COMPARISON OF VERTICAL AND VOLUMETRIC SWELLS OF COMPACTED EXPANSIVE SOILS

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ABSTRACT: Swell percentage of expansive soils is commonly obtained from oedometer swell tests under fully lateral restraint condition. In situ heave, however, is not a one-dimensional volume change but more likely a three-dimensional process. Consequently, surface heave predicted from results of oedometer tests is usually conservative and largely differs from heave actually observed in the field. To account for the discrepancy between oedometer and in situ boundary conditions, some researchers have suggested a lateral restraint factor to be applied to heave predictions evaluated based on parameters obtained from oedometer swell tests.

This paper describes a laboratory testing procedure by which the vertical and the volumetric swells of compacted expansive soil samples were concurrently measured using a hydraulic triaxial stress path apparatus. A set of triaxial swell tests was conducted and the ratio of swell in the vertical direction to the volumetric swell, SR, was evaluated. The test results indicated that for a particular swell test, SR is not constant but rather changing with elapsed swelling time. Besides, the value of SR increases as the applied confining pressure increases.

1. INTRODUCTION

The high cost of repairing structural damages associated with swelling soils has drawn attention to the need for more dependable evaluations of various engineering characteristics of such problematic soils. After identifying a soil as being expansive, the next most important step is to accurately quantify the amount of anticipated heave the soil will undergo when subjected to variance in moisture content. Reliable estimate of surface heave is required for the selection of treatment alternatives to minimize volume change or in the preparation of a foundation design to accommodate the anticipated volume change.

The oedometer swelling tests are the methods most often used to identify soils that might swell and to evaluate the amount of swell that may occur. The reason for the frequent use of oedometer swell testing technique has been one of practical convenience sustained in its simplicity, expediency, and the availability of the consolidometer in most, if not all, of the soil mechanics laboratories. However, a large discrepancy is usually found between heave predicted using parameters obtained from oedometer swelling tests and that actually realized in the field. Comparison of field and laboratory data obtained from oedometer tests revealed that the laboratory results from oedometer tests overestimate the in situ heave by a factor of about 3 [1],[2],[3],[4],[5]. This suggests that about one-third of the volume change is reflected as a surface heave, the remainder will be laterally. Accordingly, to convert the potential volume change to the anticipated vertical heave, some researchers have suggested a lateral restraint or a correction factor in the order of one-third to be applied to swell percentages obtained from the oedometer laboratory measurements [3],[4]. However, as indicated by [6] the ratio of vertical to volumetric strain is not constant throughout the swelling layer and the use of a single factor would tend to overestimate movement near ground surface and underestimate it at depth.

Evidently, the vertical movement is more relevant to the design of foundation systems on expansive soils than the total volume change since it is the main cause of deterioration in light buildings or pavements. Oedometer testing methods do provide a measure of the anticipated vertical heave but they significantly overestimate it because of the lack of similarity between the states of stress conditions in the oedometer testing as compared to the actual states in the field. The conventional triaxial swell tests, on the other hand, furnish more realistic loading conditions and offer a more satisfactory way of measuring swelling of expansive soils. However, in these studies in which expansive soil samples were tested in the triaxial apparatus under multi-axial state of stress it has been possible to measure only the total volume change of the tested samples (e.g., [7],[8],[9]).

This paper presents a testing procedure through which the vertical swell and the total volume change were simultaneously measured from swell tests carried out on statically compacted samples subjected to triaxial loading conditions. The swell tests were conducted in a hydraulic stress path cell complemented by a manometer for measurement of sample volume change. The presented testing technique was specifically designed to examine the ratio of vertical swell to volumetric swell, hereafter called the swell ratio or for short SR, of expansive soil samples subjected to triaxial state of stress, and how this ratio is related to the magnitude of applied confining pressure.

2. APPARATUS AND TESTING PROCEDURE

2.1 Equipment

The swell tests were carried out in a hydraulic triaxial stress path cell of the type reported by Bishop and Wesley [10]. A schematic diagram of the layout of the testing system is shown in Fig. 1. The cell is self-contained, portable, and requires no loading frame. The axial load is applied to the sample by pressurizing the lower chamber at the bottom of the cell. The piston pushes up a loading ram, at the top end of which is the pedestal on which the soil sample is mounted. Thus, in the conventional triaxial apparatus the loading ram is pushed downward against the top of the sample. In the stress path cell, however, it is the sample that is pushed upward against a stationary submersible load cell. This is a salient feature of the stress path cell that makes it possible to measure not only the vertical swell of the tested sample but also its total volume change. In the conventional triaxial apparatus it has been possible to monitor only the total volume change of the tested soil samples.

2.2 Swell Measurements

The vertical swell of the tested samples was measured with two micrometer dial gauges. They read to 0.01 mm mounted on the top of the cell and deflected by two vertical extension rods that pass through clearance holes in the cell base and connected to the loading ram. The volume change was measured with a manometer, which consists of a transparent U-tube of 6 mm-bore glass tubing. The manometer is mounted on a supporting frame and is fitted with a scale marked in millimeters. A water-filled rigid nylon tubing of small bore connects one limb of the manometer to the base of the triaxial cell through valve 2 and the other limb is connected to a pressure gauge. The basic layout and the principal features of the volume measurement system is shown diagrammatically in Fig. 1.

The volume change of the sample was measured by observing the quantity of water entering or exiting the cell to compensate for the change in volume of sample. To make this observation, it was necessary to measure the displacement of a free surface between the water supply to the cell and some other fluid having different density. Such surface was first provided by the boundary between the water and mercury. However, because of the high specific gravity of mercury, a significant head difference arises as the volume of the sample changes and the mercury is displaced from one limb of the manometer to the other.

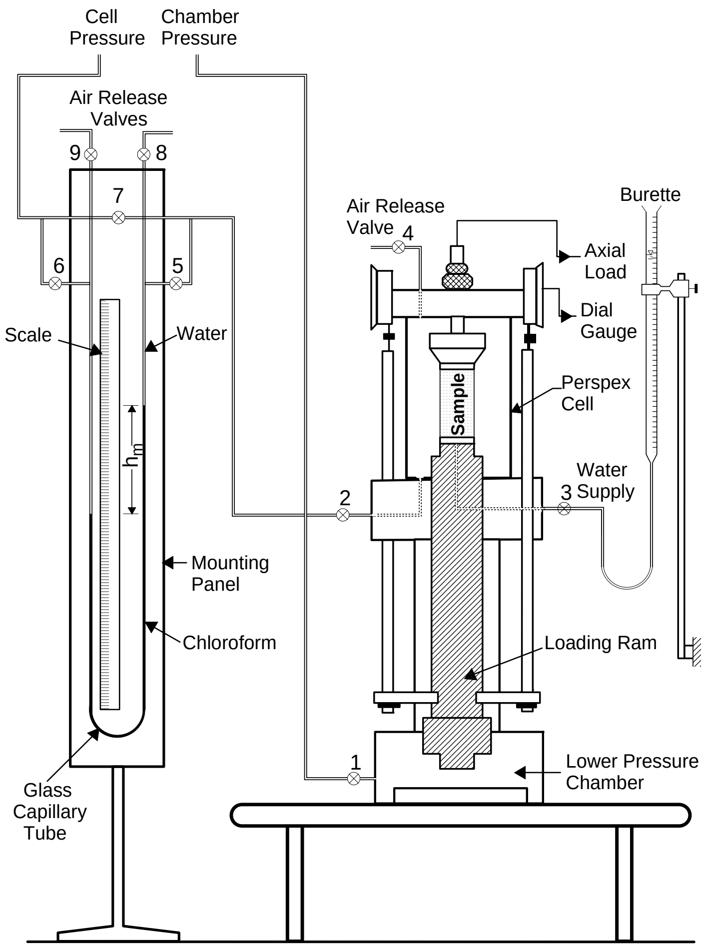

Figure 1: Bishop-Wesley stress path cell and experimental set-up

Therefore, the lower part of the U-tube of the manometer was filled with Chloroform (CHCL3). The difference between the specific gravity of water (1.0) and of Chloroform (1.5) is sufficiently small for volume change to result in less than 5.0 kPa pressure per meter difference in the level of the surfaces. Potassium lodide was added to the Chloroform to define clearly the meniscus between it and the water. The position of the Chloroform in the limbs of manometer can be adjusted by opening valves 8 and 9, which remain closed during the measurement of volume. It is essential that the measuring system is thoroughly de-aired and is watertight without the slightest leak.

Observation of the sample total volume change is dependent on whether the sample is allowed to swell vertically or not. If in a certain test the vertical swell was not permitted then when a volume increase occurs in the sample due to swelling, and if the triaxial cell containing the soil is completely filled with de-aired water before the swelling test is started, water will flow from the cell to the manometer causing the Chloroform to move from one limb to another. The sample volumetric swell, S_v, is then given by

$$S_v = A_m h_m \tag{1}$$

where A_m is the manometer cross-sectional area and h_m is the difference in the levels between the Chloroform in one limb measured initially and again after expansion has taken place after known time t. Readings are taken at the interface meniscus inside the indicator.

If the sample is allowed to swell vertically, the load piston is pushed downward out of the cell and the movement of water from manometer to the cell or vice versa will depend on the relative magnitudes of vertical and total volumetric swell of the tested sample. Recorded data should indicate whether the left-hand or right-hand limb was observed (i.e. if inflow or outflow). In all tests conducted water moved into the cell. In this case, the sample volumetric swell is obtained from

$$S_v = A_p \Delta h - A_m h_m \tag{2}$$

where A_p, is the piston cross-sectional area and Δh is the change in sample height at time t. The accurate measurement of volume change is particularly important when the cell pressure is large and the swelling is small. A small 6-mm diameter tube was used to give greater accuracy in the volume readings. The size of the tube has been found convenient for most tests on 76-mm high ×38-mm diameter samples. If the cumulative flow exceeds the null indicator capacity, valve 2 is then closed and the Chloroform column is brought back to its original location, or to another location which becomes a new datum for subsequent readings, by opening valve 8 and valve 9. The clearance is 70 mm (i.e., maximum h_m) and that provides capacity for the anticipated volume change of the tested samples often without needing reversal of flow.

2.3 Test Procedure

Immediately after compacting, the specimen was removed from the mold and with the aid of a stretcher it was enclosed into a single watertight rubber membrane and was mounted on the base of the triaxial cell. The base platen was lightly coated with a film of thin grease prior to attaching the membrane. The specimen was seated against a saturated porous stone and a second similar porous stone was placed on the top of the sample. The membrane was then sealed to the top loading cap and the bottom platen with O-ring seals. Subsequently, valves 2 and 7 were opened, and the perspex cell was filled with de-aired tap water flowing through valve 2. The air release valve 4 on the triaxial cell was opened to release trapped air. The rate of filling was reduced when the level was almost full and valve 4 was closed when water began to flow. Then valve 1 was opened and the chamber pressure was incrementally increased until the loading ram, along with the sample, began to move upward. The chamber pressure required to move the ram upward is easily determined by knowing the combined weight of the loading ram and the specimen.

The upward movement of the loading ram slowly continued until the top loading cap touched the stationary load cell, which recorded the load, and then valve 2 was closed. Utmost care was taken with the alignment of the top loading cap with the load cell. It was important that the loading cap gently touches the load cell so that the sample will not be subjected to axial compression. In the meantime, it was essential to ensure a full contact between the top loading cap and the load cell so that the entire vertical swell will be detected and measured by the dial gauges shown in Fig. 1. If a space is left between the top loading cap and the load cell, the specimen will expand upward, and this expansion will not be detected by the dial gauges. Therefore, to maintain contact between the top loading cap and the load cell a nominal axial pressure of about 2 kPa was applied to the sample.

A self-compensating mercury control was used for applying both the lateral and chamber pressures. The axial pressure, σ_a, is applied by pressurizing the lower pressure chamber. However, in the stress path apparatus the axial stress, σ_a, and cell pressure, σ_c, are interrelated. The value of σ_a depends on both σ_c and the pressure in the lower pressure chamber, *p,* and the key to the operation of the cell lies in the relationship between σ_a, $\sigma_{c,}$ and *p*. Therefore, after deciding the desired cell pressure for the given test, the chamber pressure was determined accordingly. For any particular test, a nominal cell pressure is initially applied and the value of p is gently tuned to balance the cell pressure, $\sigma_{c,}$ plus the weight of loading ram and soil sample. Considering the equilibrium of the loading ram shown in Fig. 1, the specific value of *p* necessary to produce the required σ_a for a given value of σ_c can easily be determined.

With valves 1, 2 and 4 closed, the chamber pressure, *p,* and cell pressure, σ_r, were increased to the specified values. Their values were monitored by pressure transducers connected to electronic readout devices. After reaching the specified values for the chamber and cell pressures valves 1 and 2 were simultaneously opened (valve 7 was also opened). In case the initial setting of the dial gauges changes, fine touching is obtained by a screw arrangement at the top of the cell so that the top loading cap remained in full contact with the load cell. Then valve 7 was closed and valves 5 and 6 were opened. Accumulated air through the manometer is released through the opening of valves 8 and 9 to bring the null indicator back to its original position.

The specimen was allowed to consolidate under the applied isotropic confining pressure for a period of about 24 hours before it was given free access to water. Initial manometer and dial gauge readings were taken, and water was introduced to the bottom of the sample by opening valve 3 which is connected to a 50 ml single-tube drainage burette as shown in Fig. 1. Readings were taken at convenient time intervals until the change in vertical and volumetric swells under the applied confinement was negligible at which swelling was assumed to be completed and the test was terminated. The sample was then removed from the cell, weighed, and its length and average diameter were measured. Three slices were taken from the bottom, middle, and top of the specimen and used to find the final water contents.

3. SWELL TESTS

3.1 Preparation of Test Specimens

Remolded samples were used in the testing program to minimize variations in test data due to variability of soil samples. In order to ensure uniformity of testing, the bulk samples were dried, pulverized into a powder in batches, and screened through ASTM sieve No. 40. Individual samples were oven-dried for about 24 hours and then thoroughly mixed to the chosen molding moisture content and stored in air-tight plastic bags and were allowed to cure at room temperature for a minimum of 24 hours to allow the water distribute itself evenly throughout the soil.

The material selected for preparation of samples was brought from the town of Al-Ghatt, located 270 km Northwest of Riyadh. The soil formation in the region represents typical expansive shale 8 to 10 meters thick and with relatively high swelling parameters (i.e., volume change and swell pressure). Soil samples for laboratory testing were obtained from a test pit at a depth of about three meters. The pit was excavated in an area where many residential buildings, sidewalks, and pavements have been severely damaged due to differential heave of the supporting soft rock shales.

Laboratory testing on extracted samples involved the performance of routine classification and mechanical properties tests. The liquid and plastic limits are 60 and 30, respectively, and the soil has a specific gravity of 2.8. The natural moisture content is about 22%, which is far below the plastic limit and hence relatively high values for swell parameters are expected. The soil contains 28% silt-size particles (0.075-0.002 mm) and 72% clay-size particles (< 0.002 mm). It is classified as a CH soil as per the Unified Soil Classification System (USCS).

The 38 mm-diameter, 76 mm-long specimens for the triaxial tests were statically compacted to the desired density in a vertically-split compaction mold. The use of a split mold ensures that the density of the sample will not be changed, as otherwise would be the case if it were jacked out of the mold. Static compaction method was chosen as it provides better control of the specimen condition. In addition, to maximize overall uniformity, the soil was compacted in three layers each with about 25-mm thickness. The required soil weight for the first layer was poured into the compaction mold. The soil was then compacted by inserting into the mold a 35 mm-diameter aluminum rod whose length is 25 mm shorter than the high of the mold. Using a jack, the rod was pushed against the soil sample until a flange at its top touched the rim of the compaction mold. The same procedure was repeated for the other two layers, except that the rods used for compacting the second and the third layers are, respectively, 25 mm and 50 mm shorter than the first rod.

3.2 Results and Discussions

In order to examine the reliability of the testing equipment and procedure, two replicate tests T-a and T-b were first conducted under a confining pressure of 25 kPa on samples compacted at an initial water content of 18% and dry density of 16 kN/m^3. The measured percentages of vertical and volumetric swells are plotted against time in Fig. 2. It can be seen that the results of the two tests are comparable with only minor discrepancy in the values of the volumetric swell towards the end of the tests. The percentage of vertical swell is defined as the ratio of the increase in height of the sample to its initial height before it was given free access to water. The increase in volume of the sample after wetting expressed as a percentage of initial sample volume before wetting is the sample volumetric swell or total volume change.

The second set of tests comprises eight swell tests, carried out to determine the ratio of vertical swell to volumetric swell, SR, for samples prepared at different values of initial water content and subjected to different magnitudes of applied confining pressure. The samples for all of the eight swell tests were statically compacted at a dry density of 17.3 kN/m^3, following the procedure described in the previous section. The first four swell tests were performed on samples prepared at an initial water content of 14% and tested under confining pressure of 25, 50, 100, and 200 kPa, respectively. In the fifth and the sixth swell tests, the samples were prepared at initial water content of 18%. The former was tested under a confining pressure of 25 kPa while the applied confining pressure for the latter was 50 kPa. The seventh and eighth swell tests were, respectively, similar to the fifth and sixth tests except that the initial water content for the samples was 22%.

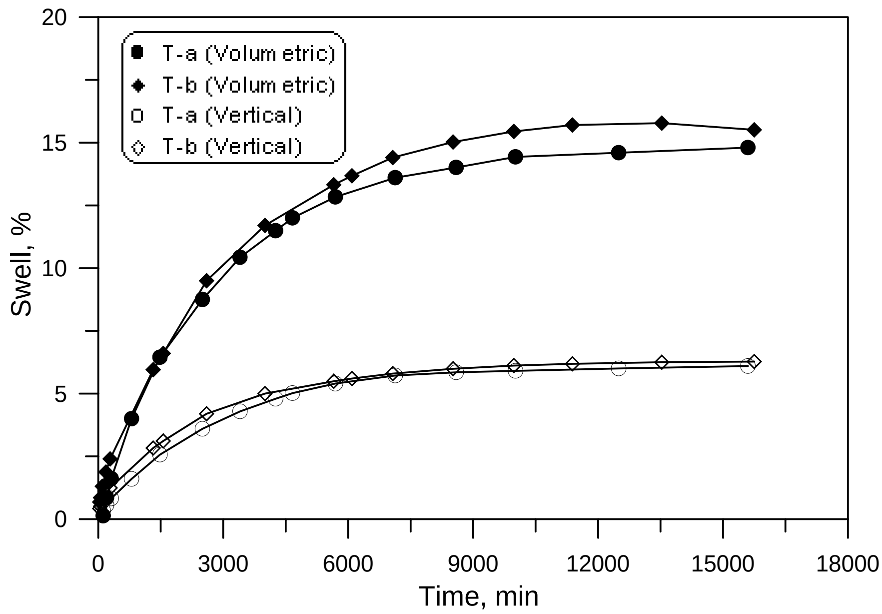

Figure 2: Swell-time relationships for two replicate swell tests

Typical variation of the percentage of vertical swell and total volume change against time is shown in Fig. 3 and Fig. 4 for Test #1 and Test #4, respectively. Similar patterns have also been observed for the other six swell tests. It is noted from the results of Fig. 3 and Fig. 4 that the swell ratio, SR, is not constant throughout the test but rather changing with elapsed swelling time. It can be seen, for instance, from Fig. 3 that the ratio increased from about 0.45 at the start of the test to around 0.54 at the time when the test was terminated. The average value for SR for this test is about 0.50. However, for Test #4 where the confining pressure was 200 kPa, it seen from Fig. 4 that SR ranged between 0.49 and 0.78 at the commencement and termination of the test, respectively, and the average ratio is about 0.64.

The value of initial water content was found to have almost little or no effect on the vertical swell to volumetric swell ratio. Depending on the magnitude of confining pressure, however, the value of SR at the beginning of the performed swell tests lie between 0.40 and 0.49 and ranged from 0.54 to about 0.78 at the end of the tests. The relationship between the logarithm of confining pressure and SR values at ultimate swell for Test #1 Through Test #8 is shown in Fig. 5. The average value of SR for each test was also evaluated and drawn in Fig. 5 against the logarithm of confining pressure. It is noted that the average swell ratio as well as the swell ratio at ultimate swell approximately assumes a linear relationship with the logarithm of confining pressure. If only the ultimate state is considered, the average value of SR is around 0.64. However, if the swell ratios for all tests at all time intervals are considered, the average value of SR is about 0.55.

The results of Fig. 5 also indicate that the ratio of vertical swell to volumetric swell increase as the confining pressure increases. This implies that the level of confinement has relatively more effect on the total volume change than on the vertical swell of expansive soil samples. The increase, for instance, in confining pressure from 25 kPa in Test #1 to 200 kPa in Test #4 reduced the percentage of ultimate vertical swell and volumetric swell by about 41% and 57%, respectively. This reality is more obvious when the percentages of ultimate vertical and volumetric swells for Test #1 through Test #4 are plotted against the logarithm of applied pressure as shown in Fig. 6. It is noted that the ultimate volumetric swell decreases at a higher rate in comparison to the swell in the vertical direction.

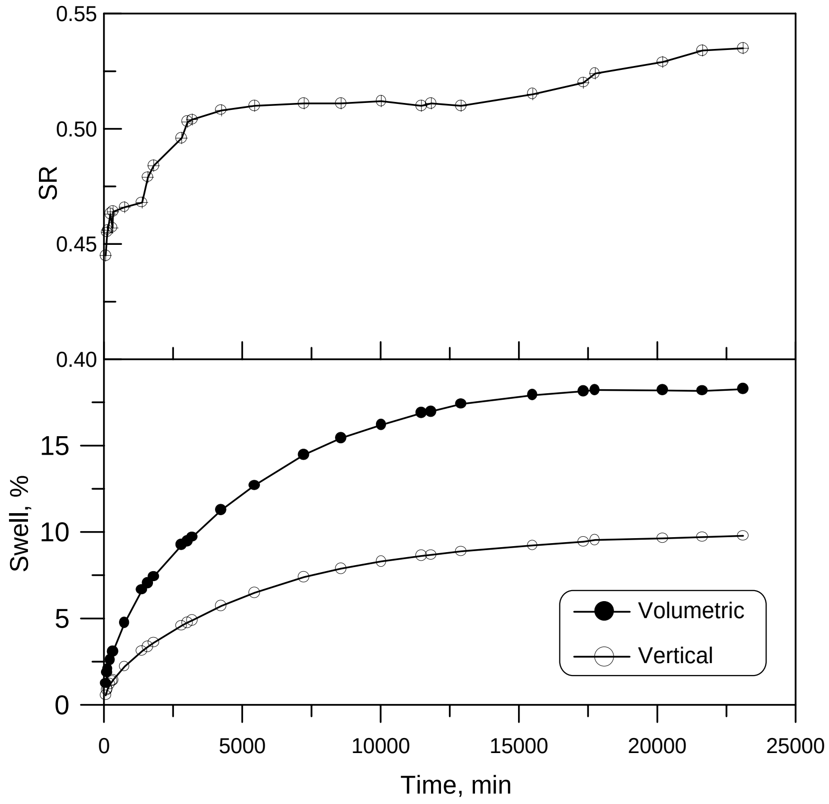

Figure 3: Vertical and volumetric swell percentages versus time for Test #1

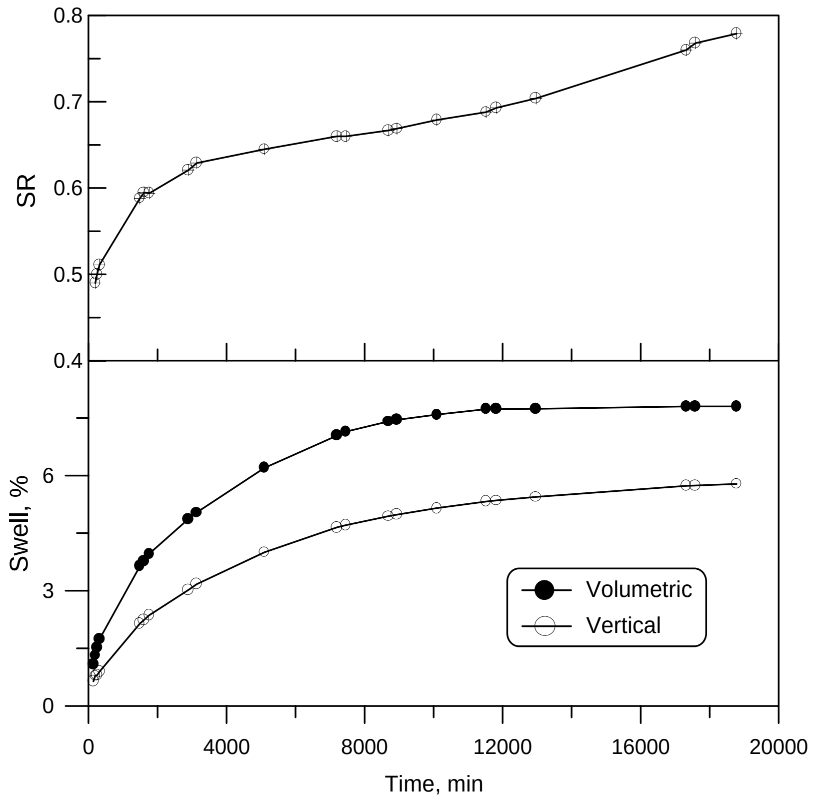

Figure 4: Vertical and volumetric swell percentages versus time for Test # 4

Therefore, as one would intuitively expect, the higher is the applied confining pressure the more volume change would be reflected as a surface heave. The maximum percentage of vertical swell takes place under the fully lateral restraint condition maintained in the different forms of oedometer swell tests. In these tests, volume change occurs in the vertical direction only, resulting in the percentages of vertical swell and volume change being identical; and hence SR is equal to unity. Therefore, the ratio of vertical swell to volumetric swell could be as low as about 0.4 for samples subjected to low confinement under multi-axial state of stress to exactly one for samples tested under one-dimensional loading conditions in the oedometer.

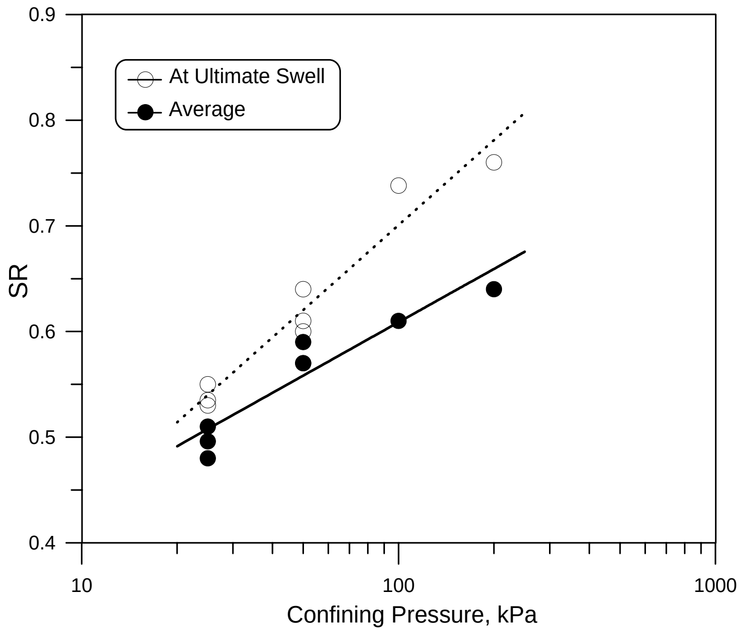

Figure 5: Relationship between swell ratio and logarithm of confining pressure

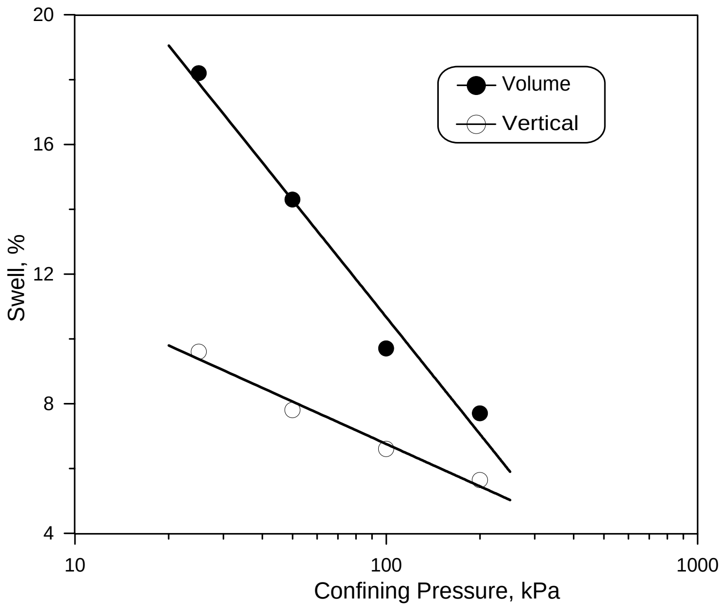

Figure 6: Relationship between applied confining pressure and ultimate vertical and Volumetric swells for Test #1 through Test #4

4. CONCLUSIONS

In this paper, it was demonstrated that the hydraulic triaxial stress path cell is versatile equipment that can be used effectively for measuring swell parameters of expansive soils. Complementing the cell with a manometer for the measurement of volume change, it has been possible in this study to measure both the vertical swell and the total volume change of the tested samples. This is to the writers' knowledge the first attempt in which both vertical and volumetric swells of expansive soil specimens were directly and concurrently measured in the same triaxial swell test.

Based on the results compiled in this study, the value of the ratio of vertical swell to volumetric swell, SR, is not constant but changes with elapsed swelling time. Furthermore, SR linearly increases with increasing applied confining pressure. The minimum and maximum values for SR were about 0.40 and 0.78, respectively, and the overall average swell ratio for all tests at all time intervals was around 0.55. The ratio of vertical swell to volumetric swell could, therefore, be as low as about 0.40 for samples subjected to relatively low triaxial confining pressures to exactly one for samples tested under one-dimensional loading conditions in the oedometer.

These results are, however, limited to a relatively small number of tests on a single soil. Further work is still required to determine whether these findings are more generally applicable to other reconstituted and natural soils with different conditions of initial water contents and dry densities and tested under different loading conditions. It would also be advantageous to compare the vertical and volumetric swells measured under triaxial load condition with the volume change (which is also the vertical swell) of samples prepared under the same initial conditions of dry density and moisture content and tested under one-dimensional loading conditions in the oedometer.

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مقارنة الانتفاخ الرأسي والحجمي لتربة انتفاخية مدكوكة

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الملخص : عادة يتم الحصول على نسبة الانتفاخ للتربة الانتفاخية من التجارب التي تجرى في جهاز الأودوميتر تحت حصر جانبي كلي. لكن الانتفاخ الحقلي يتم غالباً في ثلاثة اتجاهات وليس في اتجاه واحد. وبالتالي تكون قيمة الانتفاخ السطحي الذي يتم تقديره من نتائج تجارب جهاز الأودوميتر أعلى كثيراً من القيمة الحقيقية للانتفاخ الحاصل في الحقل. ولتصحيح اختلاف حالة الحصر الجانبي في جهاز الأودوميتر عنها في الحقل، أقترح بعض الباحثين عامل حصر جانبي يتم تطبيقه على الانتفاخ المقدر بناءاً على المتغيرات التي يتم إيجادها من تجارب الانتفاخ التي تتم في جهاز الأودوميتر.

تشرح هذه الورقة طريقه معملية تم من خلالها قياس متزامن للانتفاخ الرأسي والانتفاخ الحجمي لعينات تربة انتفاخية مدموكة وذلك باستخدام جهاز ثلاثي الضغط هيدروليكي. تم إجراء عدداً من تجارب الانتفاخ تحت ضغط ثلاثي الأبعاد ومنها تم إيجاد نسبة الانتفاخ في الاتجاه الرأسي للانتفاخ الحجمي. وقد بينت نتائج التجارب أن هذه النسبة ليست ثابتة خلال تجربة الانتفاخ بل تتغير مع الوقت. أيضاً فأن قيمتها تزيد بزيادة الضغط الجانبي المؤثر على العينة.