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Interpretation of Expansive Soils Data and its Application to Prediction of Heave

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Synopsis

The paper stresses the importance of the application of unsaturated soil mechanics to the problem of predicting heave in expansive soils. The need for applying correction to sampling disturbance to oedometer test data in order to obtain "corrected" swelling pressure has been mentioned. A basic closed form solution has been presented to the equation for prediction of heave.

Introduction

Lightly loaded structures commonly suffer severe distress, subsequent to their construction. Changes in environment around the structure result in changes in the (negative) pore water pressure thereby producing volume changes. The soil engineers are well aware that in many situations light structures move upward after construction. A typical diagram showing the types of movement commonly experienced by light structures, placed on swelling clays, was shown by Hamilton (1978), refering the depth below the structure undergoing volume change to as the active zone.

In order to predict heave, the Geo-technical engineer must visualise volume changes of a soil, in terms of appropriate stress variable changes. The success of practice of Soil Mechanics associated with saturated soils can be attributed largely to the ability of the engineers to relate soil behaviour, to changes in effective stress. Swelling soils are generally unsaturated and engineers have found it much more difficult to understand soil behaviour in terms of stress variables. When investigating a potential heaving problem, the engineer should evaluate the present state of stress in a soil and determine suitable physical properties to predict future behaviour. The prediction of future ground movements requires a knowledge of (i) the initial in-situ State of stress (ii) Swelling moduli and (iii) the final State of stress. The initial State of stress can be quantified from the measured value of swelling pressure in the laboratory. The swelling moduli can be obtained from an oedometer test. The final state of stress corresponding to several years of construction must be based on local experience or estimated.

The measurement of swelling pressure, commonly involves the use of the one-dimensional consolidation apparatus (i.e. Oedometer). Varying testing procedures are used such as the "constant volume" and "free swell", testing methods (NOBLE, 1966). The Oedometer can only perform a test on the total stress plane. Therefore the assumption is made that it is possible to eliminate the matrix suction from the soil, by immersion of soil in water and obtain the necessary soil properties, and stress values from the total stress plane. The "free swell" test has the limitation that it allows volume change and incorporates hysteresis, into the estimation of in-situ stress state. Therefore the constant volume test has received more attention for the measurement of swelling pressure and is further referred in this paper. The importance and significance of correcting this measured swelling pressure for sample disturbance has been amply stressed by FREDLUND (1983).

The need for applying a correction for sampling disturbance to the laboratory measured swelling pressure is revealed in numerous ways. First, it would be anticipated that such a correction is necessary as a result of experience in determining preconsolidation pressure. Second, attempts to use the "Uncorrected" swelling pressure in the prediction of total heave result in values which are too low. Predictions using "corrected" swelling pressure may often be twice the magnitude of those predicted when no correction is applied. Third, the analysis of oedometer results from desiccated deposits often produce results which are difficult to interpret if no correction is applied for sampling disturbances.

The 'ideal' and 'actual' stress paths followed during the 'constant volume' test can be more readily understood by use of a three-dimensional plot with each of the stress state variables for an unsaturated soil forming an independent axis (Fig.1).

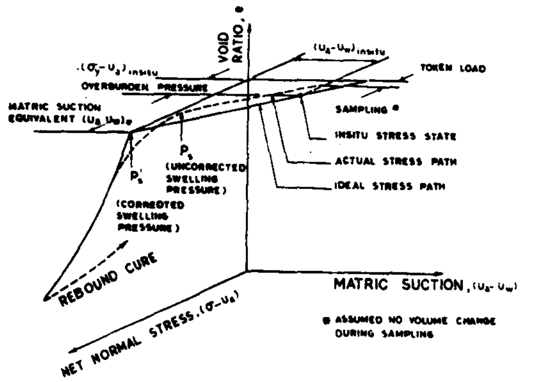

Figure 1 : Ideal and Actual Stress Paths showing the effect of Sampling Disturbance.

Fig.2 shows the actual stress path that would be followed by a soil element at the depth of the sample. Swelling would follow a path from the initial void ratio, e_o, to the final void ratio, e_f, along the rebound surface in the matric suction plane.

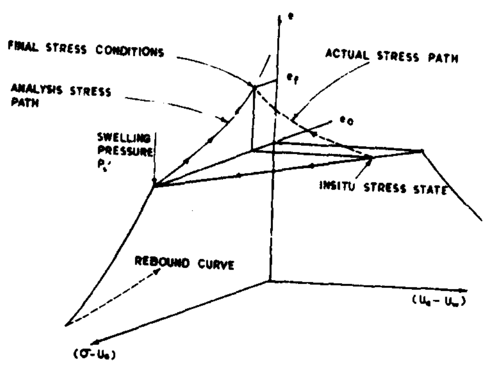

Figure 2 : 'Actual' and 'Analysis' stress paths representing swelling of the soil.

The entire rebound surface can be assumed to be unique since the direction of deformation is monotonic (Matyas and Radhakrishna 1968; Fredlund and Morgenstern 1976). Therefore, it is also possible to follow the stress path from the insitu stress point over to the "corrected" swelling pressure and then proceed along the rebound curve in the total stress plane to the final stress condition. The advantage of the latter stress path lies in the fact that the soil properties determined in the total stress plane can be used to predict total heave.

Sample Disturbance

A procedure for correcting for sample disturbance in a constant volume test was originally suggested by Fredlund (1983) and was shown in Fig.3. The point of maximum curvature is located where the void ratio versus pressure curve bends downward into the recompression branch. At the point of maximum curvature, a horizontal and tangential line are drawn. The "corrected" swelling pressure is designated as the intersection of the bisector

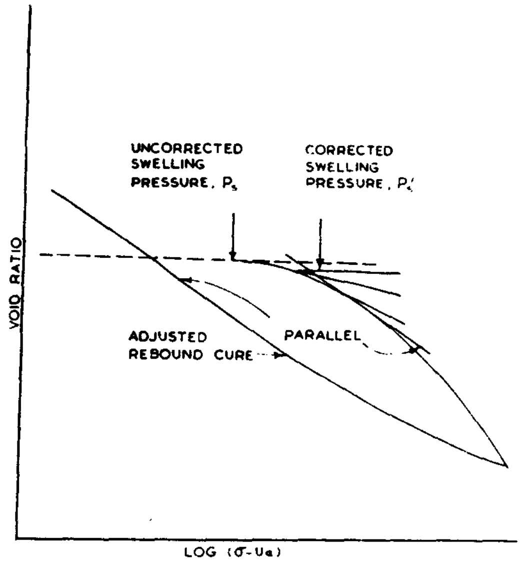

Figure 3 : Fredlund's (1983) construction procedure to correct for the effect to sampling Disturbance

of the angle formed by these lines and a line tangent to the curve which is parallel to the slope of the rebound curve. This procedure is applicable for soils where the slope of the rebound curve is steep. However, for some Indian black cotton clays, the rebound curve is observed to be flat and in such cases the above suggested procedure can not be successfully applied to obtain the "corrected" swelling pressure. Such a typical situation is shown in Fig.4, and the following modified procedure is suggested in such cases of flat rebound curve.

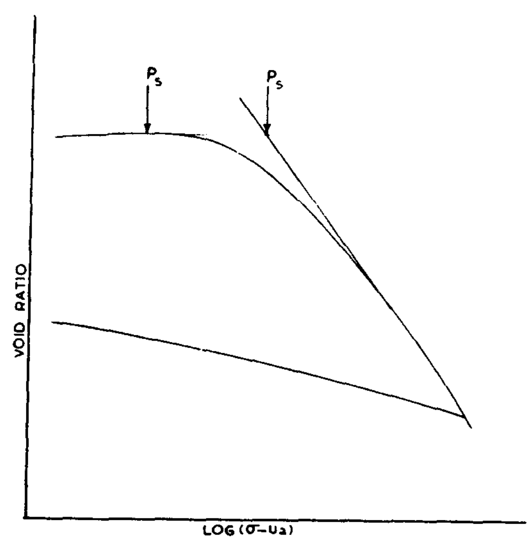

Figure 4 : Modified procedure to obtain corrected swelling pressure in case of flat rebound curve

The initial straight line portion of the compression curve is extended forward. The final straight line portion of this compression curve is extended backwards. The intersection point of these two straight lines is taken as the "corrected" swelling pressure (Fig.4).

Heave Prediction: Closed form Solution

An equation for the prediction of heave has been previously derived using the theory of unsaturated soil behaviour (Fredlund, Hasan and Filson 1980). This equation in its final form is as follows:

$$\Delta h_i = h_i \frac{C_s}{1 + e_o} \log \frac{P_f}{P_o} \qquad (1)$$

where,

Δh_i = heave in a layer,

h_i = thickness of the layer under consideration,

C_s = swelling index,

e_o = initial void ratio,

P_o = initial stress state

$= \sigma_v + (U_a - U_w)_e = P_s'$

= 'corrected' swelling pressure,

P_f = final stress state

$= \sigma_v \pm \Delta_\sigma - U_{w_f}$,

σ_v = original over burden pressure,

$(U_a - U_w)_e$ = matric suction equivalent,

Δ_σ = change in total stress due to excavation or placement of fill,

U_{w_f} = estimated final pore-water pressure.

Fig.5 shows a case where the corrected swelling pressure, P_s', is constant with depth.

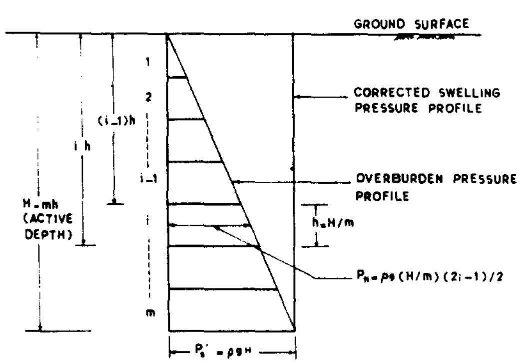

Figure 5 : Overburden and swelling pressure distributions versus depth for the case of constant swelling pressure

The soil is assumed to be homogenous (i.e., e_o, ρ and C_s are constant with depth). It is also assumed that pore-water pressure goes to Zero for the entire soil profile. The final stress state, P_f, is assumed to be equal to the total overburden pressure. The unsaturated, expansive soil, swells upon wetting. Most of the heave will occur near ground surface where there is the largest difference between the corrected swelling pressure and the total overburden pressure. The heave continues to occur until a depth where there is no difference between the corrected swelling pressure and the total overburden pressure. In this paper, the depth at which the corrected swelling pressure equals to the total overburden pressure will be defined as the 'active depth', H.

$$H = \frac{P_s'}{\rho g} \qquad (2)$$

where,

H = 'active depth'

ρ = total density of the soil which is assumed to remain constant

g = gravitational acceleration

The heave analysis can be performed by first subdividing the computed 'active depth' into m number of layers of equal thickness (i.e., $h_i = h$).

$$h = H/m \qquad (3)$$

where,

h = thickness of a soil layer

An attempt is first made to determine the optimum number of layers required to accurately predict the total heave. The initial stress state, P_{oi}, is equal to the corrected swelling pressure, P_s', defined in terms of the 'active depth' in Eq.2.

$$P_{oi} = \rho g H \qquad (4)$$

The final stress state, P_{fi}, in the ith layer from ground surface is computed as the average overburden pressure of the layer.

$$P_{fi} = \rho g \frac{(i-1)h + ih}{2} \qquad (5)$$

where,

i = soil layer number (i.e., 1,2,.....m)

The thickness of soil layer, h, in Eq.5 can be substituted by Eq.3.

$$P_{fi} = \rho g H(2i-1)/2m \qquad (6)$$

The heave equation is written for each soil layer and then summed to give the total heave. Substituting Eqs. 3, 4 and 6 for h_i, P_{oi} and P_{fi}, respectively, into Eq.1 gives the amount of heave for each layer.

$$\Delta h_i = \frac{C_s}{1+e_o} \frac{H}{m} \log \left[\frac{\rho g H(2i-1)/2m}{gH}\right] \qquad (7)$$

Equation (7) reduces to the following form,

$$h_i = \frac{C_s}{1+e_o} \frac{H}{m} \log [(2i-1)/2m] \quad (8)$$

The total heave for the entirely wetted 'active depth' is the summation of the individual heave in each layer.

$$H = \frac{C_s H}{1+e_o} \frac{1}{m} \sum_{i=1}^{m_i} \log [(2i-1)/2m] \quad (9)$$

Eq. 9 is a basic closed form heave equation when swelling pressure is a constant. This equation has been successfully applied by Rama Rao, Rahardjo and Fredlund (under consideration with ASCE for possible publication) for several typical situations encountered in engineering practice.

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