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Effect of matric suction on swelling behaviour of compacted expansive soils from Sudan

A. Karim & M. Zein
University of Khartoum, Khartoum, Sudan

ABSTRACT: This study investigates the effects of initial matric suction on swelling characteristics of typical Sudanese expansive soils prepared in the laboratory by static compaction. The main objective was to propose simple models based on soil suction concept for estimating the volume change and swelling pressure parameters. The matric suction was determined by the filter paper method whereas the swell percent, swelling pressure and swelling index parameters were determined from oedometer tests following the swell load method. The study showed that the initial soil suction and moisture content are strongly and inversely interrelated by a non-linear equation. It was revealed from study results that the soil matric suction has a significant effect of the swelling behaviour of expansive soils. Reliable relationships were established between the swell percent and swelling index parameters and initial matric suction. However, the swelling pressure tendency was to increase with matric suction to certain values beyond which it decreases with increasing suction.

1 INTRODUCTION

Expansive soils are those by the virtue of their mineralogical composition exhibit appreciable volume changes associated with variations in their moisture content. If the moisture content increases, they swell or develop swelling pressure if prevented and if the moisture content decreases, they shrink (Chen 1975). Such soils present significant geotechnical and structural challenges which involve huge sums of money. It has been reported that expansive soils cause more damage to structures than any other natural hazard including earthquakes and floods (Krohn & Slosson 1980). In the USA alone the annual repairs of damages of foundation and structures related to the expansive soils problem was estimated in 1987 to be nine billion dollars (Jones & Jones 1987).

The main problem associated with expansive soils is that their volume changes are excessive compared to the permissible deformations for various structures. The soil volume changes result in detrimental movements under foundations in an uneven pattern and of such magnitudes that extensive damage is caused to structures resting on them. The places where structural damage were reported in Sudan spread all over the clay plains in the central and southern eastern parts of the country (Osman & Hamadto 1984)

Various techniques and testing methods have been developed to determine the swelling characteristics of expansive soils in the laboratory, but basically two approaches have been followed (Fredlund 1983, Nelson & Miller 1992). The first approach is defined as saturation type and involves measuring the soil response after it has been subjected to complete inundation with free water. The second approach, defined as controlled suction type, embraces the methods in which the water intake by the soil is controlled during testing.

The main advantage of the saturation type swelling tests is the relatively simple equipment and procedure involved; however, the parameters determined usually represent the highest values that can be measured for a given soil. Empirical methods are typically used in estimation of the swelling potential parameters directly from soil index properties (Vanapalli & Lu 2012). However, these equations are based on tests performed on local soils and hence are not necessarily valid for all soil types. The soil suction is defined as a measure of the energy required to remove a water molecule from the soil matrix without the water changing state (Ridley 1993). In unsaturated soil mechanics, it is most notably defined as the difference between the pore air and the pore water pressure (u_a-u_w). The matric suction develops from the particle surface and cation attractive forces of water and the surface tension forces of water within the soil mass. Changes in the moisture content of a given soil are caused by changes in the soil suction.

The suction approach is considered to be the most reliable in the evaluation of swelling characteristics although the measurement and control of suction during testing is tedious and time-consuming (Mou & Chu 1984).The relationship between initial suction and swelling behavior of expansive soils is useful in addressing various geotechnical issues related to the design and construction of various foundations and earthworks.

Due to their unsaturated nature in tropical and semiarid regions the behavior of expansive soils is greatly influenced by the soil matric suction. Several previous researchers have investigated the relationship between volume change and soil suction of natural and compacted expansive soils (Compton 1970, Mou & Chu 1984, Zhan et al. 2007). It has been revealed that the soil-suction approach is invaluable in the prediction of the swelling potential parameters of expansive clays (Mou & Chu 1984). Generally, the findings of previous research works indicate that soils of higher matric suction exhibit higher swelling potential magnitudes than those of lower initial suction. Therefore, the influence of soil suction on expansive soil behaviour is important and is dependent on its initial value. It has been reported that for a change in moisture content of say 2% the resulting swell will vary considerably depending on changes in soil suction (Compton 1970).

Attempts were made by many previous researchers to establish empirical or semi-empirical methods relating the soil suction to the swell percent (Mou & Chu 1984, Zein 1999, Krishnapriya & Sasidharan 2016) or swelling pressure (Abduljauwad et al. 1993, Rao et al. 2004, Pandya 2018) of natural and compacted expansive soils. However, the reliability of methods developed need to be examined and verified for soils from different origins.

The test results of a study by Elsharief et al. (2014) on a Sudanese clay with very high swelling potential showed that swelling pressure increases with increase in soil suction. The maximum swelling pressure measured was 80kPa. A smooth and excellent relationship was found between swelling pressure and soil suction. Similarly, a relationship showing an increase in the pressure with initial matric suction was proposed by Zhan et al. (2007) for natural and compacted expansive soil samples subjected to swelling from air dry to saturation moisture conditions.

In the present research study, the focus has been directed towards investigating the effects of initial matric suction on the swelling characteristics of typical Sudanese expansive soils prepared in the laboratory by static compaction. The main objective is to propose simple relationship models based on the suction concept for estimating the volume change and swelling pressure parameters of studied soils.

2 EXPERIMENTAL WORK

2.1 *Study Soils*

The soil types used for this study were highly plastic clays collected as disturbed samples from different sites in Khartoum State and prepared in the laboratory by static compaction. The basic properties of the three soils designated as S1, S2 and S3 are listed in Table 1 below.

Table 1 Basic properties of study soils

Soil designation	S1	S2	S3
Fines content (%)	93.1	90.2	86.7
Clay fraction (%)	58	44	60
Liquid limit LL (%)	67	69	59
Plasticity index PI (%)	40	48	30

2.2 *Matric Suction Measurement*

Several laboratory suction measurement methods are available but all of them have advantages and limitations with respect to technique simplicity or complexity, suction range to be measured, time required for equilibration, availability and cost.

The filter paper method is widely used for indirect measurement of total and matric suction of undisturbed and remoulded soils (Bulut et al. 2001, Fattah et al. 2015, Pandya & Sachan 2018). The method is relatively simple, inexpensive and covers the range of suction normally encountered in practice. It was therefore adopted for matricsuction measurement of study soils. The filter papers used to determine the matric suction of soil samples were of the Whatman No. 52 grade calibrated for suction at different moisture contents. The test procedure followed in this study was in general conformance with the basic approach suggested by the ASTM designation D5298. During testing, each filter paper was weighed by 0.0001g accuracy electronic balance and inserted between two other papers for protection. The soil sample was dissected in two layers and the filter papers were carefully and quickly placed sandwiched between the soil sample portions. The sample was tightly wrapped in plastic after ensuring that it was in intimate contact with filter papers and was finally stored in a sealed chamber at controlled room temperature of 22°C for 7 days. After completion of the specified duration, the test filter paper was removed from the sample and its wet mass was determined. Thereafter it was dried and its moisture content was determined. Finally, the matric suction corresponding to filter paper moisture content was determined using the standard calibration curve for the paper grade used.

2.3 *Swelling tests*

Various laboratory test procedures are usually followed for determining the volume change and swelling pressure of expansive soils but the three oedometer test types illustrated in Figure 1 have been standardized and widely used (Sridharan et al, 1986). These are termed as the swell-loaded, constant volume and swell under loads methods. Several researchers (Sridharan et al. 1986, Thompson et al., 2006, Zein, 1999; Dhowian, 1990) have reported that the swelling behaviour of expansive soils is dependent on the stress path followed during testing with respect to the wetting and loading sequences.

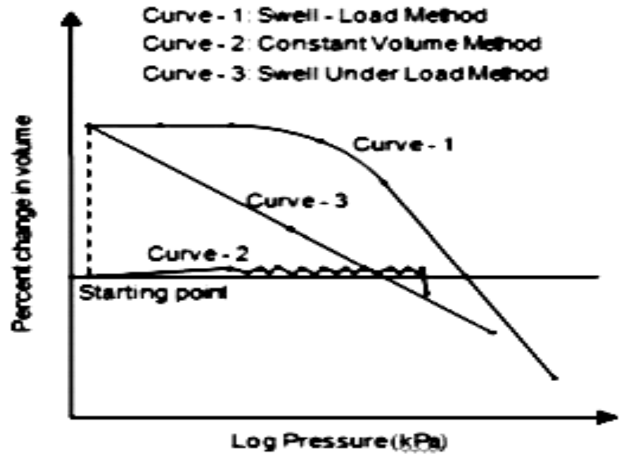

Figure 1. Laboratory swelling pressure test methods (after Sridharan et al, 1986)

In this study the swell load test procedure (curve 1 in Fig. 1) was followed during testing. Each soil sample was initially prepared by static compaction at variable moisture contents and a constant dry density of 16kN/m3in 7.1mm diameter and 19mm height steel ring. The soil specimens were then placed in the odometer and subjected to a seating pressure of 7kPa before being allowed to swell. The test was performed in three successive stages of swelling, consolidation and rebound as illustrated by the stress paths shown in Figure 2 for a typical test sample of soil S1. In all stages the vertical deformation of test samples was recorded by dial gauges at various time intervals. After the soil samples had swollen under full saturation condition, they were subjected to consolidation under applied load increments to a maximum pressure of about 1.25MPa. Finally, the applied loads were removed in few steps and the deformations due to soil rebound were recorded.

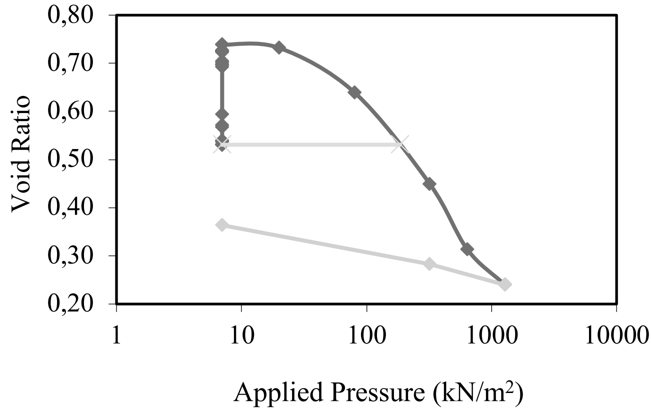

Figure 2. Typical swell load test results for Soil S1

3 RESULTS AND DISCUSSIONS

3.1 *Preparing the new file with the correct template*

To study the relationship between the initial moisture content and soil matric suction the two variables were plotted against each other as shown in Figure3 for all soil types.

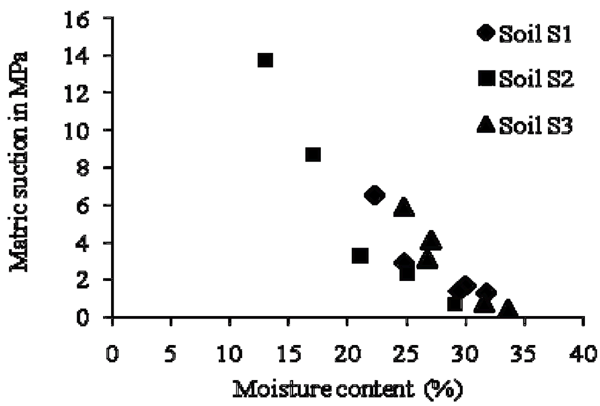

Figure 3. Suction-moisture content curves

The trends revealed in the figure indicate that the relationship is inverse and non-linear i.e. the higher the suction the lower would be the moisture content and vice versa. Such relationship is in agreement with the conceptual model proposed for general description of the soil-water characteristics in several previous studies (Compton 1970, Julio 2002, Zhan et al. 2007).

Based on regression analysis of test data highly reliable correlation relationships were developed between matric suction (σu–σw) and moisture content (w) for each soil with very high determination coefficient values (R2=0.92 to 0.98). A combined power type formula was also derived for the expansive soils studied with a fairly high correlation degree (R2=0.73) for all soils to describe the relationship between matric suction (in MPa) and moisture content w (%) as given below.

$$(u_a - u_w) = 12.674\, w^{-3.36} \quad (1)$$

3.2 *Variation of volume change with initial suction*

The results of tests performed to investigate the effects of initial matric suction on soil volume change in terms of swell percent (S_p) and swelling index (C_s) parameters are discussed below.

3.2.1 *Swell Percent*

The swell percent parameter (S_p) was computed as a percentage of change in its void ratio due to swelling under 7 kPa pressure from its initial suction condition to full saturation. The variations of the swell percent with matric suction for the samples of the three soils were plotted in Figure 4.

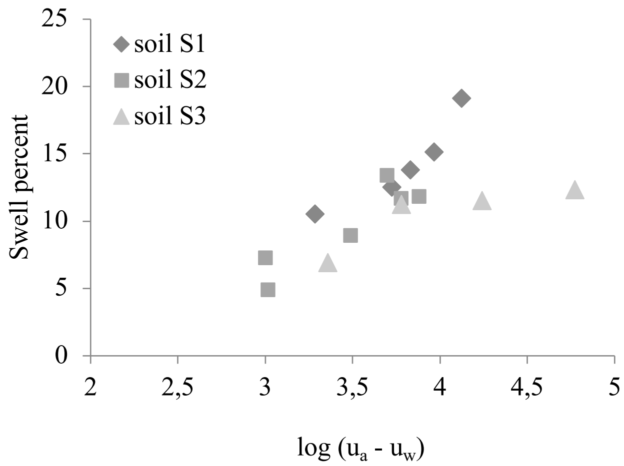

Figure 4. Variations of swell percent with initial suction

The general trends revealed for the variation of the soil swell percent (S_p) and the initial matric suction were similar for the different expansive soils. The trends depicted in Figure 4 indicate that for the same soil, the swell percent is higher in samples of high initial suction and lower in those of lower suction values. Such a soil behaviour is expected and is consistent with the results of many previous research studies (Mou & Chu 1984, Zein 1999, Krishnapriya & Sasidharan 2016).

Relatively high swell percent magnitudes (10.5 to 19.1 %) were exhibited by the S1 soil type followed by soil S2 (4.9 to 13.4 %) whereas Soil S3 indicated relatively low S_p magnitudes (6.9 to 12.3 %). Soils S1 and S2 were both classified as having a very high potential for swelling whereas soil S3 was rated having a high swelling potential. The data in Table 1 show that the PI of soil S1 is lower than that of Soil S2 but the clay content is much higher than of soil S2. It can be inferred from comparison results that the swelling behaviour cannot be accurately estimated by either of the two basic soil indices. The montmorillonite mineral is known to be dominant in both clay soils but the greater potential for swelling in soil S1 compared to soil S2is believed to be due to its higher clay content.

A reliable relationship with fairly high of correlation was established between S_p and the initial matric suction $(\sigma_u – \sigma_w)_0$ expressed in kPa units. This relationship for the soils of very high swelling potential is given by the following equation of high correlation degree (R^2 = 0.83):

$$S_p(\%) = 9.552 \log(u_a - u_w) - 23.1 \qquad (2)$$

For Soil S3 which has a high swelling potential a similar relationship with a slightly lower correlation degree (R^2 = 0.73) was developed as follows:

$$S_p(\%) = 3.42 \log(u_a - u_w) - 3.3 \qquad (3)$$

The increase of swell percent with matric suction may be attributed to the mechanisms contributing to swelling phenomenon at variable soil moisture conditions. At relatively high suctions the available water is held to soil particle surfaces with strong attraction forces and the soil ability to attract free water and swell more is high. At lower suctions the forces holding particles together become weaker and the affinity of the soil to attract water and swell is reduced.

3.2.2 *Swelling Index C_s*

The swelling index, C_s is another important volume change parameter, which is determined as the slope of the rebound line in the swell load oedometer test. This parameter is required for the prediction of anticipated heave movement of expansive soils subjected to moisture variations in under field conditions.

To investigate the effect of suction on the swelling index C_s, the two variables were plotted against each other as shown in Figure5.

The trends of C_s versus log $(\sigma_u– \sigma_w)_0$ relationship are generally consistent with those revealed for the swell percent parameter. They indicate that for a given soil, higher C_s values were obtained in samples of higher matric suctions.

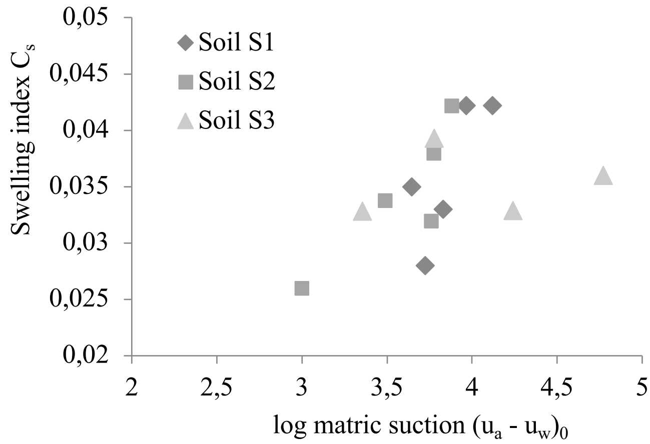

Figure 5. Variation of swelling index with initial suction

A relationship of reasonable correlation (R^2 = 0.63) was developed for the soils of very high swelling potential as given below:

$$C_s(\%) = 0.014 \log(u_a - u_w) - 0.09 \qquad (4)$$

However, no useful relationship was found between the swelling index and initial suction in soil S3 which has a high swelling potential.

3.3 *Effect of initial suction on swelling pressure*

Figure 6 shows the variations of swelling pressure (P_s) with the initial matric suction for the soil types tested.

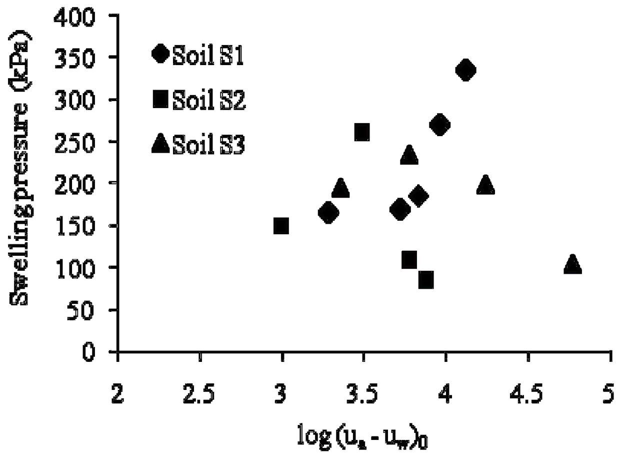

Figure 6. Variation of swelling pressure with initial suction

The highest swelling pressure values were measured in soil S1, followed by S2 whereas soil S3 exhibited lower P_s values. The trend reflected by the variation of P_s with $(\sigma_u - \sigma_w)_0$ in soil S1is generally consistent with those revealed for the volume change parameters shown in Figure 4 and Figure 5. However, the effect of initial matric suction on the swelling pressure was not clearly reflected by the results of tests conducted on the other two soil types. In the latter soils the swelling pressure tendency was to increase with soil suction to certain values beyond which it decreases with increasing suction. This implies that at relatively high suctions the swelling pressure is not strongly influenced by initial matric suction. Such soil behaviour is generally inconsistent with the findings revealed from studies on a highly plastic soil tested by constant volume method (Elsharief et al. 2014) and a medium expansive compacted soil subjected to swelling tests following the swell load method (Zhan et al. 2007). It has been reported that significantly different swelling pressure values may be obtained for identical samples following the constant volume and swell load test methods shown in Figure2. The results of two independent studies (Gilchrist 1963, Abduljauad et al. 1998) indicate that for the same sample the swelling pressure determined by the swell load method could be 2.44 to 5.96 times that obtained from a constant volume method. This may interpret the differences in the behaviour noted for the Sudanese expansive soils in this and some previous studies e.g. Elsharief et al. (2014). Furthermore, for the same test procedure the effect of soil suction on swelling pressure may also depend on the range of suction covered during testing. In the present study the suction range covered during testing was 1 to 10MPa while in the study by Zhan et al. (2007) the maximum suction reached was 0.8 MPa. Unfortunately, the swelling pressure tests performed in the three studies were so small in number to enable explaining the observed differences in soil behaviour.

4 CONCLUSIONS

Based on the analysis and interpretation of the results of suction and swelling tests performed on highly expansive soils the following conclusions may be drawn.

For a given soil the initial soil suction and moisture content are strongly and inversely interrelated. A non-linear equation of a general form conforming to the conceptual soil-water characteristics model proposed in previous studies was developed for the highly expansive Sudanese soils considered in the study.

The initial soil matric suction has a significant effect of the swelling behaviour of the expansive soils tested in the following the oedometer swell load method. The general trends revealed from test results were consistent with those reported in literature and indicate that the higher the initial suction the higher would be the swelling potential.

A simple and reliable relationship was established between the swell percent and initial matric suction. The correlation between the two variables is slightly better for the soils of very swelling potential than that of high potential.

The swelling index C_s parameter is influenced by the initial matric suction. For the soils of very high swelling potential the two variables may be related to each other by a reasonably reliable equation.

The trends reflected by variations of swelling pressure with initial suction were different from those revealed for volume change parameters. The swelling pressure tendency was to increase with soil suction to certain values beyond which it decreases with increasing suction. This implies that at relatively high suctions the swelling pressure is not strongly influenced by initial matric suction. In view of the limited tests conducted in this study further research would be required to explain such unusual soil behaviour.

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