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Review of Oedometer Method for Predicting Heave on the Expansive Soil

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Abstract: In foundation design on an expansive soil, the most critical step is to quantify accurately the magnitude of heave and swelling pressure due to change in moisture content. The one-dimensional oedometer has been widely accepted method to determine the heave and swelling pressure of expansive soil. Its simplicity, suitability, and the availability were the reasons for the frequent use of oedometer swell testing technique, but many procedures were identified to measure the swelling properties. Each testing procedures were not unique and resulted different swelling properties and heave prediction. Then, this paper provides an overview of various existing heave prediction by oedometer methods and evaluate common practices of this methods. The techniques were reviewed systematically and summarized. The study summarized a state-of-the-art heave prediction based on the oedometer methods. Various equations forms to predict heave based on the oedometer method have been presented, but the fundamental principles were the same to propose the equation of heave prediction. The differences in these methods were related to the procedures in which the heave index parameter were determined. The three main procedures of oedometer test, i.e. consolidation swell (CS), constant volume CV, and swell overburden (SO), have been summarized. Most of the heave prediction uses the parameter from CS and CV methods. Several reports have shown that the closest estimates of field heave were predicted based on CV method.

Keywords: Expansive soil, Heave prediction, Oedometer method.

1. Introduction

Expansive soil is generally defined as any soil or rock material that exhibits volumetric deformation when its water content changes. It has a potential to swell and shrink under increasing and decreasing water content and suction. If the swelling potential of expansive soils is restrained by surrounding soils or prevented by the overburden pressure or other loads, a counter force which is commonly referred to as swelling pressure will be generated. The primary problem that arises with regard to expansive soils is that deformations are significantly greater than elastic deformations and they cannot be predicted by classical elastic or plastic theory. Movement usually exists in an uneven pattern and such a magnitude can cause extensive damage to structure and pavements resting on them (Nelson & Miller, 1992). The lightweight structure and pavements are very susceptible to damage caused by volume change in expansive soil. The infrastructure such as the foundation slab, highway pavement, the basement wall, and pipeline would be imposed by the expansive soil swelling pressure and consequently results in extensive damages. Muntohar (2006) identified that the swelling pressure caused the pavement damages in Sta. 8 + 127 of the Purworejo-Wates Highway. The weight of the

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pavement layers was lower than the swelling pressures. Therefore the vertical heave pressure will lift the pavement and then caused larger deformation owing to traffic load.

The removed and replaced expansive soil layer (Houston et.al., 2006), the variety of design construction (Briaud et.al., 2012; Dafalla et.al., 2017), and stabilization techniques are used to reduce the losses associated with expansive soil (Puppala et.al., 2016). The determination of swell pressure and predicted heave that soil will undergo are important not only as a key information to determine the success of the remediation and mitigation techniques and procedures (Lu, 2010; Vanapalli & Lu, 2012) but also to make the structure design effective and economical (Gao et.al., 2017). At the preparation of foundation design stage, the heave information and the swelling pressure are a fundamental part to accommodate the anticipated volume change and foundation movement (Al-Shamrani & Al-Muhaidib, 2000; Nelson et.al., 2015).

In recent years, investigation has been an increasing interest in the prediction of soil movement. The focus of the mostly proposed prediction methods is not only to estimate the maximum heave potential, but also to predict the soil movement over time which occurs when soil attains the saturation condition. Prediction method that uses one-dimensional heave on expansive soil is summarized by Vanapalli & Lu (2012). Furthermore, the state-of-the-art methods for predicting the vertical movements of unsaturated expansive soils subjected to environmental changes over time are succinctly summarized and critically reviewed by Adem & Vanapalli (2015). In unsaturated expansive soils, the soil movement prediction techniques have been studied both using the 3-D (Marr et.al., 2004; Adem & Vanapalli, 2015; Wray et.al., 2005) and the 1-D analysis (Adem & Vanapalli, 2013; Adem & Vanapalli, 2016).

Several attempts have been made to formulate the heave prediction methods and procedures. Recent researches have established that the methods can be grouped into three main categories. These include oedometer methods (Fredlund et.al., 1980; Briaud & Zhang, 2004), soil suction methods (Dhowian, 1990; Cocka & Birand, 2000) and empirical methods (Nayak & Christensen, 1971; Puppala et.al., 2016). The calculations using the data resulted from oedometer tests are called oedometer method and the suction method was calculated from suction tests data result, while empirical methods correlate empirical heave data to various characteristics of the soil. Of the proposed techniques over the past several decades, the one-dimensional oedometer is the most widely accepted method to identify and evaluate the amount of swell that may occur. Its simplicity, suitability, and the availability are the reasons for the frequent use of oedometer swell testing technique. Although the amount of heave evaluation by oedometer data have been used extensively, the procedures to perform this test are varied and the reliability of the available predicted heave methods is still limited in terms of experience. To date, there are only a few of these methods that have been validated experimentally (Dhowian, 1990; Diana et.al., 2018). On this account, the purpose of this paper is to review and to provide comprehensive summary of recent research into the predicting 1-D heave on the expansive soil focus on oedometer method.

2. The Oedometer Method

Oedometer test is a one-dimensional test in which a soil sample is being wetted, subjected to vertical stress and confined in lateral direction. The advantage of the oedometer test is that it can measure the amount of swell with a simple operation. Moreover, the testing equipment is commonly available in most soil mechanics laboratories which is familiar among the geotechnical engineers (Nelson et.al., 2015). There are three basic types of oedometer tests that are standardized, and are commonly performed to determine the swell and swell pressure. The first method is the swell-consolidation method (CS) or swell-load method. In this test, the stress on vertical direction is subjected to specimen and wetted under that vertical stress while the specimen is laterally confined. The swell percentage is a vertical strain that specimen will undergo due to wetting. The term ε_s% refers to the swell percentage. Once it completes its swelling process, the specimen may be subjected to additional vertical stress. Muntohar (2003) explained that measurement for complete swelling was time consuming and there is very limited reference about the rate of swelling. However, the rate of swelling may be approached as similar as in the coefficient of consolidation determination as given in Equation 1 to estimate the complete swelling.

$$C_v = \frac{T_v \left(\frac{H}{2} \right)^2}{t_{50}} \tag{1}$$

If T_v and H are taken as constants and C_v is symbolized with C_s , then the equation can be expressed as follows

$$C_s \cong \frac{1}{t_{50}} \tag{2}$$

The t_{50} is the time required to achieve 50% of swell.

The consolidation of swelling pressure is termed to the vertical stress that will be required to restore the specimen to its initial height or initial pore ratio (Nelson et.al., 2015). This method is time consuming, but one specimen needs to have a sufficient time to determine the swell percentage and swelling pressure. The second method is the constant volume (CV) or zero-swell method. The vertical stress of this second method is subjected to the specimen and the vertical strain that is confined during wetting. The stress that is needed to prevent the swell of the specimen is measured and it is termed as CV swell pressure (Nelson et.al., 2015). This method is quick and only needs one specimen, but, the method is sensitive to load increment and rate of loading (Nagaraj et.al., 2009). Its difficulty is associated with the maintenance of an absolute constant volume during operation, deformation of apparatus and the influence of sample disturbance **Error! Reference source not found.**. The result of CV test is found to be rather sensitive and may even leads to small changes of the soil specimen volume. The stress control can be individual during the maintenance of constant volume. Moreover, the compressibility of the apparatus may contribute to some inevitable volume changes of the soil specimen but also influences the result of CV test. It is necessary to determine the apparatus compressibility before performing the CV test. The swelling pressure must be corrected with two respective correction procedures, not only for apparatus compatibility but also for sample disturbances (Nelson & Miller, 1992; Fredlund & Rahardjo, 1993). The last method is swell overburden method (SO). In this test, a number of specimens (three or more specimens) are loaded to the different initial applied vertical load around estimated swelling pressure, and water is added to monitor the swell until the primary swell completes or is compressed to reach equilibrium positions, which lies in straight line on the swell versus log pressure plot (Dhowian, 1990; Al-Shamrani & Dhowian, 2003). The advantage of SO method is that it more represents the actual loading and wetting condition **Error! Reference source not found.**. It requires at least three identical specimens, leading to shorter time required but with difficulties to provide those identical specimens (Nagaraj et.al., 2009).

Procedures for the three kinds of test are described by ASTM D4546 (2003). The three oedometer procedures produce different swelling pressure measurement. The swelling pressure from the SC test leads to the greatest measurement, the intermediate value results in the constant volume (CV) test, and the smallest value is resulted from swell overburden (SO) test (Dhowian, 1990; Al-Mhaidib, 1999). The loading conditions, the side friction effect, and the wetting process are the factors to cause different swelling pressure values (Al-Shamrani & Dhowian, 2003). Although the closest estimates of field heave are predicted based on CV method, it is not considered as the best oedometer method. This can possibly be explained by the fact that the stress path in CV testing does not simulate in situ conditions, since the loading and unloading stage in this test are carried out in soaked condition.

There are various factors to influence the oedometer test result such as initial stress state conditions, the soil fatigue, sample of initial condition, method and time of wetting (inundation), sample of handling and storage, and laboratory skill competency (Nelson et.al., 2015). Table 1 presents the development of oedometer test used to determine expansive soil parameter for the last 30 years.

Table 1 - Development of oedometer test used for determination of expansive soil parameter and heave prediction for last 30 years (modified and expanded after the original contribution of Nelson & Miller (1992); Vanapalli & Lu (2012).

Test	Location	Description	Reference
Erol, Dhowian, Youssef method	Saudi Arabia	There are three main types of study design used to proposed heave prediction. There are various oedometer methods such as ISO (Improved Swell Oedometer Test), CVS (Constant Volume Swell Test) and SO (Swell Overburden Test).	Erol et.al. (1987)
Shanker, Ratnam &Rao method	India	The study used cubical specimen, to study the behavior of swelling soil in multi-dimensional specimen. Under the specific vertical stress, the specimens were allowed to swell in 1, 2, or 3 dimensions.	Shanker et.al. (1987)
Basma, Al-Homoud &Malkawi method	Jordan	The study of swelling pressure used zero swell test and the swell consolidation test, the relative common methods, to be compared with the relative new techniques called restrained swell test and double oedometer swell test. The advantage of the restrained swell test is that its determined swelling pressure of the test closely resembles the real field condition.	Basma, et.al., (1995)
Al-Shamrani &Al-Mhaidib method	Saudi Arabia	The study evaluated not only the vertical swell of an expansive soil, but also the influence of the confinement of the specimen on the predicted vertical swell. The series of both the triaxial cell and oedometer test were carried out to evaluate the stress path of triaxial cell and oedometer under multi-dimensional loading conditions.	Al-Shamrani & Al-Muhaidib (2000)

Table 1- Development of oedometer test used for determination of expansive soil parameter and heave prediction for last 30 years (modified and expanded after the original contribution of Nelson & Miller (1992); Vanapalli & Lu (2012). ***(cont…)***

Test	Location	Description	Reference
Subba Rao & Tripathy method	India	The study evaluated the swell-shrink behavior of the expansive soil using one-dimensional oedometer. The two kinds of specimen were used i.e. aged and un-aged specimen. The specimen was subjected to incrementally loading (compression) and unloading (rebound) stage. In fixed oedometers, the cyclic swell-shrink test was performed. The apparatus was facilitated to allow the specimen to shrink at certain temperature under constant vertical stress.	Rao, Tripathy, (2003) Tripathy & Rao (2009)
Controlled strain test	CTL Thompson Inc. Colorado	The study developed a computer hardware and software to control small increment strain when swelling occurred by applying an additional stress (load) to keep the volume of the specimen constant. The similar computer-controlled apparatus to those reported in Tripathy & Rao (2009). The load-back pressure procedures were used to determinate the swelling pressure.	Thompson et.al. (2006)
Controlled strain test	Paris	The influence of strain control during the swelling pressure measurement was studied. The basic laboratory experimental setup to determine swelling pressure (reaction frame, an oedometer cell, and load cell) added with vertical strain control system (i.e. the piston is instrumented with a digital displacement gauge). Oedometer rings were specially designed to incorporate the measure of lateral stress.	Marcial et.al. (2006)
Agus & Schanz Method	Technical University of Catalonia Barcelona, Spain	Several volume cells were used to perform the swelling pressure test. The circulating distilled desired water was used to inundate the specimen in constant volume cell. The water was flowed through the boundaries of the specimen i.e. bottom and top. The air bubbles collected beneath the porous disks flushed out by the distilled desired water. The swelling pressure developed and closed the air-filled pore in the specimen when the air bubbles come out. The load cell was used to measure the development of swelling pressure. The precision weighing balance was used to measure regularly the weight of specimen (with entire cell).	Agus & Schanz (2008) Agus et.al.(2013)
Tripathy, Subba Rao method	India	The ring oedometer cell was made to conduct the cyclic swell-shrink test. The swelling and shrinking of the specimen under predetermined vertical stress were facilitated in the developed apparatus. The stainless box was equipped to the fixed oedometer ring to accommodate the oedometer, loading frame, and heating arrangement. During the shrinkage cycles, the specimens were desiccated, and the stainless steel boxes with the heating arrangement were incarcerated. The only thing left is the apparatus functioning to enhance the ambient temperature in the closeness of the oedometer.	Tripathy & Rao, (2009)
Nagaraj, Munnas, and Sridharan Method	India	The study used swell load and constant volume method to determine swell and swelling pressure. To provide better drainage and ensure that the specimen is in fully saturated condition in the swelling test, the study introduced varying numbers of vertical sand drains.	Nagaraj, et.al. (2009)
Tang C, Tang AM, Cui, Delage, Schroeder, De Laure Method	Paris	The study used four methods, i.e. constant-volume, swell-reload, zero swell, and adjusted constant volume methods. The swelling pressure was investigated using a clay stone sample named Callovo-Oxfordian (COx) that was crushed and compacted. This study introduces a relatively new method to improve the swelling pressure measurement technique, wherein the swelling pressure was measured without any strain adjustment and any effect of stiffness of the testing device. The swelling pressure was measured by stress sensor. The top surface of the specimen was connected directly (in contact) with the sensor swelling pressure and its inside was fixed to the cell (upper part).	Tang, et al. (2011)
Al-Yaqoub, Parol, Znidarcic Method	Kuwait	There are two main apparatus used to identify swelling pressure namely triaxial cell and conventional oedometer ring with inner diameter of 63 mm. The constant volume oedometer test (CVOT) procedure was used to identify swelling pressure. The study also used moveable base plate, with an oedometer ring place on its top and the assembled triaxial cell. Before the specimen was subjected to a constant load of 0,15 kN, a good contact between top surface of the specimen and top platen was confirmed by moving the base plate. Then the base plate position was fixed, and the specimen was not permitted to absorb water as much water as possible. While the specimen was not allowed to swell within the soil when an internal swelling pressure developed, the pressure was measured. The swelling pressure increased by the increasing amount of water absorbed in the soil until reaching an equilibrium swelling pressure (a maximum value). The specimen was unloaded after a specimen reached its equilibrium swelling pressure. The base plate was lowered slowly by the speed of 0.1 mm/min. The specimen was allowed to swell and release the internal pressure during the unloading stage by a prescribed amount. Once the prescribed swell was obtained, the base plate was fixed again. The specimen was permitted to absorb more amount of water and the redeveloped swelling pressure was measured. Thus, the new equilibrium swelling pressure for the condition was reached. The loading-unloading cycle was repeated until the difference in equilibrium swelling pressure between two consecutive cycles became asymptotic.	Al-Yaqoub et.al., (2017)
Osmotic oedometer Method	France	The study developed and improved osmotic oedometer, by taking an advantage of electrical resistivity technique for direct measurement of the change in degree of saturation and volumetric water content.	Li, et al. (2018)

3. The Heave Predicting Using Oedometer Method

The heave prediction methods were first developed as an extension of methods to estimate volume changes due to consolidation in saturated soils using results of one-dimensional consolidation tests in the late 1950's (Nelson et.al., 2015; Chao, 2007). When predicting heave, some factors to consider were expansion properties of the soil, depth of wetting, degree of wetting, initial and final effective stress state conditions, soil profile and thicknesses of the soil strata, groundwater conditions, and etc (Chen, 1975; Fredlund, 1987; Nelson et.al., 2015).

3.1 Fredlund (1983) Method

To calculate soil heave based on the CV test data result, Fredlund (1983) proposed the method and developed and refined in Fredlund & Rahardjo (1993) and Fredlund et.al. (2012). The corrected swelling pressure from the CV test and the swelling index, C_s are the basic data required for this method. Fig. 1 shows the swelling index which measured the unloading portion of the curve. The sum of the heave for each layer is the total heave of the entire profile as givenin Equation 2.

$$\Delta H = \frac{C_s}{1+e_0} H \log\left[\frac{\sigma''_{cv}}{\sigma''_f}\right] \qquad (3)$$

where,

ΔH = the soil heave,
H = the thickness of soil layers,
σ''_{cv} = swelling pressure from CV test,
σ''_f = final vertical effective pressure,
e_0 = initial void ratio of the soil layer,
C_s = slope of unloading portion (rebound curve).

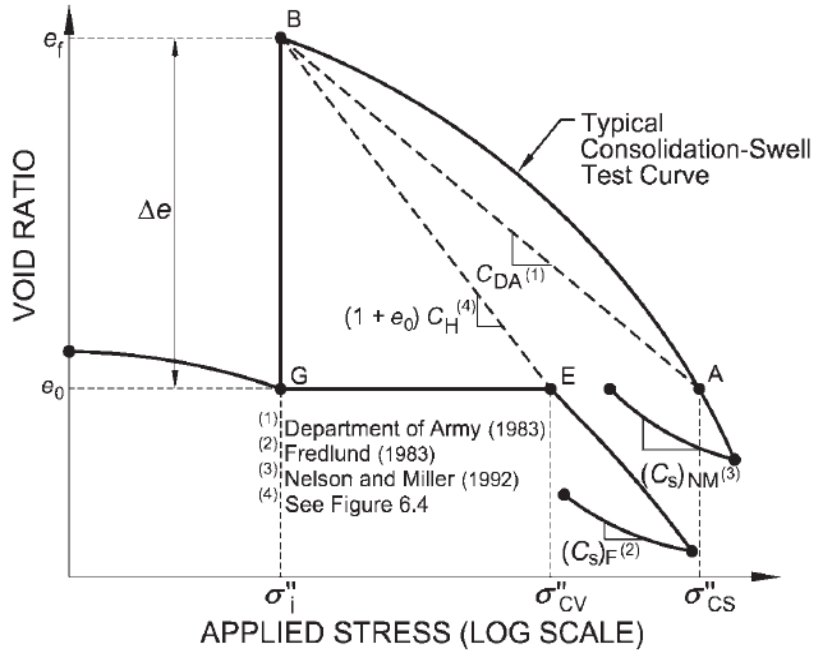


Fig. 1 - Comparison of the different heave parameters (after Nelson, et.al., 2015)

3.2 Dhowian (1990) Method

In a study estimating soil heave of expansive shale formation Dhowian (1990) used test result from three types of oedometer test such as (i) improved swell oedometer (or free swell) tests (ISO); (ii) constant volume swell tests (CVS), and (iii) swell overburden tests (SO). The proposed prediction heaves is as in equation (4),

$$\Delta H = H \frac{C_s}{1+e_0} \log\left[\frac{P_s}{P_0}\right] \tag{4}$$

where,

C_s = swell index,
P_s = swelling pressure,
P_0 = effective overburden pressure.

The Dhowian method used the same equation as used by Fredlund method. The difference is that the Dhowian method used parameter for swelling pressure and also the rebound slope from three kinds of oedometer test. The heave prediction model tends to overestimate compared to the field heave measurement when using modified consolidation swell (ISO) test parameters. However, when the constant volume swell test parameters were used, good agreement between predicted and measured heave could be achieved **Error! Reference source not found.** .

3.3 Nelson & Miller (1992) Method

The index parameter used in the formula was determined from both the CS test and CV test result. The difference in index parameter used by Fredlund method (Fredlund 1983) and Nelson & Miller method (Nelson & Miller,1992) is presented in Fig. 1. The equation for calculating heave is as shown below,

$$\Delta H = H \frac{C_s}{1+e_0} \log\left(\frac{\sigma'_f}{\sigma'_{cv}}\right) \tag{5}$$

where,

C_s = heave index,
σ'_{cv} = swelling pressure from volume constant swell,
σ'_f = vertical stress at the midpoint of the soil layer for the conditions under which heave is being computed.

3.4 Marr et al. (2004) Method

Marr et al. (2004) proposed a practical method to predict the soil vertical movement based on water content changes. The term vertical strain (ε_v) refers to ratio between the volume changes in vertical direction to the initial height of samples. The predicting vertical strain (ε_v) was proposed as a function of changes in water content (Δw) at a given total vertical stress (σ_v). This method used changes in water content than changes in suction pressure because the water content is more readily measured and may be sufficient for predicting volumetric strain. The method tried to simulate the behaviour of the soil when subjected to extreme water content changes condition under a constant vertical pressure.

The series of test was conducted to determine the soil behavior under field stress conditions and seasonal changes in moisture content. The data from several test was plotted in volume strain or changes in void ratio against changes in water content, and the curves related to those factors was formed. The fixed ring oedometer cells was used to measure the shrink-swell properties. The three swell-shrink tests of in-situ to wet, in-situ to dry, and dry to wet tests was performed under various vertical stresses. In each test, the vertical stress subjected to specimen was held constant. The relationships between vertical strain (ε_v) and water content variation (Δw) at a given total vertical stress (σ_v) would be obtained in each test. The response was found to be approximately linear in the region by representing typical seasonal changes in soil water content for constant total vertical stress conditions. As expected, at the higher vertical stress, the slope of swelling line ($C_{\varepsilon,w}$= ε/Δw) decreases which indicated less expansion. The relationship between void ratio (e), water content (w) and vertical stress (σ_v) were also plotted. At each test series, the initial water content and the final water content was measured, representing the initial and final soil conditions. The slope of lines $C_{e,w}$ for constant vertical total stress is related to the initial void ratio, $C_{e,w}$= $C_{\varepsilon,w}$ /(1+e_o). The test result that define a constitutive model surface was used to predict volumetric changes. The total surface displacement due to water content changes is as follow,

$$\Delta H = H_0 \times \frac{\Delta w \times C_{\varepsilon,w}}{100} \tag{6}$$

where,

ΔH	= the ground surface movement (heave),
H_0	= the thickness of soil layer,
Δw	= changes in water content,
$C_{\varepsilon,w}$	= slope of swelling line,

The advantage of this method is that these predictions can be made using only water content data. The data resulted from routine geotechnical laboratory test and most geotechnical engineering laboratory are well equipped to set up and run the test. However, setting up and running the swell-shrink test are time consuming and the test procedure needs a lot of specimens.

3.5 Nelson et al. (2006) Method

The heave index C_H used in this method is an important constitutive parameter (Nelson & Chao, 2014). C_H is the ratio of the percent swell that soil sample will undergo to the vertical stress subjected to the sample observed in the oedometer test when it was inundated. It is to be developed from two or more oedometer tests, not just the slope of a stress strain curve. Fig. 2 showed the stress-strain curves from consolidation swell and constant volume swell test, the heave index parameter C_H that is the slope of the line BDE. The term of ε_s% is a percentage swell corresponding to the particular value of vertical stress σ'_i in consolidation-swell test. At a pressure of σ_v during inundation the percentage swell would be zero, while in constant volume swell test, it is called a swelling pressure σ'_{cv}, where a load is needed to maintain zero strain. The consolidation swell test result is shown as the path GBA, while GFE is shown as a path of constant volume test result. The equation (7) presents the ratio between percent swell and vertical stress namely the heave index (CH).

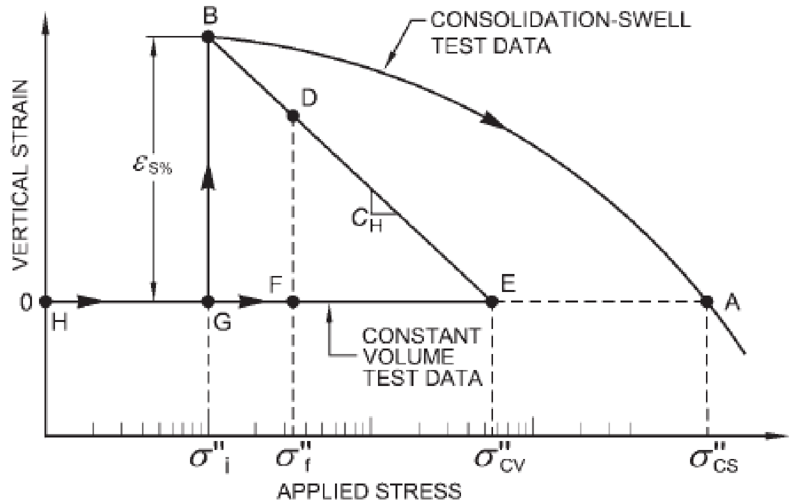


Fig. 2 - Determination of Heave Index, C_H (after Nelson et.al., 2015)

$$C_H = \frac{\%S_A}{\log\left[\frac{\sigma'_{cv}}{(\sigma'_i)_A}\right]} \tag{7}$$

and the equation for heave prediction is,

$$\Delta H = HC_H \log\left[\frac{\sigma'_{cv}}{\sigma'_{vo}}\right] \tag{8}$$

where,

$\%S_A$ = percent swell corresponding to the particular value of σ''_i expressed as a percent,
C_H = heave index,
σ'_{cv} = swelling pressure from constant swell test,
σ'_{vo} = vertical stress at the midpoint of the soil layer for the condition under which heave being computed

From the result of CS and CV test using identical sample, the heave index C_H value can be obtained. In the field, it is difficult to obtain identical samples. Nelson et. al. (2007) developed relationship between σ''_{cs} and σ''_{cv} to facilitate use of Equation (6) and to determine both $\%\varepsilon_S$ at certain vertical pressure σ'_i from a single oedometer test, so that both of the constant volume (CV) and consolidation-swell (CS) swelling pressure can be determined from the same oedometer test. The relationship is shown in the equation (9).

$$\sigma'_{cv} = \sigma'_i + \lambda\left(\sigma'_{cs} - \sigma'_i\right) \quad (9)$$

where,
λ = a coefficient needs to be determined for the general soil materials.
σ'_{cv} =the constant volume swelling pressure,
σ'_{cv} =the consolidation-swell (CS) swelling pressure,

3.6 Kezhen and Luocheng (2009) Method

Kezhen & Luocheng (2009) conducted a series of swelling laboratory tests to investigate the relationship between the swelling pressure, initial moisture content and dry density. It can be used to evaluate the soil characteristics in practical expansive soil engineering when the water contents and total stress levels were changed. The factor affecting the magnitude of swelling deformation were change of water content, surcharge load pressure and initial dry density. The swelling coefficient when upper load pressure is zero, c_{ei}, w_o can be obtained through a series of swelling laboratory test by soil samples with different compaction degree. Then, the swelling value can be calculated as described in equation (10) **Error! Reference source not found.**,

$$\Delta H = \sum_{i=1}^{n} h_i c_{ei,wo}\left(w_i - w_{oi}\right)\left(\frac{\sigma_{zi} + P_a}{P_a}\right)^{-B} \quad (10)$$

where,

h_i = the thickness of soil layer,
$c_{ei,wo}$ = the swelling coefficient of soil layer,
P_a = the atmospheric pressure,
B = the parameter influenced by the types of soils and the variations of water content,
σ_{zi} = upper load.

This method needs a lot of specimens and laboratory works (swelling test) to obtain the swelling coefficient and the relationship with the others. The prediction model is only adequate for the soil specimen they used and needs to validate. Hence, on a universal basis, it cannot be used with confidence. A much-debated question is whether the initial water content influences the swelling pressure. On the one hand Chen (1975) and Villar & Lloret (2008) state that the swelling pressure did not affect the initial water content, conversely other researchers state otherwise **Error! Reference source not found.**.

3.7 Method Gao et.al. (2017) Method

Gao et.al., (2017) performed a series of wetting tests on weakly expansive soil from China. The study investigated the influence of different initial water contents and initial dry density on the volume of change behavior under applied vertical pressure. The swell-underload procedure test used for this study and the test result plotted in logarithm scale between vertical pressure (σ) and pore ratio (e) are as shown in Fig. 3. The behavior of volume changes due two wetting on weakly expansive soil consist of two regions, are swelling and compression regions. Due to wetting, the weakly expansive soil would swell in the swelling region or compresses in the compression region depends mainly on the combination of void ratio and vertical pressure. When the swelling pressure is smaller than vertical pressure, the unsaturated expansive soil will compress during wetting. On the other hand, when the swelling pressure is larger than vertical pressure, the soil will swell during the inundation stage.

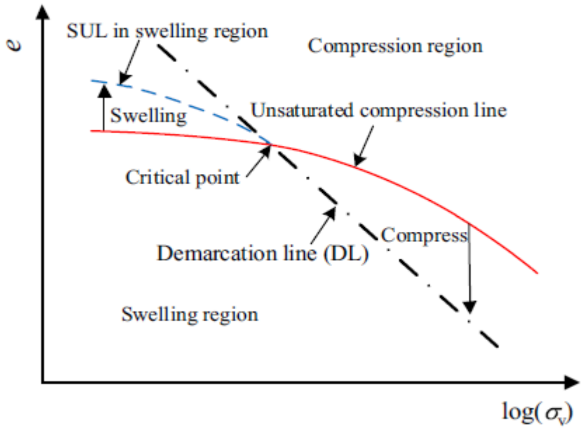
From the wetting test by using specimen with different initial dry density and water content under various vertical pressure, the unsaturated compression line (UCL) and swell under load line (SUL) can be drawn. A unique line called the demarcation line (DL) obtained from intersections of unsaturated compression lines and the swell-under load lines with different initial dry densities, which can be used to judge the swelling or compression of unsaturated expansive soil due to wetting. The physical meaning of DL is that the specimen volume remains unchanged during wetting. Fig. 3 presented sketch of volume change and swelling calculation for weakly expansive soil.

The swelling deformation of an individual soil layer regarding changes in void ratio base on one-dimensional swelling deformation test is as follows,

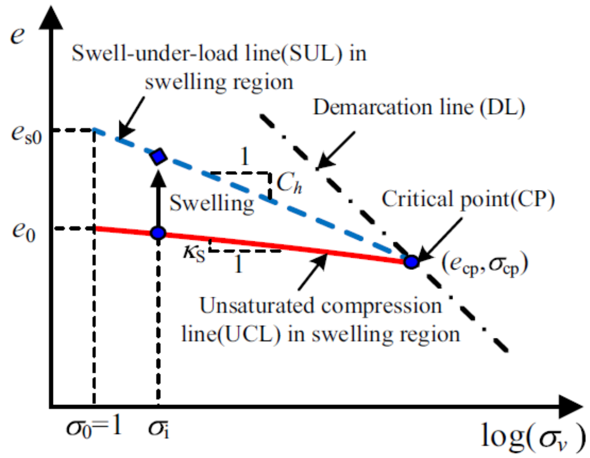
$$\Delta H = \frac{(\kappa_s - C_h)\log_{10}\sigma_i + e_0 - e_{s0}}{1 + \kappa_s \log_{10}\sigma_i + e_0} h_i \qquad (11)$$

where,

ΔH = the change in the height of the soil,
h_i = the thickness of unsaturated soil layer,
κ_s = the slope of UCL,
C_h = the slope of SUL,
e_0 = the void ratio of unsaturated specimens for pressure one kPa,
e_s = the void ratio in the SUL in swelling region,
e_{s0} = the void ratio of the specimen in SUL in the swelling region for the vertical pressure of 1 kPa.
σ_i = the vertical pressure applied.



a. Volume change sketch



b. Sketch of swelling calculation

Fig. 3 - Determination of Heave Index, C_H (after Gao et.al., 2017)

4. Discussion of the Heave Prediction Method

According to Nelson et.al., (2015) several factors must be considered when predicting heave on expansive soil, which are expansion properties, wetting depth (Nelson et.al., 2010), degree of wetting, effective stress at initial and final condition, the thickness and profile of soil, and condition of the groundwater. Previous research has established that expansion properties determined from the different oedometer procedure has a different result. The swelling pressure from CS is higher than CV method (Dhowian, 1990; Al-Mhaidib, 1999; Nelson et.al., 2006; Gao et.al., 2017). Many attempts have been made to propose the relation between CS (σ'_{cs}) and CV (σ'_{cv}) swelling pressure (Nelson et.al., 2006; Nelson & Chao, 2014), most of which proposed a simple equation that used a simple ratio between σ'_{cs} and σ'_{cv}. However, the heave prediction is closely associated with both swelling pressure and percentage swell that determined oedometer test.

The heave prediction using parameter obtained from oedometer test has found a large discrepancy with the actual heave measured in field (Dhowian, 1990; Al-Shamrani & Dhowian, 2003), This may be attributed by the following factors (i) rigid lateral restrain in oedometer ring making volumetric swell measured as vertical swells, wherein a vertical swell is measured in field is only part of the total volume change, (ii) the small size sample used in laboratory making the sample be homogeneous and less contaminated by non-expansive material (Dhowian, 1990; Al-Shamrani & Dhowian, 2003). A reasonable agreement between measured and predicted heave was obtained when a lateral restrain correction factor was applied to heave predictions based on oedometer result, in the absence of better data, the adoption of a 1/3 value for correction is applicable (Al-Shamrani & Dhowian, 2003; Al-Mhaidib, 1999).

Different forms of equations to predict heave based on the oedometer method have been presented, but the same fundamental principles are used to propose the heave prediction. The differences in these methods are related to the manner in which the heave index parameter is determined (Nelson et.al., 2015). The Fredlund method used unloading curve slope from both corrected constant volume (CV) and consolidation swell (CS) test to determine the heave index (C_s). Dhowian method used slope curve from modified CS and CV to determine the heave index and found that the heave prediction closed to field heave measurement when used CV data result. The heave index used by the Nelson and Miller Method is from the slope of unloading curve of CS test. The Nelson et.al. method used heave index from both CS and CV test. The Marr et.al. method used the slope of changes in water content and swell strain namely swelling line ($C_{\varepsilon,w}$) to predicted the heave. The Kenzen and Louceng method used swelling coefficient that is influenced by some factors such as change of water content, surcharge load pressure and initial dry density. The Gao et.al. method used two slope curves, which are unsaturated compression line (UCL) slope and swell under load line (SUL) slope, the UCL and SUL line obtained from swell-under load oedometer test. They define that the expansive soil will compress or swell depend on the vertical pressure and pore ratio condition.

Several studies have shown that most researchers investigating heave prediction has utilized heave index. The evolution of heave prediction methods using oedometer tests has been largely related to the appropriate definition of the heave index (Nelson et.al., 2015). The design parameter used in the analyses must be selected carefully to make the most accurate prediction. The conservative scenarios must assume that the uncertainty conditions occurred and attempt to apply the most rigorous theoretical concepts available, to obtain accurate heave prediction. It is important to consider the influence of mechanical stress (overburden pressure) on the extent and rate of future movement of unsaturated expansive soil (Adem & Vanapalli, 2016). Over and under prediction of heave can lead to unreasonable foundations, costly, inappropriate mitigation, and possible large maintenance costs. When exact values of heave parameter are not known, reasonably conservative values should be used. The development of testing instrumentation equipment allows to obtain several data such as volumetric water content, suction, strain and stress simultaneously, more accurately and faster, that can simulate the natural conditions of the soil in the field.

5. Conclusion

This paper reviewed the state of art of the oedometer method to predict heave of unsaturated expansive soil. Overall, the study highlights the development of the oedometer test for last 30 years to determine swell parameter of expansive soil, and the evolution of heave prediction methods using oedometer tests, an attempt to define appropriate heave index associated with heave prediction computation. The three main procedures of oedometer test, CS, CV, and SO, have been summarized. The reviewed literatures in this study was concluded that the swelling pressure determination with CS (σ'_{cs}) test leads to the highest value of swelling pressure and the smallest is resulted from SO test.

Different forms of equations to predict heave based on the oedometer method have been presented. The same fundamental principles are used to propose the heave prediction. The differences in these methods are related to the way in which the heave index parameter is determined. The Fredlund method, the Nelson and Miller method, the Nelson et.al. method used both of CS and CV procedure to determine heave index. The difference is that the Fredlund method and the Nelson Miller method used unloading curve slope, while the Nelson et.al. method used loading slope curve of the stresses (in logarithmic scale) and strain. The Dhowian method used index heave parameter that was defined from CS and CV test, compared the heave prediction with heave measurement in field, and found that index heave parameter from CV test had a good agreement with the field measurement. The Marr et.al. method used slope from changes in water content and strain curve (swelling line) to predict the heave. The Kenzen and Louceng method used swelling coefficient and the Gao et.al. method used two slope curves, known as unsaturated compression line (UCL) slope and swell under load line (SUL) slope. The UCL and SUL line was obtained from swell-under load. Together, these studies provide important insights into the heave prediction using oedometer data result and selection of the appropriate heave parameter to make the most accurate prediction.

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