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Triaxial Testing of Unsaturated Agricultural Soils

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In this paper, triaxial testing procedures and equipment as they have been applied to unsaturated soils are surveyed. Modifications to conventional triaxial apparatus and procedures for testing unsaturated soils based on principles of "unsaturated soil mechanics" are described in some detail. The modifications accommodate the independent measurement or control of pore-air and pore-water pressures and the resolution of both air and water components of volume change. This makes it possible to study the influence of soil suction on soil strength and volume change behaviour. To illustrate this approach, an agricultural soil was tested in a modified triaxial apparatus using independent stress state variables to describe stresses in the specimen. Matric suction, mean net stress and deviatoric stress were monitored or controlled in a series of constant water content tests. Volume change and shear strength behaviour were evaluated based on unsaturated soil mechanics principles. For low stress regimes, matric suction remained essentially constant under constant water content testing; however, as loading was increased matric suction varied significantly. The relevance of using matric suction as an independent stress state variable in fundamental studies of agricultural soil behaviour, as opposed to a total stress approach, is discussed.

Notation

c	total cohesion of unsaturated soil, kPa
c'	effective soil cohesion, kPa
e	void ratio
K_0	coefficient of earth pressure at rest
L/D	length to diameter ratio for triaxial specimens
S_r	degree of saturation, %
u_a	pore-air pressure, kPa
u_w	pore-water pressure, kPa
$u_a - u_w$	Matric suction, kPa
ΔV_a	specimen air volume change, ml
ΔV_w	specimen water volume change, ml
w	gravimetric water content, %
χ	soil parameter in Bishop's effective stress equation for unsaturated soil
ϕ'	soil angle of internal friction, deg
ρ	soil wet bulk density, Mg/m^3
σ	total stress, kPa
$\sigma - u_a$	net stress, kPa
σ'	effective stress ($\sigma - u_w$), kPa
σ_1	axial stress, kPa
σ_3	radial stress, kPa

1. Introduction

The most widely used laboratory equipment for investigating the strength and deformation behaviour of soils is the triaxial apparatus. The apparatus is versatile and can be used for the measurement of many parameters, including shear strength characteristics, consolidation characteristics and the permeability of soil. Its key features include facilities for the control of the magnitude (but not direction) of the principal stresses, the control of drainage, and the measurement of pore pressures.[1] With a suitable control system, modern triaxial cells provide the ability to perform stress path tests (i.e. time-varying functions of stress or strain) while precisely controlling or measuring pore fluid pressures, volume change, axial forces and deformation. These capabilities are key to the derivation of constitutive models for soils such as those based upon critical state concepts, and to improving our fundamental understanding of soil behaviour.

The conventional triaxial apparatus is designed to measure and control stress and strain related variables for saturated soils. A review of the agricultural soils literature shows that few modifications in equipment and procedures have been implemented when testing unsaturated soils. Pore-water pressures are widely assumed to remain constant under undrained loading conditions, and therefore data has been analysed in terms of total stresses.[2] Over the last 30 years, significant developments have been made for laboratory testing and analysis of unsaturated soils. Modifications for testing unsaturated soils take into account the nature of stresses and strains in an unsaturated granular medium.

1.1. *Stress state variables for unsaturated soils*

Unsaturated soils are characterized by the presence of an air phase, a water phase and an air-water interface in the voids. Because of this, it has been difficult to describe an appropriate stress state variable for unsaturated agricultural soils.[2–4]

For a *saturated* soil both the strength and volume change behaviour are governed by the effective stress

$$\sigma' = \sigma - u_w \tag{1}$$

where σ is the total stress (kPa), σ' the effective stress (kPa) and u_w the pore-water pressure (kPa).[5]

Since different pressures can exist in the air and the water phases of an unsaturated soil, this simple idea of effective stress does not apply. In 1959, Bishop[6] proposed an effective stress relationship for unsaturated soils. The proposed equation introduced a soil parameter, χ, as a stress partitioning factor. At saturation, with water as the pore fluid, χ was equal to 1 and the expression reduced to Terzaghi's effective stress [Eqn (1)]. Jennings and Burland[7] and Burland[8] showed that effective stress for unsaturated soils was unable to fully explain the mechanical behaviour of unsaturated soils. The soil parameter, χ, was difficult to evaluate[9] and was different when determined for shear strength and for volume change.[10]

Fredlund and Morgenstern[11] reconsidered an unsaturated soil as a four-phase system. They call the fourth phase, representing the air–water interface, the *contractile skin*. On the basis of multiphase continuum mechanics they showed that the total stress σ, pore-air pressure u_a, and pore-water pressure u_w must be combined in two independent stress parameters. The two stress state variables most often selected for practical engineering analysis are the net stress: $(\sigma - u_a)$, and the matric suction: $(u_a - u_w)$. The stress state variables separate the effect due to changes in normal stress from the effect due to change in pore-water pressure. Matric suction is considered here as an independent stress variable and, therefore, the need for a single-valued effective stress equation for unsaturated soil is eliminated.[10] This framework for an "unsaturated soil mechanics" is becoming widely accepted in the engineering research community as is evident by the many recent papers dealing with the mechanics of unsaturated soils (e.g. see Refs 12–17).

In general, it can be assumed that for agricultural conditions, the air in the pore spaces join up and ultimately interconnect with the atmosphere. Under these conditions, u_a is equal to 0 kPa (gauge) and the two stress variables, net stress and matric suction, become total stress σ and tension in the pore water, u_w, respectively.

2. Triaxial testing of unsaturated soils

Triaxial equipment and testing procedures have been described in detail by Bishop and Henkel[18] and Head[1] for saturated soils and by Fredlund and Rahardjo[10] for unsaturated soils. The triaxial test is performed on a cylindrical soil specimen subjected to an all round confining pressure usually applied by pressurizing a water-filled cell. Axial stress can be applied to the specimen through a loading rod, typically in contact with the top of the specimen. In saturated soil testing, the soil specimen is enclosed in a rubber membrane and its ends placed between porous caps with drainage ducts to allow movement of water from the sample. The change in volume of the sample is given by the volume of water expelled from the sample. Modern triaxial testing for unsaturated soils accomodates the independent measurement and control of pore-air, pore-water pressures and volume changes with provision for control and measurement of matric suction. Modifications to procedures employed during the testing of unsaturated soils are highlighted below.

2.1. *Specimen preparation*

Triaxial tests may be performed on undisturbed field samples or on remoulded specimens prepared in the laboratory. Although undisturbed specimens provide better representation of field conditions than remoulded specimens, they can be difficult to obtain. Undisturbed field samples shrink when soil moisture is lost, and difficulties may be experienced with stones, vegetative cover and non-homogeneity in the soil. During triaxial testing of undisturbed specimens, the likelihood of generating uneven stress distributions and pore pressures within the soil is therefore greater. Thus, for fundamental, theoretically based investigations into the nature of soil behaviour, remoulded specimens are generally used. Nevertheless, since it is practically impossible to reproduce "natural" structures using remoulded specimens, undisturbed specimens should be used when comparing model predictions with field data or when evaluating the natural variability of soil properties.

Remoulded specimens are prepared by compacting a soil sample to desired water content and bulk density specifications in a mould. The compaction process may be static (using a piston), impact (using a hammer) or kneading (in which the soil is loaded using a tamper, and can undergo extensive shearing strains) depending on the object of the test, soil type and desired initial structure. If strength is the primary object of the test, a flocculated structure can be achieved by static compaction methods. If plasticity or flexibility is required, a dispersed structure can be achieved by a kneading compaction on the wet side of the optimal water content for compaction.[19]

In using remoulded specimens, only specimens with identical structures should be used to determine unique shear strength parameters for the soil, i.e. specimens with the same texture and stress history. If they do not have the same structure, they may produce different shear strength parameters. Thus, specimens must be compacted at the same initial water content and bulk density to represent an "identical soil".

Triaxial specimens are usually prepared at-length-to diameter ratios (L/D) of between 1.5 and 2 in order to minimize end effects due to the end platens of the apparatus and to reduce the likelihood of buckling during testing.[20,21] Data presented by Grisso *et al.*[22] for triaxial specimens of an agricultural soil with L/D ratios of 1, 1.5 and 2, indicated that the L/D ratio had little effect on hydrostatic compaction of these specimens.

2.2. *Pore-water pressure control or measurement*

Unsaturated soils are characterized by negative pore-water pressures, i.e. $u_w < 0$. Pore-water pressure in an unsaturated specimen is usually measured or controlled through a saturated fine ceramic disk integrated with a base pedestal connected to the measuring system water compartment.[10] The matric suction in the specimen ($u_a - u_w$) must not exceed the air entry value of the disk (i.e. the minimum matric suction at which air can pass through the disk), or air will enter the water compartment which will become filled with air bubbles and no longer maintain continuity between the pore-water and the water in the measuring system.[10,23] Another limitation to the measurement of pore-water pressure of unsaturated soils with large negative pore-water pressures is that water cavitates as a gauge pressure of -101 kPa is approached. As a result, air bubbles will accumulate in the water compartment below the disk leading to erroneous readings (*Fig. 1a*). The limitation to the measurement or control of pore-water pressures in unsaturated soils with high matric suction can be overcome using the axis-translation technique (see below).

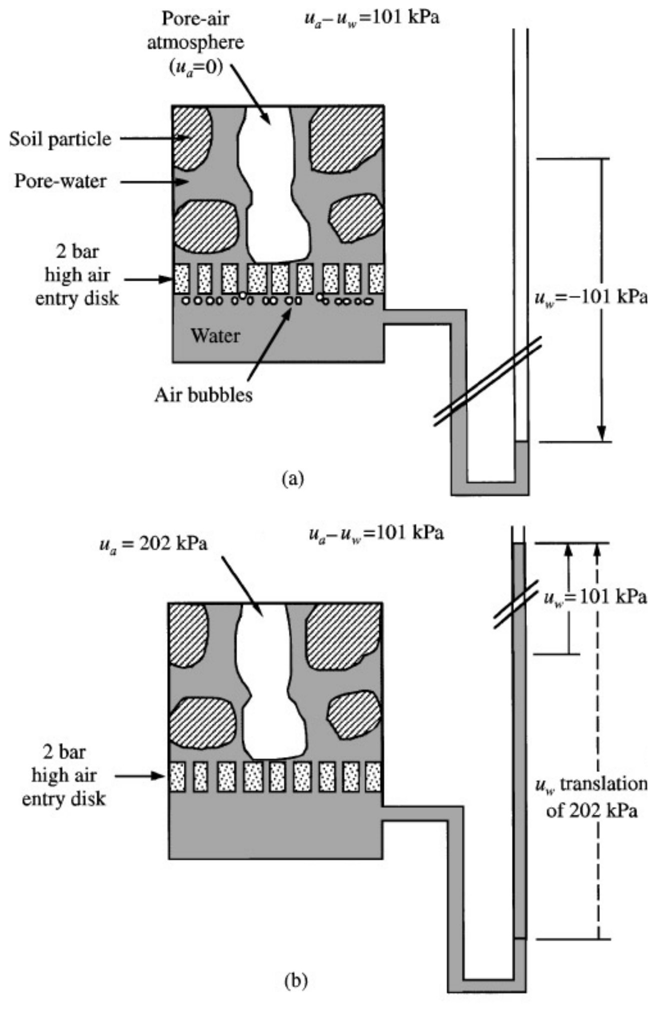

Fig. 1. Measurement of pore-water pressures in an unsaturated soil specimen (after Fredlund and Rahardjo[10]). (a) Direct measurement of negative pore-water pressure showing air diffusion through the high air entry disk and water cavitation in the measuring system; (b) axis translation of 101 kPa

2.3. *Axis-translation technique*

In this procedure, the pore-air pressure is elevated above atmospheric pressure (i.e. to an artificial atmosphere) such that pore-water pressure becomes positive, yet the same matric suction relative to the artificial atmosphere is maintained in the soil sample.[10,24,25] The application of the axis-translation technique is illustrated in *Fig. 1b* for a soil specimen with a matric suction of 101 kPa. The pore pressure is measured below the saturated ceramic disk (high air entry disk) which has an air entry value of 202 kPa. In the example shown, an air pressure of 202 kPa is applied to the specimen to raise the pore-air pressure by 202 kPa, which in turn increases the pore-water pressure by the same amount to a positive value of 101 kPa. The pore-water pressure can now be measured since there is no risk of cavitation in the measuring system and continuity between the pore-water and the water in the measuring system is maintained. Note that it is still possible for air to diffuse into the water, and a system for flushing the water compartment is needed. Use of the axis-translation technique does not appear to affect the measured shear strength of unsaturated soils.[26]

2.4. *Pore-air pressure control or measurement*

Even under conditions where the pore-air remains atmospheric in agricultural soils, it is necessary to control pore-air pressure when implementing the axis-translation technique. The control or measurement of pore-air pressure is conducted through a coarse corundum disk placed on top of the specimen which provides continuity between the air voids and the pressure control system. The porous disk has a low air entry value to prevent water from entering into the control or measuring system. Pore-air pressure can be measured using a pressure transducer. Because of the high compressibility of air, the volume of the pore-air pressure measuring system should be kept to a minimum to obtain accurate measurements.[27]

2.5. *Volume change measurement*

In an unsaturated specimen, the total volume change during compression is equal to the sum of the air and water components of volume change. Agricultural engineers frequently perform testing under constant gravimetric water content conditions, so that the total volume change is due to air expelled from the specimen. The measurement of air-volume change is difficult because of the high compressibility of air, its sensitivity to temperature change, and the tendency for air to diffuse through the porous membrane.

Because of the difficulty in measuring air-volume change, many arrangements measure the overall volume change and the pore-water-volume change and then calculate air-volume change by the difference between the two. Measurement of the water component of volume change is relatively straightforward and is commonly done using a conventional twin burette volume change indicator. The measurement of overall volume change, on the other hand, is more difficult. Arrangements for overall volume change measurement have involved the use of mercury,[18] double-walled triaxial cells,[16] optical transducers[28] or non-contacting Hall effect transducers located around the specimen.[29–31] The latter method is not suitable if large deformations and radial bulging take place, e.g. for agricultural soils under deviatoric loading.

Bishop and Henkel[18] and Matyas[32] used two burettes to measure air-volume change under atmospheric conditions. This arrangement, although it has its merits, is cumbersome and limited to measurements at atmospheric conditions. Dunlap and Weber[33] described a volumeter for measuring air-volume change in triaxial testing. The volumeter was submerged into a water bath to promote constant temperature conditions. This design is also used in the NSDL/Auburn University triaxial arrangement.[22,34] Adams *et al.*[27] used a digitally controlled hydraulic actuator for measurement of air-volume changes.

Hettiaratchi *et al.*[35] described a constant cell volume triaxial apparatus for evaluating critical state parameters of agricultural soils under constant water content conditions. They modified the deviatoric loading system such that any volume change within the cell jacket was entirely due to changes in the volume of the soil specimen and the compliance of the cell. They used the pressure–volume characteristics of the system to determine specimen volume change from system pressure changes. They proposed the addition of a variable compliance unit to facilitate a wide range of controlled state path tests.

2.6. *Matric suction control*

Before setting up a triaxial specimen, it is important to measure, estimate or impose the initial matric suction. Petersen[36] brought specimens to the desired suction using a sand table and ceramic plates. Cui and Delage[37,38] imposed an initial matric suction by enclosing specimens in semi-permeable membranes and bringing the water content to equilibrum with a polyethylene glycol solution of known osmotic pressure. Adams[39] estimated matric suction of triaxial specimens by measuring the matric suction in a thin specimen using a null-pressure plate apparatus.

Triaxial testing of unsaturated soil usually requires control or measurement of suction. Independent control of pore-air and pore-water pressures by the axis-translation technique allows the measurement or control of matric suction. Thus, accuracy of matric suction measurement or control depends on the accuracy of pore-air and pore-water pressure measurements. Testing rates should also be chosen to ensure equalization of these pressures within the specimen. As an alternative to the axis-translation technique, Cui and Delage[37] used an osmotic technique to control the matric suction in a series of triaxial tests. With the osmotic technique, drainage length is reduced to half of the height of the specimen allowing faster equalization of matric suction across the specimen. It is difficult, however, to implement undrained triaxial procedures such as constant water content tests using the osmotic technique.

2.7. *Air diffusion and leakage*

The measurement of pore-air pressures and volume change is complicated by the tendency of air to diffuse into the pore-water and through the rubber membrane. Bishop and Donald[40] used mercury as the cell fluid to prevent diffusion of pore-air through the rubber membrane. They observed a significant reduction in pore-air pressure due to diffusion when water was used as the cell fluid. Caution must be exercised in using mercury columns to apply lateral pressures, particularily if high pressures are applied to the pore-air in the specimen.[41] Dunn[42] showed that diffusion through the pore-water and membrane was greatly reduced when the sample was enclosed in two rubber membranes with two slotted aluminium sheets separated by a layer of silicon grease between the membranes. The aluminium sheets were slotted vertically so that they would not add strength to the soil specimen. Komornik *et al.*[43] used rubber membranes soaked in silicon oil to prevent leakage of air or water through the specimen; however, silicon oil causes rapid deterioration of the rubber membrane, such that it cannot be reused.

2.8. *Constant water content shear test*

The constant (gravimetric) water content triaxial test is of particular relevance to agricultural engineers who are generally interested in dynamic loading of soils by agricultural equipment, i.e. undrained pore-water conditions. The constant water content test generally consists of two stages: a compression test followed be a shearing test. The specimen is consolidated under isotropic conditions at a fixed confining pressure σ_3, while the pore-air (u_a) and pore-water pressures (u_w) are controlled. When equilibrium is reached at the end of consolidation, the soil specimen has a net confining pressure ($\sigma_3 - u_a$) and matric suction ($u_a - u_w$). The specimen is then sheared, with drained pore-air phase and undrained pore-water phase, by increasing the deviatoric stress ($\sigma_1 - \sigma_3$) until the specimen fails. During shear the same pore-air pressure is maintained as that applied during the consolidation process. The pore-water pressure, however, changes during shear under undrained conditions.[10] Thus, the net confining pressure remains constant throughout the tests, whereas the matric suction may vary.

2.9. *Strain rates for triaxial testing*

In the determination of fundamental soil parameters and the investigation of soil behaviour, the triaxial specimen is assumed to represent an "element" of soil. Furthermore, most constitutive models assume that soil is a homogeneous material. Thus, loading rates are usually applied to triaxial specimens in such a manner that the applied stress is propagated through the soil as uniformly as possible. Loading rates should also permit adequate time for drainage of pore fluid or equalization of pore pressures. If the loading rate exceeds some critical value, compressive strength can be significantly affected.[44] Tensile strength is, however, not significantly affected by loading rate.[45] In constitutive models, fundamental soil parameters are presumed to remain unchanged with rate of loading and must be measured under slow testing conditions. Rate effects are then superimposed upon static strength functions.

Niyampa *et al.*[46] measured axial stress at the lower and upper parts of sandy loam triaxial specimens and observed significant differences in readings from the two locations when loading speed was increased. They also showed that loading rate increased strength up to a maximum value after which further increases in rate resulted in reduced strength. Hanson *et al.*[47] reported linear increases in shear strength with shear rate, while Flenniken *et al.*[48] observed that an increase in shear strength with rate did not occur at a strain rate below $10\,s^{-1}$. Dechao and Yusu[49] observed that increases in soil shear strength, with decreases in water content (or increases in matric suction) or with increases in bulk density, are intensified by the rise in shear rate.

3. A triaxial testing apparatus for unsaturated soils

The following describes the triaxial apparatus used in the Department of Agricultural and Bioresource Engineering at the University of Saskatchewan, Saskatoon, for the testing of unsaturated agricultural soils.

3.1. *System layout*

The system arrangement is shown in *Fig. 2*. The system includes a cabinet mounted triaxial cell, a digital pressure–volume controller, plumbing arrangements, data acquisition system and host computer. The system is capable of computer-controlled stress or strain rate testing and can produce real-time graphical outputs.

Fig. 2. Triaxial testing system. (1) triaxial cell, (2) digital pressure–volume controller for pore-air-volume change measurement or pressure control, (3) burette for pore-water volume change measurement, (4) pore-water pressure transducer, (5) data acquisition and signal conditioning unit, (6) host computer

3.2. *Triaxial cell*

The computer-controlled triaxial cell was designed and built by GDS Instruments Ltd. (Egham, Surrey, UK). The design specifications were intended to accommodate some of the unique features of triaxial testing of agricultural soils as compared with conventional triaxial testing, e.g. extremely large strains and quasi-static loading rates. The cell is based on the classic stress-path triaxial cell design of Bishop and Wesley[50] and is capable of withstanding pressures of up to 1·7 MPa.

The cell was supplied with the standard three ports necessary for saturated soil testing and was modified for unsaturated soil testing by installing an additional port (c) to accommodate a pore-air pressure line (*Fig. 3*). A constant cell pressure up to 800 kPa is supplied by a compressor through port d. Pore-water pressure is measured by a pressure transducer through port b. This port connects to the base plate and can also be used periodically to flush both the porous stone and the water compartment below the disk. Pore-water-volume change measurement is conducted through port a. The pore-air line c is connected to the top cap via a small-bore polythene tube. Pore-air pressure control and volume change measurements are made through the pore-air line using a digital pressure–volume controller, described below.

The cell can accommodate 38, 50, 70 and 100 mm diameter test specimens using interchangeable base pedestals and triaxial extension top caps. A 70 mm base pedestal was re-designed in this study to accommodate a grooved water compartment below the disk (*Fig. 4*). High air entry ceramic disks (Soilmoisture Equipment

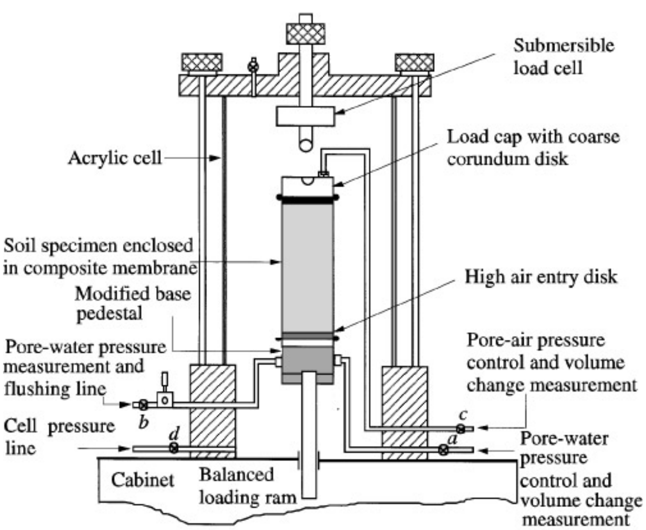

Fig. 3. Modified triaxial cell for unsaturated soil testing

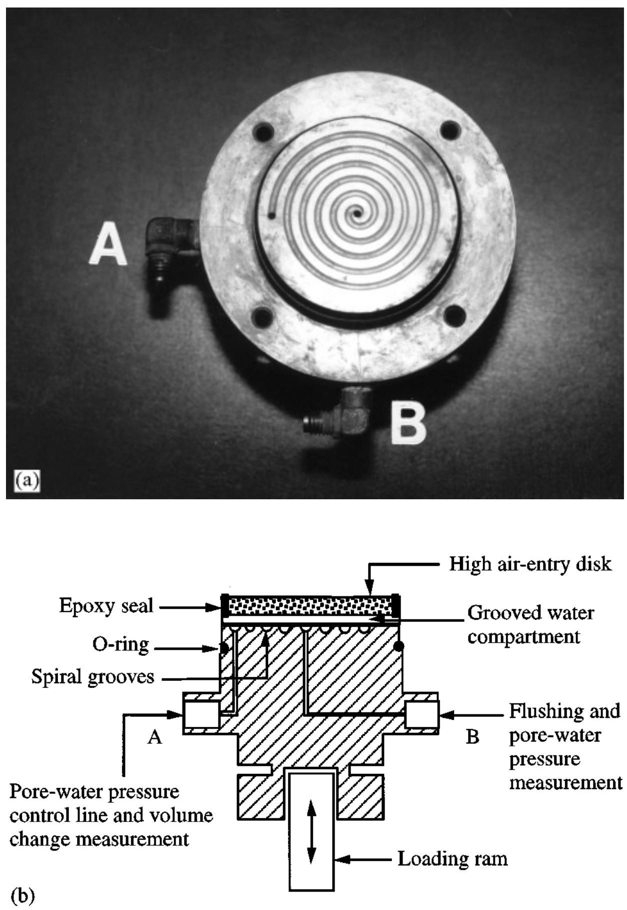

Fig. 4. Modified base pedestal. (a) plan view showing grooved channels for flushing porous disk above water compartment, and pore-water ports (A, B); (b) schematic drawing

Corporation, Santa Barbara, CA) with different air entry values (200, 300 and 500 kPa) were sealed into interchangeable aluminium rings using an epoxy resin and mounted on the base pedestal. The water compartment formed between the top of the pedestal and the base of the ceramic disk ensures that the disk remains saturated. Two drainage holes (A, B) on top of the pedestal are connected by the spiral groove which serves as water channels for flushing any diffused air bubbles that may accumulate inside the water compartment during tests.

The axial force and axial displacement are applied from the base of the cell through a screw-driven actuator with a stroke of 100 mm. A balancing ram ensures that high-speed movement of the ram does not cause disturbance to the constant cell pressure (within ± 2 kPa) during dynamic testing. Axial force is measured with an internal 5 kN submersible load cell located at the top of the cell (*Fig. 3*). Measures of axial displacement (0·2 μm resolution) are derived from the axial actuator encoder. The system is capable of static and dynamic cyclic tests at rates of up to 1 Hz and axial displacement versus time ramps of up to 5 mm/s. The maximum cyclic deformation amplitude at 1 Hz is 5 mm (i.e. 10 mm peak to peak). At 0·1 Hz, cyclic deformation amplitude can be 50 mm.

3.3. *Digital controller*

The digital pressure–volume controller[51] is a microcomputer controlled hydraulic actuator for the precise regulation and measurement of liquid pressure and volume change. The results of tests to evaluate the controller for measurement of air volume changes were reported by Adams *et al.*[27] By taking precautions such as maintaining essentially isothermal conditions (± 2°C), preventing leakage at connecting points, pre-compressing the confined air space, and minimizing the total volume of the air-confined space, the controller was found to be a suitable device for measuring air-volume changes. The time response of the controller (12 ml/min air-volume change) is acceptable for slow strain rate testing of soils. The controller also permits implementation of the axis-translation technique, making it a versatile device for general unsaturated soil testing, e.g. it can be integrated with the pressure-plate apparatus for precise determination of the soil-water characteristic.

3.4. *Software*

The triaxial testing system is computer controlled by a BASIC (HTBasic, TransEra Corporation, Provo, Utah) programme MINIDYN.[52] With the physical modification of the system, the programme was modified and named MINIDYN2. The modified software allows the monitoring of parameters associated with unsaturated soil testing including suction measurement and control. A new subroutine was also added to control and measure air-volume changes during isotropic compression.

3.5. *Future enhancements to the testing system*

Under the current configuration, the apparatus is equipped with a single digital pressure–volume controller, which is dedicated to air-volume change measurement, while constant cell pressures up to 800 kPa are supplied by a compressor. In future enhancements, an additional digital controller will be used to supply constant cell pressures up to 1·7 MPa (the specified capacity of the cell), or, using the control software, to provide various cell pressure stress paths. Equipped with two controllers, the system has the capability of performing K_0 consolidation tests (i.e. consolidation in which there is no lateral deformation of the sample), which better simulate the *in situ* consolidation process. If the second controller is used instead for pore-water pressure control, the precise control and measurement of matric suction is also possible. To perform dynamic stress path tests, a high-speed controller is required.

4. Evaluation of unsaturated triaxial testing procedures

A sandy clay loam soil (48·1% sand, 28·3% clay and 23·6% silt) was air-dried and passed through a US. Standard sieve series 10 (2 mm opening). A batch sample was produced by spraying the soil with fine droplets of water until the desired water content (20%) was attained. The optimum compaction water content for this soil is 18·3%. Cylindrical specimens of 70 mm diameter (D) × 140 mm length (L) were formed by compacting the sample in five uniform layers in a specially designed mould.[39] The approximate bulk density, degree of saturation and matric suction of the resulting specimens were 1·2 Mg/m^3, 32% and 50 kPa, respectively.

In a typical test, the specimen was placed on the saturated ceramic disk mounted on the base pedestal. It was then sealed onto the pedestal by a composite membrane (slotted aluminium foil sandwiched between two latex membranes). The cell was set in place and filled with water. Cell pressure and air backpressure were simultaneously increased to prevent premature consolidation or compression of the specimen. Continuity of pore-air space with the pore-air pressure and air volume change measurement devices was ensured by backpressuring air through the coarse disk sealed to the top of the specimen. An air backpressure of 50 kPa was chosen (using the axis-translation technique) such that the negative pore-water pressure in the specimen was elevated to about 0 kPa (gauge). Continuity of the water phase between the specimen and pore-water pressure measurement system was ensured by the axis-translation technique and the saturated ceramic disk on the pedestal. The specimen at this stage had a net confining stress of $(\sigma_3 - u_a)$ equal to 0 kPa and matric suction $(u_a - u_w)$ of 50 kPa.

Once the initial conditions were set, the compression or consolidation stage was initiated by elevating σ_3 above u_a to give a desired net confining stress $(\sigma_3 - u_a)$. During consolidation, specimens were held at a matric suction of 50 kPa and net confining pressures between 1.5 and 60 kPa.

Shearing during the constant water content tests was performed at a strain rate of 10 mm/h. This rate was considered to be quasi-static; it is much slower than rates the soil is expected to undergo under agricultural field operations, yet faster than rates used in static tests. As discussed in Section 2.9, static testing rates are necessary to allow excess pore-water pressures to dissipate through the specimen. The use of quasi-static rates should not introduce great error because of the undrained pore-water conditions and the low degree of saturation of the test specimens. The pore-air pressure was maintained at 50 kPa, throughout the shearing process.

5. Results

5.1. *Isotropic compression*

Table 1 gives the states of nine specimens after isotropic compression under initial net confining stresses $(\sigma_3 - u_a)$ ranging between 0 and 250 kPa, and a matric suction $(u_a - u_w)$ of around 50 kPa. All specimens were initially in loose states as shown in the first row of values.

Pore-air-volume changes (ΔV_a) accounted for nearly all the total volume change (95–100%) in the specimens during isotropic compression. Significant changes in the soil pore space were produced by the isotropic compression of the specimens as evident by the changes in void ratio (e), bulk density (ρ), and degree of saturation (S_r). These results are associated with the initial loose state and low degree of saturation of the specimens.

5.2. *Constant water content tests*

Figure 5 shows deviatoric stress–strain relationships for seven constant water content tests conducted under net confining pressures from 1·5 to 60 kPa. A typical three-stage pattern was observed for the changes in deviatoric stress with axial strain. A rapid rise in deviatoric stress over a short axial strain range was quickly followed by a fairly wide range of constant rate of change in deviatoric stress with axial strain. These transition stages indicate the progressive mobilization of shear strength of the specimens. The third stage shows a greatly reduced, almost steady, change in deviatoric stress with axial strain. Most of the specimens approached failure states at around 40% axial strain. Volume changes due to the expulsion of air during the shearing stage ranged between 20 and 25% for six of the specimens at failure (*Fig. 6*).

Figure 7 shows the failure envelope for the series of constant water content tests. The envelope was drawn approximately tangentially to five Mohr circles constructed from the data. It should be noted that these specimens failed at similar values of matric suctions. Based on this series of tests, the soil has a total cohesion $c \approx 20$ kPa and an internal angle of friction $\phi = 35°$. Note that the total cohesion can be approximated by $c \approx c' + (u_a - u_w) \tan \phi'$, where c' and ϕ' are the effective strength parameters.[10,17]

Table 1
State of the triaxial specimens after isotropic compression

Test	$\sigma_3 - u_a$ *kPa*	$u_a - u_w$ *kPa*	ΔV_a *ml*	ΔV_w *ml*	*w* *%*	*e*	S_r *%*	ρ Mg/m^3
Initial state	0	50·0	0	0	20·1	1·65	32·3	1·20
1	1·5	50·8	0·0	0·0	20·2	1·65	32·5	1·20
2	8·7	49·9	− 16·1	0·0	20·3	1·57	34·2	1·24
3	18·8	49·9	− 29·9	0·0	20·2	1·50	35·6	1·27
4	29·5	49·1	− 57·2	− 0·2	20·1	1·37	38·9	1·34
5	37·6	49·4	− 80·4	− 0·2	20·1	1·25	42·4	1·41
6	48·0	51·0	− 88·7	− 0·3	20·0	1·21	43·9	1·44
7	60·4	50·4	− 101·4	− 0·3	20·0	1·15	46·3	1·48
8	150	50·8	− 135·2	− 4·1	19·7	0·98	53·3	1·60
9	250	50·6	− 162·0	− 7·9	19·0	0·83	60·7	1·72

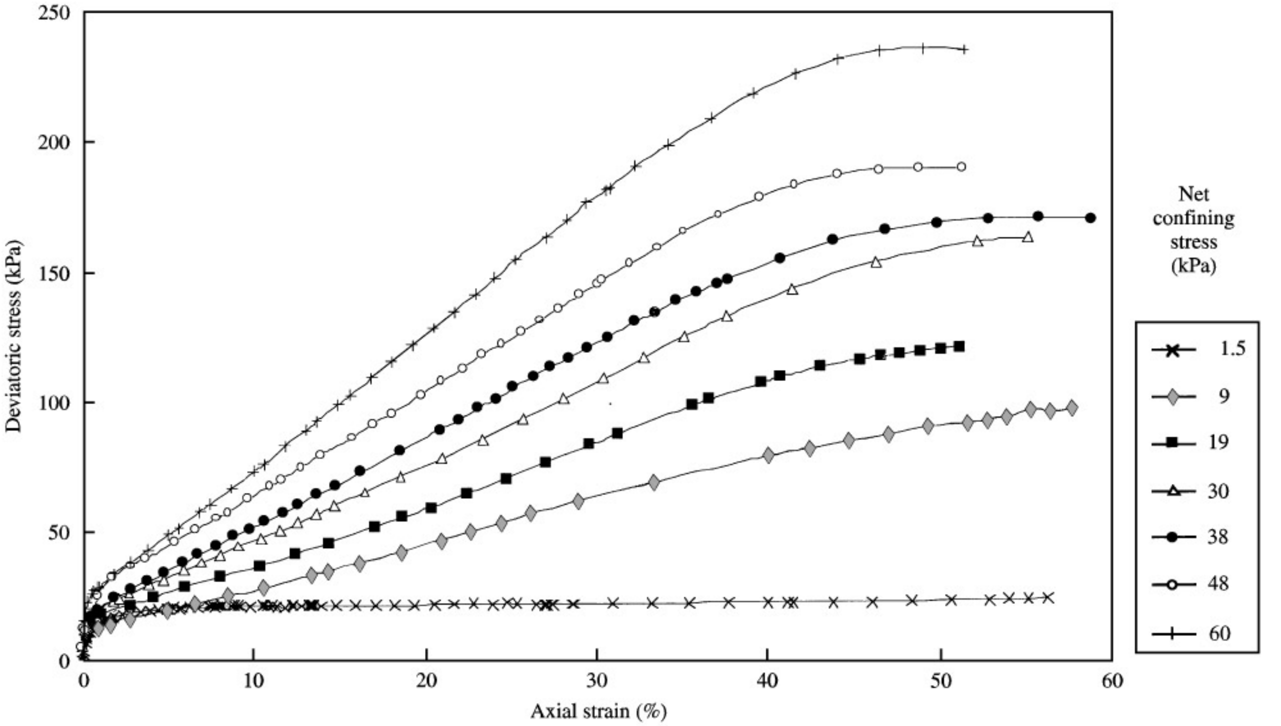

Fig. 5. Variation of deviatoric stress with axial strain for constant water content tests under low confinement pressures

In the constant water content tests (under lower net confinement), pore-water pressure changes between 2 and 8 kPa were measured at the end of shearing compared with an initial value of 0 kPa. With the air pressure u_a maintained at 50 kPa, the matric suction $(u_a - u_w)$ varied between 42 and 48 kPa (*Fig. 8* and Table 2),

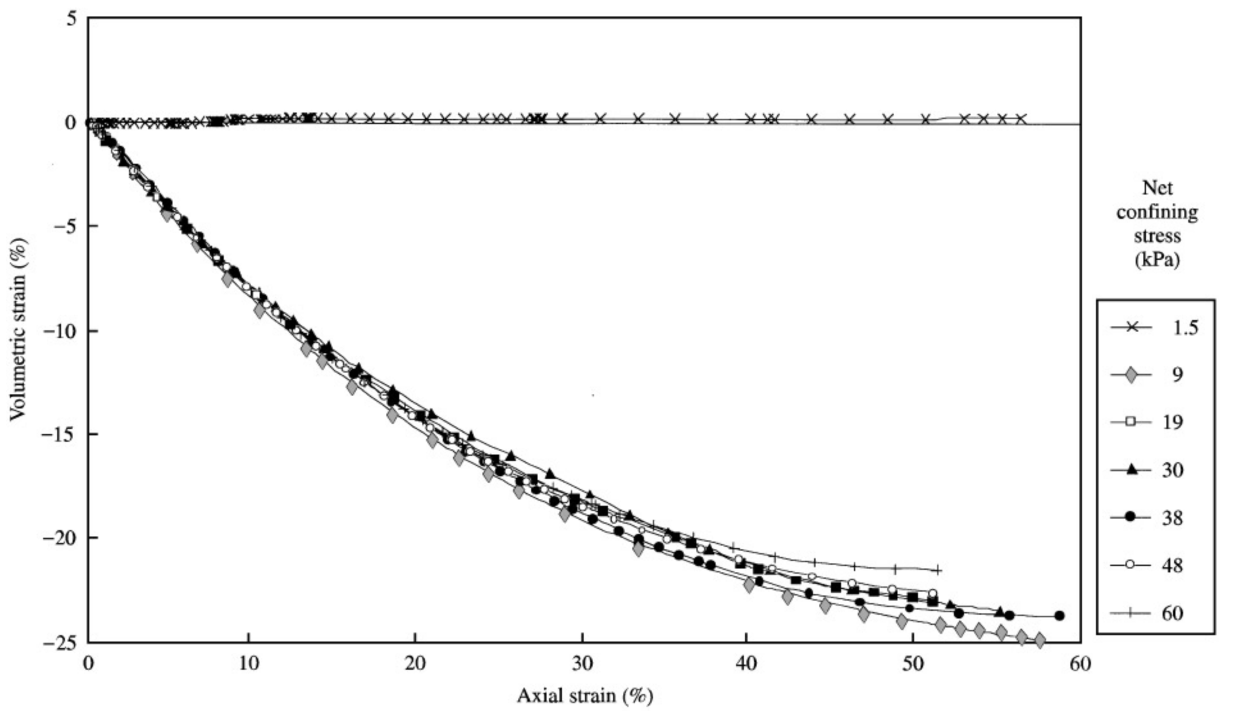

Fig. 6. Variation of volumetric strain with axial strain for constant water content tests under low confinement pressures

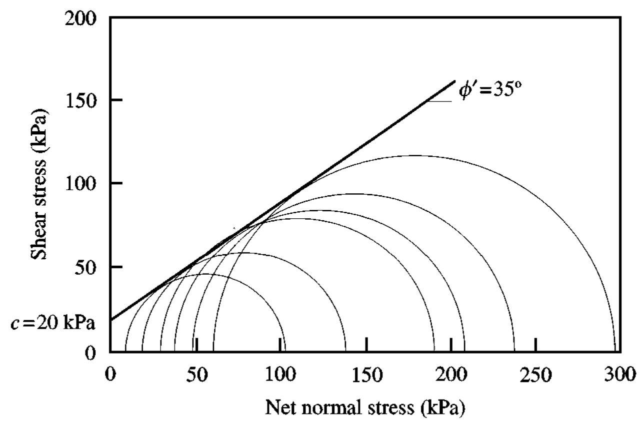

Fig. 7. Mohr–Coulomb failure envelope constructed from a series of constant water content tests (w = 20%), yielding a total soil cohesion of 20 kPa and an internal friction angle of 35°

Table 2
State of the triaxial specimens at failure

Test	$\sigma_3 - u_a$ *kPa*	$\sigma_1 - u_a$ *kPa*	$u_a - u_w$ *kPa*	ΔV_a *ml*	*e*	S_r *%*
1	1·5	20·6	50·5	0·0	1·65	32·5
2	8·9	102·7	45·6	– 127·7	0·98	56·5
3	18·9	138·3	47·7	– 115·5	0·93	56·0
4	29·2	190·7	52·4	– 111·3	0·82	63·5
5	37·8	208·0	44·4	– 107·8	0·72	72·3
6	48·0	237·6	43·3	– 99·3	0·71	75·3
7	60·6	296·6	43·6	– 93·8	0·69	76·2
8	149	416·9	+ 5·0*	– 29·3	0·87	60·0
9	249	603·0	+ 23·3*	– 4·5	0·80	62·7

* Development of positive pore-water pressures.

i.e. within 4–16% from the initial value of 50 kPa. For specimens confined at 48 and 60 kPa, a steady decrease of matric suction with axial strain can be observed.

Variation of deviatoric stress and volumetric strains with axial strain for two constant water content tests conducted under net confining pressures of 150 and 250 kPa were similar to those observed for the specimens under lower net confinement pressures. A different trend was observed in pore-water pressure change and, therefore, matric suction change. *Figure 9* shows that the pore-water pressure increased considerably from the initial values of 0 kPa (i.e. $u_a - u_w = 50$ kPa) to 50 kPa (i.e. $u_a - u_w = 0$) and beyond in two triaxial specimens under net confinement of 150 and 250 kPa. Thus, positive pore-water pressures with respect to the artificial atmosphere were generated, as indicated in the figure. Technically, zero matric suction implies saturation and the development of positive pore-water pressures are usually associated with saturated soils, yet these latter specimens

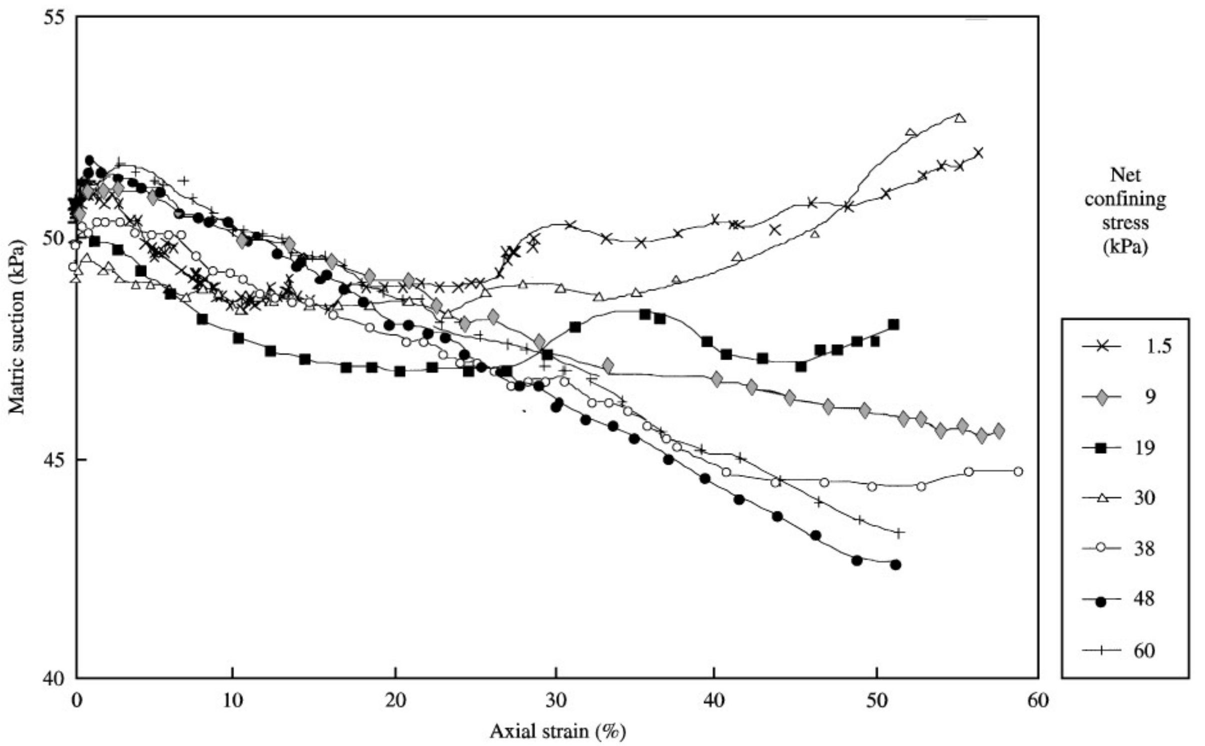

Fig. 8. Matric suction versus axial strain for constant water content tests under low confinement pressures

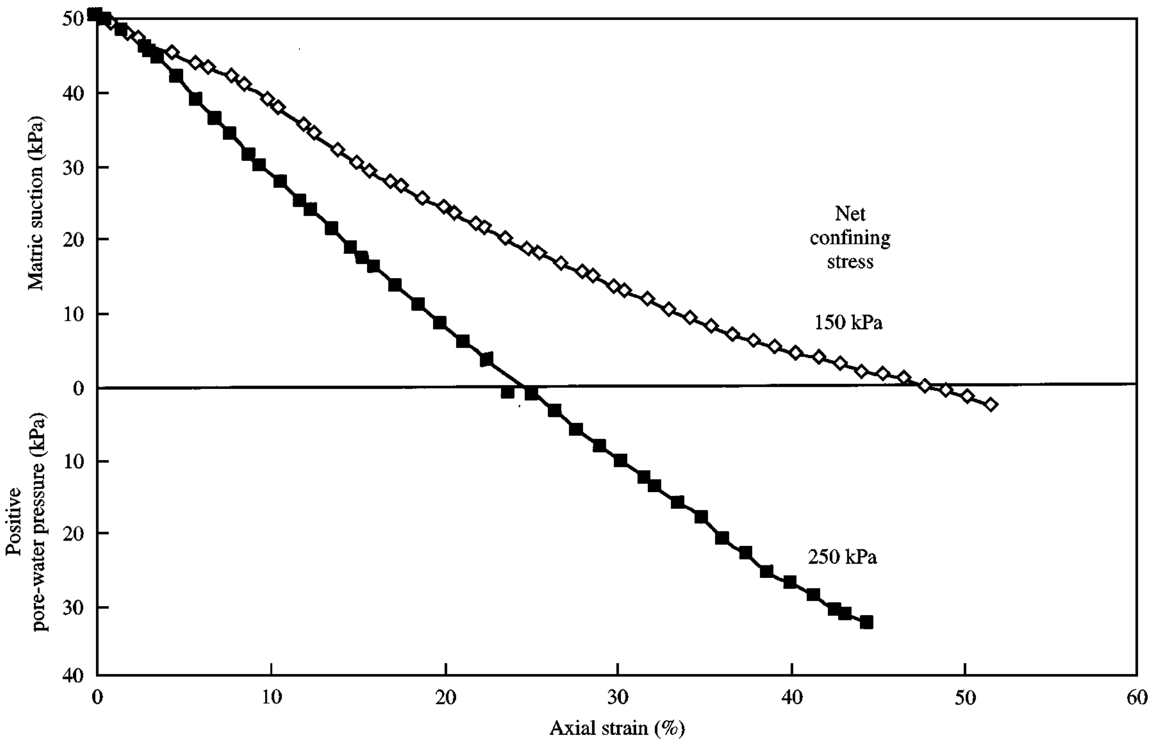

Fig. 9. Matric suction versus axial strain for constant water content tests under high confinement pressures. Tests were conducted with a pore-air pressure of 50 kPa (guage) and an initial pore-water pressure of 0 kPa, using the axis-translation technique to produce an initial matric suction of 50 kPa. Since pore-air pressure was maintained at a constant value of 50 kPa, the reduction of matric suction with axial strain is associated with a build up of pore-water pressure

had attained degrees of saturation of only 60 and 63%, respectively (Table 2).

6. Discussion

6.1. *Volume change*

Agricultural soils generally have low to moderate degrees of saturation (or water contents), are under low net confinement stresses, and undergo large deformations during loading. Under these conditions, air-volume changes in triaxial tests account for most of the total volume change, and water-volume changes might be neglected if errors of the order of 5% are acceptable. Since the measurement of air-volume changes is very sensitive to temperature changes, adequate precautions must be taken to ensure isothermal conditions during testing.

During the constant water content shearing tests, there was a tendency for reduced volume changes under higher net confining pressures (*Fig. 6*). This trend was also observed by Herkal *et al.*[53] and Adams *et al.*[27] This is largely attributed to the fact that higher net stresses caused a greater reduction of the pore spaces (i.e. compaction) during the preceding isotropic compression stage. An explanation in terms of soil structure is that more closely packed particles result in reduced interconnections between pore spaces as well as reduced porosity. Under these conditions, pore-air and water may become entrapped and less air will be expelled. Close particle packing also gives specimens more resistance to external stress, particularly for frictional soils.

An implication of pore-air becoming entrapped in the specimen is that it may be difficult to measure volume changes during the shearing stage under high net confining pressures.

6.2. *Variation of matric suction*

Because changes in matric suction during constant water content tests under low net confinements, are not significant, the assumption that matric suction remains constant during triaxial tests under low confining stresses will not introduce much error and simplifies the testing procedure considerably. This simplifies the application of constitutive models to practical agricultural soil mechanics problems, but will apply only to conditions involving low net confinement and a low degree of saturation.

The variation in matric suction for specimens under higher net confinement pressures was markedly different than that for the specimens under lower confinements. There appears to be a stress range and transition point beyond which constant suction assumptions will not hold. This transition point will be at some stress level directly related to the matric suction, and thus indirectly to the water content, of the specimen.[17] The soil-water characteristic curve can be considered as a constitutive relation; it relates matric suction (a stress state variable) to the water content (a deformation state variable).[10,17] We propose that the transition between "low" and "high" stresses is approximately equal to the as-compacted matric suction of the soil (i.e. 50 kPa for this soil) and that estimates over a range of water contents can be obtained from the soil-water characteristic curve for a particular soil structure. In other words, the as-compacted matric suction is considered to be a stress history variable analogous to the pre-compression stress for $e - \sigma_1$ loading paths. Triaxial shearing tests conducted under consolidation pressures above this transition value will involve changes in matric suction, which will in turn affect the soil response (a correction factor would probably be required for swelling soils).

It has been observed in various studies that significant variations in soil properties for specimens under low suctions (high water content) and/or high confinement pressures, may be attributed to the build up of pore-water pressures within specimens (see Refs. 54,55, and 17). Under such conditions, the variation of matric suction must also be accounted for in constitutive models, as the use of a total stress analysis may introduce considerable errors.

Applying this scenario to field situations, matric suction will change significantly as a result of some agricultural operations even under constant water content conditions, for example, high axle loads causing severe compaction. This has important implications with respect to water availability for plant growth and soil strength.

7. Conclusions

In the development of constitutive models for unsaturated agricultural soils, it has generally been assumed that stresses can be described using total stresses, and that matric suction remains constant under the undrained (constant water content) conditions existing under field operations. Laboratory testing equipment and procedures, such as the triaxial test, have reflected this. Over the last few decades, modifications to the conventional triaxial apparatus and instrumentation for unsaturated soils have been developed, making it possible to monitor and control both pore-air and pore-water phases of a test specimen, and thereby examine the influence of matric suction on unsaturated soil behaviour.

For soils having a low degree of saturation and under a low stress regime, the matric suction will remain fairly constant under undrained conditions. Under such conditions, a total stress analysis will provide reasonable approximations of soil behaviour. The imposition of large stresses on the same soil may cause significant changes in matric suction and in turn affect the strength and volume change behaviour. Under such conditions the use of a total stress analysis may introduce considerable errors. It is then important to monitor matric suction changes in triaxial tests.

The combination of water content and matric suction defining the transition between these two types of behaviour is provided by the initial state (i.e. stress history) of the soil. For the soil tested in this study with an initial degree of saturation of 32%, the transition stress was estimated to be about 50 kPa.

The use of independent stress state variables, as opposed to total stresses, to describe the behaviour of unsaturated agricultural soil is relevant and can be implemented in laboratory tests. To accomplish this, modifications to the conventional triaxial cell are required.

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