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Multistage Direct Shear Testing of Unsaturated Soils

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ABSTRACT: A conventional direct shear box was modified to accommodate the testing of an unsaturated soil. The design concepts and necessary modifications to the apparatus are described. A multistage testing procedure is outlined. Typical results from direct shear tests are presented. The results illustrate the relationship between suction and shear strength for a glacial till soil.

KEYWORDS: shear strength, direct shear tests, unsaturated soils, negative pore-water pressure, soil suction, friction angles, high air entry disks

The shear strength testing of unsaturated soils has been performed by several researchers using triaxial equipment [*1-3*]. The long time required to fail a specimen using triaxial equipment is due to the length of the drainage path and the low permeability of both the soil and the high air entry ceramic disk. Triaxial testing must, therefore, be reserved for relatively permeable unsaturated soils [*3*].

A relatively thin specimen can be used when using a direct shear box. This greatly reduces the time required for testing, making it feasible and more practical to test unsaturated soils of low permeability. Large shear displacements in two opposing directions are also possible in the direct shear box. These features make the direct shear box more suitable than the triaxial apparatus for testing unsaturated soils.

Escario [*4*] successfully applied the axis-translation technique to the direct shear testing of unsaturated soils. His modifications allowed the independent control of the air and water pressures. Further results were presented by Escario and Sáez [*5*]. The basic ideas used in his research program have been used in the modification and development of the equipment for the study presented in this paper.

The shear strength theory for unsaturated soils proposed by Fredlund et al. [*6*] is the basis for the interpretation of the direct shear box results. The shear strength equation is expressed as follows

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

where

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

This investigation concentrates mainly on the design of the direct shear box and the relationship of shear strength to matric suction. A glacial till from Indian Head, Saskatchewan, Canada, is used in this investigation.

Design Concepts

In order to determine the stress variables in the shear strength equation, that is, $(\sigma_n - u_a)$ and $(u_a - u_w)$, it is necessary to measure both the pore-air and pore-water pressures, or to maintain these pressures at predetermined values. Modifications are necessary to the direct shear box in order to render the equipment capable of independently controlling or measuring the pore-air and pore-water pressures. Water may cavitate when the water pressure falls below atmospheric pressure. Cavitation will disrupt the continuity of the water in the measuring system. This phenomenon will limit the magnitude of suction that can be directly measured to about 90 kPa. The cavitation problem is commonly circumvented in the laboratory through the use of the axis-translation technique. The essence of the technique is to raise the total, air, and water pressures by equal amounts; therefore, the value within each parenthesis of Eq 1 is not changed. This procedure does not affect the curvature of the air-water meniscus and allows the water pressure to be maintained at a positive value.

The independent control of the pore-air and pore-water pressures requires the use of a high air entry disk. The high air entry disk allows the slow passage of water but does not permit the flow of free air as long as the difference between the air and water pressures does not exceed the air entry value of the disk. The flow of water through the disk ensures a continuous column of water from the soil specimen to the water pressure measuring system below the disk. In this way, the pore-air and pore-water pressures are independently controlled.

Equipment Modification

A conventional direct shear apparatus manufactured by Clockhouse Engineering Limited of England was selected for modifica-

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tion. The modified apparatus is shown in Fig. 1. The main addition to the standard apparatus was the air pressure chamber, which completely enclosed the direct shear box in order to elevate the ambient air pressure in which the test was run. Two major modifications were done in this study, both related to the control of the pore-air and pore-water pressures. These modifications are described in detail in the following two paragraphs.

Shear Box Base Design

A plan view of the shear box base is shown in Fig. 2. The high air entry ceramic disk is removed in order to show the details of the water chamber. The raised sections inside the water chamber serve both as a support for the high air entry disk and as a guide for water flow (Figs. 2, 3, and 4). Water can be circulated from the entry port to the exit port below the high air entry disk. This ensures a thorough flushing of the channels and compartment below the ceramic disk, to remove entrapped air bubbles. Although the high air entry disk does not allow the passage of free air, dissolved air diffuses through the water in the high air entry disk and appears as air bubbles below the disk.

The high air entry disk is placed on the raised channel guides. It is tightly sealed into position with epoxy cement to ensure that air will not enter the water chamber. The time for pressure equalization across the high air entry disk increases with greater thickness and higher air entry value of the disk. The time for pressure equalization affects the testing time, making a thin disk superior. On the other hand, a thin high air entry disk may easily crack, particularly if care is not taken to ensure that the vertical load and the air pressure are applied before pressurizing the water chamber beneath the high air entry disk. On the basis of past experience, a 6.4-mm (that is, 1/4-in.) thick ceramic disk was used. The completed shear box base is shown in Fig. 5.

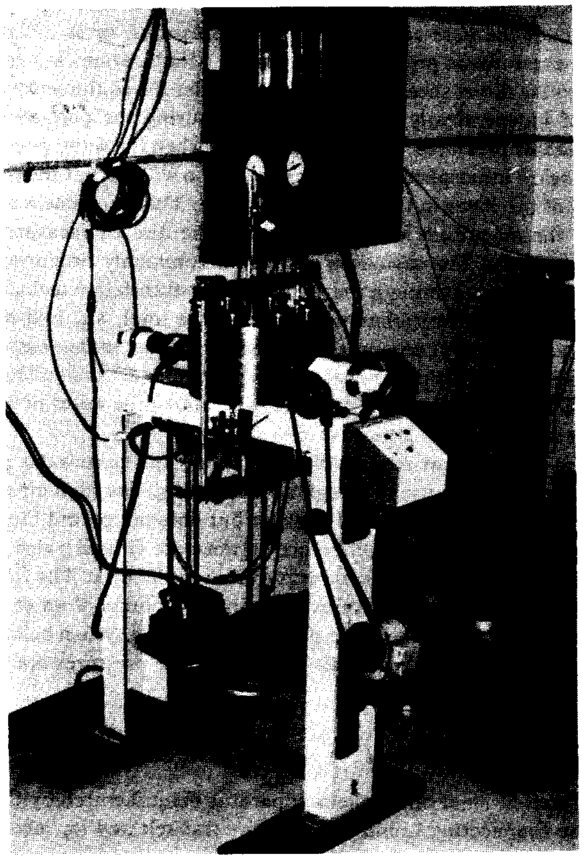

FIG. 1—*Layout of the complete direct shear box apparatus.*

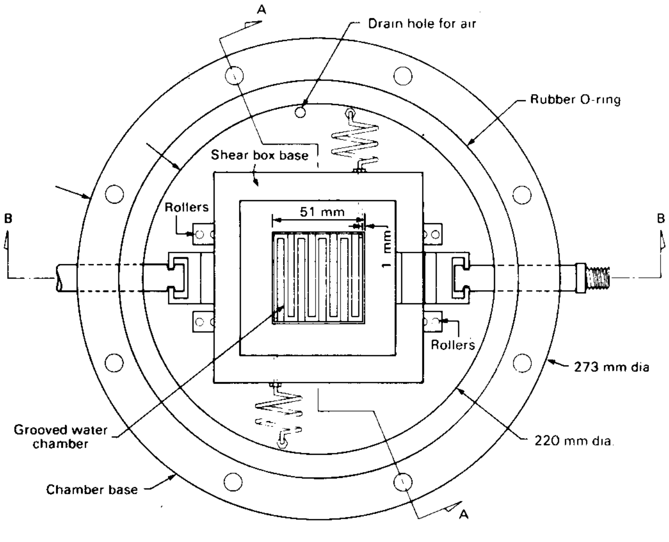

FIG. 2—*Plan view of shear box in pressure chamber (with high air entry disk removed).*

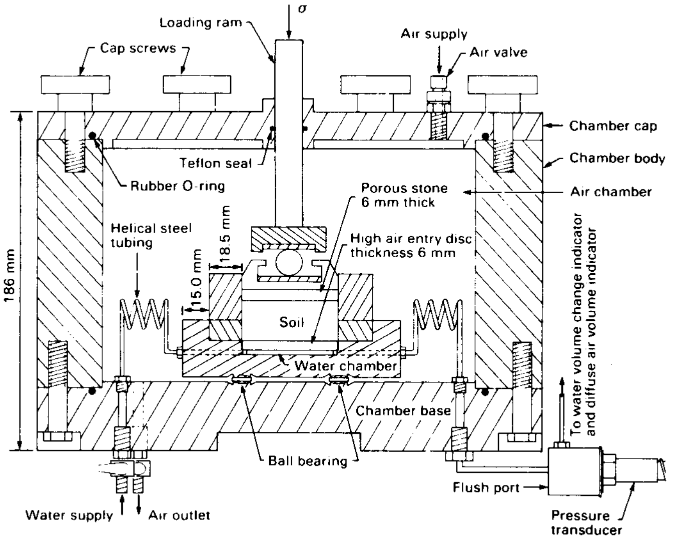

FIG. 3—*Cross-sectional view A-A of shear box and pressure chamber.*

In the original equipment and the present modified equipment, shearing was induced by displacing longitudinally the lower portion of the shear box. As well, the alignment of the box separation with the axis of the shear load application and the shear load measurement is provided in both devices (Fig. 4). The base of the shear box is seated on rollers that run in grooved tracks on the chamber base. Steel tubings rolled into two flexible helical springs were used to connect the water chamber to its inlet and outlet in the chamber base (Figs. 2 and 3). The resistance to movement of the lower box

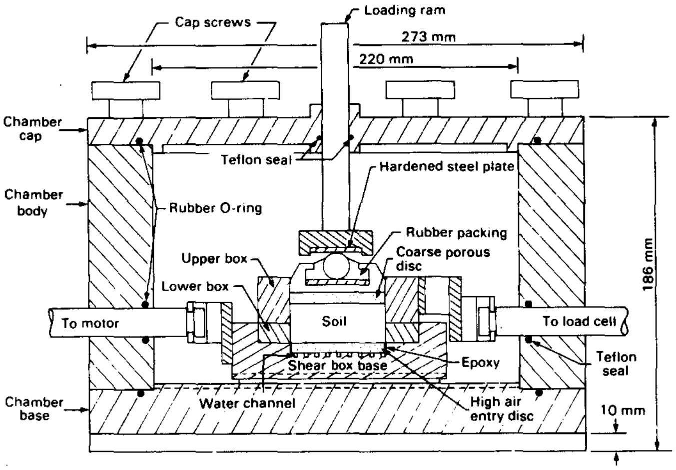

FIG. 4—*Cross-sectional view B-B of shear box and pressure chamber.*

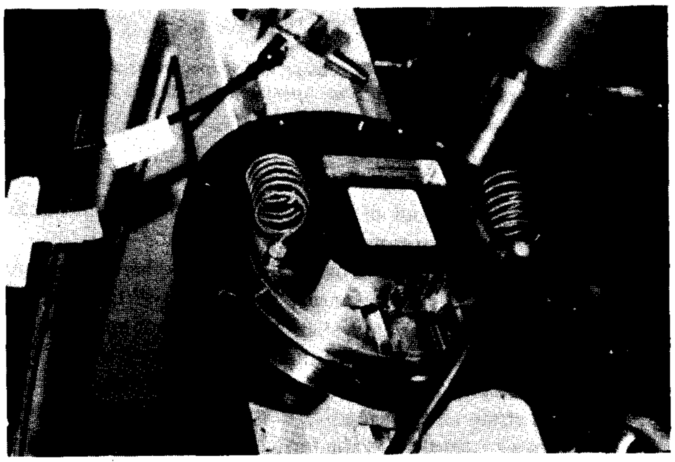

FIG. 5—*Details of shear box base and chamber base.*

resulting from these helical steel tubings and the frictional resistance from the rollers do not introduce significant errors or inaccuracies to the shear resistance measured on the upper box.

Several features of the modified direct shear box are different from the design described by Escario [4]. The main differences relate to the lower portion of the shear box. In Escario's design, the lower portion of the shear box was immovable and the shear force was applied through the upper portion of the box. This simplified the plumbing into the water chamber but resulted in problems related to eccentric normal loading of the specimen. The shear load in Escario's design was measured on the loading ram, thereby including the friction of the roller bearings. The present shear box also included the use of low friction, Teflon® seals, as well as a water volume change indicator and a diffused air volume indicator.

Air Pressure Chamber Design

A pressure chamber surrounds the entire shear box in order to maintain any selected air pressure in and around the specimen. The cylindrical chamber was built of stainless steel and designed for pressures of up to 1000 kPa. The investigations reported in this paper are limited to suctions of 500 kPa. Safety must be a high priority when working with compressed air, and this explains the robustness of the air pressure chamber.

The chamber consists of three components. These are (1) the chamber cap, (2) the chamber body, and (3) the chamber base. All three components are built of stainless steel. The air-tightness of the entire chamber is ensured through the use of two rubber O-ring seals, one on the chamber cap and the other on the chamber base (Fig. 6). The cap is held to the body through the use of six cap screws. When testing soil specimens, only the chamber cap is removed. The chamber body is dismantled from the chamber base only in the event that the shear box base must be removed (that is, for replacing the high air entry disk).

The chamber cap has an air valve and an axial loading ram (Figs. 3 and 6). The circular hole has a Teflon® ring seal to ensure air-tightness when the loading ram is in place. An ample quantity of vacuum grease should be used around the loading ram. An air supply is connected to the chamber via the air valve and is controlled by a pressure regulator (Fig. 7).

The chamber body is a 26.5-mm-thick stainless steel cylinder of 220-mm internal diameter. Two holes, diametrically opposite each other, provide the necessary housing for the pistons that apply the shear force acting on the shear box assembly. These holes are lined on the inside with a Teflon® seal and are airtight. A plan view of the chamber base with the shear box base in position is shown in Fig. 5. Details of the chamber base have been shown in Figs. 2, 3, and 4.

Suction Control and Auxiliary Appurtenances

The desired matric suction is applied to the soil specimen by maintaining a constant air pressure in the air pressure chamber and a constant water pressure in the water chamber below the high air entry disk. The pore-air and pore-water pressures in the soil are then allowed to come to equilibrium with these applied pressures.

Several test procedures have been investigated, but the following procedure appears to be most satisfactory. The specimen is initially subjected to water (that is, from the top in the air pressure cham-

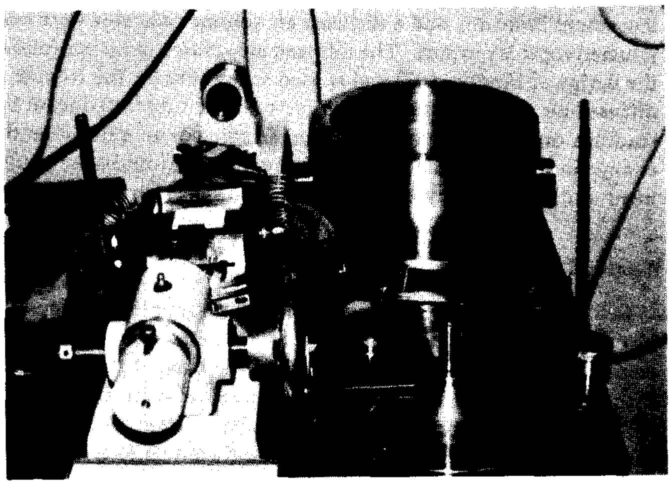

FIG. 6—*Dismantled direct shear apparatus showing the various components.*

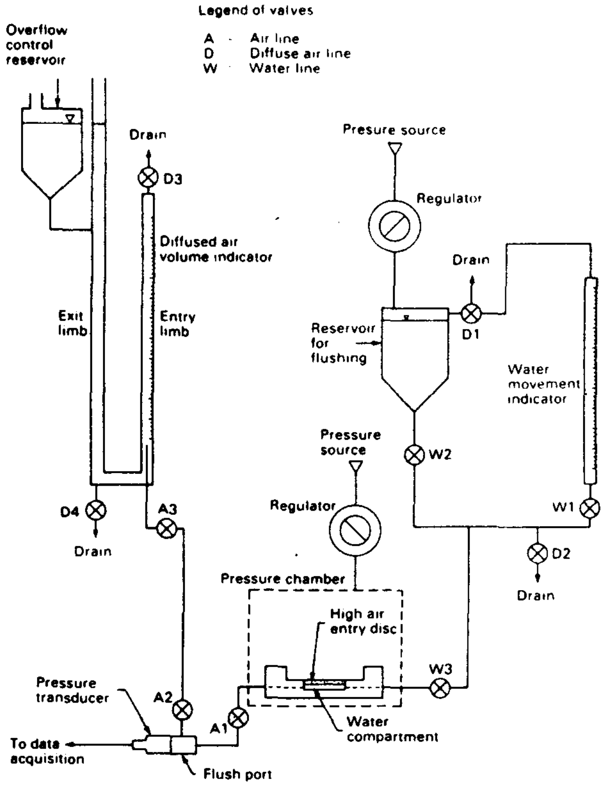

FIG. 7—*Schematic of plumbing layout of modified shear box system for testing unsaturated soils.*

ber) in order to reduce its suction value toward zero. After equalization, the air and water pressures are then applied to give the desired matric suction. The applied air pressure causes water to flow out of the base of the specimen. The flow of water ceases when the desired suction value is attained (Fig. 8). At equalization, the pore-water and pore-air pressures in the soil are equal to the applied pressures. To determine the point of equilibration, it is necessary to monitor the movement of water from the specimen. A water movement indicator and a diffused air volume indicator were constructed for this purpose. The diffused air volume indicator follows the design of Fredlund [7] and is used to account for the volume of diffused air. The diffused air volume must be subtracted from the readings on the water volume change indicator to determine the change in water volume in the specimen. The layout of the equipment and the auxiliary appurtenances are shown in Fig. 7.

Testing Procedure

Before the soil specimen is trimmed and mounted in the shear box, it is first necessary to saturate the high air entry disk with deaired water. This is done by flooding the base of the shear box with deaired water and subsequently pressurizing the air chamber to force the water through the ceramic disk. After each flooding, the water chamber is flushed to remove diffused air from below the high air entry disk. This procedure is repeated several times. When this process is complete, the air pressure chamber is opened and the shear box base is again flooded with deaired water. This time the air pressure chamber is covered with a plastic sheet to reduce evaporation and drying out of the high air entry disk until such time that the testing is to commence.

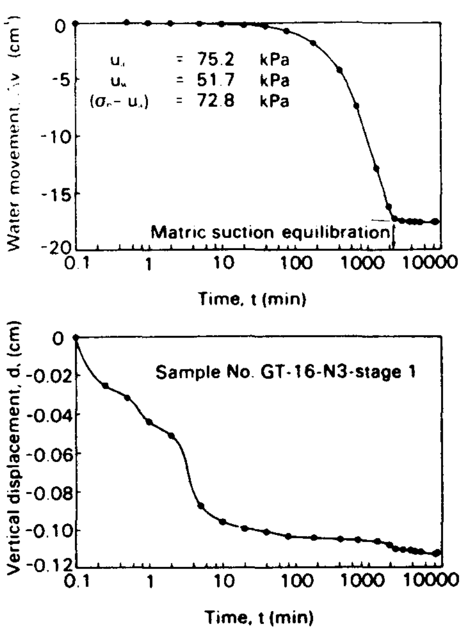

FIG. 8—*Water movement and consolidation of specimens during desaturation to attain suction equilibration: Specimen CT-16-N3, Stage 1.*

The two halves of the shear box are placed together and sealed with vacuum grease. This is to ensure that water will flow only in the direction of the high air entry disk. It is important not to smear vacuum grease onto the surface of the high air entry disk.

After the soil specimen is mounted in the shear box, the top coarse porous stone and the loading cap are installed. An ample quantity of water is applied to the top of the specimen. To ensure an adequate supply of water, a 60 by 60 mm^2 specimen trimmer is sealed onto the top of the upper portion of the shear box to hold a reservoir of water. Alternatively, the specimen may be flooded with water for a day before placing the coarse porous stone and the loading cap in place. The chamber cap is then fitted. The predetermined axial load, air pressure, and water pressure are applied in sequence. If the water pressure is applied first, there is a possibility of cracking or dislodging the high air entry disk. It is important to check that there are no detectable leaks in the high air entry disk. Leakage of air will render the determination of suction equilibration difficult because of the seemingly continuous loss of fluid from the system.

The water placed over the specimen must permeate through the soil, and then the applied matric suction is established in the specimen. While the soil specimen is coming to equilibrium with the applied suction, readings are taken of (1) time, (2) vertical deflection, and (3) water movement from the specimen. The vertical deflection reading is taken by means of a linear voltage displacement transducer (LVDT). Equalization is assumed when there is no further flow of water.

After suction equalization is achieved, the specimen is sheared at a constant displacement rate of approximately 0.00017 mm/s. This rate was sufficiently slow to ensure completely drained conditions. A multistage testing procedure is used in order to obtain the ϕ^b angle from a single specimen. The shear resistance, which is measured by means of a load cell, is monitored to ensure that the soil is not sheared beyond its peak strength. Water movement from the specimen is also observed. When the peak strength is imminent, the displacement of the shear box is stopped. The shear force is removed from the specimen by reversing the direction of displacement. The soil is left overnight in this condition.

The next day, a new matric suction is applied, and the above process is repeated. The test generally consists of at least three stages.

Typical Test Results and Their Interpretation

Direct shear tests were carried out on both saturated and unsaturated specimens of a glacial till. The glacial till had a liquid limit of 35.5%, a plastic limit of 16.8%, and contained 30.0% clay size particles. The specific gravity of the soil solids was 2.734. The maximum dry density was 1.82 Mg/m^3, and the optimum water content was 16.0%. Specimens GT-16-N4 and GT-16-N5 were statically compacted to an initial void ratio of approximately 0.63 at a water content of 12.1%.

The tests on saturated specimens were used to obtain the effective angle of internal friction ϕ' and the effective cohesion c'. Two groups of tests were conducted on the saturated specimens. One group consisted of individual specimens, sheared only once to failure. The second group of specimens were sheared to their peak strengths using five stages, each stage having a successively increasing normal applied stress. The results from the single-stage and multistage tests essentially formed a single failure envelope. The best-fit effective angle of internal friction was 25.5°, and the corresponding effective cohesion was 10.0 kPa (Fig. 9).

Tests on the modified direct shear apparatus were carried out using a constant net normal stress ($\sigma_n - u_a$) of 72.0 kPa. Each specimen was sheared using from three to seven stages. The matric suctions ranged from 0 to 500 kPa.

Results of tests on two specimens are shown in Figs. 10 and 11. The corresponding suction envelopes (that is, of τ versus $(u_a - u_w)$ at a constant $(\sigma_n - u_a)$) are shown in Figs. 12 and 13. The suction envelopes are nonlinear. It is observed that the slope of the suction envelope (that is, ϕ^b) commences at a value equal to ϕ' near saturation and starts to decrease significantly at matric suctions of 50 to 100 kPa. The suction envelopes eventually reach a fairly constant slope with ϕ^b ranging from 6 to 10° when the matric suction exceeds 250 kPa.

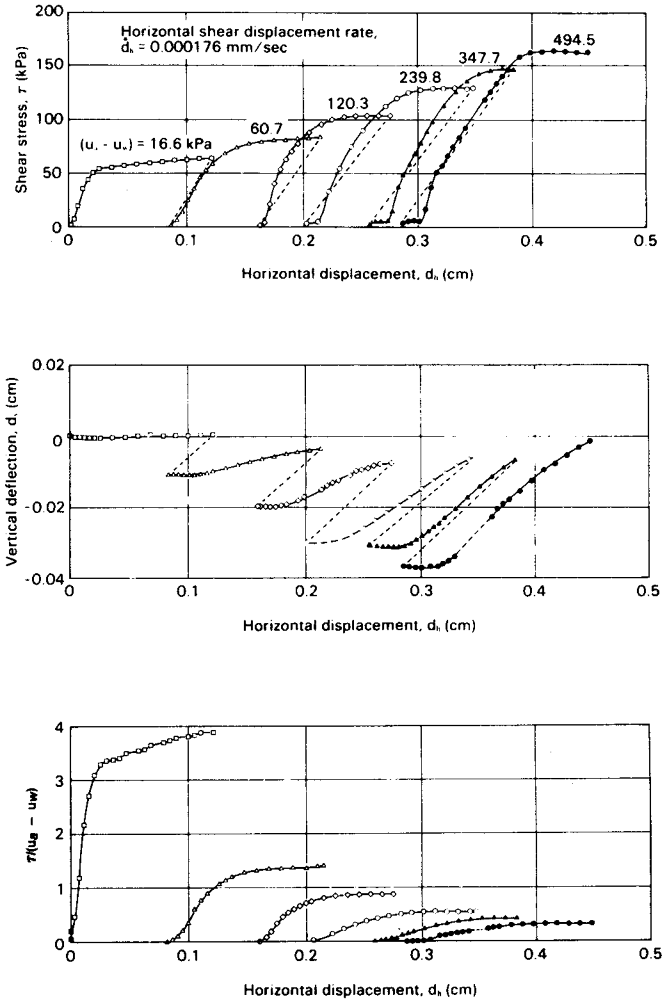

FIG. 10—*Multistage direct shear test on unsaturated glacial till, Specimen GT-16-N4.*

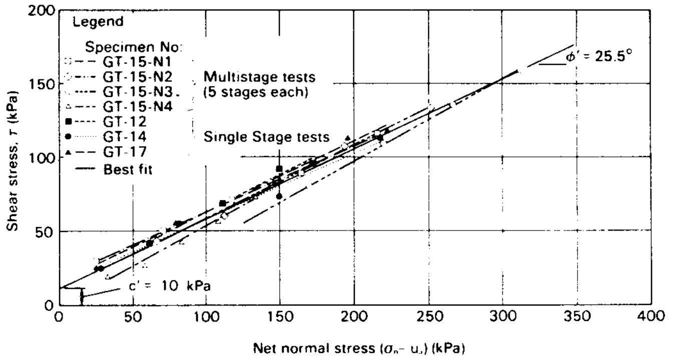

FIG. 9—*Summary of Mohr failure envelopes from direct shear tests on saturated glacial till.*

The effective cohesion (that is, $c' = 10$ kPa), and the normal component, ($(\sigma_n - u_a) \tan \phi' = 34.6$ kPa), obtained from saturated specimens gave a shear strength of 44.6 kPa. The shear strength from the unsaturated specimens, extrapolated onto the saturated plane, gave a value slightly in excess of 50 kPa. This difference is small, but further studies may reveal whether or not it is of significance.

It is postulated that in the linear section of the envelope where ϕ^b is equal to ϕ', the soil behaves essentially as a saturated soil. With an increasing suction, the soil begins to desaturate, and the ϕ^b angle decreases. While it is important to recognize the nonlinearity in the matric suction strength envelope, it would not appear to be necessary to change the form of Eq 1.

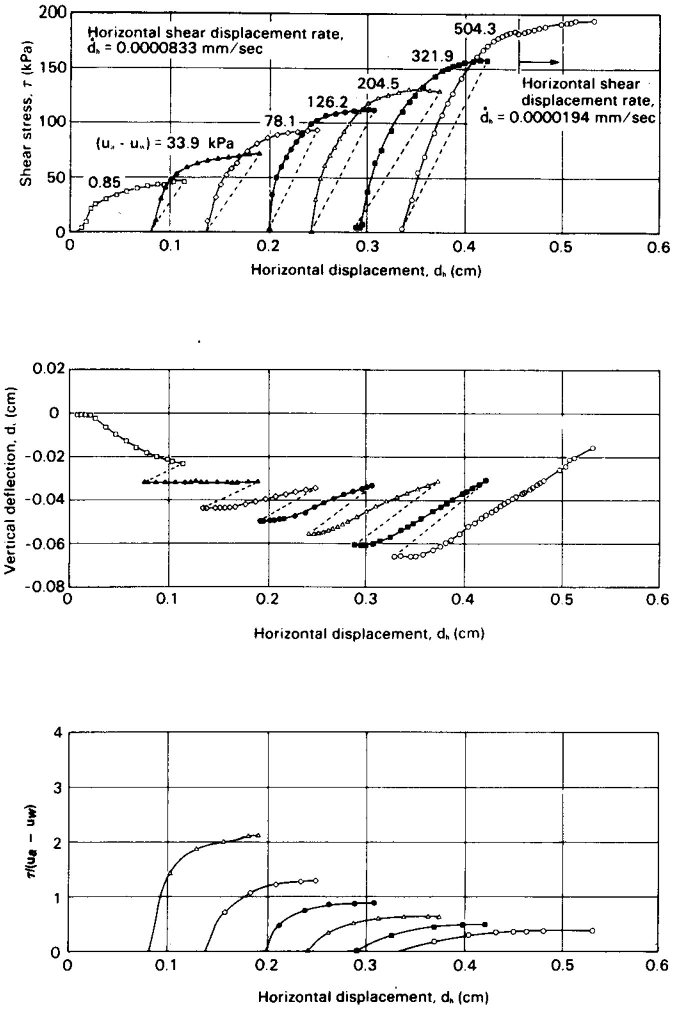

FIG. 11—*Multistage direct shear test on unsaturated glacial till, Specimen GT-16-N5.*

Summary

A conventional direct shear box apparatus has been modified for the shear strength testing of unsaturated soils. The greatly reduced length in the drainage path allows for the equalization of the pore-air and pore-water pressures within a reasonable time period. The primary modifications to the direct shear box involve the installation of a high air entry disk in the base of the direct shear box and the construction of a chamber to enclose the entire shear box. These modifications allow the use of the axis-translation technique to establish high matric suctions in the soil.

Specimens were tested by initially wetting the soil to cause the suction to approach zero. Various matric suctions were then applied, and the specimens were tested using a multistage procedure. Further studies using other procedures to prepare the specimens for testing would be of interest.

Results from the proposed multistage direct shear testing on the glacial till show that the suction envelope is nonlinear. The slope of the suction versus strength envelope approaches a ϕ' value at low suctions and reduces substantially at high matric suctions.

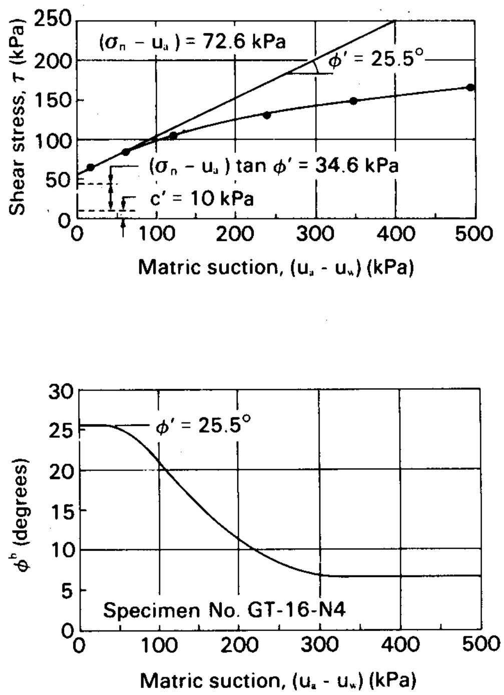

FIG. 12—*Suction envelope and variation of ϕ^b with suction, Specimen GT-16-N4.*

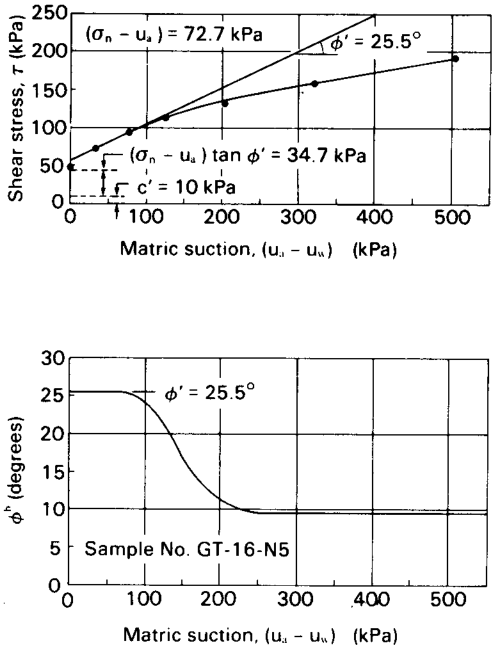

FIG. 13—*Suction envelope and variation of ϕ^b with suction, Specimen GT-16-N4.*

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