The Prediction of Heave in Expansive Soils

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ABSTRACT
Geotechnical Problems associated with expansive soils are common throughout the world. Expansive soils cover many areas in Saudi Arabia, and are responsible for many structure and road damages. Reliable prediction of ground heave is essential for the development of more effective and economical design of structures on expansive soils. It has probably received more attention than any other analysis associated with swelling soils. Some of the available methods for the prediction of swell potential in expansive soils and techniques proposed for quantitative analysis of heave are presented in this paper. Prediction methods can be divided into three categories. These are theoretical methods, semi-empirical methods, and empirical methods, all these methods will be discussed throughout this paper.

RÉSUMÉ
Les problèmes géotechniques se sont associés aux sols expansibles sont communs dans le monde entier. Les sols expansibles couvrent beaucoup de domaines en Arabie Saoudite, et sont responsables de beaucoup endommagement de structure et de routes. La prévision fiable de la poussée au sol est essentielle pour le développement d'une conception plus efficace et plus économique des structures sur les sols expansibles. Elle a probablement suscité plus d'attention que n'importe quelle autre analyse liée aux sols de gonflement. Certaines des méthodes disponibles pour la prévision du potentiel de bosse dans les sols expansibles et des techniques proposées pour l'analyse quantitative de la poussée sont présentées en ce document. Des méthodes de prévision peuvent être divisées en trois catégories. Ce sont des méthodes théoriques, méthodes semi-empirical, et des méthodes empiriques, toutes ces méthodes seront discutées dans tout ce document.

1 INTRODUCTION

Extensive areas throughout the world experience foundation problems caused by expansive clays. Problems of heave such as heaving, cracking and breaking of building foundations, slabs-on-grade, pavements and other lightly loaded structures have been attributed to expansive clays. In Saudi Arabia the swelling soils are responsible for many structure and road damages.

Predicting heave of light structures has probably received more attention than any other analysis associated with swelling soils. Numerous analytical procedures have been proposed in various countries; however, most methods have been used to a limited extent and within restricted geographical regions.

The primary objective of this paper is to present a review of some of the available methods for the prediction of swell potential in expansive soils and techniques proposed for quantitative analysis of heave, and to assist engineers in relating the volume change behavior of swelling soils to change in the stress state. This review will consider the heaving prediction analysis within the multiphase continuum analysis.

Prediction methods can be devided into three broad categories. These are loosely described as theoretical methods, semi-empirical methods, and empirical methods. The empirical procedures for predicting heave in expansive soils have validity only if they are used within the bounds of the soil type, environment, and engineering application for which they were developed (Nelson and Miller, 1992). In the subsequent section the application of heave prediction and the factors that influence heave will be presented and discussed.

Reliable estimates of anticipated heave and the differential heave are necessary for the following applications:

1. Determination of adequate designs of structures that will accommodate the differential soil movement without undue distress.
2. Determination of techniques to stabilize the foundation and reduce the anticipated heave.

2 CONSTITUTIVE RELATIONSHIPS FOR EXPANSIVE SOILS

A macroscale, phenomenological approach to the study of clay swelling has been applied in most civil engineering applications. A major step in the development of an appropriate framework for macroscale analysis was the definition of the appropriate stress state variables for unsaturated soils (Nelson and Miller, 1992). In the following subsections, the stress state variables and constitutive relationships will be discussed.

2.1 Stress State Variables Controlling Soil Behavior

Three stresses must be measured, estimated or predicted in order to describe the behavior of an unsaturated soil. These are the total stresses, σ, the pore water pressure, u_w, and the pore air pressure, u_a. These variables can be combined into two independent stress state variables for unsaturated soils (Fredlund and Morgenstern, 1977). The (σ-ua) and (u_a-u_w) combination has proven to be most advantageous since the effects of total stress changes and pore water pressure changes can be separated (Fredlund, 1995). The term (σ-u_a) is referred as "net total" stress, and the (u_a-u_w) term is referred to as "matric suction". Fredlund (1995) stated that these stress state variables provide a smooth transition when going from the unsaturated to the saturated soil cases. As the degree of saturation approaches 100 percent, the pore air pressure and the pore water pressure become approximately equal in magnitude. When the matric suction term goes to zero, the pore air pressure in the (σ-ua) term becomes the pore water pressure. He also, suggested when studying a potential heaving problem, the engineer must evaluate the present state of stress in the soil and determine suitable physical properties for predicting future behaviour.

2.1. Constitutive Relationships

Volume changes of an unsaturated soil may be related to the stress state variables using appropriate constitutive relationships. Because the stress state variables are independent, the stress-strain relationship must be depicted on three-axis plots, as shown in Figure 1 (Nelson and Miller, 1992).

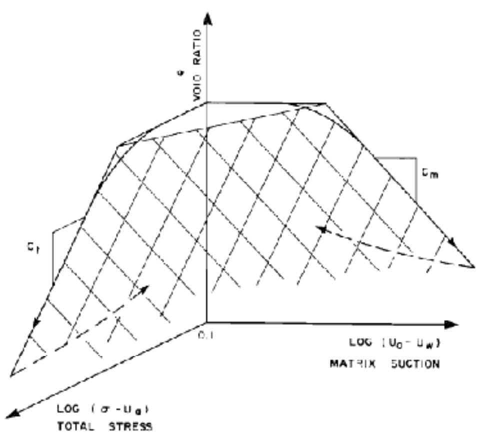

Figure 1. Logarithm of Stress State Variables versus Void Ratio (After Fredlund, 1979)

The constitutive surface in Figure 1 may be represented by an equation as follows (Fredlund, 1979):

$$\Delta e = C_t \Delta \log(\sigma - u_a) + C_m \Delta \log(u_a - u_w) \qquad [1]$$

where;
e = void ratio
C_t = compression index
$(\sigma\text{-}u_a)$ = saturated effective stress variable or net total stress
C_m = suction index in term of void ratio and matric suction
$(u_a\text{-}u_w)$ = matric suction

3 METHODS OF HEAVE PREDICTION

Prediction methods can be separated into three broad categories. These are loosely described as theoretical methods, semi-empirical methods, and empirical methods (Dhowian, 1990). The investigation associated with expansive soil for prediction of heave divided into two stages; namely are qualitative and quantitative characterizations. The qualitative characterization serves the purpose of warning of potential problems. In the identification methods, consistency limits and shrinkage properties are taken as the basis for the swell classification (Dhowian, 1990). The quantitative characterization of expansive soil is performed to estimate the amount of anticipated volume change. There are several techniques for this purpose, such as, oedometer methods, suction methods, and empirical relationships. In this paper, the three different methods will be discussed, especially the oedometer methods, since it is the most widely method for prediction of heave.

3.1 Heave Prediction Based on Oedometer Tests

The one-dimensional consolidation apparatus (i.e. oedometer) has become the most widely test for testing expansive soils. There are several procedures which have been used in attempts to duplicate insitu conditions, these different procedures can be subdivided into two categories; namely, constant load oedometer test and constant volume oedometer test. In the following section the two categories with the subdivided methods will be discussed. Highlighting is given to the standard methods.

3.1.1 Constant Load Oedometer Test

The first category involves an initial loading of an unsaturated sample to a prescribed stress, and then the sample is allowed to swell after inundation. The initial load may represent overburden pressure, overburden plus structural load, or any other arbitrary surcharge. After primary swell is complete, the specimen is loaded and unloaded in the conventional manner. The swell pressure is defined as the pressure required to recompress the fully swollen sample back to its initial volume. The subsequent sections will discuss the different subdivide methods.

Free Swell Oedometer Test Procedure

In the free swell oedometer test, the sample is inundated and allowed to swell freely under an applied token load. Then, the specimen is loaded after primary swell has occurred until its initial void ratio is obtained, Figure 2. The three dimensional plot shown in Figure 2 demonstrate the free swell stress path. ASTM D4546-03 standardized some modification for this method, namely as method A and method B. In method A, the specimen is first loaded to the insitu vertical overburden pressure and then unloaded to the token load. This modification provides a correction to the initial reading at the token load in an effort to more closely duplicate the insitu void ratio of the soil (Shuai, 1996).

For method B, the specimen is inundated after first loaded to vertical pressure more than the token load, it may be the insitu vertical overburden pressure or the structural loading or both. The amount of heave in method B will simulate the insitu heave, where, in the field the loads are first applied to the soil and soil undergoes compression as a result of these loads, then the soil comes into contact with water and swells. However, the free swell test procedure involves both a volume increase and decrease and incorporates hysteresis into the estimation of insitu stress state, however, the advantages of this procedure is that it appears to somewhat compensate for the effects of sampling disturbance (Fredlund, 1995).

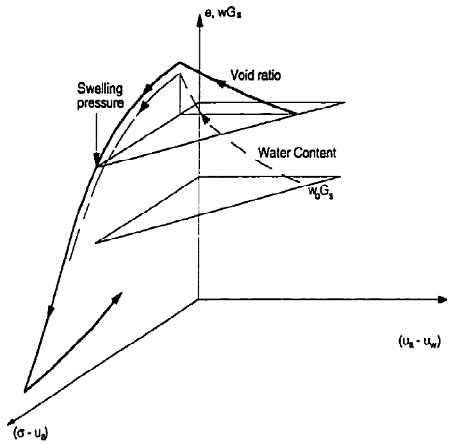

Figure 2. Stress Path Representation of "Free Swell" Oedometer Test (Fredlund, 1995)

Double Oedometer Test Method

Two specimens are tested in this procedure, one is following the free swell test procedure with inundation pressure equal to 1 kPa, namely method A, the another specimen is initially subjected to the token load of 1 kPa, then loaded according to the covenantal oedometer test with its natural water content (i.e. without inundation). Figure 3, shows the stress path followed when using the Double Oedometer method. The "natural water content" oedometer test data must be adjusted vertically to match the free swell test results at high applied loads.

The total heave expected upon inundation is the vertical difference between the two curves. Some researchers found that the Double Oedometer test overestimates the measured insitu heave, and that this method gives a swell prediction about one and one and half to two times the swell which occurs under field stress conditions (Shuai, 1996). The free swell method, method A, is tantamount to assuming that the compression curve for the sample with the natural water content is a horizontal line, so, for large initial loading values and/or where the curve for the sample at natural water content has significant slope, the free swell procedure can underpredict heave, and the Double Oedometer test would be preferred in such cases (Nelson and Miller, 1992).

The direct model method is based on free swell oedometer tests and it is primarily used for estimating heave in undisturbed samples. The samples are subjected to the overburden pressure (or the load that will exist at the end of construction) and allowed free access to water, the stress path followed during this procedure.is shown in Figure 4. It is depicted from the figure that the predicted heaves are generally below actual field heaves (Fredlund et al., 1980).

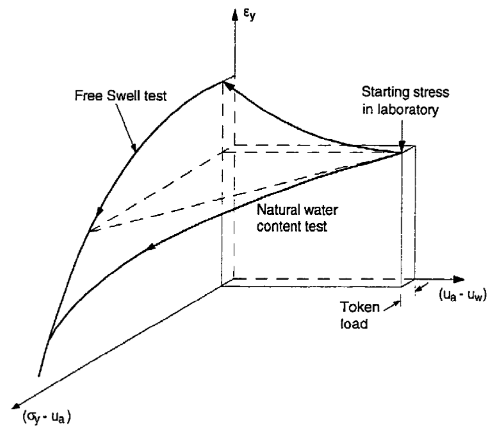

Figure 3. Stress Path Followed When Using "Double Oedometer" Method (after Shaui, F., 1996)

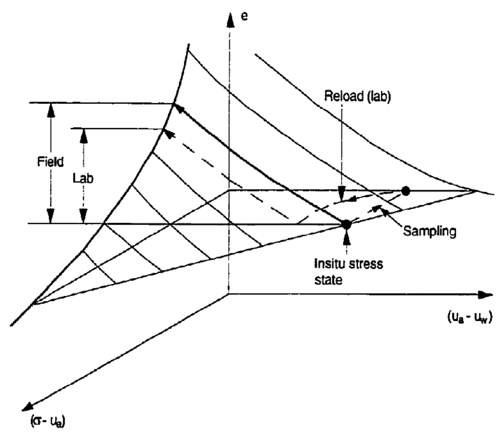

Figure 4. Stress Path Representation of "Direct Model" Method (Fredlund et al., 1980)

3.1.2 Constant Volume Oedometer Test

In the constant volume oedometer procedures, the applied load is allowed to be changed during the tests. In the following subsections some of test procedures belong to this category will be discussed.

Constant Volume Oedometer Test method

In this test procedure, the specimen is maintained at constant height by adjustments in vertical pressure after the specimen is inundated in free water to obtain swell pressure, which refer to no further tendency for swelling. A conveniently oedometer test is subsequently performed.

The rebound data is used to estimate potential heave. Figure 5 shows the conventional constant volume data plot and the stress path followed during this test procedure.

The constant volume method has been recommended by many research workers due to the advantage that it doesn't involve volume change and doesn't incorporate hysteresis into the estimation of swelling pressure. However, constant volume method suffers from a serious limitation that the sampling disturbance has not been taken into account (Shuai, 1996). Fredlund et al. (1980) proposed an empirical procedure to compensate for the effect of sampling disturbance. The sampling disturbance is of particular importance when using the "constant volume" testing procedure, since it results in a significant reduction in the measured swelling pressure (Fredlund, 1983). The effect of sample disturbance on the stress paths can be depicted as shown in Figure 6. Fredlund (1983) suggested the following procedure for finding the corrected swelling pressure. First, an adjustment should be made to the laboratory data in order to account for the oedometer apparatus compressibility. Second, a correction procedure similar to Casagrande empirical procedure that applied to saturated soils to compensate for the effect of sampling disturbance must be applied with slight deviation. The deviation lies in the use of the rebound curve slope in the construction instead of the virgin compression curve slope, Figure 7. The complete correction procedure is discussed in ASTM D4546-03. The importance of obtaining the corrected swelling pressures, that it should be known to estimate the total heave.

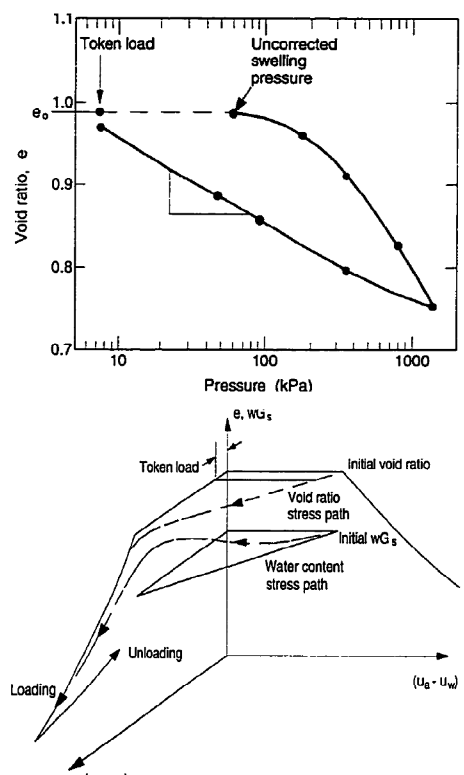

Figure 5. Stress Path Representation of "Constant Volume" Oedometer Test (Fredlund, 1995)

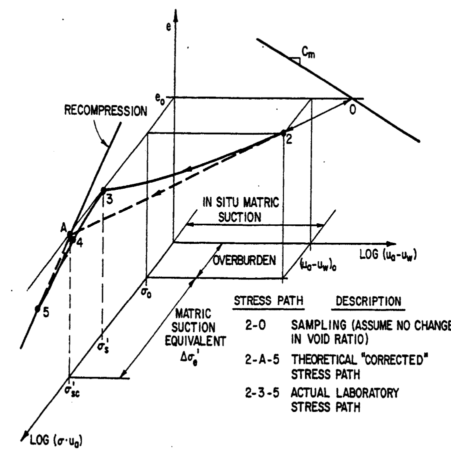

Figure 6. Idealized and actual Laboratory Stress Path for "Constant Volume" Method (Fredlund, 1995)

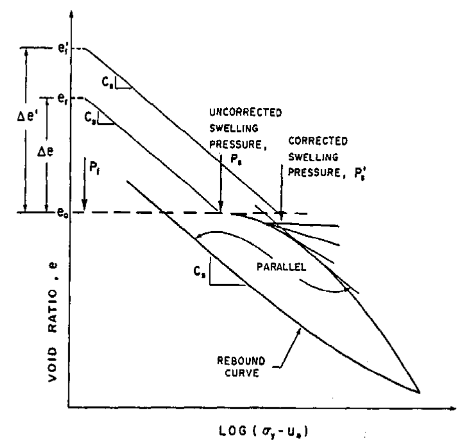

Figure 7. Construction Procedure to correct the effect of sampling disturbance

Sullivan and McClelland Method

This method is based on the constant volume oedometer test executed on an undisturbed sample loaded initially to the overburden pressure. The specimen is rebounded once the swelling pressure has been reached. Figure 8 illustrate the stress path for this method. Fredlund (1980) expressed that this method underestimate heave, since the sample disturbance has not been taken into account.

Strain Controlled Test Method

The procedure of strain control swell test consists of initially confining the sample in the load frame so that no volume change can take place when water is added. After water has been added the swelling pressure is allowed to develop to a maximum value. After the maximum pressure has been reached, the sample is allowed to swell by a prescribed amount and the resulting vertical pressure is again measured, Figure 9. This procedure is repeated in increments until the recorded vertical pressure has reduced to a low value. The sample is then incrementally compressed to its original height (Porter and Nelson, 1983).

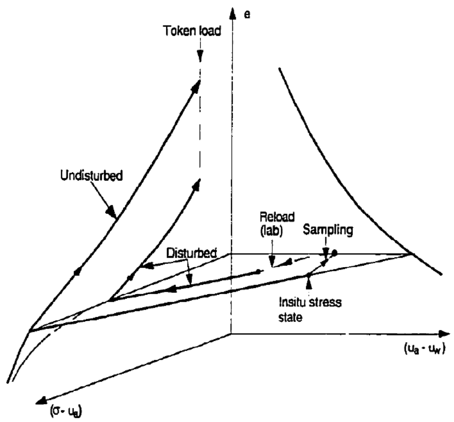

Figure 8. Stress Path depiction of "Sullivan & McClelland" Method (Fredlund et al., 1980)

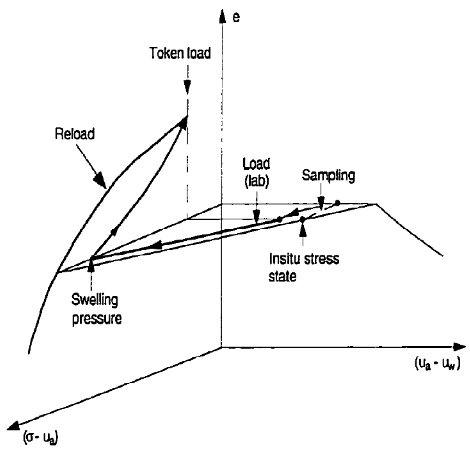

Figure 9. Stress Path Followed in "Strain Controlled" Method (after Shaui, F., 1996)

Comparison of Different Oedometer Test Procedures

The advantage of using oedometer tests for heave prediction is that the geotechnical engineers are familiar with it and the oedometer apparatus are available in most laboratories. In spite of that the mentioned methods for predicting heave and swelling pressure are widely accepted and spread in many countries, and some of them are standardized. Nevertheless, the predicted values differ according to the used method.

Many researchers observed this difference between oedometer methods (Erol et al. 1987, Dhowian, 1990, Ali and Elturabi, 1984). The discrepancies in swell parameter predicted from different oedometer methods are due to that the volume change behavior and the swell parameters are dependent on the stress path and wetting sequence in the oedometer tests, which differ according to the used method (Dhowian, 1990). Erol et al. (1987)-based on testing specimens from Saudi Arabia-stated that the free swell method invariably tends to reveal higher magnitudes for swell parameters as compared to constant volume oedometer method, he refers that to in the free swell method, the soaking sample, which is disturbed due to relaxation of insitu stresses during sample recovery, under a low confining stresses promotes water penetration into the sample in a most efficient way. Therefore the swell parameters are relatively high and indicate higher magnitudes of potential swell as compared to constant volume method where water entry is restricted by relatively high value of vertical stress which also restores the influence of sampling defects (Erol et al., 1987). Ali and Elturabi (1984) observed the same manner for specimens from Sudan tested with free swell and constant volume oedometer tests. Nelson and Miller (1992) stated that the use of controlled strain test with correction for disturbance appears to provide the most accurate heave prediction considering effective stress, and the primary limitation in that method is the inability to obtain high quality undisturbed samples.

3.2 Heave Prediction Based On Soil Suction Tests

Soil suction is important in controlling mechanical properties of expansive soils. The soil suction measurements became a routine procedure after the application of thermocouple psynchrometers to soil suction measurements. These methods have the advantage that eliminate the need for oedometer tests, also conserve both time and money, since these tests are quick and need inexpensive equipment. Soil response to changes in suction can be predicted in the same manner as soil response to saturated effective stress changes, as discussed previous with Equation 1 and depicted in Figure 1. The second term in Equation 1 represents the contribution to change in void ratio due to change in suction. It is obvious from Equation 1 and Figure 1 that Δe is related to soil suction change through the suction index, Cm. The soil suction change is the difference between the initial and final soil suction, the initial soil suction can be determined with direct measurements, and the final suction conditions must be assumed according to every situation.

Comparison of laboratory procedures between suction test methods and the oedometer test methods showed that suction tests were simpler, more economical, and more expedient (Johnson, 1977 as cited in Dhowian, 1990).

In the following sections, some of the different methods used in suction estimations used for heave prediction will be discussed.

3.2.1 U.S. Army Corps of Engineers (WES) Method

The WES prediction method is based on the following relationship:

$$\frac{\Delta H}{H} = \frac{C_m}{1+e_o} . \Delta \log(u_a - u_w) \qquad [2]$$

where;

e_o = initial void ratio

C_m = suction index

$(u_a$-$u_w)$ = matric suction

The suction index, C_m, is calculated from the following equation:

$$C_m = \frac{\alpha . G_s}{100\ B} \qquad [3]$$

where;

α = volume compressibility factor,

G_s = specific gravity of the solid particles,

B = slope of suction versus water content curve.

The compressibility factor, α, which relates the volume and water content, may be determined by the linear shrinkage test, or the CLOD test mentioned below. Otherwise, in the absence of the determination with laboratory tests, it may be estimated from based on the plasticity index, PI, as follows:

α = 0 PI < 5

α = 0.0275 PI – 0.125 5 > PI ≥ 40

α = 1 PI ≥ 40

Since highly expansive clays often have compressibility factors equal to or close to unity, substation of unity for α in the calculation of Cm will be conservative (Johnson, 1977 as cited in Dhowian, 1990). The values of initial and final soil suction are required to evaluate the heave, Equation 2. These values are measured in WES method by thermocouple psynchrometer. Experimental studies have shown that there is a suction-water content relationship for numerous clay soils which is valid for suctions range from 100 to 5000 kPa, as follows:

$$\log(u_a - u_w) = A - B . w \qquad [4]$$

where;

w = gravimetric water content

A, B = intercept and slop of log suction-water content curve respectively

3.2.2 Snethen and Johnson's Method

Snethen and Johnson's method used an equation similar to Equation 2 as follows:

$$\frac{\Delta H}{H} = \frac{C_m}{1+e_o} . \log(\frac{h_o}{h_f + \alpha . \sigma_f}) \qquad [5]$$

where;

h_o =initial matric suction without surcharge pressure, $\log h_o = (A - B . w_o)$

h_f =final matric suction, $\log h_f = (A - B . w_f)$

σ_f =final applied pressure

In this method the parameters A, B, and α are determined from the plotted results of soil suction test procedure. The initial soil suction, h_o, is measured during suction testing and the final suction profile is assumed as one of four suggested by Snethen (1980).

- Zero throughout the depth of active zone
- Linearly increasing with depth through the active zone
- Saturated water content profile
- Constant at some equilibrium value.

Dhowian (1990) mentioned that the swell parameters is practically negligible at water content above plastic limit, so, he suggested that using the plastic limit as the upper limiting water content for determining the final matric suction.

3.2.3 CLOD Test Method

The CLOD test is a modification of the CLOE test procedure used as an identification test for expansive soils. The CLOD method was developed at New Mexico Research Institute for use in heave predictions beneath airfield pavements. Miller and Nelson extended the methodology and applied the method successfully to predict heave beneath actual loaded areas (Nelson and Miller, 1992). In this method, heave is related to soil suction change and soil suction is dependent on the moisture content of the soil; therefore, heave may be predicted by measuring either changes in moisture content or changes soil suction, the following equation is related to changes in moisture content:

$$\Delta H = \sum_i \frac{H_i}{(1+e_o)_i} . (C_w . \Delta w)_i \qquad [6]$$

where;

H_i =thickness of the i^{th} layer,

C_w =suction modulus ratio with respect to moisture content,= $\frac{\Delta e}{\Delta w}$,

Δw =moisture content change.

The suction modulus ratio, C_w, is measured from the CLOD test. The CLOD test procedure involves preparing soil samples with a variety of moisture contents. After measuring the initial soil suction, the samples are coated with a waterproof resin. The volume of the samples is then determined by weighing the saran coated soil clod in air and in water, to obtain the bulk density. The dry density of the sample is determined after oven drying the sample for approximately 48 hours (Snethen and Huang, 1992). These data provide void ratio and water content at various points. The C_w is determined by calculating the slope of void ratio versus water content curve, as depicted in Figure 10, which shows an idealized shrinkage limit curve. Nelson and Miller (1992) give an important note that this relationship is not valid below the shrinkage limit, since, below the shrinkage limit changes in moisture content are not accompanied by changes in volume, as illustrated in Figure 10.

where;

C_Ψ =suction index, = (PI-10)/10.

3.2.5 Comparison of different Suction Test procedures

Snethen and Huang (1992) performed a comparison between different suction test methods for predicting heave, and using the assumption 2- mentioned above in section 3.2.2 as the base for comparison, he concluded that Mitchell's methods provides the best estimate of the heave followed by Snethen and Johnson's method. He stated also, that CLOD method overestimated the heave by approximately 85% and McKeen's method underestimate the heave by approximately 70%. Nelson and Miller (1992) stated that the CLOD method has the distinct advantage of being easy to use and utilize soil samples having undisturbed fabric and structure. He also mentioned that this method is applicable only for determination of free field heave or heave under very light loads such as pavements, since it doesn't consider the effective stress. Miller et al. (1995) stated that the advantages of the CLOD test are of its simplicity and its suitability for testing hard, fractured soils that are difficult to test in oedometers.

3.3 Empirical methods

Many researchers have developed empirical relationships for predicting heave in order to reduce time and cost of laboratory testing. These are generally limited in application to soils outside the geographical area of consideration, and are based on limited amount of data, accordingly, caution should be exercised in their use, and their primary value is as an indicator of expansion potential (Nelson and Miller, 1992).

4 COMPARISON OF DIFFERENT METHODS FOR HEAVE PREDICTION

Dhowian (1990) carried out a comparison of measured heave with the predicted swell based on oedometer test methods and soil suction test methods, and the results is illustrated in Figure 11-a and Figure 11-b respectively. He concluded that the distribution of data points shown in Figure 11-b indicates that the suction methods are more reliable as compared to oedometer methods, Figure 11-a.

5 SUMMARY AND CONCLUSIONS

This paper has presented a review of the techniques of one of the most important property in expansive soils, that is the prediction of heave in expansive soils. A brief presentation of the necessary stress variables for describing the stress state of unsaturated soils was illusterated. Constitutive relationships governing volume change parameters have been depicted. Furthermore, an overview of the most used procedures for the prediction of heave, namely; oedometer testing, suction methods, and empirical correlation are discussed.

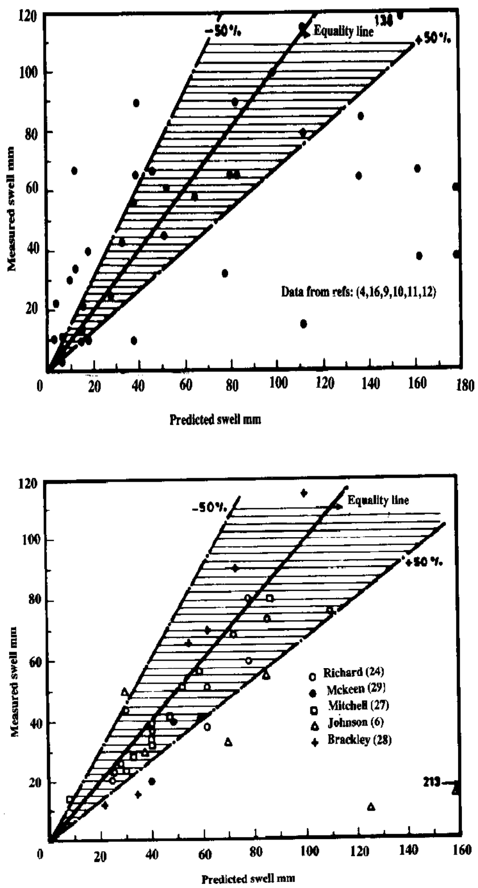

Figure 11. Comparison of Measured Heave with Prediction Based on: (a) Oedometer Data. (b) Suction Methods (after Dhowian, 1990).

Through the discussion of oedometer testing procedures, the stress path of every mentioned method was depicted for more clarification. Short comparisons of the oedometer and suction methods have been presented.

Heave prediction can be conducted in ways to involve various degrees of precision. The authors think that it is prefered that reasonable overprediction of heave instead of underprediction should be the goal of the invistigator. Caution should be exercised in the use of the emperical methods, as their primary value is to be used as an indicator of expansion potential.

Comparison of laboratory procedures between suction test methods and the oedometer test methods showed that suction tests were simpler, more economical, and more expedient and in general it gives more accurate results compared to oedometer testing. However, the use of oedometer tests has the distinct advantage of using conventional testing equipment with which most geotechnical engineers are familiar. Nonetheless, many researchers observed difference between oedometer methods. For instance, free swell and double oedometer tests overestimate measured insitu heave. The constant volume method corrected for sample disturbance has been recommended by many research workers due to the advantage that it doesn't involve volume change and doesn't incorporate hysteresis into the estimation of swelling pressure. Also its results is reasonable with respect to actual insitu heave.

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