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PREDICTION OF SWELLING POTENTIAL OF AN EXPANSIVE SHALE

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Abstract

A reliable estimate of the expected heave represents the most important factor influencing the selection and design of the foundation system which would accommodate the volume change. Several methods have been proposed in the literature for the prediction of swelling potential of expansive soils. In this paper, experiments using various methods to determine the swelling potential of an expansive shale from the middle region of Saudi Arabia were performed to quantify the amount of vertical swell and swelling pressure. Laboratory tests were used to determine the geotechnical and physicochemical properties and mineralogical composition of the tested shale. Swell tests were conducted under different loading conditions and following different procedures. The conventional one-dimensional oedometer swell tests were performed using three different procedures, namely, free swell, constant volume swell, and swell overburden. In addition, swell tests were performed in the stress path triaxial apparatus. Tests under different vertical stresses and confinements were conducted. Vertical swell and swelling pressure obtained from the various methods were compared. The reliability of the different methods for estimation of swell potential is discussed. The laboratory test results are compared with field data.

Introduction

There is no standard definition of the term 'swelling potential' and no specific definite method for its measurement. In general, swelling potential may be taken to include both the percent of swell and the swelling pressure. Different criteria have been used to provide an indication of swelling behavior of expansive soils [1,2,3,4,5,6]. Direct and indirect techniques were proposed in the literature. The indirect techniques are based on consistency limits, clay content, linear shrinkage, water content, soil suction, or combinations. The direct measurement of the swelling potential is usually obtained by the use of the conventional one-dimensional oedometer. Several test procedures have been used in the oedometer depending on the initial conditions of the specimen, surcharge load, and the stress path. The combination of direct and indirect techniques leads to the development of tables, charts or empirical equations [7].

In this paper, swelling potential of an expansive shale from the middle region of Saudi Arabia has been evaluated by four laboratory procedures including three types of oedometer tests (free swell, constant volume swell, and swell overburden), and stress path triaxial swell tests. Tests under different vertical stresses and confinements were conducted. A comparison of the test results is presented in terms of the percent of vertical swell and swelling pressure. The laboratory test results are compared with field data.

Characteristics of the Investigated Soil

A test pit was excavated in the town of Al-Ghatt in the middle region of Saudi Arabia and soil samples were obtained at a depth of about 3 meters and brought to the soil mechanics laboratory in the Civil Engineering Department, King Saud University. A laboratory testing program was designed to determine the geotechnical and physicochemical properties, mineralogical composition and the swelling characteristics of the shale. Soil samples were subjected to moisture content, unit weight, grain size analysis, specific gravity, and Atterberg limits tests using ASTM standard procedures.

The results of the tests indicated that the investigated soil is an inorganic clay of high plasticity (CH) having a liquid limit of 60 and a plasticity index of 30.The specific gravity of the clay is 2.8, the natural moisture content and the dry unit weight are 22% and 18 kN/m^3, respectively. The grain-size distribution curve indicated that the soil is composed of clay size of about 80% and silt size of about 20%.

The shale is highly weathered, and with the arid and dry desert climate in the town, it has relatively high swell parameters. The geotechnical properties of the tested soil show that the soil has swelling potential of high [2,3] to very high [4].

The results of the chemical tests (Table 1) indicated that the soil has high concentrations of K and Na. These monovalent exchangeable cations cause more swelling with water addition when compared with the divalent exchangeable cations such as Ca and Mg which the soil contains in less amount. Furthermore, the soluble sulfate concentration is 53,800 ppm which is believed to have a significant effect on the swelling potential of the tested soil. The pH value of 8.0 puts the soil in the slight alkaline range.

X-ray diffraction analysis was performed on the clay fraction of the tested soil to identify the clay minerals. A Philips PW 1050 diffractometer was used with a PW 1373 goniometer supply operating at 35 kV and 20 mA, with CuKα radiation, and Ni-filter. The XRD results indicated that the clay minerals were mostly kaolinite and some illite but no montmorillonite was present. Quartz and calcite were found in relatively small quantities.

Table 1. Chemical composition of the tested soil

Cations (ppm)*				Anions (ppm)*				
Ca^{++}	Mg^{++}	Na^{+}	K^{+}	SO_4^{--}	Cl^{-}	CO_3^{-}	HCO_3^{-}	pH
273	50	8575	6000	53800	244	Trace	3.0	8.0

* ppm = part per million

Laboratory Swell Tests

The amount of vertical swell and swelling pressure of the tested soil were obtained using the three oedometer testing procedures: free swell, constant volume swell, and swell overburden tests described in the American Society for Testing Materials (ASTM) standard No. D4546. In addition, swell tests were performed in the stress path triaxial apparatus. Tests under different vertical stresses and confinements were conducted.

Sample Preparation

The soil was oven-dried for about 24 hours, crushed, and sieved through ASTM sieve No. 40. Then it was thoroughly mixed with the calculated amount of water necessary to obtain the 22% initial moisture content. The mixture was sealed in an air-tight plastic bag and placed in a moist desiccator and was allowed to cure at room temperature for about 24 hours. Thereafter, the 70 mm-diameter, 19 mm-thick oedometer samples were prepared in a purpose made compaction unit containing the oedometer ring at an initial dry unit weight of 18 kN/m^3. Immediately after compaction, samples were transferred to the oedometer and the swell tests were performed.

Free Swell Test

In this test, the specimen is inundated and allowed to swell freely under a seating load of 7 kPa until primary swell is complete. Thereafter, it is loaded (after primary swell has occurred) until its initial void ratio (height) is obtained. The swelling pressure can be taken as the pressure that brings the sample back to its initial height (i.e. at 0% vertical swell). Two replicate tests were conducted and the results obtained are presented in Fig. 1. The two tests lead to an average value of 19% vertical swell and 1700 kPa swelling pressure.

Constant Volume Test

Soil specimen is placed in the oedometer and its vertical expansion when flooded with water is prevented throughout the test. Sufficient load is applied to the specimen in increments until swell pressure is fully developed in soaked conditions. The pressure developed by the specimen when saturation is completed represents a direct measure of swelling pressure. The results of the two replicate tests are shown in Fig. 1. The swelling pressure was found to be 960 kPa (average of two tests). The swelling pressure was calculated from the sum of the load increments divided by the cross-sectional area of the sample.

Swell Overburden Test

In the swell overburden test, the specimen is loaded to vertical in-situ overburden pressure, inundated under this pressure until the primary swell is completed. Five vertical pressures (35, 70, 140, 210 and 280 kPa) were applied on the samples in the oedometer. For each vertical pressure, two replicate tests were

performed to ensure repeatability of test results. The total number of swell tests in this method is 10 tests. The variation of vertical swell with time is shown in Fig. 2 for the applied pressures. The vertical swell-time curves could be represented by a rectangular hyperbola which is in agreement with the findings of [8]. The time/vertical swell versus time relationship can be represented by a straight line. The reciprocal of the slope of the straight line for each pressure gives the maximum vertical swell. The swelling pressure in this method was determined to be about 880 kPa.

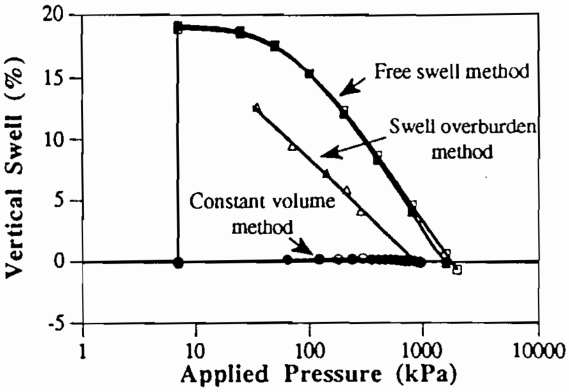

Fig. 1 Comparison of test results from the three oedometer tests

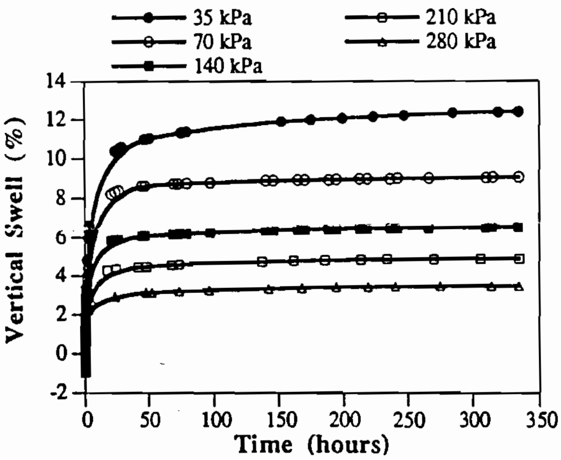

Fig. 2 Variation of vertical swell with time from the swell overburden oedometer tests under different applied pressures

Triaxial Swell Test

The tests were conducted using a hydraulic triaxial stress path cell of the type reported by [9]. In this apparatus, it is possible to measure directly the vertical swell of the sample where as in the conventional triaxial apparatus it has generally been possible only to measure the total volume change of the sample. Similar to the oedometer tests, samples were prepared after about 24 hours curing time with an initial moist content of 22% and initial dry unit weight of 18 kN/m^3. Preparation of the 35.5 mm-diameter, 71 mm-long triaxial samples consisted of statically compacting the soil in a purpose made vertically split mold. Thereafter, the samples were transfered to the triaxial apparatus and the swell tests were initiated. Details of the procedure of swell testing in stress path triaxial apparatus are given elsewhere [10]. The same five vertical pressures used in the overburden swell oedometer tests were applied on the soil samples. The total number of swell tests is 10 tests, two replicate tests for each vertical pressure were performed.

Figure 3 shows the swell behavior of the tested soil under the applied pressures. The time/vertical swell versus time relationship didn't give a straight line. Therefore, vertical swell-time curves can not be represented by a rectangular hyperbola. This method gives a swelling pressure of 1000 kPa.

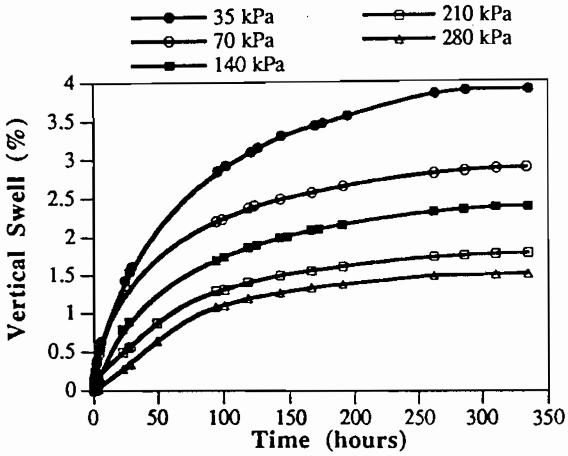

Fig. 3 Variation of vertical swell with time from triaxial tests under different applied pressures

Comparison of Results

The magnitudes of vertical swell and swelling pressure obtained from the three methods of the oedometer test are compared in Fig. 1. There appears to be no definite relationship between the values from the three methods. Free swell test gives the highest value of vertical swell and swelling pressure and the swell overburden method gives the least value of swelling pressure. The magnitude of swelling pressure obtained from the constant volume method is in between. Free swell method is time consuming since the specimen passes through two phases of deformation; complete expansion under seating load and complete compression under different loads where as the constant volume method is quick. For both methods, only one specimen is required. The constant volume method provides a direct measure of the swelling pressure. The swell overburden method has the merit that it follows the probable stress path that a soil may undergo in the field. However, requires at least three specimens, but it is less time consuming.

The discrepancies in the swelling potential (vertical swell and swelling pressure) are due to differences in loading and wetting conditions in the oedometer tests. Free swell test does not represent the normal sequence of load-wetting in the field. The soil in the field will not absorb water and swell first with the structural load applied later, but rather vise versa. Constant volume also does not simulate the in situ condition where the applied load after the structure is in service does not change with time. Also, it does not present the expected amount of heave under the application of a certain load (structure load). The swell overburden method has the important advantage of being more representative of actual field loading and wetting conditions [11]. The data obtained by this method can provide useful information for design such as swelling pressure corresponding to zero volume change, the expected vertical heave under the loads imposed by the structure, and the loads that could be applied to develop a certain swelling.

The values of maximum vertical swell obtained from swell overburden oedometer tests and triaxial tests under different applied pressures are calculated by dividing the maximum increase in height of the sample by its initial height before it is given free access to water. The relationships between the average of the maximum vertical swell (two tests) and logarithm of the applied pressure for the samples tested in oedometer (swell overburden method) and triaxial tests are shown in Fig. 4. The relationships can be approximated by the following equations with a correlation coefficient, r^2, of about 0.99:

$$S_p (\%) = 26.5 - 9 * \log(p) \quad \text{(oedometer test)} \quad (1)$$

$$S_p (\%) = 7.8 - 2.6 * \log(p) \quad \text{(triaxial test)} \quad (2)$$

where S_p is the vertical swell and p is the applied pressure (kPa). The swelling pressure was determined from the above equations at 0% vertical swell to be about 880 kPa for oedometer tests and 1000 kPa for triaxial tests. Furthermore, equation (1) predicted the vertical swell under a pressure of 7 kPa to be about 19%, the same as that found by the free swell test.

The values of vertical swell from the oedometer tests are higher than those from the triaxial tests for all the applied pressures. This may be due to many factors; the most significants are the differences in loading and wetting conditions in both equipments. The direction of swelling, lateral restraint in the apparatus, and the wetting of the sample are different in both equipments. The triaxial test is more representive of the field conditions than the oedometer.

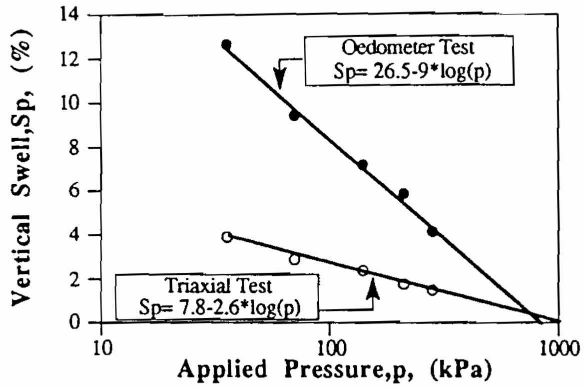

Fig. 4 Comparison of vertical swell from swell overburden oedometer and triaxial tests

The variation of the ratio of vertical swell obtained from triaxial tests to that obtained from oedometer tests with the applied pressure is shown in Fig. 5. The average value of this ratio is about one-third. Previous investigators [12,13,14] found that laboratory results from oedometer tests overestimate the in situ heave by a factor of 3. The reasons for this discrepancy may be attributed to the fact that in the field swelling takes place in three dimensions rather than one dimension as imposed by laboratory oedometer tests. Other reasons are related to the in situ stresses on the soil are released after the soil sample is disturbed and brought to the laboratory to be tested. Dhowian [13] and Erol [14] suggested that about one-third of the volume changes are reflected as a surface heave, the remainder will be laterally. Therefore, when considering a restraint factor of one-third, oedometer tests predict vertical swell very well when compared with the measured swell in the field [13,14]. The results of the stress path triaxial tests provide good prediction of the vertical swell without using any restraint factor.

Dhowian [15] found that the percent of swell in the field in the town of Al-Ghatt to be in the range of 3% to 4% throughout the investigated depth (up to five meters). The vertical overburden stress in the field is about 66 kPa at a depth of three meters. The corresponding vertical swell obtained from the stress path triaxial test (equation 2) is 3.1%. Therefore, it may be concluded that the stress path triaxial tests can predict the expected heave better than the swell overburden oedometer tests. Furthermore, the swelling pressure from the triaxial tests was found to be about 1000 kPa close to that obtained by the constant volume oedometer test (960 kPa) which directly measure the swelling pressure.

Conclusions

Results of the different swell tests conducted on an expansive shale from the middle region of Saudi Arabia indicated significantly different values of swelling potential depending on the test technique used. Swelling pressures obtained from the three oedometer methods are different. Free swell test gives an upper bound value for swelling pressure, swell overburden test provides the least value, and the constant volume method gives intermediate value. The different values may be attributed to the differences in loading and wetting conditions followed in each method. Free swell method is time consuming but only one specimen is required. Constant volume method is a quick test, requires only one specimen, and provides a direct measure of the swelling pressure. Swell overburden method has the important advantage of being more representative of actual field loading and wetting conditions. However, it requires at least three specimens at identical initial conditions.

A comparison of the results from swell overburden oedometer tests and triaxial tests shows that triaxial tests provide lower values of vertical swell than those from the swell overburden oedometer tests (about one-third). This ratio is in agreement with those suggested in the literature for the prediction of field heave from the oedometer tests. Triaxial tests provide good prediction of vertical swell when compared

with field data and also provide swelling pressure close to that obtained from the constant volume oedometer method which directly measure the swelling pressure. Therefore, it is concluded that the stress path triaxial apparatus could predict the swelling potential of the tested soil better than the oedometer methods.

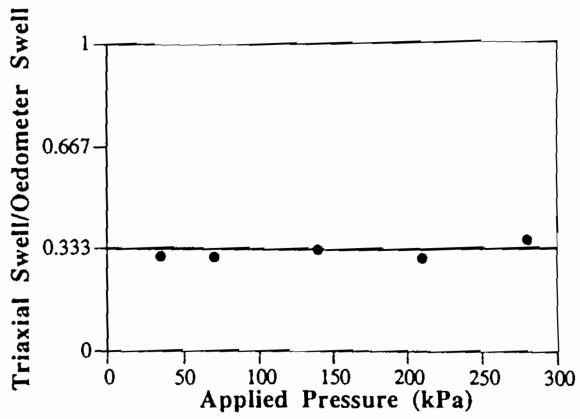

Fig. 5 Ratio of triaxial vertical swell to oedometer vertical swell versus applied pressure

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