J. King Saud Univ., Vol. 1, *Eng. Sci.* (1,2), pp. 39-52, Riyadh (1409/1989)

A Comparative Study on Observed and Predicted Heave

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Abstract. Surface and subsurface heave in an expansive shale and associated changes in soil suction and water content were measured in an instrumented field experiment station. Field observations and results of laboratory studies which include swell oedometer tests and suction measurements are presented. In-situ swell measurements are compared with the heave predicted by oedometer and suction methods.

1. Introduction

The factors that determine the swell potential of an expansive clay include mineral constituent, composition of pore fluid, dry density and soil structure, whereas environmental conditions control the magnitude and rate of swell [1]. Evaluation of these variables, in particular the environmental factors, is difficult, and requires long term assessments of climatic and other environmental effects and their impact on the moisture regime of the subsoils in the active zone. Hence, the nature of in-situ heave is complex, and one needs to consider numerous variables for proper analysis.

Although greater effort has been devoted for reliable estimation of in-situ heave in expansive soils, little progress has been made in recent years. Numerous methods have been proposed for heave predictions. These procedures fall into three major categories: i) oedometer techniques, ii) suction methods; and iii) empirical methods, [2]. However, there is a lack of standardization and agreement among the methods [3]. Moreoever, the experience regarding the reliability of current prediction methods is limited due to lack of integrated field measurements to develop reliable case study data for comparative studies on real and predicted swell behaviour. Field records are essential to assess current prediction methods which are mostly based on laboratory testing and theoretical or empirical modelling of swell behaviour.

In this investigation an instrumented field experiment station was erected in an expansive shale area where severe building damages have been reported as a result of heave of foundations [4]. In situ surface and subsurface heave and change in water contents as well as variations in the in situ soil suctions were monitored while the site was artificially saturated to attain ultimate swell conditions. The study also includes measurements of laboratory swell and suction parameters which are used in the prediction methods, and a comparison of observed heave with the swell estimated by suction and oedometer methods.

2. The Site

The site is located near Al-Ghatt town, 270 km northwest of Riyadh, the capital of Saudi Arabia. Severe and widespread damages in the residential buildings had been reported due to presence of outcroping expansive shales in various parts of the town [5]. After a preliminary exploration program at several potential sites, one location which possesses relatively homogeneous subsoil profile was selected for the construction of an instrumented field station. Several boreholes were drilled in the field station area to determine the profile characteristics and to obtain undisturbed samples for laboratory testing. Air drilling technique with double tube core barrels were used throughout the site investigation program to preserve the natural water contents of the samples [6].

The expansive stratum found at the site is a grey-green weathered shale extending to 8.0m to 10.0m depths from the ground level. Approximately one meter thick top soil overlies the shale which is underlain by a weakly cemented sandstone. The expansive stratum consists of two sublayers: i) a silty shale up to 3.0m to 4.0m depths and ii) clay shale underlying the silty shale. The natural water contents and the plasticity characteristics of the shales are shown in Fig. 1. The average soil properties of the silty and clayey shales are summarized in Table 1. Mineralogical studies indicated that kaolinite and illite constitute the clay fraction, and expandible clay minerals can not be traced in the shale [5].

Table 1. Average geotechnical properties of the shales

	Clay shale	Silty shale
Dry unit weight, γd kN/m^3	18.5	18.5
Water content, Wn %	19.0	12.0
Liquid limit, LL %	65	46
Plastic limit, PL %	30	21
Plasticity index PI	35	25
Shrinkage limit, SL %	21	16
Percent sand %	-	3
Percent silt %	28	52
Percent clay %	72	45
Specific gravity G_s	2.78	2.70
Group symbol	CH	CL
Activity, A_c	0.50	0.55

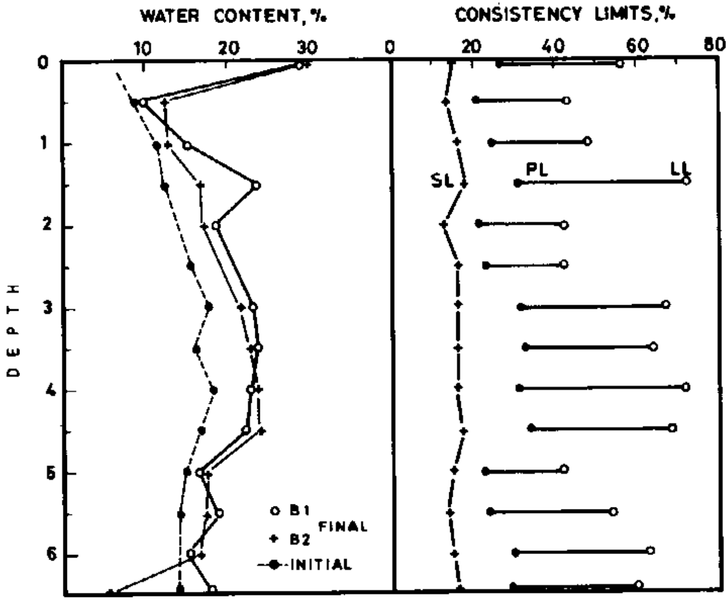

Fig. 1 . Profile characteristics of the shale in field station

Two types of oedometer tests were conducted on the shale cores to determine the swell parameters: i) improved swell oedometer (ISO) or free swell tests; and ii) constant volume swell (CVS) or swell pressure tests. The tests were performed according to the procedures described in ASTM Designation No: D.4556-85[7]. The average magnitudes of swell parameters, namely, swell pressure (P_s) and swell index (C_s), which is the slope of rebound curve on e-log p plots, are summarized in Table 2. The relatively high magnitudes of swell pressures reflect the highly expansive nature of the particular shale stratum. Typical volume change behaviour of the clay shale is shown in Fig. 2.

Table 2. Swell parameters obtained from oedometer tests

Soil type	Method	Swell pressure P_s, kN/m^2	Swell index C_s
Clay shale	Free swell	829	0.069
	Swell pressure	586	0.054
Silty shale	Free swell	258	0.035
	Swell pressure	139	0.025

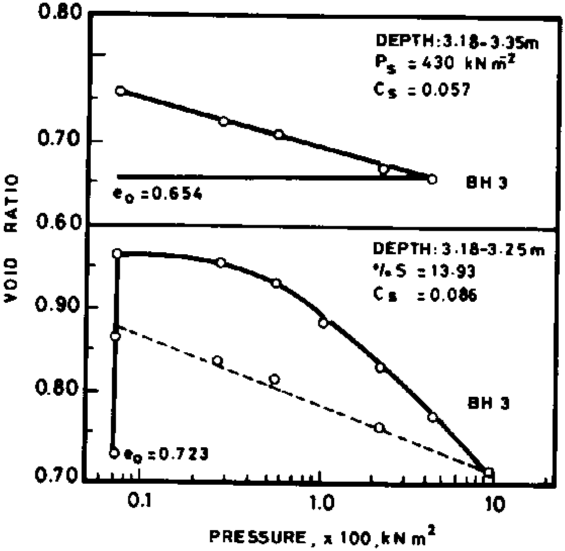

Fig. 2 . Typical volume change behaviour of the clay shale

It is noted that the magnitude of the swell pressure and swell index obtained from swell pressure tests is less than those found from free swell tests. It is believed that the discrepancies in the swell parameters when different laboratory procedures are used, arise from the testing conditions. Soaking a sample, which is disturbed due to release of over burden stresses during sample recovery, under a low confining stress promotes an efficient water penetration into the sample in free swell test. Therefore, the swell parameters are relatively high in these tests as compared to swell pressure tests where water entry is limited by relatively high magnitude of normal stress. Moreover, the application of normal stress restores sample defects arising from release of overburden stresses during sample recovery, and consequently reduces the water penetration.

3. Instrumented Field Station

The field station covers an area of 10m by 20m. The top soil was removed from the test area prior to installation of the field instruments. A saturation system consisting of 4m deep sand drains individually connected to water tanks was constructed across the site to provide controlled water access to the shale. A total of six instrumented units, referred to as Batteries were installed in the field station. Each Battery consists of a thermocouple psychrometer stack, a moisture access tube, a surface heave plate, and five deep heave plates; each placed at 1.0m depth intervals. A schematic representation of the instrumentation is shown in Fig. 3. In situ moistures were monitored by a nuclear density depth probe, and heave movements were measured by precise leveling. The details of the field instrumentation and measurement systems can be found in References [5] and [8].

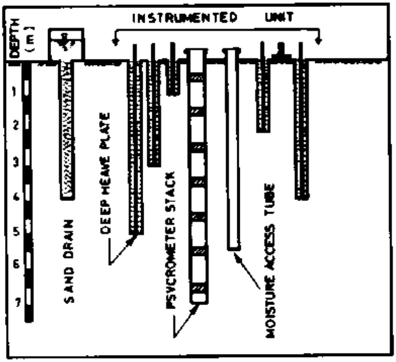

Fig. 3 . Details of field instrumentation

The erection of the field station has been completed and initial readings were taken in July 1985. Watering was commenced in August 1985, and continuous water supply has been secured till September 1986. Periodic water content, soil suction and heave measurements have been taken for a period of 54 weeks. Typical progress of heave with time and corresponding suction variations are shown in Fig. 4. Distribution of cumulative heave along the depth of the soil profile is given in Fig. 5 for Battery 2.

At the end of the observation period the surface heave was not uniform and varied over a range from 60mm, to 200mm, depending on the distance of the measuring point from the saturation line. Field records indicate that Batteries B. 1 and B. 2 which are located 1.5m from the sand drains reached ultimate swell in about 20 weeks while swell was continuing at locations further from the saturation tanks. Therefore, the discussion of the in situ swell behaviour will be based on the field data obtained from Batteries B.1 and B.2, assuming that the ultimate swell conditions were reached at these particular measuring points.

Typical in situ soil-suction profiles recorded at various times of swell are shown in Fig. 6, for B.2. A substantial reduction in the soil suction (*i.e.* in the order of 35 bars) has occured as a result of flooding the site for almost a year. At the end of the observation period, five boreholes were drilled in the field station to determine the final moisture profiles. The final water content profile is shown in Fig. 2, together with the initial moisture conditions. The moisture increase is not uniform in the

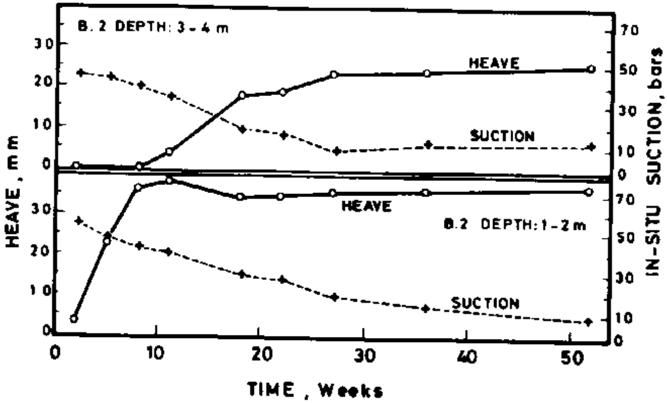

Fig. 4 . Typical field heave and suction measurements with time

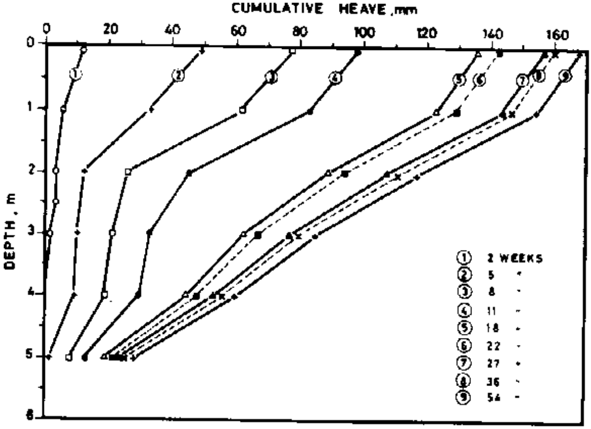

Fig. 5 . Distribution of cumulative heave with depth

upper portion of the profile, perhaps due to heterogeneous nature of the shale close to surface. Within the depths from 2.0m to 5.0m where the shale is relatively more homogeneous, the watering of the site resulted in a uniform increase of approximately 7% in the water contents.

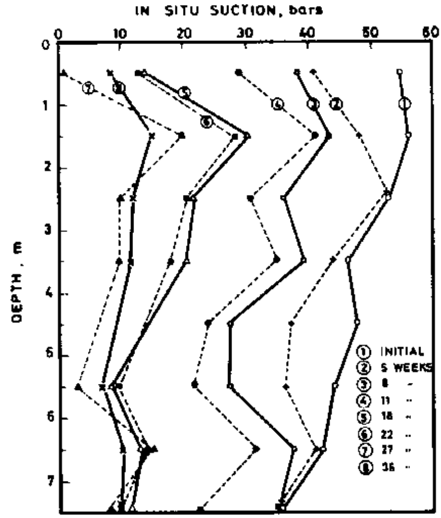

Fig. 6 . Suction profiles

4. Predictions from Oedometer Data

The results of swell tests summarized in Table 2 are used to predict the total potential heave from oedometer test data. In oedometer methods, the fraction of swell (ΔH) may be characterized by evaluation of a swell index (C_s) which is defined as the slope of e-log p curve for unloading; and swell pressure (P_s) at an initial void ratio (e_0) [2]:

$$\frac{\Delta H}{H} = \frac{C_s}{1+e_0} \log \frac{P_s}{\bar{\sigma}_{vf}} \qquad (1)$$

where ΔH = potential heave, H = thickness of the swelling layer, and $\bar{\sigma}_{vf}$ = final effective overburden pressure. For ultimate swell condition where the soil profile is saturated, the value of $\bar{\sigma}_{vf}$ may be taken as the total vertical pressure. The ultimate values of swell calculated from the two sets of oedometer data (*i.e.* ISO and CVS tests) using Eq. (1) are compared with the measured heave in Fig. 7. The surface heave is estimated as 137mm and 207mm by using CVS and ISO test results, respectively; whereas the measured swell is in the range of 133mm to 140mm in batteries 1 and 2, within the upper 5m of the soil profile. Excellent agreement is noted between the predictions based on CVS tests and the measured swell. ISO data, however, overestimates the in-situ heave by approximately 50%.

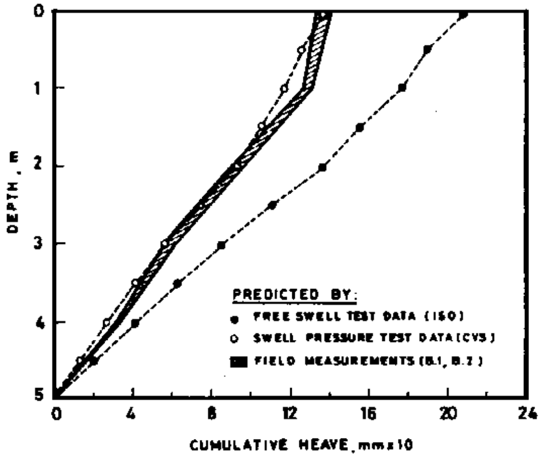

Fig. 7. Comparison of measured heaved and swell predicted from oedometer test results

5. Predictions using the Suction Method

In the swell prediction methods based on soil suction, swell is related to the change in the soil suction through a volume change parameter. This parameter is analogous to the compression index (C_c) for consolidation process, and is an intrinsic property of the soil. Aitchison [9] gives the following relationship to estimate heave of a soil profile due to any change in suction:

$$\Delta H = \frac{\partial \varepsilon}{\partial \log \psi} H \, \Delta \log \psi \tag{2}$$

where ΔH is the heave, ε is the vertical strain in the soil, $\Delta \log \psi$ is the change in the soil suction, and H is the thickness of the expansive layer. In Eq. (2), $[\partial \varepsilon / \partial \log \psi]$ is defined as the instability index (I_p) which relates vertical heave to change in soil suction. The measurement of this parameter through laboratory testing is difficult, but an approximate value can be determined by swell-shrinkage tests to represent the in situ soil conditions appropriate to the problem [10]. Johnson and Snethen [2] define a similar parameter (*i.e.* suction index, C_ψ), which is determined in the laboratory by measuring specific volume (*i.e.* reciprocal of dry density) of undisturbed specimens and corresponding soil suctions independently at various water contents. In this method the swell is given by the following equation.

$$\frac{\Delta H}{H} = \frac{C_\psi}{1 + e_0} \log \frac{\psi_i}{\psi_f + \alpha \sigma_v} \tag{3}$$

where ψ_i and ψ_f are the initial and final soil suction values. σ_v is the vertical stress and e_0 is the initial void ratio. The suction index C_ψ reflects the ratio of change of void ratio with respect to soil suction and can be calculated as follows:

$$C_\psi = \frac{\alpha\, G_s}{100\, B} \tag{4}$$

where α is volume compressibility factor, and B is the slope of log suction versus water content curves, and G_s being the specific gravity of the solid particles. In this investigation Eq. (3) will be used to predict the magnitude of in-situ swell.

In order to define the suction index (C_ψ) first the experimental relationship between the specific volume and the water content should be established. Typical specific volumes versus water contents are given in Fig. 8. The behaviour shown in Fig. 8 can be approximated by a straight line in the water content range above 20%. Below this range, however the slope of the curve tends to decrease as the shrinkage limit of the clay shale is approached. In the present study the compressibility factor α is taken as the slope of the linear portion of the specific volume-water content plot given in Fig. 8.

Figure 9 shows the range of soil suction values measured at various water content for the clay shale. A linear relationship can be assumed between the logarithm of suction and water content within relatively lower range of moisture contents (*i.e.*

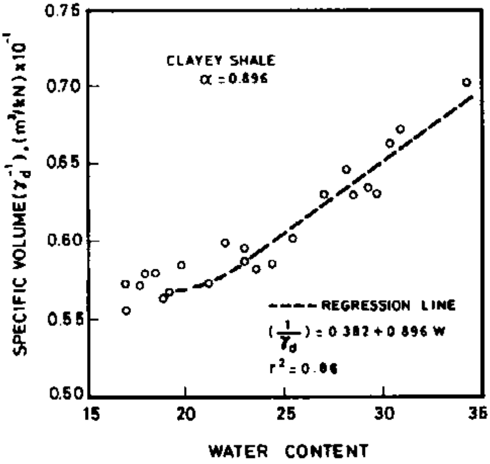

Fig. 8 . Specific volume versus water content plot for clayey shale

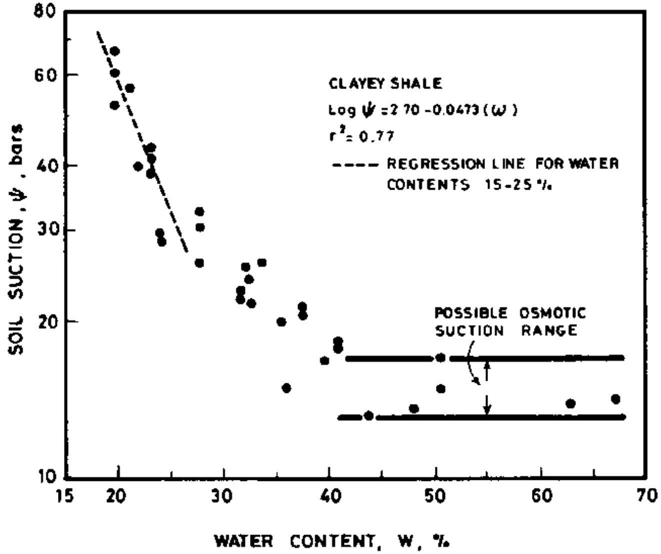

Fig. 9 . Suction water content relationships in clayey shale

15% to 25%), which corresponds to the in-situ moisture changes in the field station. The parameter B is defined as the slope of the linear portion of the log suction versus water content plot in Fig. 9. The data show in Fig. 9 reveals that the particular shale possesses osmotic suction component of 12 to 16 bars as indicated by constant suction values obtained with increasing water contents beyond 40% range. The magnitudes of the suction indices as well as the parameters α and B, for the clayey and silty shales determined from laboratory tests are summarized in Table 3.

Table 3. Swell parameters obtained from laboratory tests

Parameter	Clayey shale		Silty shale
	lab. data	field data	
Compressibility factor, α	0.900	0.287	0.850
Slope of log suc. vs. water cont., B	0.047	0.051	0.070
Suction index, C_ψ	0.517	0.152	0.327

The initial and final suction profiles given in Fig. 6 and the suction indices listed in Table 3 are used in the evaluation of in-situ heave from Eq. (3). The comparison of predicted and measured heave in Fig. 10 indicates that the suction method used appreciably overestimates the surface heave.

Throughout the site investigations, it was experienced that the material within the depth of 2m to 5m is relatively uniform. For the particular depth increment, the average change in the soil suction and water content coupled with the average ultimate swell measured at the end of the observation period are used to backcalculate the parameters α, B and C_ψ from the field measurement. The results are included in Table 3 for comparison with the ones obtained from laboratory data. It is noted that laboratory and in situ suction-water content relationships are consistent, revealing comparable values for parameter B. Thus the discrepancy between measured and predicted swell can be attributed to the compressibility factor α. This factor as defined in Fig. 8 is a parameter which reflects the volumetric strain rather than vertical swell. Therefore, it is generally assumed that some fraction of the volumetric swell occurs in vertical direction [11].

Comparison of values of α obtained from field and laboratory data in Table 3 reveals that the ratio of volumetric to linear (*i.e.* one dimensional in-situ heave) compressibility factors is 3.14, suggesting that one third of the volume changes is reflected as surface heave. Direct measurements of volumetric and linear instability indices published by Richard *et al* [10] have shown that the ratio of compressibility

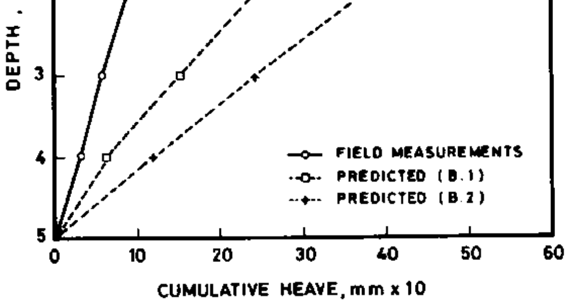

Fig. 10 . Measured heave versus heave predicted by suction method

factors are in the order of two. These considerations suggest that the substantial difference between the measured swell and the potential volume change given by Eq. (3) primarily arises from the parameter α. According to the available field data a correction factor in the order of one third should be applied to the volumetric compressibility factor obtained from the laboratory measurement to convert the potential volume change to anticipated vertical heave. Figure 11 illustrates the improvement in the prediction when a correction factor of one third is applied to the value of the α factor.

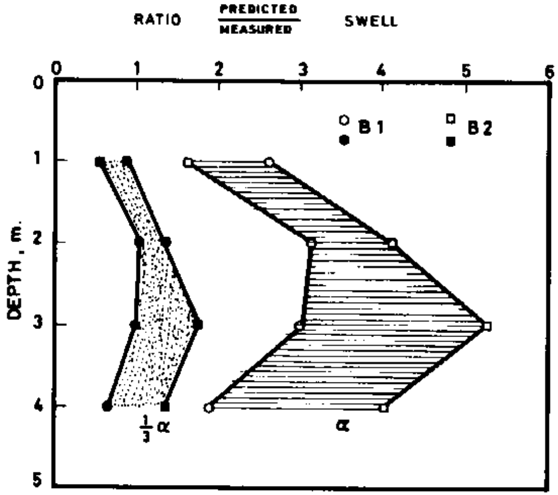

Fig. 11 . Ratios of predicted to measured heave values calculated using corrected and uncorrected values of α

6. Conclusions

The major limitation to the estimation of potential heave arises from the fact that the moisture regime, the suction changes in subsoil profiles and the depth of active zone are difficult to predict accurately. There are uncertainties in the assumptions made for predicting the ultimate moisture and suction profiles which are necessarily incorporated in the analysis of the swell. In the present investigation in situ measurements in the instrumented field station provided data on the final water content and suction profiles and eliminated the need for assumptions regarding the ultimate swell conditions. The following conclusions are drawn from comparison of the predictions with the observed in situ heave:

i. Excellent agreement has been found between measured and estimated swell when results of constant volume swell tests are used. The magnitude of the heave was overestimated by about fifty percent when parameters from free swell tests were used in the calculations.

ii. There is an appreciable difference between the field measurements and the heave predicted by the suction method. Backcalculations from the field data for the known ultimate swell and the associated suction changes strongly indicate that the discrepancy between measured and predicted swell may be attributed to the value of the compressibility factor (α) which is defined in terms of volumetric strains. Values of the compressibility factor calculated from the field data is about one third of the value of the volume compressibility factor determined from laboratory measurements. Therefore, it is suggested that a correction factor of one third should be applied to values of α determined from laboratory test data.

Acknowledgement: This material is a part of the ongoing three year research program supported by King Abdulaziz City for Science and Technology (KACST) under Grant No: AT-5-88.

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(*Manuscript Received:* 29.4.87; *Accepted:* 1.12.87)

دراسة مقارنة بين الانتفاخ المقاس والمتوقع

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ملخص البحث: هذا البحث يشتمل على قياس الانتفاخ السطحي وتحت السطحي للتربة الصخرية الصفحية مع ما يصاحب ذلك من تغير في خصائص التربة الامتصاصية ومحتوى الماء وذلك في محطة تجارب حقلية مجهزة. كما يشمل البحث المشاهدات الحقلية ونتائج التجارب المعملية ومنها اختبارات الانتفاخ الاودومتري وقياسات الامتصاص. وقد تم مقارنة قياسات الانتفاخ الحقلية مع الانتفاخ المتوقع والذي تم حسابه بالطرق التي تعتمد على نتائج الاختبارات الاودومترية والامتصاص.