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Volume change measurement in triaxial testing of unsaturated soils

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ABSTRACT: Change in the volume of a soil specimen is related to its pore-fluid. In saturated soils, volume change can be measured by monitoring the inflow or outflow of pore water from the specimen. However, conventional techniques of measuring the volume change are not applicable to unsaturated soil specimens due to presence of air phase. Over the past decades, several volume measurement techniques have been developed for testing of unsaturated soils. This paper first summarizes basic working principles of different volume change measurement techniques used in triaxial apparatuses. Advantages and disadvantages of these measurement methods are debated, based on the most-recent literature. Finally, the technique that is most implementable to the commercial practice, namely cell liquid variation technique, is investigated at greater depth. The performance of this technique is experimentally observed by applying it to a saturated specimen, in a fully automated triaxial apparatus without any modification to the equipment. In these experiments, volume change during consolidation and shearing is measured by variation in cell liquid and compared to simultaneous measurements of change in pore water volume. A modification to the calibration procedure is proposed. The accuracy ofthe volume change measurements is demonstrated to improve with themodified procedure.

1 INTRODUCTION

Unsaturated soils are frequently encountered in geotechnical engineering all over the world. Pore space within an unsaturated soil is filled with both water and air, unlike saturated and dry soilsin which, pores are completely filled with only water or only air. The volume change in a soil specimen is related to pore fluid. In saturated soils volume change can be measured by monitoring the inflow or outflow of pore water from the specimen. However, such techniques are not applicable in unsaturated soils because of presence of the compressible air phase whose volume can change in addition to volume changes due to drainage. Even though volume changes in the air phase have been measured (Ludahn et al. 2005), majority of unsaturated triaxial test setups rely on external measurement of specimen volume.

Various methods have been suggested in the literature to measure the volume changes of unsaturated soils externally in triaxial test setups and these may be classified in three categories as (i) Cell liquid variation measurement, (ii) Direct measurement on the specimen, and (iii) Non-contacting measurement techniques.

All of these methods require some modification to the conventional triaxial setup or involve additional pieces of equipment. The only exception is cell liquid measurement method with only one cell. These methods are explained in the following sections of this paper. The latter half of this paper explains our work, in which accuracy of cell liquid measurement with single cell is experimentally observed and a calibration procedure is proposed.

2 CELL LIQUID MEASUREMENT

In this method, volume change of the specimen is related to variation of volume of the triaxial cell liquid. This can be done by (i) using a single triaxial cell, monitoring the inflow/outflow of cell fluid, (ii) using an open ended inner cell and monitoring the variation in fluid level in the inner cell, or (iii) using a sealed inner cell and monitoring inflow/outflow of fluid in the inner cell.

The advantage of using a single cell is simplicity: conventional triaxial equipment can be employed without any modification. Volume change of the triaxial cell fluid is related to the soil specimen volume change, expansion of the cell and tubing, and piston intrusion into the cell. Moreover, a calibration process needs to account for not only the immediate expansion of the cell caused by pressure increase, but also time dependent volume changes such as creep behavior of the cell under constant stress and possible water leakage (Rifai et al. 2002).

To eliminate the errors related to the expansion of cell, and to reduce measurement error due to large volume of confining liquid, Bishop and Donald (1961) proposed a modified triaxial cell, which included an additional inner cylindrical cell sealed to the outer cell base (i.e. a double cell). The inner and outer cells were filled with mercury and water respectively, up to level of the top cap. Pressure in the two cells are connected through compressed air that fills the upper half of the setup. As the pressures inside and outside the inner cell are equal, the inner cell does not expend due to variation in cell pressure. Then, soil volume change can be related to variation of fluid level in the inner cell. This level change was monitored by tracking the movement of a steel ball floating over the mercury surface, using a cathetometer.

Ng et al. (2002) used a bottle-shaped open-ended inner cell, as shown in Figure 1a. The smaller surface area of the inner cell around the loading ram makes the water level in the inner cell more sensitive to specimen volume changes. Moreover, they incorporated a differential pressure transducer to measure changes in the water level with greater precision.

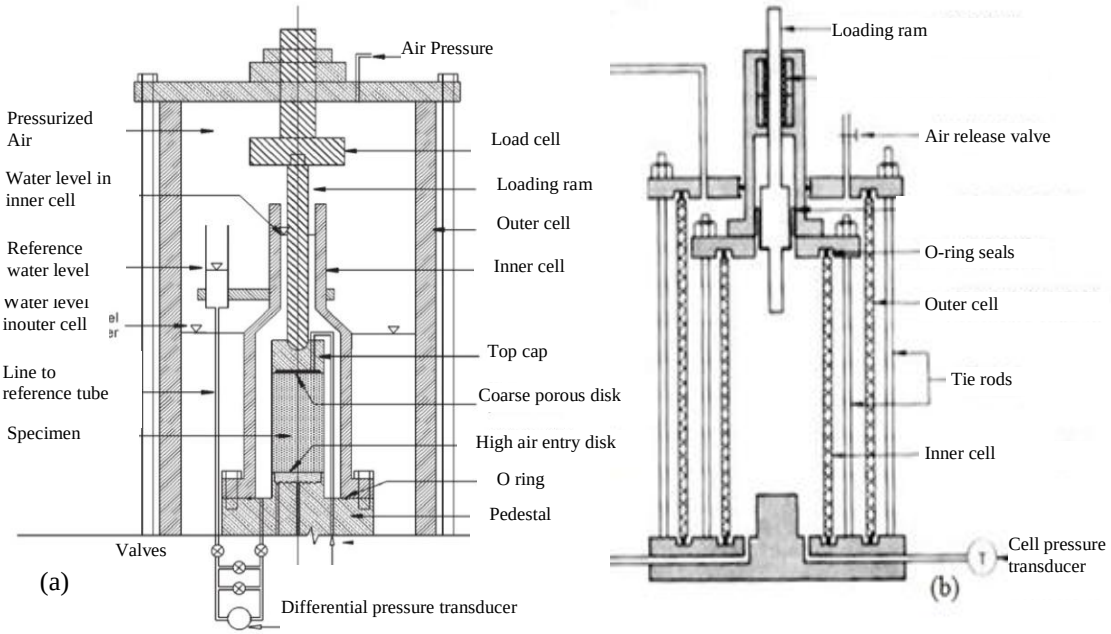

Figure 1. Double wall volume measuring triaxial setup a) (Ng et al. 2002) b) (Wheeler 1988)

In the double-wall triaxial apparatus developed by Wheeler (1988), the inner cell was sealed at both ends and both the inner and outer cells were filled completely with water. Equal cellpressures were applied to the inner and outer cells to avoid expansion of inner cells. The volume change in the soil specimen was measured by monitoring the flow of the water into or out of the inner cell with a burette system connected to a differential pressure transducer or a volume-change device (Figure 1b).

3 DIRECT MEASUREMENT ON THE SPECIMEN

Volume measurement in a triaxial test can be performed by locally monitoring the axial and radial strains of the samples (Figure2). Axial and radial strains can be measured directly by using different approaches. Several technologies have been tested (Laureano et al, 2008), such as mounting miniature LVDTs (Costa-Filho, 1982; Klotz and Coop, 2002), proximity sensors and Hall Effect transducers (Clayton and Khatrush, 1986) onto the specimen. Generally, radial displacements are measured at one to three discrete points and assumptions are made as to the shape of the specimens to assess the volumetric strain. Sensor placement is quite delicate; if not done correctly, it may lead to experimental errors; hence this approach is best suited for initially rigid specimens. Such local measurements become meaningless as a means of measuring soil volume change at large strains or if a shear plane forms across the specimen.

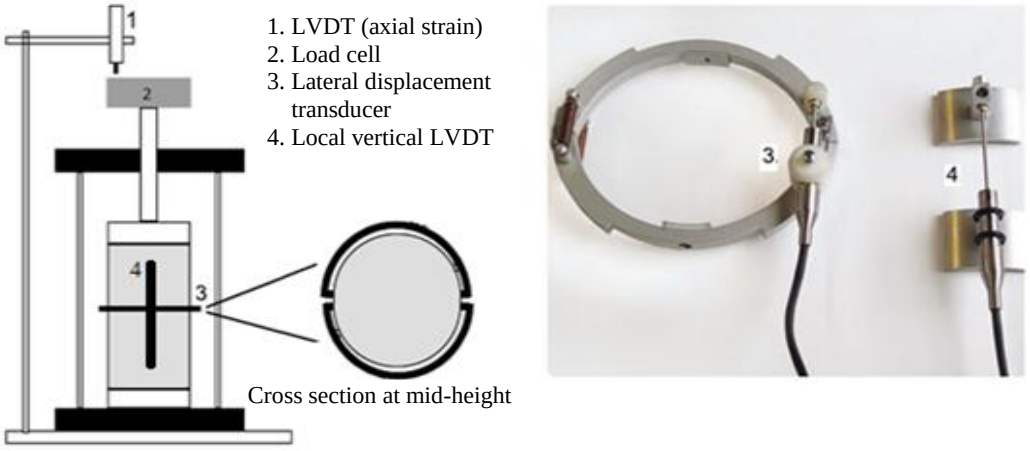

Figure 2.Local strain gauges for measuring of sample volume change in a triaxial apparatus

4 NON-CONTACTING MEASUREMENT TECHNIQUE

Non-contacting measurement techniques include laser mapping and image processing techniques. Romero et al. (1997) suggested mapping the specimen with lasers that sweep over the entire specimen height, allowing more accurate determination of the specimen volume. Radial deformations on two diametrically opposite sides of the specimen are measured via non-contact, long-range, electro-optical lasers mounted outside the chamber. The technique requires costly and sophisticated equipment and installation procedures.

Macari et al. (1997) proposed the use of image processing technique to measure volume change. This method includes one or several computer-controlled digital cameras, which are placed at a fixed distance from the specimen. The images are then analyzed by software, which also accounts for magnification due to unequal refraction indices of air, cell wall and cell fluid, to obtain specimen geometry profiles and volume values. The main advantage of this method is that once image processing algorithm and cameras are provided, a conventional triaxial setup can be employed to measure volume change without any modification. Note that multiple cameras are necessary unless the specimen is symmetrical, i.e. without strain localization.

5 EQUIPEMENT OVERVIEW

In this study, cell liquid variation technique with single cell is applied on a GEOCOMP LoadTrac-II/FlowTrac-II fully automated triaxial setup without any modification. A schematic diagram of the test setup is shown in Figure 3.

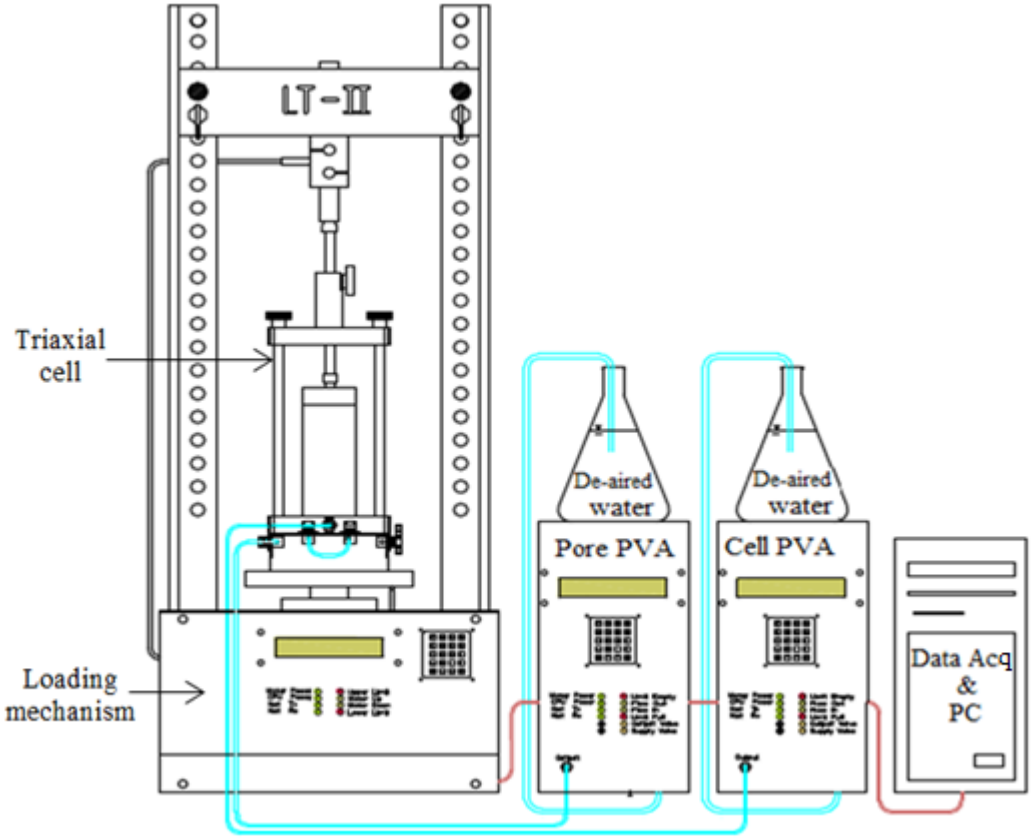

Figure 3. Schematic view of triaxial system (adopted from Geocomp, 2010)

Apart from the triaxial cell, the triaxial system consists of a load frame, two pressure volume actuators (PVA) for controlling volume and pressure for the cell and specimen, a computer for test control and data acquisition.

Each PVA utilizes a high speed, precision micro stepper motor to regulate pressure and volume in the cell or specimen. The built-in microprocessor controls the micro stepper motor, which drives a piston in and out of a sealed cylinder. A pressure transducer on the end of the cylinder provides the feedback for control of pressure. Movement of the motor is used to compute volume change. The PVAs are capable of maintaining the desired pressure to within ±0.35 kPa (0.05 psi) while monitoring volume changes to within ±0.001 cc or ±1 mm^3 (Geocomp, 2010).

6 CALIBRATION

A series of calibration tests were performed to take the expansion and creep behavior of the cell into account. For this purpose, the cell was filled with distilled de-aired water and pressurized, without specimen, under different loading and unloading conditions and pressurization rates (figure 4a). Through different pressurization schemes, the triaxial cell was loaded up to 1000 kPa and unloaded, over the course of. In all of these tests, a nonlinear-elastic behavior was observed. At cell pressures lower than 200 kPa the behavior isnon-linear,possibly due to air bubbles which dissolve as the pressure increases from 0 to 200 kPa. Beyond this pressure, behavior becomes linear and repeatable. If the volume measurement at 200 kPa is taken as reference (similar to zeroing volume measurement at the end of pressure saturation in a real test) the pressure-volume relationship fits onto a unique line

with R^2 = 0.9999. In addition, a hysteresis behavior was detected between loading and unloading (figure 4b).

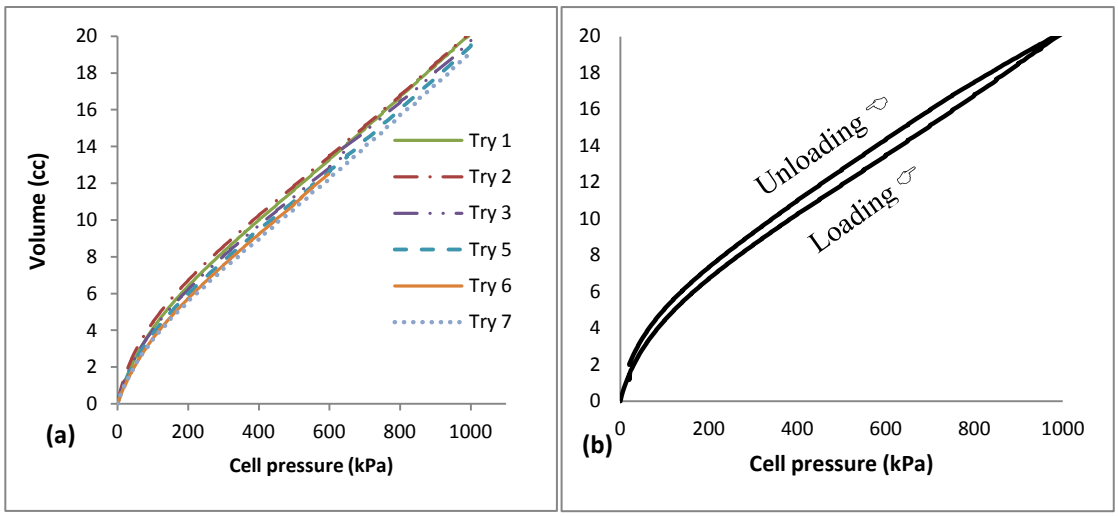

Figure 4. Calibration cycles with gradual loading/unloading.

To monitor the creep behavior of the cell,the pressure was quickly increased to a target pressure and kept constant at that pressure for 200 minutes. The time dependent portion of volume change that is due to creep of the cell as well as micro-scale leakage is measured as the change in volume in reference to the volume measurement at the end of rapid pressurization. This type of measurements were performed for 950, 900, 800, 700 and 520 kPa cell pressures (figure 5).

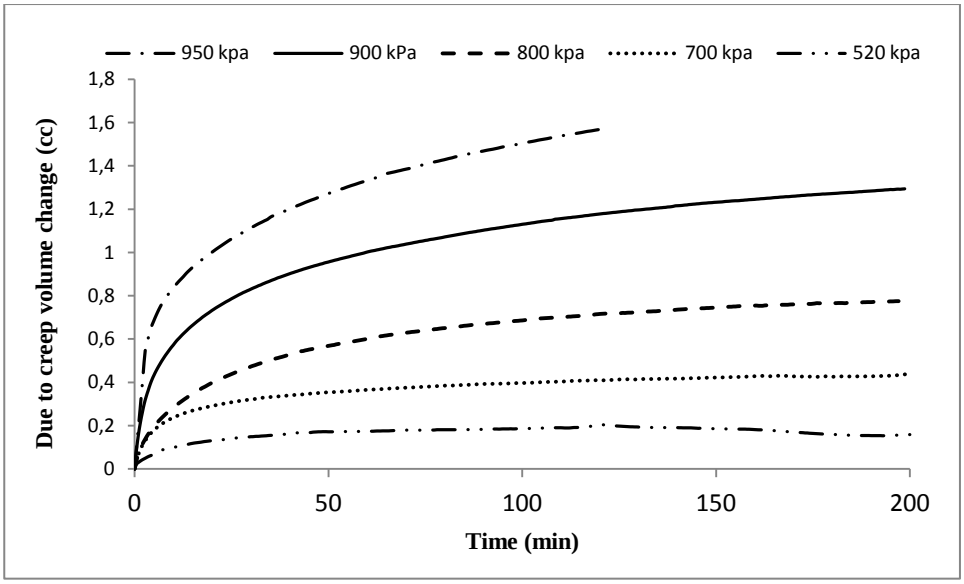

Figure 5. Creep behavior under constant pressure. Time axis starts from the end of pressurization

An additional factor is the movement of the loading ram into and out of the cell. Volume change measurement must be corrected by the product of axial displacement during the test and cross section area of loading ram as follows:

$$\Delta V_{corrected} = \Delta V_{measured} - \Delta L \,.\, S \quad \text{Eq.1}$$

Where, ΔV is for expansion, ΔL is compressive axial deformation and S is cross section area of loading ram.

7 VOLUME MEASUREMENT IN SATURATED SAMPLE

In order to confirm the performance of the cell liquid variation method with a single cell,four isotropically consolidated drained compression tests were done on saturated soil. Volume change of the specimen was measured by both conventional method (measuring inflow and out flow of water from the specimen through the pore PVA) and monitoring the variation of cell liquid volume through the cell PVA.

In all of these four tests, first a sandy specimen with 5 cm diameter and 10 cm height is prepared by under-compaction method (Ladd, 1978) on the triaxial pedestal. Then triaxial cell is filled with distilled de-aired water. Next, the test conditions arespecified and triaxial test is controlled by the computer from start to finish. First the specimen is back-pressure saturated until B value reaches 0.96. In these four tests, saturation required cell pressures between 320 and 850 kPa. Then the specimen is consolidated for 8-12 minutes at all-round stresses of σ_c = 930, 900, 760 and 520 kPa. Finally the specimen is sheared in compression. During consolidation and shear, volume change of the specimen is measured by measuring specimen pore water exchange and variation in cell fluid independently. Results of the calibration and creep tests, as well as loading ram calculation, were utilized to correct the volume change measured by cell liquid variation (generic calibration).Change in specimen volume was predicted somewhat successfully (with 0.39 cc accuracy on average) by applying the corrections listed above to the cell fluid volume data (Figure 6).

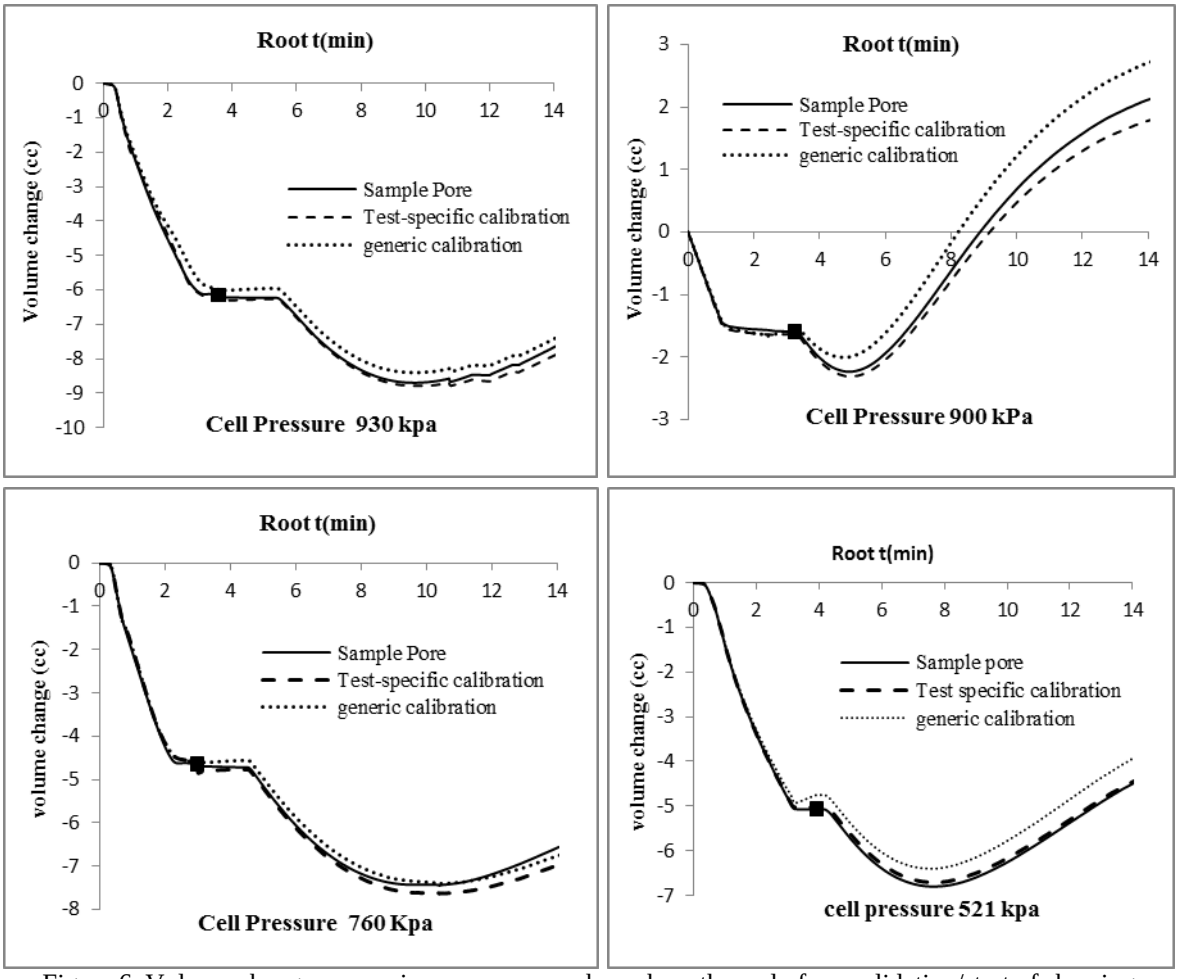

Figure 6. Volume change comparisons, square markers show the end of consolidation/start of shearing

The sequences of cell pressures were not the same in the triaxial tests and creep-calibration tests. In order to reduce errors associated to this difference in durations of pressure application, test specific calibrations were performed. In these, the exact same sequence cell pressures (including

saturation, consolidation and shear), that was in each triaxial test, was repeated with a cell filled with water without a specimen.

When these test specific calibration results were used for correcting the cell fluid volume change data of the triaxial tests, the errors in specimen volume predictions were reduced significantly (Figure 6).

If the absolute errors in volume change and volumetric strain measurements are α and β respectively, the average values of maximum α and β among the four tests were 0.25 and 0.13% respectively, using test-specific calibration. The variation of α value for test-specific calibration versus square root of time for the four tests is presented in figure 7. Table 1 compares the accuracy obtained in this work with that of different volume measurement techniques.

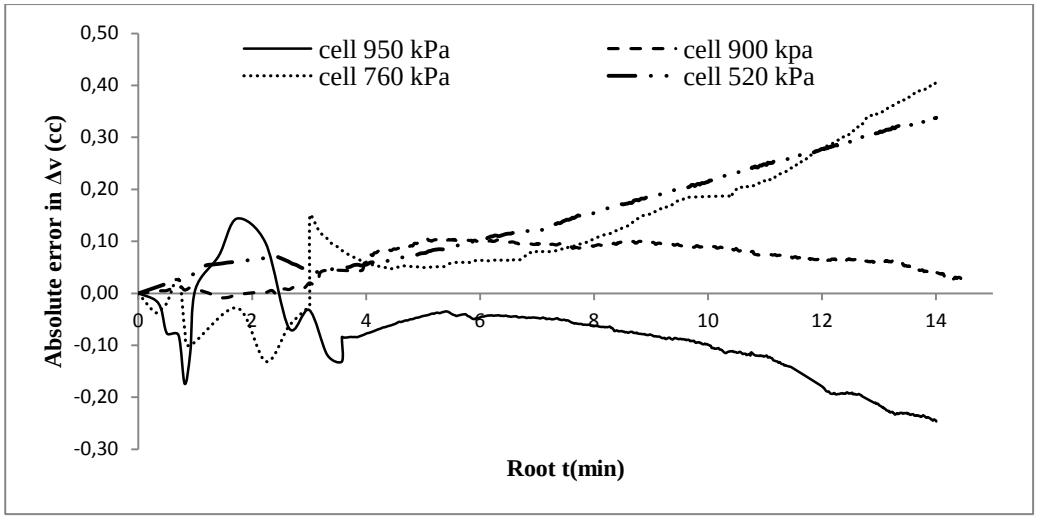

Figure 7. Absolute error in volume change over the course of each test.

Table 1 Comparison of accuracies of volume measurement methods (adopted from Laloui et al, 2006)

Technique	Absolute errors
Cell liquid measurement	
Single standard cell	$\alpha = \pm 0.45$ cm^3 $\beta = \pm 2.2 \times 10^{-3}$
Double-Cell with open inner cell	$\alpha = \pm 0.1$ cm^3 $\beta = \pm 10^{-3}$
Sealed Double cell	$\alpha = \pm 0.6$ to 1.02cm^3 $\beta = \pm 6 \times 10^{-3}$ to 10^{-3}
Direct measurement on the specimen	
Radial and Axial strain measurement	Varies with instrumentation and layout
Non-contacting measurement techniques	
Laser-mapping	$\beta = \pm 7 \times 10^{-5}$
Image processing	$\alpha = \pm 0.25$ cm^3 $\beta = \pm 10^{-3}$
This work	
Single standard cell with generic calibration	$\alpha = \pm 0.39$ cm^3 $\beta = \pm 2 \times 10^{-3}$
Single standard cell with test- specific calibration	$\alpha = \pm 0.25$ cm^3 $\beta = \pm 1.3 \times 10^{-3}$

8 CONCLUSION

Volume change measurement techniques in triaxial tests on unsaturated soils are reviewed and compared. Among these, the technique that is simplest to implement onto a conventional setup is found to be cell liquid variation with single cell. Proper use of this method requires an extensive calibration scheme that consists of multiple corrections to the measurements. These calibration components are first devised from measurements taken from the pressurization of the triaxial cell without a soil specimen inside. Applying the technique to a saturated specimen, the accuracy of the technique is investigated (assuming conventional pore water volume measurements as true values). The accuracy is found to be close to what has been reported in the literature.

One of the calibration components is the time dependent volume change of the cell liquid (due to creep behaviour of the cell wall as well as micro-scale leakage). Rather than correcting any given set of measurements with a single volume change vs. time calibration at constant pressure, test-specific calibration is proposed. In this method, the measurements of each test are corrected using a separate time dependent calibration curve under variable pressure sequence that exactly mimics the variation ofpressure during the test. Even though it doubles testing duration, the proposed correction improves accuracy of the specimen volume change measurements.

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