

Swell Behavior of Expansive Soil with Free Lateral Movements

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Abstract. Expansive soils are characterized by volume increase upon saturation. Extensive damages to structures may occur as a result of soil heave. Prediction of field expansion is essential prior to foundation construction. Experimental tests using oedometer equipment are used to predict field swell. However, in these tests, full lateral expansion is restrained which does not represent the actual field behavior where part of volume increase is consumed in the lateral direction. To improve the quality of field swell estimation, different testing techniques must be adopted. In this paper, experimental testing program is carried out on expansive soil with no lateral restraint. It is found that the lateral swell constitutes about one third of the total swell. More attention should be directed to such unconventional testing procedure to replace the oedometer tests for more accurate heave prediction.

Introduction

Expansion of soil is the volume increase upon saturation. Soil formation that is subjected to such deformation is characterized by the existence of lattice particles that will undergo significant swelling due to increase in water content. Lattice structure consists of fine grained particles of clay nature; however, clay mineralogy plays a major role in causing soil expansion. For example, clay mineral of montmorillonite is known for its high water intake resulting in remarkable volume increase. Other clay minerals such as kaolinite and illite have insignificant volume change upon inundation with water. Structural damages due to soil expansion have been recorded in several parts of the world. The problem of soil swelling is of enormous financial losses amounting to billions of dollars (Krohn and Slusson, 1980). The damages are caused by differential soil expansion as wetting does not occur uniformly under the structure. Instead, it happens gradually and during a long period of time that may require years to reach full saturation. In Saudi Arabia, several regions have been found to be covered by expansive soils of variable thickness (Dhowian *et al.*, 1990). Due to vast development in Saudi Arabia in the recent decades damages to structures, particularly of light weight and

pavements have been attributed to soil expansion. It is estimated that expansive soil formations cover an area of about 800,000 km² in Saudi Arabia (Ruwaih, 1987).

The nature of climate that predominates in the area is characterized by severe dryness which will promote the existence of expansion soil formation. The soil strata that are subjected to successive periods of hot and dryness seasons will have strong desire to water that will result in high volume increase.

When preliminary soil exploration indicates the existence of expansive soil, thorough field and laboratory testing program must be carried out to determine the swelling parameters, mainly, swell pressure, and swell index. These parameters are then used to predict soil heave under structures. The magnitude of the estimated swelling will determine the seriousness of the problem. The methods of prediction are generally based on empirical equations relating the soil expansion to some soil properties such as the dry unit weight, percent of clay fraction, Alterberg limit, initial water content, etc. Such procedure is of limited value as it applies to specific soil in specific location. Dhowian *et al.* (1990) summarize these empirical methods in their study on the expansive soil in Saudi Arabia. The use of the experimentally determined soil parameters are,

however, more reliable technique in predicting heave as they are almost based on theoretical bases that can have widespread application. Another method of prediction based on suction parameters is used. Suction can be defined as the negative pore pressure reflected by high water intake desire which decreases with increase in water content accompanied by volume increase. When suction stabilizes, i.e. approaches zero value, the swell reaches its maximum value. The procedure described by Johnson and Snethen (1978) is the most convenient method which can be used in heave prediction. Other researchers have used suction parameters to estimate field volume change (Dhowian *et al.*, 1990; Snethen and Huang, 1992; Fredlund and Rahardjo, 1993; Dhowian, 1992; and others).

Prediction of heave using swell parameters based on oedometer tests tends to over-estimate field expansion due to difference in soil behavior in the laboratory as compared to field conditions. In the laboratory, the resulting swell is the volumetric swell as the lateral expansion is completely restrained, i.e. zero lateral swell, whereas in the field the vertical swell constitutes part of the volume expansion and the rest is consumed by lateral swelling.

The objective of this paper is to examine the effect of lateral restraint by allowing expansive soil specimens to swell in all directions as there will be no lateral restraint. The results of the swell tests will then be compared with the conventional oedometer swell tests. It is expected that expansive soil specimens with free lateral movement will be relatively more accurate in comparison to complete lateral restraint conditions.

Laboratory Determination of Soil Swell

The conventional technique used to evaluate soil expansion is by using the oedometer method procedure which can be explained as follows:

The magnitude of swell expansive clay, laboratory oedometer tests are conducted on undisturbed specimens. There are four alternative methods to determine the swell parameters used in the quantitative analysis of swell by oedometer techniques. The testing procedures are standardized as given in the annual book of ASTM standards 1986, with the designation number of D4546-85. All testing methods require that a soil specimen be restrained laterally and loaded axially in a consolidometer with access to free water. The four testing procedure can be outlined as below.

Method 1

The sample is allowed to swell freely under a seating load, and then loaded to overburden pressure plus the simulated foundation stress, P_o (Jennings, 1969). The corresponding stress path is denoted by ISO, improved swell oedometer test, and the volume change is given the vertical interval (ac) in Fig. 1.

Method 2

In this method, the sample is soaked in the oedometer at a low confining pressure (i.e. 7 kPa) and the amount of well is determined. The sample is then loaded to a stress level which is also referred to as swell pressure, P_s to attain the original void ratio. The swell of the soil under load behavior is then predicted by a straight line, define by the swell at low confining stress and zero swell condition, on swell versus long pressure curve, as shown by the dotted line in Fig. 1 (Brackley, 1975). The anticipated volume change under the stress, P_o , is defined by the vertical segment (be) in the figure. The slope of the straight line will be referred to as the swell index C_{s1} .

Method 3

The sample is loaded to vertical stress P_o , in one increment and then water is added to saturate the sample under the stress P_o . The amount of volume change is given by the vertical interval (ce) and the corresponding stress path is denoted by SO, swell overburden test (Fig. 1) (Johnson and Snethen, 1978).

Method 4

The sample is saturated at a constant volume in the oedometers followed by a reduction of load to vertical stress, P_o . The corresponding volume change given by (de) and stress path is denoted by CVS, constant volume swell test (Fig. 1) (Sullivan and McClelland, 1969). The slope of the unloading portion of volume change versus log stress curve is denoted as the swell index, C_{s2} .

In the prediction of heave by Methods 2, 3 and 4, three swell parameters characterize the volume change behavior; free swell S_s , swell pressure P_s , and swell index C_{s1} and C_{s2} . Analytically, the swell can be calculated by the following equation:

$$\Delta H = \frac{S_s}{1+e_o} H \log \frac{P_s}{P_o} \quad (1)$$

where ΔH is the heave or volume change, H is the height of the expansive layer, C_s the swell index, the P_s , swell pressure, P_o is the overburden pressure, and e_o is the initial void ratio.

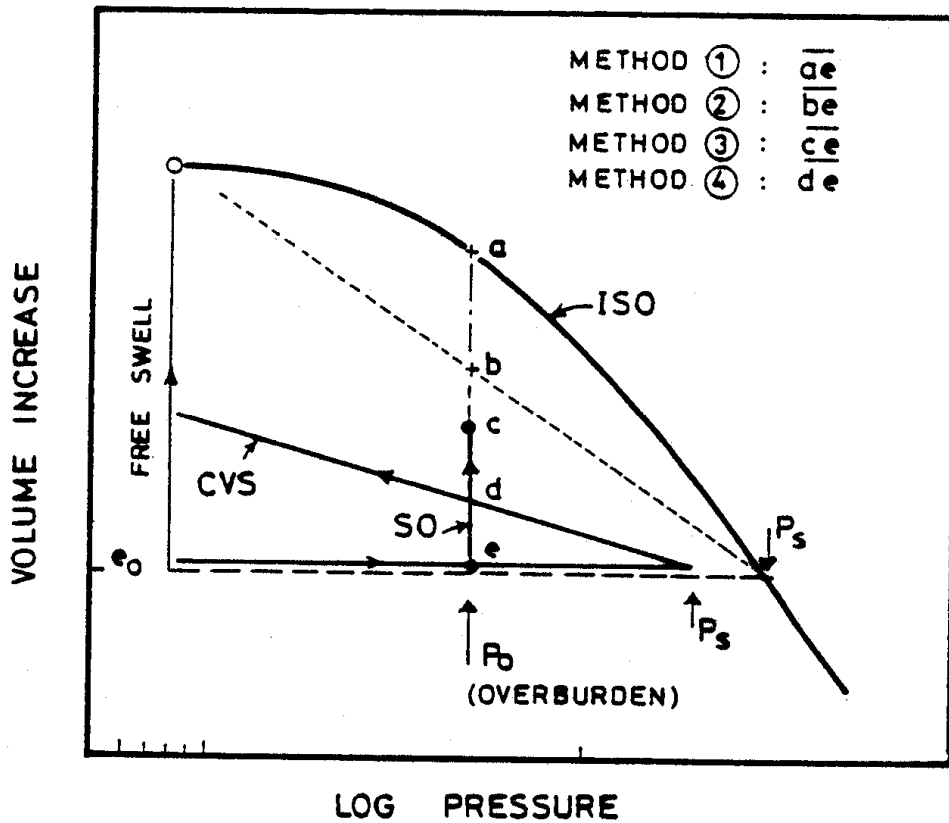


Fig. 1. Swell prediction method.

Swell Test with Free Lateral Movement

The discrepancy between the measured heave and heave estimated based on swell parameters obtained from oedometer tests data has been attributed to the stress path and behavior of swelling samples in the oedometers. As pointed out earlier the measured swell using oedometer technique represents a volumetric volume change as the swell in the lateral direction is fully restrained. This is contrary to the field value change during swelling where vertical swell constitutes part of the total swell. For this reason, swelling soil sample will be allowed to expand without lateral restraint. To achieve this special equipment is designed consisting mainly of a circular metal base of sufficient thickness. The diameter of the base is about 100 mm. In the center of the circular base another circular base of diameter equal to the soil specimen diameter of 25 mm rising about 40 mm above the larger metal base. Water is allowed to flow through the smaller circular metal base by circular tube of about 1.5 mm diameter penetrating the metal base. On top of the small circular base a porous stone of the same diameter is

placed to allow water to flow freely from the metal base through the porous stone and to the expansive soil specimens. The soil specimen is placed on top of the porous stone inside rubber membrane. Another porous stone is placed on top of the soil specimen that is in contact with top metal circular platen with the same diameter as the soils specimen. Top metal plates are also penetrated by circular tube that allows water to flow out of the soil specimen. Small vertical load is applied to the specimen (7 kPa) to ensure complete contact of the platen with the soil sample.

For the measurement of the lateral swelling, four dial gages are mounted and placed at equal interval and made in lateral contact with the soil specimen. Dial gage D is the closest to the base of the specimen, and dial gage A is the closest to the top of the specimen. Vertical swell can be measured by another dial gage mounted at the top of the specimen. The test set up is shown in Fig. 2.

Characteristics of the Tested Specimens

The expansive soil is obtained from Al-Ghatt region about 220 km north of Riyadh. The soil

consists of silt and gravel of the quarterly age underlain with olive-green shales which are part of the predominant formation in the area called Dhurma Formation. The shales are formed from the accumulation of mud deposits which, after accumulation, get compacted under the weight of the overlying deposits accompanied with some high earth temperature. Under the above mentioned natural agents, a very thin layered (varved) structure is induced to the mud deposits, transforming them to

shale rock. This rock, owing to its grain size and very thin bedding planes (varved structure), is highly weathered formation.

The expansive formation of Al-Ghatt region consists of grey green or yellowish-green shales which underlie the collapsing gypsum rich clayey silts. Typical profile characteristics of Al-Ghatt shale and the range of swell parameters obtained from the undisturbed samples are shown in Fig. 3 (Dhowian *et al.*, 1990).

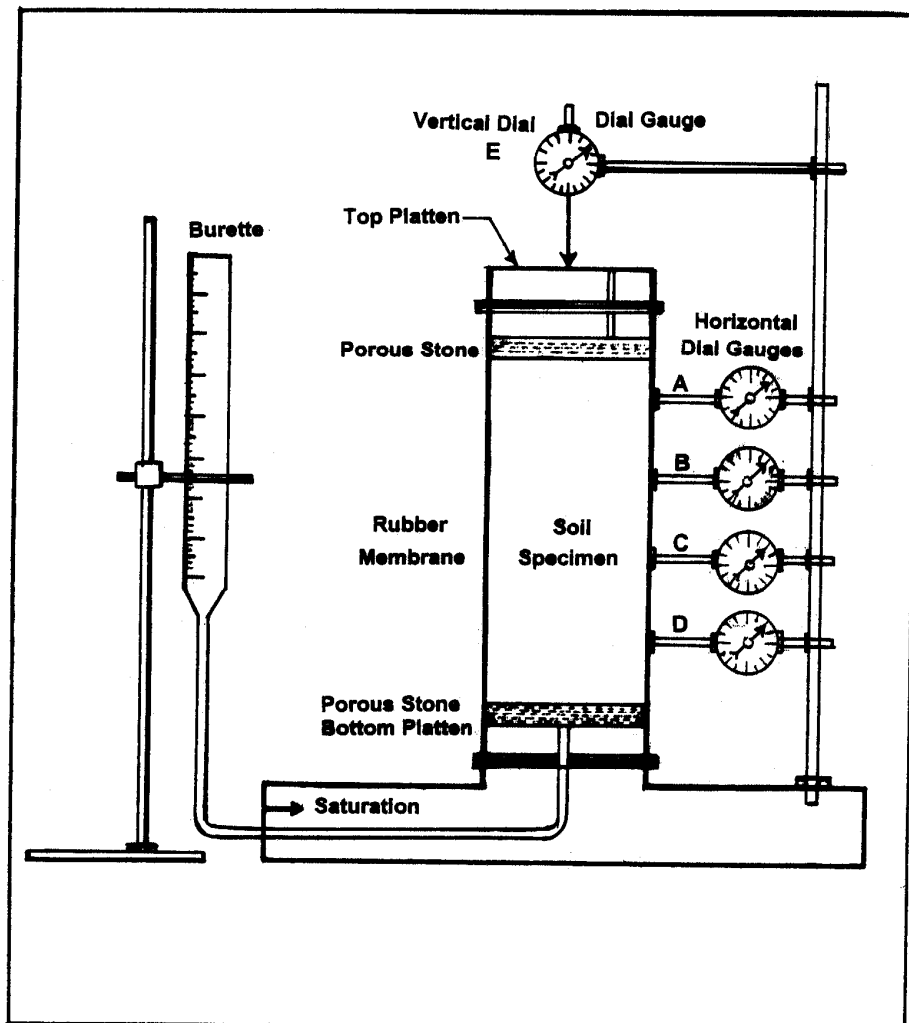


Fig. 2. Set-up for free lateral movement test.

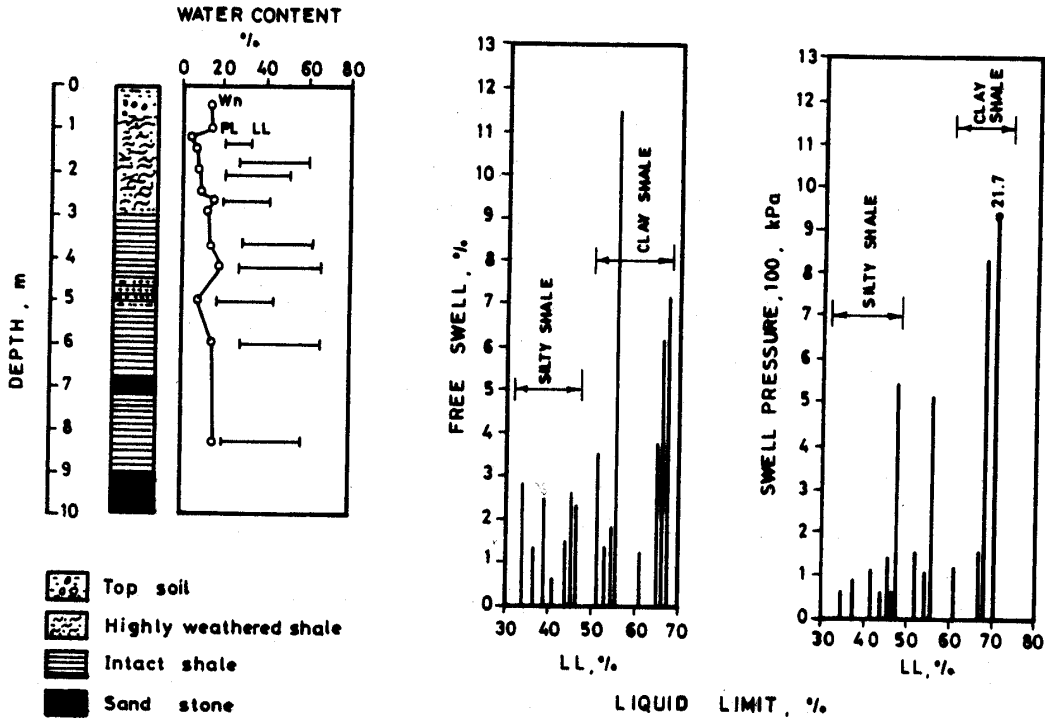


Fig. 3. Typical profile characteristics and swell parameters in Al-Ghatt shale.

Undisturbed block samples are obtained from the expansive shale of Al-Ghatt region. For the purpose of determining the swell parameters using the oedometer tests, undisturbed samples that properly fit the oedometer rings were prepared. Free swell test (ISO tests) and constant volume tests (CVS) were performed on the expansive soil samples. However, due to excessive dryness and thinly layered (varved structure) of the expansive shale, it was difficult to obtain undisturbed samples for the laterally unrestrained testing since the samples are relatively long (76 mm). Therefore, only compacted samples were prepared with dry unit weight and moisture content fairly represent the natural conditions. Prior to molding the samples to the desired dimensions, the block samples were dried, pulverized into powder and screened through sieve No. 40. The soil was then thoroughly mixed with the required water content. They were molded to the right size placed in tight plastic bags to avoid any losses of moisture. It is assumed that with this careful preparation and storage of the expansive soil that fairly identical expansion behavior will be obtained.

Experimental Testing Program

To investigate the behavior of expansive soil in restraint and free lateral movement conditions, two testing procedures have been adopted. For lateral movement restraint oedometer testing equipments have been used according to the method of testing outlined in the preceding section where free swell test and constant volume change oedometer tests were performed to compare the expansive soil behavior with the free lateral movement testing method. The results will be presented in the next section.

As far as the free lateral movement technique is concerned, a circular base at about 25 mm diameter metal base is used. At the center of this base, another smaller diameter base extruding about 3 cm above the larger base is provided with a diameter equal to the diameter of the tested expansive samples (about 25 mm). The testing equipment used is similar to the base of the triaxial cell.

Water connection to allow the flow from and to the soil sample has been provided through the central small base. Figure 2 shows the details of the test set up. Dial gages at the top of the soil sample and at four

levels of the sample have been provided. Vertical deformation as well as the lateral expansion can be measured through these gauges. Water is introduced to the soil sample at the circular small base to the bottom of the sample. A seating load of 7 kN/m^2 is applied to secure complete contact of the loading head to the top of the soil sample.

Testing is commenced by introducing water at the bottom of the expansive sample. Expansion is started taking place as water percolate through the sample. Clearly, the expansion begins at the bottom and extends upward. Readings of the dial gages are recorded with time and continued until expansion reaches a stabilized condition where it attains its ultimate values for all the dial gages. The reading process may require several weeks before reaching the maximum value of expansion at each gage. Due to the gradual wetting of the sample from the bottom to the top, it is noticed that lateral expansion is not uniform but becomes clear at the bottom at the beginning of testing, whereas the upper part of the sample is not affected since water has not reached yet the level of saturation.

Testing Results

Typical results of the free swell test (ISO) and constant volume test (CVS) are shown in Figs. 4 and 5. The vertical swell measured with zero lateral restraint is about 8%, less than that measured in the oedometer test. This is an expected behavior as the vertical swell in the oedometer represents the volumetric swell, whereas the vertical swell with free lateral movement constitutes only part of the total volume change. The result of expansion with lateral swell is consistent with the findings in a previous study conducted by Shamrani and Dhowian (2003) where triaxial testing technique has been used to measure the vertical and lateral expansion.

The void ratio is plotted versus the logarithm of pressure from which the swell parameters, namely, the free swell, the swell pressure, and swell index is determined. The average free swell is found to be about 11% and the estimated swell pressure ranges in values from 200 to 300 kN/m^2 with swell index about 0.07. These values are obtained from the free swell test. In the constant volume test, however, the swell pressure is found to be around 200 kN/m^2 , the estimated free swell is about 23% and the swell index is found to be about 0.25, for more than that recorded in the free swell test. The variation of the swell parameters as indicated by the above values may be attributed to the variation in

the tested soil properties. Also, the method of testing can contribute significantly to the differences in the values of swell parameters. However, the objective of this paper is not the magnitude of the swell parameters, but rather the effect of lateral restraint on the value of the swell.

For the laterally unrestrained soil samples, the vertical swell and lateral expansion are shown in Fig. 6 in which the swell percentage is plotted against the logarithm of time. In general, it is noticed that the vertical swell is higher than the lateral expansion. The lateral swell varies according to the location along the height of the soil sample as indicated by the dial gages, i.e. it is not uniform, but rather indicated higher values at the bottom and decreases with higher height. The lowest value is recorded for the upper dial gage. This behavior of the lateral expansion can be attributed to the sequence of wetting as it started from the bottom and propagate upward. Longer time is needed to attain saturation for the upper part of the sample. However, at end of the upper dial gages reach almost the same value indicating eventually uniform lateral swelling, as show in Fig. 6. Thus, lateral expansion depends on the sequence of wetting and not on the variation of soil behavior for the same sample.

In Fig. 7, the average value of the lateral expansion obtained from the four dial gages is compared with the vertical swelling. When the average value of the lateral swell is related to the vertical swell as illustrated by Fig. 8, the ratio indicated fairly consistent values. An average ratio of about one third is obtained (26%). This is a fair agreement with the previous study by Dhowian *et al.* (1991) in which it is estimated that about one third of soil expansion is in the lateral expansion although no direct measurement has been made in that study.

Figure 9 shows a comparison between vertical swell in the free swell test (ISO) where no lateral deformation is allowed (complete restraint) and vertical swell with free lateral movement. As illustrated by the figure, the vertical swell in the free swell test is much higher than the vertical swell without lateral restraint specially in the early stages of expansion. This confirms the argument that considerable amount of deformation is consumed in the lateral direction and that unlike the oedometer test case where vertical swell represents the volumetric increase, whereas in the case of free lateral movement testing condition, vertical expansion constitutes part of the total expansion.

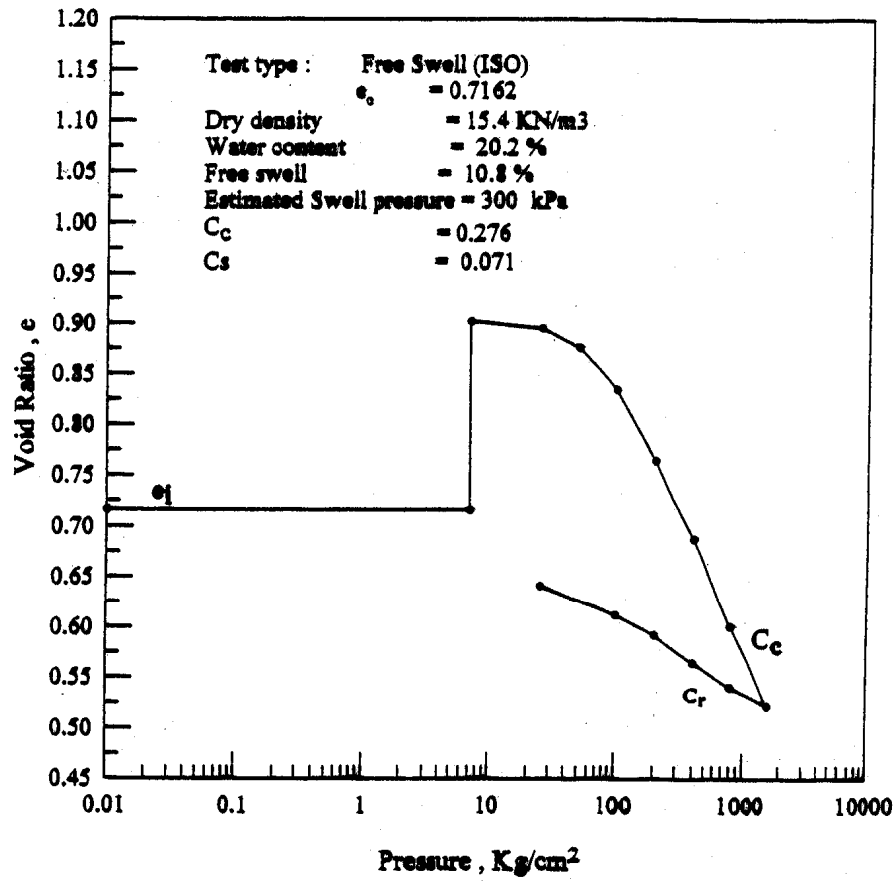


Fig. 4. e-log p curve from free swell test.

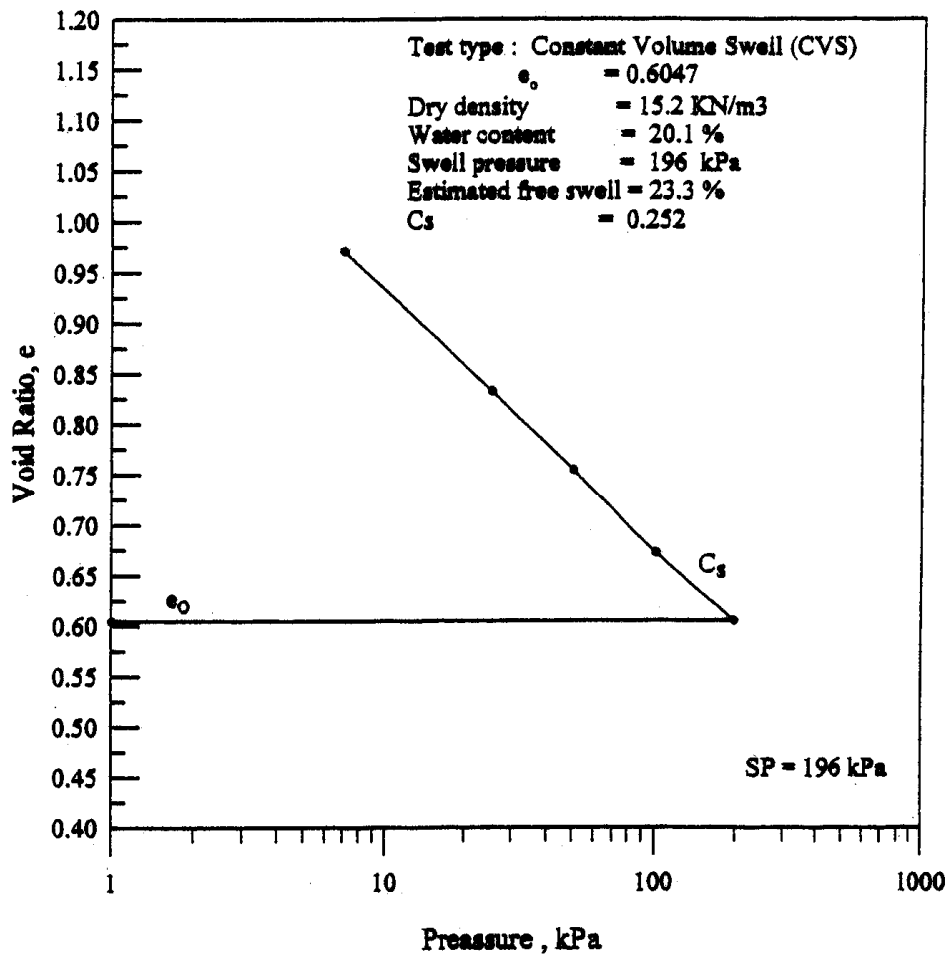


Fig. 5. e-log p curve from swell pressure test.

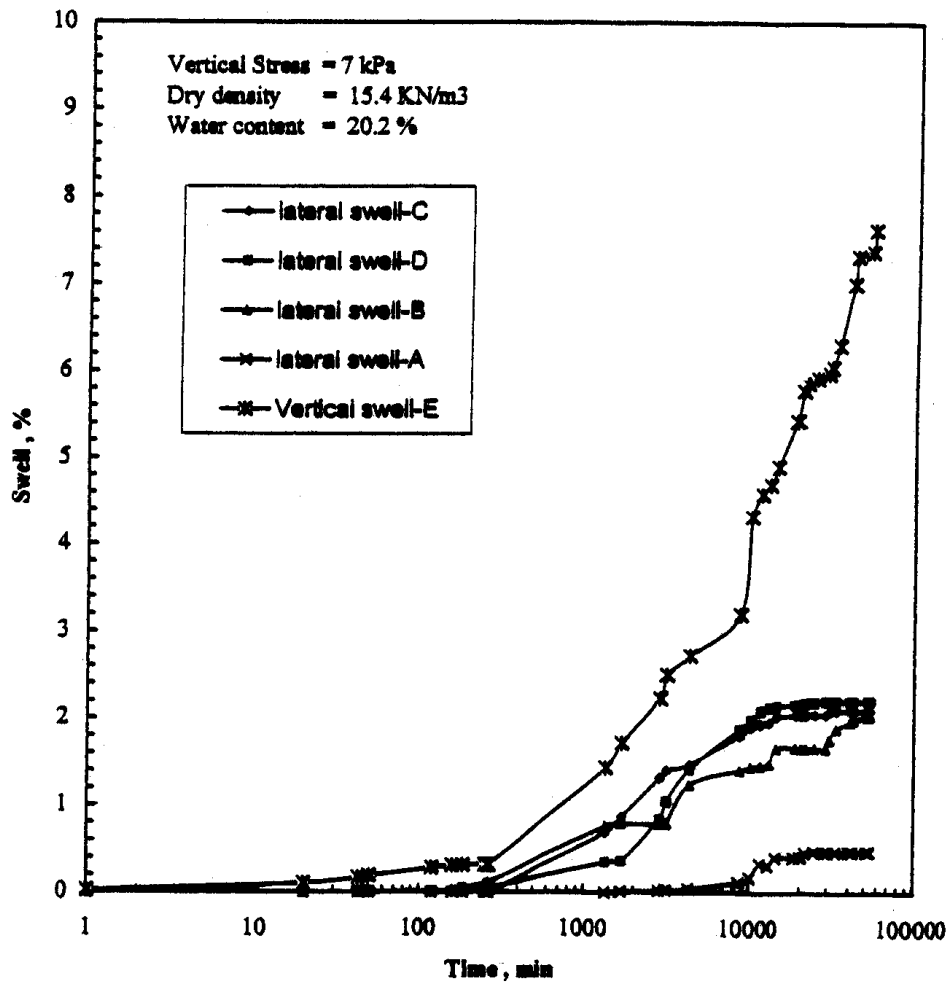


Fig. 6. Vertical and lateral swell.

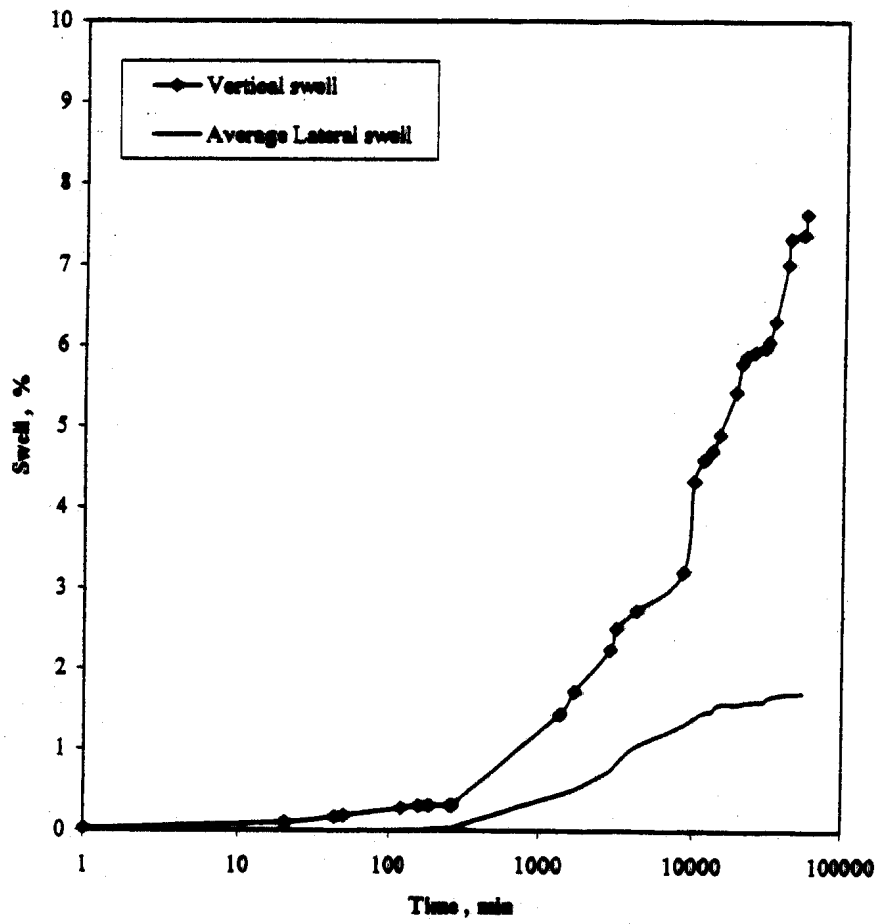


Fig. 7. Comparison between vertical swell and average lateral swell.

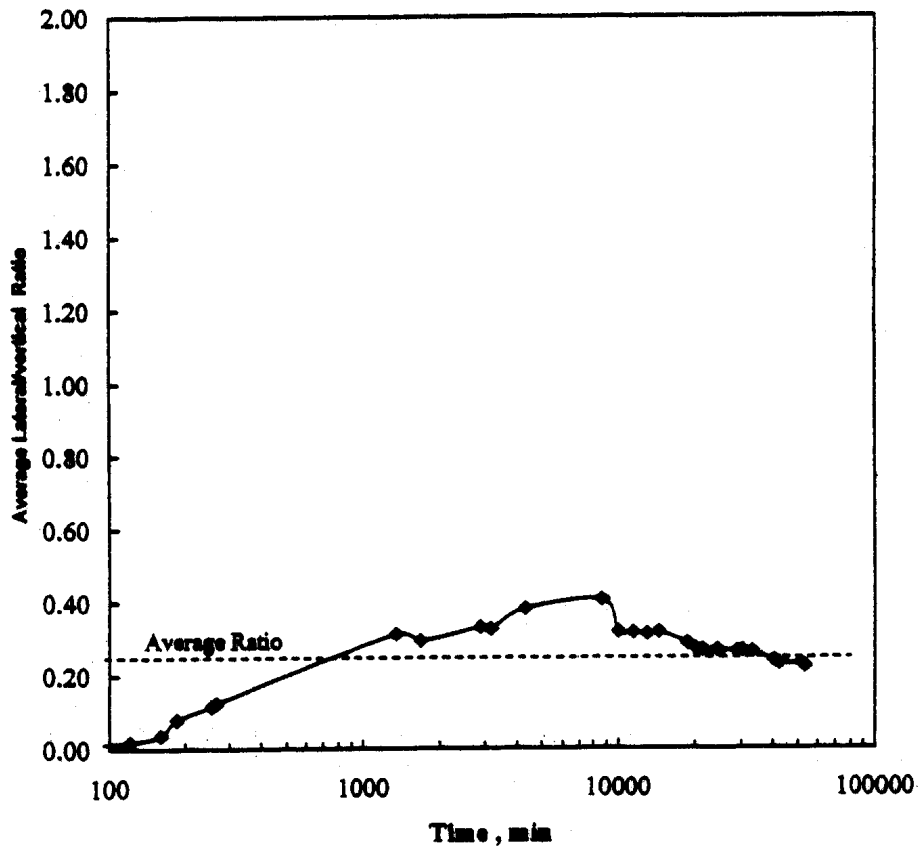


Fig. 8. Ratio of average lateral swell to vertical swell.

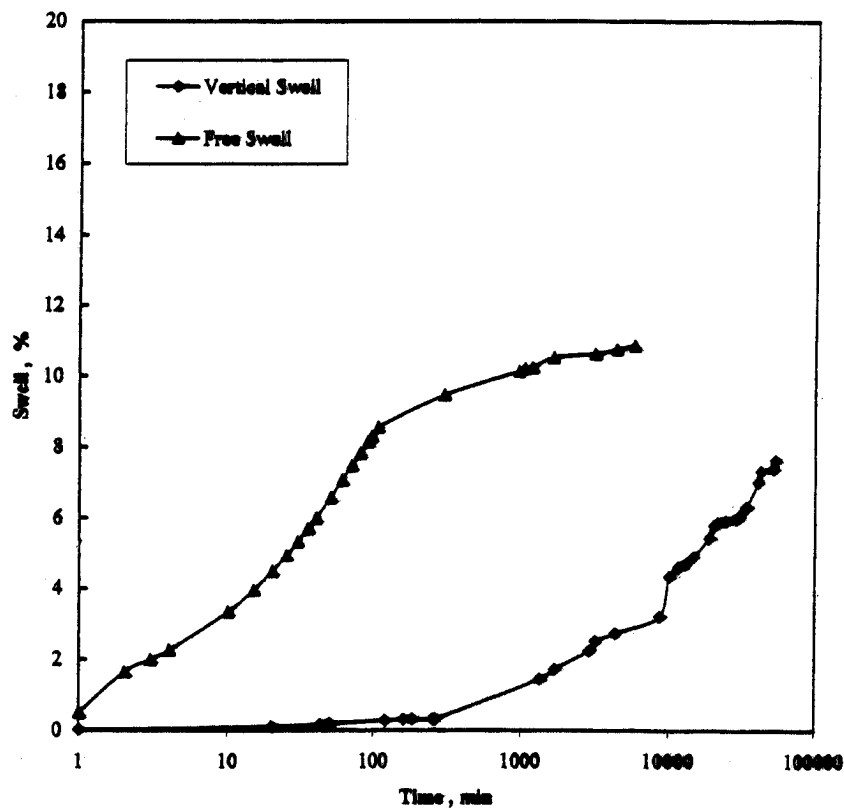


Fig. 9. Vertical swell measured in oedometer ring and vertical swell measured in free lateral movement test.

Analysis of Results

The results of the expansion test in laterally restrained and unrestrained conditions reveal that the lateral expansion constitutes a significant amount of expansion that cannot be overlooked. Therefore, using swell parameters to predict the field heave depends on the stress path followed during the course of testing. Realistically, the adopted method of testing must allow a certain degree of lateral movement as such movement and its effect cannot be neglected. However, it is difficult to estimate the magnitude of lateral expansion in the field. It is true that the use of the results of the test generated in this study will be more appropriate in predicting field heave under structural facilities, but still the method adopted in this experimental program does not reflect the actual field conditions. The procedure developed in this investigation full lateral movement is allowed, whereas in the conventional oedometer tests (free swell test, ISO, and constant volume test, CVS) there is a 100% lateral restraint. Field behavior, though, is neither free lateral movement nor complete restraint

conditions. In other words, some lateral expansion together with partial restraint does exist and hence, the swell parameters obtained from the conventional oedometer testing method and the method used in the investigation presented in this study are not expected to produce an accurate heave prediction, although it is expected that the free lateral movement technique will be closer to the actual case.

It is essential, therefore, that for more accurate estimation of field expansion behavior to adopt a different testing technique that represents as much as possible the field conditions. The method of testing should allow partial lateral movements and certain degree of side restraint. This may be achieved by applying lateral pressure around the tested expansive soil samples that allows a certain degree of lateral expansion. The estimation of the lateral pressure that can be applied to the soil sample during testing has to be carefully examined. It is expected to have values between lateral earth pressure at rest and active condition. How close to either condition has to be thoroughly investigated. Once the lateral pressure that closely simulates the field condition is determined,

non-conventional method of testing can be then adopted that specifies the magnitude of the lateral pressure during soil sample expansion. Such testing technique can replace the conventional oedometer testing method as it will be more representative of the field behavior. The swell parameters determined from these suggested testing technique will be used in Eq. (1) for heave prediction. Possibly, the method of testing outlined by Shamrani and Dhowian (2003) may be modified to allow a predetermined lateral pressure on the swell sample and obtain the swell parameters under these testing conditions. However, the proposed testing technique must be supported by field measurements as has been done by Dhowian *et al.* (1990) in their field experimental station in Al-Ghatt region.

Conclusions and Recommendations

The results of the testing program adopted in this paper indicated that the lateral expansion constitutes about one third (26%) of the vertical expansion. Thus, it is expected that swell parameters obtained from such unconventional testing technique will give more realistic estimation of field behavior. The free swell and the constant volume oedometer swell tests allow no lateral movement, i.e. complete side restraint. In the testing procedure used in this study, full lateral movement is allowed. However, it must be mentioned here that field conditions are not truly represented in either testing technique. Certain lateral restraint, although not complete, does exist and hence, even the method of testing utilized in this investigation has to be modified to be closer to field case. Nevertheless, the results of this study prove that lateral expansion constitutes a significant part of the total swelling.

Further studies have to be recommended in which laboratory as well as field investigation is carried out. Direct field measurements of expansion provide the heave that takes place in which lateral restraint and side movement exist concurrently.

Laboratory testing program must be carefully designated to represent the field conditions. If the swell parameters obtained from the experimental studies give relatively more accurate heave estimation using Eq. (1) as compared to the directed field heave measurements, then it can be concluded that the adopted testing technique will be more appropriate to consider in obtaining the swell parameters that can be used in the prediction equation, and therefore replace the conventional oedometer testing procedure.

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أداء التربة المنتفخة حرة الحركة أفقياً

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الكلمات المفتاحية: تربة منتفخة، ضغط الانتفاخ، مؤشر الانتفاخ، الحصر الجانبي.

ملخص البحث. تتميز التربة المنتفخة بزيادة حجمها عند تشبعها بالماء. ونتيجة لانتفاخ التربة تحدث أضرار كبيرة للمنشآت المقامة عليها. ولذا من المهم تقدير كمية الانتفاخ المحتملة قبل تنفيذ الأساسات. وتستخدم تجارب الأودوميتر للحصول على العوامل التي تستخدم في تقدير كمية الانتفاخ، إلا أن هذا النوع من التجارب لا يسمح بانتفاخ التربة في الاتجاه الأفقي حيث يحصر جدار الأودوميتر الحركة الأفقية؛ ولذلك فإن هذا النوع من التجارب لا يعكس واقع الحال في الموقع حيث إن جزءاً من الانتفاخ يحصل في الاتجاه الأفقي، وفي هذا البحث تم إجراء اختبارات الانتفاخ لعينات من التربة مع السماح الكامل للتمدد في الاتجاه الأفقي. وقد وجد أن مقداره يشكل حوالي ثلث مجموع الانتفاخ مما يستوجب اعتماد هذه التجارب في تقدير كمية الانتفاخ الحقلية بدلاً من تجارب الأودوميتر المعتادة.