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A 3000 kPa unsaturated soil stress path cell

Une cellule de sentier de tension de sol de unsaturated de 3000 kPa

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ABSTRACT: As the advances of triaxial testing equipment have evolved, more and more has been learned about the behavior of unsaturated soils. There has been a limitation on the level of matric and total suction that could be achieved in a triaxial cell due to limitations on the materials that could be used in its construction. Advances in our understanding of partially saturated soil mechanics can be achieved by using newly available materials and technology. The use of 3000 kPa porous disks, an internal load cell, on-specimen axial and radial deformation devices, and a closed-loop feedback control system makes this partially saturated triaxial cell unique in its ability to measure and characterize unsaturated soil behavior. Behavioral data from this triaxial testing system will form the basis of a more comprehensive and robust soil constitutive model for unsaturated soils.

RÉSUMÉ: Comme les avances d'équipement d'essai de triaxial ont évolué, a été appris de plus en plus du comportement de sols de unsaturated. Il y a eu une limitation sur le niveau de matric et la succion totale qu'atteint dans une cellule de triaxial grâce aux limitations sur les matériels qu'utilisé dans sa construction. Les avances dans notre comprend de mécanique de sol partiellement saturée peut être atteint matériels et la technologie en utilisant récemment des disponibles. L'usage de 3000 kPa des disques poreux, et la cellule de chargement interne, axial de sur-spécimen et les appareils de déformation radiaux, et un système de contrôle de réactions de fermé-boucle ceci fait la cellule de triaxial partiellement saturée unique dans sa capacité à la mesure et caractérise le comportement de sol de unsaturated. Les données de Behavioral de ce système d'essai de triaxial formeront la base d'un modèle de constitutive de sol plus compréhensif et robuste pour les sols de unsaturated.

1 INTRODUCTION

The triaxial test is one of the most common laboratory procedures in geotechnical engineering. Its value can be traced back to Rendulic (1937) with tests on clays. Through the years, improvements have been made to triaxial testing equipment by researchers such as Bishop and Henkel at Imperial College in London. Bishop & Blight (1963) branched into testing unsaturated specimens. Their tests led to the realization that the two stress components ($\sigma - u_a$) or the net normal stress and ($u_a - u_w$) or the matric suction must be considered as independent stress-state variables for an unsaturated soil. See Fredlund & Morgenstern (1977). Gulhati & Satija (1981) further extended this concept by performing triaxial tests on unsaturated soils using an axis-translation technique wherein the matric suction is developed by an increase in pore air pressure with the pore water pressure being controlled or near atmospheric using a high air entry (low permeability) porous stone.

As the advances of triaxial testing equipment have evolved more and more sophisticated measurements can be made to study the behavior of unsaturated soils. There has been a limitation on the level of matric and total suction that could be achieved in a triaxial cell using the axis translation technique due to limitations on the materials (ceramic porous disks) that could be used in its construction. Advances in our understanding of partially saturated soil mechanics can be achieved by using newly available materials and technology. The newly constructed partially saturated stress path cell is a step in the direction of expanding the characterization of unsaturated soil behavior.

2 EQUIPMENT AND INSTRUMENTATION

The triaxial cell (Fig. 1) is designed to employ the axis-translation technique (Hilf 1956) for the application of suction to the soil sample. The cell has a confining pressure capacity of 7000 kPa, axial load capacity of 89 kN, and a suction capacity of 3000 kPa using a powdered stainless steel porous disk. The cell is designed to test 75 x 150 mm soil specimens. The axial force is provided by a steel load frame with a capacity of 445 kN. The

frame consists of two steel plates parallel to each other. The triaxial cell rests on the lower plate while the top plate houses a loading mechanism that provides the axial force to the sample.

The suction in the sample is controlled through end caps on each end of the specimen. The top cap is dedicated to the application and measurement of pore-air pressure, through a corundum porous stone linking the top of the sample to a controlled continuous air phase. The low attraction for water (low air entry value) of the stone prevents water from entering the pore-air pressure system. Therefore, continuity between the air in the voids of the sample and the controlling system is ensured. More problematic is the bottom cap, dedicated to the pore-water pressure and suction control. The interface between the pore-water pressure measuring system and the soil sample is critical to prevent air bubbles from penetrating the measuring system. A high air entry disk is used for this purpose. The high air entry disks are sintered 316L stainless steel (starting with a stainless steel powder) that have an air entry value of 3000 kPa. The air entry value is the air pressure required on one side of the saturated disk to force air through the pores. This 3000 kPa air entry value is double the maximum value of most ceramic disks, therefore extending the range of matric suction that can be applied during the axis translation. By placing a cellulose membrane on this high air entry disk, the suction level can be increased to 10,000 kPa.

The instrumentation inside the cell consists of a 89 kN load cell, three AC/AC type LVDT's mounted in a yoke on the specimen at 120° to measure axial strains, and three fiber optic sensors placed 120° around the circumference of the specimen to monitor radial strains. The cell fluid is a nonconductive low-viscosity Dow Corning silicon oil. The triaxial cell is also equipped with two internal temperature sensors to measure the temperature in the silicone oil next to the unsaturated specimen to the nearest 0.01° C. A micro-fan inside the cell keeps the oil stirred throughout testing. An external temperature control system consisting of heat sources with continuously circulating fans and a mercury contact switch at a preset testing temperature allows for the temperature to be maintained within the cell at a tight tolerance. The air temperature outside of the cell is maintained to within 0.1° C.

The external instrumentation for the triaxial testing system consists of four long-stroke LVDT's with ranges of 0.2-m, 0.3-

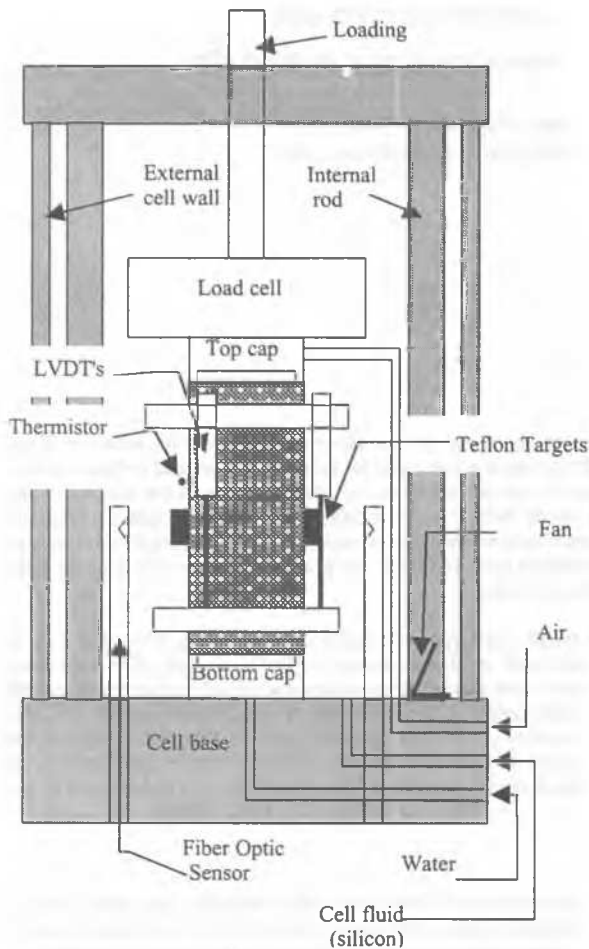


Figure 1. Unsaturated Soil Stress Path Cell Layout

m, 0.25-m, and 0.05-m. These LVDT's are mounted on each of the four control axes (axial force/displacement, cell pressure, pore air pressure, and pore water pressure) and provide the measurement of volume changes in the specimen water phase, specimen air phase, cell fluid, and large axial deformation.

3 CLOSED-LOOP FEEDBACK SYSTEM

The four axes of cell pressure, specimen air pressure, specimen water pressure, and specimen axial force/displacement are controlled by a closed-loop feedback system. The closed-loop feedback system consists of three pressure or volume servo controls (cell, pore-air, and pore-water), and one axial deformation servo control. The pressure controllers are digital pressure-volume controllers (DPVC). The central mechanism of each of the pressure/volume controllers consists of a DC-Type servomotor linked to a ball-screw actuator and a piston housing air, water, or silicone oil. The piston moves inside a hydraulic cylinder whose inside chamber is connected to the fluid or gas phase. The rotation of the servomotor is turned into an axial translation of the pressurizing piston by the ball-screw actuator that moves the piston in or out of the hydraulic cylinder increasing or decreasing the fluid pressure. The axial force/displacement axis consists of a DC type servomotor connected to a ball screw actuator that is connected directly to the loading piston of the triaxial cell.

An electrical sensing device that measures the system response provides the feedback for each one of these control axes. For example, a pressure transducer is used to measure the actual pressure or a displacement transducer is used to measure strain or volume change. The output of each feedback sensing device is compared to a desired output (target value that can be stationary or moving) and the ball-screw actuator is advanced or retracted in order to "find" the target. In order to make this calculation, the

analog signals must be converted to a digital signal by a A/D converter and fed into a computer.

4 COMPUTER CONTROL

There are three A/D-D/A boards needed to complete the feedback loops required by a triaxial test on unsaturated soils. Each board has 8 differential A/D channels (successive approximation type) and 2 D/A channels. The range for each channel is +/- 10V with a maximum sampling rate of 50,000 samples/sec per channel. These A/D converters are of the successive approximation type and have a 12-bit conversion accuracy.

A control program (written using LabView) manages the four closed-loop feedback systems simultaneously. A proportional integral derivative (PID) controller is used to optimize the stability of the feedback system for each axis. DeGroot et al. (1991) showed the efficiency of this type of controller in overcoming stability problems encountered in soil testing using a proportional controller.

The A/D boards are set to run in continuous mode taking 16,000 samples/sec and a circular buffer in the central computer stores the readings. For a particular control point calculation, 800 input voltage readings from each channel are downloaded from the buffer and averaged. This process makes the less accurate successive approximation voltmeters perform as an integrating voltmeter in order to provide more accurate and stable readings for the control/feedback calculations. Based on the incoming voltages, calculations are made by the central computer in the LabView program and voltage signals are sent to the servomotors that move the ball-screw actuators in order to come as close as possible to the target value and hold that target value.

With this type of control of the system numerous loading conditions can be applied to the sample. These include but are not limited to isotropic consolidation, K_0 consolidation, shear at constant rate where the rate is selectable, constant stress creep test, relaxation test, swell test, and dynamic loading in compression and extension. In order to improve the precision of the measurement data, a separate and higher precision voltmeter system is employed.

5 DATA ACQUISITION

A second computer conducts an independent measurement of the output voltages from all instrumentation as well as the excitation voltages. This computer is linked to a HP 3852 Data Acquisition Unit through a GPIB interface and is capable of 16-bit precision on the measured voltages with a calibration traceable to the National Bureau of Standards. A data collection program, also written in LabView, permits the collection of data at different time intervals. This program also allows for the sampling rate to vary during the course of a test without interrupting the testing process.

All instrumentation is linked to an instrumentation junction box where the signals are sent to both the A/D boards and the data acquisition system as shown in Figure 2. A multi-meter attached to the junction box allows the operator to access transducer readings at anytime during the test. This meter provides an independent check on the system readings not only on the output voltages from the transducers but the excitation voltages as well.

6 INITIAL PROOF TEST OF SYSTEM

Proof testing (verification) of any measurement system is essential to demonstrate that the system is capable of measuring quantities with an appropriate level of precision and accuracy. All electronic transducers were calibrated against standards traceable to the National Bureau of Standards with resulting R-squared values of 0.9999 or greater for those that have linear calibration curves. Calibration curves for the fiber optic sensors are inherently nonlinear and these have been developed as piecewise linear approximations. In order to ensure the system is working properly and that there is no loss of precision in different loading environments, the system has been proof tested using a stainless

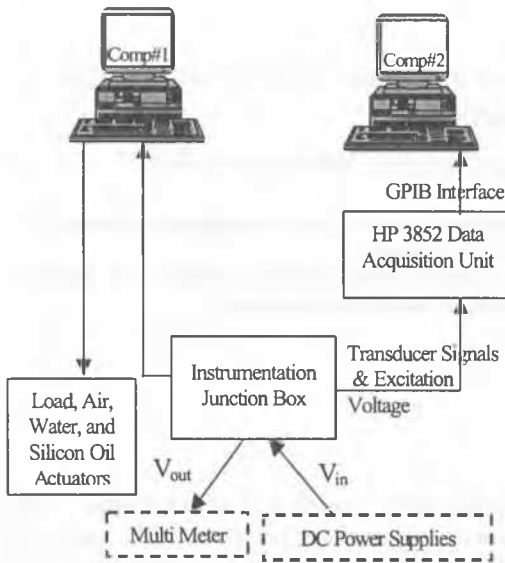


Figure 2. Data Acquisition Layout

steel “dummy” specimen with known properties as a check on the accuracy of the measurements.

The first proof test involved placing the axial displacement yoke directly on the stainless steel specimen and loading it in compression. This test was performed at two confining pressures, atmospheric and 5.52 MPa. This test permitted the evaluation of the effect of confining pressure on the axial and radial deformation measurements while eliminating the potential effect of the membrane. Next, these compression tests were repeated with the previous confining pressures but with a membrane surrounding the specimen. This permitted the investigation of the effect of the membrane on the measured axial and radial deformations.

The results of the four tests produced an average Young’s modulus of 190.1 GPa with a standard deviation of 2.9 GPa. The lowest R-squared value for the stress-strain curves was 0.99906. Each curve consisted of about 70 data points. A published value for the Young’s modulus of stainless steel is 193 GPa, Callister (2000). Hence, the measurement system for axial stress and radial strain is accurate for the levels of confining pressure envisioned in these tests. Figure 3 presents the measured stress-strain curves from these tests for the full range of confining pressures to be investigated. The modulus of an unsaturated soil will be lower than that of the stainless steel and hence this “proof test” gives a confirmation that the axial strain and axial stress measurement systems are providing accurate and precise data for modulus values that are expected.

Volume changes in the unsaturated specimen are measured by three redundant systems, the displacement yoke and fiber optic sensors (measuring axial and radial strains), from changes in the volume of the cell fluid (measured by the pressure/volume controller), and from changes in volume of the air and water in the

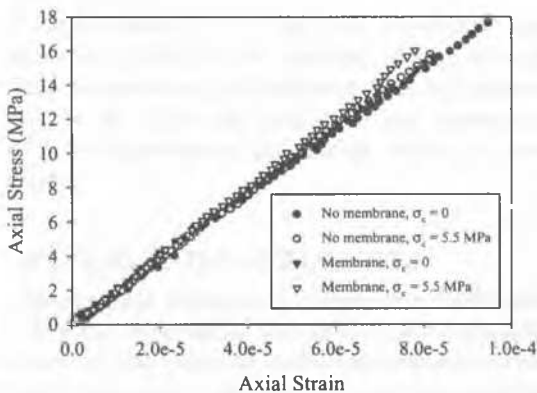


Figure 3. Measured Stress-Strain Curves for Stainless Steel

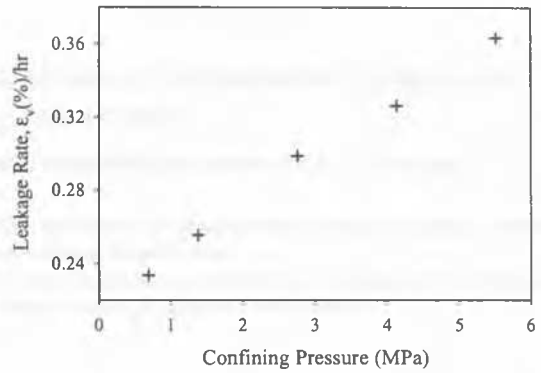


Figure 4. Volumetric Change in Cell Fluid

specimen (measured by the corresponding pressure/volume controllers). For actual tests on unsaturated specimens, these three quantities will be compared as an absolute check on accuracy.

In order to check the accuracy and precision with which volume changes can be measured by changes in the cell fluid, leakage rate tests were conducted on the triaxial cell with a dummy stainless steel specimen at various confining pressures. Figure 4 presents the measured leakage rates in terms of volumetric strain per hour as a function of cell pressure. Note that the maximum correction that would need to be applied to the volume change occurs at the highest confining pressure and corresponds to an accuracy of 0.36% of the volumetric strain per hour of shearing. Or in other words, the volume change measured by changes in volume of the cell fluid can be used to reliably infer volume changes in the specimen down to 0.36% volumetric strain per hour of shearing without correcting for leakage.

7 DISCUSSION AND CONCLUSIONS

An axis translation triaxial cell has been developed for measuring the engineering properties of unsaturated soils for matric suction levels up to 3000 kPa. Initial proof testing has been performed on the strain and stress measurement systems and on one of the redundant measurement systems for volumetric strain. These tests demonstrate the ability of the testing equipment to reliably measure small strain constitutive behavior and to verify the measured volumetric strain behavior.

Initial tests are currently being conducted on unsaturated soils located in the Bryan-College Station area. These tests will significantly expand the envelope of constitutive data that is available to characterize the behavior of unsaturated soils.

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