OBSERVATIONS ON THE PTI 3RD EDITION DESIGN PROCEDURE

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Abstract

The 3rd edition of the PTI design procedure for ground-supported slabs presents a new method for arriving at the e_m and y_m design parameters. An empirical method is presented in the manual based on changes in soil suction to evaluate the value of y_m. In lieu of manually developing y_m from equations and charts in the manual, the computer program VOLFLO© may be used.

Two soil variables, the unsaturated diffusion coefficient and the suction compression index, are introduced in the 3rd Edition. These two values are then used to obtain the edge moisture variation distance and edge movement. A brief theoretical review and discussion of these two parameters is presented.

Analysis using the VOLFLO© program of two sites in two different geologic conditions, using measured suction profiles, differed significantly from that which would have been predicted using a "trumpet" shape profile. The predicted amount of heave using VOLFLO© and the measured suction profiles were also much greater than historically observed.

Based on studies to date, it would appear that the PTI procedure or VOLFLO© program is not any more reliable predicting expansive soil movement than other readily available empirical methods. It is recommended that additional analysis be performed objectively comparing documented movement versus movement predicted by use of either the PTI or VOLFLO© procedures.

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Introduction

The purpose of this paper is to independently evaluate the new method for developing the soil parameters in the 3rd Edition of the Post-Tensioning Institute's (2004) design procedure for ground-supported slab foundations. To limit the length of the paper, familiarity by the reader with the design procedure in the first two PTI editions is assumed.

Two critical soil variables are required to use the structural equations for foundation design; the edge moisture variation distance, e_m, and magnitude of movement, y_m. This paper concentrates principally on the recommended procedures in the 3rd Edition for development of the y_m variable.

The new procedure introduces two soil variables used to determine e_m and y_m, the unsaturated diffusion coefficient, α, and the suction compression index, γ. The unsaturated diffusion coefficient is shown in the PTI manual to be dependent upon the suction compression index. A method is included in the PTI manual to derive the suction compression index by empirical relationships, which were reportedly developed from data obtained from the National Soil Survey Center.

The unsaturated diffusion coefficient is used to derive the edge moisture variation distance. The suction compression index, coupled with an assumed or measured suction profile, is used to develop the magnitude of movement, y_m. In lieu of charts and graphs within the PTI manual to determine e_m and y_m, the computer program VOLFLO© may be used. A discussion of Volflo and results using the program from two geologic conditions are presented.

Unsaturated Diffusion Coefficient

The unsaturated diffusion coefficient is presented in the PTI manual and is calculated by the following formula.

$$\alpha = 0.0029 - 0.000162(S_s) - 0.0122(\gamma) \quad \text{- where}$$

$$S_s = -20.29 + 0.1555(LL) - 0.117(PI) + 0.0684(\%\text{-}\#200)$$

No specific literature reference was provided in the PTI manual for this derivation.

An exhaustive review of the available literature was not performed; however, research literature regarding the unsaturated diffusion coefficient could not be found. Two of the more popular textbooks on unsaturated soils written by Lu and Likos (2004) and Fredlund and Rahardjo (1993) do not discuss this coefficient.

Conceptually, it is important to evaluate how the above PTI formula was developed. How, for example, is a diffusion coefficient in unsaturated soils even measured? Based on the above formula, it would appear that the rate of movement of water through an unsaturated soil would be inversely related to the suction compression index, i.e., the higher the compression index the lower the diffusion coefficient. Since a higher compression index is also generally associated with a soil with higher activity or plasticity, this relationship would appear to be reasonable for intact soil specimens.

However, consideration must be given to micro versus macro soil behavior if the time rate of moisture flow is being evaluated. This concept can be illustrated by reviewing literature relative to unsaturated permeability. Fredlund and Rahardjo (1993), for example, report that the permeability of an unsaturated soil decreases as the suction increases as shown in Figure 1. This is correct for an intact specimen of soil; however, the field permeability of an unsaturated soil will likely be significantly higher due to an increase in open joints and shrinkage fractures.

Research by Day (1997) indicates the mass permeability of an expansive soil decreases with saturation because of closure of joints and desiccation cracks. Day's results are shown in Figure 2. Jayawickrama and Lytton (1992) reported that the permeability of a compacted soil decreased within saturation. Jayawickrama and Lytton's results are shown in Figure 3.

The above discussion illustrates the variation in permeability relative to the micro versus macro analysis. It is anticipated that derivation of an unsaturated diffusion coefficient should incorporate similar concepts.

Considering the macro perspective, it is anticipated that drying of a soil below a covered surface would result in development of desiccation features below the surface. Opening of a desiccation crack would result in a barrier to movement of moisture from the inboard side of the crack to the perimeter. On the other hand, it is anticipated that as a soil swells, closure of any desiccation features would allow the wetting front to continue movement below a covered surface as long as a source of moisture is available at the perimeter of the covered surface. This simple concept would affect the edge moisture distance for the edge lift condition and must be accounted for if any realistic estimate of a diffusion coefficient is to be obtained.

Suction Compression Index and Development of y_m

The PTI manual defines the suction compression index as "the change in volume related to a change in suction for an intact specimen of soil". Effectively, the procedure consists of determination of a compression index through empirical procedures then use of changes in stress associated with suction to evaluate movement, y_m. The equation basically consists of multiplication of the suction compression index times a "Stress Change Factor". Both of these variables are discussed in the following paragraphs.

Suction Compression Index - Use of the suction compression index (sometimes called compressibility or suction index) to evaluate volume change is not new and has been proposed by numerous authors. Mathematical relationships between the suction compression index (or similar term) and change in suction proposed by Snethen and Johnson (1978), Nelson and Hamberg (1984), Mitchell (1984), and McKeen (1980) were summarized and discussed by Snethen and Huang (1992).

Snethen and Huang compare the recommended compression index/volume change equations published by Nelson and Hamberg, Mitchell, and McKeen for a particular site, using two starting and ending conditions. Predicted movement varied between the three equations from 3.0 inches to 17.2 inches for one assumption and from 2.2 inches to 13.2 inches for Assumption Two. Clearly, a wide range of calculated movement can be obtained, dependent upon the method applied and assumptions relative to the starting and ending points.

With the exception of McKeen, the above authors use actual measured values for the suction compression index. McKeen (1992) presents an empirical linear relationship between the suction compression index, soil activity (Ac) and cation exchange activity (CEAc). (Formulas for calculating Ac and CEAc were provided in the first two editions of the PTI manual.)

Additional discussion of determination of the suction compression index is provided by Perko, Thompson and Nelson (2000). In this paper, they discuss methods for determining the compression index but also evaluate the McKeen linear empirical relationship. They report McKeen's relationship to be reasonable within the mid range of the compression index, but that it is "less dependable at the extremes". The Perko, Thompson and Nelson relationship is shown in Figure 4.

The purpose of the preceding discussion is to illustrate that significant difference of opinion exists relative to development and use of a compression index.

The 3rd Edition of the PTI design manual presents a new empirical relationship to be used to obtain a suction compression index. Development of the relationship was presented by Covar and Lytton (2001) and is based on statistical analysis of soil information from the Soil Survey Laboratory of the National Soil Survey Center. Two graphs are required to obtain the suction compression index. The first graph, a mineral classification chart, categorizes the soil into one of six types based on liquid limit and plasticity index. A zone chart for each the six soil types is then used to obtain the suction compression index. Copies of the mineral classification chart and Zone I and Zone II suction compression charts from the PTI 3rd Edition are provided as Figures 5 through 7.

The PTI 3rd Edition advances the use of the suction/volume change analysis by developing an independent empirical relationship for determination of the suction compression index. This relationship is reported by Covar and Lytton (2001), with the actual statistical analysis performed as a part of Covar's doctorial dissertation. As of June 2008, this dissertation has not been published; therefore, there is no means at present to independently verify this analysis.

To use the PTI procedure, the soil is classified into one of six types (Figure 4) and then an initial raw suction compression index is determined (using Figures 5 or 6 for soils within Zone I or Zone II, for example). This process is required for each stratum. A weighted index is then obtained in a manor similar to the method for determining the effective plasticity index presented in the FHA BRAB (1966) manual. This weighted or modified value is then multiplied by a Stress Change Factor to obtain the appropriate y_m. Discussion of the Stress Change Factor is presented in the following section.

Analysis of Figures 5, 6 and 7 encountered a discontinuity within the procedure in determination of the compression index for soils that plot on the dividing line between the various soil zones. For example, for a soil that plots on a line between Zone I and Zone II, two different suction compression indices are obtained, dependent upon which Zone chart is used. An example of this condition is provided in Table 1. (Values for the x and y axis are plotted on Figures 6 and 7.)

Table 1

LL	PI	-#200	% Clay	Suction Compression Index, Zone I	Suction Compression Index, Zone II
70	50	100	60	0.10	0.15

The formula for calculating y_m is equal to the suction compression index times the Stress Change Factor. Given a 50% increase in the suction compression index, one would obtain a 50% increase in y_m. Obviously, the question is which suction compression index is correct?

Stress Change Factor (SCF) – Various stress change factors are presented in the PTI manual for differing initial and end conditions. No specific discussion is provided in the manual relative to development of the SCF for various conditions. The PTI manual recommends that the computer program VOLFLO© be used to generate the design values of y_m for most stress change conditions.

In lieu of the use of VOLFLO©, SCF values are provided in PTI Tables 3.2 through 3.6 for five different initial and ending values of suction. Table 3.2 provides SCF values for a "typical trumpet shape" suction profile and is not recommended for other types of profiles. Table 3.2 is reproduced for reference as Figure 8.

The trumpet shape suction profile from the PTI manual is shown in Figure 9. More discussion relative to the trumpet shape profile is provided in the VOLFLO© discussion; however, preliminary review of suction profiles within the north Texas region indicate that the trumpet shape profile is more the exception than the rule. The trumpet shape has been observed where a water table is present at a depth of less than 20 feet, and for a short period following the seasonal wet or dry periods of the year where the surface was vegetated with predominately grass or was cultivated. Profiles within geologic formations where shallow rock was encountered (rock within approximately 10 feet of the surface), were typically either completely moist or dry to the full depth after the effect of seasonal rainfall or drying. Uniform drying is also typical where extensive tree cover was present prior to development.

Tables 3.3 through 3.6 provide special SCF values for specific conditions such as Lawn Irrigation, Flower Bed Case, and Tree Drying Cases for both with and without root barriers.

Calculation of y_m for both edge lift and center lift using the described procedures in the manual is relatively simple but very time consuming. Alternatively, and conveniently, a computer program, VOLFLO© is available to relieve the tedium associated with manual computation of the edge variable, y_m. This program is also recommended for suction profiles that do not fit the trumpet shape.

Evaluation of VOLFLO©

VOLFLO© is marketed through Geostructural Tool Kit, Inc. Based on the Geotechnical Tool Kit web site, "Using un-saturated soil mechanics theory, Volflo 1.5 was developed to calculate the shrink and swell capabilities of clay soils." The use of the 3rd Edition of the PTI manual for deriving the y_m values and using the VOLFLO© program were presented by Meyer and Read (2001).

Using the VOLFLO© program is relatively easy and straightforward. The only input values for each strata required are the liquid and plastic limits, percent passing the No. 200 sieve, percent clay fraction and unit dry weight. If the active zone is estimated, suction profiles are not required if the individual doing the analysis wants to use one of the standard design envelopes and the recommended maximum and minimum suction values. The "typical" trumpet shape suction profile is shown in Figure 9.

To evaluate the use of VOLFLO©, two suction profiles were obtained from two geologic conditions; one from relatively deep alluvial clay and the second from shallow residual clay over weathered limestone of the Austin Chalk Formation. The VOLFLO© program was then used to evaluate the magnitude of movement given a trumpet shape profile versus the measured profile. Both suction profiles are from the late summer and represent drier conditions and are considered to be typical for the end of the dry portion of the year. A summary of classification and suction test results for the alluvial deposit and residual Austin Chalk Formation are presented in Tables 2 and 3, respectively. Both tables have two soil layers. In Table 2, the upper layer extends from the surface to a depth of 4-1/2 feet. In Table 3, the upper layer extends from the surface to a depth of 7-1/2 feet. Classification data is shown at the top of the layer.

Table 2. Classification and Suction Data, Alluvial Soil Profile

Depth, ft	Liquid Limit	Plastic Limit	%-#200	Clay Fraction	Suction, pF
1.5 - 3.0	45	17	55	15	3.6
3.0 - 4.5					3.8
4.5 - 6.0	84	30	100	60	3.8
9 - 10					4.5
14 - 15					4.2
19 - 20					4.1

Table 3. Classification and Suction Data, Austin Chalk Profile

Depth, ft	Liquid Limit	Plastic Limit	%-#200	Clay Fraction	Suction, pF
1.5 - 3.0	71	31	100	60	4.3
3.0 - 4.5					4.4
4.5 - 6.0					3.6
9 – 10	48	24	88	35	4.0
14 - 15					3.6

The VOLFLO© program was used to calculate the magnitude of heave using either the above measured profiles or the default trumpet shape. A uniform moist condition of 3.0 pF was used for the end condition in each analysis. The results for both geologic conditions are summarized in Table 4.

Table 4, Summary of VOLFLO© Calculations

Geologic Condition	Potential Heave, inches	
	Trumpet Shape, Dry	Measured Profile
Alluvial Clay	2.55	20.3
Residual Austin Chalk	3.87	6.94

As illustrated in Table 4, it will be critical that anyone using the VOLFLO© program to have a clear understanding of the starting and ending suction profiles.

It should be mentioned that the movement values calculated for the trumpet shape profile exceed the y_m values that would have been developed using the procedures outlined in the 1st and 2nd PTI Editions; therefore, any foundation designed using the new y_m values would be stiffer. Dye, Zapata and Houston (2006) have also reported that using the VOLFLO© program for typical site soil conditions in Phoenix, Arizona, would result in a stiffer foundation relative to one designed using the previous PTI editions. It is unknown if similar results would always be obtained using the VOLFLO© program versus the design procedure in the 1st and 2nd PTI Editions.

However, the VOLFLO© program reports to be an alternative method for prediction of movement, not simply for development of the PTI y_m values. Simply developing "more conservative" PTI stiffness values than the previous method is not a reason to adopt the procedure. Based on the writer's use to date, the VOLFLO© program does not appear to be any more, or any less, accurate for prediction of movement than other empirical methods.

Additional apparent inconsistencies within the VOLFLO© program were also noted. For soil profiles evaluated to date, the magnitude of heave is significantly greater than the magnitude of shrinkage. This implies that for any soil profile, if one was analyzing seasonal movement, a net gain in surface elevation would be obtained each wet dry cycle.

In addition, if an analysis is performed for a soil profile, the magnitude of heave or shrinkage predicted using beginning and ending suction profiles does not equal the sum of calculated heave or shrinkage if the analysis is performed using incremental suction values between the same beginning and ending points. An example of this statement is shown in Figure 10. As noted in Figure 10, 9 % heave is calculated using VOLFLO© for the example soil varying from starting and ending suction values of 5 pF to 3.0 pF (15.1 inches for the 14 foot profile).

If the program is used to calculate heave from 5.0 pF to 4.5 pF, then 4.5 pF to 4.0 pF, then 4.0 pF to 3.5 pF, then 3.5 pF to 3.0 pF, and these calculated values are summed, the magnitude of heave is 2.7 % (4.5 inches for the 14 foot profile). Because the actual equations within the VOLFLO© program are not available for review, it is unknown why this inconsistency occurs, however, it would appear that the value used for the suction compression index varies with the difference between the beginning and ending suction values.

It is also unknown how the VOLFLO© program addresses the apparent discontinuity in the suction compression index when soils plot on a line between two zones. As shown in Table 1, two compression indexes were obtained for a soil plotting on the line between Zone I and II. It is unknown which value of the compression index the program would generate.

Conclusions

Both the PTI manual and VOLFLO© literature indicate that the new procedure is based on an alternative method for prediction of movement in expansive soils. Preliminary investigation indicates that the procedure results in more conservative values of the design parameters, e_m and y_m, to be used for design of stiffened slabs.

For soils that plot on the zone division lines on the PTI mineral classification chart, two separate suction compression indexes varying by a significant amount can be obtained, with the higher index associated with the less plastic zone. Because the compression index is directly related to the edge movement through the stress change factor, this can result in a significant difference in the design y_m value.

Analysis using the VOLFLO© program of two sites in two different geologic conditions, using measured suction profiles, differed significantly from that which would have been predicted using a "trumpet" shape profile. The predicted amount of heave using VOLFLO© and the measured suction profiles were also much greater than historically observed.

Based on studies to date, it would appear that the PTI procedure or VOLFLO© program is not any more reliable predicting expansive soil movement than other readily available empirical methods. It is recommended that additional analysis be performed objectively comparing documented movement versus movement predicted by use of either the PTI or VOLFLO© procedures.

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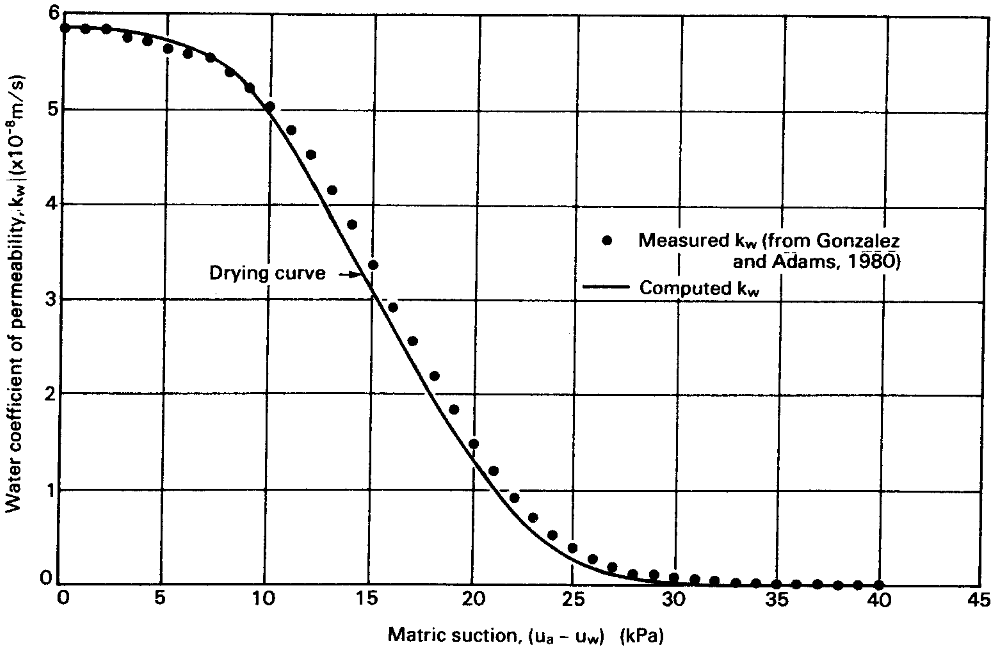


Figure 1 Comparisons between the computed and measured coefficients of permeability. Fredlund, D.G., and Rahardjo, H. (1993)

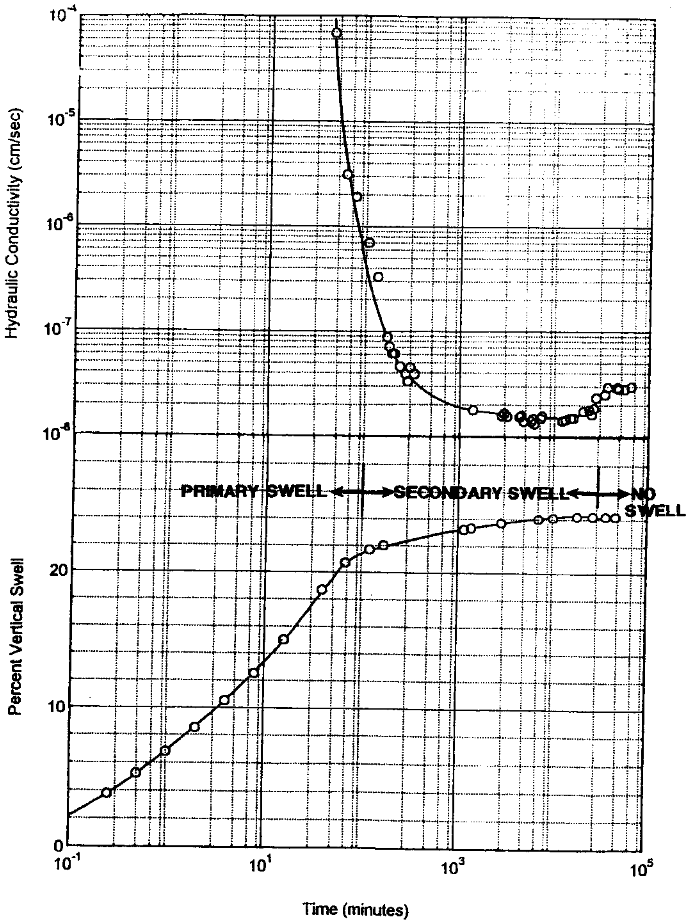
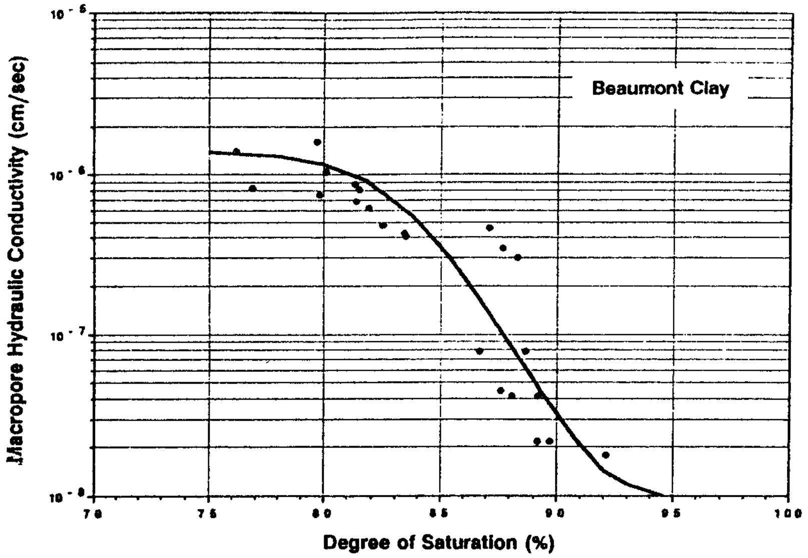


Figure 2 Hydraulic conductivity and percent swell versus time. Day, R.W. (1997)



K_0, S_0, α and γ Parameters

BEAUMONT CLAY	
K_0	1.40 x 10^{-6}
S_0	0.675
α	1.5
γ	4.5

Figure 3 Macropore Hydraulic Conductivity vs. Degree of Saturation (%) Relations for Beaumont Clay Jayawickrama, P.W., and Lytton, R.L. (1992)

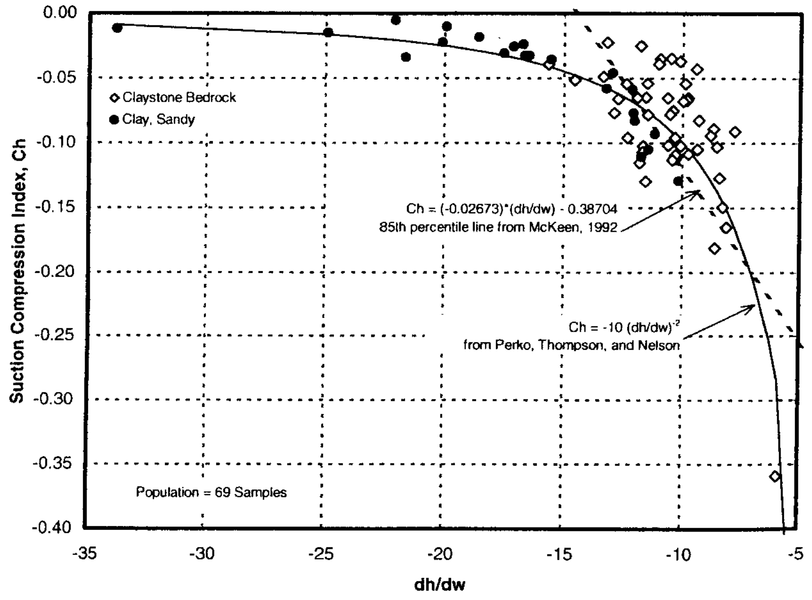


Figure 4 Suction to Water Content Ratio and Suction Compression Index Data From Perko, Thompson & Nelson (2000)

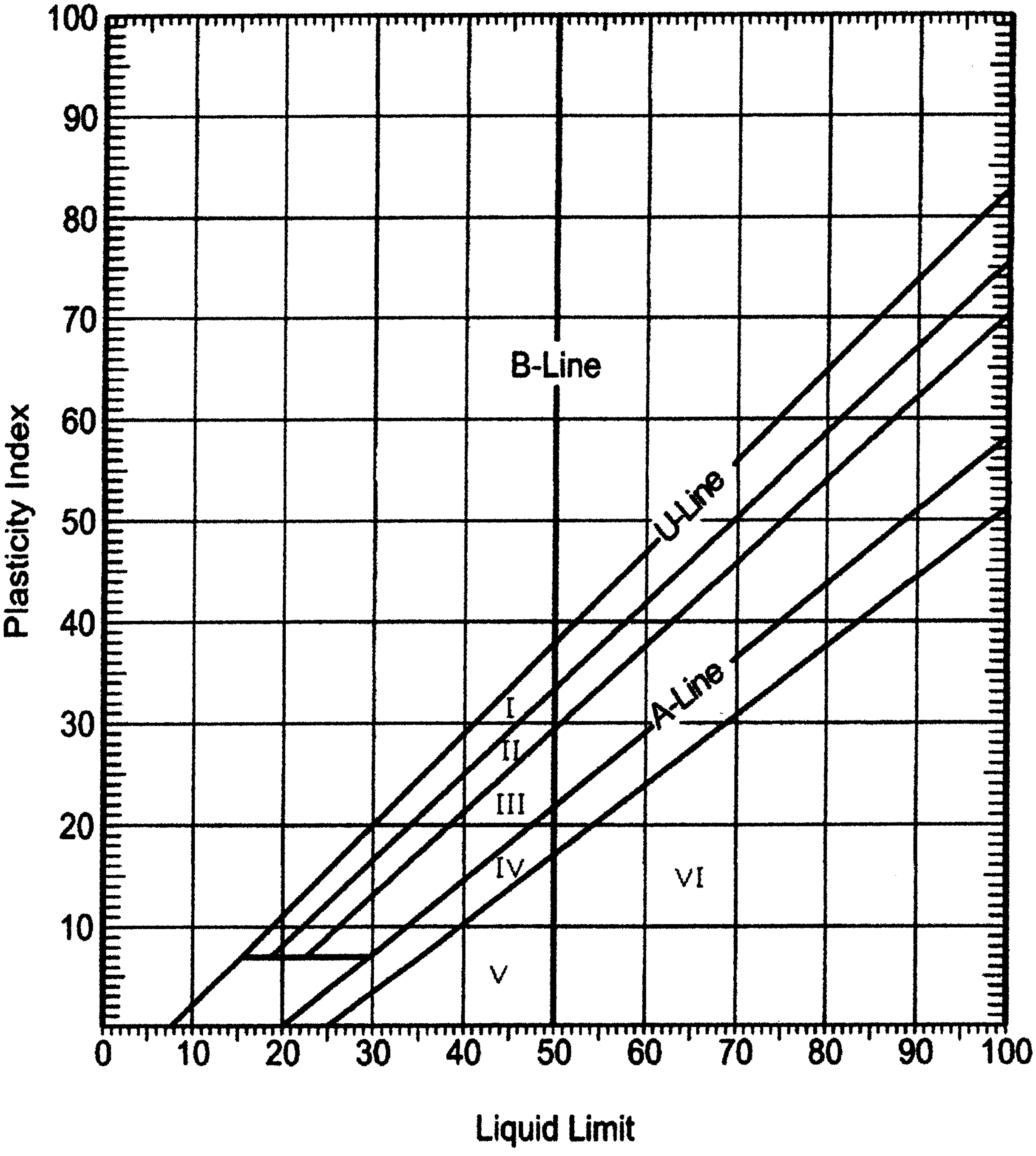


Figure 5 Mineral Classification Chart

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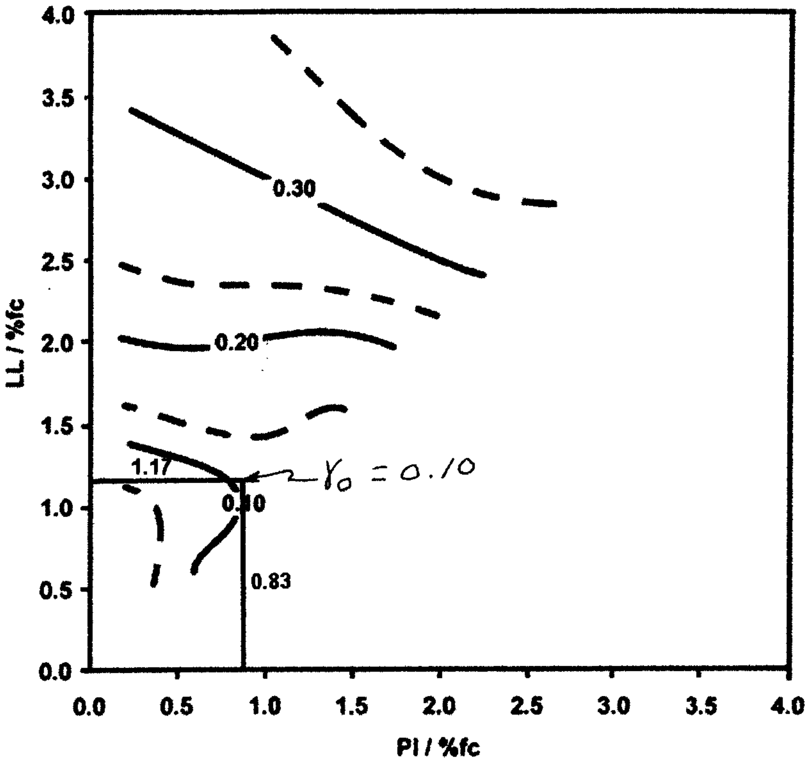

Figure 6 Zone I Chart for Determining γ_0
3rd Edition PTI Manual

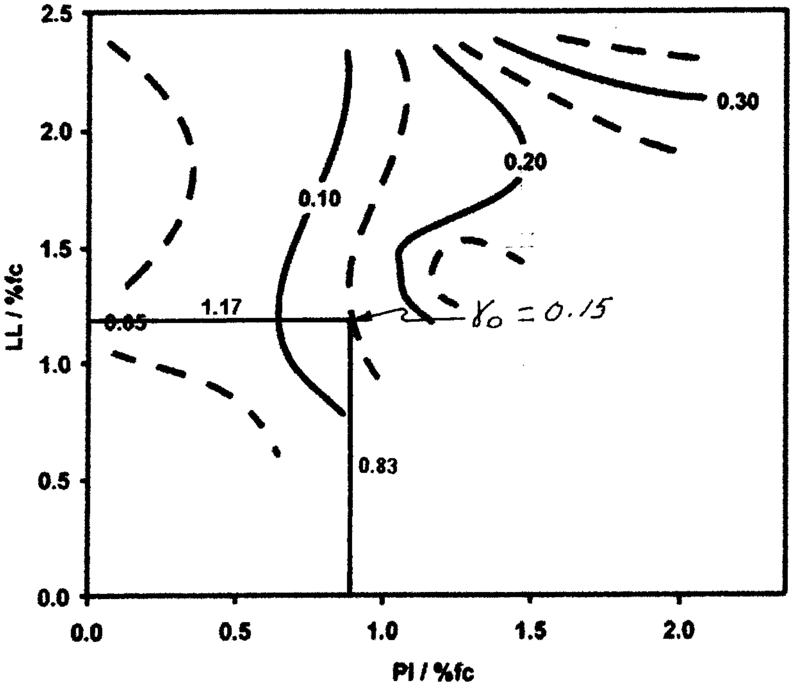

Figure 7 Zone II Chart for Determining γ_0
3rd Edition PTI Manual

Measured Suction (pF) at Depth z_m	Final Controlling Suction At Surface, pF						
	2.5	2.7	3.0	3.5	4.0	4.2	4.5
2.7	+3.2	0	-4.1	-13.6	-25.7	-31.3	-40.0
3.0	+9.6	+5.1	0	-7.5	-18.2	-23.1	-31.3
3.3	+17.7	+12.1	+5.1	-2.6	-11.5	-15.8	-23.1
3.6	+27.1	+20.7	+12.1	+1.6	-5.7	-9.4	-15.8
3.9	+38.1	+30.8	+20.7	+7.3	-1.3	-4.1	-9.4
4.2	+50.4	+42.1	+30.8	+14.8	+3.2	0	-4.1
4.5	+63.6	+54.7	+42.1	+23.9	+9.6	+5.1	0

Figure 8 Stress Change Factor (SCF) for Use in determining y_m
3rd Edition PTI Manual Table 3.2

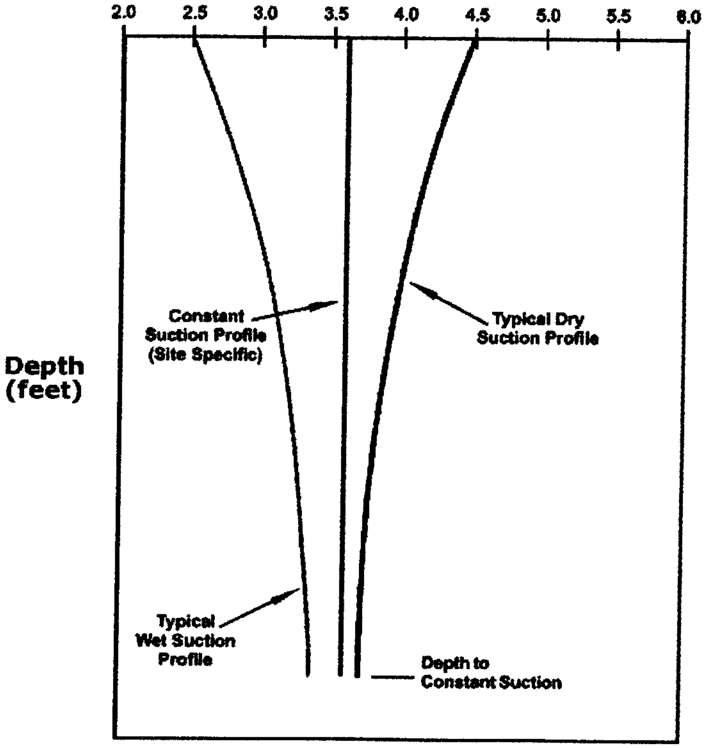

Figure 9 Soil Suction Profiles
3rd Edition PTI Manual

LEGEND

—>——>— ONE INCREMENT

— > — — MULTIPLE INCREMENTS

SOIL PROFILE

14'; LL=68, PL 27; 100% -200; 67% -2μ; Dry Density = 98

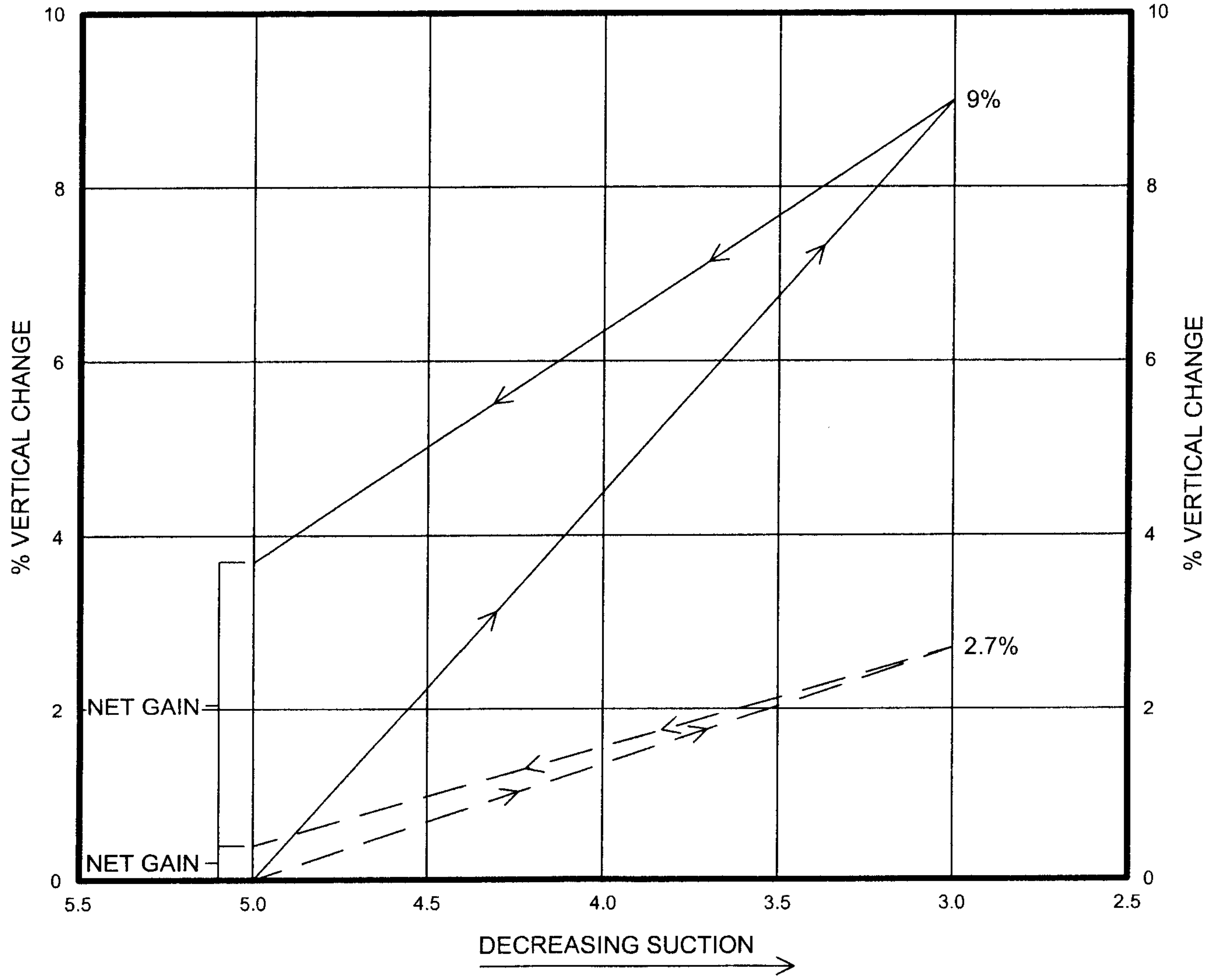

FIGURE 10 CALCULATED MOVEMENT