Prediction of Heave Using "Effective" Stress

Ronald F. Reed, P.E.[1]

Abstract

Application of "effective" stress principles in the prediction of heave in unsaturated expansive clay requires an evaluation of the swell index and changes in the matric suction. The latter, in turn, requires knowledge of water balance principles. This paper presents a case study to illustrate the practical application of an effective stress approach to heave prediction.

The purpose of this paper is to present application of a method to predict heave proposed by Fredlund and Rahardjo (1993) in typical engineering studies. A brief review of the method is provided, followed by areas of application. A case history with measured movement, swell pressures and matric suction is presented to illustrate the information required and its application in an engineering environment.

Introduction

Prediction of heave generally relies on empirical correlations based on classification tests or direct application of swell tests using laboratory oedometer test devices. Summaries of the typical methods have been provided in various publications to include Johnson and Snethen (1978), and Fredlund and Rahardjo (1993). However, neither the initial nor final stress conditions within the expansive strata are typically quantitatively defined in these methods of analysis. Evaluation of matric suction and application of an effective stress approach provide the geotechnical engineer a theoretical base to evaluate and explain the cause or causes of observed versus predicted heave.

The purpose of this paper is to present application of a method to predict heave proposed by Fredlund and Rahardjo (1993). This procedure varies from the normal direct methods using a standard oedometer by "correcting" the swell pressure

[1] President, Reed Engineering Group, Inc., 2424 Stutz Drive, Suite 400, Dallas, Texas 75235; phone (214) 350-5600; rreed@reed-engineering.com

for sampling disturbance. The corrected swell pressure is then considered to be equal to the sum of the overburden stress plus matric suction.

A brief review of the method is provided, followed by areas of application. A case study is then presented to illustrate application of the method in an engineering environment.

Methodology

Prediction of heave requires:

1. definition of the void volume characteristics of the profile; and

2. an estimate of initial and final stress conditions.

Fredlund and Rahardjo (1993) have proposed modifying the constant volume swell test to account for sample disturbance. The method is presented in ASTM D 4546 and consists of partially consolidating the sample once the absorption pressure is obtained, then correcting the swell pressure by application of a procedure similar to that which Casagrande recommended for consolidation. The resulting void volume curve is shown in Figure 1.

As shown in Figure 1, "correction" of the absorption pressure results in translating the swell portion of the curve to the right. This translation effectively increases the change in void ratio between any two pressures (i.e., increases the magnitude of predicted heave).

Increasing the magnitude of predicted heave from constant volume swell tests may not appear to be initially justified; however, logically, it is reasonable to conclude that an expansive soil would swell upon release of overburden stresses during sampling. The resulting expansion would be restrained by an increase in the matric suction. The effect of this would be to increase the laboratory measured suction while decreasing the absorption pressure because of the limited expansion that occurs prior to restraint by the increase in matric suction.

Historically, others have also recommended modification of the void volume curve to account for differences between laboratory measured swell and observed movement. As early as the mid-50's, Holtz and Gibbs (1956) recommended modifying the constant volume swell curve by construction of a "field" curve that was estimated to lie between the pressure/swell curve using the constant volume swell procedure and the swell/pressure curve from the improved simple oedometer procedure. This modification is shown in Figure 2.

Once the void volume characteristics of the profile are defined, an estimate of the anticipated change in stress is required. Changes in stress include structural and overburden loads and changes in the matric suction pressure. The initial stress condition is taken to equal the "corrected" absorption pressure, P'_s, as shown in Equation 1. These relationships are also illustrated in Figure 1. Pressure line 1 on Figure 1 represents the net overburden pressure plus the matric suction equivalent. Pressure line 3 represents the net overburden pressure with zero matric suction equivalent, i.e., fully saturated.

$$P_o = P'_s = (\sigma_y - u_a) + (u_a - u_w)_e \quad (1)$$

where

σ_y = total overburden pressure

$\sigma_y - u_a$ = net overburden pressure

u_a = pore-air pressure

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

u_w = pore-water pressure

The final stress condition has the same form as the familiar effective stress equation and is shown in Equation 2.

$$P_f = \sigma_y + \Delta\sigma_y - u_{wf} \quad (2)$$

where

$\Delta\sigma_y$ = change in total stress

u_{wf} = final pore-water pressure

For unsaturated conditions, the pore-water pressure is negative; therefore, decreasing matric suction reduces the magnitude of final pressure. For purposes of this paper, only changes in the matric suction will be considered.

The magnitude of heave is calculated using standard consolidation theory. The swell index is used in lieu of the coefficient of consolidation. The recommended equation and input parameters are:

$$\Delta h = [C_s/(1 + e_o)] \cdot h \cdot \log(P_f/P_o) \quad (3)$$

where

Δh = heave of the layer

C_s = swell index

e_o = initial void ratio

P_o = initial stress state, which is taken to equal P'_s

P_f = final stress state.

This procedure does not account for lateral stress relief; however, it still provides a method for evaluating input data and a means of applying engineering judgment regarding observed or predicted heave.

Application

Application of effective stress in the analysis of building performance provides a base for understanding expansive soil behavior. For example, the method can be used to explain the difference in observed versus predicted heave of ground-supported floors or foundations where extraneous sources of water are present. Some of the forensic engineering applications include evaluating the effect of:

- leaks within utilities or poor drainage;
- changes in the level of ground water; and
- pre-existing vegetation.

Space does not allow for discussion of each of these situations; however, the technique is generally the same. Basically, the initial stress state is taken to equal the corrected swell pressure, P'_s. The final stress state, P_f, is then obtained by calculating the overburden pressure plus any matric suction.

The effect of leaks within utilities and poor drainage on the prediction of heave can be noted by studying Figure 1. If the magnitude of post-construction floor movement was based on a method where 100 percent saturation of the soil profile was not assumed, then leaks within utilities or poor drainage could reduce matric suction resulting in additional movement. This is depicted in Figure 1 by the two pressures indicated as Lines 2 and 3. Assuming that the anticipated stress based on water balance considerations is equal to Line 2, then heave from the initial void ratio, e_o to the void ratio at e_2 would occur. If, however, the final matric suction is reduced to zero (100 percent saturation) and the final stress state is equal to the overburden stress, Pressure line 3 on Figure 1, then additional heave from e_2 to e_3 would be experienced.

Several end conditions can be estimated, to include full or partial saturation (i.e., some residual matric suction). Equilibrium at full saturation is generally conservative; which can result in severely over-estimating the magnitude of predicted heave. An alternative approach is to estimate an equilibrium condition based on the Russam-Coleman (1961) correlation between final matric suction and the prevailing Thornthwaite Climatic Index (I_m). The Russam-Coleman correlation is shown in Figure 3.

Changes in ground water level can also be evaluated using the effective stress approach. For conditions where the water table is less than about 9 meters, the final matric suction below a covered surface is generally taken to equal the negative of the distance above the water table times the unit weight of water. A significant rise in the water table would result in reduction in the matric suction and thus result in heave. The magnitude of heave can be calculated by application of the concepts discussed.

Case Study

The method described in the preceding sections was applied in evaluation of a distressed residence. The residence is supported by a post-tensioned slab-on-ground foundation and has been subject to approximately 140 mm of differential movement.

The site is located with weathered soil of the Upper Cretaceous Eagle Ford Formation. At the subject site, the Eagle Ford Formation consists of soft clay shale that has weathered to a yellowish-brown and light gray CH clay to a depth of approximately 6.1 meters. The weathered profile is highly jointed and fissured and desiccated to the top of unweathered shale at the 6.1 meter depth. The joints and fissures are generally tight. A summary of classification data for the weathered portion of the formation is provided in Table 1. The in situ moisture contents in the drier boring were 5 to 8 percentage points below the plastic limit. This condition is reflected in negative liquidity indices shown in Table 1.

The shape of the deflected foundation and geologic environment indicated heave. An elevation survey indicating the pattern of movement is provided as Figure 4.

Borings were performed as shown in Figure 4 to evaluate soil conditions on both the high and low sides of the house. From this information, it was determined that the soils in the vicinity of the high side of the house (Boring B-2) were relatively moist, whereas they were relatively dry on the low side of the house (Boring B-1). Absorption pressure swell tests (ASTM D 4546, Method C) and matric suction tests (ASTM D 5298) were conducted on selected samples. Plots of the matric suction profiles along with the absorption pressure and swell index are shown in Figure 5.

The initial stress condition was considered to equal the corrected swell pressure within the drier boring (Boring B-1). The final stress condition was taken to equal the overburden pressure plus the matric suction found in Boring B-2. Three conditions for matric suction were used in the analysis:

1. matric suction equal to values measured within the wetter boring (i.e., high side of the house);

TABLE 1. Summary of Classification Data

Liquid Limit L_w (%)	Plastic Limit P_w (%)	Plasticity Index, I_w (%)	Liquidity Index I_l* (%)	-2μ (%)
68 - 80	26 - 33	35 – 53	-0.13 to -0.17	58 - 63

*in situ condition from the drier boring, B-1.

1. matric suction equal to an equilibrium value predicted by the Russam-Coleman correlation; and

2. matric suction dropping to zero, or fully saturated conditions.

Three constant volume swell tests were conducted on samples from the drier boring (B-1). The average swell index, C_s, was measured to be 0.107, with an average initial void ratio, e_o, of 0.935. Swell tests were conducted at the in situ moisture content, which was 5 to 8 percentage points below the plastic limit.

The profile was divided into four layers for calculation of the magnitude of movement as shown in Table 2. The grade beams extended to an approximate depth of 0.8 meters, therefore this portion of the profile was not used in the calculations.

Application of Equation 3, considering initial stress equal to the corrected swell pressure and final stress, P_f, equal to the overburden pressure plus the matric suction values encountered in the wetter boring, B-2, is shown in Table 2. Structural loads from the single-story residence were relatively light and were not used in the calculation.

TABLE 2. Summary of Heave Calculations, Condition 1

Layer	Depth, meters	P'_skPa	u_{wf}, kPa[1]	σ_y,kPa[2]	Δh, mm
1	0.8 - 2.3	718	167	30	55
2	2.3 - 3.8	598	167	60	35
3	3.8 - 5.3	718	215	90	26
4	5.3 - 6.1	718	335	112	22

Total = 138

1. Final pore pressure, u_{wf} based on values measured in B-2.

2. Based on unit dry weight of $\gamma_d = 19.64$ kN/m^3.

TABLE 3. Predicted Heave w/Varying End Conditions

Condition	Initial Stress	Final Stress	Calculated Movement (mm)
1	P'_s	O.B.[1] + 167-335 kPa suction[2]	138
2	O.B. + 167-335 kPa suction	O.B. + 62 kPa suction[3]	91
3	O.B. + 167-335 kPa suction	O.B.	188

1. O.B. - overburden

2. Matric suction measured in Boring B-2

3. Matric suction predicted by Russam-Coleman correlation

Results of similar application of Equation 3 for the three initial and final stress conditions discussed above are shown in Table 3.

Condition 1 is considered applicable for the change in stress from that indicated on the drier side of the house to the wetter side. In other words, Stress Condition 1 should represent the approximate observed heave. The calculated value of 138 mm compares to a measured dis-elevation of about 140 mm.

Condition 2 represents additional heave for an end condition equivalent to that predicted using the Russam-Coleman correlation shown in Figure 3. For the subject site, considering the influence of irrigation, the average I_m is +20. This results in a predicted equilibrium of 2.8 pF (62 kPa). The calculation indicates that additional heave of 91 mm would occur if the suction is reduced from approximately 167 kPa to 62 kPa.

Condition 3 represents full saturation or zero matric suction. This analysis indicates that additional movement of 188 mm is possible (total heave of 326 mm) if fully saturated conditions prevailed throughout the profile. This end condition is possible if a leak developed below the residence, although it is unlikely full saturation of the entire profile would occur. By applying some engineering judgment, or measuring the matric suction profile below the house, an evaluation of the magnitude of heave associated with a leak could be made.

The advantage to this analysis is that some approximation of the magnitude of heave can be obtained for various end conditions. By changing the end stress conditions, the method provides some insight into the effects of external environmental conditions on the magnitude of heave.

As mentioned previously, the geologic formation consists of a dry, weathered clay shale. Limited desiccation cracks are present within the formation, thus limiting horizontal movement or lateral stress relief. No reduction in the calculated heave was applied to account for lateral strain relief associated with closure of desiccation cracks.

Conclusions

Use of the illustrated procedure provides a means of evaluating heave resulting from changes in the matric suction. By estimating an end stress condition, the engineer can evaluate various scenarios and make educated conclusions as to the cause of movement. By comparison of equilibrium matric suction predicted using published correlations, such as that presented by Russam and Coleman, with measured values of matric suction, the effect of leaks or drainage can be quantifiably assessed.

For the case study illustrated, application of the procedure recommended by Fredlund and Rahardjo appears to predict reasonably well the observed movement. Additional studies should be conducted to evaluate the effectiveness in other geologic settings.

References

Fredlund, D., and Rahardjo, H. (1993). "Soil Mechanics for Unsaturated Soils," John Wiley & Sons, Inc., New York, N.Y.

Holtz, W.G. and Gibbs, H.J. (1956). "Engineering Properties of Expansive Clays." Journal of the Soil Mechanics and Foundations Division, ASCE 121, 641-663.

Johnson, L.D., & Snethen, D.R. (1978). "Prediction of Potential Heave of Swelling Soil." Geotechnical Testing Journal, ASTM 1 (3), 117-124.

Russam, K. and Coleman, J.D. (1961). "The Effect of Climatic Factors on Subgrade Moisture Conditions." Geotechnique 1(1), 22-28.

APPENDIX

C_s = Swell Index

e_o = Initial Void Ratio

h = Thickness of Layer

I_m = Thornthwaite Climatic Index

P_o = Initial Pressure

P_f = Final Pressure

P'_s = Corrected Swell Pressure

σ_y = Total Overburden Pressure

U_a = Pore-Air Pressure

$(U_a - U_w)_e$ = Matric Suction Equivalent

U_w = Pore-Water Pressure

U_{wf} = Final Pore-Water Pressure

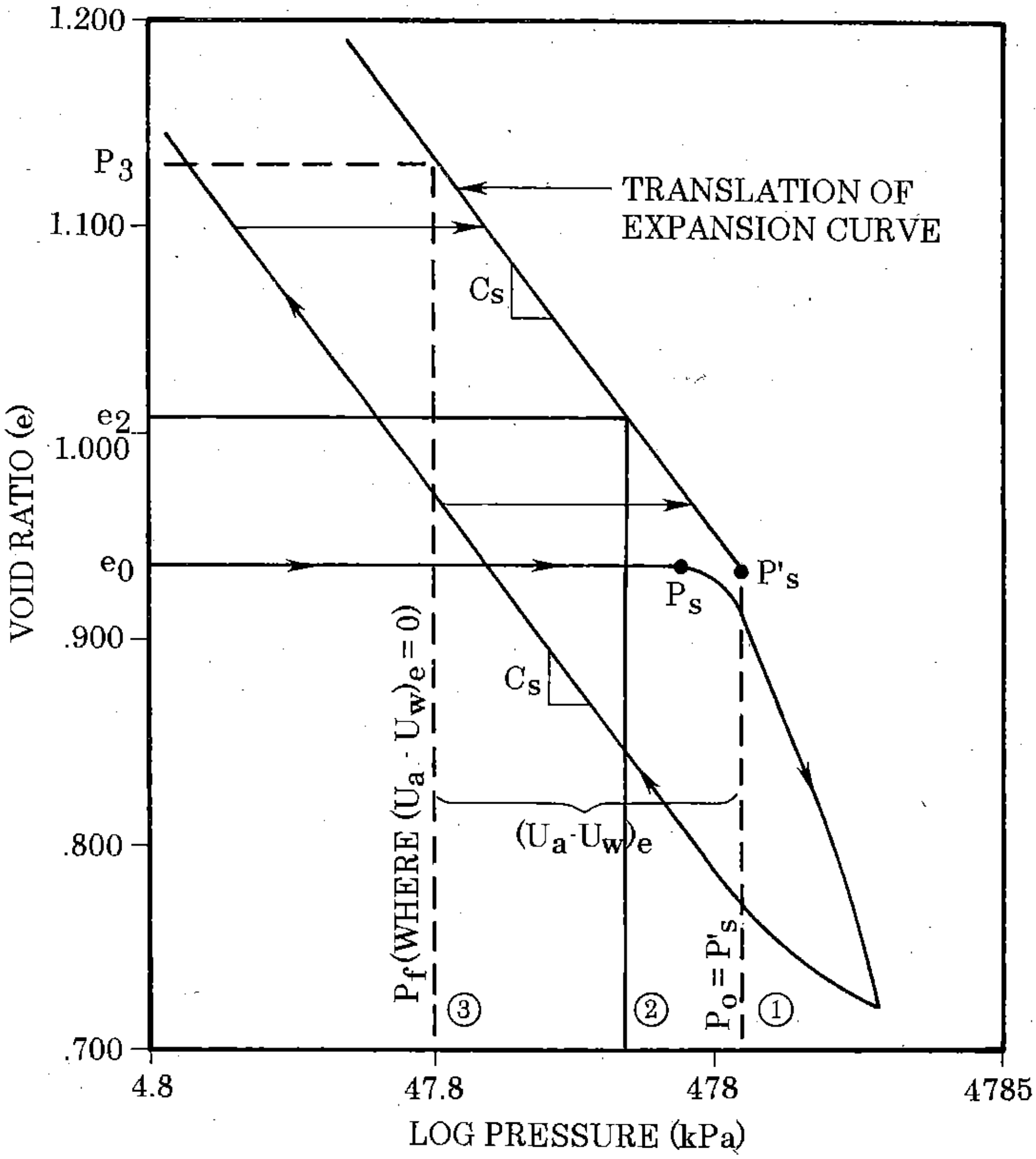


Figure 1. Pressure Swell Curve/Corrected Swell Pressure.

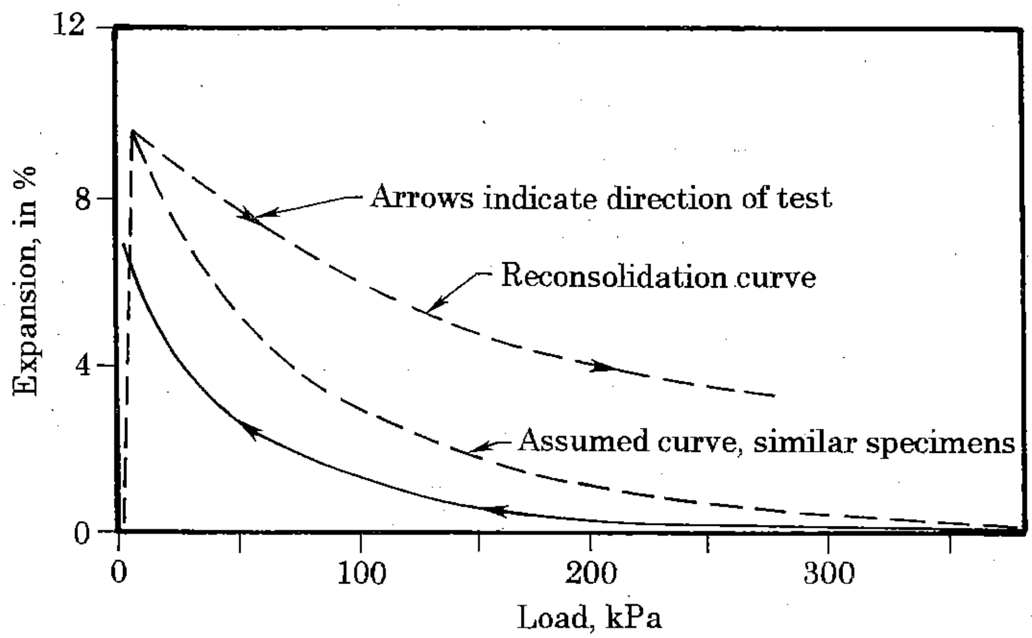


Figure 2. Holtz & Gibbs (1956) Void Volume Curve.

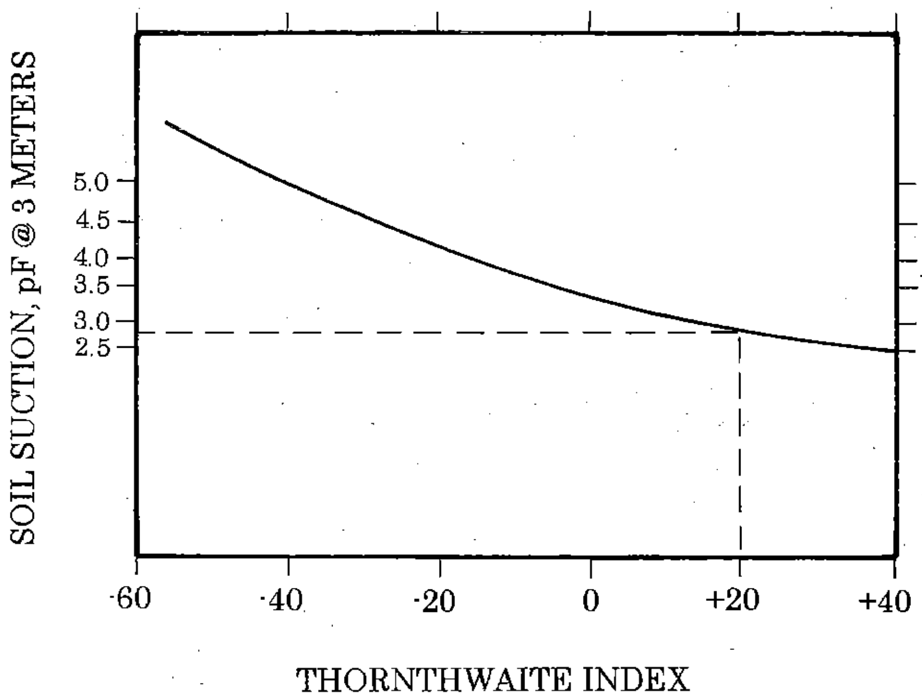
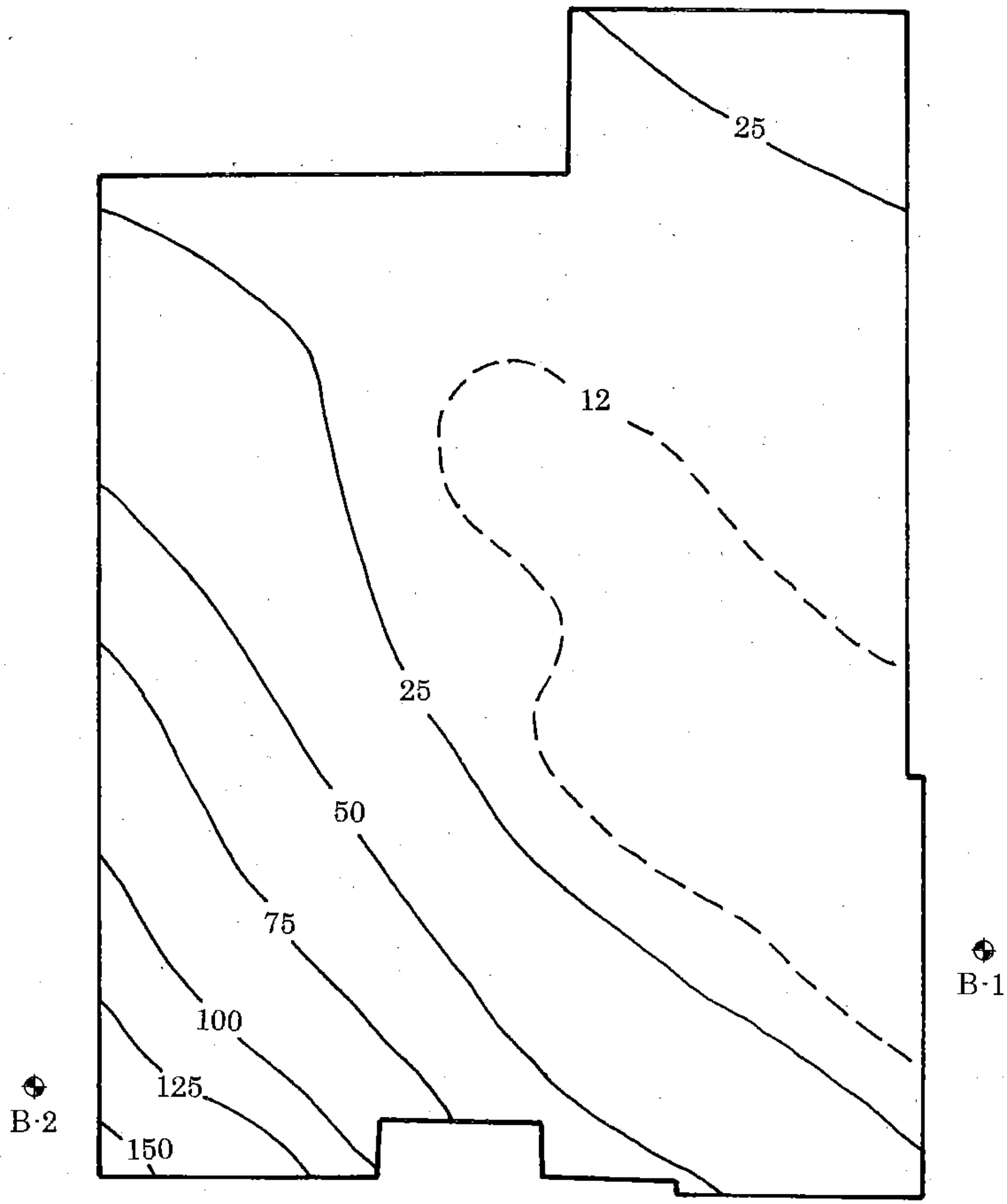


Figure 3. Russam-Colman Correlation (1961).



Measurements in millimeters

Figure 4. Plan of Borings & Relative Elevations.

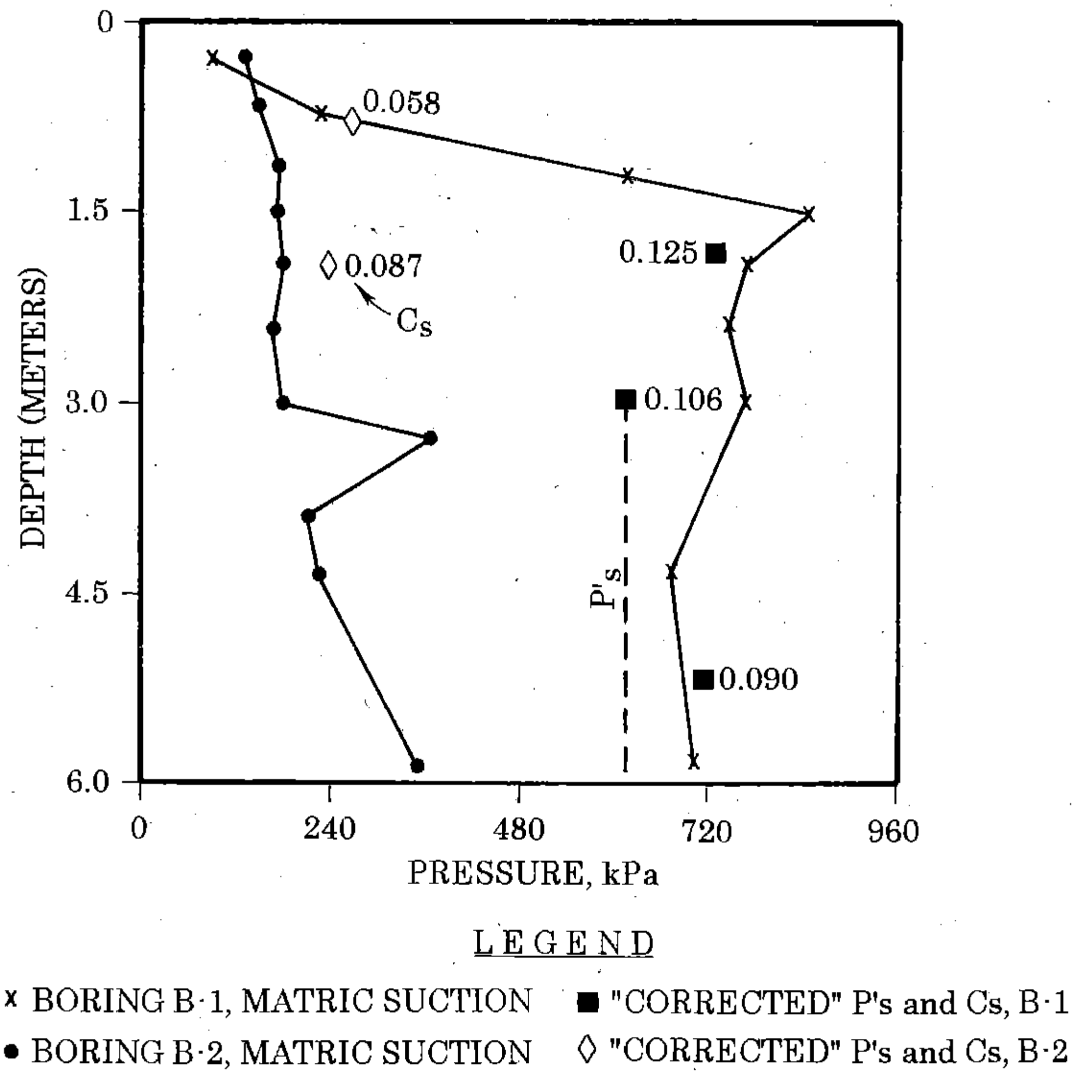


Figure 5. Matric Suction and Corrected Swell Pressure.