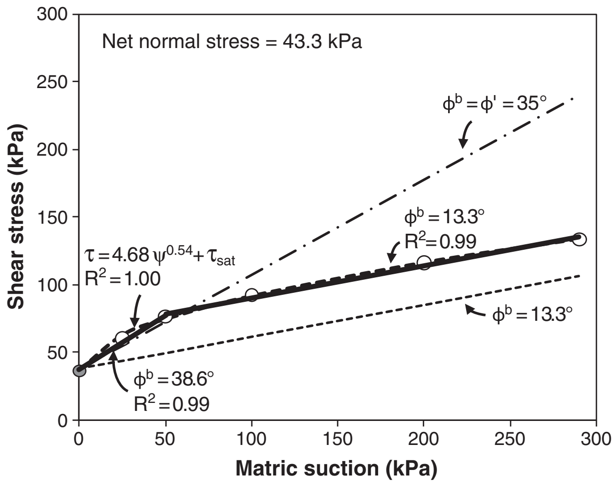

Fig. 11. Different interpretations of shear strength vs. matric suction relationship for SM soil.

An alternative to the bilinear failure envelope is to fit a nonlinear equation through the experimental data. The experimental results were found to be well represented by a power equation of the form:

$$\tau = a\psi^b + d \quad (7)$$

where a,b = fitting parameters and $d = \tau_{sat}$ = saturated shear strength. Eq. (10) is similar to the one proposed by Abramento and Carvalho (1989) except that they fixed b to 0.5. As can be seen in Fig. 11, Eq. (10) adequately fits the experimental data for the SM soil. Comparisons of Eq. (10) with the shear strength of the MH soil at net normal stresses of 21.6 and 68.1 kPa, together with the estimated failure envelope for a net normal stress of 43.3 kPa, are shown in Fig. 12. Fig. 13 shows the use of Eq. (10) in modeling the unsaturated shear strength of the CL1 soil. The fitting parameters a and b for the four soil types are summarized in Table 2. As the calculated values of b were 0.54, 0.39, 0.46, and 0.35 for silty sand SM, upper clay CL1, silt MH, and lower clay CL2, respectively, setting the value of b to 0.5 as in the model of Abramento and Carvalho (1989) seems to be a reasonable approach to simplify the equation. As shown in Fig. 13, there are no significant differences between the case where b is fixed at 0.5, and the case where b is allowed to vary to obtain a best fit regression of Eq. (10) through the experimental data, although the differences could be larger in higher suction range.

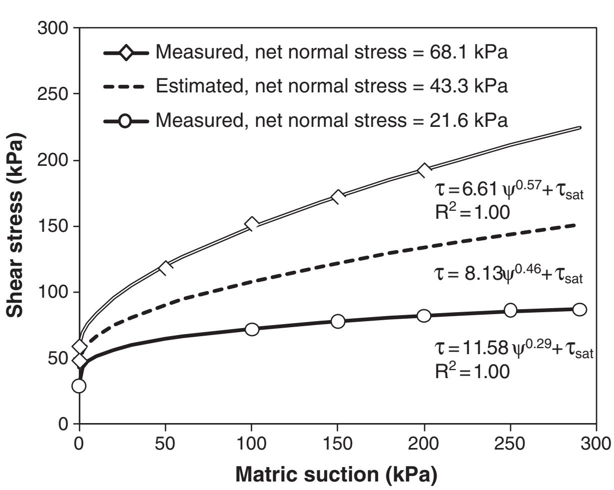

Fig. 12. Estimation of shear stress vs. suction relationship for $\sigma_n - u_a = 43$ kPa for MH soil.

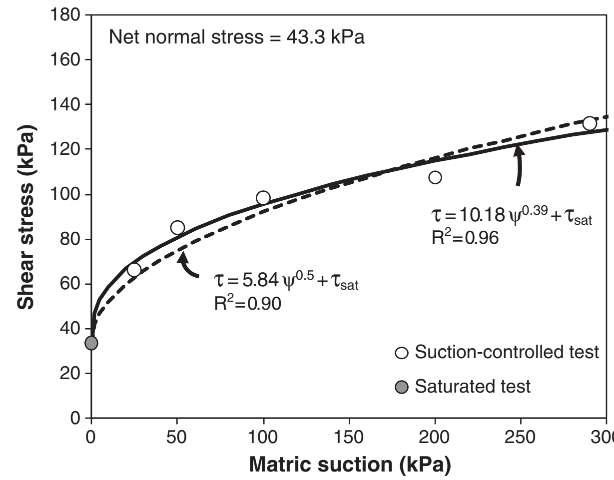

Fig. 13. Shear stress vs. matric suction for CL1 soil.

6. Conclusions

An extensive investigation was carried out to study the validity of rapid procedures in obtaining shear strength parameters of saturated and unsaturated soils using the multistage direct shear test. The laboratory tests used a newly-constructed modified direct shear test apparatus that allows independent control of matric suction, referred to as a suction-controlled multistage direct shear test. The shear strength was established using multistage loading over a range of net normal stresses and matric suction values. The study was carried out using soil samples from the four main layers of alluvial deposits at the riverbank along the lower Roanoke River. The results from the rapid test procedures were compared with those obtained from conventional direct shear tests using multiple soil samples. The main conclusions from the study are:

1) The multistage shearing technique was successfully applied to both saturated and unsaturated direct shear tests. The multistage direct shear test provided friction angles that are slightly lower and cohesion values that are slightly higher than those obtained from the conventional direct shear test. The observed differences are generally negligible for engineering practice.
2) It was shown that reliable shear strengths parameters for both saturated and unsaturated soil samples can be obtained from the multistage shearing test if some precautions are followed when testing. These precautions include not excessively shearing the soil sample beyond the peak shear stress to the strain softening region, and making sure that the samples are completely consolidated at every new effective normal stress level.
3) It was shown that potential errors in the shear strength parameters from the multistage loading can be assessed by carrying out the last stage of shearing under large shear deformation to check the validity of selecting the failure shear stress at smaller shear displacements.
4) The results demonstrated that the multistage test can provide repeatable results and be carried out using up to five loading stages and yield results that can be relied upon in engineering practice.
5) The experimental results confirmed the nonlinear relationship between the unsaturated shear strength and matric suction. The friction angle with respect to matric suction ϕ^b was higher than the effective friction angle ϕ' at suction values below the AEV, and decreased as suction increased. The bilinear relationship proposed by Fredlund et al. (1987), while simple, was inadequate to represent the experimental unsaturated shear strength vs. suction data. A better representation of the experimental data was an empirical power function, or the square-root function proposed by Abramento and Carvalho (1989).

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