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TECHNICAL NOTE

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Twin-Cell Stress Path Apparatus for Testing Unsaturated Soils

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ABSTRACT: Determination of specific volume changes of unsaturated soils remains a challenging issue in soil testing for a number of reasons. Various attempts have been made over the years to improve the techniques of sample volume change measurement. This technical note reports the benefit of using a fully automated twin-cell stress path apparatus for measuring sample volume change and hence determining the specific volume. The system requires calibration for apparent volume change due to expansion of plastic tubes and connections. The results have shown excellent repeatability of the apparent volume change during the loading and unloading process.

KEYWORDS: Unsaturated soils, suction, compressibility, volume change device, experimental techniques, triaxial test, stress path cell

Introduction

Over the years research interest regarding the behavior of unsaturated soil has gathered momentum. The majority of the research has involved the development of constitutive frameworks along with experimental study. Testing of unsaturated soil is not particularly straightforward. Unsaturated soil is a three-phase material that contains solids, water, and air. The presence of water and air in the pore spaces generates additional inter-granular stress. This additional stress is a function of suction. Therefore, for a better understanding of unsaturated soil behavior, we must be able to measure all the stress and strain parameters with reasonable accuracy. Under triaxial axially symmetric stress conditions the following state variables are necessary for a complete description of unsaturated soil behavior: mean net stress $\bar{p}$, deviator stress q, suction s, specific volume v, and specific water volume v_w. These variables are defined as: difference between the mean stress and the pore air pressure, difference between the two principal stresses, difference between the pore air and pore water pressures, volume of an element that contains unit volume of solids, and volume of water and solids in a volume of soil containing unit volume of solids, respectively.

The mean net stress and the deviator stress can be determined using the usual techniques available for testing saturated soils. Reliable ways of measuring or controlling suction have been developed over the years (Fredlund and Rahardjo 1993). Specific water volume change can be determined by measuring the flow of water into or out of the sample. However, the determination of specific volume change of unsaturated soils remains a challenging issue for a number of reasons. Various attempts have been made over the years to improve measurement techniques.

The determination of specific volume change requires the measurement of sample volume change with reasonable accuracy. The sample volume change is given by:

$$\Delta V = \Delta V_a + \Delta V_w \tag{1}$$

where ΔV_a and ΔV_w are air volume change and water volume change, respectively. Volume change of water can be measured using common laboratory techniques. However, measurement of air volume change is not particularly easy since air is highly compressible and will also slowly diffuse into the surrounding cell fluid (usually water). For this particular reason most of the laboratory testing on unsaturated soils has been performed in the oedometer. The vertical compression of the sample, subjected to one-dimensional loading will allow an easy estimation of volume change of the sample. Under triaxial stress conditions, internal strain gauges can be employed in order to evaluate sample volume change (Maatouk et al. 1995; Zakaria et al. 1995, and Blatz and Graham 2003). However, the disadvantage of this method is that measurements are not particularly reliable at large strain deformation.

Various indirect approaches have been developed over the years for the measurement of sample volume change. Bishop and Donald (1961) developed a modified triaxial cell to monitor the volume change of samples in relation to the assessment of effective stress concepts for unsaturated soils. The modified triaxial cell included an additional inner cylindrical cell sealed to the cell base. Mercury was used as the cell fluid. The overall volume change of the unsaturated sample was monitored using the movement of a stainless ball floating on the mercury. However, this method is not particularly safe in relation to the use of mercury unless adequate safety precautions are incorporated in the testing system. Cui and Delage (1996) used a similar technique to measure the total volume change of an unsaturated soil sample. However, colored water was used as a cell fluid rather than mercury. In order to avoid the absorption of air by the water and to reduce the evaporation of water, a thin layer of silicon oil was placed above the water. Rampino et al. (1999) developed a technique for measuring volume changes of unsaturated soils using the ideas proposed by Okochi and Tat-

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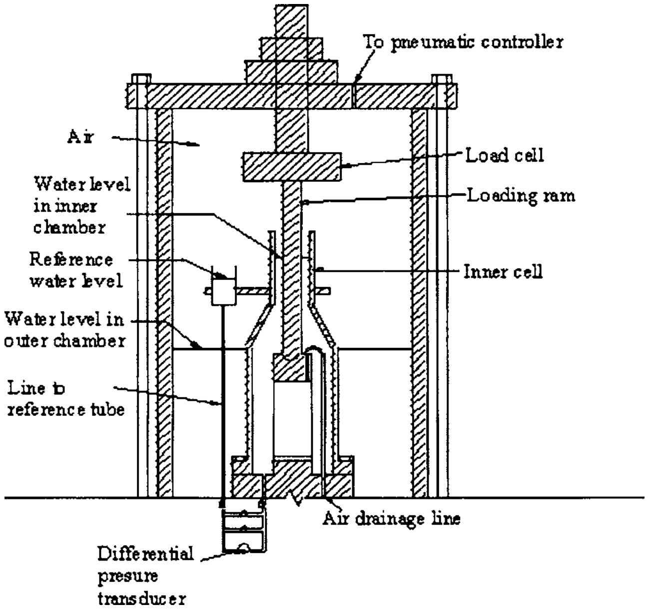

FIG. 1—*Double-cell triaxial Apparatus, Ng et al. (2002)*

suoka (1984) and Tatsuoka (1988). The method was successfully used by many other researchers, including Aversa and Nicotera (2002) and Ng et al. (2002). The method is based mainly on level measurements between the water inside the open-ended bottle shaped inner cell and the reference water level (Fig. 1). The level measurements were recorded by using a high-accuracy differential pressure transducer. Ng et al. (2002) used aluminum instead of acrylic materials to make the inner cell in order to prevent creep, hysteretic effects, and absorption of water. Ng et al. (2002) used paraffin as recommended by Tatsuoka (1988) to avoid evaporation of water with time. Allowing paraffin to float on the top surface of the water can cause additional problems when the direction of the flow is changed (Sivakumar 1993). In addition, the outer and inner cells (above the reference water levels) were pressurized with air, and this can be dangerous when operating the system under high pressures.

Twin-Cell Stress Path Apparatus

Wheeler (1986) developed a modified triaxial apparatus referred to as the Double-Walled triaxial cell to monitor the sample volume change. The volume change of the unsaturated sample was measured by monitoring the amount of water draining into or out of the inner cell by pressurizing the inner and the outer cell to the same pressure. Although this method has produced valuable information (Wheeler and Sivakumar 1995) the approach suffered from a number of disadvantages, particularly absorption of water by the inner acrylic cell wall. In addition, the setting up of the sample in the triaxial cell was a considerable task as it had to be performed under water. The effect of temperature variations on the volume change measurements was a particular concern when the room temperature fluctuated during day and night. The absorption of water by the acrylic and the effects of temperature variations in the testing environment have been successfully overcome in the new twin-cell stress path system for testing unsaturated soils. Details of this system along with the operational procedures required are discussed in the following sections.

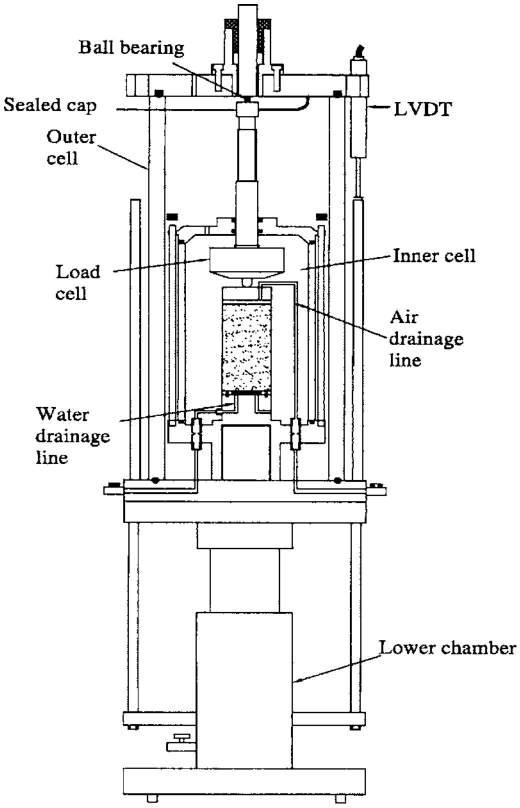

FIG. 2—*Schematic diagram of the twin-cell stress path apparatus.*

Hardware

Figure 2 shows a cross sectional view of the new twin-cell stress path apparatus. The apparatus contains two individual cells: (a) an outer cell, which is the standard stress path cell supplied by V J Tech Ltd, Reading, United Kingdom, and (b) an inner cell, which is a small triaxial cell capable of testing 50 mm diameter samples. The inner cell wall is made of high quality glass ground to have parallel ends. The use of glass has completely eradicated the absorption of water by the acrylic as occurred in the system used by Wheeler (1986) and Sivakumar (1993). A cylindrical cavity is located at the base of the inner cell so that it can be directly located on the pedestal of the standard stress path cell. Water and air drainage lines are fitted to the bottom of the inner cell and they are then passed through the outer cell in order to connect them to the relevant pressure systems. When the system is assembled, the outer cell fully encloses the inner cell, which prevents the expansion of the inner cell when the cell pressure is raised. The load cell is located inside the inner cell. A tight "O" ring seal is used to prevent any leak of inner cell fluid into or out of the outer cell through the loading ram bushing. The deviator load on the sample can be applied by controlling the pressure in the lower chamber. The lower chamber is that of the usual Bishop and Wesley stress path cell.

The system is capable of testing 50-mm-diameter samples. The assembly of the inner cell under water can avoid any entrapment of air bubbles in the inner cell. Since the measurement of sample volume change is made by detecting the flow of water into or out of the inner cell, it is important to minimize temperature variations in the room. However, the effect of temperature variation can be reduced by calibrating the cell volume change against changes in temperature measured using a temperature probe (LM35 precision temperature sensor) which is located in the outer cell.

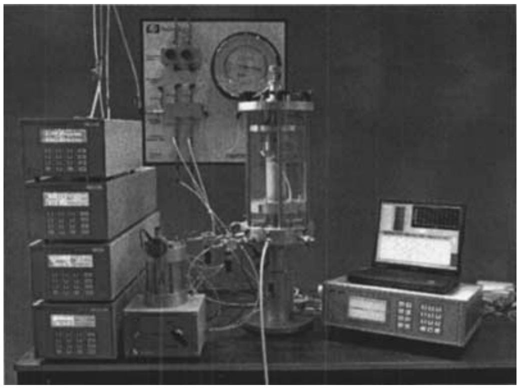

FIG. 3—*Twin-cell stress path system.*

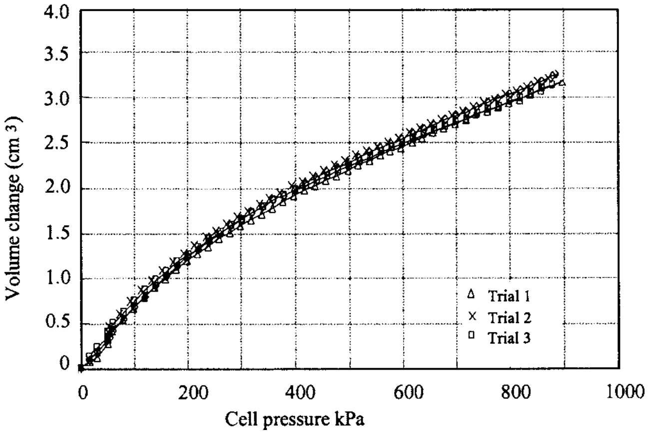

FIG. 4—*Apparent volume change of inner cell with increasing cell pressure.*

Control System

The system is operated by a software application called WinClip. The software is designed for testing unsaturated soils. Figure 3 shows the configuration of the experimental system. The pore air and cell pressures are controlled by pneumatic control devices (Ref: VHT2270). If the pressure in the compressor is not sufficiently high, the hydraulic control is used to apply cell pressure (Ref: VJT 2260). Pore water pressure is also controlled by a hydraulic control unit. The same pressure source applies pressure to the inner and outer cells. However, a volume change unit (Ref: VJT 0310) is located in the pressure line that applies pressure to the inner cell so as to monitor the flow of water into or out of the inner cell. The accuracy of the volume change unit is ±0.02 cm^3. The suction is controlled by controlling pore air pressure and pore water pressure using the common axis translation method. The axial load can be controlled using stress or strain control depending on the desired test specifications. The WinClip program allows various stress path tests to be performed automatically. The types of test which can be performed include: wetting and drying at a constant or variable mean stress and stress path tests at various stress ratios $\Delta q/\Delta \bar{p}$ or $\Delta q/\Delta s$ or any combination of them. These stress paths tests can be performed using stress or strain control.

Calibration of the Cell

Even though the inner and outer cells are pressurized to the same pressure, the inner cell volume can change due to various effects. Factors contributing to this volume change are: small flexibility of the fittings and connections, slight expansion of the volume change device, compressibility of the water, deformation of inner cell, and deformation of the load cell. Calibration is also necessary in order to account for the volume of water replaced by movement of the loading ram into the inner cell during shearing. This can be easily achieved by multiplying the cross sectional area of the loading ram with the movement of the loading ram.

Figure 4 shows the volume change of the inner cell plotted against the cell pressure. The cell pressure was ramped at a rate of 15 kPa per min, to a target pressure of 900 kPa. The calibration was repeated three times and in each case the cell was re-assembled from the filling procedure. The calibration shows that the volume change of the volume system is small and repeatable even at high cell pressures.

Further calibrations were performed in order to examine the hysteresis of the system when the cell pressure was reversed. Figure 5 shows the apparent volume change of the inner cell when the cell pressure was increased from zero to 900 and subsequently reduced to 200 kPa followed by reloading to 900 kPa. The reproducibility of the volume change when the loading is reversed is good. However, it should be noted that reduction of cell pressure to a low value might trigger any dissolved air in the inner cell fluid to come out of the solution and cause inaccuracies in the volume change measurements. This will be a serious problem when a sample is actually present in the cell and the axial translation technique is used to control suction. Diffusion of air in the sample to the inner cell fluid can take place through the rubber membrane. This dissolved air comes out of the solution when the cell pressure is reduced significantly. Therefore, the proposed method of measuring volume change may not be suitable in situations where reduction of cell pressure to a very low value is required. This does not mean that the unsaturated soil cannot be tested at low pressure ranges. The behavior of unsaturated soil is controlled by the mean net stress which is defined as the difference between the cell and air pressures. The proposed system can be used to test unsaturated samples at low mean net stress either by reducing cell pressure or increasing air pressure and the latter method would be preferred for the reason stated above. Figure 5 also includes the volume change of plastic tube connections between the volume change unit and the inner cell (volume change of the volume change device and of the water contained in it) during

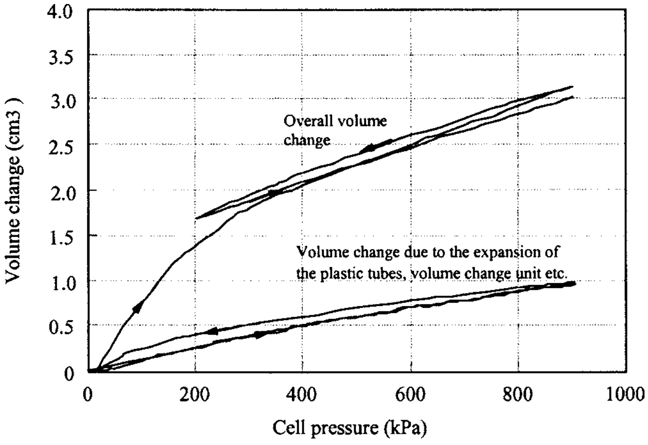

FIG. 5—*Reproducibility of the inner cell volume change during loading and unloading.*

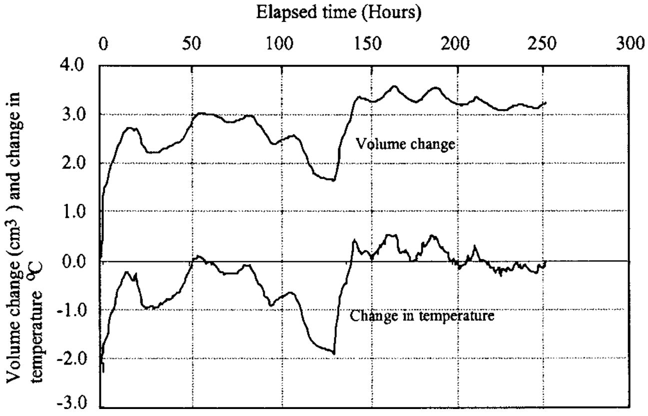

FIG. 6—*Variation of temperature and volume change with elapsed time.*

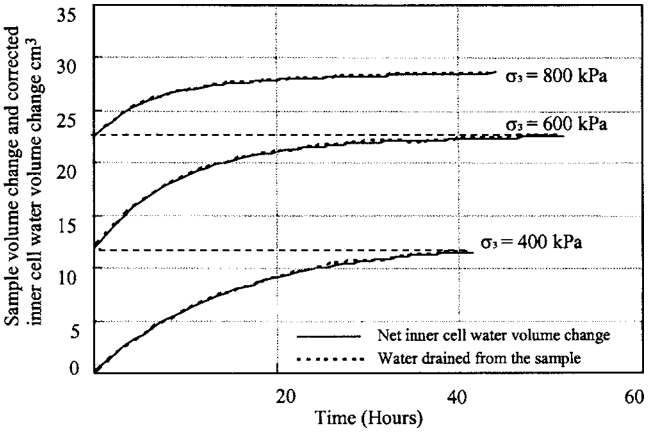

FIG. 8—*Volume change during consolidation.*

the loading and unloading. Once again the reproducibility of the volume change is good.

The effect of temperature variation on the inner cell volume change was examined by observing the flow of water into or out of the inner cell when the cell pressure was maintained at 900 kPa. Figure 6 shows the volume change of the cell plotted against time. Also included in this figure is the change in the temperature in the laboratory. During this time the temperature in the laboratory was allowed to fluctuate a couple of degrees in the early stages of the calibration. At a later stage the cooling system was set to its default setting (ie ±0.5 °C). As shown in Fig. 6, the volume change of the inner cell was significantly affected by the temperature. The variation in the inner cell volume correlates closely with the fluctuations in the temperature. A calibration was introduced to remove the effects of temperature variation in the cell volume change. Figure 7 shows the observed volume change and the calibrated volume change plotted against time. The calibration for temperature variation has significantly improved inner cell volume change.

A test was performed to examine the accuracy of the sample volume change measurements made using the twin-cell stress path system. This was performed by testing a saturated triaxial sample. The volume change of the inner cell (after calibration for apparent volume change) should be equal to the volume of water that drained out of the saturated sample. The sample was initially consolidated to 200 kPa of effective confining pressure. This pressure was increased to 400 kPa and 600 kPa. These pressures correspond to cell pressures of 400 kPa, 600 kPa, and 800 kPa. The sample was allowed to consolidate fully at each pressure. Figure 8 shows the consolidation curves for each pressure increment. The volume change of the sample was obtained using two methods: (a) the amount of water that drained out of the sample and (b) the water that flowed into the inner cell to compensate for the reduction in the sample volume. In the latter, relevant calibration was applied to eliminate the apparent volume change of the volume system caused by the increase in cell pressure. The agreement between the two volume changes is excellent. The condition of the sample at the end of each pressure increment is shown in Fig. 9, in which the estimated sample volume change is plotted against the volume of water that drained out of the sample. The line drawn at 45° indicates the expected correlation and the regression line based on the experimental data is not shown in this figure as the line drawn at 45° correlates closely with the experimental data.

Further tests were performed to assess the repeatability of the volume change measurements when unsaturated samples are actually tested in the twin-cell stress path system. Three samples, prepared under identical initial conditions were tested under a control suction value of 100 kPa. The samples were initially allowed to equilibrate to a suction value of 100 kPa. This was then followed by ramped consolidation in which the cell pressure was increased at a rate of 0.6 kPa/h. Figure 10 shows the relationship between the specific volume and the mean net stress plotted on a logarithmic

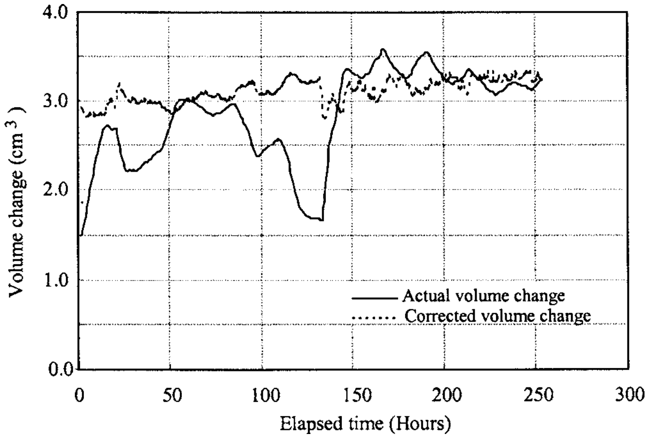

FIG. 7—*Variation of measured and corrected volume change with elapsed time.*

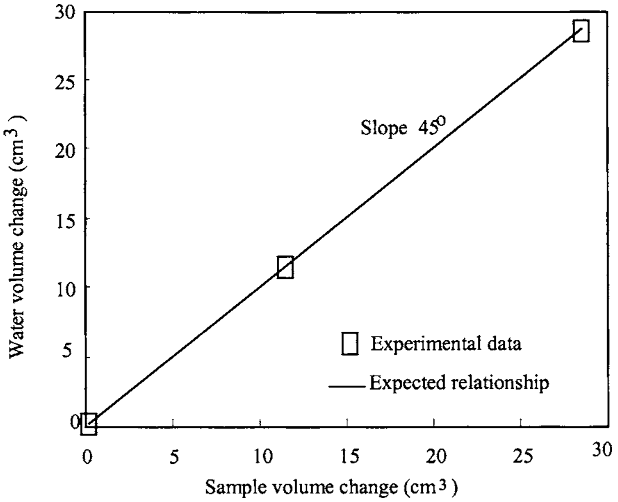

FIG. 9—*Sample and water volume change.*

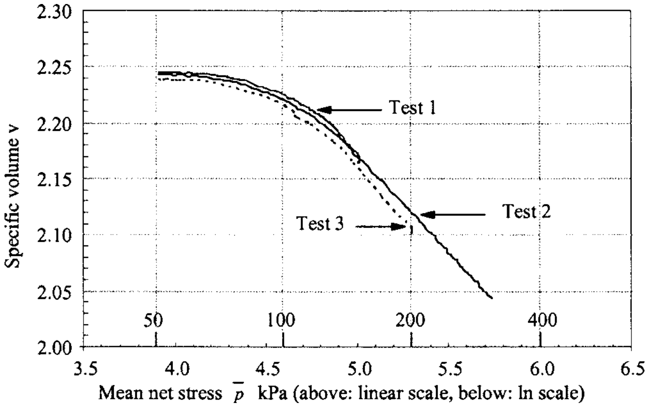

FIG. 10—*Variation of specific volume with mean net stress.*

scale. The specific volumes of the samples were calculated using the volume changes of the inner cell. Once again the consistency between the three tests is encouraging. A slight variation in the initial specific volume has been caused by small differences in the initial specific volume of the samples.

Conclusion

Measurements of sample volume change in unsaturated soils cannot be made using traditional techniques available for testing saturated soils. Many techniques have been proposed for this purpose but many of them are complex and not suitable for long-duration testing. This note reports a new twin-cell stress path system for testing unsaturated soils. The system is simple to use and produces reliable measurements of sample volume change.

Acknowledgments

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