Determination of the shear strength parameters of an unsaturated soil using the direct shear test

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Received May 20, 1987

Accepted March 17, 1988

Multistage direct shear tests have been performed on saturated and unsaturated specimens of a compacted glacial till. A conventional direct shear apparatus was modified in order to use the axis-translation technique for direct shear tests on unsaturated soils. The soil can be subjected to a wide range of matric suctions. The testing procedure and some typical results are presented. Nonlinearity in the failure envelope with respect to matric suction was observed. Suggestions are made as to how best to handle the nonlinearity from a practical engineering standpoint.

Key words: shear strength, unsaturated soils, negative pore-water pressures, soil suction, direct shear.

Des essais en cisaillement direct à étapes multiples ont été réalisés sur des spécimens saturés et non saturés de till glaciaire compacté. Un appareil conventionnel de cisaillement direct a été modifé de façon à utiliser la technique de translation d'axe pour des essais de cisaillement direct sur des sols non saturés. Le sol peut être assujetti à un large domaine de succion de matrice. La procédure de l'essai et quelques résultats typiques sont présentés. Une non-linéarité de l'enveloppe de rupture en fonction de la succion de matrice a été observée. Des suggestions sont faites quant à la meilleure façon de tenir compte de cette non-linéarité du point de vue de l'ingénieur.

Mots clés : résistance au cisaillement, sols non saturés, pressions interstitielles négatives, succion du sol, cisaillement direct.

[Traduit par la revue]

Can. Geotech. J. **25**, 500–510 (1988)

Introduction

Most man-made earth structures involve the use of compacted soils. The compaction process produces a soil with a degree of saturation usually in the range of 75–90%. Earthfill dams, embankments, and highways are typical examples of earth structures made of compacted, unsaturated soils. The theory and measurement of shear strength of unsaturated soils have gained increasing attention during the past three decades. A brief review on the development of our understanding of the shear strength behavior of unsaturated soils is presented in this paper.

This paper presents the results of a series of direct shear tests on an unsaturated soil. Direct shear testing of unsaturated soils is desirable since less time is required to fail the soil specimen than when using the triaxial test. The time to failure in the direct shear test is greatly reduced because the specimen is relatively thin. The lengthy testing period for unsaturated soils is due to the low coefficient of permeability of the soil and the high air entry disc in contact with the specimen.

A conventional direct shear apparatus was modified to accommodate a wide range of applied matric suctions (Gan 1986). A multistage test procedure was used. A description of the modified direct shear box and testing procedure is presented. The soil used in this investigation is a compacted glacial till from Indian Head, Saskatchewan. A series of single-stage and multistage direct shear tests on saturated specimens is analyzed to provide the saturated shear strength parameters of the soil (i.e., c' and ϕ'). The possibility of nonlinearity with respect to matric suction is also addressed.

Literature review and theory

Donald (1956) conducted a series of direct shear tests on fine sands and coarse silts subjected to a negative pore-water pressure. The soil specimens were exposed to the atmosphere to maintain a pore-air pressure, u_a, of zero gauge pressure. The negative gauge pore-water pressure, u_w, was controlled by applying a constant negative head to the water phase through a membrane at the base of the specimen. This apparatus limited the applied matric suction, $(u_a - u_w)$, to 101 kPa (i.e., 1 atm) because water cavitates in the measuring system at a negative gauge pressure approaching 101 kPa. The results showed an increase in shear strength as matric suction was increased.

Hilf (1956) suggested that pore-air and pore-water pressures could both be raised to positive pressures in order to apply matric suctions higher than 101 kPa without cavitation in the measuring system. The proposed procedure is referred to as the axis-translation technique. This technique is performed with the use of a high air entry disc that allows the passage of water but prevents the passage of air. As a result, the pore-air and pore-water pressures can be controlled or measured independently as long as the matric suction of the soil does not exceed the air entry value of the ceramic disc.

Bishop *et al.* (1960) proposed several techniques for measuring the shear strength of an unsaturated soil using triaxial equipment. Results obtained from several different tests were presented. Bishop and Donald (1961) performed a consolidated drained test on an unsaturated loose silt. The acceptability of the axis-translation technique for the shear strength testing of unsaturated soils was verified by Bishop and Blight (1963).

A shear strength equation for an unsaturated soil in which two independent stress state variables are used was proposed by Fredlund *et al.* (1978). The two stress state variables most commonly used are the net normal stress, $(\sigma - u_a)$, and the

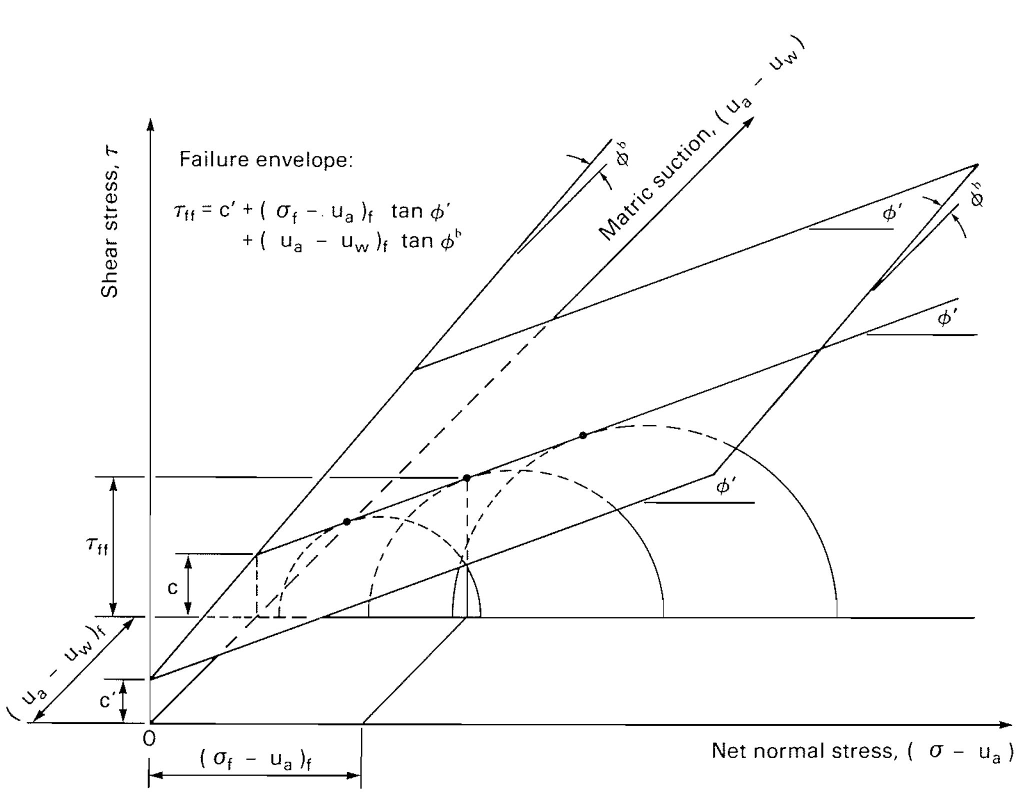

FIG. 1. Extended Mohr–Coulomb failure envelope.

matric suction, $(u_a - u_w)$, where σ is total normal stress, u_a is pore-air pressure, and u_w is pore-water pressure. The proposed shear strength equation has the following form:

$$[1] \quad \tau_{ff} = c' + (\sigma_f - u_a)_f \tan\phi' + (u_a - u_w)_f \tan\phi^b$$

where τ_{ff} = shear stress on the failure plane at failure; c' = intercept of the "extended" Mohr–Coulomb failure envelope on the shear stress axis when the net normal stress and the matric suction at failure are equal to zero; it is also referred to as the "effective cohesion;" $(\sigma_f - u_a)_f$ = net normal stress on the failure plane at failure; σ_{ff} = total normal stress on the failure plane at failure; u_{af} = pore-air pressure at failure; ϕ' = angle of internal friction associated with the net normal stress state variable, $(\sigma_f - u_a)_f$; $(u_a - u_w)_f$ = matric suction at failure; u_{wf} = pore-water pressure at failure; ϕ^b = angle indicating the rate of change in shear strength relative to changes in matric suction.

Equation [1] defines a planar surface, which is called the extended Mohr–Coulomb failure envelope (Fig. 1). The envelope is tangent to the Mohr circles representing failure conditions. The shear strength of an unsaturated soil consists of an effective cohesion intercept, c', and the independent contributions to shear strength from net normal stress, $(\sigma - u_a)$, and matric suction, $(u_a - u_w)$. The shear strength contributions from net normal stress and matric suction are characterized by ϕ' and ϕ^b angles, respectively. The failure envelope on the frontal plane (i.e., τ versus $(\sigma - u_a)$ plane) is the same as the Mohr–Coulomb failure envelope for saturated conditions.

Two sets of shear strength data reported by Bishop *et al.* (1960) were analyzed by Fredlund *et al.* (1978) using the proposed shear strength equation. The results indicated essentially a planar failure envelope when the shear stress, τ, was plotted with respect to the independent stress state variables.

Several sets of triaxial test results on unsaturated Dhanauri clay were presented by Satija (1978). The tests performed were consolidated drained and constant water content tests. These data were analyzed by Ho and Fredlund (1982) assuming that the failure surface was planar with respect to the independent stress state variables. Escario (1980) conducted a series of consolidated drained shear and triaxial tests on unsaturated Madrid gray clay. The tests were performed under controlled matric suction conditions using the axis-translation technique. A modified direct shear box, enclosed in a pressure chamber, was used to apply a controlled air pressure to the soil specimen. The specimen was placed on a high air entry disc in contact with water at atmospheric pressure. This arrangement is similar to the pressure plate system where the matric suction is controlled by varying the pore-air pressure while the pore-water pressure is maintained constant. The results exhibited an increase in the shear strength as the matric suction was increased.

A series of multistage triaxial tests on unsaturated, residual soils from Hong Kong was carried out by Ho and Fredlund (1982). The tests were consolidated drained tests with the pore-air and pore-water pressures controlled during shear. The assumption that the failure surface was essentially planar was made in the analysis of the test data.

Recent experimental evidence using a higher range of matric suction has shown some nonlinearity in the failure envelope with respect to the matric suction axis. Escario and Sáez (1986) performed direct shear tests on three soils using a modified direct shear box and the procedure described by Escario (1980). The results exhibit curvature in the relationship between shear stress and matric suction. Similarly, a reanalysis of the triaxial test results of Satija (1978) also reveals some nonlinearity in the shear stress versus matric suction failure envelope (Fredlund *et al.* 1987).

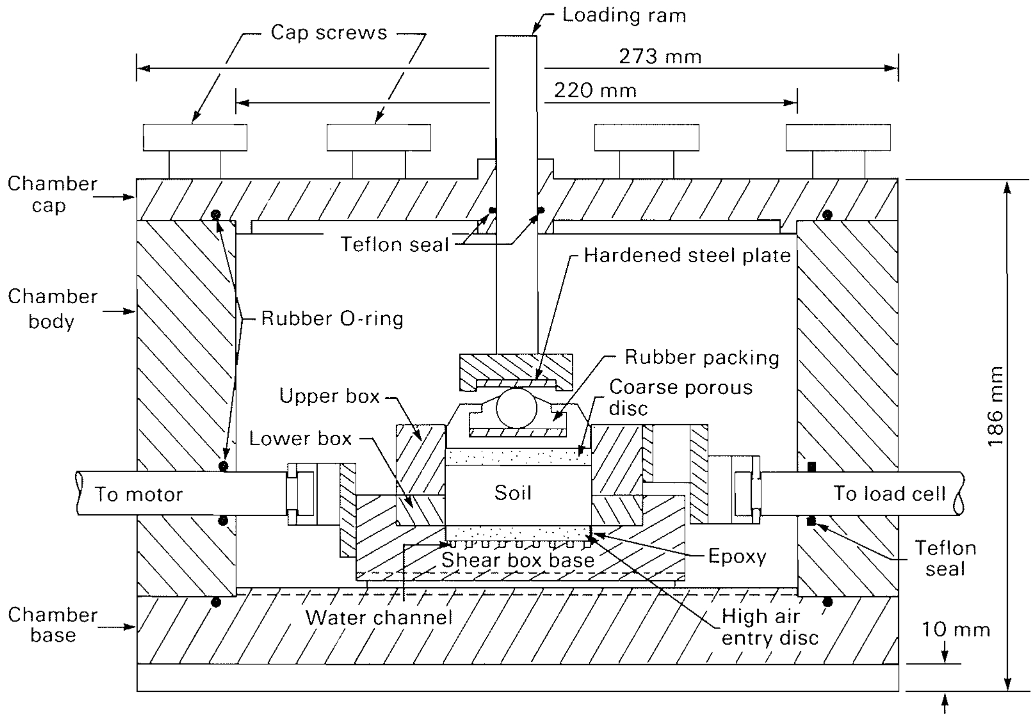

FIG. 2. Modified direct shear apparatus.

TABLE 1. Index properties for the glacial till from the Indian Head area of Saskatchewan

Property	Value
Liquid limit	35.5%
Plastic limit	16.8%
Plasticity index	18.7%
Percent sand sizes	28%
Percent silt sizes	42%
Percent clay sizes	30%
Specific gravity of soil solids	2.734
AASHTO standard compaction	
Maximum dry density	1815 kg/m^3
Optimum water content	16%

Description of equipment

A conventional direct shear apparatus has been modified to control the pore-air and pore-water pressures applied to the soil specimen. The direct shear box is placed in an air pressure chamber as shown in Fig. 2. The soil specimen has a coarse porous disc placed at its top and a high air entry disc at its bottom. The pore-air pressure, u_a, in the soil specimen is controlled by pressurizing the air in the chamber. The air pressure in the chamber has direct contact with the coarse disc on top of the specimen through the gap between the loading cap and the upper box. The pore-water pressure, u_w, is controlled through the high air entry disc at the base of the specimen. The flow of water through the disc ensures a continuous column of water between the soil specimen and the water below the disc. However, with time, pore-air may diffuse through the water in the high air entry disc and appear as air bubbles in the water compartment below the disc. Therefore, the water compartment is made to allow for the flushing of diffused air bubbles on a periodic basis. The total normal stress, σ, is applied vertically to the specimen through a loading ram. The uplift pressure of the air on the loading ram is taken into account.

The lower part of the direct shear box is seated on rollers that run in grooved tracks on the chamber base (Fig. 2). The lower box is connected to a motor, through a gear box, for the application of the horizontal shear load to the specimen. The upper part of the box is connected to a load cell in order to measure the applied horizontal shear load.

A water movement indicator was used to measure the movement of water into and out from the soil specimen. The measured volume change of water in the specimen must be corrected for the volume of diffused air (Fredlund 1975). The vertical deflection and horizontal displacement of the soil specimen were measured using linear voltage displacement transducers (LVDT's).

Soil and test program

The soil used in this investigation is a glacial till from the Indian Head area of Saskatchewan. Only material passing the No. 10 sieve was used. The index properties of the soil are summarized in Table 1. Prior to testing, the soil was compacted in accordance with the American Association of State Highway and Transportation Officials (AASHTO) standard. The maximum dry density and optimum water content are listed in Table 1. The clay fraction is predominately a calcium montmorillonite.

The testing program consisted of (i) a pilot test program of direct shear tests to determine the displacement rate required to ensure drained conditions during shear, (ii) consolidated, drained direct shear tests on saturated specimens, and (iii) consolidated drained direct shear tests on unsaturated specimens.

The pilot test program consisted of four single-stage direct shear tests on *unsaturated* specimens. The tests were performed at four different displacement rates using the modified direct shear equipment. The effect of displacement rate on the

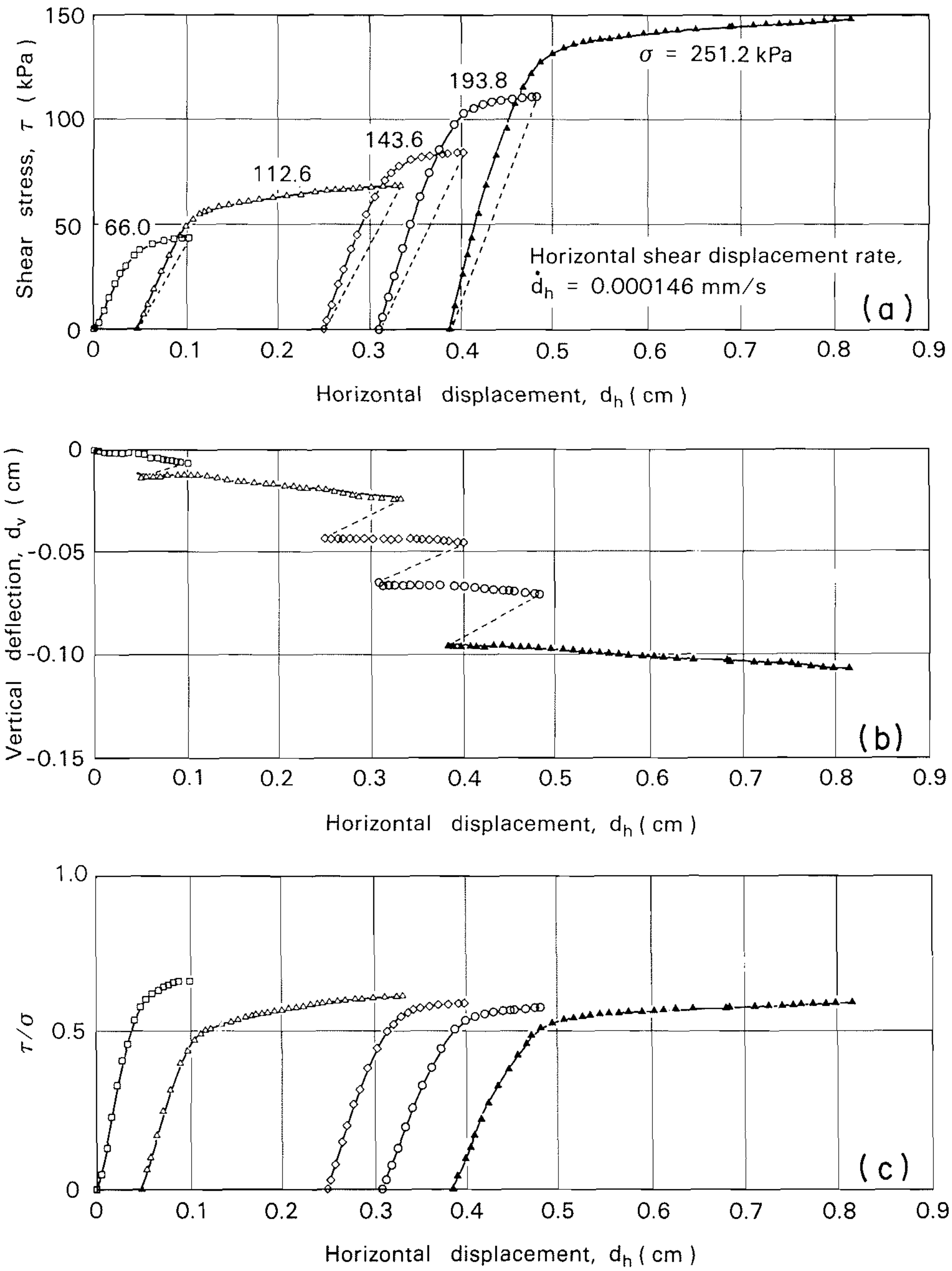

FIG. 3. Multistage direct shear test data on saturated glacial till specimen GT-15-N2: (*a*) shear stress versus horizontal displacement; (*b*) vertical deflection versus horizontal displacement; (*c*) τ/σ versus horizontal displacement.

shear strength was investigated by using a constant net normal stress and matric suction within the specimens for the four tests.

The second part of the testing program consisted of several single-stage and multistage direct shear tests performed on *saturated* specimens using the conventional direct shear apparatus and procedure. The purpose of this testing program was to obtain the shear strength parameters c' and ϕ', and to asses the applicability of the multistage direct shear procedure for Indian Head glacial till. The results of multistage direct shear tests on saturated specimens were studied to obtain a suitable failure criterion for the multistage direct shear testing. The selected failure criterion was used in the analysis of the multistage test results for unsaturated specimens.

The third part of the testing program consisted of a series of five multistage direct shear tests on *unsaturated* specimens. The tests were performed to obtain the shear strength parameter, ϕ^b. The initial volume mass properties of the five specimens are tabulated in Table 2. Each specimen had three to seven stages of shearing. The tests were performed by maintaining a constant net normal stress, $(\sigma - u_a)$, of approximately 72.6 kPa and varying the matric suction, $(u_a - u_w)$, between stages (Table 2). The matric suctions ranged from 0 to 500 kPa. As a result, the shear stress versus matric suction failure envelope was obtained and the ϕ^b parameter was computed.

The multistage direct shear tests on unsaturated specimens were conducted using the modified direct shear apparatus (Fig. 2). Each test was commenced by saturating the high air

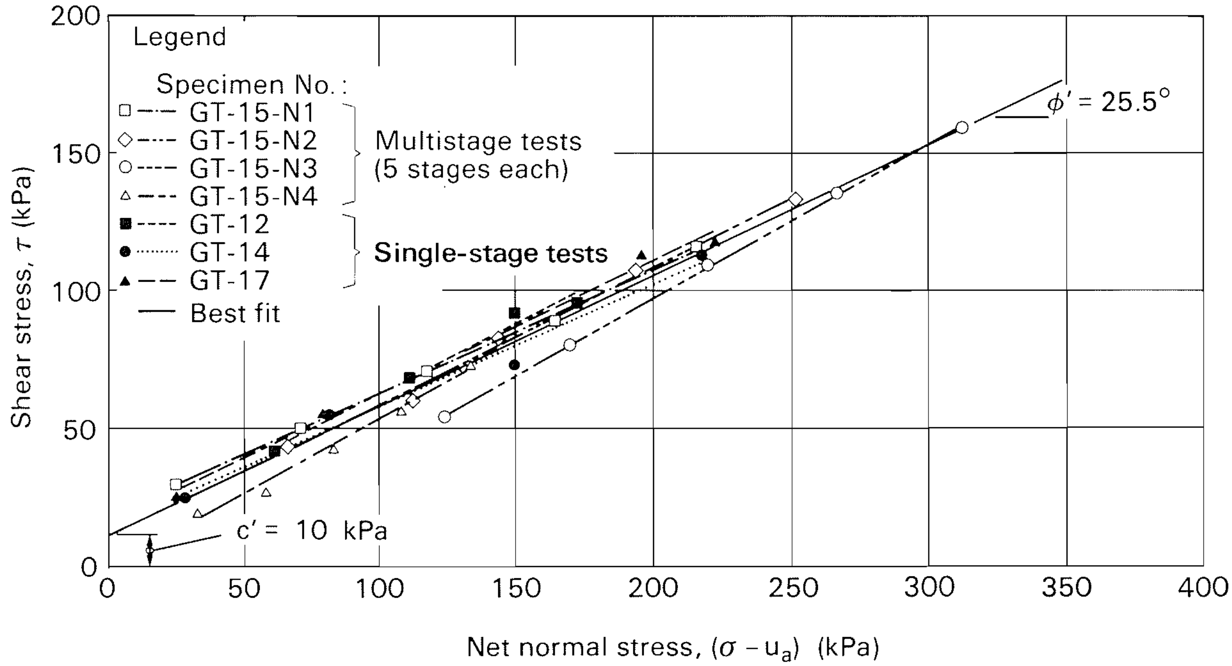

FIG. 4. Mohr–Coulomb failure envelopes for direct shear tests on saturated glacial till.

entry disc with de-aired water. The soil specimen was then mounted in the shear box and initially allowed access to water through the top coarse porous disc. The predetermined total normal stress, σ, pore-air pressure, u_a, and pore-water pressure, u_w, were then applied to the specimen, in this order.

The soil specimen was allowed to come to equilibrium under the applied net normal stress, $(\sigma - u_a)$, and matric suction, $(u_a - u_w)$. During the equalization process, the vertical deflection and the water movement from the soil specimen were measured. Equilibrium was assumed to have been achieved when there was no further flow of water from the specimen. Upon attaining equilibrium, the soil specimen was sheared under a constant rate of displacement. Water movement from the specimen was observed during shear. Part of the observed movement is due to water flow and part is due to the flow of diffused air. No attempt was made to separate these two quantities. However, the diffused air was flushed from below the high air entry disc on a daily basis. The shearing process was stopped when the peak shear stress of the soil was imminent. The horizontal shear load was then released from the specimen. The next stage was performed by applying a new matric suction to the specimen and repeating the above procedure. Details on the test procedure are given by Gan (1986).

Presentation of test results

The results of the pilot test program indicate that the peak shear stress remained essentially constant when the displacemen rate was less than 2.2×10^{-4} mm/s. On the basis of these results, a displacement rate of 1.7×10^{-4} mm/s was selected for the entire direct shear testing program.

The analysis of the multistage direct shear test results on saturated specimens shows that a shear displacement of 1.2 mm was sufficient to mobilize the peak shear stress. Figure 3 shows typical data from a multistage direct shear test on a saturated glacial till specimen. A shear displacement of 1.2 mm on specimen size of 50 mm by 50 mm was selected as the failure criterion for all multistage direct shear tests.

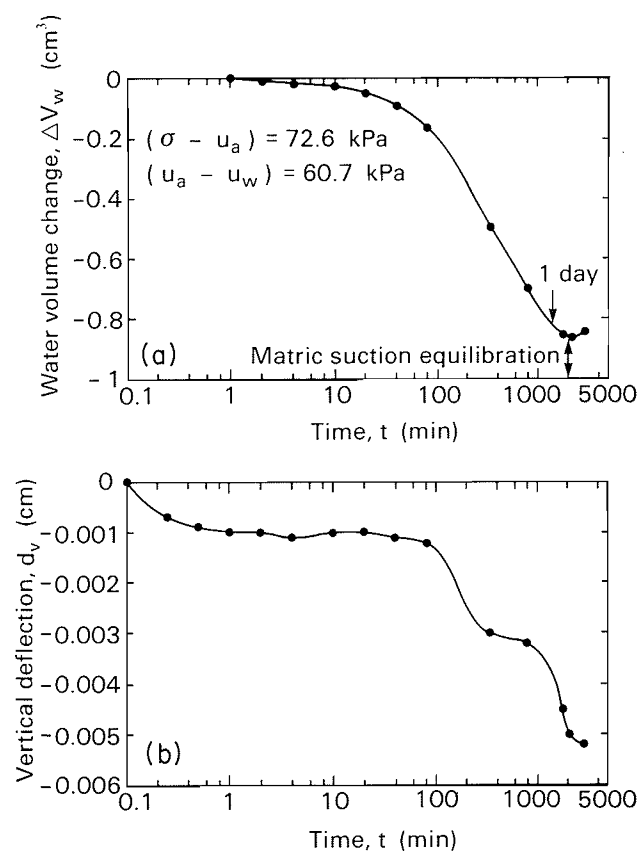

FIG. 5. Water volume change and consolidation of specimen GT-16-N4 (stage 2) during matric suction equilibration: (*a*) water volume change; (*b*) consolidation.

A plot of shear stress versus net normal stress corresponding to failure is shown in Fig. 4 for the saturated specimens. The data were obtained from both single-stage and multistage direct shear tests on saturated specimens. The peak shear stress

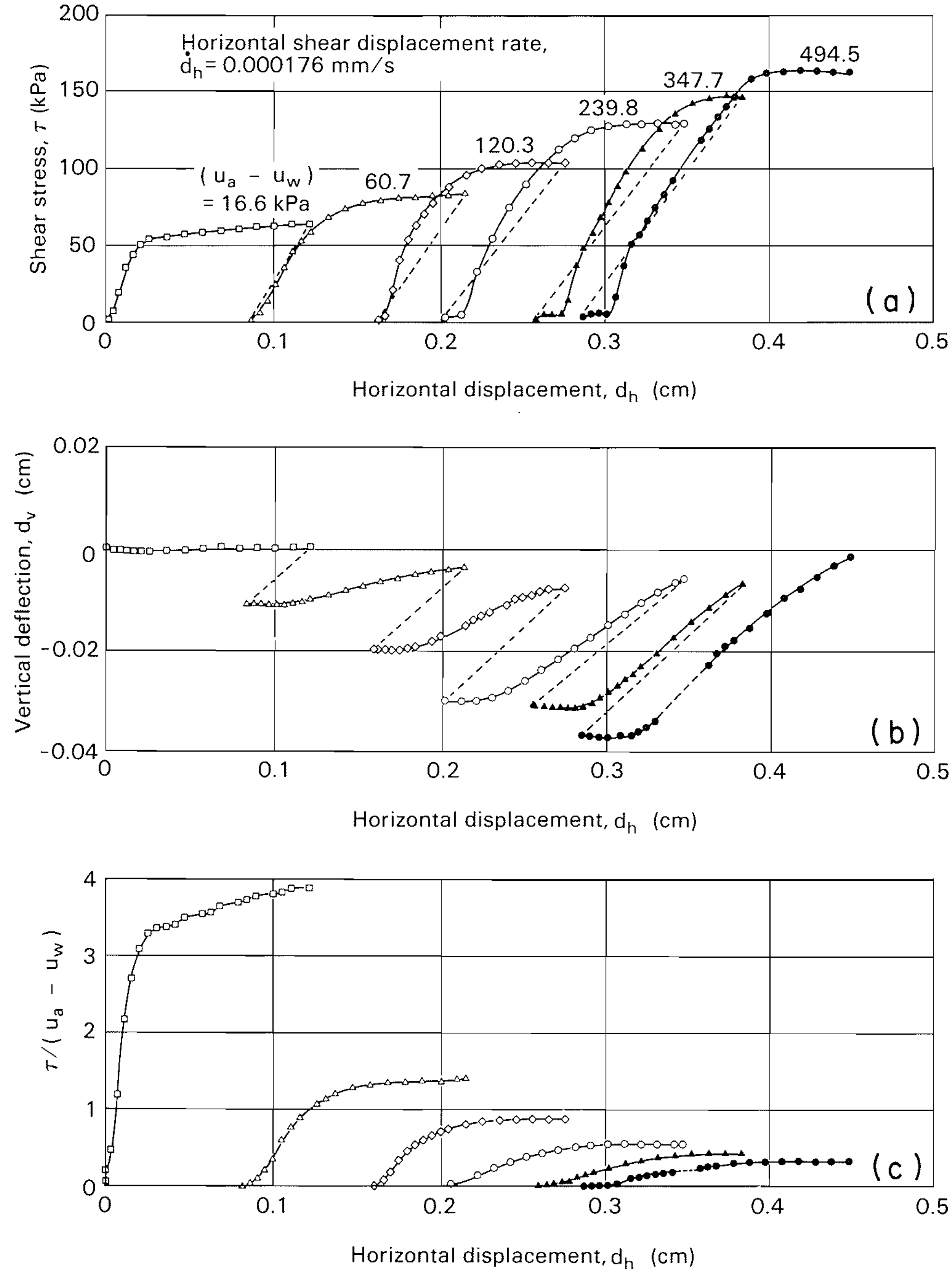

FIG. 6. Multistage direct shear test results on unsaturated glacial till specimen GT-16-N4: (*a*) shear stress versus horizontal displacement; (*b*) vertical deflection versus horizontal displacement; (*c*) $\tau/(u_a - u_w)$ versus horizontal displacement.

was used as the shear stress at failure for the single-stage tests. On the other hand, the shear stress corresponding to 1.2 mm of shear displacement was assumed to be the shear stress at failure for the multistage tests. The lines plotted through the data points in Fig. 4 form Mohr–Coulomb failure envelopes for the saturated specimens (i.e., the frontal plane of Fig. 1). The authors have no explanation as to why the test results from specimen GT-15-N3 produce a negative cohesion intercept.

A few typical results of the multistage direct shear tests on unsaturated specimens are presented in this paper. Figure 5 shows a typical plot of water volume change and consolidation for specimen GT-16-N4 at the beginning of its second stage. These volume changes occurred during matric suction equilibration. A negative volume change refers to a decrease in volume, whereas a positive volume change indicates a volume increase. Matric suction equilibration was generally attained in about 1 day (Fig. 5*a*). Some tests were allowed to equilibrate for more than 10 000 min to ensure that equilibrium was indeed attained in 1 day.

Results from one of the multistage direct shear tests on unsaturated specimens are illustrated in Fig. 6 (specimen GT-16-N4). The vertical deflection versus horizontal displacement curves (Fig. 6*b*) generally show that the soil dilated during shear, except for initial stages at low matric suctions. As the matric suction increases the curves show an increase in the specimen height with increasing horizontal displacement

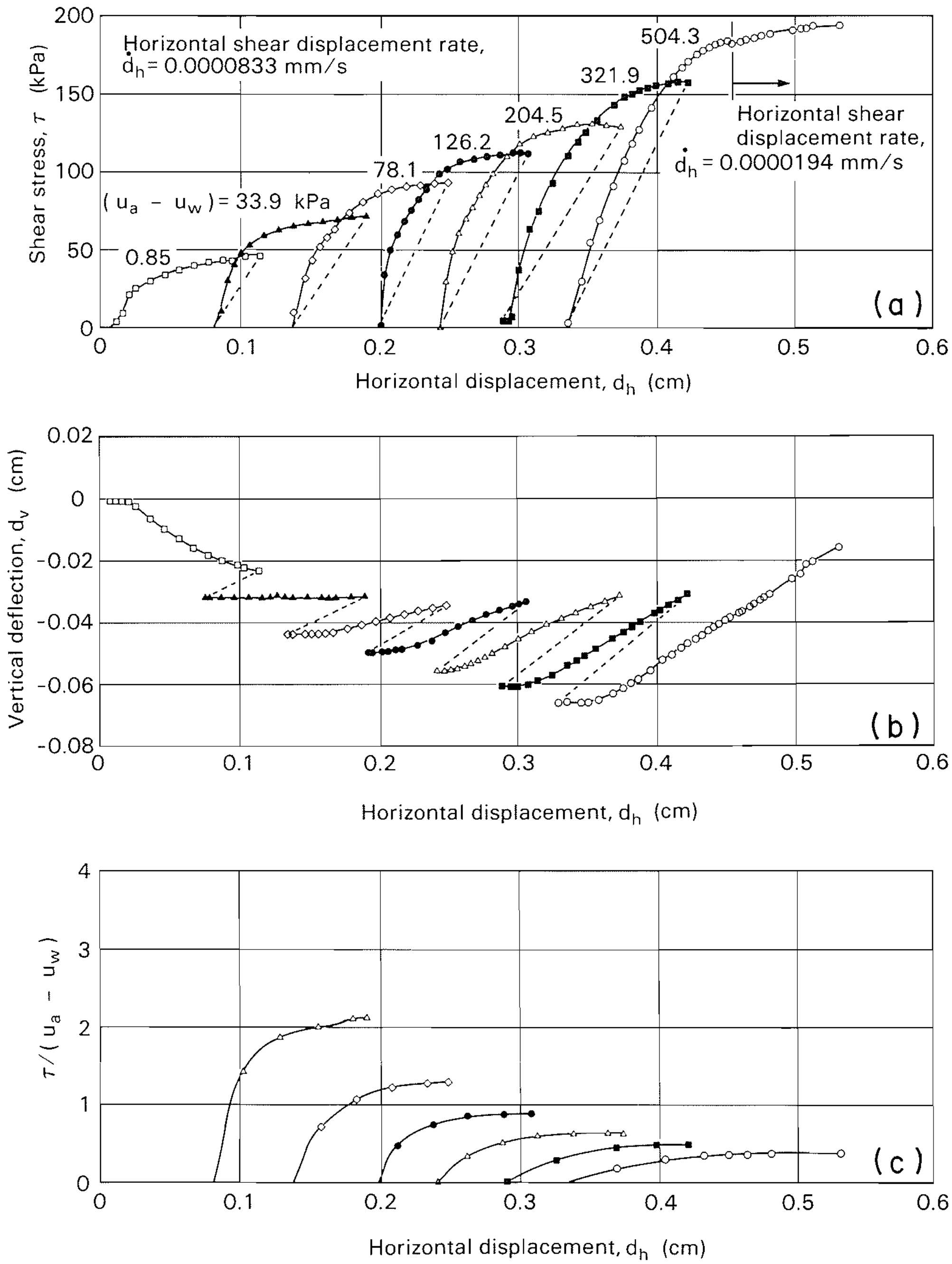

FIG. 7. Multistage direct shear test results on unsaturated glacial till specimen GT-16-N5: (*a*) shear stress versus horizontal displacement; (*b*) vertical deflection versus horizontal displacement; (*c*) $\tau/(u_a - u_w)$ versus horizontal displacement.

(Fig. 6*b*).

The shear stress normalized with respect to matric suction is plotted versus horizontal displacement in Fig. 6*c*. The curves indicate a decrease in the normalized peak stress with increasing matric suction. These peak values appear to approach a relatively low, constant value at high matric suctions.

Specimens GT-16-N1 – GT-16-N4 were tested at the selected displacement rate of 1.76×10^{-4} mm/s. Specimen GT-16-N5 was tested at a displacement rate equal to approximately one-half the above rate (i.e., 0.833×10^{-4} mm/s). Midway through the last stage of test on GT-16-N5, the displacement rate was further reduced to 0.194×10^{-4} mm/s. The reduced displacement rates were used to demonstrate that the selected displacement rate of 1.76×10^{-4} mm/s was indeed adequate to ensure drained conditions during shear. The test results obtained from specimen GT-16-N5 tested at the reduced displacement rate (Fig. 7) exhibit similar behavior to that observed from the results obtained on other specimens (Fig. 6). In the last stage, the shear stress versus horizontal displacement curve continues monotonically regardless of the further reduction in the displacement rate (i.e., 0.194×10^{-4} mm/s; Fig. 7*a*). The small drop observed was believed to be due to the "slack" in the gear system when changing from one gear ratio to another.

The shear stresses corresponding to a shear displacement of 1.2 mm are plotted against matric suction in Fig. 8*a* for speci-

TABLE 2. Multistage direct shear tests on unsaturated glacial till specimens

Initial properties	Specimen No.: GT-16-N1	GT-16-N2	GT-16-N3	GT-16-N4	GT-16-N5
Void ratio, e_0	0.77	0.53	0.69	0.51	0.54
Degree of saturation, S_0 (%)	42	59	48	65	61
Water content, w_0 (%)	11.83	11.50	12.27	12.23	12.08

	Stress state at each stage (kPa)									
Stage No.	$(\sigma - u_a)$	$(u_a - u_w)$	$(\sigma - u_a)$	$(u_a - u_w)$	$(\sigma - u_a)$	$(u_a - u_w)$	$(\sigma - u_a)$	$(u_a - u_w)$	$(\sigma - u_a)$	$(u_a - u_w)$
1	70.94	37.86	71.28	176.95	72.83	23.45	72.55	16.62	73.73	0.85
2	71.29	176.89	71.58	314.7	72.84	79.04	72.61	60.69	72.58	33.89
3	71.58	315.25	71.99	453.53	72.68	448.05	72.59	120.3	72.59	78.07
4					72.68	448.05	72.56	239.83	72.57	126.2
5							72.58	347.7	72.55	204.53
6							72.53	494.5	72.57	321.89
7									72.20	504.34

men GT-16-N4. The line joining the data points forms the shear stress versus matric suction failure envelope (i.e., the third dimension of Fig. 1). The shear stress versus matric suction plane in Fig. 8*a* corresponds to an average net normal stress at failure, $(\sigma_{ff} - u_{af})$, of 72.6 kPa. The slope of the failure envelope gives the ϕ^b angle. The ϕ^b angles are plotted with respect to matric suction in Fig. 8*b*.

Figure 9*a* presents a summary of the results obtained from five unsaturated specimens tested using the multistage direct shear test (see Table 2). The results fall within a band, forming the failure envelopes shown in Fig. 9*a*. The ϕ^b angles corresponding to the failure envelopes are plotted in Fig. 9*b* with respect to matric suction. No single-stage direct shear tests were performed on the unsaturated specimens.

Discussion of test results

The direct shear test results on saturated glacial till specimens exhibit essentially linear failure envelopes with respect to the net normal stress axis (Fig. 4). The failure envelopes also show close agreement between the single-stage and multistage direct shear test results. This would indicate an acceptability of the multistage direct shear test technique for Indian Head glacial till. It should be emphasized that the multistage test technique may not be acceptable for all types of unsaturated soils. The use of 1.2 mm of shear displacement, as the failure criterion, was verified for testing of the glacial till. A best-fit envelope drawn through the data points in Fig. 4 results in shear strength parameters c' and ϕ' of 10 kPa and 25.5°, respectively. The scatter in the cohesion intercept was about ± 7 kPa.

The direct shear test results on the unsaturated specimens exhibit significant nonlinearity for the failure envelope with respect to the matric suction (Figs. 8 and 9). The ϕ^b angles commence at a value equal to ϕ' (i.e., 25.5°) at matric suctions close to zero and decrease significantly at matric suctions in the range of 50–100 kPa. The ϕ^b angles reach a fairly constant value ranging from 5 to 10° when the matric suction exceeds 250 kPa (Fig. 9*b*). The scatter in the failure envelopes (Figs. 4 and 9) appears to be due to variations in the initial void ratios of the soil specimens. There also appears to be some change in the thickness of each specimen during shear. However, it is difficult to quantify the change in void ratio of the soil near the failure zone.

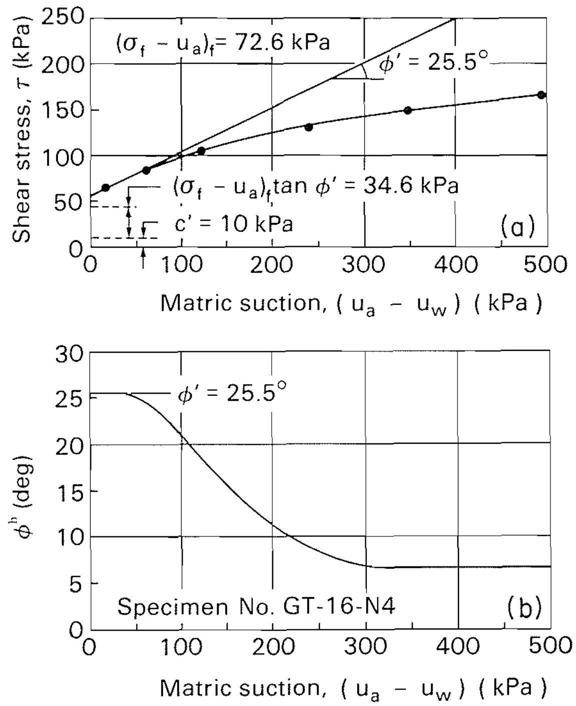

FIG. 8. Failure envelope obtained from unsaturated glacial till specimen GT-16-N4: (*a*) failure envelope on τ versus $(u_a - u_w)$ plane; (*b*) corresponding ϕ^b values.

Figures 8*a* and 9*a* show that there is a slight discrepancy in the intercepts where the saturated strength envelope intersects with the strength envelope obtained while the matric suction is controlled. For example, when the strength equation is applied to Fig. 8*a*, the following equality should be satisfied:

[2] $\tau_{ff} = c' + (\sigma_f - u_a)_f \tan \phi' + (u_a - u_w)_f \tan \phi^b$

[3] $55 \neq 10.0 + (72.6) \tan 25.5$

The difference in [3] is 10.4 kPa. The authors feel that this difference can be explained in terms of (i) variation in the initial void ratios of the specimen used for the saturated and

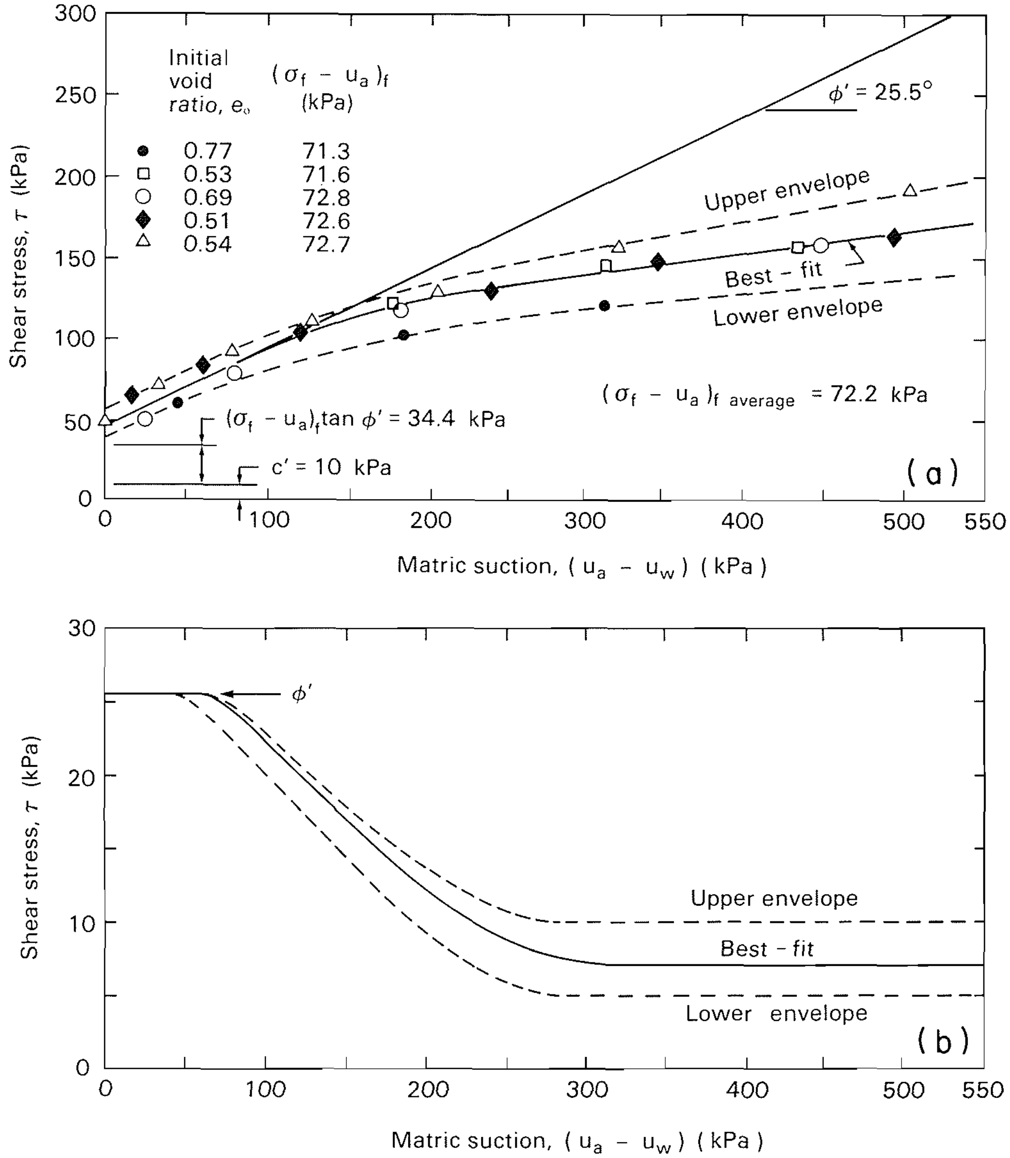

FIG. 9. Failure envelopes obtained from unsaturated glacial till specimens: (*a*) failure envelope on τ versus $(u_a - u_w)$ plane; (*b*) ϕ^b values corresponding to the three failure envelopes.

unsaturated tests and (ii) the fact that two different direct shear machines were used: the conventional apparatus for testing the saturated specimens and the modified apparatus for the unsaturated specimens. The variation in the initial void ratios produces scatter in the intercepts obtained for both the saturated and unsaturated specimens.

The angle ϕ^b can be viewed in terms of being either part of the frictional component of shear strength or part of the cohesional component of shear strength. As part of the frictional component, its maximum value can be assumed to be equal to ϕ'. As the soil becomes unsaturated the cross-sectional area through which the water phase acts is decreased, and as such, an increase in the matric suction is not as effective in increasing the shear strength as is an increase in the normal stress. As part of the cohesional component, the angle ϕ^b is simply used as a mathematical convenience for defining the increase in strength as matric suction is increased. It would appear preferable to view the soil as having one angle of internal friction, namely, ϕ'.

The direct shear tests on the unsaturated specimens have been conducted at a constant net normal stress of 72.2 kPa. Therefore, comments regarding the nonlinearity in the failure envelope strictly apply to a net normal stress of 72.2 kPa. Further testing at different net normal stresses is recommended to more fully characterize the entire failure envelope.

The nonlinearity of the failure envelope with respect to matric suction has been addressed and discussed in detail by Fredlund *et al.* (1987). Triaxial test results on compacted Dhanauri clay were reanalyzed using the assumption of a curved failure envelope. The consolidated drained and constant water content test failure envelopes exhibited close agreement, indicating uniqueness in the strength designation. In other words, both the consolidated drained and constant water content test data yielded the same nonlinear shear strength surface. It should be noted however, that this was not the case when the same data were analyzed using a planar failure envelope (Ho and Fredlund 1982). In summary, the nonlinear interpretation of the shear strength test data for unsaturated soils appears to

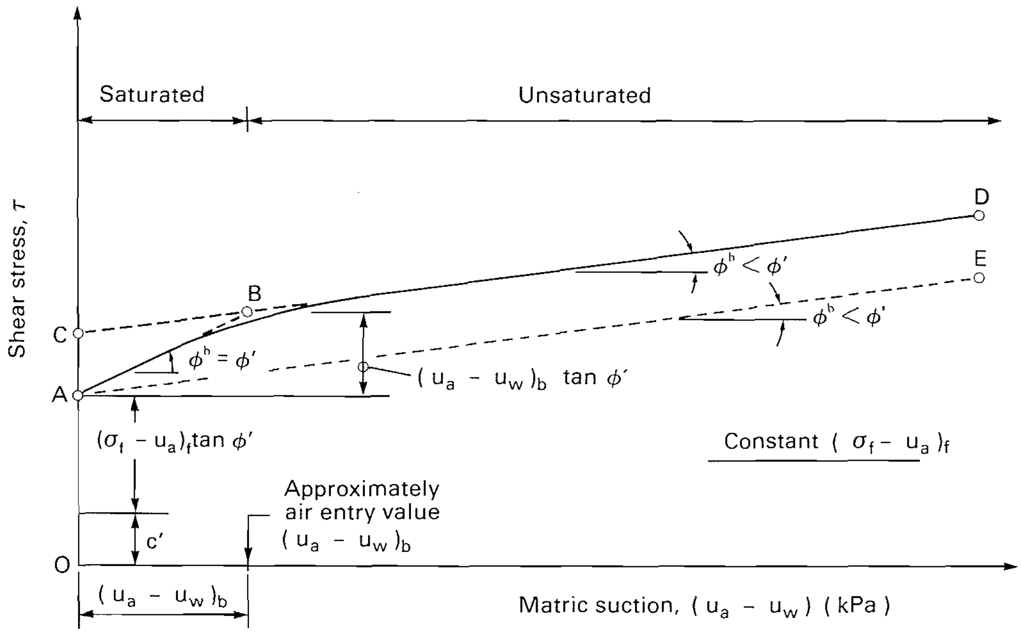

FIG. 10. Several procedures for handling the nonlinearity of the failure envelope.

provide a unique failure envelope. In some cases, however, it may not be necessary to use a nonlinear interpretation.

Procedures for accommodating the nonlinearity of the shear strength envelope

Several procedures for handling the nonlinearity of failure envelope have been proposed by Fredlund *et al.* (1987). These are illustrated in Fig. 10. The failure envelope shown in Fig. 10 has a cohesion intercept of c' plus the term $((\sigma_f - u_a)_f \tan \phi')$, which is due to the applied net normal stress at failure (i.e., point A). The ϕ^b angle along the $\overline{AB}$ portion is equal to ϕ' and decreases to a value lower than ϕ' as matric suction is increased beyond point B. The matric suction at point B appears to be correlative with the air entry value of the soil, $(u_a - u_w)_b$. The ϕ^b angle is equal to ϕ' when the soil remains saturated (i.e., $\overline{AB}$) and the ϕ^b angle decreases to a lower value when the soil has become unsaturated.

The first procedure suggested for handling the nonlinearity in the failure envelope is to use two linear envelopes, $\overline{AB}$ and $\overline{BD}$, for the two ranges of matric suction (Fig. 10). The second procedure is to use a lower limit failure envelope (i.e., $\overline{AE}$) along with the lower ϕ^b angle for the entire range of matric suction. This procedure is simpler, but gives a lower shear strength than the actual shear strength. The third procedure is to discretize the failure envelope into several linear segments if the envelope is highly nonlinear. Fourthly, the $\overline{AB}$ portion can be translated onto the shear stress versus $(\sigma - u_a)$ plane, since the ϕ^b angle is equal to ϕ'. As a result, the failure envelope on the shear stress versus matric suction plane constitutes the $\overline{BD}$ portion of Fig. 10. In this case, the nonlinear failure envelope is linearized by commencing the matric suction axis at the entry value of the soil, $(u_a - u_w)_b$.

Conclusions

The shear strength parameters of an unsaturated soil can be obtained using a direct shear apparatus, modified in order to apply matric suctions greater than 101 kPa (1 atm) to the soil specimen. The direct shear test uses a relatively thin specimen, in comparison with the triaxial test, and can significantly reduce the time required for testing unsaturated soils of low permeability.

The multistage direct shear test on Indian Head glacial till yields consistent results. It appears that the failure envelope for an unsaturated soil may be somewhat nonlinear with respect to the matric suction axis. When the soil remains saturated, the ϕ^b angle is approximately equal to the ϕ' angle. As the soil desaturates at higher matric suctions, the ϕ^b angle appears to decrease to a relatively constant value. The nonlinearity in the failure envelope becomes noticeable when the soil is tested over a wide range of matric suctions (e.g., 0–500 kPa).

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