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PTI DESIGN PROCEDURE, WHY SHOULD WE CARE?

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Abstract

The 3rd Edition of the Post Tensioning Institute's (PTI) design manual is based on a new procedure for development of the soil stiffness parameters. The procedure is based on changes in soil suction, with a recommended "trumpet" shape design envelope. Use of the "trumpet" shape profile reportedly negates measurement of actual suction.

Both the theoretical development of the "trumpet" shape profile and the analysis of statistical data provided by Bryant (2009) are discussed. The PTI foundation stiffness values in two geologic formations using the recommended PTI procedures for edge movement using the recommended "trumpet" shape are shown to be 80% to 1000% less than the calculated edge movement using observed suction profiles. Anticipated legal ramifications of the recommended profile are also discussed.

Historical Perspective

The first edition of the Post Tensioning Institute's (PTI) manual for design of post-tensioned, ground-supported foundations was based on a PhD dissertation by Warren (Kent) Wray (1978). This dissertation and subsequent development of the PTI design procedure significantly advanced the design of ground-supported slabs.

Wray (1978, pg. 55) identified three soil parameters affecting slab behavior: "(1) the swelling soil profile beneath the slab; (2) the differential soil movement; and (3) the edge moisture variation distance."

Based on a study by Tucker and Poor (1973) of the foundation shape of 69, 9- to 17-year old residential foundations in Arlington, Texas, Wray (1978, pg. 59) concluded that the long-term shape of a ground-supported slab is "center lift". He also concluded that edge lift is a short-term condition associated with seasonal changes in soil moisture.

Unfortunately, the geologic setting of the residences in the Tucker and Poor study was not included in the analysis. The residences studied by Tucker and Poor are underlain by a moderately thick layer of highly plastic clay alluvium which is underlain by weathered shale of the Eagle Ford Group. The site is also near the surface exposure of the geologic contact with the underlying Woodbine Formation. Ground water is present throughout the year at depths varying from 10 to 20 feet below grade. The presence of the shallow ground water directly impacts the long-term shape of the foundation by wetting any dry soils which may be present below the center of the slab.

After relatively wide spread application of the PTI design procedure in North Texas in the early to mid 1980's, significant distress was noted in residences where the foundation was subject to edge lift conditions. Antidotal information indicated the foundations were not stiff enough in the edge lift mode to limit angular rotation to the tolerances of the superstructure. In other words, the foundations exhibited excessive differential deflection over too short of a span. A disproportionate amount of distress was observed even in structures subject to only one to two inches of edge lift.

During this same period, significant expansion of the residential market in the Dallas/North Texas area occurred in areas underlain by weathered shales, most notably the Eagle Ford Group and Ozan Formation. The developments were typically in hilly terrain, frequently covered with mature mesquite trees. Cuts associated with pad development resulted in exposure of dry, very expansive weathered shale.

By the late 1980's and early 1990's, measured differential foundation movements in the edge lift mode of 6 to as much as 14 inches was recorded in residual soils of both the Eagle Ford and Ozan Formations. The amount of distress and costs associated with foundation repair lead to development of a cottage industry for trial lawyers. The cost of litigation and repairs also directly lead to the demise of Home Owners Warranty Corporation, which at the time was one of the largest home warranty companies in the country. The magnitude of distress was so severe in Texas that in 1990, the Denver office of the U.S. Department of Housing and Urban Development (HUD) launched an investigation relative to the continued use of the PTI design procedure. The results of this investigation were summarized by Sazinski (1992).

Analysis of the shape of the distressed foundations within the Eagle Ford and Ozan Formations indicated the mode of movement was associated with edge lift, and the edge lift condition is not a simple "seasonal" effect, but rather associated with long-term gain in elevation along the perimeter of the foundation as the perimeter soils gained moisture. The "long" term condition may in fact be a "center" lift condition; however, if it takes 10 to 20 years or more for the wetting front and heave to progress from the perimeter to the interior, it would not be viewed as a "short" term condition for most home owners.

The general response of the practicing geotechnical engineers in the North Texas area to the explosion of litigation was to substantially increase the PTI design stiffness numbers relative to the recommended values in the PTI design manual. Within the last 10 years, the geotechnical community in North Texas also began the wide spread use of pre-swelling techniques to reduce the magnitude of heave prior to construction of the foundation. Most geotechnical engineers will attempt to reduce the magnitude of heave to approximately four inches; however, a significant void exists in the community as to an acceptable analysis procedure to arrive at this target movement. There also currently does not appear to be uniform agreement that any slab can withstand four inches of differential heave.

Fast forward to 2004 and introduction of the 3rd Edition of the PTI design procedure, with "required" use of the procedure in January 2008. The procedure has radically changed the method for development of the required stiffness variables, differential soil movement, y_m, and edge moisture variation distance, e_m.

The purpose of the following discussion is to evaluate part of the theory on which the new procedure is based and shed light on some of the possible legal ramifications.

Review of PTI Discussion

In general, the new procedure for development of the magnitude of movement at the foundation edge, y_m, involves multiplication of a "suction compression index" by a "Stress Change Factor". The suction compression index is obtained from charts within the PTI manual using classification tests. The Stress Change Factor is based on the estimated change in the initial versus final suction profile.

In lieu of using the suction compression index charts and Stress Change Factors provided in the PTI manual, the computer program VOLFLO© may be used to evaluate both the edge moisture variation distance and the magnitude of movement. The program requires input of classification data and estimated beginning and ending soil suction profiles, hence, these profiles become an integral part of the analysis procedure.

Papers in the Texas Section ASCE Forum have been presented by both Reed (2008) and Bryant (2009) addressing various aspects of the PTI 3rd Edition design procedure. Discussions in those papers will not be rehashed in total. The focus of the following is to evaluate the Bryant response to questions regarding moisture flow and determination of the appropriate suction profile.

Moisture Flow in Unsaturated Soil

General - Movement of water in unsaturated soil is a complex problem, principally because of changes in the degree of saturation. For dry, coarse-grained soils, where water is stored in isolated pockets, movement of water occurs principally as water vapor associated with pore airflow. As the soil becomes more saturated, and isolated pockets of water begin to connect, moisture flow occurs both as pore water and as pore air (vapor). As saturation is approached and the air pockets become isolated, the principal movement is associated with pore fluid. Thus, there are two governing analysis procedures, one for pore airflow and one for pore water flow. The range of saturation over which both types of flow occurs varies with the soil type. For very coarse-grained soils, sands and gravels, the principal movement of moisture occurs in vapor phase until near saturation. For fine-grained soils, the majority of movement of water is associated with pore water flow over a relatively wide range of saturation.

The complicating issue for analysis of pore water flow at any level below full saturation is that the hydraulic conductivity varies with the degree of saturation, or more specifically, with matrix suction. For coarse-grained soils, the degree of variation is not significant. For fine-grained soils, the variation in conductivity is significant, varying frequently by two to three orders of magnitude.

Vapor transport via pore airflow can be evaluated by use of Fick's Law. This analysis procedure can be found in Lu and Likos (2004, Page 359). However, as mentioned above, this procedure is relevant for fine-grained soils over a relatively small range of saturation at very low moisture contents. For clay, it is estimated the degree of saturation would have to fall below 25 percent for pore airflow to dominate moisture migration. The balance of any moisture migration into or out of a fine-grained soil would involve pore water flow and the analysis would have to integrate the variation in permeability with changes in suction.

Fluid Flow, Saturated Conditions – The flow of fluid in terms of hydraulic conductivity and hydraulic gradient is defined by Darcy's Law as shown in (1).

$$q_x = -k_s \frac{\partial h}{\partial x} \quad q_y = -k_y \frac{\partial h}{\partial y} \quad q_z = -k_z \frac{\partial h}{\partial z} \qquad (1)$$

For isotropic, homogeneous conditions, these equations reduce to:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = \frac{S_s}{k} \frac{\partial h}{\partial t} \qquad (2)$$

If hydraulic diffusivity, D, is defined as hydraulic conductivity, k, divided by the specific storage, S_s, equation (2) reduces to the standard diffusion equation for <u>saturate</u>d soils as shown below.

$$D\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2}\right) = \frac{\partial h}{\partial t} \qquad (3)$$

Unsaturated Soils – In unsaturated soils, the hydraulic conductivity varies with the degree of saturation, or more specifically, with the suction head. The governing equation, in the "x" dimension, is shown below.

$$q_x = -k_x(h_m) \frac{\partial h}{\partial x} \qquad (4)$$

Equations (1) and (4) are similar in form with the exception of the additional term, h_m, the matric suction head.

Equation (4) was solved by Richards (1931) in the following form, where C is defined as the specific moisture capacity, which is the slope of the soil-water characteristic curve.

$$\frac{\partial}{\partial x}\left[k_x(h_m)\frac{\partial h_m}{\partial x}\right]+\frac{\partial}{\partial y}\left[k_y(h_m)\frac{\partial h_m}{\partial y}\right]+\frac{\partial}{\partial z}\left[k_z(h_m)\left(\frac{\partial h_m}{\partial z}+1\right)\right]=C(h_m)\frac{\partial h_m}{\partial t} \quad (5)$$

This equation can be used to solve for the suction field in space and time (Lu and Likos, 2004). An example of use of Equation (5) by Lu and LeCain (2003) is presented in a subsequent section.

To arrive at an analytical solution, Bryant (2009) used Equation (3), substituting an unsaturated diffusion coefficient, α, for the hydraulic diffusivity as shown in Equation (6). Bryant indicates that the concept of the unsaturated diffusion coefficient is discussed within a paper by Bulut, Aubeny and Lytton (2005). Bryant states that the method for measuring the unsaturated diffusion coefficient is also presented in the same paper.

$$\frac{\partial P}{\partial t}=\alpha\frac{\partial^2 P}{\partial x^2} \quad (6)$$

Equation (6), with soil suction, u, substituted for P was reportedly solved by Mitchell (Ref.) and apparently further solved by Bulut, Aubeny and Lytton to arrive at a governing equation for modeling a suction profile. To date, the writer has not been able to obtain and review a copy of either the Bulut, Aubeny and Lytton or Mitchell papers. The equation shown by Bryant is provided below.

$$u(x,t) = u_c+\sum_{n=1}^{\infty}\frac{2(u_0-u_a)\sin z_n}{z_n+\sin z_n\cos z_n}\exp\left[\frac{z_n{}^2\alpha t}{L^2}\right]\cos\left[\frac{z_n{}^x}{L}\right] \quad (7)$$

The analytic solution to Equation (7) reportedly results in the bell or trumpet shape suction profiles recommended within the PTI design manual. The recommended curves shown by Bryant (2009) are reproduced in Figure 1.

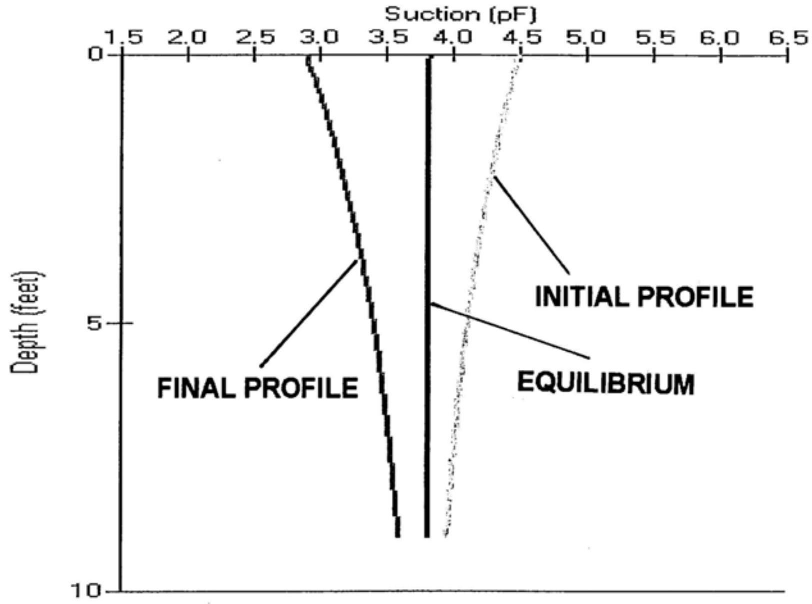

Figure 1. Moisture envelopes bell or trumpet shaped after Mitchell's (1979) solution to the diffusion equation for unsaturated soils for the post-construction edge lift mode. (from Bryant (2009))

As indicated above, an alternative mathematical model of the transient matric suction profile has been developed by Lu and Likos (2004). Derivation of the required model is beyond the scope of this paper. The general analysis procedure was applied by Lu and LeCain (2003) to a relatively thick layer of alluvium overlying fractured rock. The analysis attempted to model the effects of varying rainfall events on the degree of saturation during a period from December 1997 through February 1999. One of their plotted results is provided in Figure 2 for reference.

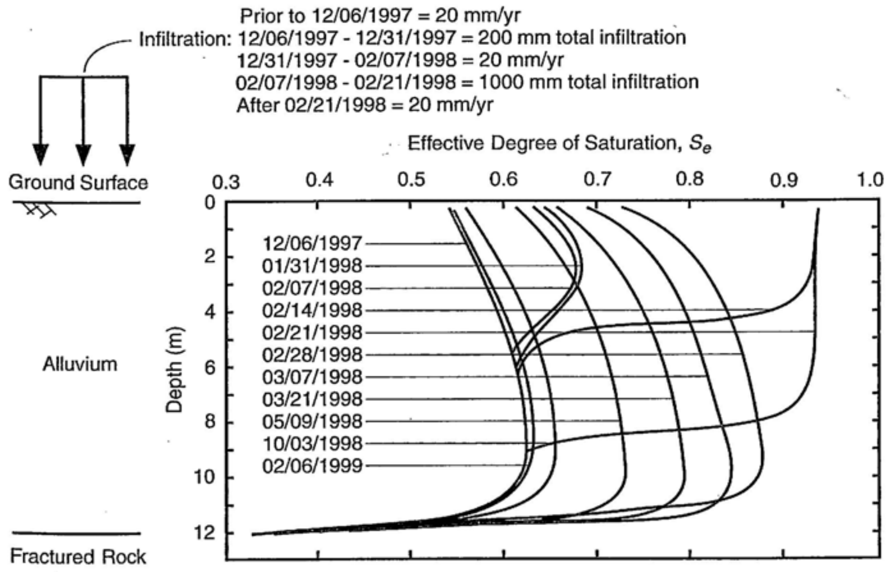

Figure 2. Effective degree of saturation profiles modeled using integrated finite-difference method for 12-m-thick alluvium deposit. Saturation profiles show effects of two separated precipitation events simulated during 1998 El Niño year (Lu and LeCain, 2003).

It is reasonable to anticipate that the transient matric suction profile would be mirror images of the unsaturated profile, with high saturation being associated with low suction. As noted in Figure 2, the shape of the matric suction profile would be significantly different than the bell or trumpet shape profile developed by Bryant.

Comparison of Models with Reported Suction Data

Bryant (2009) stated that:

> "As one can see from Figures 2 and 3, (*reproduced here as Figures 1 and 3*) the shape of these curves approaches the bell-shape. The implications of theses (sic) analysis are that theory of diffusion would predict with one stroke, what thousands of experiments would eventually predict, viz. that moisture diffusion into the ground from climatic influence follows the Gaussian distribution, and therefore the change in suction for design and analysis using the trumpet or bell shaped curve is not only reasonable, but a fact of nature."

As part of Bryant's discussion, he offered the data set shown in Figure 3.

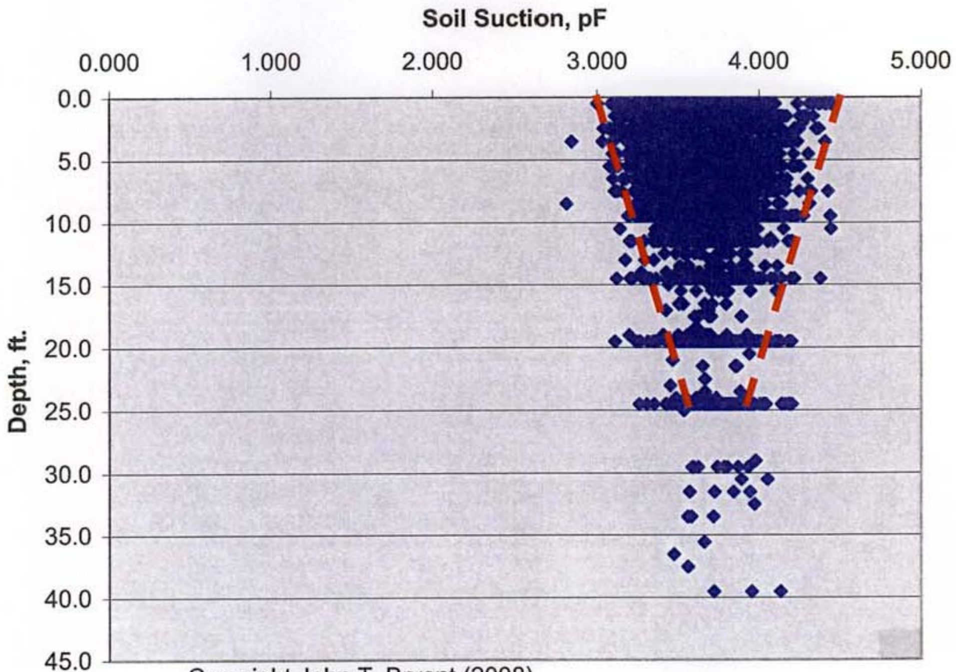

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Figure 3. Triangle (bell-shaped) suction distribution consistent with theory. (From Bryant (2009).

Superimposing Figures 1 and 3 results in Figure 4. As noted in Figure 4, the vast majority of suction data reported by Bryant do not plot within the reported "fact of nature" and diffusion theory curves. Analysis of Figure 4 also clearly indicates that measured suction can vary significantly from the recommended design curves.

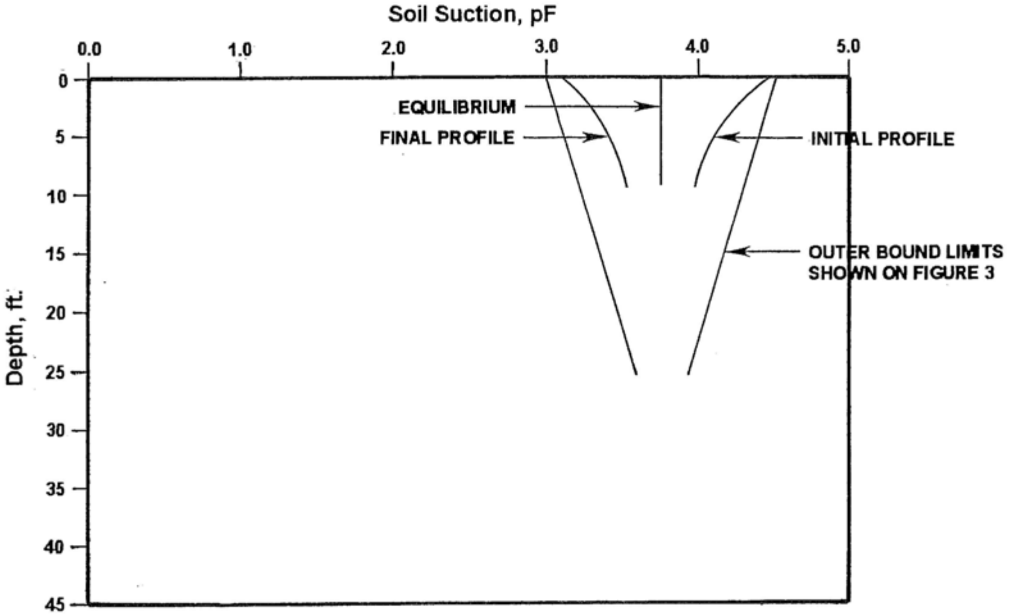

Figure 4. Plot of design suction curves (Figure 1) on boundary outline of statistical data shown in Figure 3.

It is also important to note that the data set shown in Figure 3 would plot within the estimated transient suction profiles shown in Figure 2. The data set shown in Figure 3 also are in agreement with profiles measured by the writer and presented in papers in 2009 (Reed, 2009). It appears the more rigorous mathematical model shown in Equation (5) is significantly more accurate than the model developed in Equation (7).

Why Does it Matter

The magnitude of difference between edge lift movements using trumpet-shape suction curves versus actually measured suction profiles can be significant.

Suction profiles were measured in two geologic settings: 1) relatively deep alluvial clay; and 2) 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 measured suction profiles are from the late summer and represent drier conditions. They 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 1 and 2, respectively. Both tables have two soil layers. In Table 1, the upper layer extends from the surface to a depth of 4-1/2 feet. In Table 2, 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 1. 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 2. 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 edge lift using either the above measured profiles or the default trumpet shape. For comparison purposes, a uniform moist condition of 3.0 pF was used for the end condition in each analysis. The results for both geologic settings are summarized in Table 3.

Table 3, Summary of VOLFLO© Calculations		
Geologic Condition	Design Edge Lift, inches	
	Trumpet Shape, Dry	Measured Profile
Alluvial Clay	2.55	20.3
Residual Austin Chalk	3.87	6.94

Clearly, there is a significant difference in the design edge lift numbers illustrated in Table 3. Which numbers are correct? Or, is some number in between these values correct?

Possible Legal Ramifications

It has been the writer's experience to date that the 3rd Edition PTI procedure for development of the required design slab stiffness variables using the recommended trumpet shape suction profile has resulted generally, but not always, in stiffer variables than those that would have been developed using the procedure in the 1st or 2nd Editions. Dye, Zapata, and Houston (2006) indicated that, for soil conditions in Arizona, the new procedure resulted in stiffer foundations.

However, the question is not, will trumpet-shape design suction envelops develop stiffer design variables than the previous method, but rather, are they correct? If measured suction values as shown by Figure 3 exist, as they apparently do, is the trumpet-shape suction envelope as recommended really applicable?

Where will the design engineer stand from the perspective of legal liability if he or she uses the recommended trumpet-shape suction profiles, and some "expert" later claims it was the wrong profile and thus the foundation is not rigid enough for the conditions? By not even measuring the suction profile, as inferred by Bryant (2009), how can the design geotechnical engineer say they used "engineering judgment" in deciding which profile to use?

It is also anticipated that, "blind" obedience to the concept that the "change in suction for design and analysis using the trumpet or bell shaped curve is not only reasonable, but a fact of nature" will result in an inability to recognize outlying or unusual conditions. Surely, if the suction test results shown in Figure 3 exist outside the bell- or trumpet-shape suction curves, then conditions must exist where the theory is not valid.

Conclusions

The theory of moisture flow through unsaturated soils is relatively complex but has been defined by various researchers, to include Lu and Likos (2004). Analytical solutions to their basic equations for analysis of degree of saturation and soil suction, would result in envelopes which would encompass all of the data points reported by Bryant (2009).

It is clear from the data points shown in Figure 3 that all suction profiles do not adhere to bell- or trumpet-shape profiles within the confines shown in Figure 1. Verbally, Bryant stated at the Fall 2009 Texas ASCE Section meeting in Houston that he reported all of his historical data points, not simply the ones subject to seasonal moisture changes. It is an interesting statement, since apparently one can distinguish which suction tests are associated with seasonal changes and those which are associated with some other environmental condition.

The initial PTI design procedure was introduced in the late 1970's. Many practicing engineers at the time raised various questions and concerns about the procedure, which were routinely ignored by the PTI Committee. From the writer's perspective, it feels like déjà vu. Hopefully, this time around, the trial lawyers do not have another field day at the expense of the geotechnical engineering community.

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