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# OBSERVED SOIL SUCTION PROFILES WITHIN NORTH TEXAS

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## Abstract

The Post Tensioning Institute's (PTI's) 3rd Edition design manual requires use of either measured or estimated suction profiles to calculate edge movement, $y_m$ and the edge moisture variation distance, $e_m$. Understanding both pre- and post-construction suction profiles is therefore critical to estimating correct $y_m$ and $e_m$ design values.

Common suction profiles (described as uniformly moist or dry, "p", "b", trapezoidal, and trumpet shape) measured within the North Texas area are presented. Profiles include site geologic conditions, laboratory classification data and sampling date to account for prevailing weather.

The PTI manual recommends use of the "trumpet" shape suction envelope for evaluating edge movement design values. The values of $y_m$ and $e_m$ calculated using the PTI recommended program VOLFLO© are compared using both measured profiles and the trumpet shape envelope.

Based on research to date, the trumpet shape appears to be more atypical than typical. Other than at selected times of the year or within specific geologic settings, this shape may not be applicable for design.

## Introduction

The PTI 3rd Edition design manual utilizes measured or estimated suction profiles to calculate edge movement, $y_m$ and the edge moisture variation distance, $e_m$. Understanding suction profiles is therefore critical to evaluating the effectiveness of this procedure.

Reed Engineering Group, Ltd. has been measuring suction profiles within the North Texas area for over 15 years. To date, suction profiles have been developed on over 8,000 projects in a wide variety of geologic settings and climatic conditions. Six representative samples of profiles measured from February 1996 through September 2007 are presented. This period represents a change in the Thornthwaite Climatic Index[1] of

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[1] Thornthwaite, C.W. (1948). "An Approach Toward a Rational Classification of Climate." Geographical Review, 38(1), 54-94.

approximately -14 to +17 inches and is believed representative of the typical weather pattern in North Texas. A summary of the calculated Thornthwaite Index (TI) for the period of 1974 through 1999 is provided in Figure 1.

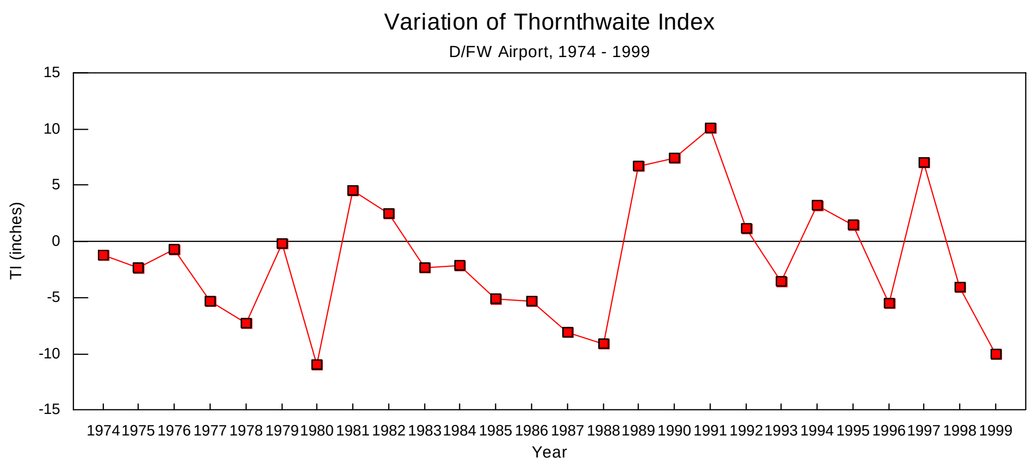


Figure 1. Calculated TI for 1974 through 1999.

The “typical” pattern of rainfall within the North Texas region consists of moderate to extended rainfall from February through early June, generally dry during July through early October, then moderate during the balance of October through January. The average monthly rainfall for the Dallas area is presented in Figure 2. Analysis of Figure 2 indicates the average rainfall for July and August is 2 to 2-1/2 inches. This rainfall typically occurs in one or two events and because of prevailing high temperatures, evaporates relatively rapidly.

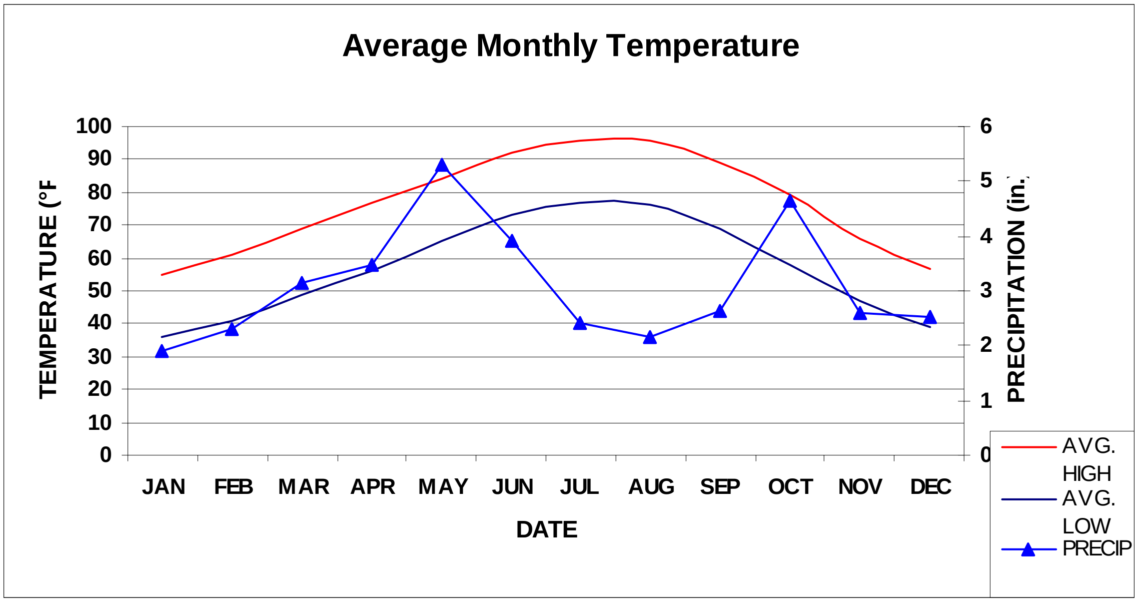


Figure 2. Average monthly maximum and minimum temperatures and rainfall based on Dallas/Fort Worth Airport.

Six studies are presented to provide a variation in both the geologic setting and prevailing weather. Studies were initially screened based on analysis of the prevailing weather, then screened considering the geologic setting. The purpose of the second reduction in the number of case studies was to limit the number of studies in similar geologic settings. Approximately 35 projects were reviewed. These 35 were then reduced to 6 as representative of the variation in observed suction profiles.

Since the studies are from historical data, the profiles are on different sites and do not represent continuous or intermittent data on a particular site. However, based on observation of historical profiles over a 15-year period, they are believed to be representative of the natural changes which occur on any particular site.

The profiles have been "named" relative to the prevailing shape. These include "uniform" (either wet or dry), "p", "b", "trapezoidal" and "trumpet". The case studies are provided to illustrate the uniform, trapezoidal and trumpet shapes. The "b" and "p" are considered to be variations in the trapezoidal shape. The case studies include site geologic conditions, prevailing weather and measured suction.

All suction test results were determined by use of filter paper in accordance with ASTM D 5298. Total suction is reported. No attempt has been made to date to separate osmotic from matric suction.

**Geologic Setting**

The locations of the six case studies are shown in Figure 3 superimposed on the Dallas and Sherman Sheets of the Geologic Atlas of Texas produced by the Bureau of Economic Geology, The University of Texas at Austin.

A summary of the geologic settings for each case study is provided in Table 1.

| Case Study | Geologic Setting |
|---|---|
| 1 | Alluvial Clay |
| 2 | Residual Soil of the Marlbrook Marl |
| 3 | Residual Clay of the Austin Chalk |
| 4 | Residual Clay of the Eagle Ford Shale |
| 5 | Austin Chalk West of Contact with Taylor Marl |
| 6 | Taylor Marl East of Contact with Austin Chalk |

Table 1. Summary of Geologic Settings.

More discussion on each study is provided in the following sections.

**Case Studies**

**Case Study 1 -** This study is located on relatively deep alluvial CH clay deposits. The clays are generally dark brown becoming brown to yellowish-brown below depths of 8 to 12 feet. Ground water was not encountered during the study, although typically, it is present at depths of 25 to 30 feet, varying with seasonal and yearly rainfall.

Sampling was performed in mid-December 1996. The daily mean temperature and rainfall for the period of August 1996 through December 1996 is provided in Figure 4.

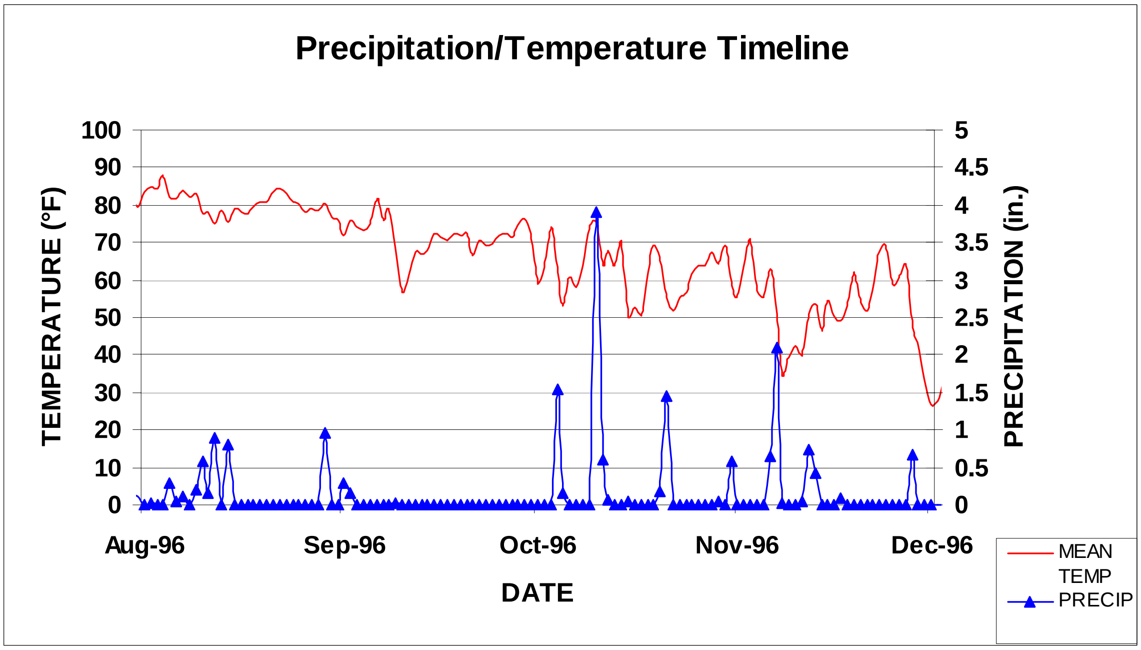


Figure 4. Temperature and daily rainfall for Case Study 1.

As noted in Figure 4, prevailing weather through the summer of 1996 was relatively dry, with limited rainfall beginning in October and November.

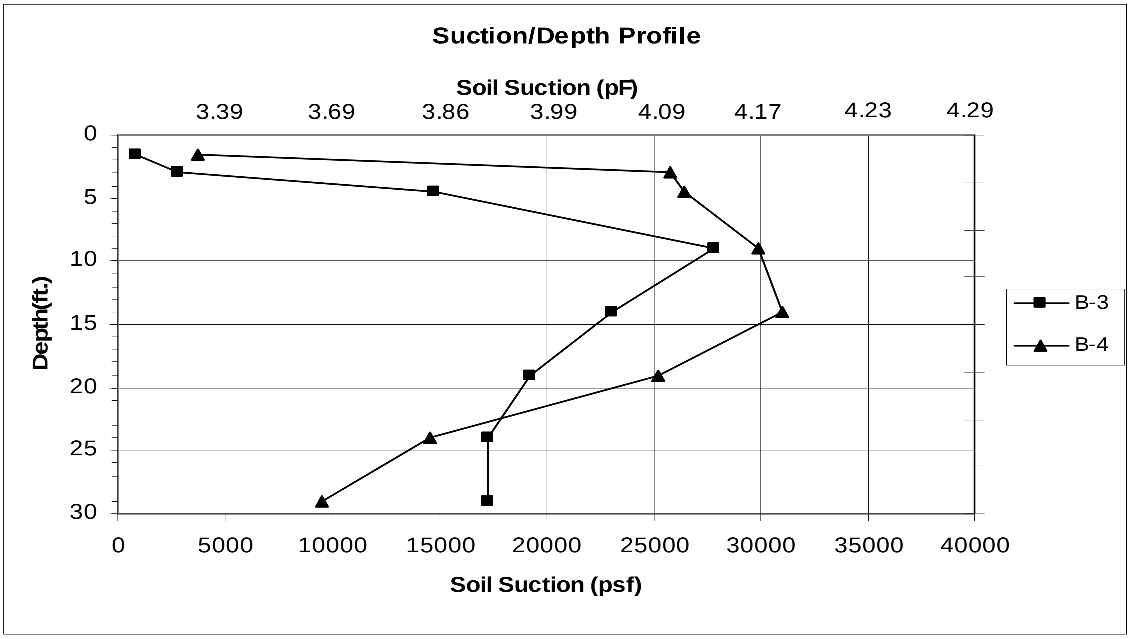


Figure 5. Trapezoidal shape. Case 1.

This pattern of weather can be observed in the suction profile shown in Figure 5. This profile is labeled as “trapezoidal” since the upper soils are gaining moisture and the suction values decrease with depth. This pattern is observed following extended dry weather as the upper soils become moist with the beginning of seasonal rainfall. As the yearly pattern of seasonal rainfall extends into early to late spring, the depth of wetting will increase. As the depth of wetting increases from the surface down, the shape typically will morph into a “b”.

**Case Study 2 -** Study 2 is considered representative of seasonally active sites following seasonal rainfall going into the drier portion of the year.

The site is underlain by CH clay derived from the Marlbrook Marl Formation. The clay is generally dark brown near the surface becoming olive to olive-gray with depth. Soils below a depth of approximately five feet have iron-stained joints and fissures characteristic of weathered marl. Ground water was located at an approximate depth of 12 feet. Based on experience, ground water in the vicinity is generally encountered at depths of 10 to 15 feet throughout the year.

Sampling was performed in early August 1997. Mean temperature and daily rainfall for April through August, 1997 is shown in Figure 6.

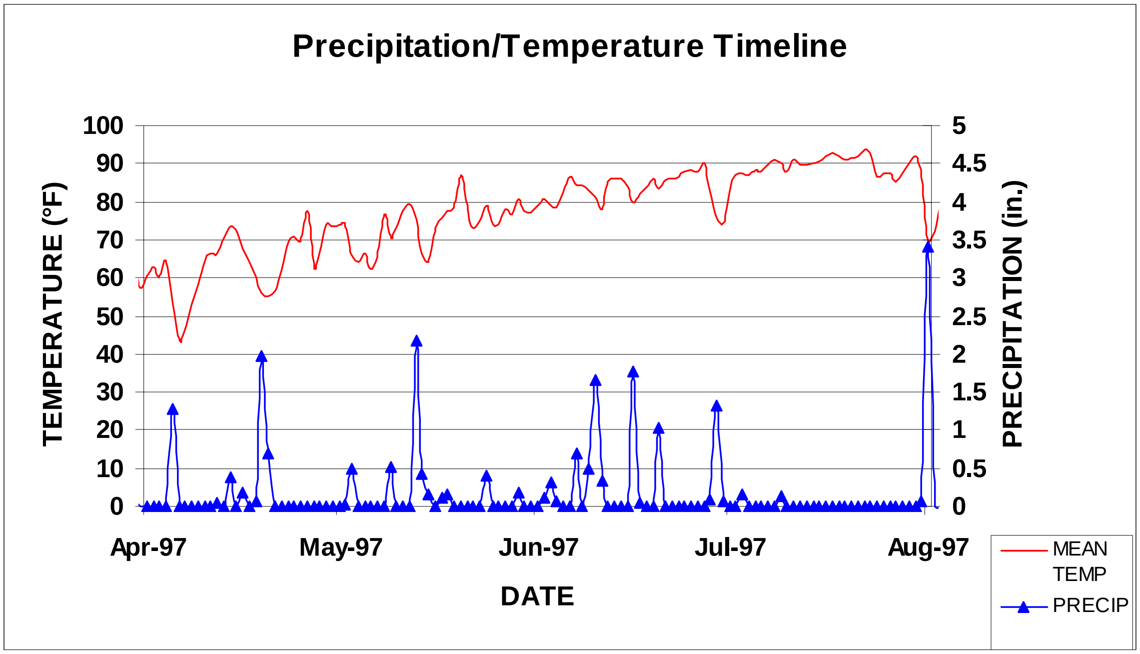


Figure 6.  Precipitation and mean temperature for Case Study 2.

As noted in Figure 6, moderate rainfall occurred through the first week of July, 1997, followed by the typical pattern of no rainfall through the balance of July and August. This high moisture followed with approximately eight weeks of drying resulted in a "trumpet" shape observed in Figure 7.

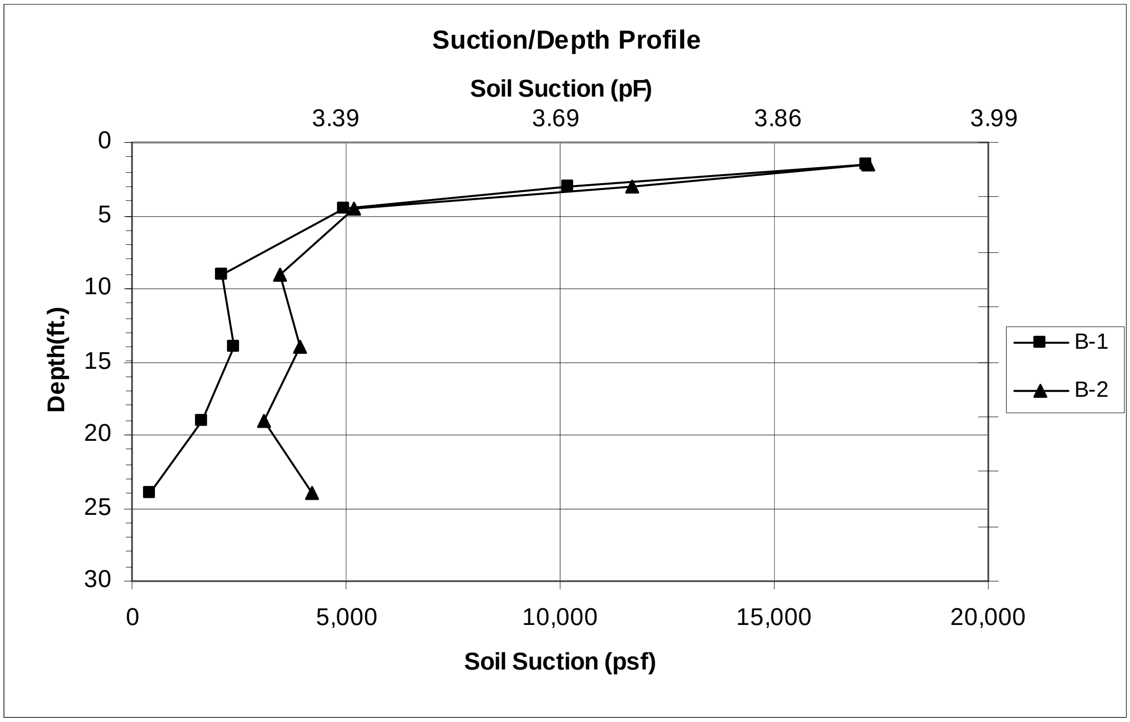


Figure 7. Suction profiles for Case Study 2.

As the surface dries, the "hinge point" of the trumpet shape will extend to a greater depth, with the depth dependent upon the prevailing weather in any particular year. Because of the presence of relatively shallow ground water, it is not anticipated that any significant drying would be observed below a depth of approximately 8 to 10 feet. It has also been observed that as the surface dries to near the maximum suction, the depth of the zone of maximum suction will extend to greater depths, resulting in a "p" shaped suction profile.

**Case Study 3 –** This case study is considered to be characteristic of a uniformly dry condition. This is a typical profile observed in geologic formations where relatively shallow rock is present and the site is subject to extensive drying weather.

Subsurface conditions consisted of residual soils of the Austin Chalk Formation. The soil profile consists of CH clay to a depth of 8 feet over severely weathered limestone or CL calcareous clay to a depth of 10 feet. Weathered grading to unweathered limestone was encountered below 10 feet.

The site was sampled in early November 2004 following a prolonged dry climatic period. The climatic condition is noted in Figure 8. Note that two rainfall events of approximately three inches occurred in early August and October. It is anticipated that the majority of this rainfall resulted in runoff.

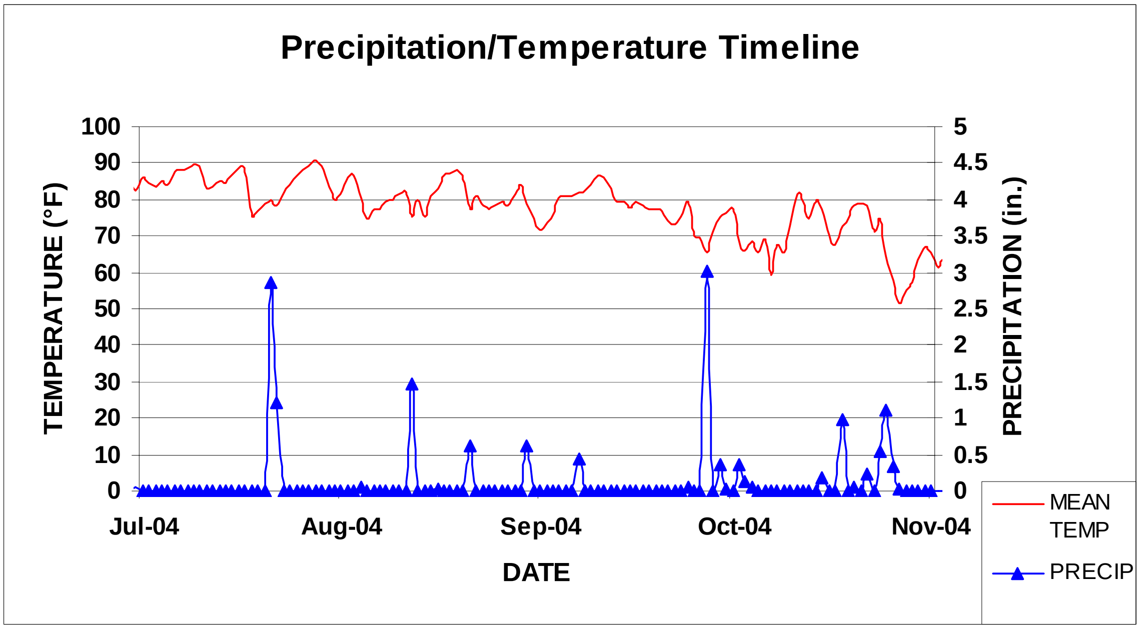


Figure 8. Precipitation and mean temperature for Case Study 3.

The measured suction profile is shown in Figure 9. Although this profile may appear to be similar to the trumpet shape in Figure 6, it should be noted that the suction at nine feet is equivalent to 4.2 pF with the maximum suction of 4.6 occurring at a depth of 3 feet.

Although the shape is somewhat trumpet, it is extremely dry. Suction profiles on nearby sites with similar geologic conditions were noted to be uniformly moist to the top of rock after periods of extended rainfall.

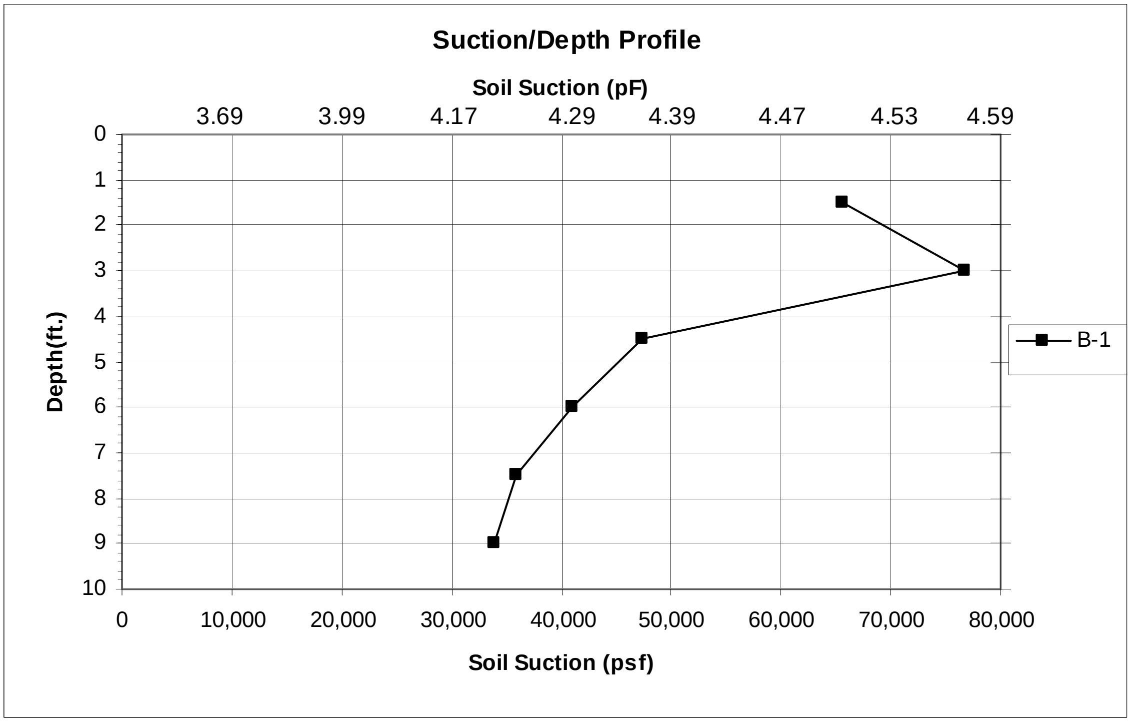


Figure 9. Measured suction profile for Case Study 3.

**Case Study 4 –** This study is an example of relatively dry conditions within residual soils of the Eagle Ford Group. The site was sampled in early July 2005. Subsurface conditions consist of approximately three to five feet of alluvial sandy clay over severely weathered shale dual classified as olive to olive-yellow CH clay. The clay (severely weathered shale) is hard and has extensive secondary joints and fissures that are iron-stained. Ground water was not present at the time of the investigation and is generally not present in any appreciable quantities.

Within the North Texas region, 2005 was an extremely dry year, with a total recorded rainfall approximately 16 inches below normal. Recorded mean temperature and rainfall is provided in Figure 10.

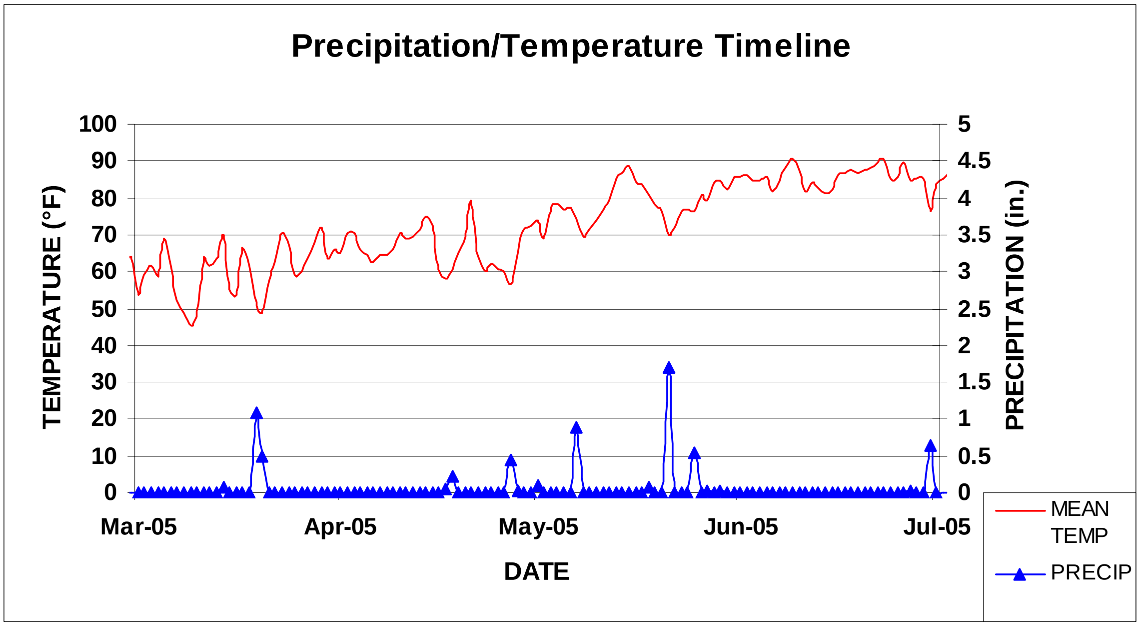


Figure 10. Rainfall and mean temperature for Case Study 4.

The measured suction profile is provided in Figure 11. The site was also covered with scattered medium size mesquite trees. Sites with mesquite typically exhibit extremely low moisture and high suction. It is anticipated that the extreme dry weather coupled with the presence of mesquite resulted in a relatively dry profile.

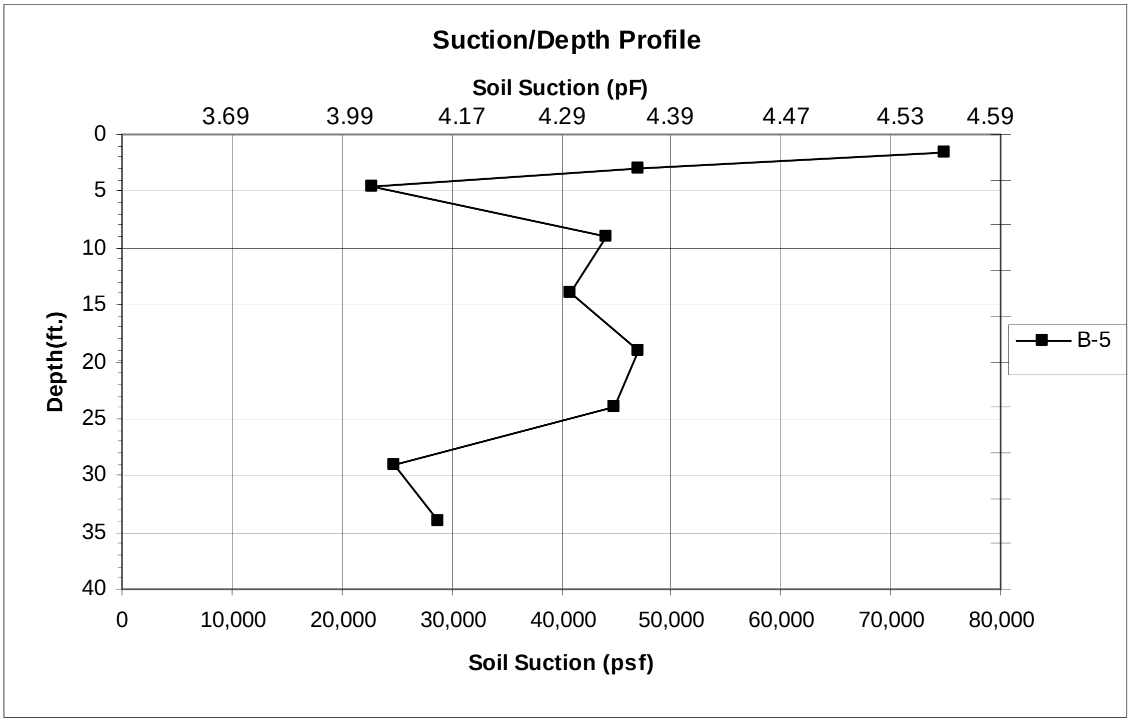


Figure 11. Suction profile for Case Study 4.

As noted in Case Study 3, the general shape of the profile could be called "trumpet"; however, it should be noted that the suction values from approximately 9 to 28 feet are above 4.3 pF.

**Case Study 5 –** Case Studies 5 and 6 are companion studies located within approximately 1 mile of each other. Case Study 5 was sampled in early December 2005 after an extensive dry period. The site is located on the west side of the contact between the Austin Chalk and Taylor Marl.

Subsurface conditions consisted of 9 to 11 feet of CH clay over weathered grading to unweathered limestone. The clay was dark brown to dark grayish-brown to the top of the weathered limestone. Ground water was encountered at a depth of approximately 13 feet, within joints and fractures of the weathered limestone.

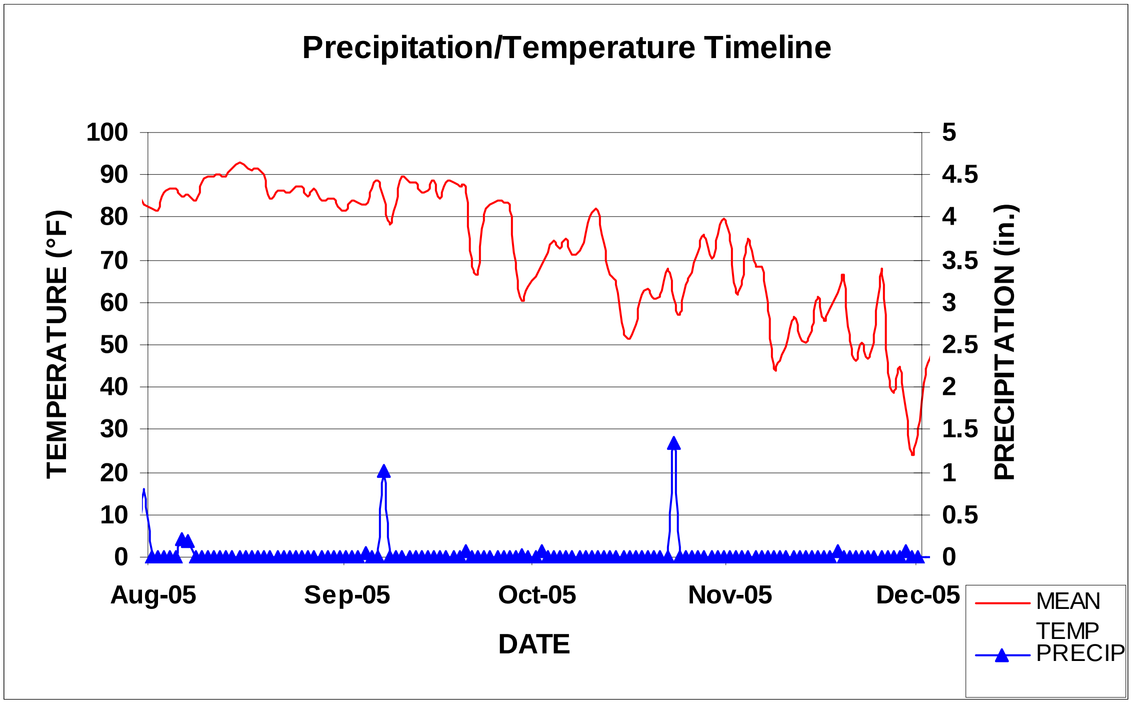


Figure 12. Temperature and rainfall data for Case Study 5.

Prevailing weather for the period of August 2005 through December 2005 is provided in Figure 12. As noted in Figure 11, the climatic period was relatively dry with limited rainfall events for the period of August through December. This condition resulted in drying of the soils to a depth of about eight feet. The suction profile for two borings is provided in Figure 13.

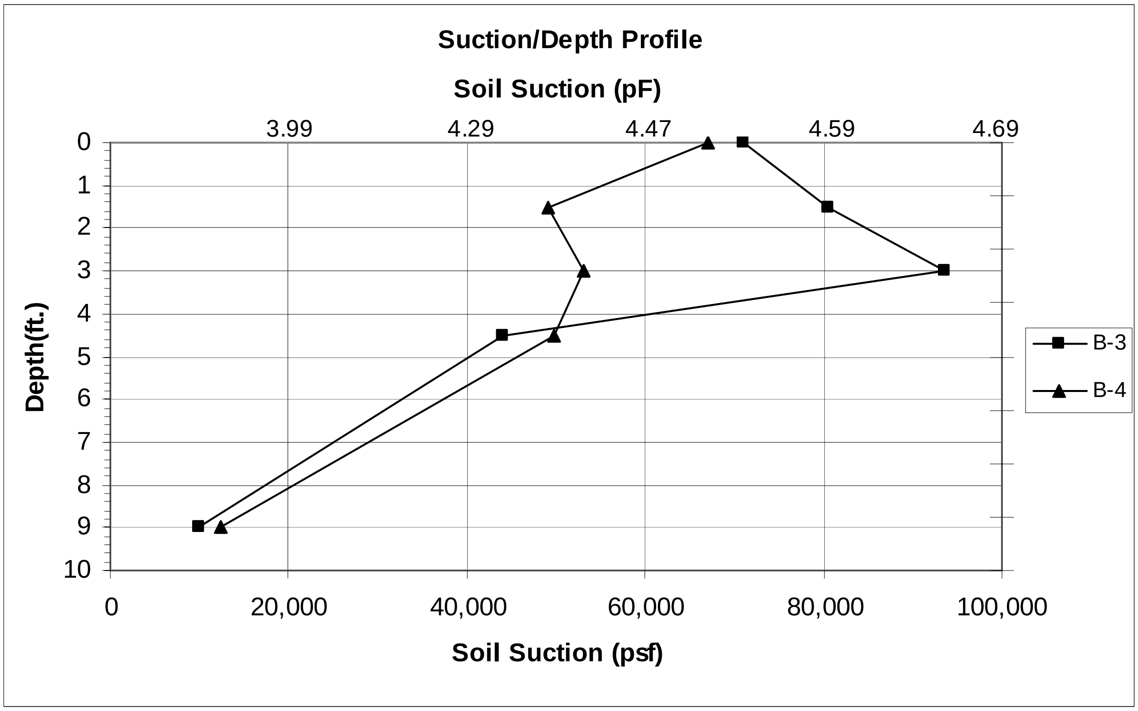


Figure 13. Suction profile for Case Study 5.

The shape of the profile is considered to be "p" since the upper soils have very high suction to a depth of at least 5 feet. It is anticipated that the upper soils will gain moisture during seasonal rainfall and because of the relatively shallow clay over limestone, the upper soils are anticipated to become relatively moist throughout their depth.

**Case Study 6 –** Case Study 6 is located approximately ¼ mile east of Case Study 5. The site is located on the Taylor Marl side of the geologic contact with the Austin Chalk.

Subsurface conditions consisted of dark brown to dark grayish-brown clay becoming yellowish-brown and light gray below depths of seven to eight feet. The clay exhibited extensive jointing and fracturing characteristic of severely weathered calcareous shale below a depth of 13 feet. Ground water was noted at a depth of 12 feet at the time of the field investigation which was conducted in mid-September 2007.

Weather conditions for the period of June through mid-September 2007 are provided in Figure 14. As noted, 2007 was a very wet year with extensive rainfall throughout a normally dry period. It is anticipated the high rainfall attributed to the relatively high water table noted during the field investigation.

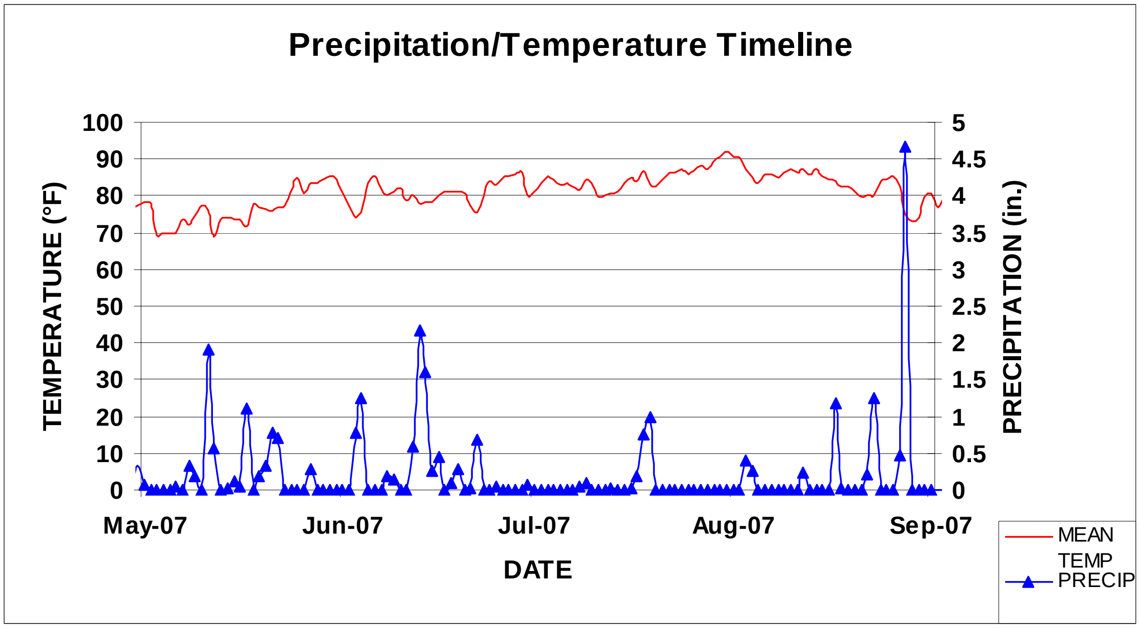


Figure 14. Rainfall and mean temperature for Case Study 6.

The extensive rainfall and high water table resulted in high moisture and very low suction throughout the 25-foot depth explored. The suction profile is shown in Figure 15.

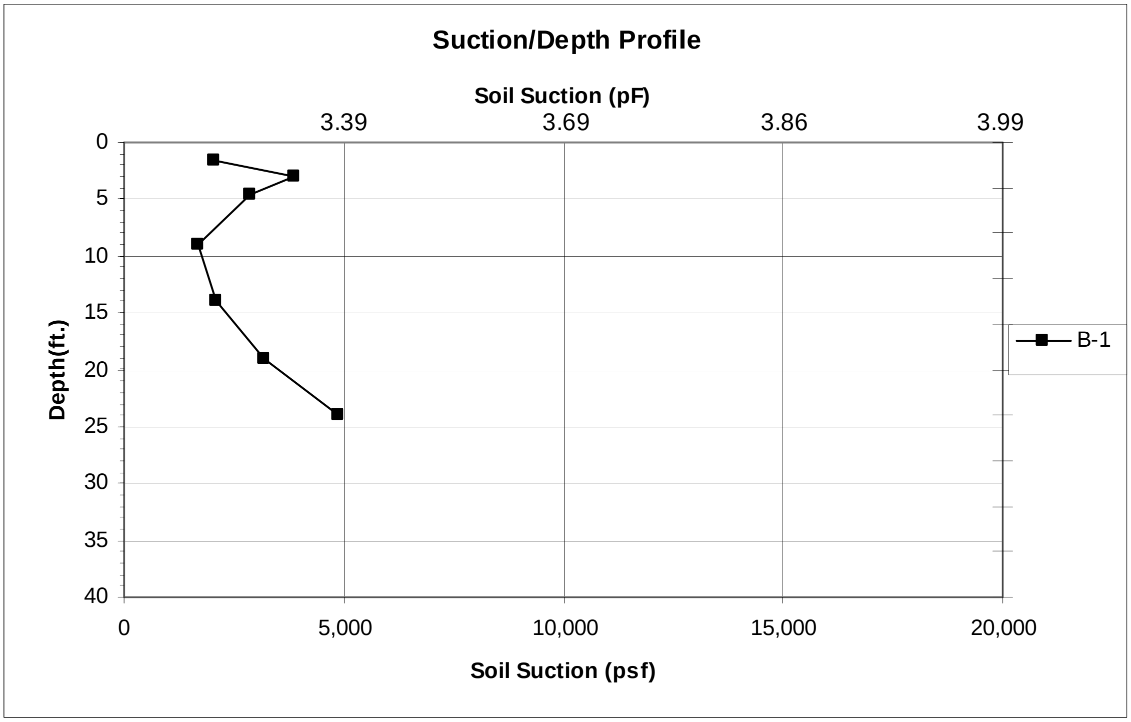


Figure 15. Suction profile for Case Study 6.

The profile illustrated in Figure 15 is considered to be uniformly moist.

**Analysis of $y_m$ and $e_m$**

Analysis using the PTI recommended program, VOLFLO, was performed on Case Studies 1 and 5. Analysis consisted of evaluation using a default "trumpet" shape for dry to a uniform wet condition. The values obtained for $y_m$ and $e_m$ were then compared with the values calculated using the measured profile to a uniformly wet profile. All other input for each case study was left constant. The results of the VOLFLO calculations are summarized in Table 2.

| Table 2. Summary of VOLFLO Calculations | | | | |
|---|---|---|---|---|
| **Case Study** | **Initial Profile** | **Final Profile** | **$Y_m$, inches** | **$e_m$, feet** |
| 1 | Default Trumpet | Uniformly Moist | 3.3 | 3.5 |
| 1 | Measured | Uniformly Moist | 5.8 | 3.5 |
| 5 | Default Trumpet | Uniformly Moist | 2.7 | 4.1 |
| 5 | Measured | Uniformly Moist | 5.8 | 4.1 |

As noted in Table 2, the value of $y_m$ increases 175 to 210 percent using the measured profile versus the default trumpet shape recommended in the VOLFLO and PTI literature. Since $y_m$ is a design number for determining the relative stiffness of a post-tensioned slab, this variation in the magnitude of movement is significant.

Considering Table 2, it would appear that use of a trumpet shape suction profile may not be conservative relative to designing post-tensioned slabs. Alternatively, it may be that the VOLFLO program is no more accurate at estimating soil movement than currently available empirical methods.

**Analysis of Suction Profiles**

Antidotal information from daily analysis of suction profiles over the last 15 years has indicated to the writer that significant variation in the suction profile for any particular site will be observed, dependent upon the prevailing weather and the specific geologic setting. If suction is to be used as a stress variable in prediction of movement associated with expansive soils, a complete understanding of the variation in the profile will be required.

Based on observation and analysis, it would appear that the suction profile within soils in the North Texas region undergo various transformation during the year and from year to year. Figures 16 and 17 are believed to be representative of changes in the shape of the suction profile for an idealized site, given a constant and uniform weather condition. For example, in Figure 16, given moist conditions at the start of a dry period, increasing suction (drying) from the surface down results in eventual development of the “trumpet” shape. However, extended drying has been seen to result in drying of the near-surface soils to near-minimum moisture to depths well beyond the surface. This specific condition was observed in Case Studies 4 and 5.

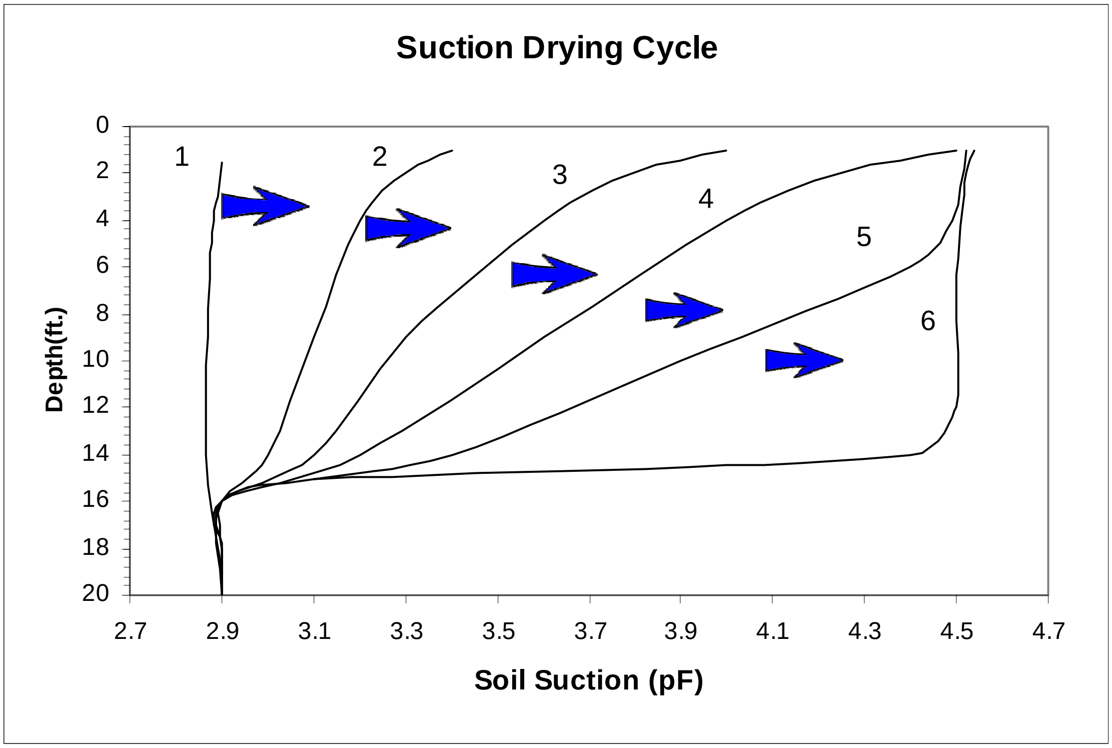


Figure 16.  Idealized drying suction profiles; Curve 1 being the wettest profile.

Upon development of a dry profile, subsequent moisture gain occurs from the surface down.  The wetting cycle is believed to be represented in Figure 17.  After initial moisture gain, the suction profile takes a trapezoidal shape as observed in Case Studies 1, 3 and 5.

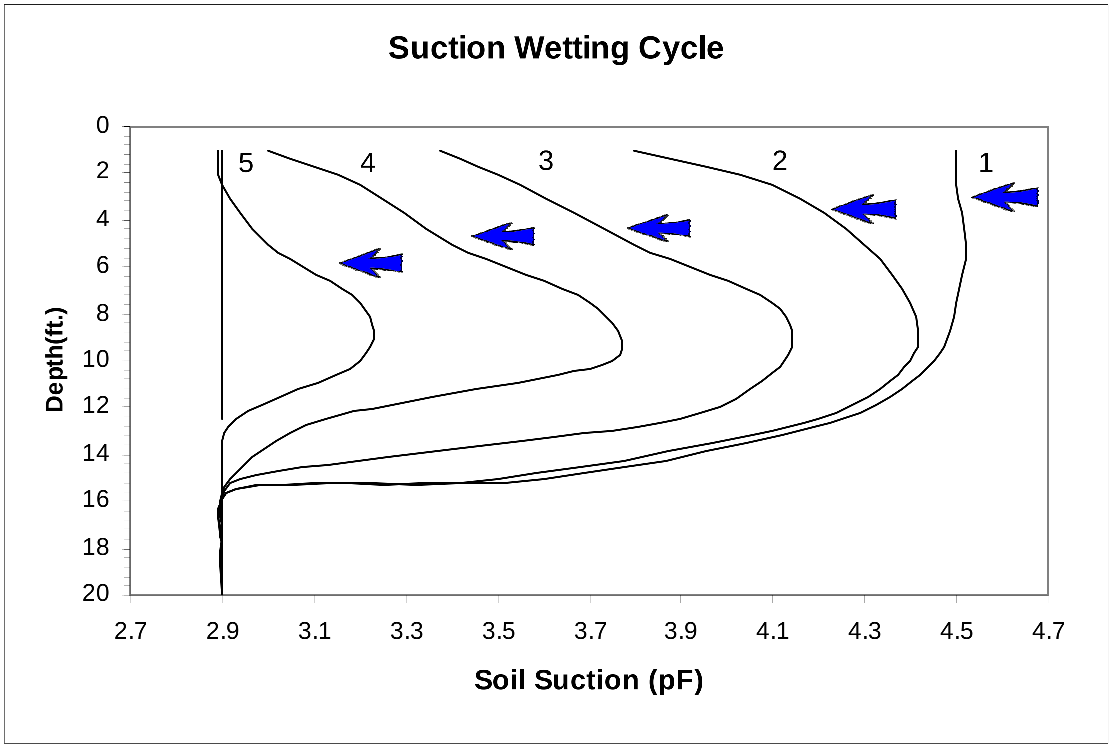


Figure 17. Idealized wetting suction profiles; Curve 1 being the driest profile.

Figures 16 and 17 represent conceptual drying and/or wetting from the extreme condition. Review of observed profiles over the last 15 years indicates that interruptions caused by changes in the prevailing weather pattern can result in odd shapes. It is not unusual to observe "Z" shape suction profiles matching odd wet, dry, wet (or conversely, dry, wet, dry) patterns of weather where the cycles are of short duration.

**Summary**

The 3rd Edition PTI design procedure reports to contain a new method, based on use of suction, to predict movement in expansive soils. The method involves use of the computer program VOLFLO. This program incorporates the ability to analyze soil movement using suction as a stress variable coupled with a suction compression index.

If the method of using suction as a stress variable is to be evaluated, a thorough understanding of the suction profile will be necessary. Six case studies have been presented that indicate that significant variation in the suction profile exists and that the profiles vary with both the seasonal and yearly variation in rainfall as well as site geology.