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Field Performance of Expansive Shale Formation

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ABSTRACT. Surface and subsurface heave of shale formation have been monitored in an experimental field station. The field measurements include variations in soil suction using thermocouple psychrometers as well as the changes in moisture by means of a nuclear depth probe. Swell oedometer tests and suction measurements, in addition to soil characterization constitute the laboratory testing program. Comparison of measured heave with the predicted volume change using the oedometer and suction techniques indicates that the two methods overestimate the actual behavior.

Introduction

Extensive damages and building distress have been reported lately in several parts of Saudi Arabia. Thorough geotechnical investigations of these sites have indicated that the major cause of the problem is attributed to ground upward movement due to the expansion of shale formation[1-4]. Reliable estimate of field heave is a requisite for the selection of treatment alternatives to minimize the volume increase or preparation of a foundation design and construction to accommodate the expected volume change. However, the nature of *in situ* heave is complex, as indicated by the need to consider numerous variables for proper analysis. Although great efforts have been devoted for reliable estimation of *in situ* heave in expansive soils, little progress has been made in recent years so far as implementable procedures are concerned. Numerous methods have been proposed for heave predictions, however, there is a lack of standardization and agreement among the methods. Furthermore, there is limited amount of experience regarding the reliability of the available prediction methods. This arises from the fact that, there is a general dearth of integrated field measurements to develop reliable case-study data for evaluating the available analytical prediction methods which are mostly based on laboratory testing and theoretical or empirical modelling of swell behavior.

In this paper, the results and analysis of heave parameters determined from an instrumented field station under well controlled conditions, will be presented and discussed. The parameters include surface and subsurface heave, and suction and water content variation during the course of swelling. The study also comprises a comprehensive laboratory investigation program to determine the swell parameters which are used in the heave prediction methods.

Profile Characteristics at Experimental Site

A preliminary search was initiated throughout the expansive formation of Saudi Arabia, for a site which possesses relatively homogeneous and expansive soil profile. A site located at the town of Al-Ghatt was selected for the experimental work, 270 km north-west of the capital city of Riyadh. Previous investigations have indicated that severe building damages were experienced due to occurrence of outcropping expansive shales in various parts of the town. After an exploration program at several potential sites, one location was selected, and further borings were made to provide information on *in situ* conditions and samples for the laboratory testing program. A special drilling technique, which utilized double tube core barrel with compressed air circulation was used to recover high quality shale samples. The method was found to be particularly successful in preserving the natural water contents of the samples.

The expansive formation found at the site is a gray-green weathered clay shale constituting the top, 8-10m of soil profile. Approximately, one meter thick top soil overlies the shale which is underlain by a weakly cemented sandstone at the particular location of the experimental site. The upper few meters of the shale profile is relatively more weathered as compared to the deeper part. Although a distinct stratification cannot be detected at the site, thin silty shale layers are encountered at various depths. However, these layers are not continuous and can be considered as part of the clay-shale strata. The *in situ* water content, plasticity and grain size characteristics of the shale are shown in Fig. 1, and the average soil properties are summarized in Table 1.

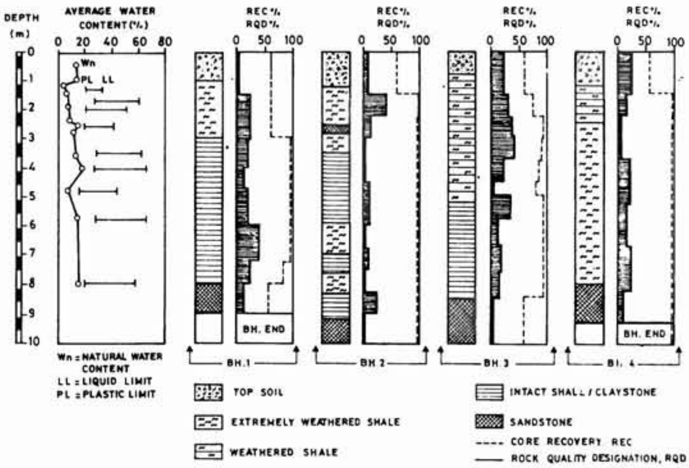

FIG. 1. Soil profiles in the field station. (Boreholes 1, 2, and 4 are at the corners of the field station and Borehole 3 is within the field station at distance 5m from the watering system).

TABLE 1. Properties of the clay shale.

Property	
Liquid Limit	55–70%
Plastic Limit	23–30%
Plasticity Index	25–40%
Shrinkage Limit	17–22%
Grain Size: Sand	2– 4%
Silt	4–22%
Clay	72–75%
In situ water content	14.8 - 18.5%
In situ dry density	16.4 - 17.4 kN/m^3

The results of x-ray diffraction analysis on clay fraction of oriented samples of the shale are shown in Fig. 2. Mineralogical studies indicate that kaolinite with minor amounts of illite comprises the clay fraction of the shale and expandable clay minerals, such as montmorillonites, cannot be traced.

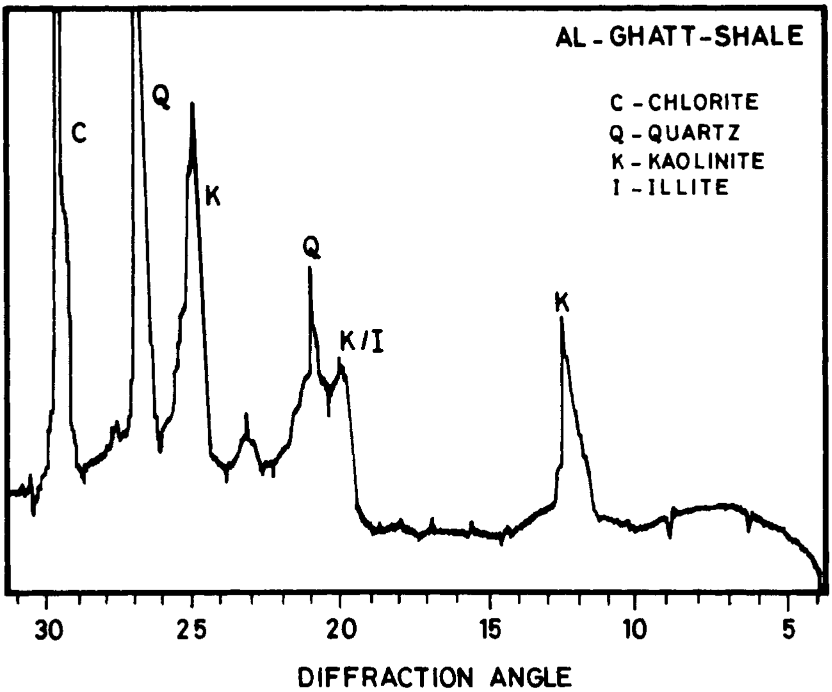

FIG. 2. X-ray diffraction patterns of Al-Ghatt shale.

To determine the swell behavior of the shale in the laboratory, three types of oedometer tests were performed: (i) improved swell oedometer (or free swell) tests (ISO); (ii) constant volume swell tests (CVS), and (iii) swell overburden tests (SO). In *ISO* tests, the specimen is permitted to swell under a seating load of 7 kPa (1 psi) after it is loaded to *in situ* overburden pressure to determine its *in situ* void ratio. In CVS tests, sufficient load is applied to the samples in increments to prevent swelling until swell pressure is fully developed in soaked conditions. In SO tests, the specimen is loaded to the vertical *in situ* overburden pressure and water is added to monitor the swell until the primary swell is completed. The details of testing procedures can be found in Dhowian *et al.* (1984) and Johnson and Snethen[5]. Typical results of oedometer tests are shown in Fig. 3. The oedometer tests conducted on the undis-

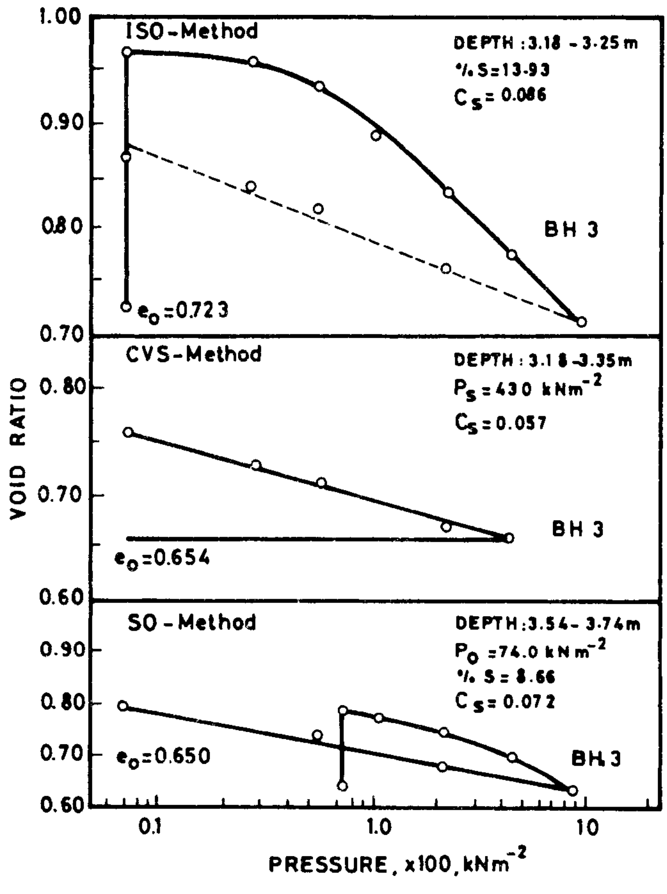

FIG. 3. Swell parameters from the different oedometer test methods.

turbed shale cores indicated that the swell pressures of the shale vary over a range from 429 to 571 kNm^{-2}, whereas free swell deformations are in the range of 8.4 to 16.1 percent. Relatively high magnitudes of swell parameters obtained in oedometer tests clearly reflect highly expansive nature of the particular shale formation. The swell parameters attain significant magnitude despite the absence of the montmorillonite clay mineral, usually responsible for soil expansion. However, it must be mentioned that the shale formation exists in a very dry condition possessing enormous water intake potential. Thus, the destruction of the intrinsic stress arising from extreme desication together with the destruction in laminated shale structure through water infiltration can be considered as the primary cause of expansion.

The experimental field station covered an area of 10m by 20m. Approximately, 1.5m of overburden were removed from the test area prior to installation of field instruments. A saturation system consisting of 19 sand drains, each 4m deep, was installed to provide water entry to the shale formation. At the ground level, each sand drain was attached to a water tank which was kept half-full to prevent overflow and surface flooding, as shown in Fig. 4. A total of 6 instrumented units each comprising a thermocouple psychrometer stack, moisture access tube, surface heave plate and 5

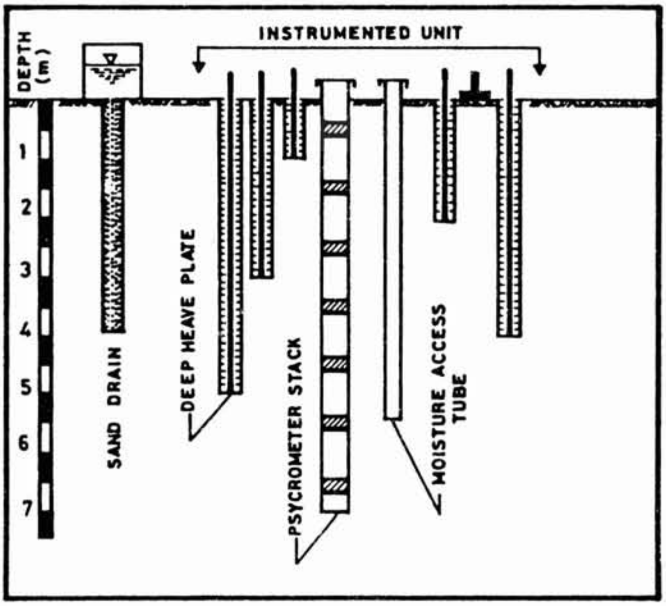

FIG. 4. Details of field instrumentation.

deep heave plates, each placed at one meter intervals, were installed in the experimental site. The schematic representation of the field instrumentation is shown in Fig. 4. The psychrometer stacks were formed by fixing and sealing individual psychrometers into small tubes which were then fitted into 8 cm diameter pipes. The pipe was then lowered into a borehole which was drilled by continuous coring with air circulation. This method of installation has been found successful in *in situ* soil suction measurements, Williams and Snethen[6].

In situ moisture content measurements were made with a nuclear device, CPN Model No. 501 DR. The equipment consists of a readout device (scaler) and a nuclear probe that is inserted in previously installed access tubing. Prior to its use in the field, the nuclear probe was calibrated in the laboratory by measuring the moisture contents of several shale samples compacted at various water contents and densities in a steel drum. The surface and subsurface heave measurements were made by precise levelling with reference to four deep seated bench marks situated at adequate distances, in order not to be influenced by the saturation and subsequent heave at the experimental station. The surroundings of each instrument including heave plates were sealed with a cicular thin slab of concrete and bituminous material at the surface to prevent infiltration of rain or overflow water into the field instruments. The site was covered with a 15 cm thick gravel blanket which served as a working platform. The details of installment methods and field measurements are given by Dhowian *et al.* (1985).

Observations

The establishment of the field station was completed in July 1985 and two sets of initial readings were taken prior to watering of the site. The watering was commenced in August 1985, and continuous water supply was secured for a period of 54 weeks. The period from August to November 1985 was hot and dry and there was no occurrence of rainfall. During December 1985 and January 1986, some rainfall took place, however, no flooding or significant infiltration was observed. Therefore, the increase in water content and the subsequent heave at the site was primarily due to the horizontal seepage from the sand drains. This method has been found to be effective in shale formation, where laminations and horizontal jointing systems promote water movements. Readings of heave were continued long after the termination of saturation process, until the end of the 86*th* week. Field suction, however, was measured for a period of 36 weeks. The relatively short period of suction measurements is due to the fact that, by the end of the 36*th* week, most of the psychrometers were out of order. Nevertheless, the measured suction reached a near-terminal stable value by the end of the 27*th* week particularly for the instrumented units No. 1 and 2, which were situated at the nearest distance from the saturation system.

The cumulative heave distribution along the depth of the profile is shown in Fig. 5 for different periods of observation obtained from unit No. 2. The surface heave exceeds 183mm for this unit at the end of the 86*th* week. However, the volume change decreases in magnitude for units 3, 4, and 5 placed at distances 5m, 10m, and 15m from the saturation system, respectively, units 5 and 6 are at the same distance from the watering system. For instance, units 3, 5, and 6 did not show any measurable amount of heave until the end of the 11*th* week, whereas in unit 3 the recorded surface heave was 16mm as compared to about 100mm for units 1 and 2 as indicated by Fig. 6. In Fig. 7, the ratio of the surface heave of unit 6, the farthest to the watering system, to surface heave of unit 2 is plotted versus time. As shown by the figure, the ratio was zero at the end of the 11*th* week and started to increase with time until a ratio of 0.62 was reached by the end of the 86*th* week.

Figure 8 illustrates the cumulative heave as a function of time. Initially, heave movements take place at relatively high rate then start to decrease approaching a small constant value near the end of the 27*th* week. The recorded magnitudes of heave for the layer intervals for which the volume change is measured are almost

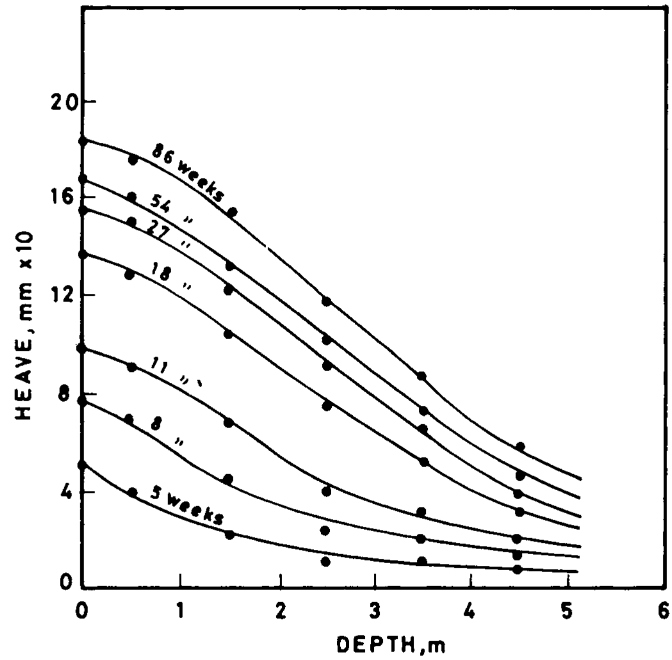

FIG. 5. Distribution of field heave with depth for different periods of observation.

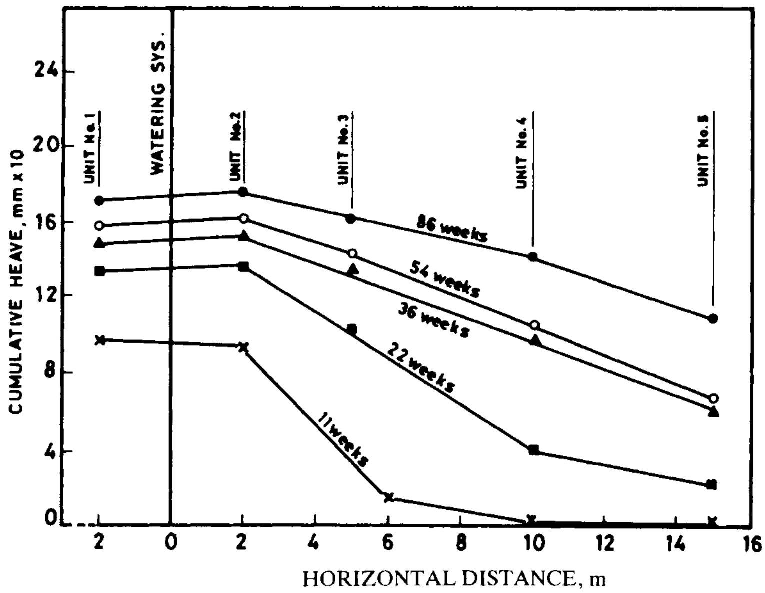

FIG. 6. Field heave as a function of horizontal distance from the watering system.

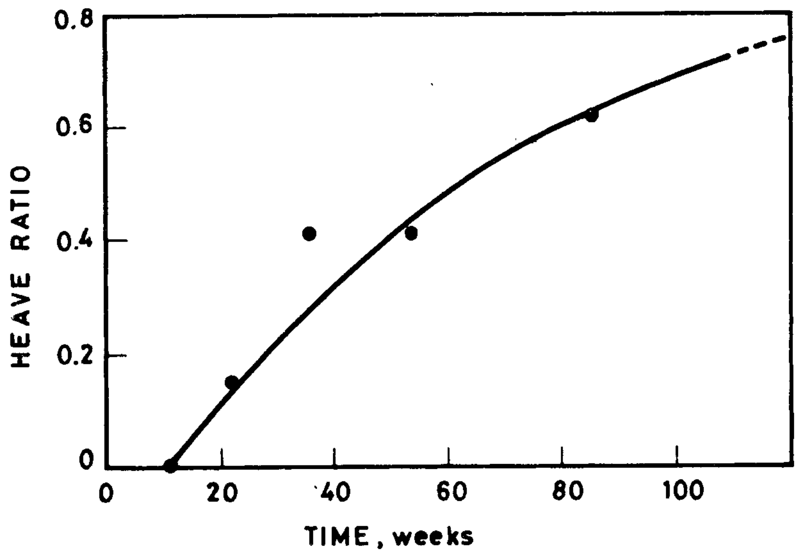

FIG. 7. Heave ratio-time relationship.

identical as shown in Fig. 8. The observed heave is 28mm, 33mm, 28mm, and 28mm for the layer intervals 0-1, 1-2, 2-3, 3-4m, respectively. Therefore, the percent swell is apparently independent of depth for the investigated shale formation. Figure 9 presents more elaboration on this behavior where the percent swell is plotted versus depth. Except for the first layer inte rval, the swell is in the range of 3 to 4 percent throughout the depths investigated. The lower value of swell in the first layer interval may be attributed to the nature of soil in this layer being contaminated with granular and less expandable materials.

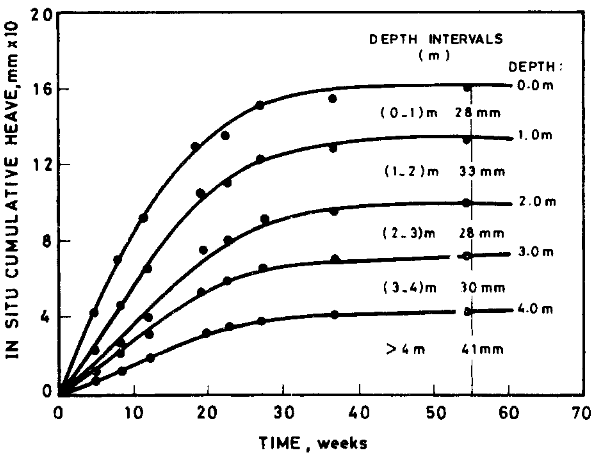

FIG. 8. *In situ* heave versus time relationship for different depth intervals.

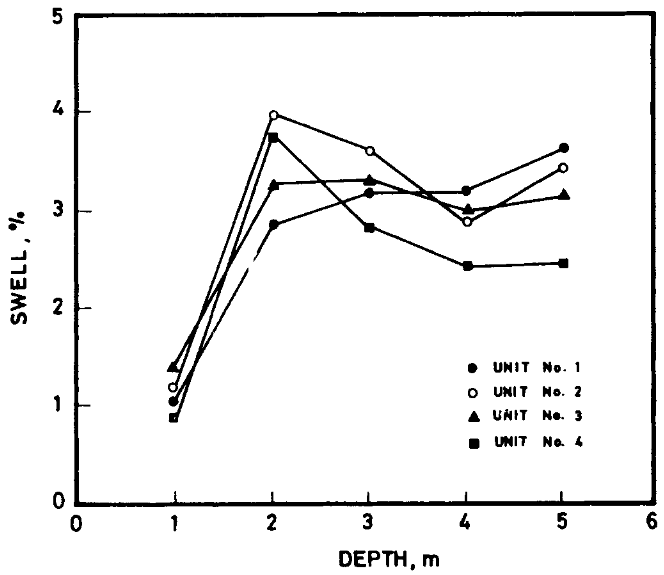

FIG. 9. Percent swell as a function of depth.

The variation of suction with depth and time is shown in Fig. 10 and 11, respectively. The initial value is significantly high, in the range of 50 to 60 bars. The suction started decreasing at relatively high rate as the swell process proceeded reaching a stable level at nearly the end of the 28*th* week. The magnitude of suction at this stage,

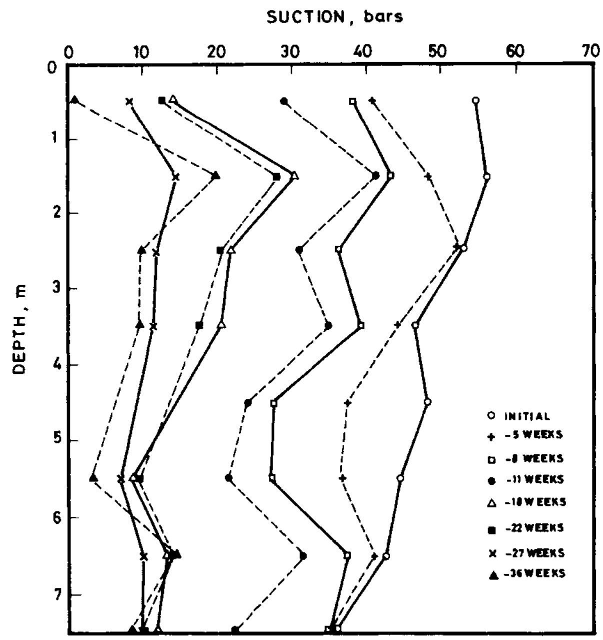

FIG. 10. Changes of field suction with depth for different periods of observation.

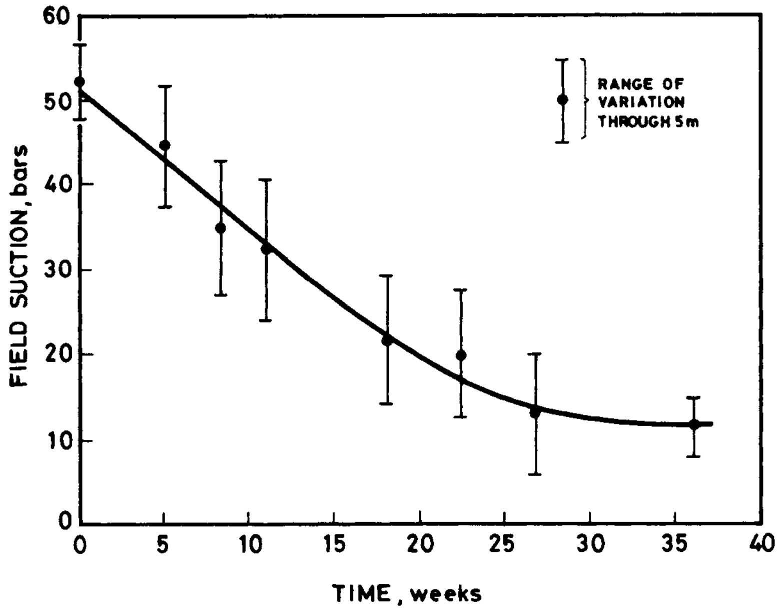

FIG. 11. Field suction-time relationship.

though significant in the range of 8 to 15 bars, does not show a sign of decrease, although the swelling is still developing. This behavior is analogous to that of organic soils where compression continues *o take effect, although the pore pressure has reached minimum value[7]. The shape of suction versus time curve is comparable to the pore pressure versus time during the consolidation of compressible soils. The similarity in behavior between the compressible soils in consolidation and expansive soils is expected since the two processes are promoted by pore pressure, suction in the case of expansive soils, dissipation resulting in volume changes with time. The suction reached the minimum value at almost the same time the swell attained its lowest rate, thus substantiating the phenomenon that swelling and suction are interdependent processes. The change of suction with depth is represented in Fig. 12. As in the case of swell, suction tends to be independent of depth although a slight decrease in value is noticed at deeper depths.

When the percent swell is plotted against the logarithm of time, the relationship can be approximated by a straight line as indicated by Fig. 13. The constant rate of swell, which may be defined as the swell-time coefficient S_s, is analogous to the constant rate of secondary compression in compressible, organic soils, known as the coefficient of secondary compressionS[7]. The swell-time coefficient for the studied shale has a value of about 2.0. Long term field test of shale needs to be performed to further investigate the swell behavior long after the suction reached a terminal minimum value and to quantitatively examine the mechanism of soil expansion during this stage of volume change. According to the data presented by the figure, the average swell-time relationship can be approximated by the equation:

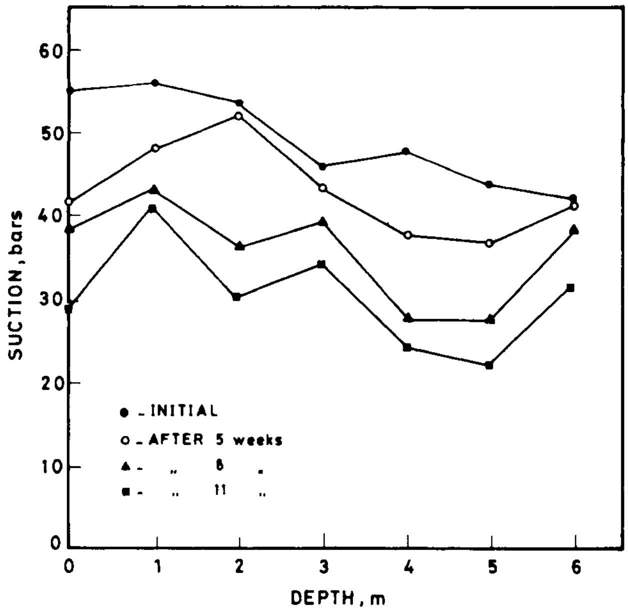

FIG. 12. Variation of field suction with depth for different time of observation.

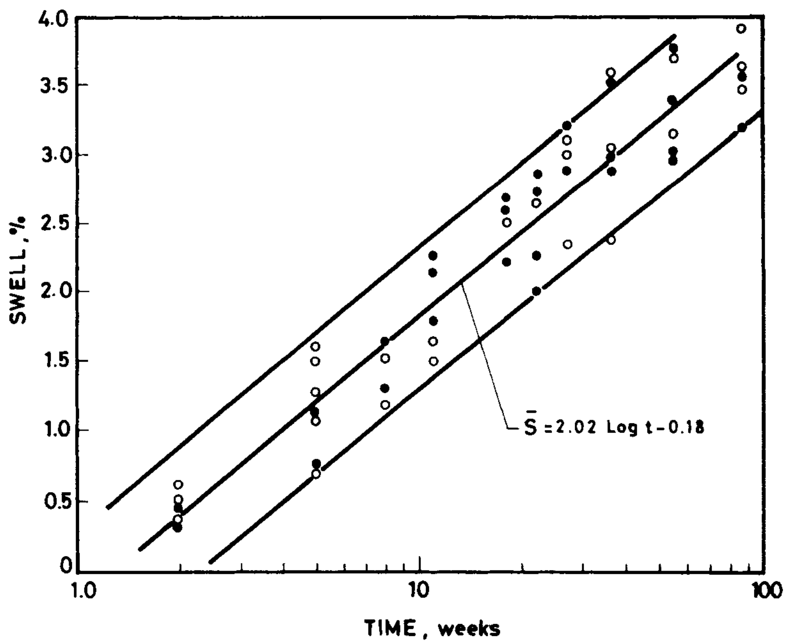

FIG. 13. Changes of field swell with time.

$$\bar{s} = 2.02 \log t - 0.18 \tag{1}$$

where $\bar{s}$ is the average percent swell and t is the time in weeks.

Using the above equation the field heave of one meter thick of the investigated soil after 86 weeks is estimated to be 36mm. The prediction is fairly acceptable when compared with the actually measured average heave of 32mm.

Since it is known that suction and swelling are closely related processes, it is conceivable to relate the swelling to change in suction, so that knowing the magnitude of one process will lead to the determination of the other. For this purpose, the percent swell is plotted versus the logarithm of suction in bars. The relationship indicates that swell is inversely proportional to suction in approximately linear manner as given by Fig. 14. The relationship may be represented by the equation,

$$\bar{s} = 5.278 - 3.153 \log \bar{\psi} \tag{2}$$

where $\bar{s}$ is the average percent swell, and $\bar{\psi}$ is the average suction in bars.

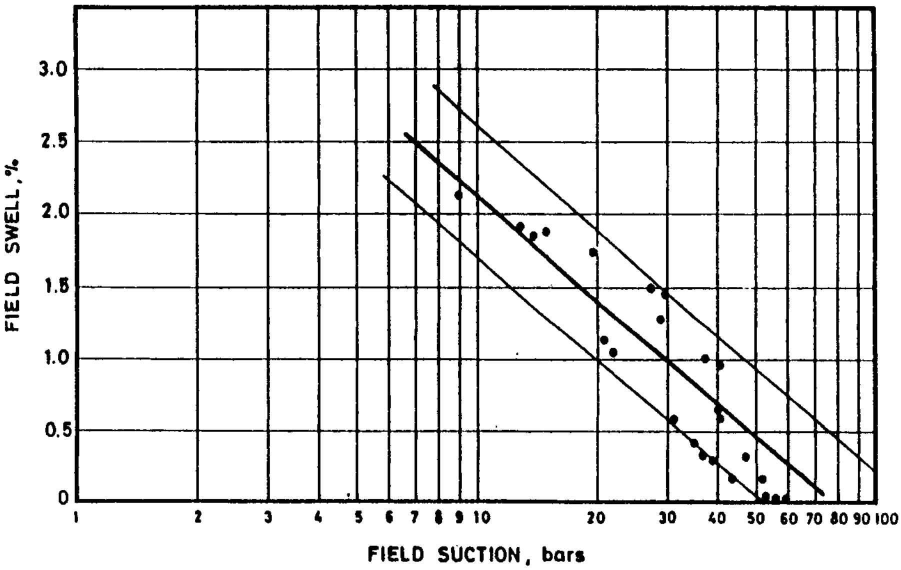

FIG. 14. Field swell versus field suction relationship.

The increase in moisture content until the end of the watering period, 54 weeks, is shown in Fig. 15. An amount of 160mm surface heave is measured in units No. 1 and 2 as a result of an average moisture content increase of 7 percent. The increase in moisture content reported for the oedometer shale samples when swelling is fully developed is in the range of 10 to 12 percent. The difference between the field and laboratory moisture content variation during swelling is attributed to the fact that the samples were exposed to most favorable saturation conditions in the oedometer chamber, whereas such conditions may not prevail in the field. It is, therefore, conceivable to assume that the swell will be fully developed in the laboratory shale samples long before the field shale formation attains its terminal value.

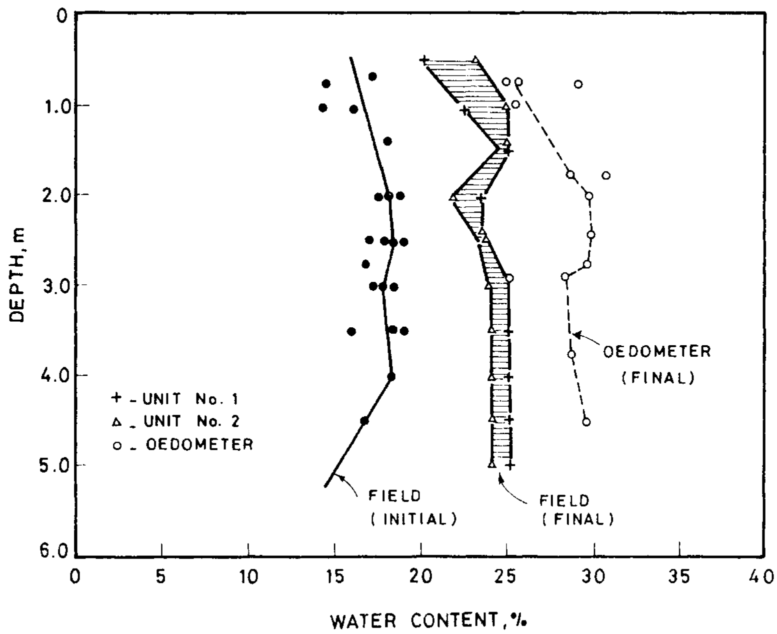

FIG. 15. Field and laboratory water content before and after swelling.

Comparison and Predictions

Prediction of heave based on experimental data, empirical model, and theoretical analysis has been attempted by researchers[8-10]. In most cases, the drawback of the prediction technique is the lack of field measurements that can be compared with the estimated behavior to evaluate the reliability of the prediction models. In this study, two methods, the oedometer, and suction method, will be used to predict the field heave.

The swell parameters determined by the oedometer technique, mainly the swell pressure, P_s, and swell index, C_s are used to calculate the field heave according to the equation,

$$\Delta H = \frac{H}{1 + e_0} C_s \log \frac{P_s}{\bar{P}_o} \tag{3}$$

where ΔH is the field heave, H is the thickness of the expansive layer, e_0 is the initial void ratio, and $\bar{P}_0$ is the effective overburden pressure[11].

In the suction method, the initial and final values of suction during the swelling process are used to evaluate the ground movements[12]. According to Johnson and Snethen[5], the swell is given by the equation,

$$\frac{\Delta H}{H} = \frac{C_\psi}{1 + e_o} \log \frac{\psi_i}{\psi_f + \alpha\sigma_v} \tag{4}$$

where C_ψ is the suction index, α is a volume compressibility factor, σ_v is the effective vertical stress, and ψ_i and ψ_f are the initial and final suction, respectively.

The suction index may be defined as the ratio of change of void ratio with respect to soil suction. The compressibility factor, reflects the change of specific volume with water content.

To investigate the validity of the two methods undisturbed shale samples were recovered from the field station representing the general characteristics of the soil formation. The samples were tested in the oedometer and suction chambers and the swell and suction parameters were determined experimentally as presented by Table 2. The parameters were then utilized in equations (3) and (4) to estimate the possible heave which can be compared with the actual behavior.

TABLE 2. Swell and suction parameters obtained from laboratory tests.

Parameter	Clay shale	Silty shale
Compressibility factor, α	0.900	0.850
Slope of suction, *vs*	0.47	0.070
Water content, β		
Suction index, C_ψ	0.517	0.327

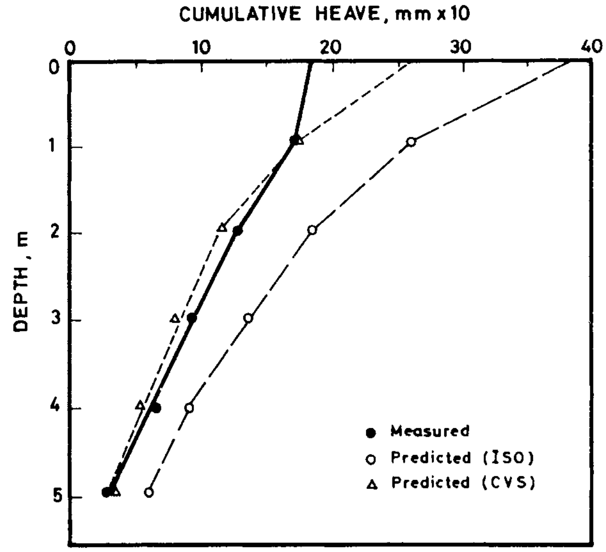

FIG. 16. Predicted and measured heave based on oedometer technique.

The calculated volume change based on oedometer test is shown in Fig. 16 along with the measured values. The model tends to overestimate the field heave when the parameters based on the modified swell test, ISO, are used. Good agreement, however, between predicted and measured heave is achieved when the constant volume swell test, CVS, parameters are used. It is believed that the difference in swell magnitude predicted by the two oedometer methods is primarily caused by the testing conditions. Soaking a sample, which is disturbed by the release of the overburden pressure during sampling, under low stress promotes greater water penetration into the sample in ISO tests. Therefore, the swell is relatively high as compared to CVS tests where the water entry is limited by the high pressure which also limits the influence of sampling disturbance.

The experimentally determined suction parameters are substituted in equation 4 to evaluate the anticipated volume change. As illustrated by Fig. 17, the suction equation highly overestimates the field heave, particularly near the ground surface. The inconsistency between the predicted swell and the measured value may be attributed to the laboratory evaluated parameters, which are highly affected by the testing conditions. Analysis has shown that the suction index has much smaller value when determined from field data compared to experimental value[12] and hence, to have more reliable prediction, field parameters need to be used instead.

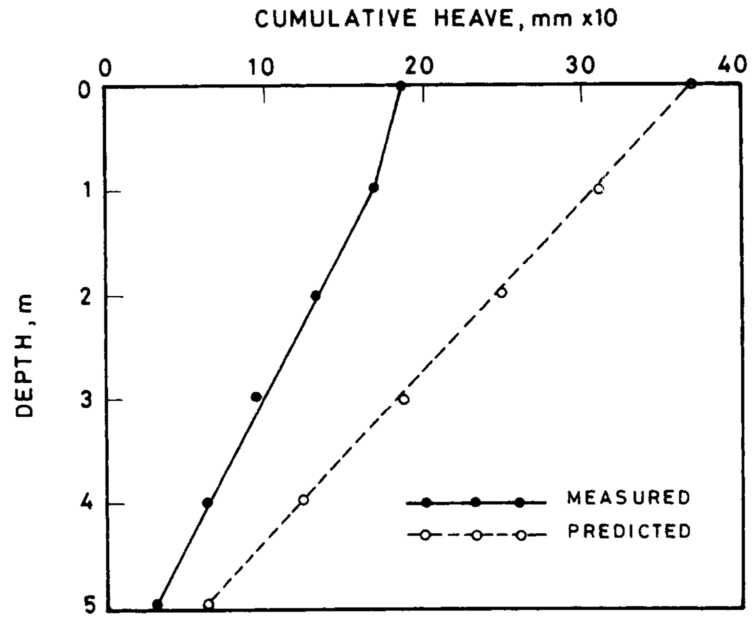

FIG. 17. Predicted and measured heave based on suction method.

Generally, the discrepancy between the experimentally and field determined parameters is caused by the following two factors:

1. The tested samples are carefully selected from the specified location and depth

and due to their small size they tend to be more homogeneous and less contaminated by non-expandable materials. Invariably, the shale formation contains seams of limestones, pockets of gypsum, and sand lenses that reduce the overall soil volume increase.

2. The samples in the oedometer chamber are laterally restraint thus, the volume increase takes place in the vertical direction only, whereas the field vertical movement constitutes a fraction of the volume change.

These two factors, in addition to the favorable saturation condition in the laboratory, as has been discussed earlier, account for the high magnitude of predicted heave as compared to measured volume change. Research by the author and colleagues in progress aims at determining the proper value of swell parameters that can be used in the equations to achieve better prediction.

Conclusion

The *in situ* measurements of heave from an instrumented field station are presented in detail in this paper. A significant magnitude of soil movement in excess of 180mm has been reported during the course of observation which continued for 86 weeks. The oedometer swell parameters and initial and final suctions are used to estimate the anticipated heave. The following conclusions may be advanced with respect to the comparison of predicted swell with the measured values:

1. The oedometer technique highly overestimates the volume change when the swell parameters are determined by the ISO test. However, good prediction is obtained when the parameters are based on CVS test.

2. The predicted heave using the suction method appreciably overestimates the *in situ* soil movement.

3. The field measurements indicate a semi-logarithmic linear relationship between soil suction and swell. This behavior is consistent with the analytical swell prediction model based on suction. However, there is a substantial difference between suction indices evaluated from field measurement and laboratory testing which leads to the heave overestimation mentioned above.

Acknowledgement

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أداء تكـــوين الصخــــر الطيــــني القابـــل للانتفـــاخ

عبد المحسن وني الضويان
قسم الهندسة المدنية ، كلية الهندسة ، جامعة الملك سعود
الرياض ، المملكة العربية السعودية

تم في هذا البحث قياس الانتفاخ السطحي وتحت السطحي للتكوين الصخري الطيني وذلـك في محطة التجـارب الحقلية في مدينة الغاط . وقد شملت تجهيزات المحطة قياس الامتصـاص والتغير في المحتوى المائي للتربة بجهاز القياس الذري . كذلك تم القيام ببرنامج اختبار معملي شمل قياس الانتفاخ الأودومتري والامتصاص بالإضافة إلى خواص التربـة الفيزيائية . وقـد أمكن حسـاب الانتفـاخ المتـوقع باستخدام نتائج الاختبارات الأودومترية والامتصاصية ووجد أن الانتفاخ المحسوب يزيد عن الواقع والذي تم الحصول عليه مباشرة من محطة التجارب بالقياس المساحي الدقيق .