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An Automated Triaxial Testing Device for Unsaturated Soils

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Abstract

This paper presents a new triaxial testing device for unsaturated soils. It describes the main features of the triaxial system including double wall cell, pressure/volume controllers, frictionless volume change device, automatic flushing device, and software. The use of a double wall cell eliminates almost all of the volume change compliance errors inherent to single wall cells while the frictionless volume change device accurately measures the change in sample volume. An important feature presented is the automated flushing device which removes diffused air during unsaturated soil testing. Diffusion causes a small amount of air to escape through high air entry ceramic disks during testing. The diffused air accumulation beneath the ceramic disk affects water flow and volume change measurements. In addition, large air pockets created over time can reduce the contact area between the water and the ceramic, which may eventually cause de-saturation of the ceramic disk. Therefore, diffused air should be regularly eliminated to make accurate water content measurements. The accessories of the new diffused-air flushing device include a computer-controlled ball valve and a water level sensor. The flushing device can be integrated into other unsaturated soil testing systems such as the direct shear apparatus, and soil-water characteristic devices. The software provides sophisticated algorithms for automating all testing procedures including diffused air flushing.

Introduction

The new automated triaxial testing device for unsaturated soils is a versatile system that can be used to perform various types of tests, as listed in Table 1. A schematic of the system is shown in Figure 1, illustrating the components.

Table 1. Tests that can be performed using the new system.

Problem Type	Test
Strength Testing	• Triaxial shear (UU, CU, CD) • Constant water content (CW) • Unconfined compression (UC) • Hollow cylinder (HC) with compression, torque, or combination
Volume Change & Compressibility	• Determination of Soil-Water Characteristic Curves (SWCC) • 3-D, multi-stage consolidation • Response to wetting (swell/collapse)
Seepage & Permeability	• Hydraulic conductivity and permeability of water or air (k_{sat}, k_w, k_a)

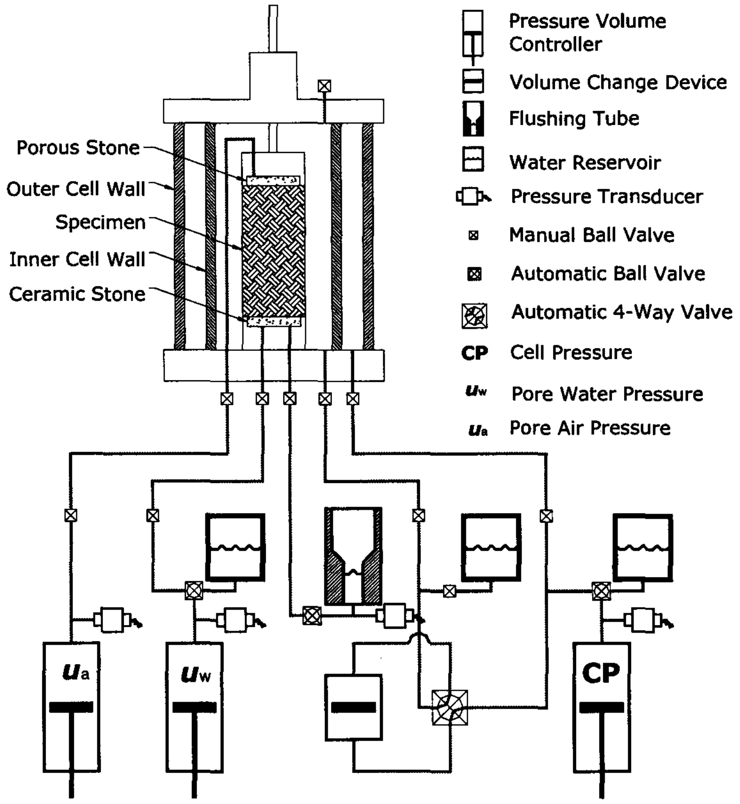

Figure 1. Schematic of an unsaturated triaxial system.

The system presented has evolved over several years of development and research, attempting to obtain more precise and accurate results with each improvement. The main frustrations encountered during the development of the system included precise specimen volume change measurements and diffused air accumulation beneath the high air-entry disks (HAEDs).

Double-Walled Triaxial Cell

First attempts to measure the volume change of a specimen were made by measuring the confining fluid displacement and correcting for cell expansion and loading piston intrusion /extrusion. Accounting for the loading piston volume displacement was a relatively easy task, and therefore, did not pose any problems. The computer tracks the loading piston movement and its area remains constant. The calibration of cell wall expansion was more challenging. Figure 2 shows an attempt to obtain a calibration curve for a single-walled triaxial cell. There were several problems associated with adopting this calibration. First, acrylic cell walls exhibit hysteresis, and therefore, must be specially conditioned prior to using. Secondly, the acrylic material permeates some water and obtaining the permeability (or diffusion) rate for each cell was difficult. Lastly, the precision of the measurement was disputed as the correction value (cell expansion) was typically an order of magnitude larger than the actual value being measured (specimen volume change). A double cell wall was developed to overcome these problems.

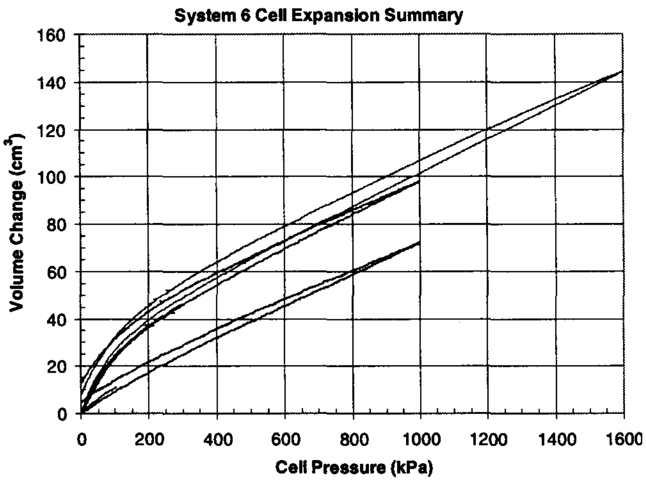

Figure 2. System and cell expansion summary (Lawrence, 2004).

A photograph of a double-walled triaxial cell is shown in Figure 3. The main feature of the double-walled triaxial cell is that the inner cell wall does not experience a pressure differential, eliminating cell expansion and leakage. A simple correction for load shaft intrusion/extrusion is required. In addition, another requirement is a correction for the triaxial cell tie rod deformation due to cell pressure changes. This correction is very small and can be accurately determined as a linear function of the cell pressure.

Volume Change Device

At first, specimen volume change measurements were made by monitoring the inner cell fluid displacement with a standard differential volume change device. However, friction in the volume change device allowed a small pressure differential across the inner cell wall to resulted in significant cell expansion. The solution was to develop a frictionless differential volume change device, which utilizes a rolling diaphragm that eliminates sliding friction. A photograph of a volume change device is shown in Figure 4. This volume change device includes a computer-controlled four-way valve programmed to automatically reverse flow when reaching the volume capacity of the device, essentially providing infinite capacity.

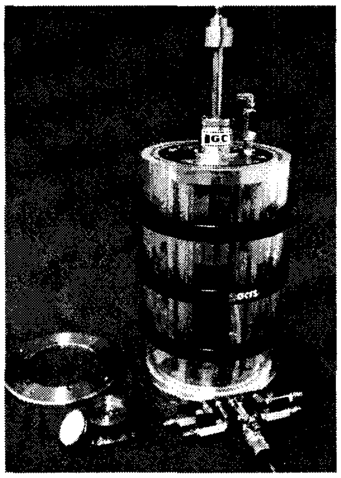

Figure 3. Double-walled triaxial cell

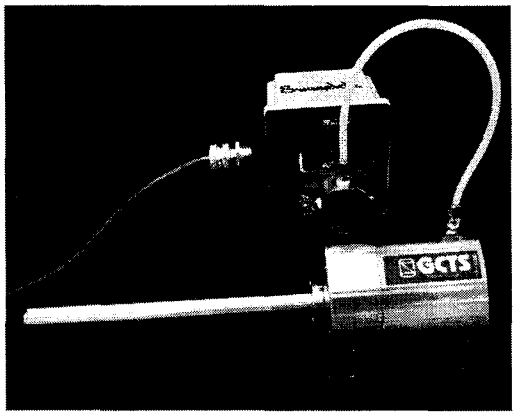

Figure 4. Volume change device.

Automatic Flushing Device

Air diffusing through the high air entry disks is of constant concern in unsaturated soil testing. The diffusion process occurs in response to an air concentration gradient (Fredlund and Rahardjo, 1993). Diffused air will introduce testing errors if not properly accounted for. If enough diffused air accumulates beneath a high air entry disk, it can reduce the hydraulic conductivity of this disk as suggested by Padilla, et. al. (2006). As the high air entry disk is exposed to air, menisci appear to form on the surface and begin to recede into the disk, thereby reducing the hydraulic conductivity. Reduced hydraulic conductivity of the high air entry disk will lead to, at best, a large time delay in suction equalization within the specimen during drained tests. De-saturation of the high air entry disk can result, halting the equilibrating flow of water to or from the specimen. For undrained tests with pore-water pressure measurements and a closed water phase system, diffused air accumulation will lead to a change in the suction value, $(u_a - u_w)$. Therefore it is essential that diffused air is periodically flushed from the pore-water lines while conducting unsaturated soil testing.

It is important to know the diffused air volume in order to obtain the correct pore-water volume change in a specimen. The "true" pore-water volume change during a test is calculated by subtracting the diffused air volume from the total pore volume change measurement. Flushing the diffused air from the compartment below the high air entry disk and the pore-water lines while reading the volume change values (before and after flushing) provides the necessary information to calculate the diffused air volume. Several devices have been proposed to measure the volume of diffused air during unsaturated soil testing. Bishop and Donald (1961) introduced "the bubble pump" while Fredlund (1975) presented a diffused air volume indicator. Padilla, et. al. (2005) developed a simple system to flush the diffused air from a SWCC device.

There are alternative methods for measuring the diffused air and correcting the pore-water volume change readings without flushing. One such method is the pulsing technique (Lawrence, et. al., 2005) where the pressure in the pore-water lines is changed rapidly to find the air volume using the ideal gas law. This method however, does not address the problem of air accumulation below the high air entry disk reducing the hydraulic conductivity of the disk and even allowing the disk to de-saturate. Furthermore, if the diffused air rate is high or the test period extends to several days, air diffusion through the high air entry disk can exceed the total volume of water in the soil specimen (Fredlund, 1973). Measurement significance or accuracy of the pore-water volume change will be reduced when the diffused air volume change (i.e., correction to the pore-water volume change) becomes much larger than the actual pore-water volume change.

The new diffused-air flushing device described in this paper is an automatic apparatus designed to eliminate diffused air bubbles from beneath ceramic disks during unsaturated soil testing. Figure 5 displays a photograph and a schematic of the Fredlund diffused-air flushing device. This device can be programmed to periodically flush the diffused air, and thus correct the pore-water volume change measurements while maintaining saturation in the high air entry disk. Figure 5 shows the three main components, namely the differential pressure transducer, the computer-controlled ball valve, and the water reservoir. The differential pressure transducer has a 7 kPa range and is used to measure the water height in the reservoir while compensating for any barometric pressure change. With proper calibration, the accuracy of this pressure transducer is 0.08 cm of water. The water reservoir is built with a 10 mm inside diameter measuring shaft and a 65 mm inside diameter overflow shaft. The change in the reservoir inside diameter increases the overall accuracy of the device while providing sufficient volume to flush the pore pressure lines of the testing system. The total flushing capacity is greater than 400 cm^3. The area of the measuring shaft is 0.785 cm^2. The device accuracy is calculated using the measuring shaft area and the pressure transducer accuracy as follows:

$$Volume\,Accuracy = Shaft\,Area \times Height\,Accuracy = 0.785\,cm^2 \times 0.08\,cm = 0.06\,cm^3$$

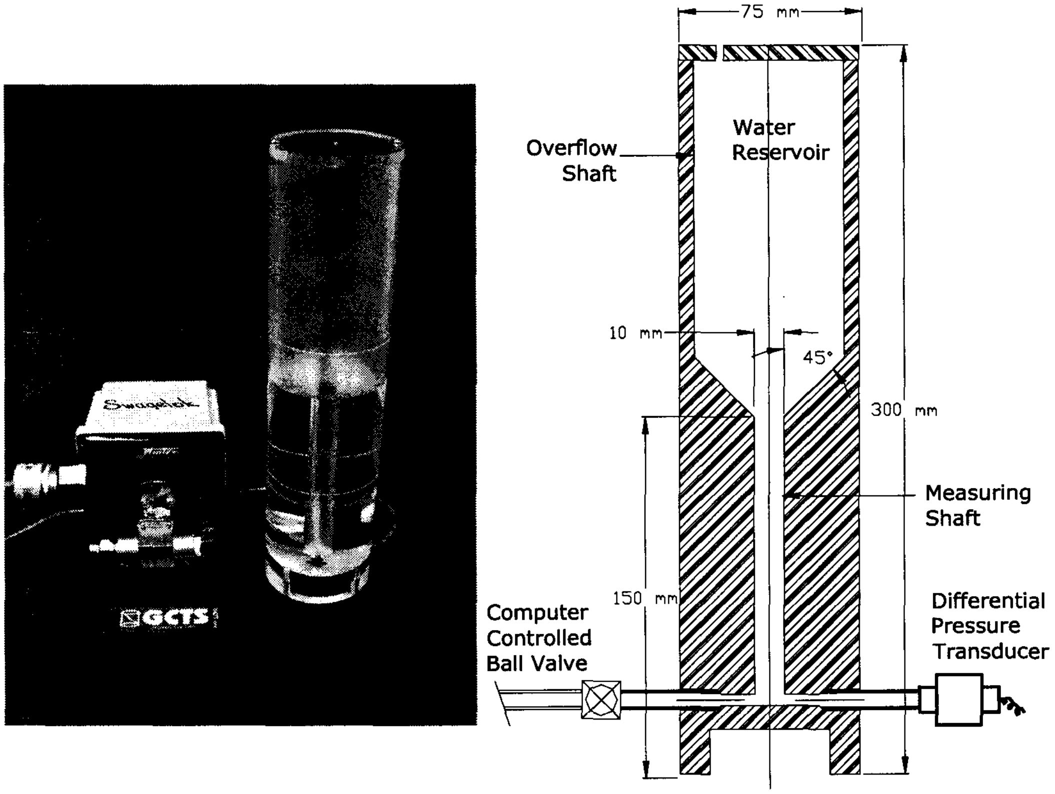

Figure 5. Fredlund diffused-air flushing device.

This value represents the maximum error introduced into the specimen pore-water volume data each time the system is flushed. To put it in perspective, this error represents only 0.01% of the volumetric water content, θ_w for a 71 mm diameter by 150 mm tall triaxial specimen. A more precise pressure sensor or a smaller diameter measuring shaft could be used but is not necessary as 0.01% water content is well within the range required for soil water content data. There are also other issues that must be considered in order to achieve the above accuracy. For example, using a measuring shaft with a smaller diameter causes the meniscus to behave strongly, making accurate readings more difficult. The inside surfaces of the flushing device are polished to achieve a smooth surface preventing water drops from adhering onto the walls. A few drops of "Fantastik" or a similar commercial surface cleaner can be added to the water in the flushing device to reduce the surface tension thereby promoting the upward movement of air bubbles in the device (Fredlund and Rahardjo, 1993).

This type of device is also susceptible to mechanical vibrations as the pressure transducer acts as a sensitive accelerometer. A running average electronic filter with an averaging period of several seconds was used to "smooth" the pressure transducer output. Both the pressure transducer port and the specimen pore-water port were "welded" into the flushing device thereby avoiding pipe threads where air bubbles can cling. The diffused-air flushing device is hydraulically connected to the bottom of the high air entry ceramic disk through a computer-controlled ball valve. The valve has tube fittings to connect the tubes to the flushing device and specimen pore-water lines, again avoiding the use of pipe threads. This ball valve has zero volume change when actuated.

In order to automatically flush diffused air, a pressure-volume controller is required in addition to the flushing device described in this paper. Both, the pressure-volume controller and the flushing device are connected to the pore-water pressure line at the bottom of the high air entry disk. Each device is connected to opposite sides of a spiral groove in the high air entry disk compartment. Figure 6 shows the triaxial platen with a piecewise spiral-flushing groove and an un-mounted high air entry disk.

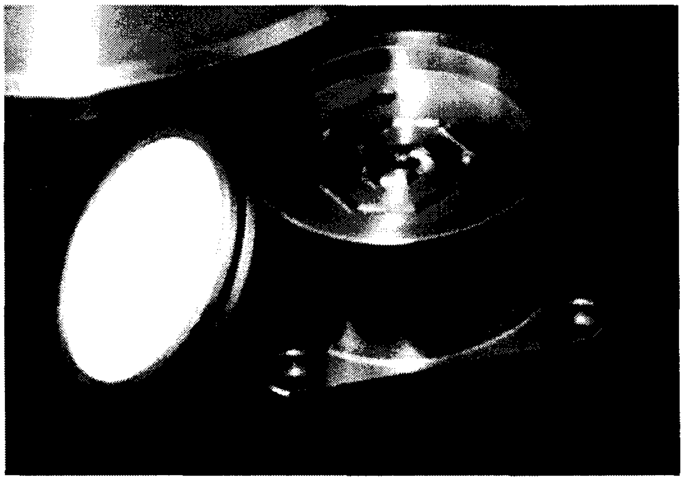

Figure 6. Triaxial platen and high air entry disk for testing unsaturated soils.

Overall System Operation

The schematic diagram of a modern triaxial system is presented in Figure 1 and includes all the components typically used for testing unsaturated soils. Figure 1 shows the double-walled triaxial cell together with a "frictionless" volume change device used to measure specimen volume changes during testing. Volume change measurements for unsaturated soil specimens are performed by measuring the volume of fluid entering or leaving the inner confining pressure cell to compensate for the change in volume of the specimen. The use of a double-walled triaxial cell has been proposed by several authors (e.g. Bishop and Donald 1961; Wheeler 1986) and greatly reduces the compliance, creep, and leakage errors associated with single cells when measuring specimen volume changes. Volume changes resulting from loading piston intrusion or extrusion can be calculated precisely and used to easily correct the specimen volume change measurements. It is important to note that even a small pressure differential between the inner and outer walls may cause a significant compliance error. The volume change device used in this study uses a rolling diaphragm with essential zero differential pressure. This volume change device has 0.01 cm^3 accuracy with an essentially infinite volume measurement capacity due to an automatic, computer-controlled flow reversal valve. The system depicted in Figure 1 includes automated three-way ball valves to automatically recharge the pressure volume controllers.

Air flushing is performed by opening the flushing ball valve and moving a sufficient amount of water. The water level in the flushing device is brought back to the original level by the pressure/volume controller. The difference between the original position and the new position of the pressure/volume controller gives the amount of diffused air. Note that the water level in the flushing device is used as a reference only, and it does not measure any volume change. The detailed flushing procedure is as follows:

1. Determine if flushing is required by measuring the compliance in the pore-water pressure line, u_w with a pressure pulse (Lawrence et al., 2005).
2. If required, recharge the pore-water pressure/volume controller, u_w. A water volume of at least of 200 cm^3 remaining in the pressure/volume controller is required.
3. Record the current volume, V_o and pressure, u_{wo} of the pressure/volume controller.
4. Record the water level in the flushing device.
5. Set the u_w pressure/volume controller to volume control.
6. Open the flushing ball valve and program the u_w pressure/volume controller to pump 200 cm^3 at a rate of 1 cm^3/second. Note, this rate may need to be adjusted depending upon the dimensions of the existing pore pressure and flushing lines. The pressure in these lines should not exceed more than 10 to 20 kPa.
7. Pump back 210 cm^3 into the u_w pressure/volume controller from the flushing device.
8. Repeat Steps 6 and 7 at least once more.
9. Set the u_w pressure/volume controller to the flushing height control by setting the output of the flushing device as feedback for the u_w pressure/volume controller.
10. Adjust the water height in the flushing device to the original position.
11. Close the flushing valve and set the u_w pressure/volume controller to the original pressure value.
12. Record the new volume, V_f of the u_w pressure/volume controller. Diffused air volume is then calculated as:

$$Diffused\ Air\ Volume = V_o - V_f$$

At completion of the flushing procedure, a pressure pulse compliance test should be conducted to ensure that all the air was flushed out of the pore pressure lines. All of the above steps can be readily programmed for automatic execution. Consequently, an undrained soil test can be fully automated.

Typical Test Results

Several soils have been tested in the new triaxial testing systems. One representative is a silty, clayey sand (70% sand, 20% silt, 10% clay), locally named ASU East, that is essentially non-plastic with a standard proctor maximum dry unit weight of 19.5 kN/m^3 and an optimum water content of 10.5%. The soil was tested under a suction of 50 kPa and net normal stresses of 20 and 75 kPa. The results obtained are shown in Figure 7 and 8.

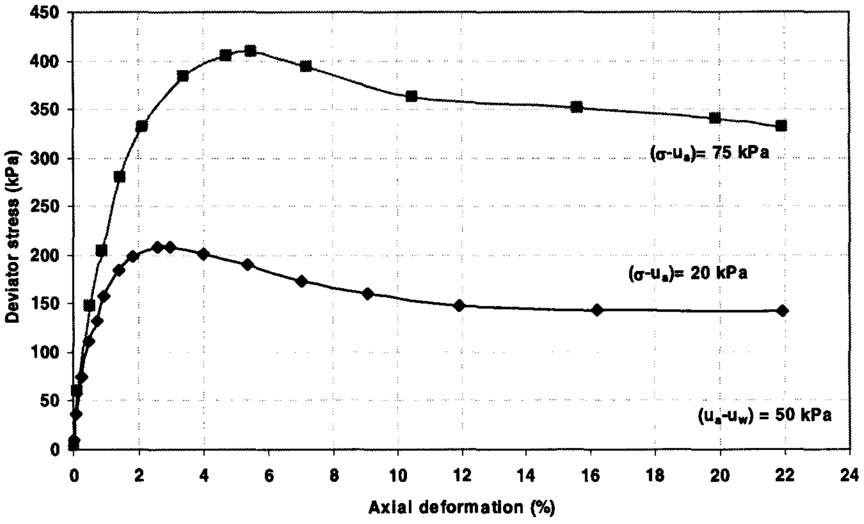

Figure 7. Unsaturated shear strength for two ASU East soil samples.

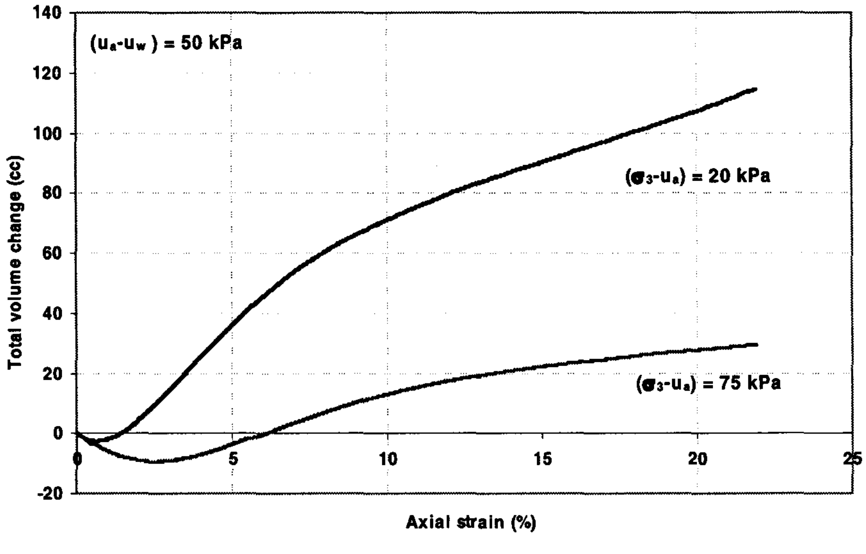

Figure 8. Volume change measurements for ASU East soil.

This soil was also tested under a suction of 400 kPa and a net normal stresses of 20 kPa. The results obtained are shown in Figure 9 and 10.

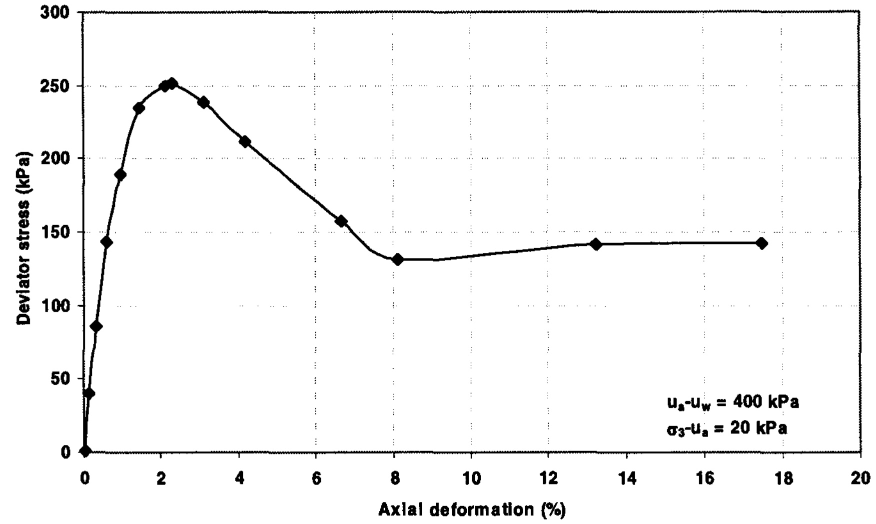

Figure 9. Unsaturated shear strength for ASU East soil.

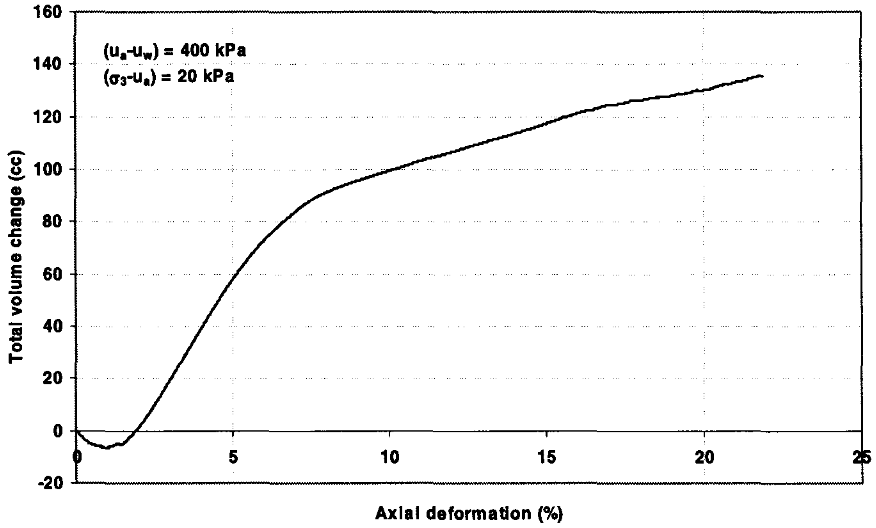

Figure 10. Volume change measurements for ASU East soil.

As mentioned above, accurate shear strength data was easily obtained, even with the first iteration of the new testing system. Examples of other volume change data with the double cell wall system are given here.

It was found that under low imposed soil suctions, the amount of air accumulated beneath the high air entry disk did not prevent the water from flowing out of the sample, allowing the specimen to come to pressure equilibrium with the imposed suction. An example of this is given in Figure 9, which shows a plot of the volume of water exiting the specimen with time, during the pressure equilibrium consolidation phase. For a suction of 50 kPa and a net normal stress of 75 kPa, the amount of diffused air was about 0.9 cm^3 after nearly 10 days.

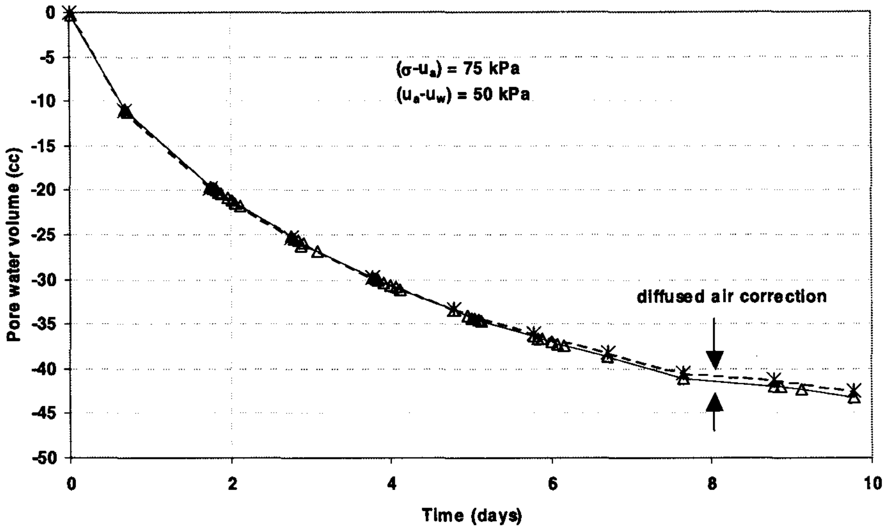

Figure 11. Pore water volume change with time at 50 kPa suction.

On the other hand, when the level of imposed suction was high (above 700 kPa), the volume of air diffused through the high air entry disk quickly prevented pore water from flowing out of the specimen. In this case, it was shown that equilibrium suction was not reached, even though the flow of pore water had stopped. Figure 10 shows the results of a sample under 1000 kPa imposed suction, giving 7 cm^3 of diffused air in 8 days. In this figure, the lower line represents the uncorrected amount of water flowing from the specimen and the upper represents the

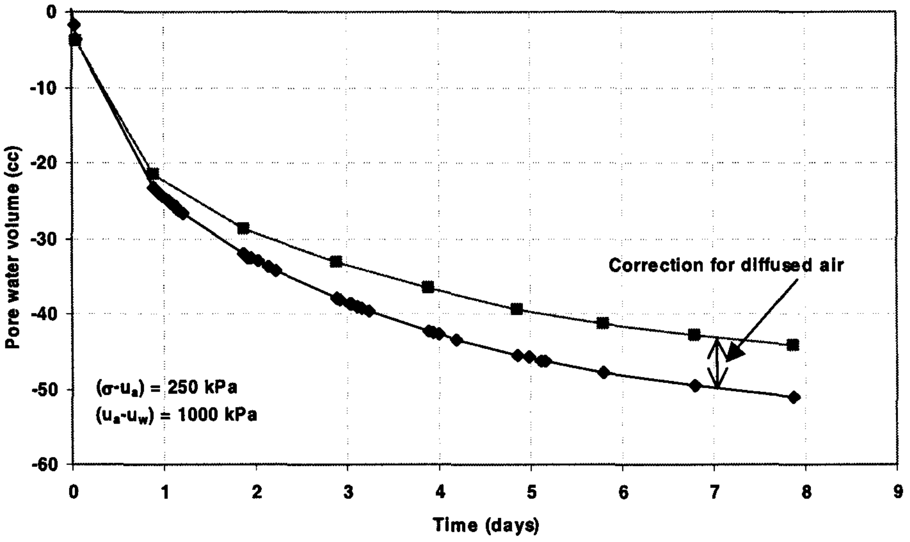

Figure 12. Volume change with time at 1000 kPa suction.

real water volume change (subtracting the amount of diffused air in each point from the uncorrected).

Summary

A modern unsaturated soils triaxial test system has been developed. This new system was designed to address the most challenging aspects of unsaturated soil testing and properly determine the specimen volume change and remedy the amount of air diffused through high air entry disks. The new test equipment utilizes new and well demonstrated technologies and the design incorporates solutions to problems that have been identified by various unsaturated soils researchers and experimentalists.

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References

Bishop, A.W. and Donald, I.B. (1961). "The experimental study of partially saturated soils in the triaxial apparatus" *Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering*, Paris, 1, 13-21.

Fredlund, D.G. (1975). "A diffused Air Volume Indicator for Unsaturated Soils" *Canadian Geotechnical Journal*, 12(4), 533-539.

Fredlund, D.G. and Rahardjo, H.H. (1993). *Soil Mechanics for Unsaturated Soils.* John Wiley & Sons, Inc., New York.

Lawrence, C.A. (2004). *Development of a closed-loop, hydraulically actuated testing system and methodologies for unsaturated soils.* PhD Dissertation, Arizona State University, Arizona, USA, May 2004.

Lawrence, C.A., Houston, W.N., Harraz, A.M., and Houston, S.L. (2005). "Pressure Pulse Technique for Measuring Diffused Air Volume." *Proceedings of the International Symposium on Advanced Experimental Unsaturated Soil Mechanics*, Trento, Italy. June 27 – 29, 2005.

Padilla, J.M., Perera, Y.Y., Houston, W.N., and Fredlund, D.G. (2005). "A New Soil-Water Characteristic Curve Device." *Proceedings of the International Symposium on Advanced Experimental Unsaturated Soil Mechanics*, Trento, Italy. June 27 – 29, 2005. pp. 15-22.

Padilla, J.M., Perera, Y.Y. Houston, W.N., Fredlund, D.G., and Perez, P.N. (2006). "Quantification of air diffusion through high-air entry value ceramic disks." *Proceedings of the Fourth International Conference on Unsaturated Soils*, Carefree, Arizona, USA. April 2 – 6, 2006. To Be Published.

Wheeler, S.J. (1986). "*The stress strain behavior of soils containing gas bubbles.*" Ph.D. Thesis, Oxford University.