A Soil Suction-Oedometer Method and

Design Soil Suction Profile Recommendations

for Estimation of Volume Change of Expansive Soils

by

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ABSTRACT

The experience base of practitioners with expansive soils is largely devoid of directly measured soil suction. This historical lack of soil suction measurement represents an impediment to adoption of modern unsaturated soil engineering to problems of expansive soils. Most notably, soil suction-based analyses are paramount to proper design of foundations in expansive soils. Naturally, the best method to obtain design suction profiles is to perform an appropriate geotechnical investigation that involves soil moisture change-appropriate drilling depths, sampling intervals, and requisite laboratory testing, including suction measurement. However, as practitioners are slow to embrace changes in methodology, specifically regarding the adoption of even relatively simple suction measurement techniques, it has become imperative to develop a method by which the routine geotechnical procedures currently employed can be used to arrive at acceptable approximations of soil suction profiles.

Herein, a substitute, or surrogate, for soil suction is presented, such that the surrogate agrees with observed field soil suction patterns and provides estimates of soil suction that are acceptable for use in practice. Field investigations with extensive laboratory testing, including direct suction measurement, are used in development of the soil suction surrogate. This surrogate, a function of water content and routinely measured soil index properties, is then used in estimation of field expansive soil suction values. The suction surrogate, together with existing geotechnical engineering reports, is used to augment the limited existing database of field soil suction profiles. This augmented soil suction profile database is used in development of recommendations for design suction envelopes and design suction profiles. Using the suction surrogate, it is possible to proceed

from the beginning to the end of the Suction-Oedometer soil heave/shrinkage analysis without directly measuring soil suction. The magnitude of suction surrogate-based heave estimates is essentially the same as heave estimates obtained using direct soil suction measurements.

The soil suction surrogate-based approach, which uses a complete-stress-state approach, considering both net normal stress and soil suction, is an intermediate step towards the adoption of unsaturated soil engineering in expansive soils analyses, wherein direct soil suction measurements are routinely made.

DEDICATION

This work is dedicated to my supporting wife and companion Kristine Celine Vann. When Kris married me, I asked her what I needed. She replied, “a wife.” My response was “a companion.” And that she has been. Day to day love, tolerance of my faults, understanding of my high-strung nature and unceasing worry, support of all my worthy endeavors, and knowledge of my belief that there is no such thing as “it’s just business” have been made manifest through our relationship. She knows that for me, it’s all personal. That’s what makes us continually strive to improve. In two lifetimes I could not pay her back for her love and support (not to mention how much she says I owe her). “When the rain is blowing in your face and the whole world is on your case, I could offer you a warm embrace to make you feel my love.” – Bob Dillan. So true.

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CHAPTER 1 INTRODUCTION AND SCOPE OF WORK

1.1 Introduction and Goals of this Research Study

Expansive soils have received extensive attention from the geotechnical research community since the 1950s due to the pervasiveness of this type of soil worldwide and the tens to hundreds of billions of dollars of damage annually to infrastructure and slope failures resulting from moisture intrusion into expansive clay and swelling and shrinkage movements (Nuhfer et al, 1993; Wray and Meyer 2004, Hammerberg, 2006). In recent decades, expansive soils research has typically fallen under the broader study of unsaturated soils, and interest in development of enhanced understanding/modeling of expansive soils has grown. Thus, the geotechnical literature is replete with expansive soil studies. Methods of estimating field heave range from index property correlation, to oedometer test methods, soil suction-based methods (Aitchinson and Martin, 1973; Johnson, 1977; Fredlund, 1979; Snethen, 1980; Lytton, 1977; Covar and Lytton, 2001; McKeen, 1981; Wray, 1989), and water content-based methods (Briaud, et al. 2003; Vanapalli, et al. 2010a). Despite these efforts, no agreement on the best approach to estimate expansive soil movements or methods for mitigation for expansive soil problems has emerged, and the issue of expansive soils and their remediation is widely debated and disputed.

Expansive soils swell excessively when wetted and shrink when dried, leading to billions of dollars of infrastructure damage annually. Current mitigation practices applied by geotechnical consultants often assume that full wetting to essentially zero soil suction is going to occur in the field, and then the laboratory swell testing is performed in accordance with this assumption. Typical site preparation involves the removal and replacement of huge volumes of expansive clay, often along with the use of deep foundations. These current practices are almost always overly conservative, and this over-conservatism is costing developers and taxpayers tens of billions of dollars annually, although these losses are typically not public domain.

Estimation of unsaturated soil movements, and associated foundation movements, requires measurement and/or estimation of the initial and final state of stress within the soil profile. For unsaturated soils, the stress state determination must take into consideration both total (net) stress and soil suction, which is related to soil moisture (Fredlund and Morgenstern, 1977). Indeed, for moisture sensitive soils, such as expansive soil or collapsible soil, it is the change in matric soil suction over the life of the structure that is most commonly the predominant driver of soil movements. Few geotechnical engineers would attempt to estimate the consolidation settlements of a soft saturated clay deposit without estimating both the initial and final effective stresses within the soil profile. However, geotechnical engineers commonly inadequately assess the initial and final total stress and soil suction when making estimates of soil movements for expansive soils and other unsaturated soils.

Typical urban development practices in the United States are associated with increases in soil moisture (reduced soil suction) compared to soil moisture for undeveloped conditions, with substantially fewer cases of post-construction drying. Thus, for estimation of movements (e.g. heave or shrinkage) of unsaturated soils, it is essential to understand the impacts of past development history on the soil suction profile. For example, Lytton's soil suction-based methods for computation of heave and shrinkage are based on sound fundamentals and require input of the initial soil suction state of the soil as well as input of the final soil suction state (Lytton and Woodburn, 1973; Wray, 1987; Lytton, 1994; Lytton, 1997; Lytton, Aubeny, and Bulut, 2005; PTI, 2004; Naiser, 1997). Despite the general recognition of the importance of past development history on future wetting-induced soil movements, often computational methods fail to properly consider impacts of development on the initial and final stress state (change in stress state) of the soil. The results of improper consideration of the effects of development on boundary conditions include highly inaccurate estimates of soil heave or collapse and associated high variability in heave or collapse estimates across engineering firms/geotechnical engineers.

Even though geotechnical engineers are typically aware of the basic principles that govern movements in expansive clays, varieties of assumptions are used and correspondingly, multiple prediction techniques have ensued. Also, of concern are seasoned practitioners that may be reticent to adopt new methodologies because of one or more of the following: perhaps they have not yet grasped the needed concepts; are not comfortable with change as the methods currently in use appear to work; or are comfortable with conservative methods while not recognizing the need for change. Whatever the reason, a new and improved method that utilizes a combination of what engineers have been doing in practice, with a new twist that is easy to use and reliable, is needed as a design option moving forward. The primary goal of this research study will be the development of an improved method for computation of volume change of expansive clays.

The objective is to outline the relevant principles for expansive soil movements and to put forth a computational procedure that embodies these principles. Furthermore, a merger will take place that will combine existing procedures in the industry that are successful, with some new ideas to yield an improved procedure for practitioners. In other words, the method will combine the best features of all methods, current and proposed. The proposed heave computation method is a marriage of soil suction-based and oedometer swell test-based methods. The combination of methodologies gives rise to the name chosen to describe it: Soil suction-Oedometer Method (Houston and Houston, 2018).

The methodology focuses on wetting and the corresponding swelling and heave, but a simple approximation to allow estimation of shrinkage and settlement due to drying is presented using the same laboratory-measured properties as input. The conventional overburden swell test is the cornerstone of the proposed method. However, the conventional overburden swell test involves submergence of the test specimen, producing a fully-wetted swell strain, ε_{fw}, corresponding to the applied confining stress. The use of ε_{fw} from the ground surface down to the depth of wetting would result in an overly conservative heave estimate and excessive construction costs. Therefore, to obtain a best estimate of heave or a slightly conservative estimate, it is necessary to account for partial wetting by employing a final, pseudo-equilibrium soil suction profile that is consistent with experience and measurements.

The solution to this problem is to develop a well-founded basis for estimating the final, post-wetting (and post-drying) soil suction – a basis that rests convincingly on principles of unsaturated soil theory and on directly measured values of field soil suction for various boundary conditions of relevance**.** It is the study of and development of recommendations for initial and final field soil suction profiles that represents the second goal of this research study.

Another set of problems that exist currently is that geotechnical consultants, with few exceptions, do not possess the laboratory equipment or the experience to measure soil suction and integrate it into their solutions. To conduct a soil-water characteristic curve (SWCC) test on clay can require nearly 6 to 8 weeks, which is excessive for practitioners (not to mention that there is little chance of receiving compensation from their clients to perform the work). Field and laboratory soil suction measurement methods have been recently improved and methods including new devices for the high soil suction range. Some such devices and their respective manufacturers are presented in Table 1.1.

Table 1.1: High Range Suction Measurement Apparatus

Product Name	Application	Manufacturer
WP4C	Laboratory method to measure water potential by determining the relative humidity of the air above a sample in a sealed chamber (using the chilled-mirror dew-point technique)	Meter
SWC-150 Soil-Water Characteristic Cell	Laboratory device for determining the complete SWCC of the soil	GCTS, Inc.
Fredlund Thermal Conductivity Sensor (FTC Sensor)	Field device for determination of field matric soil suction measurements	GCTS, Inc.

However, many consultants have not caught on to the tremendous benefits of owning and operating a Meter WP4C to facilitate rapid total soil suction measurements, as compared to other methods such as filter paper or use of SWCC. As a result, routine soil suction measurement in practice has not yet been realized and may not be realized for many years into the future. In addition, the experience base of practicing engineers and the vast history of field data on expansive soil sites, by and large, does not include direct measurements or even estimates of soil suction. This history of lack of soil suction measurement, together with both real and perceived difficulties in making soil suction measurements in practice, represents an impediment to adoption of modern unsaturated soil engineering.

A third major goal of the research is to develop a substitute or surrogate for soil suction that will facilitate the selection of soil suction design curves for the improved heave computation method. It is intended that the soil suction surrogate match soil suction patterns in the field. This surrogate is to be a function of water content and index properties routinely measured as a part of the site investigation. Using the field measurement-based soil suction surrogate, it is possible for the user to proceed from the beginning to the end of the soil heave or soil shrinkage analysis without measuring or estimating soil suction. However, the user is required to think about the role of soil suction and to estimate the initial and final soil suction values, even if through use of the surrogate. Thus, the soil suction surrogate-based approach serves as an intermediate step towards the adoption of unsaturated soil engineering in expansive soils analyses, wherein a complete-stress-state approach that takes into consideration both net normal stress and soil suction is applied to the solution, while direct soil suction measurements are not required.

A soil suction-based approach for estimation of heave/shrinkage of expansive soils, using soil suction measurements and/or estimates, will also be developed. Simultaneously, as a fourth goal of this study, this heave computation approach will be extended for use with soil suction surrogate values. Users of the heave computation method will be able to choose the approach with which they are most comfortable or for which they have the available data: soil suction measurements or soil suction surrogates.

The research will build on the research findings of others (Olaiz, et al, 2017; Vann, et al, 2018, Houston and Houston, 2018; Singhal, 2010). To summarize, the primary goals of this research study are: (1) development of an improved soil suction-based method for computation of volume change of expansive clays, (2) the study of and development of recommendations for initial and final field soil suction profiles for use in heave computations, and (3) development of a substitute or surrogate for soil suction that will facilitate the selection of soil suction design curves for the improved heave computation method, and (4) extension of the heave computation approach for use with soil suction surrogate values.

1.2 Motivation for Development of a New Heave Computation Method

It is not surprising that geotechnical engineers cannot agree on approaches to dealing with expansive soils, largely because of the great uncertainty associated with estimating final soil suction conditions. It is a generally accepted opinion among researchers that expansive soil must be understood within the context of unsaturated soil mechanics principles, because changes in soil suction under field net normal stress conditions represent the driving force for expansive soil movements. The relationship between expansive soil movements and what are termed here “soil suction surrogates” have been utilized by numerous researchers in the past, and consist of such things as relationships between water content and index properties, including plasticity index (PI), plastic limit (PL), liquid limit (LL), percent clay, P_{200}, activity, and others; however, no attempts have been made to use any such soil suction surrogate in the estimation of design soil suction profiles. Most research investigations on post-development expansive soils conditions have been soil suction based, and thus not widely adopted, due to difficulties in measuring soil suction. Unsaturated flow/deformation models are widely available and used in research applications and have been demonstrated to be quite useful in evaluation of “what if” scenarios. However, there remains the challenge of input parameter determination and complexities of boundary conditions, and unsaturated flow codes have not been demonstrated to the point of being adopted widely in geotechnical design for most infrastructure projects. Perhaps the most common method for estimating final soil suction profiles is based on the Thornthwaite moisture index (TMI) which is a representation of regional climatic conditions alone, irrespective of site-specific irrigation, drainage, and topography conditions. Site-specific conditions and development modifications render direct usage of TMI in the estimation of design soil suction profiles challenging, if not inappropriate. Uncertainties in the development of design soil suction profiles, particularly when coupled with difficulties in measurement of the field soil suction values, promote the continued use of empirical methods in practice that are only regionally applicable, at best. It is not uncommon to see engineers use index-based methodologies developed in the mid-1950s, such as the PVR (potential vertical rise) method, even though it has been demonstrated that this method leads to very conservative estimates of heave and costly mitigation (Lytton, et al, 2005).

Current expansive soil analysis and mitigation approaches are at odds with efforts towards sustainable development. From a sustainability perspective, the detrimental effects of lack of understanding of field soil suction conditions lead to the tacit acceptance that subsurface soils will just get wet – and associated acceptance of excessive use of landscape irrigation water and wasted resources required for unnecessarily robust site mitigation schemes and foundation elements. There is no question that the solution to cost-effective mitigation of expansive soils lies in the appropriate application of the theory of unsaturated soil mechanics. After six or more decades of geotechnical engineering study of expansive soil problems, a consistent approach to estimation of soil heave that is both soundly based on fundamentals and easy for practitioners to use is past-due.

In keeping with the above commentary, a new design methodology will be developed that is crisp, much easier for the practitioner to use, theoretically sound, provides results and subsequent recommendations that are both reasonable and within an acceptable degree of engineering certainty, as well as robust. Practitioners will be able to use the new method, knowing that its basis has been benchmarked against known data and relationships, while considering the two-stress state approach.

1.3 Motivation for the Development of a Soil Suction Surrogate

There exists a strong temptation to simply assume that water content and soil suction are uniquely related via the soil water characteristic curve, SWCC. Based on this assumption it is easy to go back and forth from water content to soil suction. This tendency has led to potential failures in the ability to recognize the uniqueness of the SWCC. However, there are some significant problems with this practice of estimating soil suction from an assumed unique SWCC, as follows.

First, it should be noted that geotechnical engineers have inherited the SWCC from agriculture and soil science researchers, who have focused on the drying curve, often starting from a slurry or from a fully wetted compacted (usually loosely compacted) specimen. The effects of soil volume change on the SWCC are largely ignored in agricultural applications. The drying of slurry soil, including from a slurry, has some important applications other than agricultural – notably the drying of oil-sand slurries and slurries from other mining operations. However, for conventional geotechnical foundation engineering dealing with characterization and mitigation of moisture sensitive soil problems, the slurry-based (or even compacted specimen-based) SWCC has limited relevance for volume change analyses. The SWCC as a plot of water content versus log of soil suction is pronouncedly different for an undisturbed sample of moderately stiff clay compared to a slurry SWCC for the same soil. The slurry is of course very compressible and exhibits substantial loss of water for small increases in soil suction – the curve starts at a much higher water content. The differences in the two SWCCs just cited can be reduced, but not eliminated, by expressing the water content as degree of saturation. Fredlund and Houston (2013) have pointed out that a much more meaningful and accurate air entry value can be ascertained when degree of saturation is used and when volume change is tracked during measurement of the SWCC. However, the SWCC obtained is dependent not only on soil structure, but also on net normal stress and stress history. Thus, there is no such thing as ‘the’ soil-water characteristic curve. It is appropriate to note here that the unsaturated soil state surfaces, such as those presented in Fredlund and Rahardjo (1993) represent the “set” of various SWCCs over a range of net normal stress values.

The problem with the slurry-based curves is persistent in geotechnical engineering for the following reason. Because of the labor-intensive and challenging aspects of direct, site-specific soil-specific SWCC measurements, many researchers have chosen to estimate

SWCCs as a function of index properties (Zapata, et al. 2000). These correlations tend to be skewed to the soil science literature – because that is where most of the data are from– and thus the final resulting family of SWCC curves is contaminated with slurry-based curves, compacted specimen curves, and curves developed under essentially zero net normal stress.

Even if site-specific SWCCs were to be measured, the issue of hysteresis remains insurmountable. For a clay of moderate or higher plasticity, the difference between the drying and wetting laboratory SWCC curves at a given degree of saturation can be a factor of 3 to 5 or maybe more (perhaps on the order of a full log cycle at a degree of saturation of 50%) and is also dependent on number of cycles of wetting and drying (Lin and Cerato, 2013). Although advances have been made in efficient SWCC determination (Delage, 2008), even if both a site-specific drying and wetting curve are available, it is not known in the general field case which curve is being followed, or whether the soil is on a scanning curve.

In this study, the non-uniqueness of the SWCC in relating water content to soil suction is not considered. First, it is not desired to force the ultimate user of the methodology to be required to measure the site specific SWCC, with hysteresis. Second, it is expected that, even if the SWCC were available, the soil suction predicted from the knowledge of the degree of saturation and the SWCC would not be sufficiently accurate. Instead, it has been decided to develop a soil suction surrogate which can be related to soil type and commonly obtained soil index parameters. Soil suction values will be determined in this research by direct measurements on undisturbed samples under field appropriate net normal stress to the extent possible, and these data will be used in the development of the suction surrogate. The surrogate is meant to represent soil suction for undisturbed field clay soils within the range of soil suction typically encountered in-situ. Once the soil suction surrogate function is known, a huge database of soil suction surrogate profiles becomes available from existing files of geotechnical engineers and agencies. Such soil suction surrogate profiles are used extensively in this study.

1.4 Motivation for the Study of Field Soil Suction Profiles and Design Recommendations

The plan for the research is to develop a well-documented basis for estimating the soil suction beneath and next to structures resting on expansive soil. The results of this research will demonstrate to the users of the methodology that it is unnecessary to make the very costly and over conservative assumption of full wetting for the general case, as is typically the status quo. The basis for estimating the final (equilibrium) values of water content and/or soil suction will not be speculative, but rather based on direct observations, measurements, and careful statistical characterizations. It is therefore reasonable to expect that practitioners will adopt and use the methodology and the developers and taxpayers will subsequently reap the benefits of elimination of the over-conservatism.

It is assumed that initial, preconstruction water content and a suite of index tests will be a part of all routine site investigations. As a part of data collection for the study, boring logs will be reviewed, and data gathered on depth of weathering and depth and presence of any granular layers. These data will be used to establish the beginning point for the field wetting or drying process for the soil suction surrogate-based approach. The soil suction will be estimated from existing geotechnical engineering reports via use of the established soil suction surrogate (a function of index tests, and water content). Initial soil suction will also be ascertained as part of the data mining task and laboratory test program for developed and undeveloped sites. Determination of a reasonable value for the final water content and final soil suction is the most challenging task of the research and estimating the initial soil suction is the second most challenging. For this purpose, existing geotechnical reports from developed locations will be used, along with the soil suction surrogate, to estimate typical final soil suction profiles for various common types of surface boundary conditions. All steps in the process of estimating soil heave, other than the estimation of soil suction design profiles, are relatively simple, and generally familiar to practitioners and researchers.

1.5 Scope of Work

1.5.1. Data Mining and Field Investigations

Data mining of projects completed or that are in progress is essential to gather pertinent field response information according to location (also tied to the Thornthwaite Moisture Index, TMI). Information collected for known projects has included data about the soil profile with depth, laboratory classification data (Atterberg Limits, grain-size distribution, moisture content, and total soil suction results, where available), and information of surface flux boundary conditions.

To augment the data mining process, knowing that all the data needed does not exist in the records, additional sites must be explored to gain additional information, particularly on directly measured soil suction. Sites from different cities with varying TMIs are critical. Regarding expansive clay soil sites, and those that typically experience problems associated with damage arising from heaving clays, a focus must be made on locations with arid or semi-arid climates, where the TMI is typically less than zero. This research, therefore, has concentrated on cities that are representative of TMIs of -10 to -55 (Phoenix and Mesa, Arizona; San Antonio, Texas; and Denver, Colorado), and geotechnical reports from the southwest region of the USA. Where such sites become available, exploratory test borings advanced to depths of 30 feet are completed, with samples obtained every foot throughout the entire depth of the test boring. However, a full range of TMI regions has been included in the study, particularly through incorporation of existing geotechnical engineering reports.

Samples obtained through the drilling effort (discussed above), were tested for direct soil suction (using both the oedometer pressure plate device and WP4C), response to wetting (ASTM D4546), moisture content, grain-size distribution, and Atterberg Limits. As the sample acquisition and laboratory testing efforts are completed, a detailed and thorough literature search has been essential to document prior soil suction prediction methods, as well as soil suction envelopes, depths to equilibrium soil suction, and the range in surface suction pertaining to field soil suction profiles.

In this study, suction measurements were made primarily using the WP4C device. Miller and Wei (2018) addressed the use of the Meter WP4C for use in obtaining soil suction measurements. The WP4C operates on the premise of measuring relative humidity by means of a chilled mirror device (CMD). The relative humidity is related to the total suction of the pore space. As such, total suction is measured from the relative humidity measurements. Miller and Wei (2018) recognize that the chilled mirror hydrometer, and specifically the WP4C, has become a common and accepted device for measuring soil suction, and is increasing in use. Additionally, the WP4C can also be utilized to establish a laboratory soil water characteristic curve. Care of operation is recommended when using the chilled mirror device to measure total suction in cases where the suction measurements are near the accuracy limit of the device. By mixing a companion unsaturated soil sample to its saturated state, accompanied by measuring its gravimetric moisture content, Miller and Wei (2018) state that it is also possible to determine the osmotic suction component, thereby estimating both total and matric suction from WP4C measurement.

Using the results of the 2006 TMI (Witczak et al. 2006), information from the data mining effort, and laboratory testing completed on samples from the drilling efforts, a soil suction surrogate is presented herein. Statistical analyses have supported the surrogate selection, with reasonable confidence.

Using the soil suction surrogate equations and ongoing data mining, the research will arrive at a method to predict the depth to equilibrium soil suction, soil suction profiles, adjustments to profiles to account for imposed surface flux changes and develop a method of computation of heave that is based on sound unsaturated soils principles, including appropriate incorporation of both net normal stress and matric soil suction.

1.5.2. Determination of a Soil Suction Surrogate for Estimation of Field Soil Suction Profiles, and Recommendations for Design Soil Suction Profiles.

The drilled sites discussed above and any available site with direct soil suction data are used in this study to determine a soil suction surrogate based on commonly available soil index properties. Indeed, the determination of the soil suction surrogate represents a major goal for this study because the determination of actual field soil suction profiles for many sites cannot be accomplished without such a surrogate given the historical lack of direct soil suction measurements contained in geotechnical reports. Determination of a suitable soil suction surrogate requires development of an extensive data set, over a range of TMI locations, where a full suite of soil index properties and direct soil suction measurements are available. A statistical evaluation of this data results in a soil suction surrogate that can then be used in the interpretation of many historical geotechnical engineering reports for evaluation of field soil suction profiles.

1.5.3. Development of Recommendations for Design Soil Suction Profiles for Heave and Shrinkage Computations

It is essential that this research culminates in recommendations for the geotechnical engineering practitioner that are easy to use. That said, recommendations coupled with equations, as part of this research, must be developed to arrive at design soil suction profiles based on ongoing research and data collection, summary data from sound studies that have been completed to date, and adopted unsaturated soil mechanics principles. To understand and utilize the soil suction profile, it must be clearly stated that the practitioner can rely on specific relationships presented herein related to:

1. TMI versus the magnitude of equilibrium soil suction
2. TMI versus the depth to equilibrium or constant soil suction
3. TMI versus the variation in soil suction at the surface
4. The ability to adjust 2 and 3 above, based on changing boundary conditions that may occur as a site whose changes in surface character and soil type, e.g. liquid limit, also result in changes to the soil suction profile.

Directly connected to the soil suction profile methodologies will be the ability to either direction measure the soil suction or arrive at a close approximation of the soil suction using the surrogate.

1.5.4. Development of a Practical-to-Use Method of Heave Estimation based on Unsaturated Soil Mechanics Principals.

The two most-used method of heave estimation are: (1) Oedometer methods, and (2) Soil suction-based methods. As discussed above, implementation of these methods in practice as met with only limited success, typically leading to overly-conservative decisions on design input parameters affecting estimates of heave. Thus, the goal of this research is the development of a robust, easily implemented heave computation methodology that can be used together with directly measured soil suction values or, alternatively, soil suction surrogate values.

CHAPTER 2 RELEVENT LITERATURE REVIEW OF HEAVE COMPUTATION METHODS

Current design methodologies have been studied for undisturbed samples of expansive clay. The four design methodologies available can be described as:

1) Water Content-Based Methods
2) Empirical methods
3) Oedometer methods (typically using ASTM D4546)
4) Soil suction-based methods

While mentioned herein, water content-based methods and empirical methods have not been the focus of practitioners. Of particular use and interest in this study are the oedometer methods and soil suction-based methods, the focus of the following literature review. The advantages and disadvantages of oedometer based and soil suction-based methods are described in Table 2.1. In this research a method will be developed for estimation of field heave of undisturbed samples of expansive soils that incorporates the best features of the Oedometer ASTM-D4546 approach and the Soil Suction-Based approach.

Table 2.1: Advantages and disadvantages of four heave prediction methods

Method	Advantages about Heave Prediction	Disadvantages about Heave Prediction
Oedometer Method (ASTM D4546)	Ability to account for field-appropriate net normal stress. The test additionally inherently considers the soil structure and initial field suction value. The stress path of wetting under constant stress is followed.	Specimens are fully wetted, lending the oedometer test method useful in estimating the theoretical maximum amount of heave for an expansive soil. As such, ASTM D4546 has limitations for partial wetting efforts and associated soil suction considerations. It does not include direct methods for dealing with field soil suction profiles.

Method	Advantages about Heave Prediction	Disadvantages about Heave Prediction
Soil suction-based Method	Account for partial wetting response. Uses soil suction compression index to relate change in suction to volume change. Leads to estimates of the anticipated volume change under actual field suction conditions.	Direct lab testing associated with very slow equilibration times. Soil suction Compression index typically estimated due to testing difficulties. Estimation methods often use test results performed at inappropriate net stress level or use methods that incorporated only gross estimates of soil suction change, such as laboratory conditions of full wetting.

In addition to the above cited suction-based and oedometer methods, a relatively new method for estimation of partial wetting swell strains, the Surrogate Path Method (SPM), will be presented and used within the suction-oedometer method of heave computations (Houston and Houston, 2018). In the suction-oedometer method, it is intended that the heave computation will incorporate the best parts of the current oedometer methods and soil suction-based methods, and that the SPM will be used to account for partial wetting such that testing of soils under soil suction-control is not required in making heave estimates.

2.1 Water Content-Based Methods

2.1.1. Fityus and Smith (1998)

Two equations for water-content based estimation of volume change are presented as Equations (1) and (2).

$$\Delta H = HI_v a\left(w_{oi} - w_{of}\right) \tag{1}$$

$$\Delta H = HC_w\left(w_f - w_i\right) \tag{2}$$

Where,

I_v is the volume index
α is the empirical factor accounting for confining stress differences in lab and field
w_{oi} and w_{of} are the average initial water content and the average final water content, respectively;
σ_v is the vertical stress at the midpoint of layer

2.1.2. Briaud et al. (2003)

Equations (3) through (5) present the method by Briaud et al. (2003) to predict heave.

$$\Delta H = H_f(\Delta w - E_w) \tag{3}$$

$$E_w = \Delta w\left(\frac{\Delta V}{V_o}\right) \tag{4}$$

$$f = \left(\frac{\Delta H}{H_o}\right)\left(\frac{\Delta V}{V_o}\right) \tag{5}$$

Where,

E_w is the shrink-swell modulus, slope of the water content versus the volumetric strain line
f is the shrinkage ratio, ratio of the vertical strain to volumetric strain

2.2 Summary of Empirical Methods to Estimate 1-D Heave

Empirical relationships to predict one dimensional heave are presented in this section, and only a brief description of the calculations associated with the method are reported here. Typically, empirical methods use soil classification parameters to predict the expansion behavior of swelling clay soils. The methods are typically developed based on data from common geotechnical tests, and are commonly only locally or regionally appropriate, having been developed on regionally-specific soil specimens and experiences.

2.2.1. McDowell (1956)

McDowell (1956) developed an index property approach for estimation of heave of Texas pavement subgrades, the initial moisture content, w_i, beneath a pavement prior to construction was determined to be expressed as Equation (6):

$$w_i = 0.2LL + 9 \tag{6}$$

Based on the equation, the percent volume change, for capillary absorption under a confining pressure of 1 psi was determined to be directly related to the plasticity index, as indicated by Equation (7):

$$\left(\frac{\Delta V}{V}\right)\% = 0.37PI - 3 \tag{7}$$

Further, using the master curves as presented in Figure 2.1, it was possible to consider an expression for the needed overburden to prevent swell as a function of the plasticity index, as expressed in Equation (8):

$$P_o = 0.5PI - 5 \tag{8}$$

Where,

P_o is the overburden pressure required to prevent swelling, expressed in tons/m^2

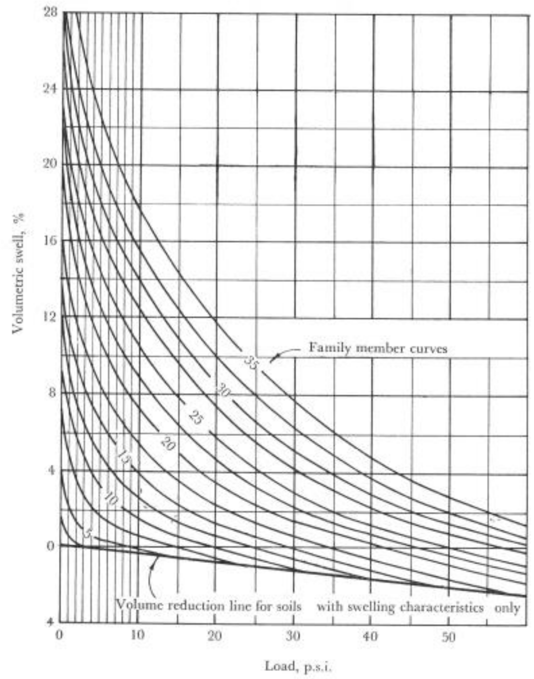


Figure 2.1: Relation of Load to the Volume Change of an Expansive Clay Soil (McDowell, 1956)

Figure 2.2 presents the surface heave as a function of plasticity index of the clay profile under consideration. The clay layer is assumed to be uniform and extend a great depth.

P.I. %	Surface heave cm
10	0
20	1
30	4
40	7
50	13

Figure 2.2: Surface Heave as a Function of PI (McDowell, 1965)

2.2.2. Seed et al. (1962)

Seed et al. (1962) presented Equation (9) for swell pressure.

$$SP = -.0021 {I_p}^{2.44} \tag{9}$$

Where,

SP is the swelling potential
Ip is the plasticity index

2.2.3. Van der Merve (1964)

Equation (10) was proposed by Van der Merve (1964) to predict total heave.

$$\Delta H = Fe^{-0.377D}(e^{-0.377H} - 1) \tag{10}$$

Where,

H is the volume change
ΔH is the total heave
F is the correction factor for degree of expansiveness
D is the thickness of the non-expansive layer

2.2.4. Expansion Index (EI)

The Expansion Index (EI) test was developed in the late 1960s by the Los Angeles Section of the American Society for Civil Engineers (ASCE) as a method to create an index property for soil. The EI test will provide an indication of the soils swelling potential. The test procedure does not attempt to duplicate any actual field conditions such as soil density, moisture content, soil structure, or soil water chemistry. The test procedure does, however, attempt to control variables that may influence the expansive characteristics of a soil and provide a simple yet sensitive testing method for practical engineering applications.

The test method involves using an approximately 1 kg (2 lb) representative air-dried sample that has been passed through the 4.75-mm (No. 4) sieve. The sample is mixed with distilled water and brought to a moisture content that has a corresponding degree of saturation of 50±2% once compacted. After mixing, a representative companion sample is used for determination of the water content and the remaining sample is cured in an airtight container for a period of at least 16 hours. Once cured, the sample is compacted in two equal lifts in a 101.9-mm (4.01-in.) diameter mold to give a total compacted depth of 50.8-mm (2-in.). The compacted sample values and calculated water content from the companion sample are used to determine the degree of saturation using Equation (11).

$$S = \frac{wG_s\gamma_d}{G_s\gamma_w - \gamma_d} \tag{11}$$

Where,

S = degree of saturation, %
W = water content, %
G_s = specific gravity, use a value of 2.7 unless the specific gravity is known to be less than 2.6 or more than 2.8
γ_w = unit weight of water, 9.79 kN/m^3 (62.3 lbf/ft^3) at 20°C (68°F)
γ_d = dry unit weight of compacted soil specimen, kNm^3 (lbf/ft^3)

If the degree of saturation is not within the range of 50±2%, a new specimen is used, and the water content is adjusted to fall within the target saturation range. Once a sample specimen is found to fall within 50±2% saturation, the sample is placed between two porous stone disks and set into a consolidometer. The sample is then subjected to a total pressure of 6.9 kPa (1 lbf/in^2) and allowed to compress for a period of 10 minutes. The sample is then inundated with distilled water and allowed to soak for a period of 24 hours while periodic readings are obtained. The change in specimen height is determined from the initial and final readings of the dial indicator. Using the dial readings, the expansion index is calculated with Equation (12).

$$EI = \frac{\Delta H}{H_1} \times 1000 \tag{12}$$

Where,

ΔH = change in height, $D_2 - D_1$, mm
H_1 = initial height, mm
D_1 = initial dial reading, mm
D_2 = final dial reading, mm

The EI of the soil is determined by the ranges presented in Table 2.2.

Table 2.2: Potential Expansion as a Function of EI

Expansion Index, EI	Potential Expansion
0 - 20	Very Low
21 - 50	Low
51 - 90	Medium
91 - 130	High
> 130	Very High

The test method for the expansion index allows geotechnical engineers to quickly produce a soil index to aid in design parameters. However, there is a level of subjectivity involved with this test method. The test requires the specimen to be within a saturation range of 50±2%, which will require trial and error without the prior establishment of a proctor curve for the material. Prior to the publication of the 2008 version of the test, ASTM 4829-08, the method allowed for the use of an equation to utilize a range of 40 to 60% saturation which correlated the saturation to 50%. Although this correlation method simplified the trial and error process, the equation was removed from the standard and is no longer considered an acceptable method for obtaining the target saturation level. In addition, the test method assumes a specific gravity of 2.7. It is important to note that even a small difference of 0.05 in the specific gravity value can may alter the degree of saturation as much as 1.5 percent, further complicating the trial and error process.

2.2.5. Ranganathan and Satyanarayana (1965)

Ranganathan and Satyanarayana (1965) presented Equation (13) for swell potential.

$$SP = 0.000413 {I_s}^{2.67} \tag{13}$$

Where,

SP is the swell potential
I_s is the shrinkage index, (LL-SL)
LL is the liquid limit
SL is the shrinkage limit

2.2.6. Nayak and Christensen (1971)

Swell potential, as opposed to the total heave, was addressed by Nayak and Christensen (1971) by Equations (14) and (15).

$$SP = \frac{0.00229 I_p (1.45c)}{w_i} + 6.38 \tag{14}$$

$$P_s(psi) = \left[(3.58(10)^{-2}) {I_p}^{1.12} c^2 / {w_i}^2\right] + 3.79 \tag{15}$$

Where,

SP is the swell potential
w_i is the initial water content
Ps is the swelling pressure
c is the clay content

2.2.7. Vijayvergiva and Ghazzaly (1973)

Vijayvergiva and Ghazzaly (1973) also provided a swell potential estimate based on LL and water content, as expressed in Equations (16) and (17).

$$SP = \frac{1}{2}(0.4LL - w_i + 5.55) \tag{16}$$

$$\log SP = 0.0526\gamma_d + 0.033LL - 6.8 \tag{17}$$

Where,

SP is the swell potential
LL is the liquid limit
γ_d is the dry unit weight
w_i is the initial water content

2.2.8. Schneider and Poor (1974)

With the plasticity index and initial water content, the swell potential is estimated, as indicated by Equation (18). Swell potential, however, is not utilized in computation of heave by these authors.

$$logSP = 0.9\left(\frac{I_p}{w_i}\right) - 1.19 \tag{18}$$

Where,

SP is the swell potential

2.2.9. Chen (1975)

Although not implemented in a heave computation, Chen (1975) developed a relationship between swell potential and the plasticity index; Equation (19).

$$SP = 0.2558e^{0.08381I_p} \tag{19}$$

Where,

SP is the swell potential

2.2.10. Weston (1980)

Weston (1980) created Equation (20) to arrive at the swell potential based on the liquid limit, initial water content, and overburden stress.

$$SP = 0.00411 {LL_w}^{4.17} {\sigma_v}^{-3.86} {w_i}^{-2.33} \quad (20)$$

Where,

SP is the swell potential
LL_w is the weighted liquid limit
σ_v is the overburden stress
w_i is the initial water content

2.2.11. TxDOT-124-E - Potential Vertical Rise (PVR)

The TxDOT procedure estimates the potential vertical rise (PVR) of the soil horizon below the placement of a pavement structure, bridge, or building foundation. The potential vertical rise (PVR) is an estimate, in units of length, of a soil's potential to swell - using a given moisture, density, and loading condition when exposed to capillary or surface moisture. Soil cuttings or core samples are secured from test borings at each subsurface soil layer during a site investigation to be tested for moisture content, particle size analysis (percent minus 425 μm [#40] material), liquid limit, plastic limit, and the plasticity index. The method utilizes layer thicknesses of 0.61m (2ft) and a wet density of 2002.5kg/m^3 (125lb/ft^3) to make the tabulation simpler. Modification factors can be used where the wet density will vary appreciably from 2002.5kg/m^3 (125lb/ft^3) if a greater accuracy is desired. To account for the loading from both the structure and the overburden of the soil layers, the load for the structure is added to the overburden pressure at the mid-height of each layer. The liquid limit is used to calculate the “dry” condition, where volumetric swell potential is the greatest, using Equation (21).

$$0.2LL + 9 \tag{21}$$

The liquid limit is then used to calculate the “wet” condition, which corresponds to the maximum capillary absorption by lab tested specimens molded at optimum moisture and a surcharge of 6.9 kPa (1 psi) load, using Equation (22):

$$0.47LL + 2 \tag{22}$$

This “wet” condition value is comparable to the moisture contents found below older pavements and other lightweight structures. The measured moisture content of the soil sample is then compared to the “dry” and “wet” values. The layer is considered “average” if the measured moisture content is closer to the average of the “dry” and “wet” values. The plasticity index and the appropriate moisture content (dry, wet, or average) is used with Figure 2.3 to determine the percent volumetric change with a surcharge of 6.9 kPa (1 psi) load.

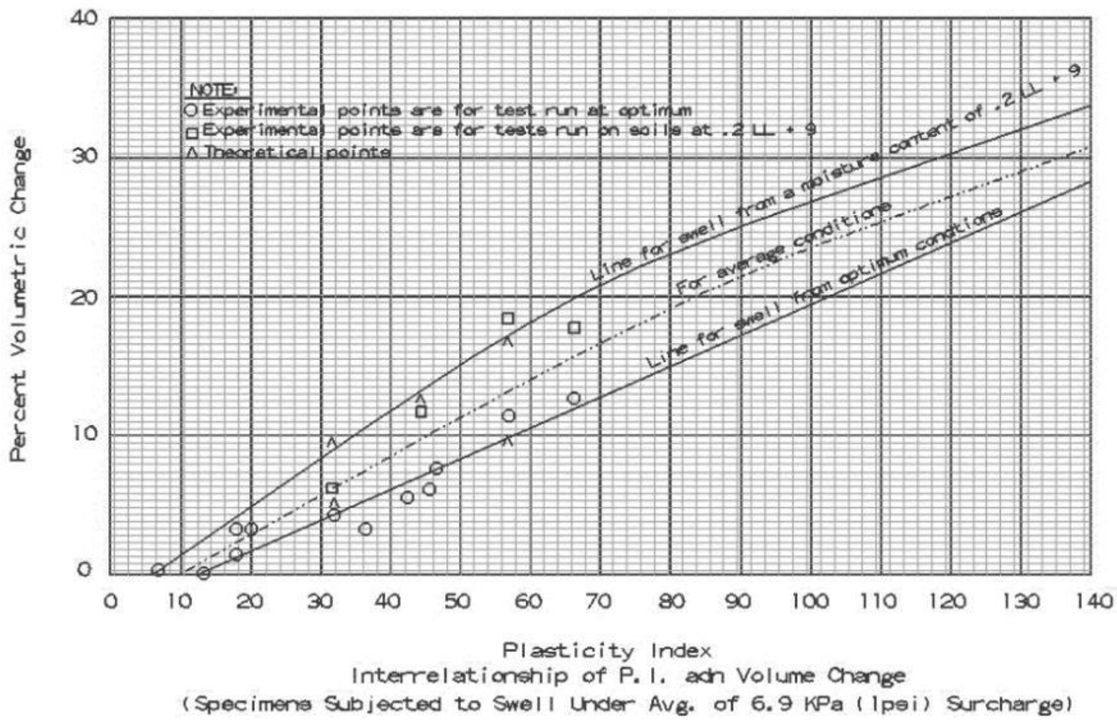


Figure 2.3: Relation of Percent Volume Change to PI (TxDOT-124-E)

The procedure is continued for each soil layer and the PVR values are summed to obtain the total PVR for the site. Similarly, a PVR can be calculated for a free swelling clay under no load using the conversions in the TEX-124-E method and the graphs in Figure 2.4 and Figure 2.5.

In the design phase, the moisture content of the soil may not be known for estimating the PVR. If moisture density control will be used for the project, or if the project exists in a high rainfall area and no moisture-density control will be utilized, the “average” line in Figure 2.3 is recommended. In an arid to semiarid climate, and with no moisture-density control for the project, the “dry” line in Figure 2.3 is recommended. In climates featuring high rainfall, and with moisture-density control being utilized for construction, the “wet” line in Figure 2.3 is recommended.

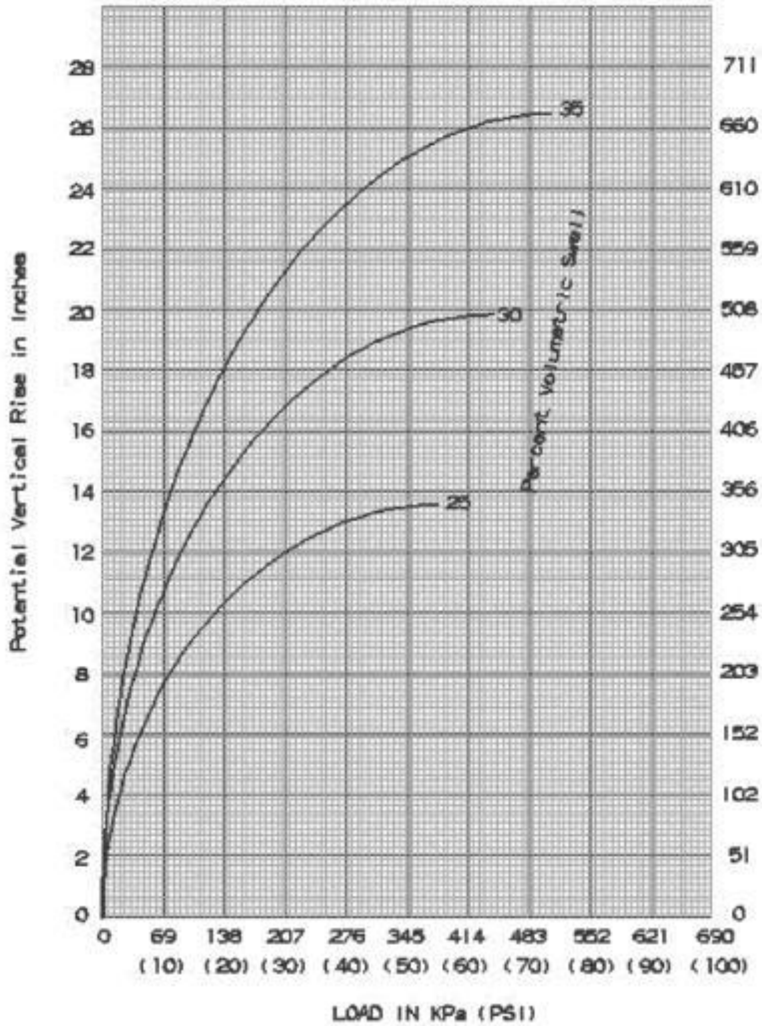


Figure 2.4: Relationship Between PVR and Load – Case No. 1 (TxDOT-124-E)

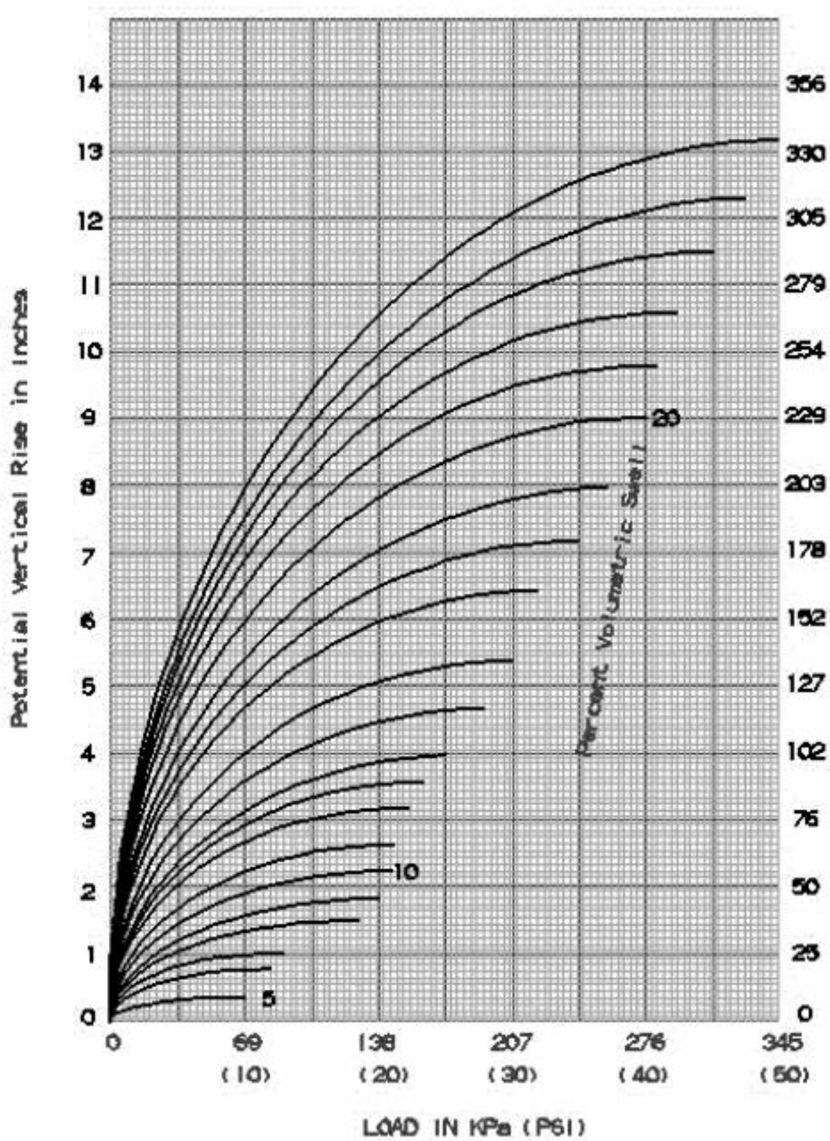


Figure 2.5: Relationship Between PVR and Load – Case No. 2 (TxDOT-124-E)

Examples of the Excel processing for the PVR determination are presented in Figure 2.6 and Figure 2.7.

Depth to Bottom of Layer [ft]	Average Load [psi]	Liquid Limit (LL)	Dry 0.2LL+9	Wet 0.47LL+2	Percent Moisture	Dry Avg Wet	Percent -No.40	Plasticity Index (PI)	Percent Volume Swell	Percent Free Swell	PVR [in] Top of Layer	PVR [in] Bottom of Layer	Differential Swell [in]	Modified -No.40 Factor	Modified Density Factor	PVR in Layers [in]	Total PVR [in]
0.0	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**3.95**
2.0	1.0	75	24.0	37.3	19.8	Dry	94.0	50	14.5	18.1	**0.00**	**0.71**	0.71	0.94	1.00	0.66	**3.28**
4.0	3.0	75	24.0	37.3	19.3	Dry	94.0	50	14.5	18.1	**0.71**	**1.92**	1.21	0.94	1.00	1.14	**2.14**
6.0	5.0	61	21.2	30.7	19.2	Dry	94.0	38	10.6	13.9	**1.46**	**2.12**	0.66	0.94	1.00	0.63	**1.52**
8.0	7.0	61	21.2	30.7	19.4	Dry	94.0	38	10.6	13.9	**2.12**	**2.61**	0.49	0.94	1.00	0.46	**1.06**
10.0	9.0	61	21.2	30.7	19.4	Dry	94.0	38	10.6	13.9	**2.61**	**2.97**	0.36	0.94	1.00	0.33	**0.73**
12.0	11.0	61	21.2	30.7	19.4	Dry	94.0	38	10.6	13.9	**2.97**	**3.23**	0.26	0.94	1.00	0.25	**0.48**
14.0	13.0	61	21.2	30.7	19.4	Dry	94.0	46	13.2	16.7	**4.42**	**4.77**	0.36	0.94	1.00	0.34	**0.14**
15.0	14.5	73	23.6	36.3	19.4	Dry	94.0	46	13.2	16.7	**4.77**	**4.93**	0.15	0.94	1.00	0.14	**0.00**
	7.5		9.0	2.0		Dry		46	13.2	16.7	**4.93**	**3.41**	-1.52	0.00	1.00	0.00	**0.00**
	0.0		9.0	2.0		Dry		37	10.3	13.6	**2.61**	**2.61**	0.00	0.00	1.00	0.00	**0.00**

Fields are chart inputs | Fields are final answers per layer | Final Total PVR for the borehole

Note: PVR calculations are based on future pavement grade being the same as present grade. Bold numbers are interpolated and extrapolated values.

Figure 2.6: Example Excel Spreadsheet Data for the PVR Method

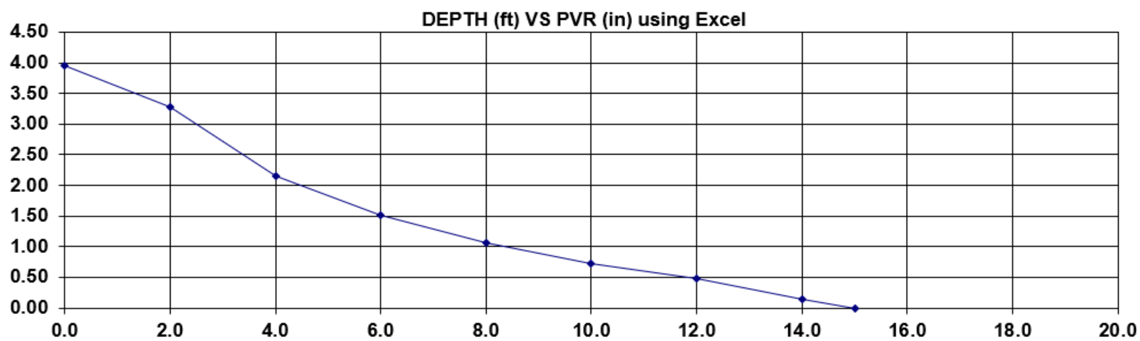


Figure 2.7: Calculated PVR Versus Depth Using Excel (Data from Figure 2.6)

This current PVR method used in TEX-124-E is based on the work of McDowell (1956) and has been questioned, as it is considered to be overconservative by some, and based on indirect methods of swell potential. Indirect methods of measuring swell potential only use geotechnical index properties to predict the swell behavior, which are based on empirical correlations that do not account for all variables such as the mineralogical composition of the soil, soil structure, or field suction conditions. As noted in Lytton, Aubeny, and Bulut (2005), McDowell used five assumptions to create the current PVR method, including soil at all depths has access to water in capillary moisture conditions, vertical swelling strain is one-third of the volume change at all depths, remolded and compacted soils adequately represent the unmolded field soils, a PVR of 1.27 cm (0.5 in) can produce unsatisfactory riding quality for pavements, finally the volume change can be predicted by use of the plasticity index alone. It can be argued that these assumptions are not based on sound analytical principles, and that a more robust method of determining the potential swell of a soil be utilized to estimate the surface movement of expansive soils.

2.3 Summary of Oedometer Test Methods Used for Heave Prediction

Table 2.3 presents a summary of the current test methods that are utilized for heave prediction based on oedometer technology.

Table 2.3: Summary of Oedometer Test Methods Used for Heave Prediction

Source	Test Method	Use Location	Brief Description
Jennings and Knight (1957)	Double oedometer method	South Africa	Two tests were performed on separate but adjacent samples. The first sample was consolidation tested under a small surcharge pressure. The second test was compressed while maintaining the natural moisture content. The analysis is intended to account for sample disturbance for simulation of various loading conditions and final suctions.
DeBruijin (1961)	Volumenometer method	South Africa	A specialized apparatus was used, involving the ability to slowly inundate air-dried samples under a given overburden pressure.
Sampson et al. (1965)	Sampson, Schuster & Budge method	Colorado, United States	Two tests were performed on adjacent samples to simulate highway cut conditions. The first test was a fully wetted swell test conducted under overburden surcharge. The second test involved maintaining constant volume upon load removal or rebound.

Source	Test Method	Use Location	Brief Description
Noble (1966)	Noble Method	Canada	Consolidation-swell tests were completed on both remolded (undisturbed) and undisturbed samples at varying surcharge pressures to develop empirical relationships for Canadian prairie clays.
Sullivan and McClelland (1969)	Sullivan and McClelland method	United States	Constant volume was maintained, while the specimen was subjected to either net total stress or inundation.
Komornik et al. (1969)	Komornik, Wiseman and Ben-Yacob method	Israel	Testing involved constant volume tests for samples from different depths and as a result, differing initial pressures. The surcharge pressures represented overburden plus soil suction. The test was used to develop curves of swell versus depth.
Navy (1971)	Navy method	United States	Using overburden plus design structural loads to represent the initial surcharge pressure, consolidation-swell testing was completed to arrive at swell versus depth relationships.
Wong and Yong (1973)	Wong and Yong method	England	Testing involved swell versus depth are determined by Komornik, Wiseman and Ben-Yacob, and the Navy method, with the exception that the surcharge pressures were a combination of overburden and hydrostatic pore water pressures.
Gibbs (1973)	USBR	United States	Two tests conducted on adjacent samples. The first test involved a consolidation-swell test under light surcharge pressures, while the second was focused on maintaining constant volume.
Smith (1973)	Direct model method	Texas, United States	Consolidation-swell tests were conducted on samples that were inundated at overburden or end-of-construction surcharge pressure.

Source	Test Method	Use Location	Brief Description
Jennings et al. (1973)	Simple oedometer method	South Africa	The procedure involved a departure from the double oedometer test. A single sample was loaded to overburden, then unloaded to constant seating load, inundated and allowed to swell, and culminating in adherence to the conventional consolidation procedure.
Teng et al. (1972 and 1973) and Teng and Clisby (1975)	Mississippi State Highway Department method	Mississippi, United States	Testing involved completion of consolidation-swell tests on both remolded and undisturbed samples that were both inundated at overburden surcharge pressures.
Porter and Nelson (1980)	Controlled strain test	Colorado, United States	The testing involved constant volume swell pressure obtained by incremental, strain-controlled pressure reduction.
Fredlund et al. (1980)	University of Saskatchewan method	Canada	The test is constant volume. The procedure included sample disturbance and deflection of the apparatus corrections.
Sridharan et al. (1986)	Sridharan, Rao and Sivapullaiah method	India	Testing was completed using three methods. The first test was a conventional consolidation test. The second involved the determination of equilibrium void ratios for differing consolidation pressures. The third test involved maintaining constant volume. The three test results were combined to evaluate the swelling pressures of expansive clay soils. The method is intended to yield an upper bound value, a least value, and an intermediate value.
Erol et al. (1987)	Erol, Dhowian and Yousef method	Saudi Arabia	An assessment of three methods was made to predict heave from clay soils. The three methods were the Improved Swell Oedometer (ISO) test, the Constant Volume Swell (CVS) test, and the Swell Overburden (SO) test.

Source	Test Method	Use Location	Brief Description
Shanker et al. (1987)	Shanker, Ratman and Rao method	India	Cubic soil samples were tested to evaluate multi-dimensional swell behavior. Swelling of the samples was allowed to occur in 1-, 2- , and 3-dimensions under a nominal surcharge.
Al-Shamrani and Al-Mhaidib (1999)	Al-Shamrani and Al-Mhaidib method	Saudi Arabia	A triaxial cell and oedometer were used to evaluate the vertical swell of expansive soils under multi-dimensional loading conditions. Several series of triaxial swell tests were conducted through which the influence of confinement on the predicted vertical swell was evaluated.
Basma et al. (2000)	Basma, Al-Homoud and Malkawi method	Jordan	Two commonly used method, zero swell test and the swell-consolidation test; and two relatively new techniques, "restrained swell test" and "double oedometer swell test" are using to study the swell pressure of the expansive soil. The intent is to obtain more reasonable results for swell pressure that more closely resemble field conditions.
Subba, Rao and Tripathy	Subba, Rao and Tripathy method	India	One-dimensional oedometer is used to study the swell-shrinkage behavior of compacted expansive soils. The compression-rebound tests were conducted on aged and un-aged compacted specimens by incrementally loading them to a certain surcharge and then unloading. And the cyclic swell-shrinkage tests were carried out in fixed ring oedometers with the facility for shrinking the specimens at fixed temperature under constant surcharge pressure.
American Society for Testing and Materials (ASTM)	ASTM D4546	United States	Using either remolded or native relatively undisturbed samples, the volume change of an expansive soil is determined under full wetting. The method may involve one or more samples from the same depth and location. An oedometer test

Source	Test Method	Use Location	Brief Description
			apparatus is used that employs initial and progressive loading characteristics. For a single specimen, the sample is loaded with an initial stress, then saturated. Subsequent stress applications are applied to the sample after the swell under the initial load has completed, or to maintain zero strain. For multiple samples, each separate sample is subjected to a different stress level and then inundated. Strains are measured for each imposed stress condition. Results can include the strain under a lightly loaded slab, swell pressure, and total strain anticipated beneath an imposed foundation contact stress.

2.4 Summary of Oedometer-Based Procedures to Estimate 1-D Heave

Oedometer-based methods are commonly used in the industry to predict heave, and as shown below, the form of the equation used to compute heave is fairly consistent, with heave strain being assumed to be linear with log net stress (or an "equivalent" net stress) , and primary differences in approach being the manner in which the heave index (modulus) is computed. Within the oedometer procedure is the ability to obtain a measure swell pressure, which is important in the determination of one-dimensional heave.

Heave prediction, arising from the determination of volume change under full wetting conditions, commonly uses an effective stress-based approach from data obtained from an oedometer test. Several alternates of the test method start with a requirement that a soil sample is laterally restrained in a consolidometer and then allowed free access to water. For undisturbed clay soils, an initial load is applied to the sample that is equivalent to a seating pressure, the existing vertical overburden stress or structural loading, after which the final strain is recorded for that condition. Then, the sample is allowed access to free-water in the consolidometer, again followed by a recording of the associated final strain from that condition. Additional loading can be applied to the sample after the wetting-induced volume change has completed. Relative to the expansion of clay soils, the method can yield the free swell of the sample under a small contact stress (or prototype stress), and an estimate of the swell pressure.

2.4.1. Jennings (1965)

Jennings (1965) presented a correlation between measured surface heave and the heave prediction based on the double oedometer test. The procedure recommended by Jennings is based on the amount of swell being independent of the stress path followed. Undisturbed samples retrieved from within the active zone are tested under a small seating load. Duplicate samples are tested for each layer represented, one at the natural water content and the second being inundated with water and allowed to swell until reaching equilibrium. A plot of the two test curves would culminate when they both coincide the virgin portion as shown in Figure 2.8 through moving each curve vertically, i.e. the soaked sample test is shifted downward to meet the sample tested at the natural moisture content.

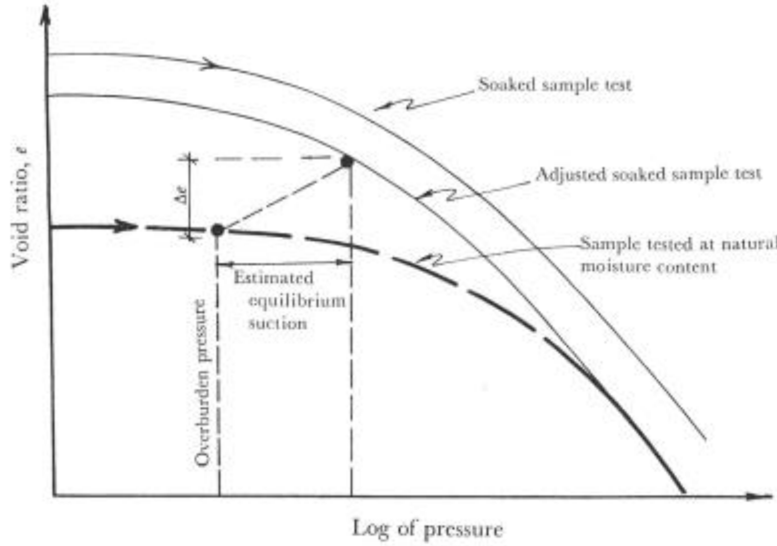


Figure 2.8: Prediction of the Surface Soil Heave Using the Double Oedometer Test (Jennings, 1965)

Relative to positions on the *e-log p* curve, the change in void ratio obtained when moving from the void ratio at the overburden pressure at the natural water to the void ratio at the overburden pressure plus the equilibrium soil suction value on the adjusted curve, is used as the predictor for heave.

2.4.2. Department of the Army (1983)

The potential total vertical heave beneath the base of a foundation is presented by Equation (23). The relationship includes an initial condition and a condition following saturation.

$$AH = N(DX) \sum_{i=NBX}^{i=NEL} \frac{e_r(i) - e_o(i)}{1 + e_o(i)} \tag{23}$$

Where,

AH is the potential vertical heave at the base of a foundation, in feet
N is the fraction of volumetric swell that occurs as heave in the vertical direction
DX is the increment of depth, in feet

NEL is the total number of increments
NBX is the number of nodal points at the base of the foundation
$e_r(i)$ is the final void ratio of element *i*
$e_o(i)$ is the final void ratio of element *i*
The bottom nodal point, equal to *NEL* + 1, is set at the active depth.

Essentially, the Army method is simply summing the strains from the active zone depth to the base of the foundation.

2.4.3. Picornell and Lytton (1984)

Picornell and Lytton (1984) used Equation (24) to compute heave – adding a factor, f, for varying lateral confinement situations, e.g. soil cracks.

$$\Delta H = \sum_{1}^{n} f_i \left(\frac{\Delta V}{V}\right)_i H \tag{24}$$

Where,

H is the stratum thickness
$\Delta V/V_i$ is the volume change with respect to initial volume
f_i is the factor to include the effects of the lateral confinement

2.4.4. Dhowian (1990)

Dhowian (1990) presented Equation (25).

$$\Delta H = H \frac{C_s}{1 + e_o} log\left(\frac{P_s}{P_o}\right) \tag{25}$$

Where,

C_s is the swell index
P_s is the swelling pressure
P_o is the effective overburden pressure

2.4.5. *Nelson and Miller (1992)*

Nelson and Miller (1992) used Equation (26).

$$\Delta H = H \frac{C_\rho}{1 + e_o} log\left(\frac{\sigma'_f}{\sigma'_{cv}}\right) \quad (26)$$

Where,

C_ρ is the heave index
σ'_{cv} is the swelling pressure from a constant volume swell test
σ'_f is the vertical stress at the midpoint of the soil layer for the conditions under which heave is calculated

2.4.6. *Nelson (2006)*

Nelson (2006) presented Equations (27) and (28).

$$\Delta H = HC_H log\left[\frac{\sigma'_{cv}}{(\sigma'_{vo})_z}\right] \quad (27)$$

$$C_H = \frac{\%S_A}{log\left[\frac{\sigma'_{cv}}{(\sigma'_i)_A}\right]} \quad (28)$$

Where,

C_H is the heave index
σ'_{cv} is the swelling pressure from a constant volume swell test
σ'_{vo} is the vertical stress at the midpoint of the soil layer for the conditions under which heave is being calculated

2.4.7. *Vanapalli et al. (2010)*

Vanapalli et al. (2010) presented Equation (29).

$$\Delta H = C_s \frac{H}{1 + e_o} log\left\{\frac{KP_f}{10^{\left(\frac{C_s}{C_w}\Delta w\right)}}\right\} \quad (29)$$

Where,

H is the thickness of the soil layer

P_f $(=\sigma_y+\Delta\sigma_y-u_{wf})$ is the final stress state
K is a correction parameter
C_s is the swelling index
σ_y is the total overburden pressure
$\Delta\sigma_y$ is the change in total stress
u_{wf} is the final pore-water pressure
e_o is the initial void ratio
C_w is the soil suction modulus ratio
Δw is the change in water content

2.5 Soil suction-based Methods

Rather than predicting the maximum potential heave, the soil suction-based approach has the capability to predict the heave of an unsaturated soil during the wetting process (Snethen, 1980) – that is, the heave in response to some specified soil suction change, typically less than that induced by full wetting, can be estimated.

For the soil suction-based methods below, oedometer tests may be used to estimate a soil suction change index (e.g. slope of percent swell versus log soil suction); however, the oedometer test at overburden stress is not used to constrain the amount of heave estimated / computed., such is done with the suction-oedometer method.

2.5.1. Kassiff et al. (1969)

Kassiff (1969) recommended the following procedure to predict the amount of soil heave at the surface:

- Determine the depth of the active zone
- Obtain undisturbed samples of the clay at fixed intervals throughout the active zone
- Estimate the pore water soil suction to be expressed throughout the active zone
- Perform swelling tests on the undisturbed samples in a consolidometer, allowing

the clay to swell in contact with free water. Each sample should be surcharged by a vertical stress equal to the overburden pressure plus an additional surcharge equal to the value of the pore water soil suction expected at equilibrium conditions

- Integrate the percent swell obtained from the swelling tests with depth (Kassiff, 1969)

It should be expected that at depths exceeding the active zone, no appreciable swell is expected for the samples surcharged by a pressure equal to the overburden pressure plus the equilibrium pore water tension.

2.5.2. Aitchison (1973)

Aitchison (1973) created Equation (30).

$$\Delta H = \frac{1}{100}\int_0^{H_s} I_{pt}\Delta u \Delta h \tag{30}$$

Where,

ΔH is the surface movement
I_{pt} is the instability index of the soil
Δu is the change in soil suction at depth Z, measured in pF, below the ground surface
Δh is the thickness of the soil layer under consideration
Hs is the depth of the design soil suction change

2.5.3. Lytton (1977)

Lytton (1977) created Equation (31).

$$\Delta H = -\gamma_h H log_{10}\left(\frac{h_f}{h_i}\right) - \gamma_\sigma H log_{10}\left(\frac{\sigma_f}{\sigma_i}\right) \tag{31}$$

Where,

h_f, h_i are final and initial water potentials

σ_f is the applied octahedral normal stress

σ_i is the octahedral normal stress above which overburden pressure restricts the volumetric expansion

γ_h, γ_σ are two constants characteristic of the soil

2.5.4. Johnson and Snethen (1978)

Johnson and Snethen (1978) created Equation (32) through Equation (34).

$$\Delta H = H\frac{C_\tau}{1+e_o} log\frac{h_o}{h_f + \alpha\sigma_f} \tag{32}$$

$$C_\tau = \frac{\alpha G_s}{100B} \tag{33}$$

$$log h_o = A - Bw_o \tag{34}$$

Where,

H is the stratum thickness
C_τ is the soil suction index
α is the compressibility index
e_o is the initial void ratio
h_f is the final matric soil suction in kPa
σ_f is the final applied overburden and external pressures
h_o is the matric soil suction without surcharge pressure in kPa

2.5.5. Snethen (1980)

Snethen (1980) created Equation (35) through Equation (37).

$$\Delta H = H\frac{C_\tau}{1+e_o}(A - Bw_o) - log(\tau_{mf} + \alpha\sigma_f) \tag{35}$$

$$C_\tau = \frac{\alpha G_s}{100B} \tag{36}$$

$$log\tau_m = A - Bw \tag{37}$$

Where,

C_τ is the soil suction index
τ_{mf} is the final matric soil suction
σ_f is the final applied overburden and external pressures
α is the compressibility factor
A, *B* are constants (y-intercept and slope of the soil suction versus water content curve, respectively)

2.5.6. Fredlund (1983)

Fredlund (1983) proposed Equation (38) to predict one-dimensional heave on expansive clay soils. The equation utilizes that constant volume swell, or CVS, from the oedometer test results.

$$\Delta H = C_s \frac{H_l}{1 + e_o} log \left\{ \frac{P_f}{P_s'} \right\} \tag{38}$$

Where,

H_l is the thickness of the i_{th} layer
$P_f=(\sigma_y+\Delta\sigma_y-u_{wf})$ is the final stress state
P'_s is the corrected swelling pressure
C_s is the swelling index
σ_y is the total overburden pressure
$\Delta\sigma_y$ is the change in total stress
u_{wf} is the final pore-water pressure
e_o is the initial void ratio

2.5.7. McKeen (1980) and McKeen (1992)

McKeen (1980) and McKeen (1992) created Equation (39) through Equation (44).

$$\Delta H = -\gamma_h H log \frac{h_f}{h_i} \tag{39}$$

$$\gamma_h = -\frac{\frac{\Delta V}{V_i}}{log_{10}\frac{h_f}{h_i}} \quad (40)$$

$$\Delta H = HC_h\Delta\tau fs \quad (41)$$

$$C_h = (-0.02673)\left(\frac{dh}{dw}\right) - 0.38704 \quad (42)$$

$$f = \frac{(1 + 2K_o)}{3} \quad (43)$$

$$s = 1 - 0.01(\%SP) \quad (44)$$

Where,

γ_h is the soil suction compression index

h_f, h_i are the final and initial weighted soil suction, respectively

$\frac{\Delta V}{V_i}$ is the volume change with respect to the initial volume

C_h is the soil suction compression index, i.e. the slope of the volume change – soil suction curve

$\Delta\tau$ is the soil suction change in pF

f is the lateral restraint factor

K_o is the coefficient of at-rest earth pressure; equal to 1

s is the coefficient for load effect on heave

SP is the percent swell pressure applied

2.5.8. Mitchell and Avalle (1984)

Mitchell and Avalle (1984) created Equation (45) and Equation (46).

$$\Delta H = I_{pt}\Delta uH \quad (45)$$

$$I_{pt} = \frac{\frac{\Delta L}{L}}{\Delta w}\left(\frac{\Delta w}{\Delta u}\right) \quad (46)$$

Where,

I_{pt} is the instability index
Δu is the change being soil suction

2.5.9. Hamberg and Nelson (1984)

Hamberg and Nelson (1984) introduced Equation (47) through Equation (50).

$$\Delta H = H\frac{C_w}{1 + e_o}\Delta w \quad (47)$$

$$C_w = \frac{\Delta e}{\Delta w} \quad (48)$$

$$\Delta H = H\frac{C_h}{1 + e_o}\Delta log(h)_i \quad (49)$$

$$C_h = C_w D_h \quad (50)$$

Where.

C_w is the soil suction modulus ratio

Δw is the change in water content

C_h is the soil suction index with respect to void ratio

D_h is the soil suction index with respect to the moisture content

2.5.10. Dhowian (1990)

Dhowian (1990) created Equation (51) through Equation (55).

$$\Delta H = H\frac{C_\psi}{1 + e^o}log\frac{\psi_i}{\psi_f} \quad (51)$$

$$C_\psi = \frac{\alpha G_s}{100B} \quad (52)$$

$$\Delta H = H \frac{\alpha G_s}{1 + e^o} (w_f - w_i) \tag{53}$$

$$\Delta H = H C_w (w_f - w_i) \tag{54}$$

$$C_w = \frac{\alpha G_s}{(1 + e_o)} \tag{55}$$

Where,

C_ψ is the soil suction index

w_i is the initial soil suction

w_f is the final soil suction

α is the volume compressibility factor

B is the slope of the soil suction versus water content relationship

G_s is the specific gravity of solids

C_w is the moisture index

2.5.11. Naiser (1997)

Naiser (1997) while working with Lytton presented five valuable advancements in conjunction with unsaturated soils:

- A procedure for determining the magnitude of equilibrium suction for a particular soil profile and location.
- A procedure that enables a practitioner to calculate the depth to equilibrium suction, for a soil profile with multiple layers.
- An equation to calculate the velocity of water in the horizontal direction as it pertains to unsaturated soil flow.
- A method by which the vertical differential soil movement from expansive clay soils can be determined. The transient case of after-construction and before the soil

under the center of a slab has reached its equilibrium moisture content was considered.

- A procedure to predict the differential movement in expansive clay soils, when considering the moisture effects described above.

The Naiser (1997) efforts were instrumental in the development of the PTI 3rd Edition method for design and construction of post-tensioned slabs on grade. The method presented by Naiser (1997) also considers modifications to suction profiles to account for post-construction vegetation planting in proximity to structures.

The series of procedures presented by Naiser (1997) can be used in a step by step process to predict the vertical differential soil movement in expansive soils through the use of calculated suction profiles and the volume strain of the soil. A suggested software design layout is presented and used to apply the theory. The initial step involves determining the soil characteristics for the soil profile including PI, percent fine clay, activity ratio, cation exchange activity, and the matrix suction compression index. Using the software package and the soil characteristic data, a baseline equilibrium suction, hm (units of pF), can be established, with all suction profiles being calculated relative to the baseline. The equilibrium suction can only be calculated for the soil layer located at the depth to constant suction through an iterative process within the software. This procedure and algorithm used to determine the depth of constant suction, z_m, is based on a set of cases for the soil surface conditions, including bare soil, grass at the surface, flower bed at the surface, tree at the surface, and measured suction profiles. Once the depth to constant suction has been established, the horizontal velocity of water flow is calculated to determine a distinct distance from under a barrier or slab to another known suction profile. The equation to determine the horizontal velocity equation and exit suction value was developed using Darcy's law and Mitchell's unsaturated permeability equations. This equation allows the determination of the suction value at any point between two distinct locations in an incremental soil layer (Mitchell, 1980).

With the depth to constant suction and the horizontal velocity established, the values can used to determine the differential soil movement using a post construction transient case. This case allows for the calculation of the volume strain immediately after construction of a slab, and before the soil near the center of the slab has achieved its equilibrium moisture content. This post construction case is modeled within the software through the use of annual weather cycles. The goal is to calculate the soil suction profile at the time of construction, and then dampen the profile using the weather data until it achieves the equilibrium profile, and thereby anticipate the maximum differential soil movement compared to all other cases. Through the use of the software and algorithms presented, practicing engineers are able to use data from common geotechnical laboratory tests and determine the necessary soil profile information, which can then be applied to the vertical differential soil movement computation.

2.5.12. Cover and Lytton (2001)

Based on Lytton (1977 and 1994) the relationship to solve the change in volume for expansive clay soils is as follows. Cover and Lytton (2001) created Equation (56) and Equation (57).

$$\Delta H = -\gamma_h H log_{10}\left(\frac{h_f}{h_i}\right) - \gamma_\sigma H log_{10}\left(\frac{\sigma_f}{\sigma_i}\right) \tag{56}$$

Where,

h_f, h_i are final and initial water potentials

σ_f is the applied octahedral normal stress

σ_i is the octahedral normal stress above which overburden pressure restricts the volumetric expansion

γ_h, γ_σ are two constants characteristic of the soil – soil suction compression indices

To address γ_h Equation (56) was proposed:

$$\gamma_h = \left[\frac{\left[\left(\frac{COLE}{100} + 1\right)^3 - 1\right] + \left[1 - \frac{1}{\left(\frac{COLE}{100} + 1\right)^3}\right]}{2} \right] \tag{57}$$

Where,

$\left[\left(\frac{COLE}{100} + 1\right)^3 - 1\right]$ is the soil suction compression index for the swelling case

$\left[1 - \frac{1}{\left(\frac{COLE}{100}+1\right)^3}\right]$ is the soil suction compression index for the shrinkage case

The calculated soil suction compression index was then adjusted to 100% fine clay content. To find the COLE (coefficient of linear extensibility) value, Figure 2.9 through Figure 2.13 can be used.

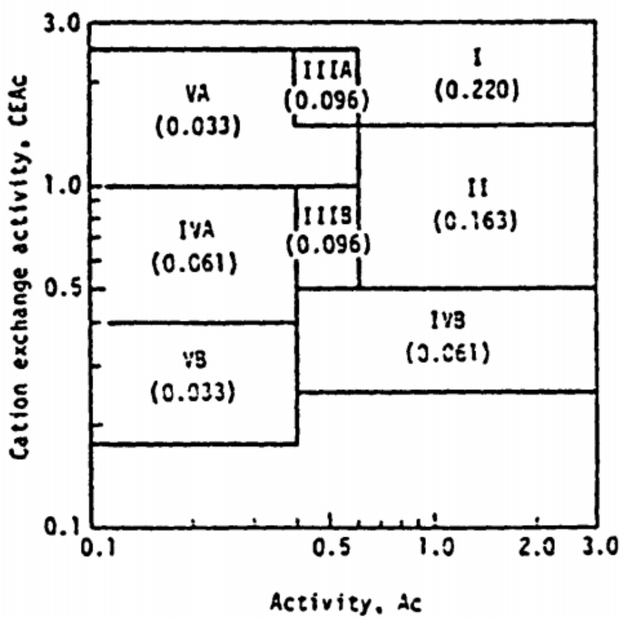


Figure 2.9: Classification Chart for COLE Values (McKeen and Hamberg, 1981)

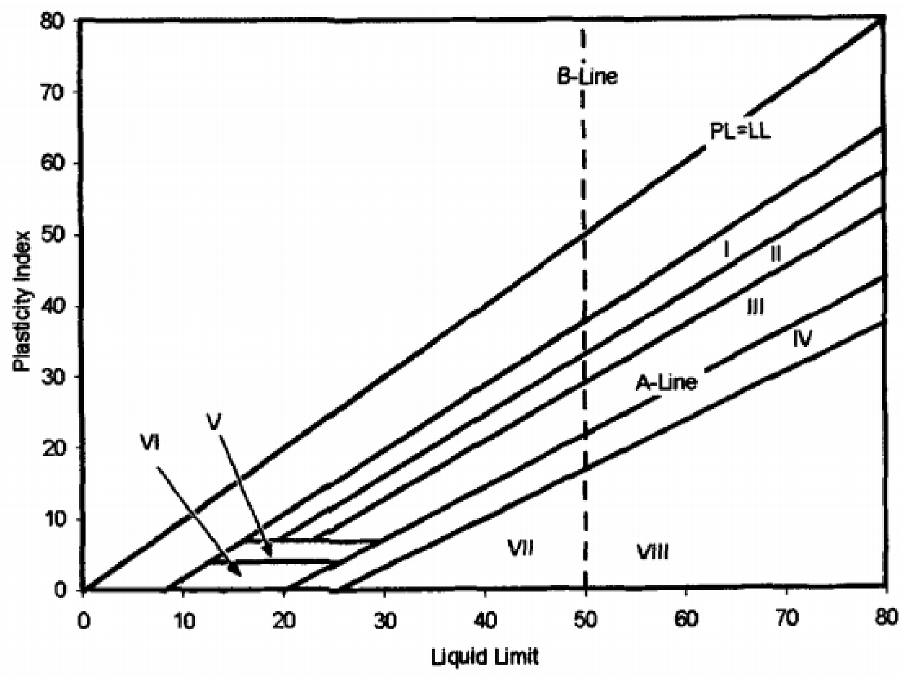


Figure 2.10: Partitions for Soil Data Based on Mineralogical Characteristics (after Casagrande, 1948, and Holtz and Kovacs, 1981)

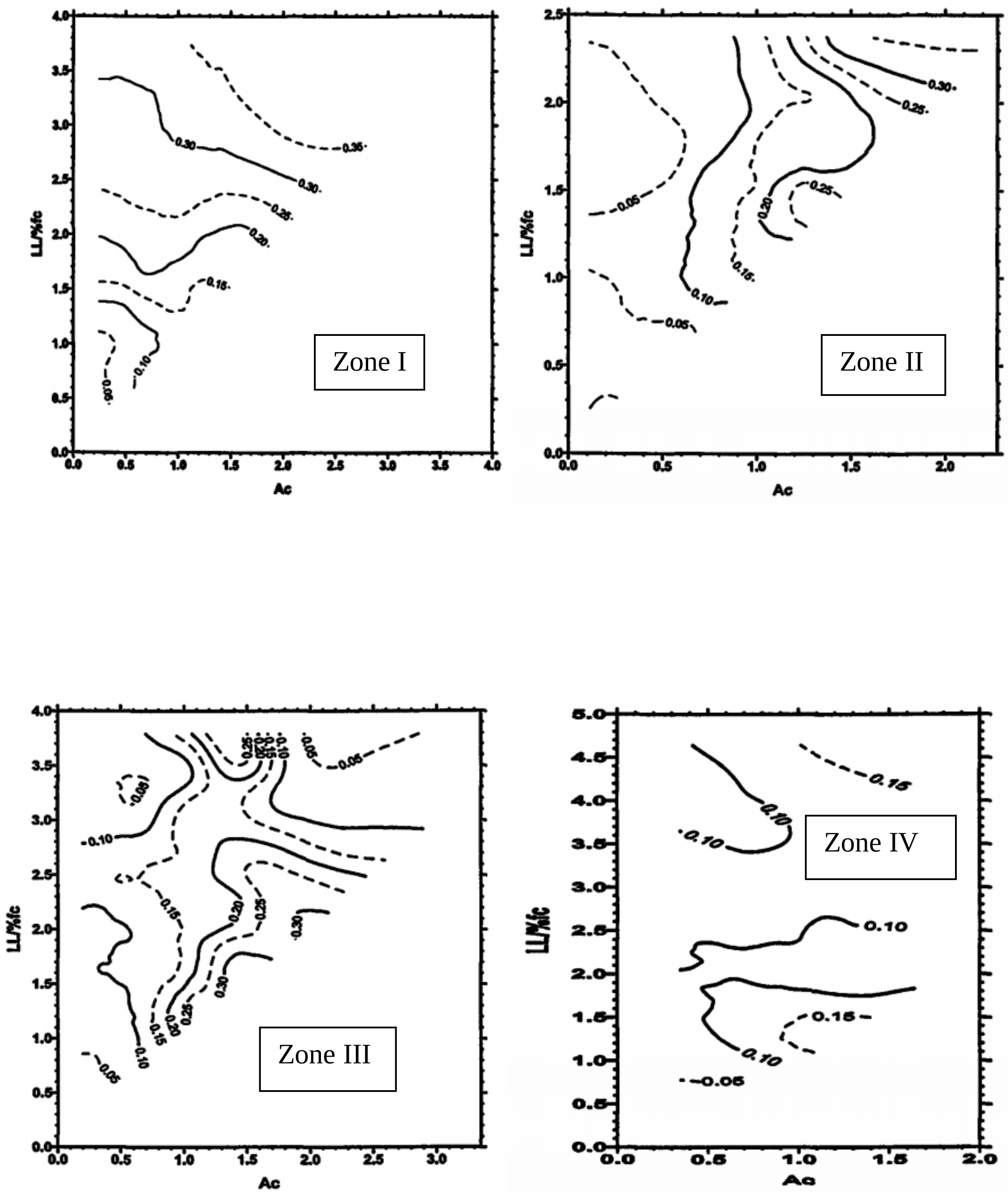


Figure 2.11: Predicted Soil Suction Compression Index Values for Zones I Through IV to be Used With Figure 2.10

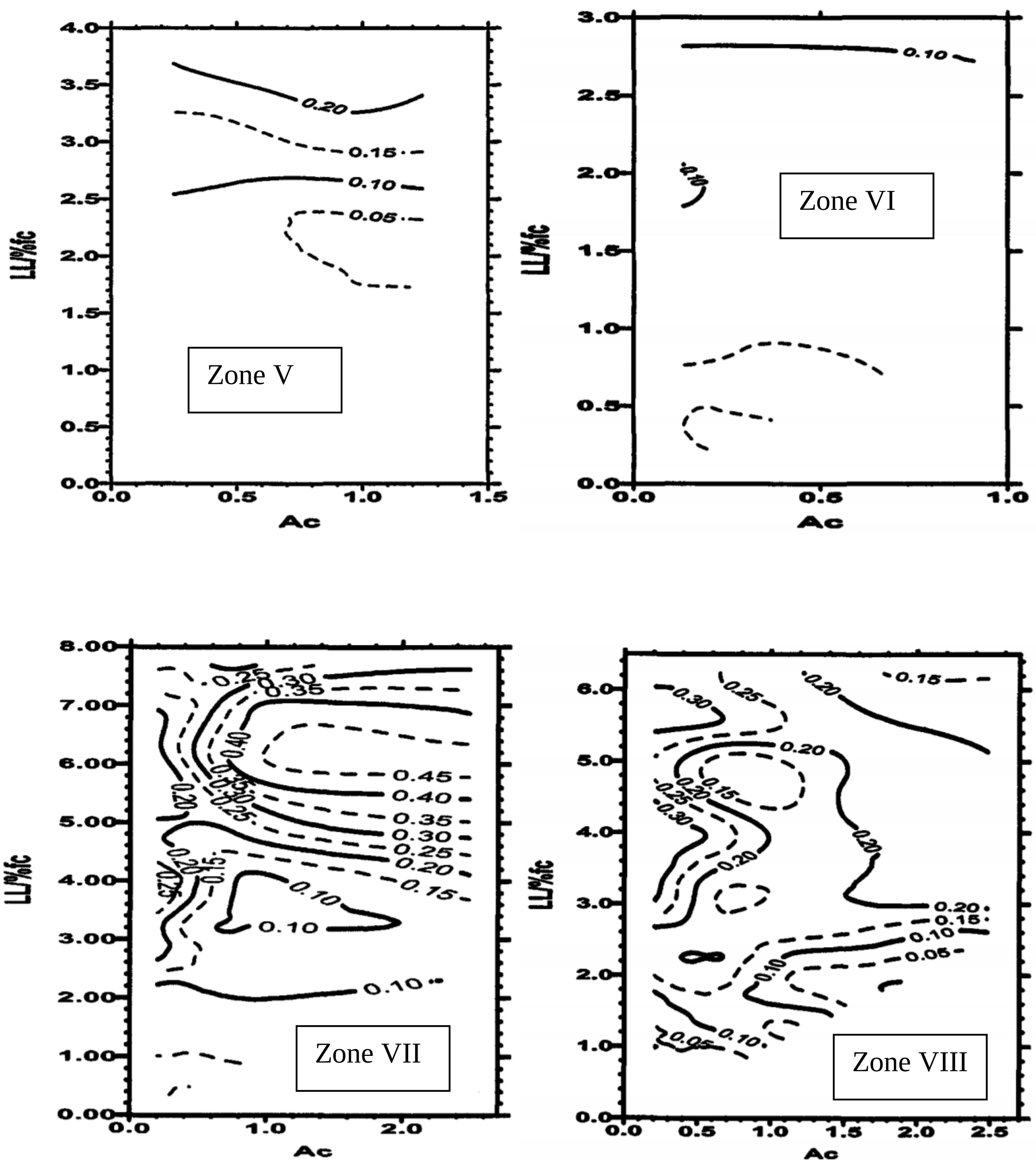
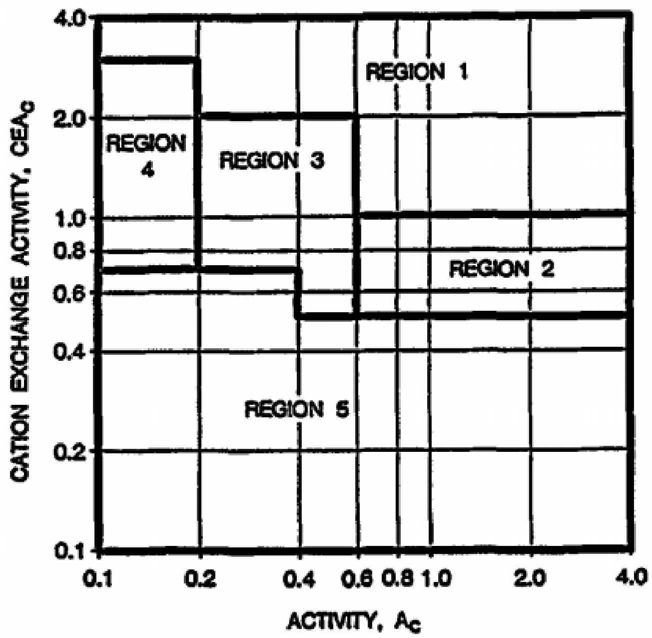


Figure 2.12: Predicted Soil Suction Compression Index Values for Zones V Through VIII to be Used With Figure 2.10



Region	A	B	n	r^2
1	0.23	-1.46	20	0.79
2	0.20	-1.14	45	0.77
3	0.14	-0.71	93	0.72
4	0.13	-0.31	21	0.51
5	0.09	-0.96	20	0.87

Figure 2.13: COLE Values That are Based on CEA_c, A_c and Fine Clay (Hamberg, 1985)

2.5.13. Post-tensioning Institute (PTI – 1980, 1996, 2004 and 2008)

The heave prediction using the PTI method is based on adherence to the following eighteen critical steps:

1. Calculate the Plasticity Index (PI) = LL - PL.

2. Calculate the percentage of fine clay (%fc) = (%-2μ / %-#200) x 100; where (%-2μ) is the percentage of the total sample finer than 2 microns, and the (%-#200) is the percentage of the total sample passing the #200 sieve expressed as a percentage. The %fc is that percentage of the passing the #200 sieve that is also finer than 2 microns.

3. Determine the soil zone based on LL and PI using the PTI (2004) Mineral Classification Chart.

4. Calculate the Activity Ratio (PI / %fc).

5. Calculate LL / %fc.

6. Determine γo using the corresponding Zone Chart based on (LL / %fc) and (PI / %fc) as described by Covar and Lytton (2001), presented in section 2.5.12.

7. Calculate Soil suction Compression Index (γ_h); where γ_h swell = γ_o eγ_o (% fc / 100) and γ_h shrink = γ_0 e-γ_o (% fc / 100). The PTI (2004) also suggests three alternative ways to determine (γ_h swell) using the expansion index (ASTM D4829) procedure, using the consolidation-swell pressure test (ASTM D4546 Method C) procedure, and using the overburden pressure swell test procedure. The PTI (2004) gives empirical equations correlating the γ_h swell with indices resulting from these tests. In addition, the PTI (2004) presents empirical correction equations to correct γ_h for soils containing coarse grains.

8. Calculate the Unsaturated Diffusion Coefficient (α):

$$\alpha = 0.0029 - 0.000162(S) - 0.0122(\gamma_h)$$

Where,

S=-20.29+0.1555(LL)-0.117(PI)+0.0684(%-#200)

S is the slope of the soil suction-gravimetric water content curve

9. Calculate the Modified Unsaturated Diffusion Coefficient (α'), for which $\alpha' = \alpha F_f$;

Where,

F_f is the soil fabric factor that depends on the soil profile content of roots, layers, fractures or joints: F_f = 1.0 for (no more than 1 per vertical foot), F_f = 1.3 (2 to 4 per vertical foot), F_f = 1.4 (5 or more per vertical foot).

10. Determine the Thornthwaite Moisture Index (TMI) from the 1948 map as indicated in the 1996 version. Of course, Based on the work of Singhar (2018), the 2006 TMI can be determined using the online interactive map.

11. Determine e_m based on the TMI for center and edge lift using the PTI (2004) e_m-TMI chart as shown in Figure 2.14.

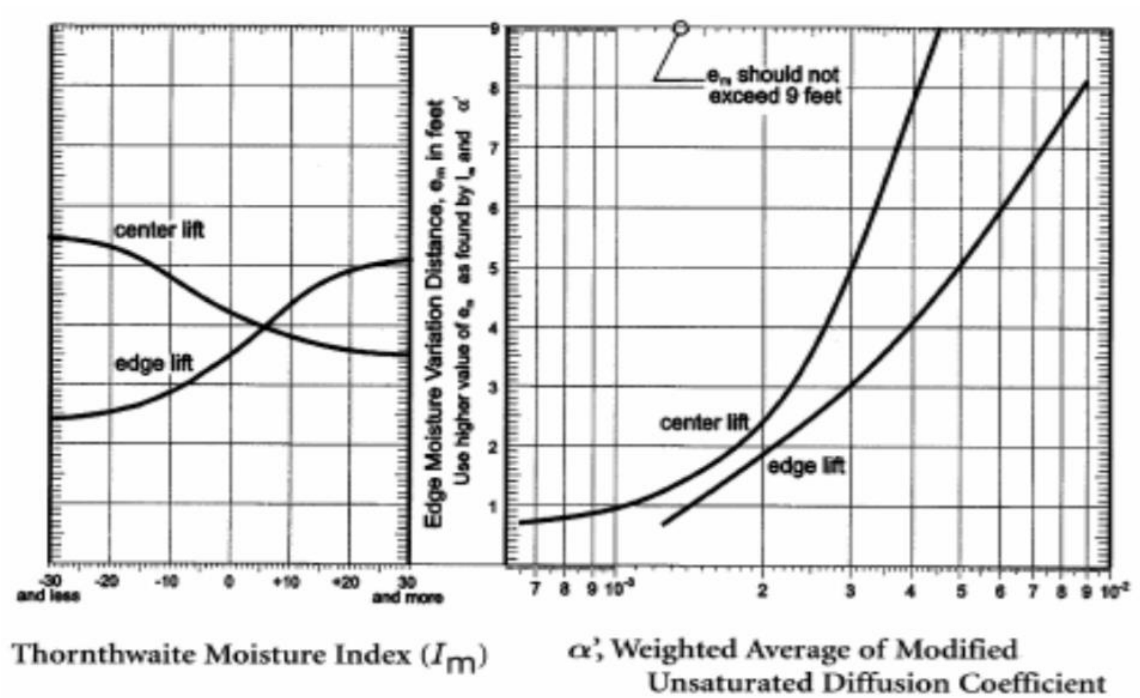


Figure 2.14: TMI (I_m) – e_m Relationship, PTI (2004)

12. Calculated the weighted (α'): α'weighted = $(\sum F_i(D_i)\, \alpha'_i)/(\sum F_i(D_i))$;

Where,

D is the layer thickness

F is the layer weight factor (for example, F=3 for the top layer is a three-layer active zone)

13. Determine the e_m based on the weighted (α') for center and edge lift using the PTI (2004) e_m-α' relationship chart (Figure 2.14) and use the maximum values of e_m obtained from this step and Step 11.

14. Determine the Equilibrium Soil suction based on the TMI (Im) using the PTI (2004) equilibrium soil suction chart.

15. Determine the wet and dry soil suction profiles at the surface with the aid of the PTI recommended values (2.5 pF for the wettest condition as in the case of heavy rain and no drainage, 4.5 pF for the driest condition if the surface soil suction is controlled by vegetation, or 6.0 pF for the driest condition if the surface is controlled by evaporation from bare soil).

16. Determine the Stress Change Factors (SCF) for both center and edge lift as directed by the PTI (2004) SCF tables, such as the example in Figure 2.15.

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 2.15: Stress Change Factor (SCF) for Use in Determining y_m (PTI, 2004)

17. Determine the weighted Soil suction Compression Index (γ_{hmod}) with the same weighting technique as mentioned in Step 12.

18. Calculate y_m for the center and edge lift as follows:

$$y_{m\ edge} = \left(SCF_{edge}\right)\left(\gamma_{h\ swell\ modified}\right)$$

$$y_{m\ center} = \left(SCF_{center}\right)\left(\gamma_{h\ shrink\ modified}\right)$$

2.5.14. Lu (2010)

Lu (2010) proposed a simple technique to estimate the 1-D heave in expansive soils. The technique requires the plasticity index, I_p, and variation of the water content with depth within the active zone. The Lu (2010) method is based on the methods employed by Fredlund (1983) and Hamberg and Nelson (1984). The simplified form of Equation (58) which is an equation incorporating both Fredlund (1983) and Hamberg and Nelson (1984) is:

$$\Delta H = C_s \frac{H_l}{1 + e_o} log \frac{KP_f}{10^{\left(\frac{C_w}{C_s}\Delta w\right)}} \tag{58}$$

Where,

ΔH is the 1-D heave prediction

H_l is the thickness of the clay layer

e_o is the initial void ratio

K is correction parameter

C_s is the swelling index

C_w is the soil suction modulus ratio

P_f is the final stress state

The method is applicable for expansive clays with a plasticity index greater than or equal to 30. Empirical relationships can be used to arrive at values for C_w, C_s and K. Figure 2.16, Figure 2.17 and Figure 2.18 can be used to determine the needed values.

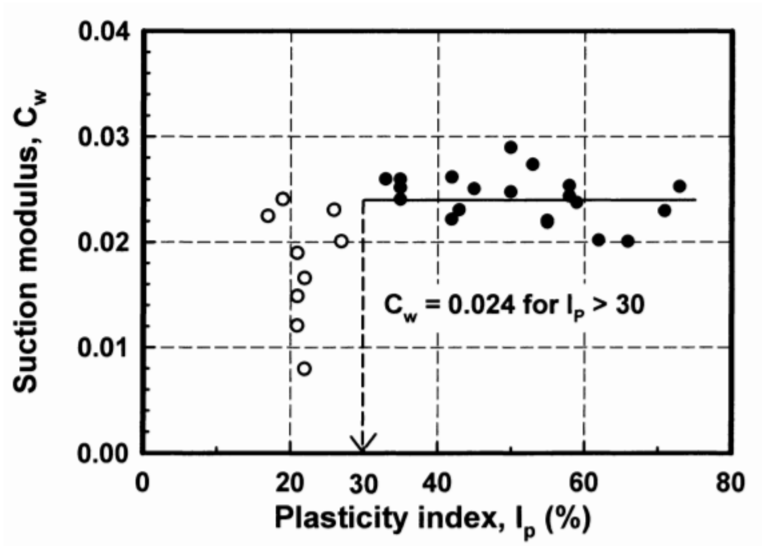


Figure 2.16: Relationship Between I_p and C_w (Lu, 2010)

Figure 2.16 shows that for a plasticity index greater than or equal to 30, the value of C_w is 0.024. Figure 2.17 is the relationship between the swelling index, C_s, and the plasticity index, I_p, using published results that are shown on the figure.

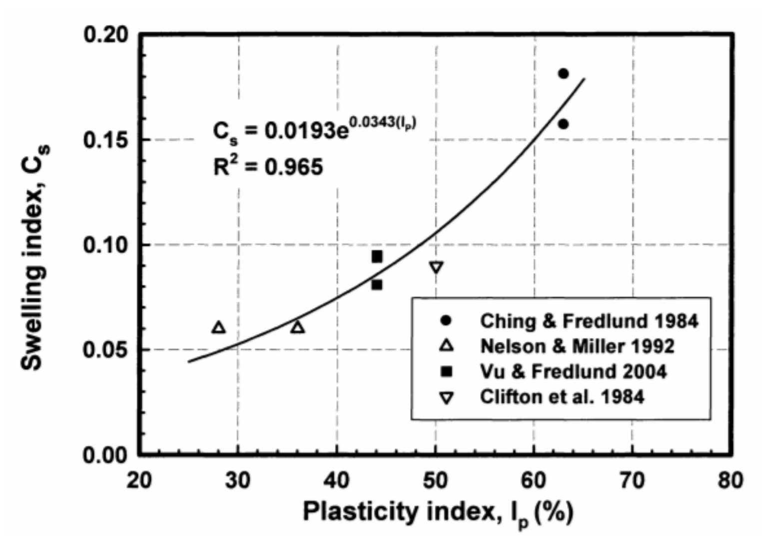


Figure 2.17: Relationship Between C_s and I_p (Lu, 2010)

The swelling index values, C_s, were determined from ASTM D4546 using undisturbed samples that were extracted from an approximate depth of 2.5 m, noted by the author to correspond to the depth of the active zone in many regions of the world. The relationship suggests that the swelling index, Cs, increases exponentially with increasing Ip, following Equation (59):

$$C_s = 0.0193e^{0.0343(I_p)} \tag{59}$$

The relationship between K and the water content change, Δw can be expressed by Equation (60):

$$K = \omega e^{\theta(\Delta w)} \tag{60}$$

Figure 2.18 illustrates the relationship between K and Δw.

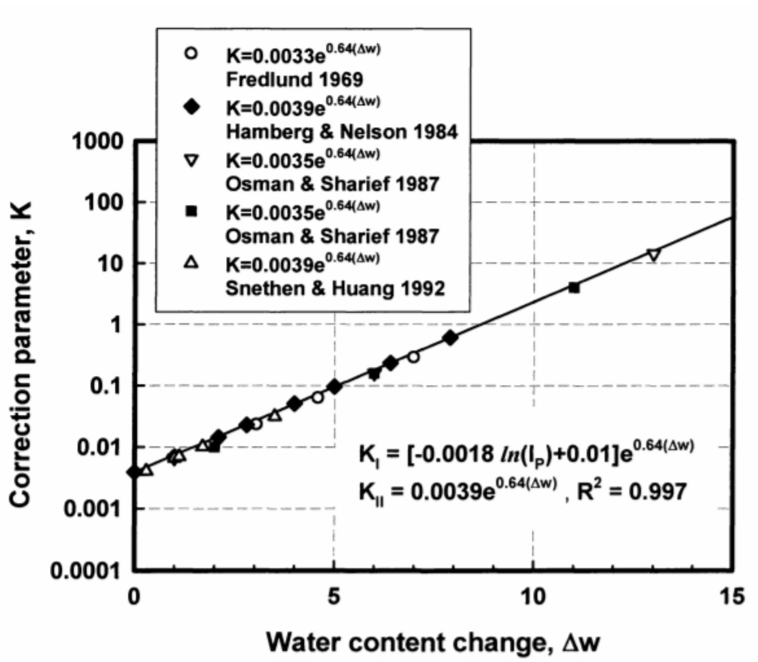


Figure 2.18: Relationship Between the Water Content Change, Δw, and the Correction Parameter, K (Lu, 2010)

Figure 2.19 shows the variation of the factor, w, with the Ip. A nonlinear trend is exhibited as the factor *w*, increases with an increasing I_p.

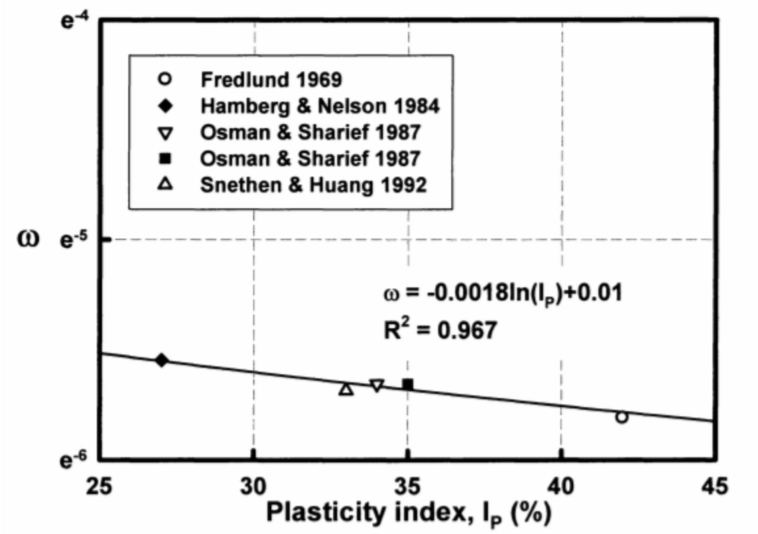


Figure 2.19: Relationship Between *w* and I_p (Lu, 2010)

The relationship between K, ω and Δw can be rewritten as Equation (61):

$$K_I = \omega e^{0.64(\Delta w)} \tag{61}$$

Where,

$\omega=-0.0018ln(I_p)+0.01$, as a function of I_p

K_I can then be rewritten as: $K_I = [-0.0018ln(I_p) + 0.01]e^{0.64(\Delta w)}$

Using the data from five case studies, a K_{II} factor is developed: $K_{II} = 0.0039e^{0.64(\Delta w)}$

Both K_I and K_{II} were utilized as separate methods to evaluate the 1-D heave potential for the Lu, 2010, study. Figure 2.20 presents the comparison data using the KI and KII techniques and five notable methods.

Reference	Fredlund (1969)	Hamberg & Nelson (1984)	Osman & Sharief (1987)	Osman & Sharief (1987)	Snethen & Huang (1992)
Site Location	Regina Canada	Colorado U.S.A.	Sudan	Sudan	Wynnewood U.S.A.
Case study	A	B	C	D	E
Measured Heave (mm)	84	72	142	150	180
Hamberg & Nelson (1984) Method (mm)	134	116	238	250	613
Estimated Heave by Author (mm)	151	116	295	295	2157
Proposed Technique I (using K_I) (mm)	110	93	154	155	290
Proposed Technique II (using K_{II}) (mm)	103	92	157	159	291
Estimated C_s	0.082	0.05	0.064	0.062	0.06
Estimated C_w	0.024	0.024	0.024	0.024	0.024
Ratio I	1.32	1.29	1.08	1.03	1.61
Ratio II	1.23	1.28	1.11	1.06	1.62

Figure 2.20: Summary of Case Study Results Compared with the Work of Lu, 2010

The Lu, 2010, study demonstrated that heave predictions were reasonably close to measured heave magnitudes.

2.5.15. AS2870-2011

Equation (62) is presented by AS2870-2011.

$$y_s = \frac{1}{100}\sum_{n=1}^{N}\left(I_{pt}\Delta uh\right)_n \tag{62}$$

Where,

Y_s is the characteristic surface movement in mm

α is the lateral restraint factor

I_{pt} is the instability index, in %/pF

Δu is the soil suction change average over the thickness of the layer under consideration, in pF

h is the thickness of the layer under consideration, in mm

N is the number of soil layers within the design depth of soil suction change

$I_{pt} = \alpha I_{ps}$

In the cracked zone (unrestrained), α=1.0

In the uncracked zone (retrained laterally by soil and vertically by soil weight, $\alpha=2.0-\frac{z}{5}$

Where *z* is the depth from the finished ground surface, in m, to the centroid of the area defined by the soil suction change profile and the thickness of the soil layer under consideration in the uncracked zone.

In the absence of exact data, the depth of the cracked zone shall be taken as:

$0.5H_s$ to H_s
$0.75H_s$ in Adelaide and Melbourne
$0.5H_s$ in other areas

H_s to be determined as presented in Figure 6.90

The ys classification is by site classification as shown in Figure 2.21.

Characteristic surface movement (y_s) mm	Site classification	Description
$0 < y_s \leq 20$	S	Slightly reactive
$20 < y_s \leq 40$	M	Moderately reactive
$40 < y_s \leq 60$	H1	Highly reactive
$60 < y_s \leq 75$	H2	Very Highly reactive
$y_s > 75$	E	Extremely reactive

Figure 2.21: Site Classification by y_s

2.5.16. Tu and Vanapalli (2015)

Knowing that expansive soils typically behave in the unsaturated state, and only extremely rarely reaching a completely saturated condition, the potential heave will decrease with a corresponding decrease in soil suction. A decrease in soil suction can result from snow, rainfall and runoff infiltration. Tu and Vanapalli (2015) proposed an approach for estimating heave for site whose moisture changes from its initial condition to it wetted, yet unsaturated, condition. Equation (63) below was presented to achieve the objective.

$$\Delta h = \Delta h_i - \Delta h_w = C_s h \left[\frac{log\left(\frac{P_o}{P_{si}}\right)}{1 + e_i} - \frac{log\left(\frac{P_o}{P_{sw}}\right)}{1 + e_w} \right] \tag{63}$$

Where,

Δh is the total anticiapted heave

Δh_i is the maximum potential heave at the initial condition

Δh_w is the maximum potential heave at a subsequent wetting condition

C_s is the soil suction compression index

h is the layer thickness

P_o is the is the overburden pressure

P_{si} is the swelling pressure of the soil at the initial condition

P_{sw} is the swelling pressure of the soil at the subsequent wetting condition

e_i is the void ratio of the initial condition

e_w is the void ratio of the subsequent wetting condition

CHAPTER 3 LITERATURE REVIEW OF SOIL SUCTION ESTIMATION METHODS THAT SERVE AS A BASIS FOR SOIL SUCTION SURROGATES CENTERED ON INDEX OR COMMON PROPERTIES UNIQUE TO EXPANSIVE CLAYS

As part of this task, an extensive literature review has been completed on expansive soils to gather data like that described above and to further study methodologies that have been proposed by researchers over the past six decades.

Since circa 1952, numerous methods have been developed to serve as predictors for soil suction. The purpose of this paper is to recap the known method and comment on their relative effectiveness. The predictive methods are presented in chronological order within each school of thought. There appear to be three schools of thought in predicting soil suction based on results from conventional and currently employed testing methods. The first method is concerned with soil suction “sign-posts,” that estimate soil suction based on differing water contents and their variation from standard index tests. The second school of thought is directly tied to SWCC fitting curve relationships. A great deal of work regarding SWCC fitting parameters has been completed to arrive at appropriate relationships that can be used to estimate soil suction. However, while the “fitting parameter” methods have significant scientific merit, they are incredibly complicated in practice and as such, are not used by practicing professionals. The third method would simply be classified as empirical relationships. Empirical relationships include, but are not limited to, associations with Thornthwaite Moisture Index (TMI), swell pressure, commonly completed index property tests, gradation to a limited extent, and any combination of such values. The purpose of this paper is to present all known soil suction prediction methods for potentially expansive soils, whether they fall under the fitting parameters approach, soil suction sign posts, or empirical relationships. Specifically, our focus is on the prediction of soil suction for expansive clay soils that are characterized by a plasticity index of at least 15. Soils with a plasticity index less than 15 are not covered in the context of this literature search as they are considered relatively non-expansive soils. A great many methods have, therefore, not been presented in this paper if they are concerned solely with soils exhibiting a plasticity index less than 15 or are otherwise specific to granular or cohesionless soils. An examination of these methods has arrived at specific target relationships that need further study for substantiation. To date, the best example of such a relationship that can be used by practicing engineers, is the wPI. This simple, yet tangible relationship, has been well received. It is the aim of this study that an equation or equations can be found that are based on common lab tests or relationships, thereby enabling greater simplicity to estimate soil suction. If such a relationship can be found (a soil suction surrogate), then greater acceptance of the practice of unsaturated soil mechanics may be realized. Possible surrogates for predicting soil suction will be gleaned from all known methods and used in further analysis to arrive at a viable option in predicting soil suction.

3.1 Soil suction Sign Posts

Soil suction sign posts are not related to any specific plasticity, grain-size distribution, or swell pressure. The premise behind soil suction sign posts is tied to specific water contents at which certain conditions occur, e.g. a soil suction of 3.0 pF will be applicable for any soil at a moisture content equal to 0.4 times its liquid limit. Other relationships of soil suction sign posts are presented below in chronological order.

3.1.1. Croney (1952-1953)

Croney (1952-1953) asserts that because the soil suction is directly affected by the geological and chemical history of the soil, there cannot be a unique relationship between soil suction and index properties. However, he does concede that in some cases in England, an apparent correlation may exist between the moisture content and soil suction for undisturbed samples. The idea being that as the moisture content corresponds to the plastic limit, the corresponding soil suction was equal to 2.0 pF on the wetting curve.

3.1.2. Uppal (1966)

Uppal concluded that remolded cohesive soils have a relationship between the plastic limit and soil suction. It was determined that a soil suction of 0.5 pF was applicable for the plastic limit on the wetting curve, whereas the soil suction on the drying curve for the plastic limit corresponds to a value of 1.5 pF (Uppal, 1966).

3.1.3. Gay and Lytton (1972)

Among the early sign post soil suction estimates are the data presented in Table 3.1 by Gay and Lytton (1972), following up on previous work by Hillel (1971).

Table 3.1: Soil Suction Values (Gay and Lytton, 1972; Hillel, 1971)

Soil Suction		State	Soil-plant-atmosphere continuum
pF	kPa		
1	1	Liquid Limit	
2	10	Saturation limit of soils in the field	15 kPa for lettuce
3	100	Plastic Limit of highly plastic clays	Soil / stem
4	1,000	Wilting point of vegetation (pF=4.5)	Stem / leaf: 1500 kPa for citrus trees

Soil Suction		State	Soil-plant-atmosphere continuum
pF	kPa		
5	10,000	Tensile strength of water	Atmosphere; 75% relative humidity (pF = 5.6)
6	100,000	Air dry	45% relative humidity
7	1,000,000	Oven dry	

The sign posts presented assume that the equilibrium moisture condition is related to the equilibrium soil suction value.

3.1.4. Braun and Kruijne (1994)

For the agricultural industry, soil suction at various states has been explained. Following a heavy rainstorm for example, the soil is described as at field capacity, corresponding to a matric head (soil suction) in the range of 2.0 to 2.3 pF (more specifically $2.0 < pF < 2.3$). As the soil reaches its wilting point (because the plant roots cannot extract any further water from the soil below this point), the corresponding matric soil suction will be at approximately 4.2 pF.

Figure 3.1 shows the soil-water retention curves of three different soils:

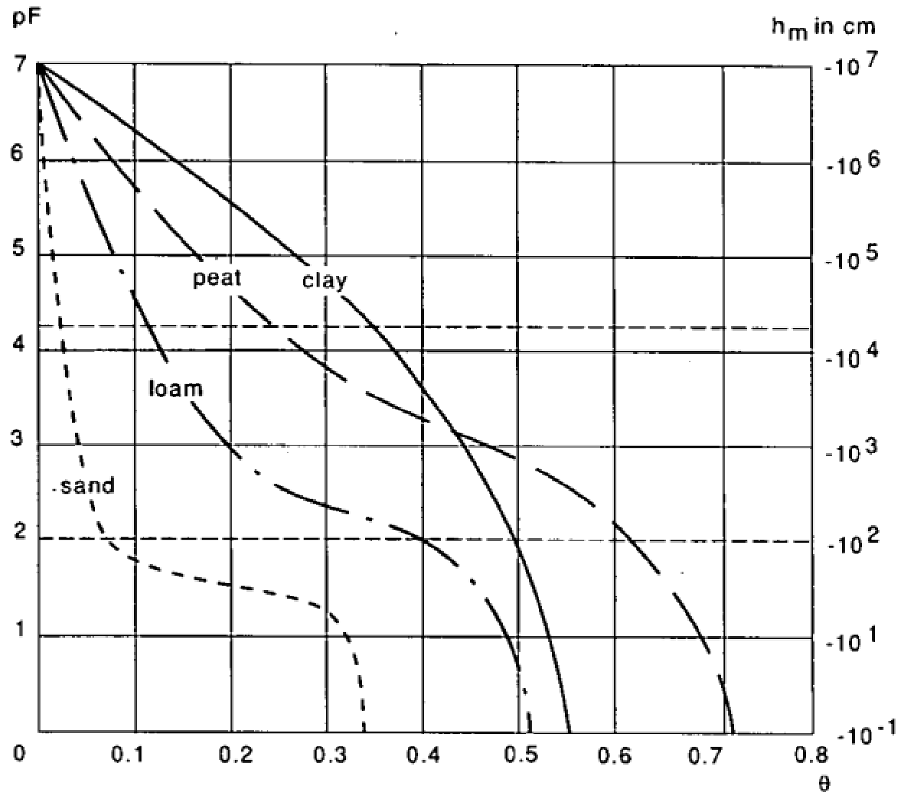


Figure 3.1: Soil-Water Retention Curves for Different Soil Types; Soil suction in pF Versus Volumetric Water Content

To more simply present Figure 3.1 in terms of volumetric water content, Table 3.2 is presented.

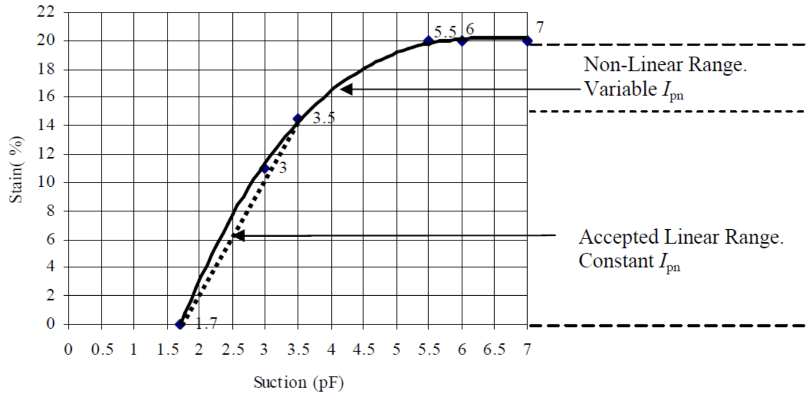
Table 3.2: Typical Soil Suction Values for Various Soils (Braun And Kruijne, 1994)

Volumetric moisture content (%)	Soil Suction (pF)			
	Sand	Loam	Clay	Peat
0	7.0	7.0	7.0	7.0
10	1.8	4.6	6.3	5.7
20	1.5	3.0	5.6	4.6
30	1.3	2.3	4.7	3.6
40	0.0	2.0	3.7	3.2
50		0.7	2.0	2.8
60		0.0	0.0	2.2
70				0.3

Braun and Kruijne (1994) note that soils in their natural state would not experience a soil suction of 7.0 pF because this value would be reserved for an oven-dried condition.

3.1.5. Lytton (1994)

Soil suction sign posts were created to avoid the need to carry out soil suction tests. Figure 3.2 presents the data.



7.0 pF	≡	Oven Dry at 105^0-110^0 C,	6.0 pF	≡	Air Dry,	5.5 pF	≡	Shrinkage Limit,
3.5 pF	≡	Plastic Limit,	3.0 pF	≡	0.4 Liquid Limit,	1.7 pF	≡	Swell Limit.

Figure 3.2: Sign Posts by Lytton, 1994

Based on the data shown above, the strain-soil suction relationship is presented as linear for soil suctions in the range of 1.7 to 3.5 pF, and non-linear for soil suctions in the range of 3.5 to 5.5 pF. Other sign posts from Lytton (1994) are reported by Naiser (1997) in Table 3.3.

Table 3.3: Soil suction Sign Posts for Lytton (1994) as Reported by Naiser (1997)

Field Capacity	2.0 pF
Wet Limit for Clays	2.5 pF
Plastic Limit	3.5 pF
Wilting Point of Plants	4.5 pF
Tensile Strength of Confined Water	5.3 pF
Air Dry at 50% Humidity	6.0 pF
Over Dry	7.0 pF

3.1.6. Lytton and Aubeny (2002)

Lytton and Aubeny (2002) have presented the following soil suction scale, Figure 3.3, for corresponding index properties or conditions.

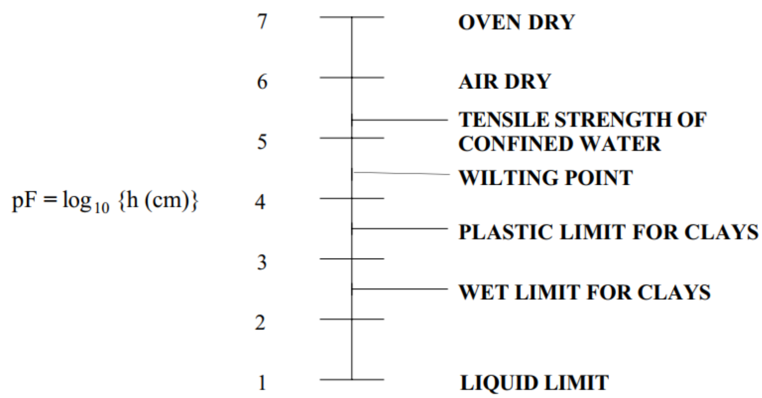


Figure 3.3: Soil suction Scale Relative to Specific Moisture Contents (Lytton And Aubeny, 2002)

Further, Figure 3.3 above was reported to not be considered in current practice, as of that time, in the shrink/swell to soil suction relationship. This relationship has been determined to be constant for soil suctions in the range of 2.4 to 4.2 pF. Additionally, the strain above 4.2 pF is ignored.

3.1.7. Lopes (2006)

Lopes (2006) presented his first listing of soil suction sign posts, Table 3.4 which has been refined through time. The values are based on shrinkage test values in conjunction with climate and geological settings.

Table 3.4: Soil Suction Sign Posts (Lopes, 2006)

Soil suction (pF)	Soil State
7.0	Oven dry (105^{o} C)
6.0	Air Dry
5.5	Shrinkage Limit
3.5	Plastic Limit
3	0.4 Liquid Limit
1.7	Swell limit

3.1.8. Lopes (post 2006)

During a visit to Australia in the 1990s, Lytton gave suggestion to the Soil suction Sign Post concept to Lopes. The soil suction sign post criteria were presented in Dominic Lopes Master's Thesis in 2000. Since that time, the sign post criteria have been expanded as indicated in Table 3.5:

Table 3.5: Modified Soil suction Sign Posts (Lopes, post 2006)

Soil suction (pF)	Soil State	References
6.5-7+	Oven dry (105^{o} C)	Cameron, Leeper, Lytton, Uren, Mitchell et al.
6.0	Air Dry	Lytton, Leeper, Uren
5.5	Shrinkage Limit	McKeen Mitchell et al
5.3	0.1 Saturation (unloaded)	Lytton
4.2-4.5	Wilting point	Lytton, Leeper, Uren et al.
3.2-3.5	Plastic Limit	Lytton
3	0.4 Liquid Limit	Driscoll
2.0-2.5	Field capacity	McKeen, Leeper, Uren
2.0	0.88 Saturation	Lytton
1.5-2.0	Swell limit (unloaded)	McKeen
1.0	Liquid Limit	Lytton, McKeen
0-1.0	Saturation (Unloaded)	Leeper, Uren

Per personal communication with the author, the references denoted have been found to be more useful to Dominic Lopes in professional practice. Further, only values in the range of 3 to 7 pF are of prime interest to his continuing work.

3.1.9. Hargreaves / AW Geotechnical – Australian Institute of Building Surveyors (AIBS) (2012)

Bruce Hargreaves (2012) has suggested the following key soil suction sign-post prediction guidelines for Australia soils (Table 3.6):

Table 3.6: Key sign posts by Hargreaves (2012)

Soil suction (pF)	**Soil suction (kPa)**	**Soil State**	**Comment**
6.5-7+	320,000 to 10^6	Oven dry (105° C)	Only achieved in a laboratory
6.0	100,000	Air Dry	Only achieved in a laboratory
5.5	32,000	Shrinkage Limit	The dry state where further drying does not result in volume change
4.2-4.5 (Typical assumed value of 4.4)	1,600 to 3,200	Wilting point	The state of the soil where trees can no longer suck moisture from the soil
3.2-3.5 (Typical assumed value of 3.5)	150 to 320	Plastic Limit	
3	100	0.4 Liquid Limit	
2.0-2.5 (Typical assumed valued of 2.5)	10 to 32	Field capacity	The moisture where in the field a soil cannot get any wetter, i.e. the wet limit for clays
1.0	1	Liquid Limit	
0-1.0		Saturation (Unloaded)	Leeper, Uren

3.2 SWCC Fitting Parameter Methods Using Index and Gradation Properties

3.2.1. Zapata (1999)

Zapata (1999) proposed the use of the Fredlund and Xing (1994) equation with the following fitting parameters presented in Equation (64) through (67):

$$a = 0.00364(\mathrm{wPI})^{3.35} + 4(\mathrm{wPI}) + 1112 \tag{64}$$

$$\frac{b}{c} = -2.313(\mathrm{wPI})^{0.14} + 5 \tag{65}$$

$$c = 0.0514(\mathrm{wPI})^{0.465} + 0.5 \tag{66}$$

$$\frac{h_r}{a} = 32.44e^{0.0186(\mathrm{wPI})} \tag{67}$$

The Zapata model from 1999 generated a family of curves for SWCC data for both granular and fine-grained (cohesive) soils. Relative to the expansive soils the predictive curves are based on wPI, as stated above. Figure 3.4 illustrates the useful family of curves developed from the Zapata model.

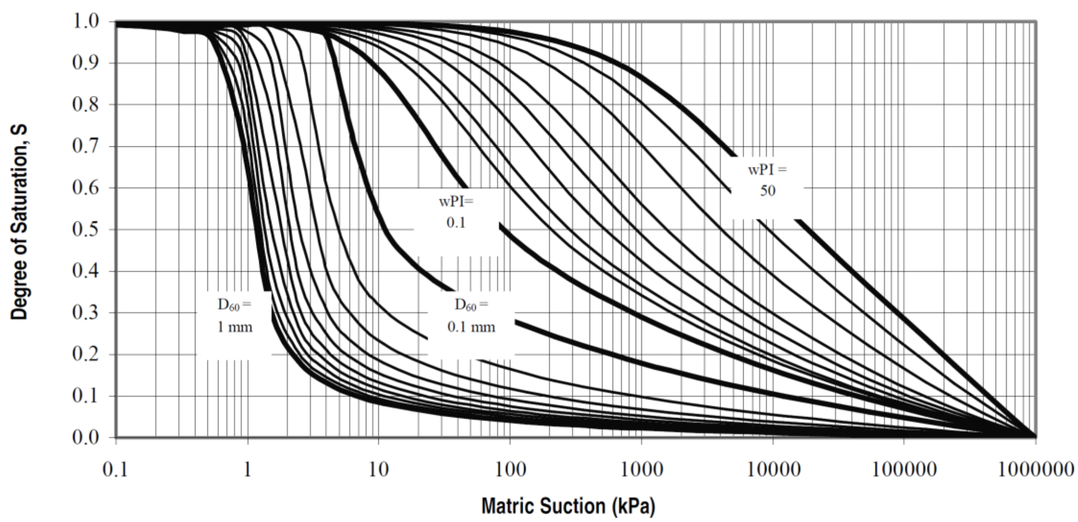


Figure 3.4: Estimating Soil Suction Based on Index Properties (Zapata, 1999)

3.2.2. Zapata, et al. (2000)

Zapata et al. (2000) showed in Equations (68) through (71) that the Fredlund-Xing (1994) curve-fitting model gives the best fitting results compared with other curve fitting functions.

$$a = 0.00364(\mathrm{wPI})^{3.35} + 4(\mathrm{wPI}) + 11 \tag{68}$$

$$\frac{b}{c} = -2.313(wPI)^{0.14} + 5 \tag{69}$$

$$c = 0.0514(wPI)^{0.465} + 0.5 \tag{70}$$

$$\frac{h_r}{a} = 32.44e^{0.0186(wPI)} \tag{71}$$

3.2.3. Lytton, Aubeny and Bulut (2004)

The slope of the relationship between soil suction and volumetric water content for a clay soil can be generated using the following process as shown in Equation (72) through (75):

The slope of the soil suction versus volumetric water content relationship is denoted as S, and can be estimated by:

$$\begin{aligned} S = -20.29 + 0.1555(LL\%) - 0.117(PI\%) \\ + 0.0684(\% - 200) \end{aligned} \tag{72}$$

From Figure 3.5, the soil suction in pF relationship to volumetric water content is:

$$\frac{\theta}{1.0} = \frac{pF_{int} - pF}{|S|\frac{\gamma_w}{\gamma_d}} \tag{73}$$

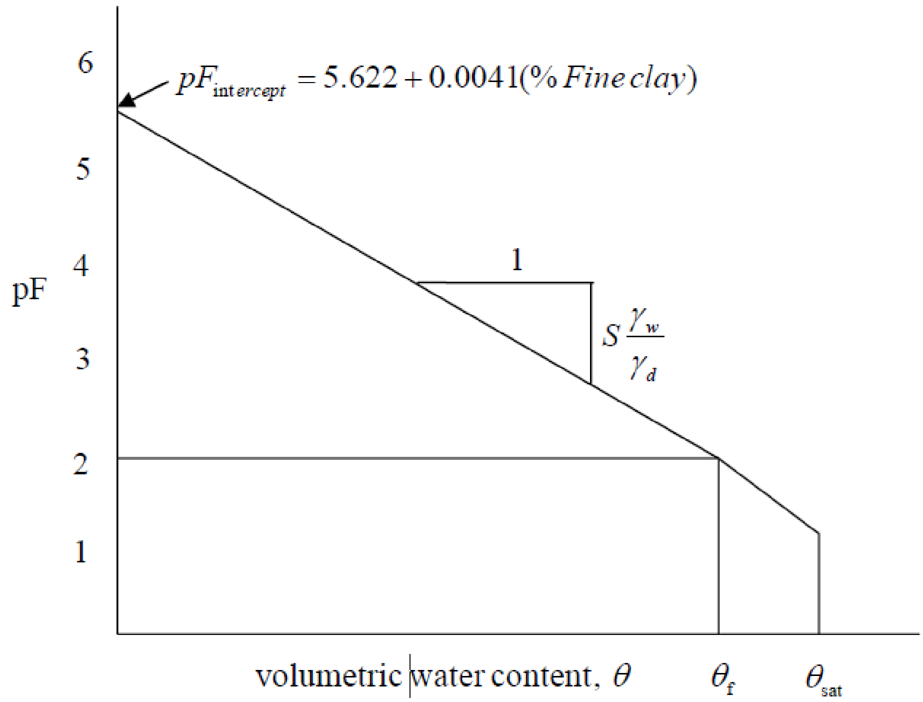


Figure 3.5: Soil suction Versus Volumetric Water Content Curve for a Clay Soil

Rearranging the preceding equation gives the relationship for the volumetric water content:

$$\theta = \frac{pF_{int} - pF}{|S|\frac{\gamma_w}{\gamma_d}} \tag{74}$$

Gravimetric water content is then given by:

$$w = \frac{pF_{int} - pF}{|S|} \tag{75}$$

3.2.4. Perera, et al. (2005)

Using the Fredlund and Xing (1994) Equation (76) through (79) as a basis, an estimation of index property based SWCC equations for plastic soils whose wPI > 0 is made possible using the following fitting parameters:

$$a_f = 32.835\ln(wPI) + 32.438 \quad (76)$$

$$b_f = 1.421(wPI)^{-0.3185} \quad (77)$$

$$c_f = -0.2154\ln(wPI) + 0.7145 \quad (78)$$

$$h_f = 500 \quad (79)$$

3.2.5. Houston et al. (2006)

For plastic soils, Houston et al. (2006) used the product of the PI and the P_{200} coupled with a one-point SWCC measurement to estimate the SWCC for the soil. Greater effectiveness for the method involves an adjustment of the PI and P_{200} product to pass through the one-point SWCC measurement. The Fredlund and Xing (1994) equation was used in the Houston et al. (2006) method, when the fitting parameters are as follows as presented by Equation (80) through (83):

$$a = 32.835\ln(P_{200}PI) + 32.438 \text{ (in kPa)} \quad (80)$$

$$n = 1.421(P_{200}\ PI)^{-0.3185} \quad (81)$$

$$m = -0.2154\ln(P_{200}PI) + 0.7145 \quad (82)$$

$$\psi_r = 500\ \text{kPa} \quad (83)$$

3.2.6. Witczak, Zapata and Houston (2006)

A work that was a major part of the NCHRP 1-40D project is known as "Models Incorporated into the Current Enhanced Integrated Climate Model." To estimate the corrected volumetric water content due to changes in density was given by Equation (84).

$$\theta_{w-corr} = \frac{G_s w}{1 + e} \quad (84)$$

Where,

θ_{w-corr} = corrected volumetric water content

G_s = Specific gravity of solids

w = Gravimetric water content

e = Void ratio

The hysteresis effect was not considered in the NCHRP 1-40D predictive equations. Using the Fredlund and Xing (1994) equation as a basis, the following Equations (85) through (89) were presented as part of the MEPDG model for plastic soils (Witczak, et al. 2006, MEPDG model):

$$a_f = 32.835\{\ln(wPI)\} + 32.438 \tag{85}$$

$$b_f = 1.421(wPI)^{-0.3185} \tag{86}$$

$$c_f = -0.2154\{\ln(wPI)\} + 0.7145 \tag{87}$$

$$h_{rf} = 500 \tag{88}$$

Where,

wPI= Weighted plasticity index

The constraints required for these equations are:

If $a_f < 5$, then $a_f = 5$

If $c_f < 0.01$, then $c_f = 0.03$

For the special case where the wPI is less than 2 for plastic soils, a weighted average is used for the a_f parameter. For the a_f parameter, the following model was proposed:

$$a_{f\,avg} = a_{fn} + \frac{wPI}{2}\left(a_{fp} - a_{fn}\right) \tag{89}$$

Where,

$a_{f\,avg}$ = a_f average

a_{fn} = a_f value using the model for non-plastic soils

a_{fp} = a_f value using the model for plastic soils

For the parameters b_f, c_f, and h_{rf}, the above equations apply.

3.2.7. Zapata et al. (2007)

The basis of the Zapata et al. (2007) model is the Fredlund and Xing (1994) equation.

Where,

$a_f = 0.00364(\mathrm{WPI})^{3.35} + 4(\mathrm{WPI}) + 11$

$\frac{b_f}{c_f} = -2.313(\mathrm{WPI})^{0.14} + 5$

$c_f = 0.0514(\mathrm{WPI})^{0.465} + 0.5$

$\frac{\psi_r}{a_f} = 32.44e^{0.0186(\mathrm{WPI})}$

WPI=PF x I_p, PF = fines content (in decimal), I_p = plasticity index, e = void ratio

3.2.8. Hernandez (2011)

Two approaches were proposed to predict the SWCC. Hernandez (2011) proposed an improved set of models for the Fredlund and Xing (1994) equation. Expressed in terms of the degree of saturation, Equation (90) can be written:

$$S(\%) = \frac{\theta_w}{\theta_s} = \left[1 - \frac{\ln\left(1 + \frac{\psi}{h_r}\right)}{\ln\left(1 + \frac{1{,}000{,}000}{h_r}\right)}\right]\left(\frac{1}{\left\{\ln\left[e + \left(\frac{\psi}{a_f}\right)^{b_f}\right]\right\}^{c_f}}\right) \qquad (90)$$

Where,

S (%) = Degree of saturation in percentage

ψ = Matric soil suction in kPa

a_f, b_f, c_f, h_r = SWCC Fitting Parameters

θ_w = Volumetric Water Content

θ_s = Saturated Volumetric Water Content

The analysis was developed separately for plastic soils (fine grained soils) with wPI greater than zero and non–plastic soils (granular soils) with wPI equal to zero. The concept of wPI (previously explained) is a geotechnical expression where the Plasticity Index and the Gradation are directly involved in the analysis. The Weighted Plasticity Index usually called wPI is expressed as Equation (91).

$$wPI = \frac{P_{200}PI}{100} \tag{91}$$

Where,

P_{200} = Percentage of material passing the #200 sieve
PI = Plasticity index expressed as a percentage

For plastic soils, the properties considered in the analysis were: Group Index, the gradation available (percent passing #4, #10, #40, and #200), the total percent of clay (% of soil finer than 0.002 mm), Liquid limit, Plasticity Index and wPI. For non–plastic soils, the properties collected were the Group Index, the gradation (percent passing #4, #10, #40, and #200), the particle sizes (D_{10}, D_{20}, D_{30}, D_{60}, D_{90}), and the shape parameters C_u and C_c. For both sets, volumetric water content values at 0.1, 0.33 and 15 bars of soil suction were available.

Group Index, GI, is an engineering parameter associated with AASHTO classification and used extensively for the analysis of pavement subgrades. The Group Index expression combines two important soil properties: gradation and consistency. The Group Index is expressed as indicated in Equation (92).

$$\begin{aligned} \mathrm{GI} = (\mathrm{P}_{200} - 35)[0.2 + 0.005(\mathrm{LL} - 40)] \\ + 0.01(\mathrm{P}_{200} - 15)(\mathrm{PI} - 10) \end{aligned} \tag{92}$$

Where,

GI = Group Index

P_{200} = Percentage of material passing the #200 sieve

LL = Liquid limit

PI = Plasticity index = LL-PL

Both the Group Index and wPI are functions of gradations and consistency limits. Based on the study, the following parameters were proposed for the SWCC model relative to fine-grained soils (applicable for wPI>0):

$$a_f = 10^{\left(0.69 - \frac{2.7}{1+e^{4-0.14GI}}\right)}$$

$$b_f = 10^{\left(\frac{0.78}{1+e^{6.75-0.19GI}}\right)}$$

$$c_f = 0.03 + 0.62e^{\left(-0.82(\log a_f - 0.57)^2\right)}$$

$$h_r = 494 + \frac{660}{1 + e^{(4-0.19GI)}}$$

To predict the SWCC based on the Atterberg Limits and the percentage passing the #200 sieve (the second approach), the Equation (93) was presented based on wPI and the particle diameter for both plastic and granular soils:

$$\begin{aligned} \log\psi = {} & 0.00005(wPI)^3 - 0.003(wPI)^2 + 0.03wPI \\ & + 1.1355 - (0.0126wPI + 0.7285)\log D \\ & - (0.0011wPI + 0.0044)\log D^2 \\ & + (0.0002wPI + 0.0056)\log D^3 \end{aligned} \tag{93}$$

Where,

D = Particle diameter

For the second approach, or model, correlations were not considered to have performed well.

3.2.9. Wang (2014)

Two existing soil suction prediction models, Zapata et al. (2000) and Fredlund et al. (1997), were used to predict the soil suction of North Carolina residual soil. In the model proposed by Zapata et al. (2000), a weighted plasticity index (PI), i.e., wPI, was used as the main variable to correlate the SWCC parameters. wPI is expressed as the percentage passing the #200 sieve (as a decimal) multiplied by the PI, which is also a percentage. The equations for the wPI and Fredlund and Xing (1994) SWCC parameters are Equations (94) through (97).

$$a = 0.00364(\mathrm{wPI})^{3.35} + 4(\mathrm{wPI}) + 11 \tag{94}$$

$$\frac{n}{m} = -2.313(\mathrm{wPI})^{0.14} + 5 \tag{95}$$

$$m = 0.0514(\mathrm{wPI})^{0.465} + 0.5 \tag{96}$$

$$\frac{\psi_r}{a} = 32.44e^{0.0186(\mathrm{wPI})} \tag{97}$$

Fredlund et al. (1997) model was used to estimate the SWCCs using grain size distribution data and volume-mass properties. The grain size distribution of the soil was divided into small groups of uniform particles. The SWCCs of each soil particle were summed to generate the final SWCC. The predicted SWCCs were generated by inputting the grain size distribution data and volume-mass properties into SoilVision software.

A new model specifically designed for North Carolina residual soil is proposed. Three categories of soil properties were included for the new model development: grain size distribution, Atterberg limits, and volume-mass relationships. The SWCCs were determined using pore size distribution, which correlates directly with grain size distribution. The included parameters are: P200, P5μm (percentage passing 5 μm), P2μm (percentage passing 2 μm), D10, D30, D60, Cu, Cc, LL, PI, Gs, and ρd.

The best subsets analysis indicates that the related soil properties with a, n, and m can be considered as the following general forms of functions, Equations (98) through (100).

$$a = f\left(\frac{1}{D_{10}}, \frac{1}{D_{30}}, \frac{1}{D_{60}}, \frac{D_{60}}{D_{10}}, \rho_d\right) \tag{98}$$

$$n = f\left(P200, \frac{1}{D_{30}}, \frac{D_{60}}{D_{10}}, \rho_d, D_{30}, D_{60}\right) \tag{99}$$

$$m = f(P200, 5\mu m, G_s, \rho_d) \tag{100}$$

The P-value of each term is shown in Table 3.7.

Table 3.7: P-values for Choosing the Terms in Prediction Model

a		n		m	
Term	P-value	Term	P-value	Term	P-value
$1/D_{60}$	0.001	P200	0.049	P200	0.036
$1/D_{30}$	0.008	D_{60}	0.000	5μm	0.000
$1/D_{10}$	0.002	$1/D_{30}$	0.000	G_s	0.012
D_{60}/D_{10}	0.004	D_{60}/D_{10}	0.012	ρ_d	0.000
		ρ_d	0.006		

The prediction models for the Fredlund-Xing (1994) a, n, and m parameters are Equations (101) through (103).

$$a = 17.2 + \frac{1.89}{D_{60}} - \frac{0.363}{D_{30}} - \frac{0.063}{D_{10}} + 2.5\left(\frac{D_{60}}{D_{10}}\right) \tag{101}$$

$$n = -0.105 - 0.018(P200) + 9.55(D_{60}) + \frac{0.012}{D_{30}} - 0.057\left(\frac{D_{60}}{D_{10}}\right) + 9.55\rho_d \tag{102}$$

$$m = 11.24 + 0.0074(P200) - 0.075(5\mu m) - 2.665(G_s) - 1.452\rho_d \tag{103}$$

3.3 Empirical Relationships

The following represents a presentation of empirical relationships for soil suction prediction or association.

3.3.1. Russell (1965)

The relationship between soil moisture tension and the consistency limits of a soil was investigated by Rollins and Davidson (1960). A separate relationship was established for each of four textural groups, as preliminary tests had indicated that this procedure yielded acceptable results. Moisture tension curves were plotted, and appropriate soil moisture tensions were approximated. Tests were then conducted at pressures near the approximate pressure until one was found that gave results with the least deviation from those that had been predetermined by the standard method. Pressure plate testing brings a sample to a specific moisture potential by applying pressure to the sample and allowing any excess water to exit through a porous ceramic plate.

Based on the above study, involving pressure plate measure tension measurements, it was concluded that if the textural classification is known, the consistency limits can be estimated by assuming them equal to an appropriate moisture tension. The moisture tension pressures they recommended are those presented in Table 3.8 also compared their deviations, qualitatively, with the tabulated results of a comparative test by several different highway departments for consistency limits of one soil and concluded within deviations that could be expected by conventional methods.

Table 3.8: Summary of results of Rollins and Davidson (1960)

Textural group	L.L. tension (in. of H_2O)	No. run	Average deviation	P.L. tension (in. of H_2O)	No. run	Average deviation
silty loam	60[a]	22[a]	1.50	168	12	3.46
silty clay loam	60[a]			415	12	3.14
silty clay	15	16	2.56	913	15	2.58
clay	6	16	1.75	1650	12	2.34

[a]Combined in one test run.

Converting the above table yields the values in Table 3.9:

Table 3.9: Conversion of Tension from Inches of H_20 to psi

Textural Group	Liquid Limit tension (inches of H_20)	Liquid Limit tension (psi)	Plastic Limit tension (inches of H_20)	Plastic Limit tension (psi)
Silty loam	60	2.17	168	6.06
Silty clay loam	60	2.17	415	14.98
Silty clay	15	0.541	913	32.95
Clay	6	0.217	1650	59.55

Russell (1965) embarked on a testing regime for five textural groups. The five groups are somewhat closely tied to the four textural groups of Rollins and Davidson (1960). Key consistency data for Russell's work is presented below.

- Silty loam was non-plastic
- Silty clay loam (29 tested) exhibited liquid limits in the range of 23 to 47; plastic limits in the range of 13 to 31
- Clay loam (11 tested) exhibited liquid limits in the range of 27 to 42; plastic limits in the range of 16 to 30.
- Silty clays tested exhibited liquid limits in the range of 32 to 53; plastic limits in the range of 16 to 28.

- Clays tested exhibited liquid limits in the range of 28 to 62; plastic limits in the range of 14 to 30.

A 1964 article in an English periodical report on the use of the relationship between soil moisture and soil suction as a new method of determining the plastic limit of soils. Both sorption and desorption curves are used, and the absence of hysteresis at a pF value at 0.5 is taken as the criteria of a non-plastic soil. Otherwise, the plastic limit value is taken as the moisture content held by the soil against a pF of 0.5 on the wetting curve or 1.5 on the drying curve of the soil-moisture soil suction relationship, where the term, pF, is the same as the log of the tension in centimeters of water. It is the same as "log-tension" which is a term sometimes preferred.

Of interest to this paper is the relationship between the soil tension and either the liquid limit or plastic limit for clays and silty clays. Refer to Figure 3.6 through Figure 3.9 below:

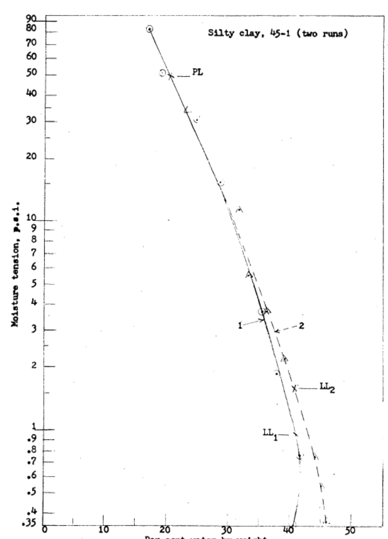


Figure 3.6: Silty Clay Soils Typical of That Tested (34 Tested). For Samples in 45-1, the Composition was 1% Sand, 66% Silt, 33% Clay.

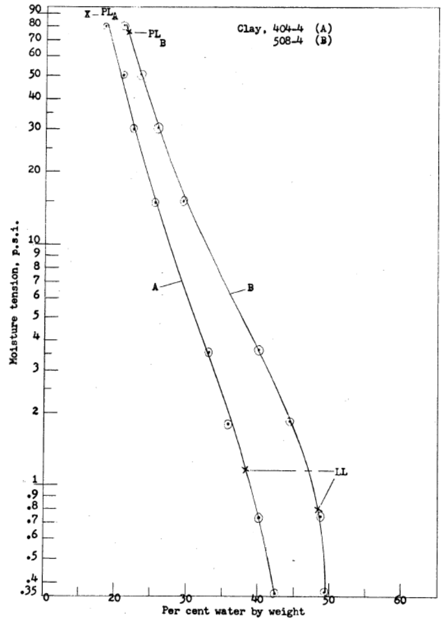


Figure 3.7: Two Clay Soils Typical of That Tested (43 Tested). For Samples in 508-4, the Composition Was 12% Sand, 42% Silt, 46% Clay. For Samples in 404-4, the Composition Was 33% Sand, 23% Silt, And 44% Clay.

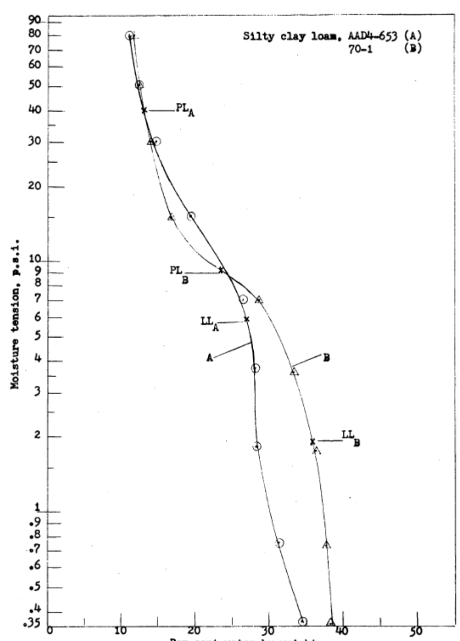


Figure 3.8: Two Silty Clay Loam Soils Typical of That Tested (29 Tested). For Samples in AAD4-653, the Composition Was 6% Gravel, 48% Sand, 27% Silt, 19% Clay. For Samples in 70-1, the Composition Was 7% Sand, 70% Silt, And 23% Clay.

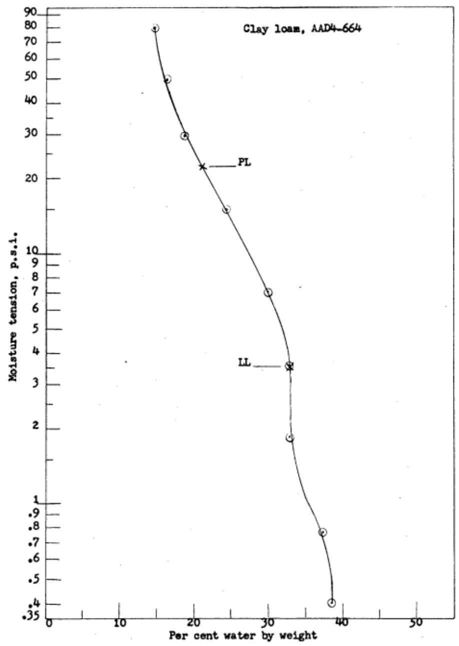


Figure 3.9: Clay Loam Soils Typical of That Tested (11 Tested). For Samples in AAD4-664, the Composition Was 1% Gravel, 41% Sand, 38% Silt, 20% Clay

Table 3.10 presents the character of the soils tested as part of the study.

Table 3.10: Composition of soils used for individual curves plotted on previously introduced graphs

Group	Designation number	Composition, percent gravel	sand	silt	clay
clay	508-4		12	42	46
clay	404-4		33	23	44
silty clay	45-1		1	66	33
silty clay	44-1		1	59	40
silty loam	AAD4-658	1	57	26	16
silty loam	AAD4-661	2	62	30	6
silty loam	AAD4-806	13	21	50	16
silty clay loam	AAD4-653	6	48	27	19
silty clay loam	70-1		7	70	23
clay loam	AAD4-664	1	41	38	20
loam	AAD4-647	3	43	35	19
silt	AAD3-12820			83	17
silt	AAD3-12822		3	90	7
silt	AAD3-12832		1	86	13
sand	AAD3-12829		90	8	2
sand	AAD4-828		89	10	1
sand	AAD4-3655		34	39	27
silty loam	I-2		1	81	18
gr. loamy sand	AAD4-809	14	71	11	4
sandy loam	AAD3-12807		63	24	13

Table 3.11 Summarizes the Expected Final Pressures Needed to Estimate the Liquid and Plastic Limits of Various Soils (Focused on Clays):

Table 3.11: Final pressures needed to estimate consistency limits of various soils

Group	Sample Number	P200	LL	PL	PI	Final Pressure for Approximating LL (psi) from paper	Final Pressure for Approximating LL (psi) from graph	Final Pressure for Approximating PL (psi) from paper	Final Pressure for Approximating PL (psi) from graph
Clay	508-4	88	49	22	27	1.44 (0.358 kPa)	0.75 (kPa)	162 (41.8 kPa)	80 (kPa)
Clay	404-4	67	38	15	23	1.44	1.3	162	90
Silty clay	45-1	99	42	21	21	1.44	1.6	70	50
Silty clay	44(45)-1	99	41	21	20	1.44	0.9	70	50
Silty clay loam	AAD4-653	46	28	14	14	2.17	6.0	35	40
Silty clay loam	70-1	93	37	24	13	2.17	2.0	35	9.5
Clay loam	AAD4-664	58	34	22	12	2.17	3.5	70	21

The plastic limit value of clay can be approximated at 162 psi and should be within the deviation established herein. However, the rest of the plastic limit groups run were questionable. The limit values obtained by moisture tension can be reproduced at the same tension with little variation; they are reproducible to a high degree. The analysis of 687 samples that constitute the study of liquid limits shows that the moisture tension values compare to values obtained by the standard method within the deviation that could be expected by using the standard method alone. A distinct double modal characteristic was observed for the silty clays, indicating the possibility that some soil may exist that have two sets of characteristics.

While the above represents the conclusions, a review of the data, plots and analysis do not support the conclusions. While the intent and efforts appear sound, the conclusions are not accurate.

3.3.2. Kassiff and Livneh (1967 – 1969)

Per Kassiff (1969) regarding Israeli clays, predictions of soil suction are presented as a function of plastic limit (PL) and moisture content (ω) expressed in percent. The predictions are limited to remolded soils and not native undisturbed soils.

For a remolded sample soil suction of 3 pF, the relationship between the PL and ω presented by Equations (104) and (105) (Livneh et al., 1967):

$$\omega = -13.5 + 1.9\ \mathrm{PL} \tag{104}$$

$$\omega = -13.47 + 1.9\ \mathrm{PL}\ \text{(based on results of Figure 3.10)} \tag{105}$$

For a remolded soil suction of 4 pF, the relationship between the PL and ω is as presented in Equations (106) and (107) (Livneh et al., 1967):

$$\omega = -16.2 + 1.6\mathrm{PL} \tag{106}$$

$$\omega = -16.21 + 1.6\mathrm{PL}\ \text{(based on the results of Figure 3.10)} \tag{107}$$

Figure 3.10 is a representation of the relationship between equilibrium moisture content and PL.

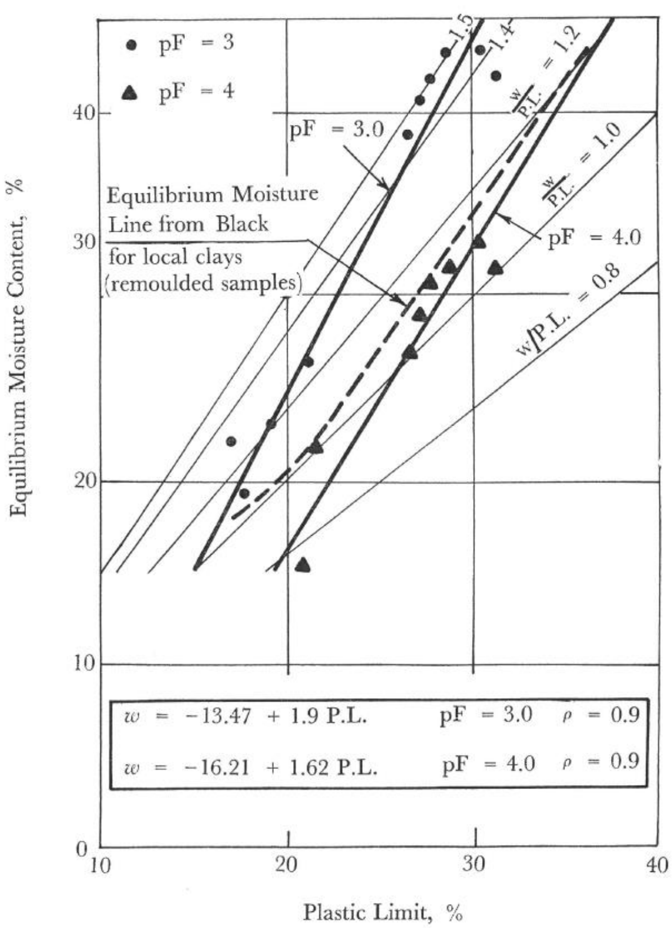


Figure 3.10: Relationship Between Plastic Limit and Equilibrium Moisture Content for Constant Soil suction Values (Kassiff, 1967)

Note that the above relationships are for remolded clay samples. For undisturbed Israeli clays, the above equations and curves in Figure 3.10 are applicable for soil suctions of 2.2 pF and 3.2 pF as opposed to 3 pF and 4 pF, respectively. The difference is attributed to a submitted 0.8 pF difference between remolded samples and undisturbed samples. As such, when moving from remolded to undisturbed, decrease the somewhat target soil suction by 0.8 pF (Kassiff, 1969).

The ratio of moisture content to plastic limit was used in the above Figure 3.10 data.

3.3.3. Hillel (1971)

As of 1971, Hillel expressed an opinion that no satisfactory theory exists for the prediction of the matric soil suction versus the wetness relationship from basic soil properties. He further opined that the adsorption and pore geometry effects were too complex to be described by a simple model.

Hillel did present several empirical equations that had been proposed, as of that time, describing the soil moisture characteristic for some soils and within limited soil suction ranges.

Visser (1966) proposed Equation (108).

$$\psi = \frac{a(f-\theta)^b}{\theta^c} \tag{108}$$

Where,

ψ is the matric soil suction

f is the porosity; ranging typically from 0.4 to 0.6

θ is the volumetric "wetness"

a, b and c are constants; b varying from 0 to 10, a varying from 0 to 3

3.3.4. Mou and Chu (1981)

Although geared toward compacted clays, the trends in the relationships between static compaction, kneading compaction and soil suction for undisturbed soils could be realized. A pressure-plate apparatus and the procedures for measuring the soil suction of soil specimens developed in this study were found to be satisfactory for the direct determination of the soil suction of soil specimens at the existing dry density and water content. The use of static as well as kneading compaction for specimen preparation results in a different soil structure or fabric of the compacted specimens. This difference in soil fabric is reflected in the measured soil suctions and the percentage of swell determined by the laboratory experiments in this study. This finding indicates that any difference in the soil fabric of expansive clay formations may be a significant factor that affects the swelling characteristics of the clay formations. In this respect, the measurement of soil suction would provide helpful information in the investigation of the volume-change behavior of expansive clays. Although using soil water content as a major variable in the evaluation of swelling potential is a convenient and practical approach, findings from the laboratory investigations indicate that it is very useful to include soil suction as an additional variable for similar purposes. This study verifies that the soil-soil suction approach is invaluable in the analysis of experimental data and the determination of the swelling characteristics of expansive clays.

Figure 3.11 depicts the relationship between swell and the anticipated soil suction when moisture content is held constant. Figure 3.12 shows the relationship between swell and soil suction when the dry density is held constant, in this case at 1.610 $\pm$ 0.015 g/cm^3.

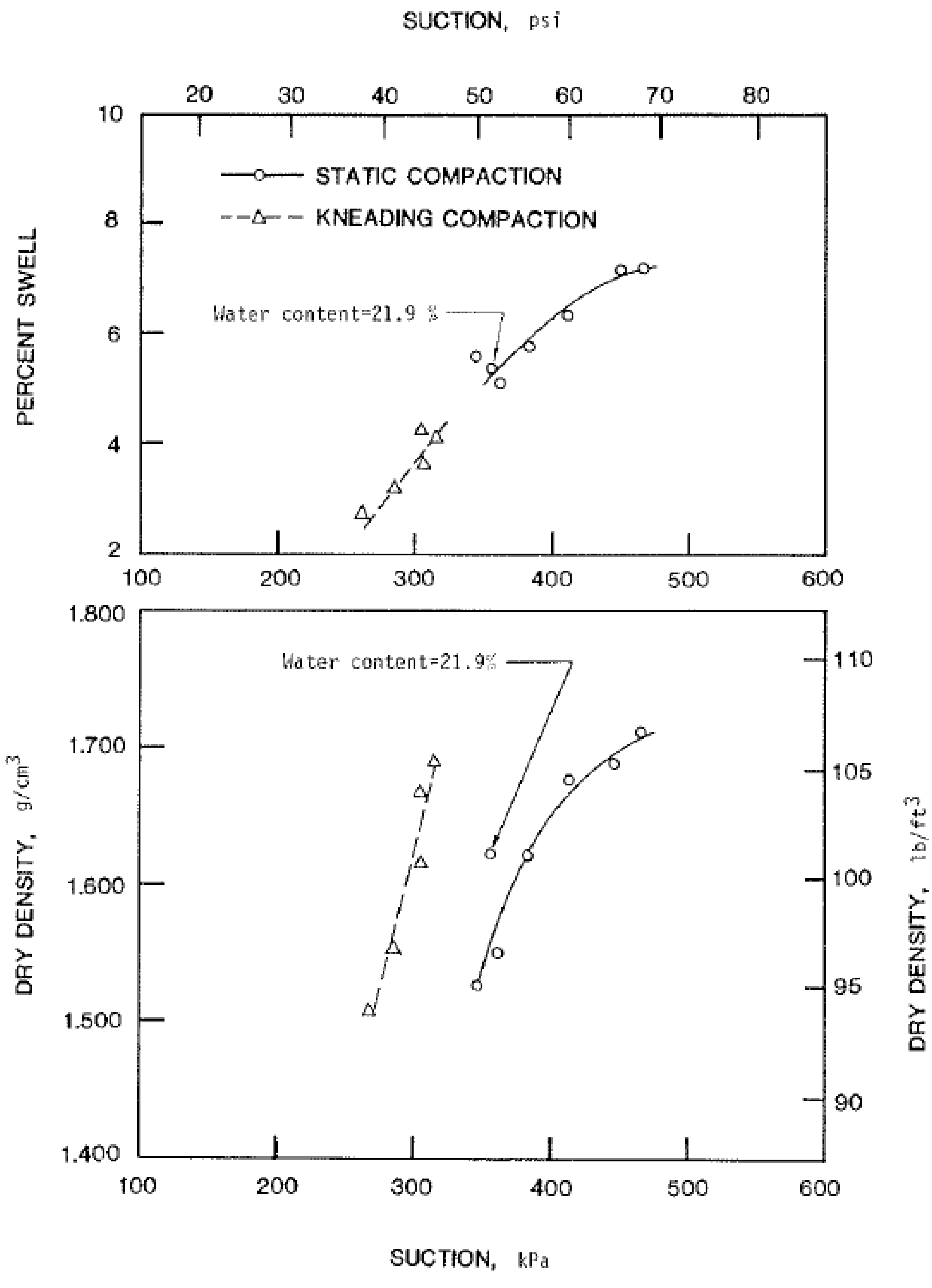


Figure 3.11: Dry Density and Percentage of Swell Versus Soil Suction for a Constant Moisture Content of 21.3 + 0.3 Percent (Unless Otherwise Stated)

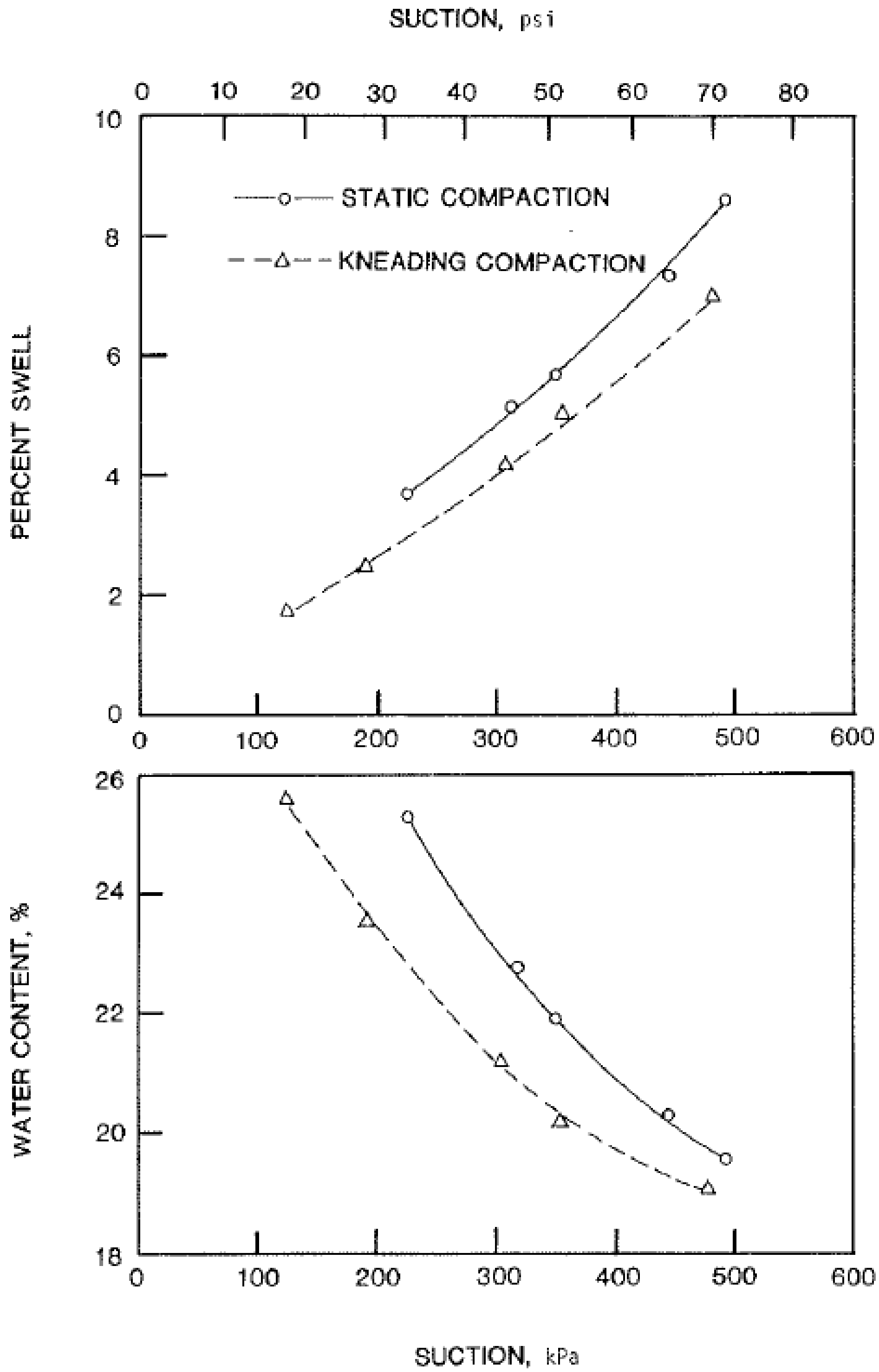


Figure 3.12: Water Content and Percentage of Swell Versus Soil Suction for a Constant Dry Density of 1.610 + 0.015 Percent

3.3.5. Department of the Army, 1983 (Snethen, 1980)

The determination of soil suction is analogous to the procedures for determining expansion from an oedometer. The matric soil suction and water content relationship is simply estimated by subtracting the osmotic soil suction from the total soil suction Snethen (1980) Equation (109), shown below in Figure 3.13:

$$\log \tau_m^o = A - Bw \text{ (after Snethen, 1980)} \tag{109}$$

Where,

τ_m^o
$=$ matric soil suction without surcharge pressure, expressed in tons per square foot
$A =$ ordinate intercept soil suction parameter in tons per square foot
$B =$ slope soil suction parameter
$w =$ water content in percent dry weight

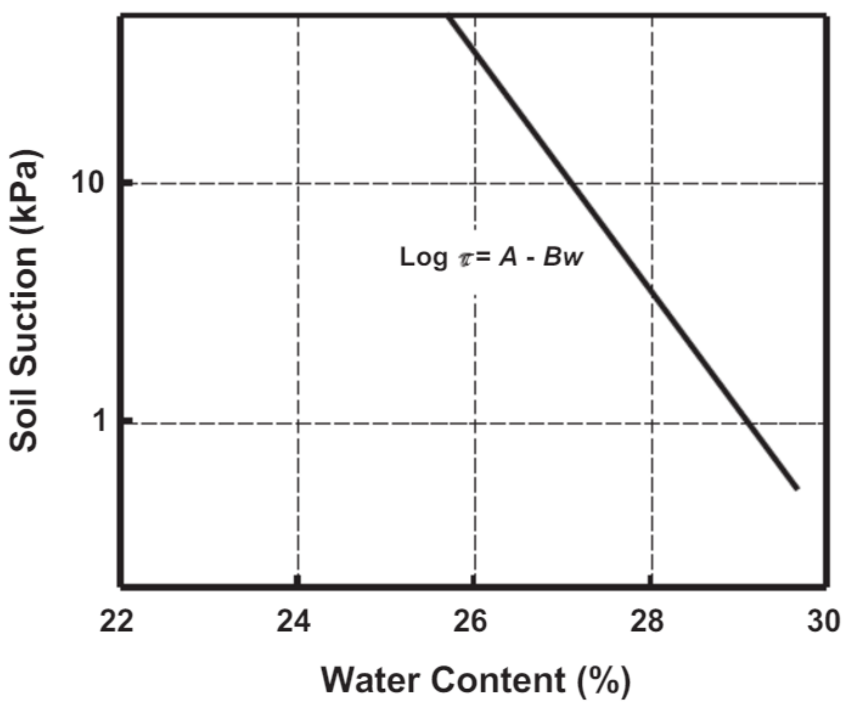


Figure 3.13: Soil Suction Versus Water Content Relationships for Blue Hill Shale (Modified After Snethen, 1980)

For a specifically tested undisturbed soil, with a natural water content of 27 percent and a total mean confining pressure of σ_m of approximately 0.1 ton per square foot, a multi-point total soil suction and water content relationship is as shown in Figure 3.14:

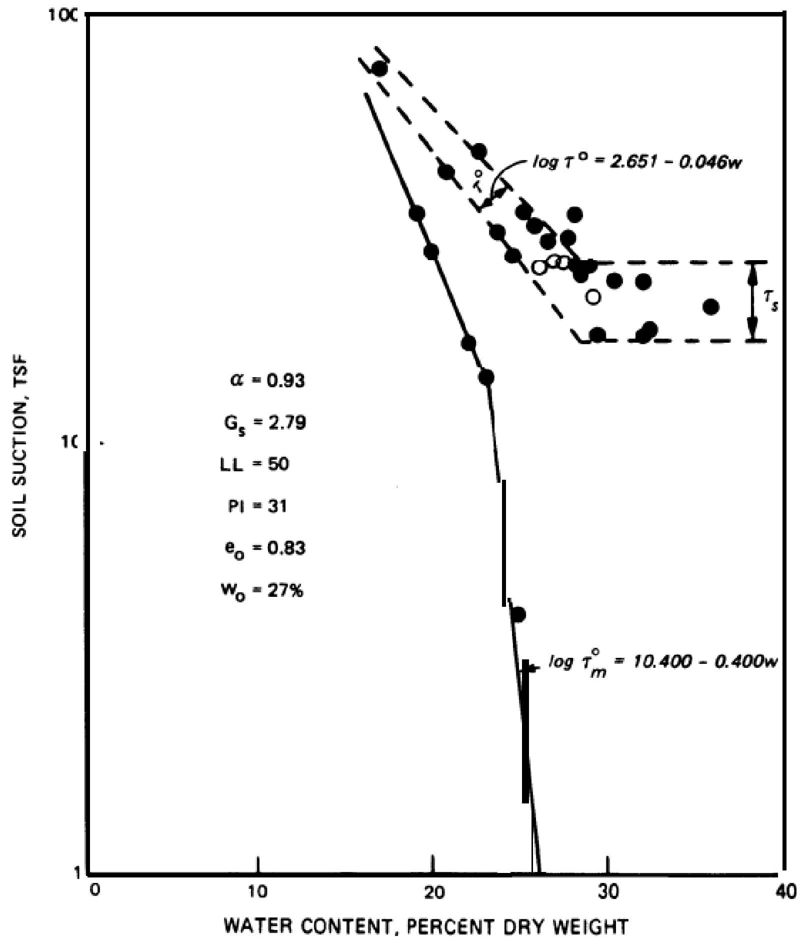


Figure 3.14: Soil Suction and Water Content Relationship for a PI=31 Soil, W=31%, Colorado Springs.

Based on the above relationship, and for the specifically tested soil, the initial matric soil suction is as presented in Equation (110):

$$\log\tau_m^o = 10.400 - 0.400w \tag{110}$$

Per the equation presented Equation (110), and expressed in tons per square foot, the matric soil suction at a water content of 27 percent equals 0.398 tons per square foot (796 psf, or 38.11 kPa).

3.3.6. Nelson and Miller (1992)

Nelson and Miller (1992) studied plots of water content versus depth during several wet and dry seasons. Using the plots, the active zone may be determined for a given site. The active zone can be determined where the water content becomes nearly constant with depth. Should discontinuous soil layers be encountered, the differences in soil type can be resolved by plotting either the water content divided by the Plasticity Index (w/PI), or liquidity index [(LL-w)/PI], rather than water content, with respect to depth.

3.3.7. Walsh, Houston and Houston (1993)

Precipitated by studies connected to collapsible soils, field sampling and laboratory testing was completed to arrive at values of water content, dry unit weight, percent passing the #200 sieve, and filter paper soil suction results for selected locations and depths. Using an assumed specific gravity value, the degree of saturation was calculated. The data was contoured, resulting in the relationship shown in Figure 3.15 (plotted degree if saturation vs soil suction, with the percentage of fines noted for each data point):

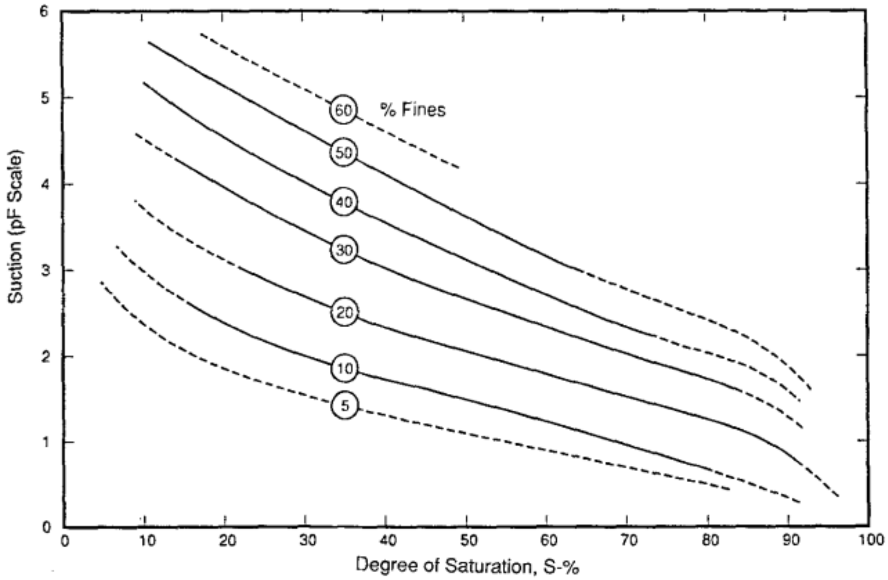


Figure 3.15: Relationship Between Soil Suction, Degree of Saturation and Percent Fines.

The proposed method was expected to be of greatest efficacy in arid regions, where the soil suctions should be high due to intense drying periods. Soil suction was recorded in terms of pF. As part of the study, it was noted that natural soil suctions of 4 pF or greater are common. As wetting occurs, drastic reductions in soil suctions must be anticipated. In fact, soil suction was used as a fundamental parameter to evaluate the extent of wetting.

For deeper samples, where the dry unit weight was not known, the following figure was entered with the percent passing the #200 sieve to arrive at a value of dry unit weight that was within one standard deviation from a known value using Figure 3.16.

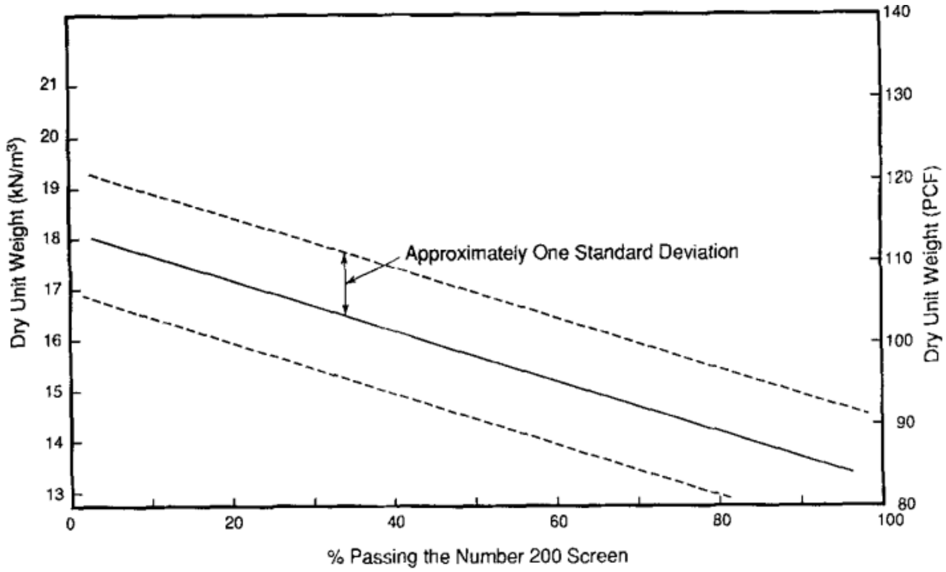


Figure 3.16: Relationship Between Dry Unit Weight and Percent Fines.

Aside from the ability to predict a reasonable soil suction value for undisturbed and disturbed samples using only dry density, percent passing the #200 sieve, with an assumed specific gravity, it was determined that soil suction values in the range of 2 to 3 pF were representative of wet conditions, whereas soil suction values of 4 pF or more were relatively dry. Based on the data from the study a soil suction value of 4 pF was selected as the lower limit to represent a wetted condition.

3.3.8. Aubertin, Mbonimpa, Bussiere, and Chapuis (2003)

In the proposed model, basic material properties are needed, including the effective grain diameter (D_{10}), the coefficient of uniformity (C_u), liquid limit (LL), void ratio (e), and the solid grain density (ρ_s). The preceding parameters are used to define the equivalent capillary rise (h_{co}), which constitutes the central parameter of the model. Aubertin, Mbonimpa, Bussiere and Chapuis (2003) created Equation (111).

For plastic-cohesive soils, the expression for residual matric soil suction prediction is Equation (111):

$$\psi_r = 0.86\left(\frac{\xi}{e}\right)^{1.2} w_L^{1.74} \tag{111}$$

Where,

ψ_r = Residual matric soil suction

$\xi \approx 0.15\rho_s$ in centimeters

w_L = Liquid limit

e= void ratio

3.3.9. Perera (2003)

Perera (2003) recounts that the original model for expressing a relationship between TMI and matric soil suction was presented in 1961 by Russam and Coleman. It provided a correlation between the TMI and the matric soil suction expressed in pF. Perera (2003) completed a study that compared in situ moisture content to matric soil suction through utilization of the SWCC. Further studies by Perera calculated the TMI, allowing for further correlation between specific soil properties, TMI and matric soil suction.

Of interest to expansive soils is the subbase and subgrade TMI-wPI model. The TMI-P_{200}/wPI model is shown in Equation (112).

$$\psi = \alpha\left[e^{\left[\frac{\beta}{\mathrm{TMI}+\gamma}\right]} + \delta\right] \tag{112}$$

Where,

ψ is the matric soil suction

$\alpha, \beta, \gamma,$ and δ are regression constants

TMI is the Thornthwaite Moisture Index

3.3.10. Marinho (2005 and 2006)

Knowing the validity of SWCC relationships, a relationship between moisture content, liquid limit and known stress history was presented. Commencing with a known LL and OCR, a soil suction capacity in percent is determined. For example, in Figure 3.17, should the LL be 55 and the OCR be 2, the Soil suction Capacity (C) would be roughly 13. A water content can be normalized using the Soil suction Capacity. The C selection is predicated on stress history as stated previously. To obtain the normalized water content, the original water content is divided by the factor, denoted as 'C.' Using the w/C value, a soil suction magnitude is obtained from a graph. The fit for determination of the soil suction at a known water content is presented as graphical although the method suggests that the relationship may follow a linear trend for liquid limits greater than 25 and with soil suctions in the range of 100 kPa and 1 MPa. In general, the predictions of the SWCC as a function of anticipated stress history; undisturbed, compacted, or compacted with high density, were "reasonably good." Discrepancies in the predicted fit were thought to be the result of a stress history that was not fully defined. The method; however, verifies the relationship that a normalized water content has with the SWCC and soil suction prediction. Further, the study recommends that further study be completed to show a potential relationship between the liquid limit (LL) and the SWCC. Coupling the two elements, normalized water content and LL is implied as a potentially viable predictor (Marinho, 2005). Refer to Figure 3.17 through Figure 3.19 from (Marinho, 2006) that are used in the method.

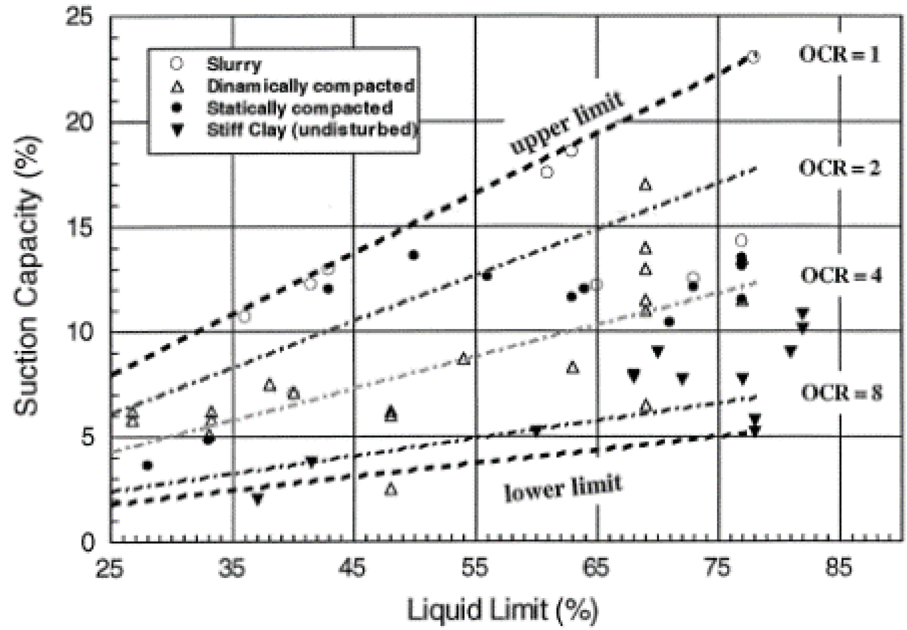


Figure 3.17: Relationship Between Soil Suction Capacity, Liquid Limit and OCR (Marinho, 2006)

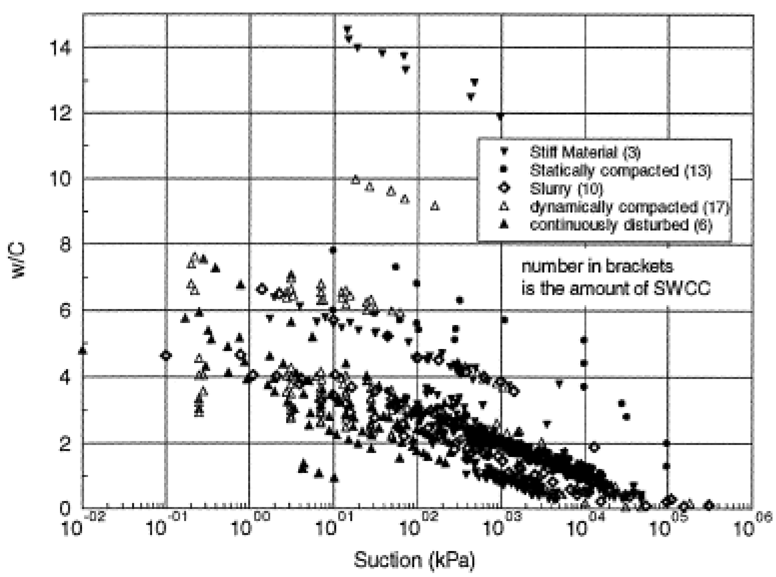


Figure 3.18: Soil-Water Retention Curve Normalization Using Soil Suction Capacity (Marinho, 2006)

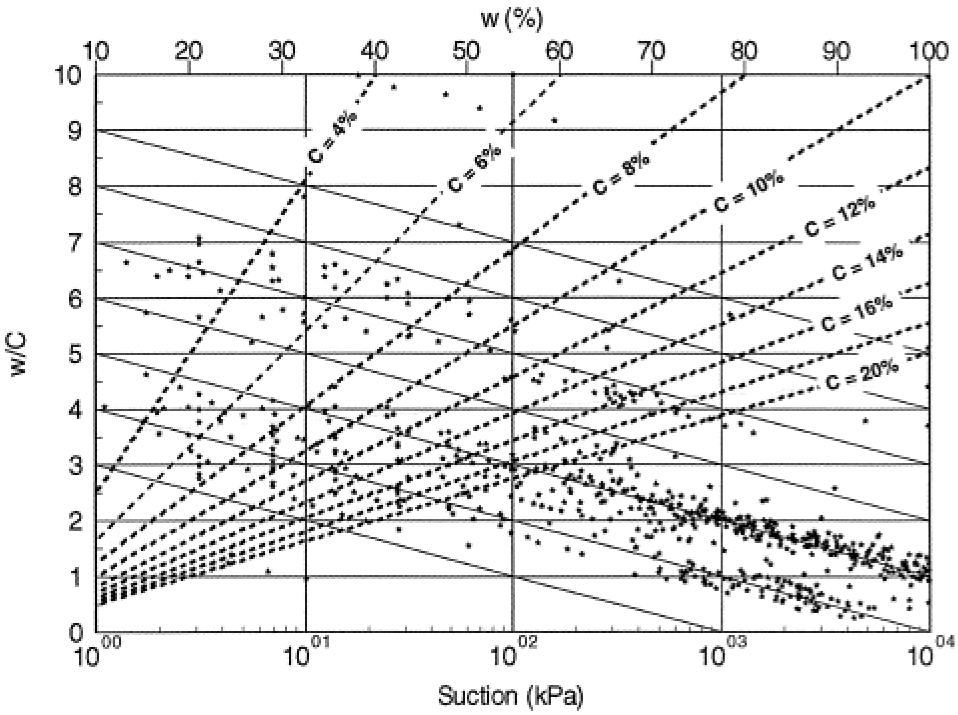


Figure 3.19: Soil-Water Retention Curve Estimation Using One Data Set and Liquid Limit (Marinho, 2006)

3.3.11. Houston, Mirza and Zapata (2006)

Continuing the work of Perera (2003), the regression coefficients were finalized and are found in Table 3.12.

Table 3.12: TMI-P200/wPI regression coefficients (Houston et al. 2006)

P_{200}	*w*PI	α	β	γ	δ
10		0.3	419.07	133.45	15.0
50	0.5	0.3	521.50	137.3	16.0
	5.0	0.3	663.50	142.5	17.5
	10	0.3	801.00	147.6	25.0
	20	0.3	975.00	152.5	32.0
	50	0.3	1171.2	157.5	27.8

The regression coefficients in Table 3.12 are obtained using Equations (113) through (118).

$$\beta = 2.56075(P_{200}) + 393.4625 \quad (113)$$

$$\gamma = 0.09625(P_{200}) + 132\ .4875 \quad (114)$$

$$\delta = 0.025(P_{200}) + 14.75 \quad (115)$$

$$\beta = 0.006236(wPI)^3 - 0.7798334(wPI)^2 + 36.786486(wPI) + 501.9512 \quad (116)$$

$$\gamma = 0.00395(wPI)^3 - 0.04042(wPI)^2 + 1.454066(wPI) + 136.4775 \quad (117)$$

$$\delta = -0.01988(wPI)^2 + 1.27358(wPI) + 13.91244 \quad (118)$$

3.3.12. Zapata, Perera, and Houston (2009)

The Zapata, Perera and Houston (2009) study is based on the equation established as part of Perera (2003) Equation (119).

$$\psi = \alpha\left[e^{\left[\frac{\beta}{TMI+\gamma}\right]} + \delta\right] \quad (119)$$

Where,

ψ is the matric soil suction
$\alpha, \beta, \gamma,$ and δ are regression constants

Based on the equation above, six contour lines corresponding to different soil materials are presented in Figure 3.20:

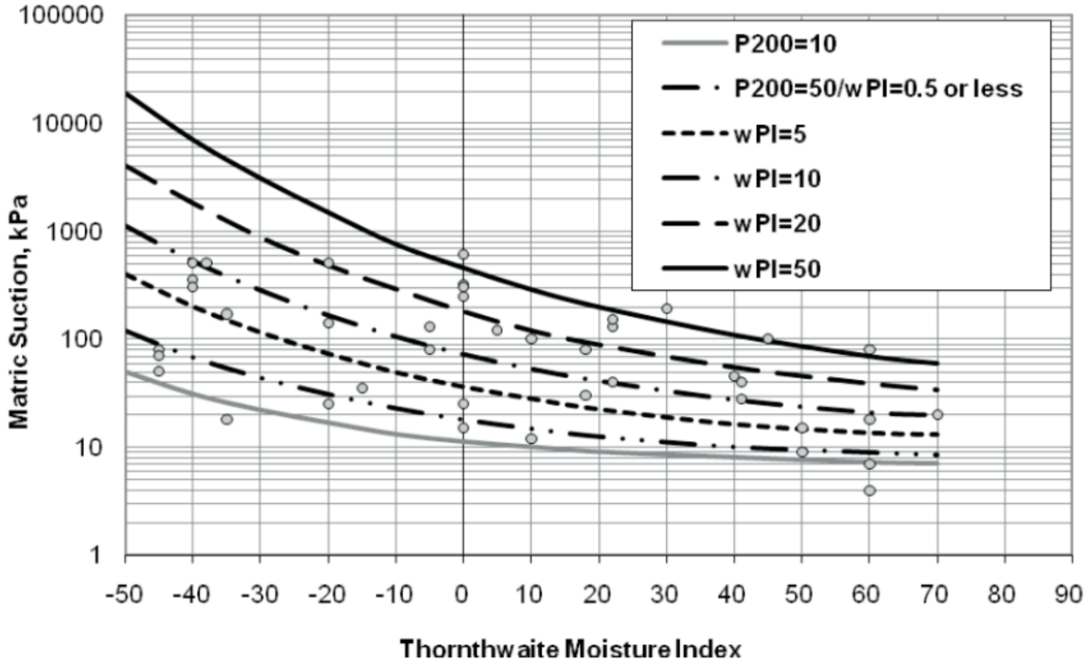


Figure 3.20: TMI Versus P200 or WPI Model for Subgrade Materials

3.3.13. Johari and Hooshmand Nejad (2015)

Several artificial intelligence methods are described. One of the methods is referred to as the "GP" model, which estimates the SWCC for soils using the equation below Johari and Hooshmand Nejad (2015) Equation (120) and Equation (121).

$$\omega = 0.794(\mathrm{w} + 0.215)\left\{\left[(0.116^{\mathrm{Su}}\mathrm{Cl}^{\mathrm{Si}})^{(\mathrm{e}+0.234)} + \left(\mathrm{Cl}^{0.368\left(\frac{\mathrm{Si}}{\mathrm{Cl}}\right)}\right)(\mathrm{Su}^{\mathrm{e}} - \mathrm{Su})\right]\mathrm{Cl}\right\}^{\mathrm{Su}^2} \tag{120}$$

The above equation can be scaled based on the initial water content:

$$\varpi = \omega\left(\frac{\mathrm{w}}{\omega_o}\right) \tag{121}$$

Where,

e=initial void ratio

w=initial water content

Su=log (soil suction (kPa)/pa where pa is the atmospheric pressure (100 kPa)

Cl= clay content (%)

Si= silt content (%)

ω=predicted gravimetric water content

ϖ = adjusted gravimetric water content

ω_o = predicted initial water content at 0.2 kPa

The EPR model is an expression presented as expressed in Equation (122) (using the same parameters as described above).

$$\omega = \frac{1.48(10)^{-6}Su^3}{e^3ClSi} + \frac{1.8SuCl^3 - 1.79eSu^2ClSi}{w} - \frac{4.07(10)^{-3}SuSi + 0.25eCl^2}{Cl} - 1.7(10)^3wSu + 2.25(10)^{-3}w^2 - 0.17ew + 3.11e^2 - \frac{2.15e^2w^3}{ClSi^2} + 0.10214 \tag{122}$$

GeneXproTools 4.0 was used in the study to perform symbolic regression using GEP (Gene Expression Programming), producing the equation below. Equation (123) was the result of 6 prior mathematical expressions for GEP models.

$$\omega = \frac{-1}{Su + 2Cl - 2.202\left(\frac{Su^4}{Cl^2}\right) - 7.285} - w(Su + 0.062(Si + e)^2 - 1) \tag{123}$$

Where,

e=initial void ratio

w=initial water content

Su=log (soil suction (kPa)/pa where pa is the atmospheric pressure (100 kPa)

Cl= clay content (%)

Si= silt content (%)

ω=predicted gravimetric water content

3.3.14. Tu and Vanapalli (2016)

For undisturbed and recompacted expansive clay soils, an equation is presented to estimate the swelling pressure Tu and Vanapalli (2016) Equation (124).

$$P_s = \left(\frac{S}{100}\right)^a \psi \tag{124}$$

Where,

P_s is the swelling pressure
S is the degree of saturation
ψ is the soil suction
a is a fitting parameter, obtained from Vanapalli and Lu (2012) – a is dependent on density as indicated in Figure 3.21 below:

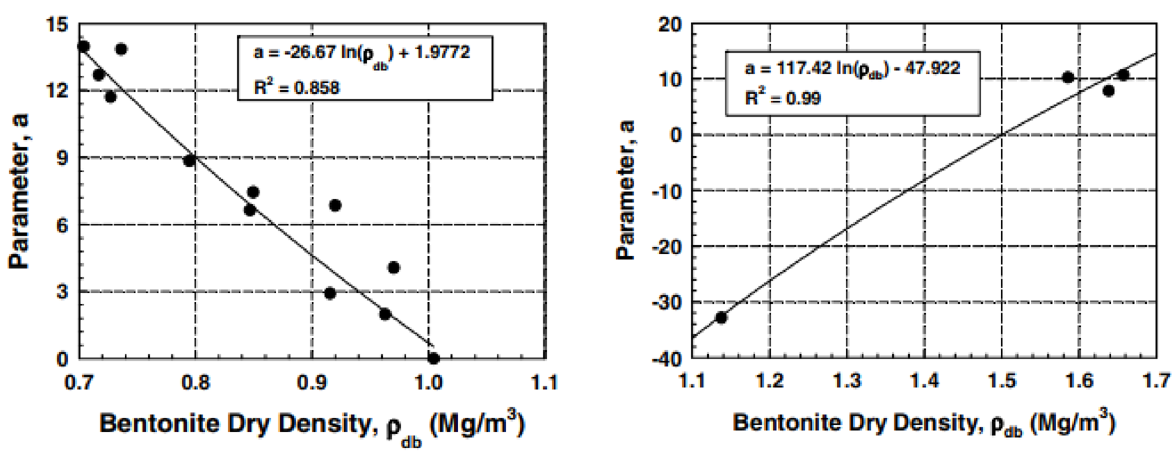


Figure 3.21: Relationship between parameter a and density (Vanapalli et al., 2012)

The above equation can be rearranged to solve for the soil suction, if the saturation, swelling pressure, and fitting parameter are known, as shown in Equation (125).

$$\psi = \frac{P_s}{\left(\frac{S}{100}\right)^a} \tag{125}$$

3.4 Summary of Simple Relationships from Research to Date

The purpose of this literature review is to explore all prior efforts to predict soil suction using index or other common soil properties. By carefully examining the literature presented above, it was possible to look for simple yet meaningful relationships that suggest a correlation to soil suction for expansive clay soils. Table 3.13 presents a listing of possible soil suction surrogates.

Table 3.13: Listing of possible soil suction surrogate relationships, based on past research

Surrogate Candidate (Base Relationship)	**Reference**
P200PI	Zapata (1999)
0.4LL	Lopes (2006)
Si/Cl (%Silt/%Clay), or (P200-P2μ)/P2μ	Johari and Hooshmand Nejad (2015)
For an undisturbed clay sample with a soil suction of 2.2 pF; $\omega = -13.47 + 1.9\ \mathrm{PL}$	Kassiff, (1969)
For an undisturbed clay sample with a soil suction of 3.2pF; $\omega = -16.21 + 1.6\mathrm{PL}$	Kassiff (1969)
$\psi = \dfrac{P_s}{\left(\frac{S}{100}\right)^a}$	Tu and Vanapalli (2016)
$\psi_r = 0.86 \left(\frac{\xi}{e}\right)^{1.2} w_L^{1.74}$	Aubertin, Mbonimpa, Bussiere, and Chapuis (2003)
$\psi = \alpha \left[e^{\left[\frac{\beta}{\mathrm{TMI}+\gamma}\right]} + \delta \right]$	Zapata, Perera and Houston (2009)
LL(CF) where CF is the clay fraction $C = 0.12\beta + 4.5$	Catana et al. (2006)

Surrogate Candidate (Base Relationship)	Reference
$\beta = \mathrm{LL(CF)}$	
$\log\psi = 0.00005(\mathrm{wPI})^3 - 0.003(\mathrm{wPI})^2 + 0.03\mathrm{wPI} + 1.1355 - (0.0126\mathrm{wPI} + 0.7285)\log \mathrm{D} - (0.0011\mathrm{wPI} + 0.0044)\log\mathrm{D}^2 + (0.0002\mathrm{wPI} + 0.0056)\log\mathrm{D}^3$	Hernandez (2011)
$\theta(-\psi) = \frac{\theta_{\mathrm{pF6}}\left(6.9 - \log_{10}(-\psi)\right)}{6.9 - 6}$	Jensen, Tuller, de Jonge and Moldrup (2014)
$\log\tau_{\mathrm{m}}^{\mathrm{o}} = \mathrm{A} - \mathrm{Bw}$	Snethen (1980)
w/PI	Nelson and Miller (1992)
L.I. (liquidity index) = [(LL-w)/PI]	Nelson and Miller (1992)
Normalized Water Content and LL	Marinho (2005 and 2006)

3.5 Conclusions and Discussion of Surrogate Candidates

In addition to the possible surrogate relationships presented in Table 3.8, other candidates should be considered such as those in

Table 3.14 below:

Table 3.14: Listing of possible surrogate candidates

Surrogate Candidate
w/PL
0.4LL
PI^n
LL^n
w/LL
w/P200LL
w/P200PL
LL/w
P200LL/w
w/S
w/PI
[(LL-w)/PI] – liquidity index
Normalized water content and LL

Potential equation for surrogates initially included the forms shown in Equations (126) through (129).

$$\psi = A\log\left(\frac{w}{PL}\right) + B \quad log\ fit \tag{126}$$

$$\psi = A - Bw - C\left(\frac{w}{LL}\right) - D\left(\frac{w}{PL}\right) \quad multiple\ regression \tag{127}$$

$$\psi = e^{\left[A-B\left(\frac{w}{PL}\right)\right]} \quad exponential\ fit \tag{128}$$

$$\psi = A\left(\frac{w}{PL}\right)^{B} \quad power\ fit \tag{129}$$

Log, multiple regression, exponential, and power relationships will be rigorously examined for all possible candidates to ascertain the best fit method in determining a suitable soil suction surrogate.

An artificial intelligence software known as Eureqa was utilized to find relationships between all captured soil parameters, including but not limited to Atterberg Limits, moisture content and particle size distribution.

The aim is to find a surrogate for soil suction that can be used by the geotechnical practitioner to predict a magnitude of soil suction with relative ease, based on the results of laboratory testing that is already implemented in the industry. Continued efforts are hopeful that one or two equations, using the most appropriate surrogate, will be found and incorporated into geotechnical-related design and construction. Finding such relationships is critical to the general acceptance of unsaturated soil mechanics into the geotechnical community.

3.6 Direct Soil Suction, Swell, and Index Tests

The purpose of this effort is to obtain matric soil suction measurements on the same soil specimens used for index testing and water content/degree of saturation measurements. The soil suction measurements will be “direct” and measured under field appropriate net normal stress conditions to the extent possible. However, the WP4C will also be used extensively, and comparisons to directly measured soil suction values under field net normal stress will be made. To accomplish the soil suction measurements, oedometer-type pressure plate devices will be used. Sealed samples from the field will be taken to the laboratory with minimal disturbance and no measurable change in moisture content. Test specimens will be transferred to the oedometer pressure plate device (Perez-Garcia, et al. 2008), without change in moisture content, and subjected to in-situ net normal stress. Soil suction will be carefully monitored and adjusted to maintain constant moisture content. This technique for obtaining a measure of the in-situ soil suction has been used extensively and has been refined in previous research projects. A method of extrapolation for soil suctions beyond 1500 kPa is available, and soil suctions more than 1500 kPa will also be checked using the WP4C dew point device (Meter, formerly Decagon, Inc.), which will provide a check-point on the higher soil suction values.

Of primary emphasis for the research is a complete grain-size distribution, Atterberg Limits, moisture content, and total soil suction measure using the Meter WP4C. Other extremely valuable completed testing includes SWCC testing of undisturbed clays under field net normal stress values, specific gravity, hydrometer testing, and ASTM D4546 on undisturbed specimens.

CHAPTER 4 DATA MINING AND FIELD INVESTIGATION

4.1 Data Mining

From the files of consulting geotechnical engineers, detailed profile and testing data, as is routinely obtained, was collected on expansive soil locations throughout the USA. A large national retail chain, in possession of hundreds of reports on expansive clays, has also made files available for this study. In addition to available literature data, the above-referenced geotechnical reports were reviewed to increase the database. Once these data were compiled, data mining was conducted, including information on soil types, Atterberg limits, water content, groundwater table, and SPT (or other blow counts) where available. Soil suction profiles or soil suction surrogate profiles were identified from the data set, for both preconstruction and post-construction conditions, and as a means of identifying a realistic range of soil suction profiles to use in numerical analyses to be performed in connection with climatic factors that will impact design soil suction and design soil suction surrogate profiles. Identification of field suction profiles is a data-intensive enterprise.

The specific criteria used for evaluation of sites as part of the data mining effort are:

- Covered – A covered site is one that is currently covered by a structure or has been occupied by a structure within the most recent 5-year period. Surface coverings can be buildings or pavements, primarily. For the sake of the test borings completed as part of the sample acquisition effort, a test boring in a covered area must be at least 10 feet inward (on the covered side) from the edge of a pavement transition from covered to uncovered.
- Uncovered – An uncovered site is one that is currently in an area not previously covered by a building or pavement, primarily. Or, an uncovered site is an area

where the ground surface has been uncovered by appurtenances for at least 5 years. For the sake of test borings completed as part of the sample acquisition effort, a test boring in an uncovered area must be at least 3.048 m (10 feet) inward (on the uncovered side) from the edge of a pavement transition from covered to uncovered.

- Irrigated – An irrigated site has one of the following conditions; 1) current agricultural activity, 2) active landscape irrigation, 3) zone of seepage accumulation from septic or retention, 4) active retention basin or other impoundment, 5) in an area within a designated FEMA floodway, or 6) any other area where the moisture introduction to the site is other than man-induced.
- Non-irrigated – A non-irrigated site is one not subject to any current activity described above as "irrigated". Further, a site that has previously been exposed to any of the elements described in "irrigated" may be re-classified as "non-irrigated if the moisture introduction effect has been absent for a period of at least 5 years.

In all, in excess of 5000 lines of data were entered into an elaborate Google spreadsheet. The soil data is a record of the soil strata extending, in general, to a depth of 9.14 m (30 ft). The data mining has entailed data retrieval from over 40 sites.

4.2 Sample Acquisition (Drilling Efforts)

The research team arranged for and supervised drilling efforts at several locations. Where possible, testing borings at the selected and approved locations extended to depths of 9.14 m (30.0 ft). The selected locations were representative of locales where expansive soils were known to exist, usually from prior data obtained by consultants. During the drill efforts, undisturbed and disturbed samples of expansive soils were obtained. This required collaboration between the research team and geotechnical engineering firms, government agencies, and other companies. For the undisturbed soil testing, expansive soil samples were obtained from field locations in AZ, CO, OK and TX where geotechnical investigations on expansive soils are available and which include commonly obtained index properties, gradation, and swell tests.

The specific criteria used for selecting drilling sites is the as used for classification of the data-mined sites: covered, uncovered, irrigated, or non-irrigated.

With permission and granted access, several sites were explored to gain as many applicable samples as possible in an allotted 1.5-year time frame. The site exploration efforts in all cases involved the advancement of exploratory test borings to depths of 9.14 m (30 feet), generally completed using Vann Engineering equipment that was mobilized from Phoenix, Arizona. Unfortunately, the sampling protocol varied slightly from site to site, depending on owner-imposed time constraints, equipment breakdowns, encountered layering that was contrary to our study intent, inclement weather, and slightly differing sampling protocols in cases where the Vann Engineering, Inc. drilling equipment was not utilized.

As an example, regarding site drilling approval, plans such as shown below were submitted to property owners for final approval before drilling was to proceed. The example is for the San Antonio site (St. Margaret Mary Church and Elementary School).

In all, seven sites were drilled. In chronological order, Table 4.1 shows the site ASU designation, city, state, number of test borings and depths, and where the current ground surface was covered or uncovered and irrigated versus non-irrigated. It should be noted that the San Antonio site is a location of prior forensic investigations associated with expansive soil related performance issues; in this study, the non-irrigated and uncovered site at San Antonio was considered to be outside of the influence of prior forensic investigation.

Table 4.1: Completed Test Boring Summary

Test Boring number	**City**	**State**	**Date drilled**	**Boring depth m (ft)**	**Classification of covered versus uncovered**	**Classification of irrigated versus non-irrigated**
HOB-1-U-I	Hobart	Oklahoma	3/21/16	8.53 (28)	Uncovered	Irrigated
HOB-2-U-I	Hobart	Oklahoma	3/21/16	8.08 (26.5)	Uncovered	Irrigated
HOB-3-U-I	Hobart	Oklahoma	3/22/16	9.14 (30)	Uncovered	Irrigated
DEN-1-C-N	Denver	Colorado	9/16/16	6.31 (20.7)	Covered	Non-irrigated
DEN-2-U-N	Denver	Colorado	9/16/17	9.14 (30)	Uncovered	Non-irrigated
DEN-3-U-N	Denver	Colorado	9/16/16	9.14 (30)	Uncovered	Non-irrigated
DEN-4-C-N	Denver	Colorado	9/17/16	3.05 (10)	Covered	Non-irrigated
DEN-5-C-N	Denver	Colorado	9/17/16	9.14 (30)	Covered	Non-irrigated
SA-1-C-N	San Antonio	Texas	9/23/16	9.14 (30)	Covered	Non-irrigated
SA-2-U-I	San Antonio	Texas	9/23/16	9.14 (30)	Uncovered	Irrigated
SA-3-C-N	San Antonio	Texas	9/23/16	9.14 (30)	Covered	Non-irrigated
SA-4-U-I	San Antonio	Texas	9/23/16	9.14 (30)	Uncovered	Irrigated
MESA-1-U-N	Mesa	Arizona	10/9/17	9.14 (30)	Uncovered	Non-irrigated
MESA-2-C-N	Mesa	Arizona	10/9/17	9.14 (30)	Covered	Non-irrigated
PHX-1-U-N	Phoenix	Arizona	10/6/17	9.14 (30)	Uncovered	Non-irrigated
PHX-2-C-N	Phoenix	Arizona	10/6/17	9.14 (30)	Covered	Non-irrigated
MUNDS	Munds Park	Arizona	2/20/18	9.14 (30)	Uncovered	Irrigated
YOUNG	Young	Arizona	5/18/18	9.14 (30)	Uncovered	Non-irrigated

Test Boring number	City	State	Date drilled	Boring depth m (ft)	Classification of covered versus uncovered	Classification of irrigated versus non-irrigated
YOUNG	Young	Arizona	5/18/18	7.01 (23)	Uncovered	Non-irrigated

The appendices present site plans test boring logs, laboratory test results and representative photographs that were taken during and because of the site drilling efforts.

The drilled sites will provide test boring logs and sufficient samples to test, which will add to the data development portion of the surrogate search.

CHAPTER 5 DEVELOPMENT OF SOIL SUCTION SURROGATES

5.1 The Need for the Soil suction Surrogate

It is common practice for a geotechnical investigation report to include considerable water content, gradation, and Atterberg limits data. In characterizing unsaturated soil profiles, much can be learned through the study of profiles of water content and degree of saturation, although soil suction is the most appropriate measure of the soil moisture state with regard to unsaturated soil behavior. Although direct soil suction measurements may or may not ever be made a part of routine practice, a useful approach for evaluation of the moisture state is to plot degree of saturation profiles alongside profiles of Plastic Limit (PL), Liquid Limit (LL), Plasticity Index (PI) and/or Percentage Passing the #200 sieve (P200). The importance of gradation and plasticity in the interpretation of water content data can be seen by comparing typical soil-water characteristic curves Figure 5.1. At a given degree of saturation, a clay soil will have higher matric soil suction compared to a silt or sand; at a given value of matric soil suction, clay will have a higher water content than silt or sand. The best measure of the moisture state of an unsaturated soil profile is the matric soil suction for two primary reasons: soil suction is a stress state variable controlling behavior and soil suction is the most stable parameter in consideration of soil type variability in typical field profiles.

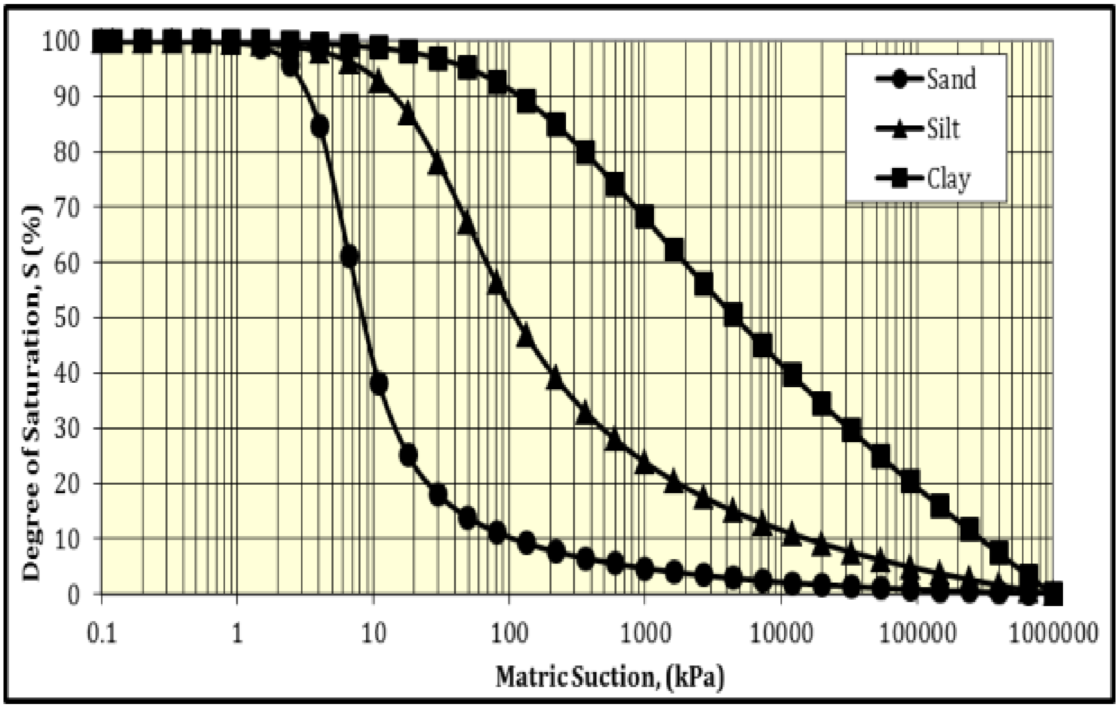


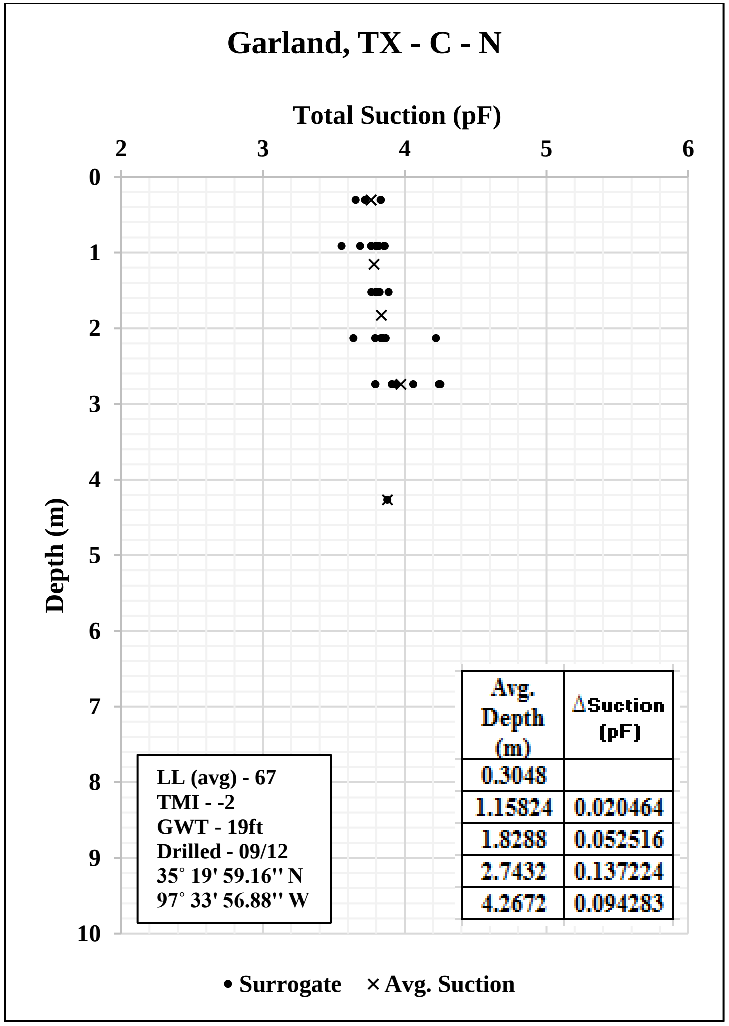
Figure 5.1: Example SWCC

Consideration of soil gradation and PI alongside water content data provides the engineer with the opportunity to qualitatively consider soil suction and helps to identify any zones of wetter soils within a profile. Consider Figure 5.2 where the water content profile exhibits a somewhat erratic pattern (Cuzme, 2018). In some cases, where the water content is relatively high, this can be explained by the presence of higher fines content. In other cases, higher water content is indicative of a wetter (lower soil suction) condition. In general, degree of saturation profiles is only slightly less erratic than water content profiles. In contrast, the soil suction tends to vary rather smoothly from a value at the surface, to zero at the ground water table. However, the degree of saturation is a much better indicator of the degree of wetting than water content alone. Soil suction profiles, such as those in Figure 5.2, are typically the least erratic and the most indicative of the degree of wetting, when compared to water content or even degree of saturation. The fact that the Atterberg limits data and fines content can be used to enhance understanding of degree of wetting within an unsaturated soil profile, suggests the desirability and applicability of using soil suction surrogates based on water content and soil index parameters, in the estimation of heave and/or shrinkage. A soil suction surrogate is simply an estimation of soil suction based on commonly measured parameters such as water content, gradation, and Atterberg limits; a soil suction surrogate can be thought of as a best-estimate, typically based on some statistical evaluation, of soil suction for typically-encountered field conditions, and does not consider hysteresis.

Based on the writer's own experience, interviews with other geotechnical engineers, and from review of over 500 geotechnical engineering reports and projects where infrastructure has been placed on expansive soil profiles, it has been observed that the clay-water content relative to the plastic limit (PL) seems to be a very good indicator of degree of wetting, further suggesting the feasibility of the approach of using a water content-Atterberg limits based soil suction surrogate for estimation of design moisture envelopes for heave computation. These very preliminary studies and experiences suggested that a good candidate for inclusion in a soil suction surrogate equation might be either water content minus plastic limit (w-PL) or water content minus the plastic limit all divided by the plasticity index (w-PL)/PI, which is the liquidity index, LI. The LL is also a strong candidate. Indeed, practicing geotechnical engineers have been known to use the above such measures of degree of wetting. However, a full suite of surrogate parameters will be considered in this study, resulting from searches of the literature and surrogate searches triggered by data from this study where direct field soil suction measurements were made.

It is known in advance that the soil suction surrogate should not be water content alone because water content is not sufficiently stable across soil types. Therefore, water content alone is not a preferred indicator of soil suction. It is realized that this assertion can be debated (Briaud, et al. 2003; Vanapalli, et al. 2010a, b), and for relatively uniform soil profiles, water content can be used to indicate degree of wetting; where initial soil water content profiles can be directly compared to post-wetting, post-construction water content profiles and water content can also be used as an indicator of degree of wetting. However, water content is not the stress variable controlling soil response, and design water content profiles are highly site-dependent. The reasons for making this assertion are given in Figure 5.2, wherein water content varies erratically and is sharply discontinuous across soil layers. An important part of this research will be to find a soil suction surrogate that exhibits good stability across soil types, and which provides an excellent estimate of field soil suction values for clays.

In this study, the best soil suction surrogate will be chosen from amongst a list of selected candidates, which will be the soil suction surrogate that correlates most closely with soil suction. The soil suction surrogate will be determined from a set of data generated from field sites where direct soil suction measurements are made, along with water content, gradation, Atterberg limits, and Thornthwaite Moisture Index (TMI). A wide range of climatic conditions will be included in the study, and soil profiles will be limited to expansive clay. This soil suction surrogate, once determined, will be used to evaluate soil moisture conditions and to estimate soil suction profiles for sites obtained from the files of geotechnical consultants.



Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.15824	0.020464
1.8288	0.052516
2.7432	0.137224
4.2672	0.094283

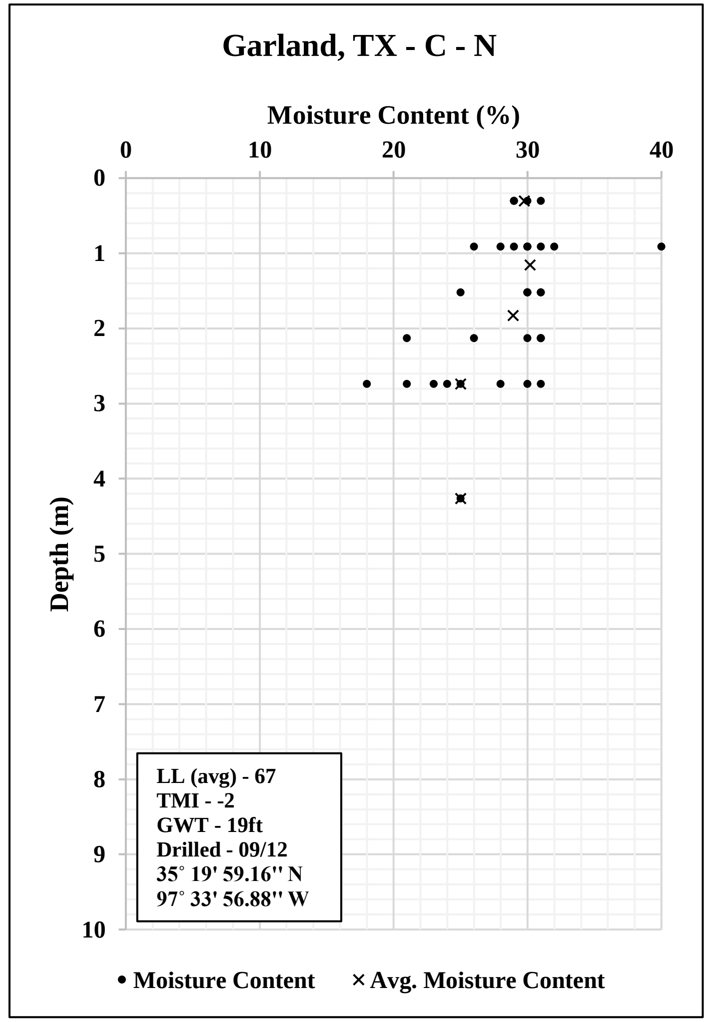


Figure 5.2: Profiles of Suction Profile (left) and Moisture Content Profile (right) for Garland, TX (Cuzme, 2018)

Once a soil suction surrogate is identified, for sites where soil suction has not been measured, suction can be estimated using the soil suction surrogate. Identification of a soil suction surrogate will necessarily include statistical analyses to determine the most appropriate soil suction surrogate. The development of a satisfactory soil suction surrogate will also entail the development of a good correlation between soil suction surrogate and directly measured soil suction.

5.2 The Search for the Soil Suction Surrogate

The search for a surrogate was initiated by accumulating the laboratory soil data from the research sites (Appendix E 1), such as Liquid Limit (LL), Plastic Limit (PL), Plasticity Index (PI), moisture content (%), percent passing the #40 sieve (P_{40}), percent passing the #200 sieve (P_{200}), nearest weather station Thornthwaite Moisture Index (TMI) and WP4C total soil suction (pF) in a spreadsheet format. The soil suction unit of pF (log to the base 10 of soil suction in centimeters of water) was selected in this study due to its extensive use in geotechnical practice; the soil suction in kPa is approximated by raising 10 to the power of the soil suction in pF and then dividing this result by 10 (e.g. a soil suction of 3 pF is (10^3/10) kPa = (1000/10) kPa = 100 kPa). The soil parameters obtained, other than directly measured soil suction, are those most commonly determined and available in geotechnical engineering investigations. To see the correlation between the collected variables and soil suction, the computer code Eureqa was used. Eureqa is a product of Nutonian, Inc. (now DataRobot). It is a statistical program that can find non-linear fitting parameters by utilizing an artificial programing tool. Eureqa is an artificial intelligence (AI) program that was created to assist people and save time by examining relationships between selected elements in a dataset. Eureqa was used essentially to sort through all the data acquired and to identify best candidate predictive models or relationships in a fraction of the time usually expected. Typically, such sorting would require months or years. Of interest in the use of Eureqa was an examination of all realistic predictive models involving moisture content, liquid limit, plastic limit, plasticity index, percent passing the #200 sieve, and total soil suction; tests that all practitioners can complete. In addition, the climatic factor, TMI, was considered.

The primary goal of the surrogate search was to estimate the total soil suction as a function of common geotechnical laboratory test results such as Atterberg limits, sieve test, and gravimetric moisture content. By gathering previously mentioned soil data in the spreadsheet format, those variables are already prepared for the Eureqa tool to find parameters for use in nonlinear function estimators of measured total soil suction. Note that in Eureqa, the user does not need to set a predefined equation to search for the best fitting parameters. Instead, the program generates equations with a wide variation in statistical error metrics that change incrementally. According to the Eureqa generated equations, it was found that the moisture content (w) in percent divided by Liquid Limit (LL) and Thornthwaite Moisture Index (TMI) are reasonably well correlated to soil suction with respect to R^2 and Standard Error (S). Although many potential forms of surrogate equations were generated by the Eureqa program, the examined forms of equations used in this study were selected to have the highest R^2 values while being relatively simple to implement and consistent with known soil suction response (e.g., for a given w, an increase in LL would result in higher soil suction), and included the forms shown in Equations (130) and (131).

$$Total\ Soil\ suction\ (w/LL,\ TMI) = A^*(w/LL)^B \tag{130}$$

$$Total\ Soil\ suction\ (w/LL,\ TMI) = A^*(w/LL)^B + C^*TMI \tag{131}$$

where A, B, C are fitting parameters.

To demonstrate the relative work intensity of the Eureqa analysis, Table 5.1 shows candidates that comprised the final grouping in the selection process. Of course, some were quite cumbersome and proved to be extremely difficult for potential use by practitioners. An example page among nearly 2500 possible candidates is presented in Table 5.1. The equation forms that were selected for further study were based on the relative ease of implementation by practitioners as well as consistency with known soil characteristics (e.g. increased LL corresponds to a soil with higher water content for a given soil suction value).

Table 5.1: Use of Eureqa to Arrive at Promising Surrogate Candidates

Possible surrogates via Eureqa program - Total Soil suction (pF)*	R^2 Goodness of fit	Correlation Coefficient	Maximum Error	Mean Squared Error	Mean Absolute Error
3.12*(Moist.LL)^(-0.234)	0.53	0.73	0.91	0.05	0.17
3.03*(0.774*Moist.LL^2)^(-0.117)	0.53	0.73	0.91	0.05	0.17
3.12*Moist.LL^(-0.234)	0.53	0.73	0.91	0.05	0.17
3.53 + 0.0321*Moist.LL*TMI + 3.92*10^-5*TMI^2*(3.25 + 0.0393*Moist.LL*TMI)^(3.23 + 0.0095*TMI)	0.69	0.83	0.79	0.04	0.14
3.53 + 0.0205*Moist.LL*TMI + 4.14*10^-5*TMI^2*(2.84 + 0.0433*Moist.LL*TMI)^3.26	0.69	0.83	0.78	0.04	0.14
3.5 + 0.0125*TMI + 0.00185*TMI^2*3.26^(0.0579*Moist.LL*TMI)	0.69	0.83	0.77	0.04	0.14
3.27 + 2.41*(-0.00103*TMI)^Moist.LL	0.67	0.82	0.76	0.04	0.15
3.62*(Moist.LL*Moist.PL)^(-0.109)	0.51	0.71	0.95	0.06	0.19
3.17 + 1.78*0.29^(0.29 + Moist.LL + Moist.LL^(1.47 + (2.54*Moist.LL)^(-540))) + 1.78*0.29^(0.29 + Moist.PL + Moist.PL^(1.47 + (2.54*Moist.PL)^(-540))) + 0.29^(0.59 + Moist.LL + Moist.PL + Moist.LL^(1.47 + (2.54*Moist.LL)^(-540)) + Moist.PL^(1.47 + (2.54*Moist.PL)^(-540)))	0.62	0.79	3.34	0.04	0.15
3.49 + 0.027*TMI*Moist.LL^2 + 0.00139*TMI^2*exp(0.076*TMI*Moist.LL)	0.69	0.83	3.40	0.04	0.14
3.49 + 0.0117*TMI + 0.00185*TMI^2*exp(0.069*TMI*Moist.LL)	0.68	0.83	3.42	0.04	0.14
3.52 + 0.0285*TMI*Moist.LL^2 + 4.029e-6*wPI*TMI^2 + 0.00172*TMI*wPI*exp(0.0286*TMI + 0.112*TMI*Moist.LL) +	0.71	0.84	2.79	0.03	0.14

Possible surrogates via Eureqa program - Total Soil suction (pF)*	R^2 Goodness of fit	Correlation Coefficient	Maximum Error	Mean Squared Error	Mean Absolute Error
0.00598*TMI^2*exp(0.0286*TMI + 0.112*TMI*Moist.LL)					
2.72 + (1.99*Moist.LL)^(0.019*TMI)	0.63	0.79	3.07	0.04	0.16
1.78 + 1.90*(1.94*Moist.LL)^(0.011*TMI)	0.64	0.80	3.17	0.04	0.15
3.61 + 0.039*TMI*Moist.LL^2 + 5.80*TMI^3*exp(TMI) + 0.00123*TMI^2*(3.61 + 0.0418*TMI*Moist.LL^2)^(0.0617*TMI*Moist.LL)	0.70	0.83	3.29	0.03	0.14
3.58 + 0.0356*TMI*Moist.LL^2 + 5.39*TMI^3*exp(TMI) + 0.00124*TMI^2*3.71^(0.0551*TMI*Moist.LL)	0.69	0.83	3.43	0.04	0.15
3.61 + 0.023*TMI*Moist.LL + 5.99*TMI^3*exp(TMI) + 0.00132*TMI^2*exp(0.066*TMI*Moist.LL)	0.69	0.83	3.30	0.03	0.14
4.51 + 0.000418*TMI^2 - Moist.PL - 0.00951*TMI - 0.00151*Moist.LL*TMI^2 - 0.0103*TMI*Moist.PL^2	0.71	0.84	2.69	0.03	0.14
3.127*Moist.LL^(-0.233)	0.52	0.72	3.29	0.05	0.17
0.812 + 4.46*(PL/LL) + 3.32*exp(-5.84*(PL/LL)*Moist.LL) + 370*(PL/LL)*(Moist.LL^12.69)^2*exp(-134233*(10454*Moist.LL^10)^10.95)	0.63	0.79	3.31	0.04	0.15
(2.00 + 1.99*wPI + 1.99*Moist.LL + 1.98*wPI*Moist.LL)/(0.113 + 0.336*wPI + 0.336*Moist.LL + wPI*Moist.LL)	0.54	0.73	3.34	0.05	0.17
5.56 + 2.03*Moist.LL^2 + 0.000543*wPI^2*Moist.LL^2 - 0.0239*wPI - 4.17*Moist.LL - 0.000491*TMI*wPI - 0.000302*Moist.LL*TMI^2	0.71	0.84	2.75	0.03	0.14
2.42 + 1.09*6.10^(0.0801*TMI*Moist.LL) - 0.055*TMI - 0.00112*Moist.LL*TMI^2	0.68	0.83	3.61	0.04	0.14
5.79548810660558 + 0.00310926810854811*w.PI + 0.00421143306375763*TMI*Moisture + -0.680388908516494*Moisture/w.PI - 0.00944876898166899*Moisture^2 - 0.000377794603762966*TMI*Moisture^2	0.62	0.79	2.11	0.03	0.13
4.33752599454846 + 5.24355967759297*(6.73720786116622e-6*w.PI)^(0.0496724774710073*w.PI*(Moist/wLL)) - 1.42021802563655*(Moist/wLL) - 0.144889273105338*w.PI*(Moist/wLL) - 0.00476153125704411*TMI*w.PI*(Moist/wLL)	0.62	0.79	2.61	0.03	0.13
2.40659478941513 + 4.00416090381926*(2.8376677276286*(Moist/wLL))^(-69)*0.000260219790476909^((2.87747181002356*(Moist/wLL))^(-49)) - 0.0640202392784641*TMI - 1.40683043513462*(Moist/wLL)	0.58	0.76	2.87	0.03	0.13
2.39170770969485 + (2.77252347727764*(Moist/wLL))^(-72)*0.000268556718032263^((2.87635024951945*(Moist/wLL))^(-46)) - 0.0645321637791535*TMI - 1.41818135011965*(Moist/wLL)	0.58	0.76	2.88	0.03	0.13
8.56657146579981 + 0.0643340820544314*TMI - Moist.PL - 0.0104448041633912*w.PI - 5.66953496265411*Moist.LL - 0.10664584982148*Moisture*Moist.PL - 0.00422256658407854*TMI*Moisture*Moist.PL - 0.0217082299169643*TMI*Moist.LL*Moist.PL	0.67	0.82	2.48	0.03	0.13
4.66449837548599 + 0.0101872882729652*Moisture*Moist.PL^2 - Moist.LL - Moist.PL - 0.021645970460077*TMI - 0.00046020225128692*Moist.LL*TMI^2	0.73	0.85	2.95	0.03	0.13

Possible surrogates via Eureqa program - Total Soil suction (pF)*	R^2 Goodness of fit	Correlation Coefficient	Maximum Error	Mean Squared Error	Mean Absolute Error
4.65947581860093 + 0.0569163524423322*TMI*Moist.LL - Moist.PL - 0.0186840347218144*TMI - 0.000683574898827557*TMI*Moisture*Moist.PL	0.72	0.85	2.96	0.03	0.13
4.70922175295731 + 0.0502549663968794*TMI*Moist.LL - Moist.PL - 0.0210218278525207*TMI - 0.000325793627403177*TMI*Moisture*Moist.PL^2	0.72	0.85	2.93	0.03	0.13
4.54249543416199 + 0.00849822373328799*Moisture*Moist.PL^2 - Moist.LL - 0.022917549458097*TMI - 0.872109931195998*Moist.PL - 0.000482229159449564*Moist.LL*TMI^2	0.73	0.85	2.96	0.03	0.13
4.42627248511768 + 0.0122216563825885*Moisture*Moist.PL^2 - Moist.PL - 0.0246759824136862*TMI - 0.581065292952347*Moist.LL*Moist.PL - 0.000562882604706016*Moist.LL*TMI^2	0.73	0.85	2.95	0.03	0.13
4.55494144747527 + 0.0354780520206129*TMI*Moist.LL - Moist.PL - 0.0247728556469964*TMI - 0.000300848630222328*Moist.LL*TMI^2 - 0.000315685397039525*TMI*Moisture*Moist.PL^2	0.73	0.86	2.83	0.03	0.13
4.37497659903463 + 0.0390813626312356*TMI*Moist.LL - 0.0281730847197703*TMI - 0.845959582435276*Moist.PL - 0.000329967608038734*Moist.LL*TMI^2 - 0.000265578363363716*TMI*Moisture*Moist.PL^2	0.73	0.86	2.81	0.03	0.13
3.96229557609989 + - 0.0041229962525857*TMI/Moist.LL - Moist.LL	0.67	0.82	3.34	0.04	0.15
4.1057968358513 + - 0.00368487513574701*TMI/Moist.LL - 1.28921772748962*Moist.LL	0.67	0.82	3.39	0.04	0.15
5.03964435781832 - 0.0120108054253236*w.PI - 2.49399599347702*Moist.LL - 0.0002732927946724*TMI*w.PI	0.68	0.82	2.89	0.04	0.15
5.57381840402839 + 0.0147371043150575*TMI - 0.0237453322595013*w.PI - 2.60515954422296*Moist.LL - 0.000621813951961605*TMI*w.PI	0.69	0.83	2.48	0.03	0.15
4.18252235805788 - 0.0229015212929148*TMI - 1.80227976451067*Moist.LL - 0.000202750644856848*Moist.PL*TMI^2	0.68	0.83	3.06	0.04	0.15
4.52170504182009 - 0.0100713891887307*TMI - 2.3341497720074*Moist.LL	0.64	0.80	3.50	0.04	0.15
5.536790965441 + 0.0660198526565713*TMI*Moist.LL - 0.0249295664899236*w.PI - 0.630802719796675*Moist.LL - 0.70386451242302*Moist.PL - 0.000579573752214903*TMI*w.PI - 0.000640373605076*TMI*Moisture*Moist.PL	0.75	0.87	2.56	0.03	0.13
5.55043270950248 + 0.0666403945083268*TMI*Moist.LL - 0.025577848425903*w.PI - 0.634644984085993*Moist.LL - 0.719835811091423*Moist.PL - 0.000593364429959483*TMI*w.PI - 0.000662804971365059*TMI*Moisture*Moist.PL	0.75	0.87	2.56	0.03	0.13

Possible surrogates via Eureqa program - Total Soil suction (pF)*	R^2 Goodness of fit	Correlation Coefficient	Maximum Error	Mean Squared Error	Mean Absolute Error
5.70724569063472 + 0.0780880921087989*Moisture*Moist.PL - 0.754950875044739*Moist.LL - 1.85598394278674*Moist.PL - 0.00878169938056138*w.PI*Moist.LL - 0.809378657881945*Moist.LL*Moist.PL - 0.00175939565476164*Moisture^2	0.63	0.79	3.43	0.04	0.15
5.60377370917998 + 0.0913652636326322*Moisture*Moist.PL + 0.0418375319584908*w.PI*Moist.LL - 2.47248168754914*Moist.PL - 0.00225193287006033*Moisture^2 - 0.122483289408464*w.PI*Moist.LL^2	0.64	0.80	3.48	0.04	0.15
5.67696150093735 + 0.0931307072731921*Moisture*Moist.PL - Moist.LL*Moist.PL - 2.16642707719309*Moist.PL - 0.00205089095276996*Moisture^2 - 5.19139396016474e23*0.00234804645512892^w.PI - 0.0353862725126523*w.PI*Moist.LL^2	0.65	0.80	3.42	0.04	0.15
5.70995231612485 + 0.0999464453481496*Moisture*Moist.PL - 2.33943257595099*Moist.PL - 0.914992779190503*Moist.LL*Moist.PL - 0.00200494767833101*Moisture^2 - 4.69578429121929e23*0.00231740455757211^w.PI - 0.00199403911270726*Moisture*w.PI*Moist.LL^2	0.65	0.81	3.50	0.04	0.14
5.39177424006098 + -0.0933686729282415/TMI + 0.00151132528025923*wPI^2*(Moist/wLL)^2 - 1.21820745999803*(Moist/wLL) - 0.145219865215836*wPI*(Moist/wLL) - 0.000244504199210343*TMI^2 - 0.00248302456336607*TMI*wPI*(Moist/wLL)	0.70	0.83	2.64	0.03	0.14
TotSoil suctionPF = 4.62137494823342 + 0.000232919181852754*TMI^2*exp((Moist/wLL) + (Moist/wPL) + 0.0674030674132013*TMI*(Moist/wLL) + 0.00126625619268696/((Moist/wPL) + 0.0656607819745139*TMI*(Moist/wLL))) - 0.891255144385577*(Moist/wPL)	0.70	0.84	3.01	0.03	0.14
4.60868735968017 + 0.00146256029792852*Moisture^2 - 0.0268166897286431*TMI - 0.0603203891764581*Moisture - 0.278422543655563*(Moist/wPL) - 0.76769689483096*(Moist/wLL) - 0.000170287240699765*TMI^2	0.68	0.82	2.97	0.04	0.14
TotSoil suctionPF = 9.78961114819484 + 2.54904154154885e-5*LL*Moisture^2 + - 42.263610209493*log(PI)/LL - 0.0137866064636734*LL - 0.0147051578269333*PI - 0.114080998029004*Moisture	0.70	0.83	0.66	0.04	0.14
TotSoil suctionPF = 8.94104024421284 + 2.67784641842618e-5*LL*Moisture^2 + - 35.2133445629562*log(PI)/LL - 0.0250145599816584*PI - 0.11574067833059*Moisture	0.69	0.83	0.68	0.04	0.14
TotSoil suctionPF = 7.13325525022708 + 6.20593314422984e-7*Percent.200*Moisture^4 + (- 2.77063560751959*PI - 3.82092331252198*Moisture)/LL	0.65	0.81	0.70	0.04	0.14

Possible surrogates via Eureqa program - Total Soil suction (pF)*	R^2 Goodness of fit	Correlation Coefficient	Maximum Error	Mean Squared Error	Mean Absolute Error
TotSoil suctionPF = 7.17459368962005 + 0.00137766269602531*Moisture^2 + (-2.54197901295116*PI - 3.67029691847053*Moisture)/LL - 0.0354491633079798*Moisture	0.66	0.81	0.68	0.04	0.14
TotSoil suctionPF = 7.1240965380577 + 1.90294496800555e-5*Moisture^3 + (-2.79680471409223*PI - 3.89812096471823*Moisture)/LL	0.66	0.81	0.68	0.04	0.15
TotSoil suctionPF = 6.84211205026892 + 0.000562514426467968*Moisture^2 + (-2.52142698002167*PI - 3.77011389354534*Moisture)/LL	0.65	0.81	0.70	0.04	0.15
TotSoil suctionPF = 5.81202343340819 + 0.220722849826157*TMI*Moist.LL + 2.84603759553394*Moist.LL^3 + 0.000515547454081331*TMI^2 - 0.0918336923172141*Moisture - 0.00127693438889607*Moisture^2 - 0.000235401881803672*TMI*Moisture^2	0.66	0.82	1.17	0.04	0.14

*Note – In the above table, the Moist.LL term refers to water content divided by LL

Although Eureqa generates coefficients for the corresponding forms of equations, it is typically not practical to statistically determine the best fit parameters due to programming features. Therefore, another program, Minitab, is utilized to statistically analyze the best fit parameters once candidate relationships are identified. The Minitab program uses iterative procedures called Gauss-Newton algorithms to come up with the coefficients for a given form of equation from given starting values, while minimizing the sum of squared errors. The most meaningful metric for Minitab is Standard Error (S), which is an estimate of the variance in the data after the relationship between the response and the predictor(s) has been considered. S is the square root of the MSE (Mean Square Error) and has the same unit as the response parameter. Additional details on the approach taken to identify a soil suction surrogate is provided in subsequent sections.

5.3 Initial Efforts for Determination of the Soil Suction Surrogate

The following section describes that initial efforts to identify a soil suction surrogate for use in practice, as presented by Vann, et al, 2018. The relationship between soil suction and what are termed here as "soil suction surrogates" has been utilized by numerous researchers in the past and consists of such things as relationships between water content and index properties, including Plasticity Index (PI), Plastic Limit (PL), Liquid Limit (LL), percent clay, percent passing #200 sieve (P_{200}), activity, Thornthwaite Moisture Index (TMI), and others. Many of these past efforts have been focused on development of correlations between index properties and soil-water characteristic curves. SWCC test specimens are allowed to achieve equilibrium with imposed soil suction conditions in the laboratory, often under controlled conditions ensuring that the soil specimens are on the extremes of the wetting or drying curve of the SWCC. In contrast, equilibrium conditions are rarely the case for the field, except at substantial depth (e.g., below seasonal fluctuation depth) where near-equilibrium soil suction is established. Field soil suction values commonly lie somewhere between the extreme wetting and drying curves measured in a laboratory setting. Field soil suction values below the moisture active zone (i.e., equilibrium soil suction values) are commonly estimated from climatic measures such as TMI, rather than water content and soil index properties.

As the focus of the soil suction surrogate search in this study was for estimation of field soil suction profiles, a search for a surrogate that included water content and soil index properties alone was undertaken, as well as a search that included water content, soil index properties, and TMI. A total of 476 data points was initially collected from soils sampled and tested from Denver, Colorado; Hobart, Oklahoma; Phoenix, Arizona; Mesa, Arizona, and San Antonio, Texas. For each sample, moisture content, Atterberg Limits, and the percent passing the #200 sieve were measured to depths of 10 m (32.8 ft). Additionally, the total soil suction was measured in 1-foot depth increments using a WP4C device. Using the entire data set from field investigations of this study (E 1), a soil suction surrogate dependent only on water content and liquid limit was initially found to be the best fit, and is illustrated in Figure 5.3 and described in Equation (132).

$$\psi = 3.2117 \left(\frac{w}{LL}\right)^{-0.2177}; 0.05 \leq \frac{w}{LL} \leq 1.0 \quad (132)$$

$$R^2=0.5099$$

$$S=0.2752pF$$

Where,

ψ is the total soil suction in pF

w is the moisture content (%)

LL is the Liquid Limit

This regression model was derived using the Minitab program. The program uses iterative Gauss-Newton algorithms to obtain the best fit coefficients for a given form of the equation by minimizing the sum of squared errors. A meaningful metric from Minitab is the Standard Error of Regression (S), which is a measure of the accuracy of the predictions. An optimized fit will minimize S. S is the square root of the Mean Square Error (MSE) and has the same units as the response parameter. For the Figure 5.3 data, S is 0.2752pF. An S of 0.2752 pF means that the observed soil suction measurement falls a standard distance (roughly an average absolute distance) of 0.2752 pF units from the fitted values.

Further statistical analyses revealed a strong R^2 correlation with the form of Equation (133), below, for the soil suction surrogate extending to a depth of 3.66 m (12 ft). Below a depth of 3.66 m (12 ft), the R^2 value decreased significantly using the form of Equation (133) for the surrogate, with the reduction in R^2 becoming quite significant below about 5.79 m (19 ft). Therefore, a TMI component was introduced into the equation for the data below 3.66 m (12 ft) to increase the level of confidence with respect to R^2 and S, Equation (134), below.

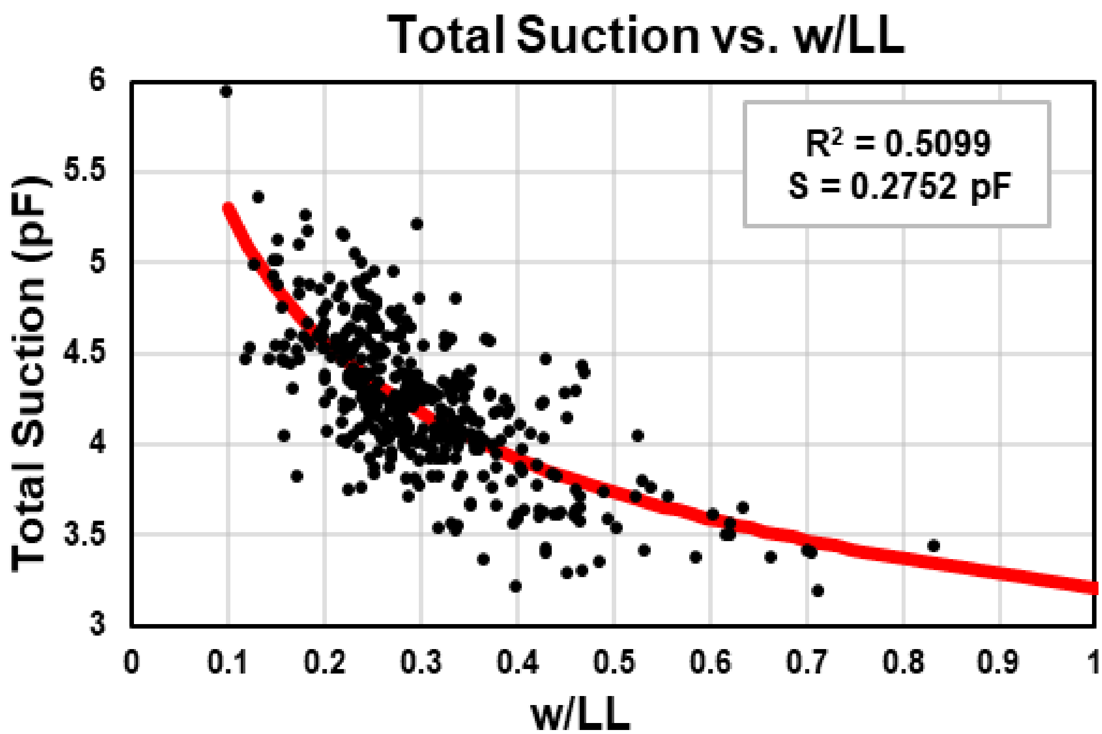


Figure 5.3: Fit of the Measured Total Soil Suction and Relationship to Water Content Divided by Liquid Limit (Not Dependent on TMI or Depth).

The Equation (135), below, for the soil suction surrogate, which encompasses a stronger TMI factor, was found to provide the strongest correlation below a depth of 5.79 m (19 ft), predicated on the optimization of the statistical parameters. The Witczak et al.

(2006) form of the TMI equation was used in the model due to simplicity of calculation and its close correlation to the original Thornthwaite (1948) TMI equation, as observed by Olaiz et al. (2017). In Equation (134), a depth-weighted function for soil suction surrogate was used to estimate soil suction between depths of 3.66 m (12 ft) and 5.79 m (19 ft). In final, a depth-dependent set of soil suction surrogate equations were derived as shown in Equations (133) through (135).

$$\psi_I = a\left(\frac{w}{LL}\right)^b; z \leq 3.66\ m\ (12.01\ feet) \tag{133}$$

R^2=0.5872

S=0.3219pF

$$\psi_{II} = \psi_I + \left(\frac{z - 3.66}{2.13}\right)(\psi_{III} - \psi_I); 3.66m < z < 5.79m \tag{134}$$

R^2=0.609

S=0.2541pF

$$\psi_{III} = c\left(\frac{w}{LL}\right)^d + eTMI; z \geq 5.79m\ (18.20\ feet) \tag{135}$$

R^2=0.67

S=0.1562pF

where a = 3.0524, b = -0.2663, c = 3.3655, d = -0.2006, e = 0.0068, z = depth in meters.

Table 5.2 describes the statistical process for the depth-dependent surrogate equation determination.

Table 5.2: Selection of applicable depths to apply to the depth-dependent and TMI-dependent soil suction surrogate (rows highlighted in gold represent best fits for a specific range)

Depth	Equation	R^2 *(%)*
Above 10'	3.07921 * 'w/LL' ^ -0.262624	58.5
Below 10'	3.38212 * 'w/LL' ^ -0.187575 + 0.00415629 * TMI	49.2
Above 11'	3.06622 * 'w/LL' ^ -0.265045	59
Below 11'	3.40576 * 'w/LL' ^ -0.182687 + 0.00434378 * TMI	48.9
Above 12'	3.05968 * 'w/LL' ^ -0.265475	58.7
Below 12'	3.41732 * 'w/LL' ^ -0.180711 + 0.00444117 * TMI	49.2
Above 13'	3.05245 * 'w/LL' ^ -0.266311	58.7
Below 13'	3.42967 * 'w/LL' ^ -0.18161 + 0.00528051 * TMI	50.4
Above 14'	3.06168 * 'w/LL' ^ -0.262837	56.9
Below 14'	3.42333 * 'w/LL' ^ -0.184744 + 0.00557451 * TMI	53.9
Above 15'	3.06288 * 'w/LL' ^ -0.262387	56.7
Below 15'	3.42961 * 'w/LL' ^ -0.186596 + 0.00647187 * TMI	56.5
Above 16'	3.07071 * 'w/LL' ^ -0.260291	55.9
Below 16'	3.42664 * 'w/LL' ^ -0.189913 + 0.00725776 * TMI	60.9
Above 17'	3.09136 * 'w/LL' ^ -0.254987	54.6
Below 17'	3.40533 * 'w/LL' ^ -0.194885 + 0.00744214 * TMI	63.6
Above 18'	3.10428 * 'w/LL' ^ -0.251659	53.3
Below 18'	3.38918 * 'w/LL' ^ -0.19692 + 0.00715441 * TMI	66
Above 19'	3.13611 * 'w/LL' ^ -0.242965	51.9
Below 19'	3.3655 * 'w/LL' ^ -0.200589 + 0.00680671 * TMI	67
Above 19'	3.36918 * 'w/LL' ^ -0.170063	59.1
Above 20'	3.1432 * 'w/LL' ^ -0.24081	52.1
Below 20'	3.37614 * 'w/LL' ^ -0.195437 + 0.00640952 * TMI	66

The overall R^2, using Equations (133) through (135) to predict soil suction, for the entire 476-point data set, increased to 0.57 (S=0.2596), compared to an R^2 of 0.5099 using Equation (132). Also, S significantly decreased for $\psi_{II,}$ ψ_{III} and increased only slightly for $\psi_{I,}$, as shown in Table 5.3. Although wetting/drying hysteresis is reduced for field situations compared to typical laboratory SWCC testing conditions, field hysteresis would be expected to be greatest in shallower soil depths where variations in soil suction due to changes in surface flux conditions (e.g. seasonal variation) are most pronounced. Therefore, the greatest scatter in soil suction data would be expected to be above the depth of equilibrium soil suction, which the Table 5.3 supports given the higher S value for shallower data. Table 5.3 statistics suggest that the equilibrium depth would be between 3.66 m (12 ft) and 5.79 m (19 ft) for the data set considered.

Table 5.3: Depth-dependent surrogate statistics

Surrogate Equation	Depth Range (m)	S (pF)
ψ_I	$z \leq 3.66$	0.3219
ψ_{II}	$3.66 < z < 5.79$	0.2541
ψ_{III}	$z \geq 5.79$	0.1562
ψ_I , ψ_{II} & ψ_{III}	*All*	0.2596

5.4 Refinement of Soil Suction Surrogate

The soil suction surrogate of Equations (133) through (135) above were derived from site-specific measurements and are relatively easy to implement by practitioners (Vann et al., 2018). However, the depth-dependency of the soil suction surrogate, together with dependence on TMI, raises some concern given recent findings by Cuzme (2018) and Singhar (2018) wherein soil suction at depth was found to be rather poorly correlated with TMI (R-squared of about 0.3 to 0.4); in this current study, which incorporated the data used by Cuzme and Singhar plus data from some additional drilled sites and literature, the correlation between suction at depth and TMI exhibited only modest correlation (R-squared of about 0.6). Therefore, further studies of soil suction surrogate were pursued, including the addition of some measured-soil suction sites from available geotechnical reports and literature – thus, expanding the data set of directly measured soil suction values beyond that used by Vann, et al. (2018). The focus of the subsequent surrogate search (detailed in

Section 5.4) was on simplification and evaluation of the appropriateness of inclusion of TMI in the surrogate equation.

For the depth-dependent soil surrogate proposed by Vann, et al. (2018) the TMI component moves the predicted soil suction in a counter-intuitive direction: when the TMI is increasingly positive the soil suction surrogate increases, and when the TMI becomes more negative, the soil suction decreases. Cuzme (2018) utilized Equations (133) through (135) to study the relationship between TMI and the magnitude of equilibrium soil suction. Further, Cuzme (2018) and Singhar (2018) found that equilibrium soil suction (soil suction at depth) was not well-correlated with TMI, thus raising questions about the use of TMI in a soil suction surrogate formulation. Singhar (2018) suggests that the poor correlation between TMI and equilibrium soil suction (at depth) could be attributed, in part, to insufficient weather stations to provide appropriate climatic data for all areas of the U.S. Singhar (2018) further concluded that TMI relates primarily to precipitation, and to a much lesser extent evapotranspiration. Singhar suggested that there is a clear need for refinement to the TMI equation, perhaps including making it a function of the number of days of rainfall, site slope, unique characteristics of the surface soil, rainfall intensity, and other factors not yet realized in the simple climate factor. However, inclusion of such site-specific factors remains a challenge in climatic index parameters. Given the poor to only modest correlation between TMI and equilibrium soil suction, further soil suction surrogate study was conducted with a focus on the following question: Should depth-dependency and TMI be included in a soil suction surrogate?

After Vann, et al. (2018) it became clear through further study that TMI did not provide a strong influence on the soil suction surrogate. Further, informal discussions with practitioners suggested that the Vann et al. (2018) soil suction surrogate equations were still too complicated and difficult to use for acceptance and incorporation into design methodologies. Taking a further look at the surrogate equation, therefore, became imperative. Given the desirability of a simple form and the non-inclusion of TMI, the initial form of the soil suction surrogate equation was revisited, i.e. Equation (132).

Whereas Singhar (2018) and Cuzme (2018) found poor correlation between TMI and equilibrium soil suction, the research of Cuzme (2018) provided extremely useful insight and a new relationship to calculate the depth to equilibrium soil suction for expansive soil profiles with deep groundwater table, which is based on TMI.

Cuzme's plot of relevant depth to equilibrium soil suction data, which was presented in his thesis and in Section 6.1.15, yielded a relationship between TMI and depth to constant soil suction as depicted in Figure 5.4.

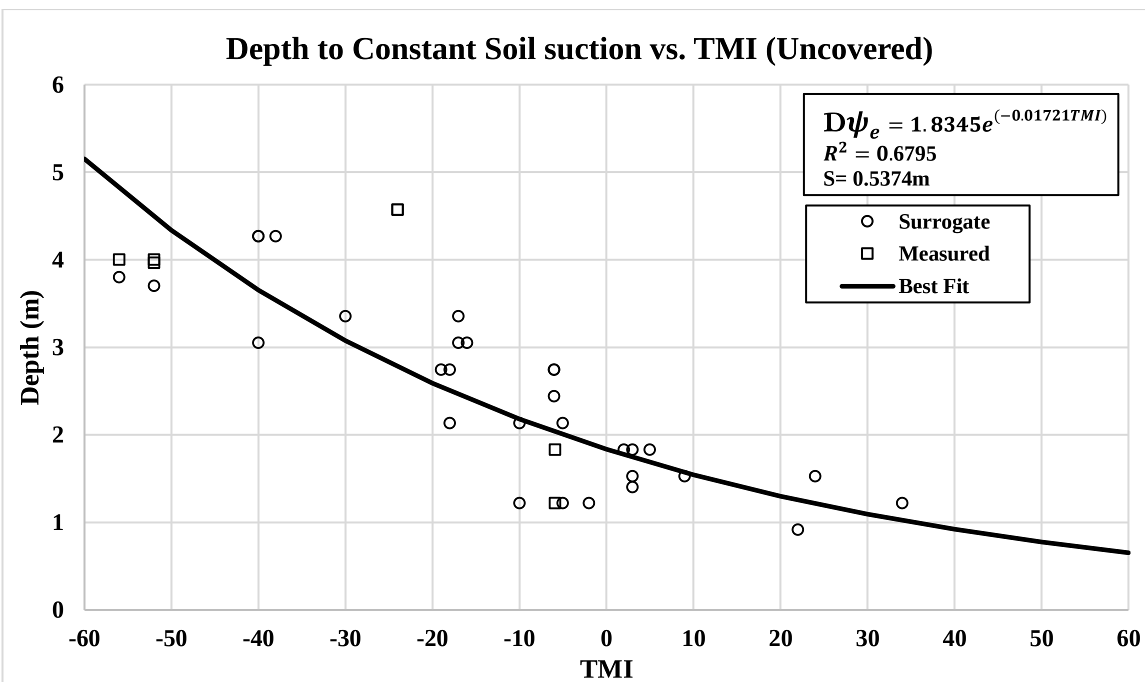


Figure 5.4: Depth to Constant Soil suction Versus TMI (Cuzme, 2018)

The Cuzme (2018) equation is given by Equation (136), with its accompanying R^2 and S.

$$D_{\psi_e} = 1.8345e^{(-0.01721TMI)} \tag{136}$$

$$R^2 = 0.6795$$

$$S = 0.5374m$$

Where $D_{\psi_e} =$ the depth to equilibrium soil suction

Using the work of Cuzme (2018) and the first proposed surrogate equation, Equation (132), the question was posed: What if the original form of Equation (132), developed initially, was the best one? And if the original form is appropriate, can we appropriately use the same equation to evaluate the soil suction with respect to values both above and below the depth to constant or equilibrium soil suction? Using a 501-point dataset of directly measured soil suction values and corresponding soil index parameters, which had been updated since Vann et al. (2018), two datasets/plots were generated. One dataset was needed to arrive at the applicable coefficients for the original form of the surrogate equation, (132), for values above the calculated depth to constant soil suction (Cuzme, 2018). The second dataset would be used to evaluate the data below the calculated depth to constant soil suction. The intent for separating the data into above and below depth to constant soil suction was to explore if there were appreciable differences in R^2 and S between the two datasets and to explore further, any differences in best fit coefficients above and below the depth to constant soil suction.

The data above the calculated depth to constant soil suction, yielded the surrogate relationship shown in Figure 5.5.

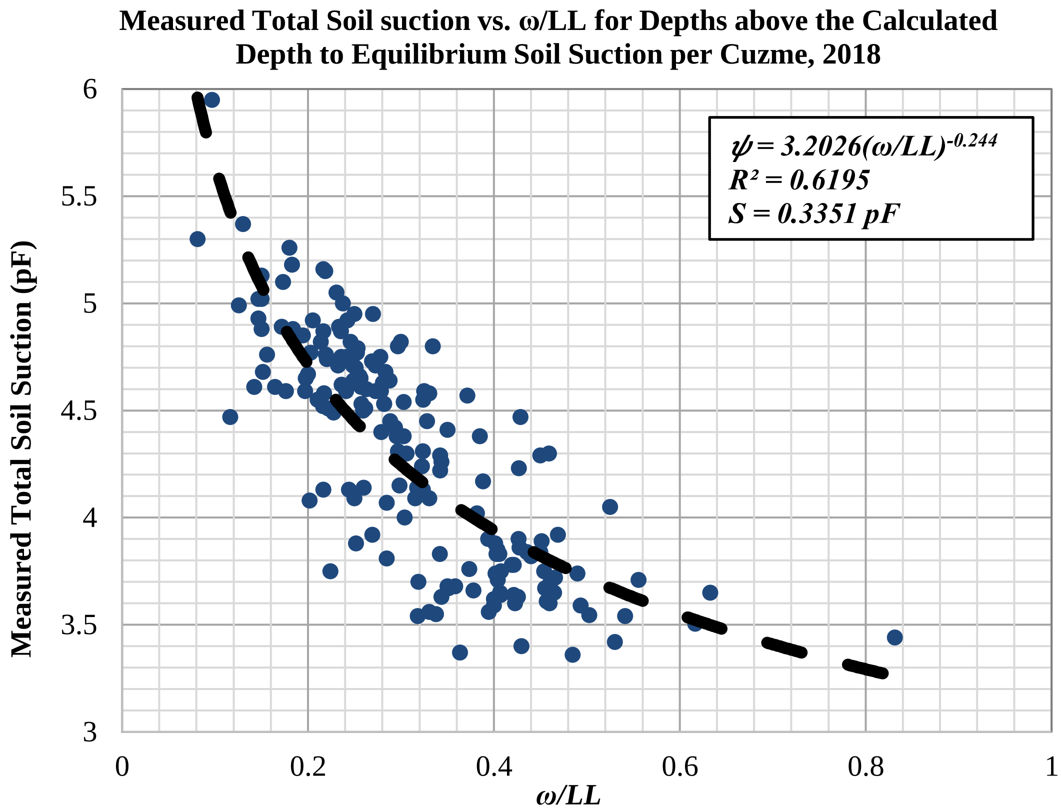


Figure 5.5: Using the Cuzme, 2018, Depth to Constant or Equilibrium Soil Suction Equation, Measured Data Above the Constant Soil suction Depth Yielded the Presented Surrogate Relationship.

The simplified form of the soil suction surrogate equation for values above the anticipated depth to equilibrium soil suction is presented in Equation (137).

$$\psi \quad = 3.2026\left(\frac{w}{LL}\right)^{(-0.244)} \tag{137}$$

$$R^2 = 0.6195$$

$$S = 0.3351\ pF$$

For the field of geotechnical engineering, the achieved R^2 of 0.6195 is quite promising, suggesting that Equation (145) is reasonable for computation of soil suction above the calculated depth to equilibrium soil suction. The second surrogate evaluation was for the data below the calculated depth to constant soil suction, as shown in Figure 5.6.

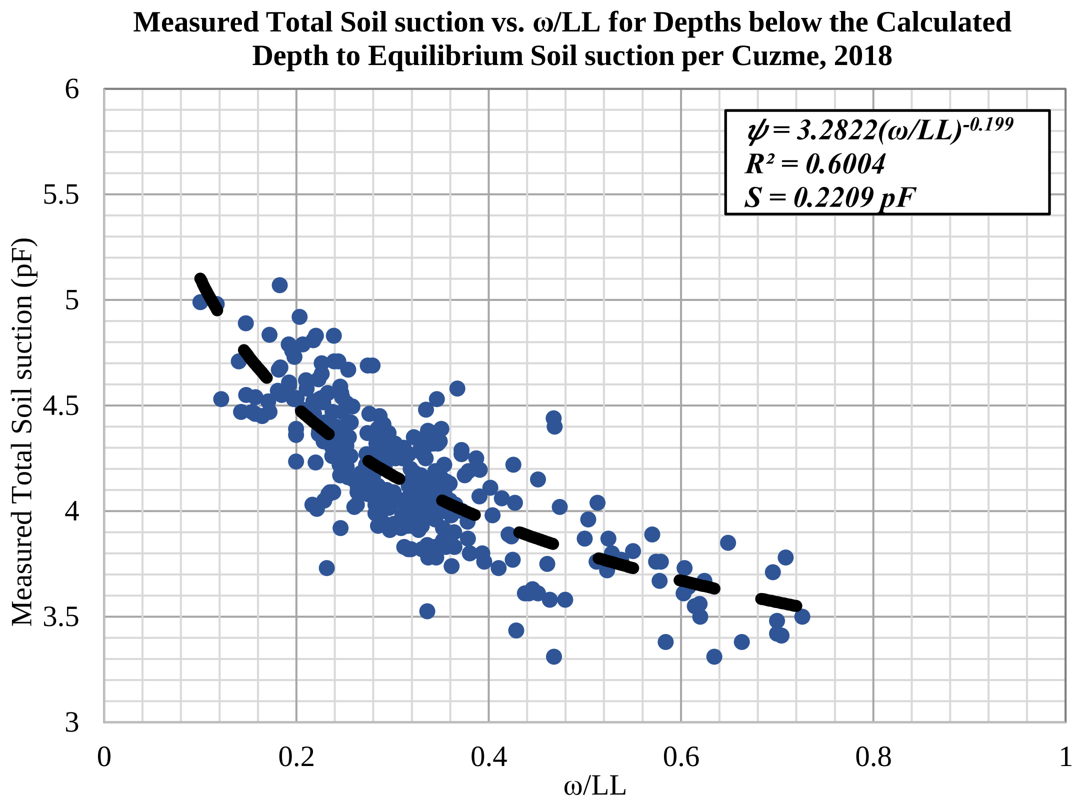


Figure 5.6: Using the Cuzme (2018), Depth to Constant or Equilibrium Soil Suction Equation, Measured Data Below the Constant Soil Suction Depth Yielded the Presented Surrogate Relationship.

The simplified form of the soil suction surrogate equation for values below the anticipated depth to equilibrium soil suction is presented in Equation (138).

$$\psi = 3.2822\left(\frac{w}{LL}\right)^{(-0.199)} \qquad (138)$$

$$R^2 = 0.6004$$

$$S = 0.2209\ pF$$

As for the preceding case, the achieved R^2 of 0.6004 is also quite promising for use of an equation of the form of Equation (147) for the data below the calculated depth to constant soil suction.

Comparing the R^2 values for both equations, 0.6195 and 0.6004, and given that the coefficients of the surrogate equation are quite close above and below the depth to equilibrium soil suction, it is not clear that use of two separate surrogate equations represents the best recommendation for simplicity of use in practice. That stated, one single surrogate equation was explored using 501 data points. The data points are presented in Appendix E 1. The resulting surrogate equation, using the entire data set and disregarding the calculated depth to constant soil suction is presented in Figure 5.7.

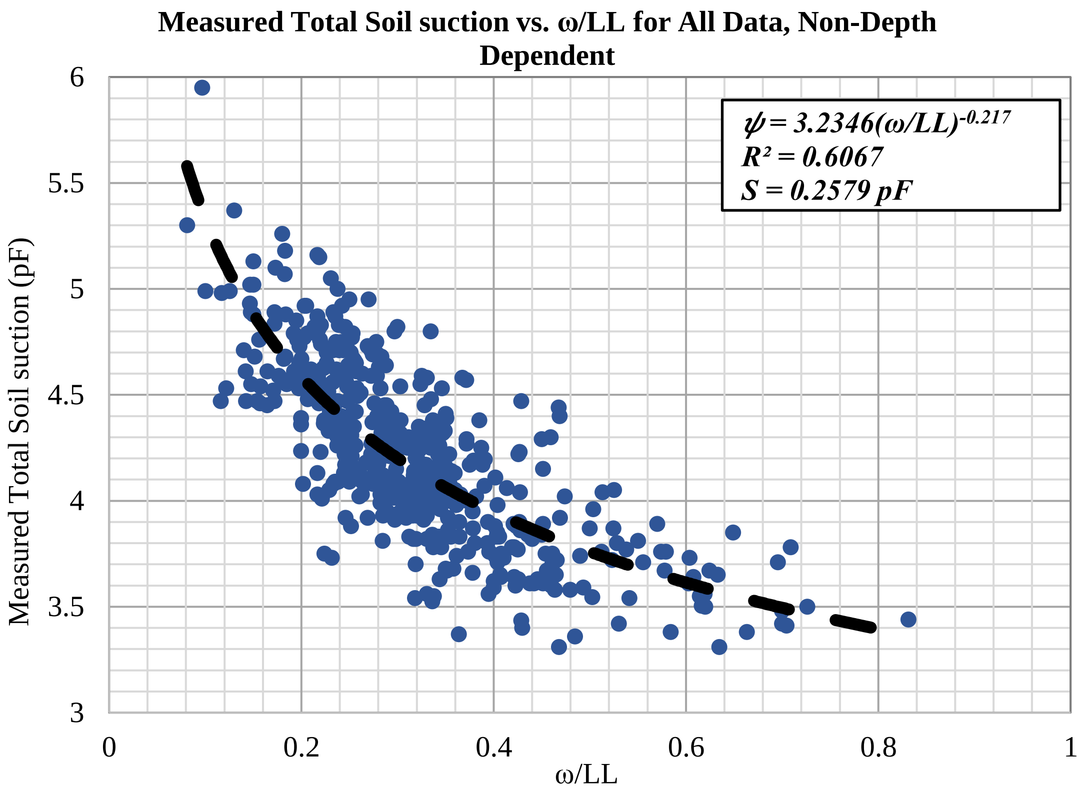


Figure 5.7: Final Non-TMI and Non-Depth Dependent Soil Suction Surrogate.

An R^2 of 0.6067 is considered very good for the "all-data" condition, suggesting a TMI-independent and simplified surrogate equation as shown in Equation (139).

$$\psi = 3.2346\left(\frac{w}{LL}\right)^{(-0.217)} \tag{139}$$

$$R^2 = 0.6067$$

$$S = 0.2579\ pF$$

As with the Vann, et al. (2018) surrogate values, the standard error of 0.2579 pF is considered good, given known hysteresis for extreme wetting to extreme drying curves of typically 1 order of magnitude for clay soils (Pham, et al. 2003).

5.5 Conclusions Regarding the Final Selection of a Soil Suction Surrogate

The surrogate research has resulted in a simple and depth-independent surrogate equation that can be utilized with a reasonable degree of confidence. The presented soil suction surrogate equation may be used by practitioners to arrive at a reasonable estimate of field soil suction magnitude using only moisture content and liquid limit, both obtained routinely in practice by means of simple laboratory tests that every geotechnical firm performs. Equation (139) is proposed for use in practice where direct soil suction measurements are not practical:

The surrogate equation described by Equation (139) is easily comprehended and used by practitioners. In Chapter 6, soil suction surrogate-estimated design field soil suction profiles will be compared to design profiles based on directly measured field soil suctions. Surrogate-based heave predictions will also be compared to heave predictions based on direct soil suction measurements. In this manner, adequacy of the soil suction surrogate for applications of heave estimation will be examined.

CHAPTER 6 FIELD SOIL SUCTION PROFILES

This chapter presents the results of an investigation of the history and features of commonly-adopted soil suction profiles and parameters for current soil suction-based methods, such as equilibrium soil suction and depth to constant/equilibrium soil suction. An attempt will be made to look at those aspects of the current state of practice that are most reasonable and the limitations of procedures and methodologies that are currently in use. Recommendations are made for estimation of design soil suction profiles, based on available data/methods from the literature and based on the data obtained from this overall research study. Directions for future research and field / laboratory testing methods that must be employed to implement soil suction-based methods for heave computation are also explored.

Three separate areas of concern, with regard to climate-related (seasonal fluctuation) suction profiles, are the focus of this chapter: 1) Determination of the magnitude of equilibrium soil suction and a given locale in terms of Thornthwaite Moisture Index (TMI), 2) Determination of the depth to equilibrium / constant soil suction for the same locale, 3) Determination of the variation in soil suction at the surface for a given TMI, and 4) Determination of the Aubeny and Long (2007) supported climate 'r' parameter. In addition, changes to design suction profiles associated with varying boundary conditions (e.g. covering of ground surface, changes to surface flux due to development/irrigation) are explored. Figure 6.1 recaps the above described key elements that are needed for design; presented in diagrammatic form.

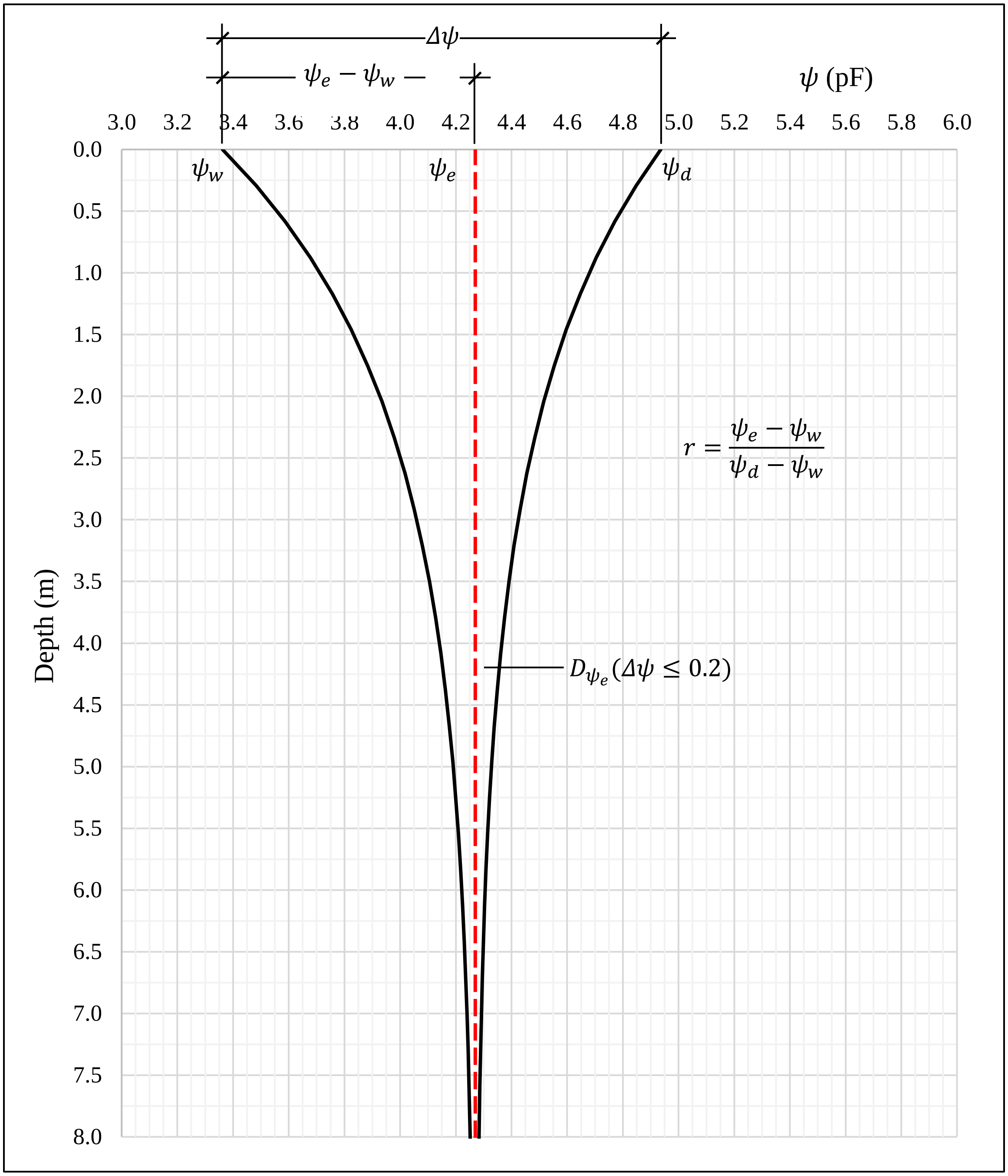


Figure 6.1: Diagram of Soil Suction Envelop with Depth Showing Key Elements Pertaining to Design

The work of Singhar (2018) and Cuzme (2018) have clearly demonstrated the value of the Thornthwaite Moisture Index (TMI) to the study soil suction profiles. As part of the development of the Enhanced Integrated Climatic Model (EICM) for the Mechanistic-Empirical Pavement Design Guide (MEPDG), the Thornthwaite Moisture Index (Witczak, et al. 2006), referred in this report as TMI_{2006}, is given by Equation (140).

$$TMI = 75\left(\frac{P}{PE} - 1\right) + 10 \tag{140}$$

where P=precipitation, and PE is the potential evapotranspiration

TMI determined by Equation (140) is intended to provide values of TMI close to those originally proposed by Thornthwaite (1948).

Singhar (2018) developed GIS software for determination of the TMI in terms of an easy-to-use format for the practitioner. The practitioner can utilize the following web address for the Singhar (2018) map:

https://asu.maps.arcgis.com/apps/webappviewer/index.html?id=fadabdb2975f4aadbde30a9894f740ca

The weather stations for the contiguous-48 states in the USA, pertinent data for any site may be obtained through interpolation. Singhar's map of the TMI is shown in Figure 6.2. As a result of the previous studies at Arizona State University, the TMI_{2006} will be utilized throughout this paper.

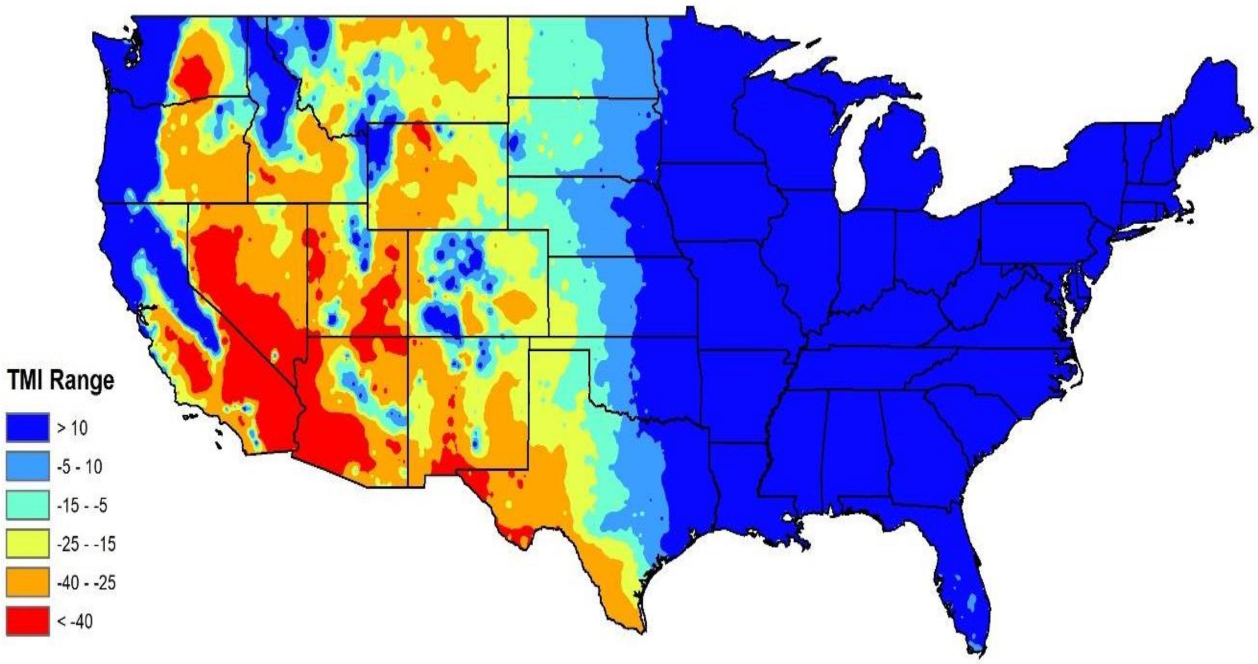


Figure 6.2: TMI_{2006} GIS Map

It must be remembered that TMI is a measure of the long-term severity of a local climate.

6.1 Magnitude of Constant Soil Suction

Over the past several decades, several authors have presented methods for estimation of equilibrium soil suction at depth that occurs in soil profiles, particularly for conditions of seasonal fluctuations in soil moisture. Herein, it will be attempted to address the following:

- Motivations for the use of TMI versus equilibrium soil suction correlations
- Sources of data for correlations between equilibrium soil suction and climatic index (e.g. TMI)
- Why the literature-based relationships, to date, are not good enough for use in estimation of equilibrium soil suction at depth
- Direct measurement methods for determination of equilibrium soil suction

Since 2004 (Post-tensioning Institute PTI 2nd Edition), a relationship has been adopted by PTI that relates TMI to the magnitude of equilibrium soil suction. The relationship is widely used by practitioners because, historically, field soil suction measurements have been challenging and not commonly made; whereas estimations of TMI are readily available. The PTI (2004) TMI versus equilibrium soil suction relationship represents a culmination of data from Snethen (1977), Jayatilaka, Gay, Lytton and Wray (1992), Naiser (1997), Wray (1989), and McKeen (1981). Aside from these key papers, other work has been crucial in the development of a connection between TMI and the magnitude of equilibrium soil suction, such as Barnett and Kingsland (1999), Mitchell (2008) and Russam and Coleman (1961). According to Cuzme (2018), however, there does not appear to be an extremely strong correlation between TMI and the magnitude of equilibrium soil suction. The discussions to follow encompass a review of work on this question of the relationship between TMI and equilibrium soil suction since 1961. The work studied has considered specifically sites that are undeveloped and not affected by limiting conditions such as shallow groundwater. In all cases, there were no occurrences of groundwater within the uppermost 9.14 m (30 feet) at any site considered. Essentially, the discussion to follow will demonstrate the basis for selection of historical (literature) data points that have been considered in this current study in determination of a relationship between TMI and the magnitude of constant soil suction for use in practice where suction measurements are not available.

6.1.1. Russam and Coleman (1961)

Russam and Coleman (1961) completed a study that compared soil suction versus TMI for three major soil types. Of interest to this study is the curve for 'Heavy Clay' as depicted in Figure 6.3. The data is for soil conditions in East Africa and Nigeria. Although not stated in the paper, the phrase 'Heavy clay' has historically been used for soils whose plasticity indices are more than 15. The Russam and Coleman (1961) plot was for soil profiles unaffected by the presence of groundwater and for pavement subgrades beneath pavements that were at least 5 years old. The presumed expectation of the study was to demonstrate that moisture fluctuations would be more pronounced near the edge of a pavement as opposed to center, that perhaps the moisture content and soil suction would tend to stabilize beneath the center of the pavement regardless of seasonal weathered changes, changes in moisture content would correspond to changes in soil suction (greater moisture content with a lesser magnitude of soil suction), and that there is a TMI based correlation with soil suction for pavement subgrades (shallow soils).

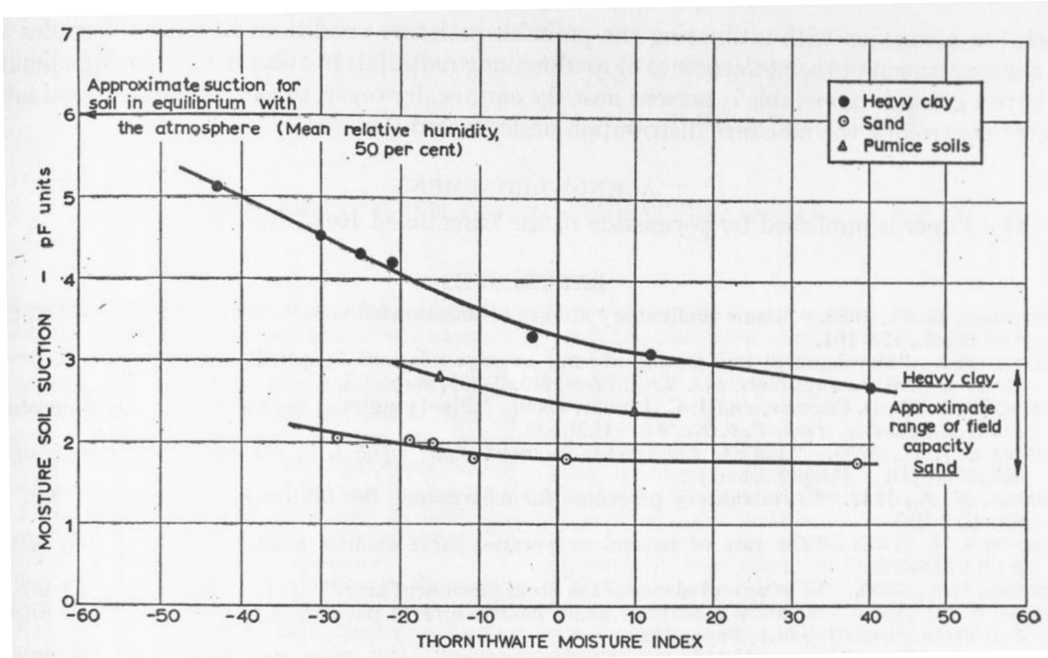


Figure 6.3: Correlation of Soil Suction with TMI (Russam and Coleman, 1961) for Subgrade Soils Beneath Pavements That Were At least Five Years Old in East Africa and Nigeria.

Seven data points constitute the curve for the 'Heavy Clay.' Cuzme (2018) picked off the data points as shown in Table 6.1.

Table 6.1: Russam and Coleman, 1961, 'Heavy Clay' data points (Cuzme, 2018)

TMI	**Soil suction (pF)**
12	3.03
-4.35	3.42
-21	4.22
-25	4.35
-30	4.64
-43	5.1
40	2.72

Through careful review of the Russam and Coleman (1961) data, it cannot be ascertained as to what depths the soils were sampled or distance from pavement edge. For this reason, the seven data points representative of the Russam and Coleman (1961) study have not been selected for use in this study.

Lytton (1997) completed commentary on the Russam and Coleman (1961) paper wherein he found inconsistencies between the semi-empirical Russam and Coleman (1961) relationship and observed magnitudes of soil suction from the field. Lytton (1997) did not specifically question the empirical relationship but used the discrepancies as impetus to examine the effects of equilibrium soil suction in greater detail. Lytton (1997) suggested further study to take a closer look at the site-specific soil water characteristic relationships.

6.1.2. Aitchison and Richards (1965)

For mainland Australia, a plot, Figure 6.4, of TMI versus equilibrium soil suction was prepared by Aitchison and Richards (1965). Soil suction measurements were obtained for seventeen locations, all at or below a depth of 3.05 m (10 ft). Figure 6.4 shows the relationship between TMI, with values ranging from +40 to -60, and equilibrium soil suction in pF. The Russam and Coleman (1961) plot is shown on the plot for comparison. Visually, the Aitchison and Richard (1965) data agrees with the Russam and Coleman (1961) for extremely positive TMI (humid conditions). Conversely, for extremely negative TMI (arid conditions), the Aitchison and Richards (1965) data is predominantly lower that the Russam and Coleman (1961) data.

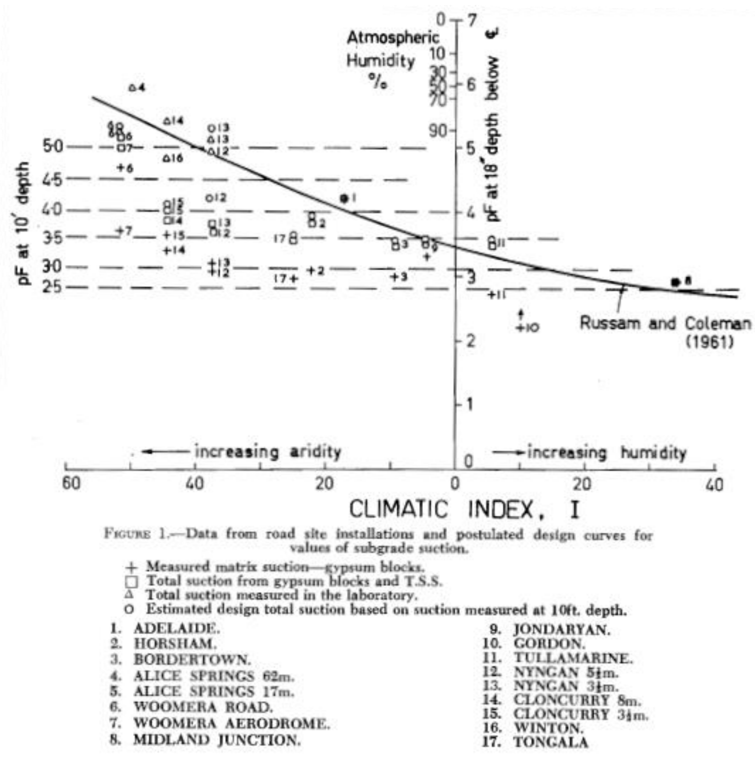


Figure 6.4: Relationship of Subgrade Soil suction and Climatic Index - Same as TMI (Aitchison and Richards, 1965)

In the above figure, there are six data points that represent measured data. The measured data are denoted by triangles. Through review of the Aitchison and Richards (1965) data, it cannot be ascertained as to what depths the soils were sampled or distance from pavement edge. For this reason, the six data points representative of the Aitchison and Richards (1965) study have not been selected for use in this study.

6.1.3. Snethen (1977)

Snethen (1977), while working with highway infrastructure, selected 20 field sampling sites to study soil suction in connection with clay soils. Site 1 (Jackson, Mississippi) was located in a covered section of a pavement structure.

Snethen (1977) states that the samples tested for soil suction were from depths shallower than 4.57 m (15 feet). Total soil suction measurement was made using the thermocouple psychrometer method on multiple cubes of undisturbed soil at the in-situ moisture content and allowing for other undisturbed cubes to wet or dry as needed. Testing of the shallow depth samples, typically within the upper five feet, is in keeping with conventional pavement studies where relatively near-surface subgrade soils are the focus.

It is important to note that no sample was retrieved deeper than 2.38 m (7.8 feet), although drilling extended to 4.57 m (15 ft). Many samples were obtained from an interval of generally 0.305 m (1 foot) to 0.914 m (3 feet), but none exceeding 2.38 m (7.8 feet). In fact, 2.38 m (7.8 feet) is the exception. In most cases, the greatest sample depth was on the order of 0.91 m (3 feet) to 1.52 m (5 feet).

With regard to using the Snethen (1977) data in connection with a relationship between TMI and magnitude of equilibrium soil suction, the following concerns arise:

- The aforementioned fact that only one of the sites involved sampling directly beneath the pavement, where equilibrium would have assumed to be achieved after a significant period.
- There is no clarity as to whether the samples tested were disturbed (remolded) or relatively undisturbed.
- As discussed previously, it is important to note that no sample was retrieved deeper than 2.38 m (7.8 feet). In fact, many samples were obtained from the extremely shallow interval of generally 0.31 to 0.91 m (1 to 3 feet). Further, 2.38 m (7.8 feet) is rather the exception, with the sample depth interval of 0.91 to 1.52 m (3 to 5 feet) being the norm. For uncovered sites, a deeper sampling interval would be required

to arrive at a value of equilibrium soil suction, that it unless the TMI of the site was positive.

- Further, because of the depth and other factors, the total soil suction measured was simply that for the sample extracted and is not, nor can it be, inferred as equilibrium.

The Snethen (1977) data is summarized in Table 6.3. Based on a review of the data, only one data point was considered in this study as magnitudes of equilibrium soil suction, as presented in Table 6.2.

Table 6.2: Snethen (1977) Values for the Magnitude of Equilibrium Soil Suction Selected by this Study

Location	TMI	Magnitude of Equilibrium Soil suction (pF)
Jackson, MS	39.41	3.67

Table 6.3: Summary of Data from Snethen, 1977

Site	Location	Sample depth interval (ft)	TMI	USCS	Moisture content (%)	Liquid Limit	Plasticity Index	Measured Soil Suction (kPa)	Measured Soil Suction (pF)	Surface Covering	Approximate Location beneath the Surface Covering	Vegetative Covering Surrounding Drill Sites, if not Beneath Pavement	Remarks Concerning Equilibrium Soil Suction*
1	Jackson, MS	1.0-3.2	39.41	CH	42.8	104	68	456.78	3.67	Pavement structure	Approximate centerline of the eastbound lane along I-220, 1.75 miles southwest of the junction of I-220 and I-55		Reasonable for consideration as an equilibrium soil suction value
2	Hattiesburg, MS	1.0-2.9	45	CH	26.7	61	41	203.01	3.32	Uncovered Right-of-way	Adjacent to the southbound lane, near the junction of US 49 and Lakeview Drive	Partial grass cover and no trees	Not considered for this study because of anticipated shallow groundwater
3	Monroe, LA	1.0-2.8	44.13	CH	49.7	96	58	30.64	2.50	Uncovered Right-of-way	East and adjacent to Milhaven Road, approximately 1000 feet south of I-20	Complete grass and partial tree cover	Not considered for this study because the sample depth is too shallow to be equilibrium, and the site is irrigated
4	Lake Charles, LA	1.0-3.1	32.87	CH	24.6	56	39	50.22	2.71	Uncovered private property	Near a borrow pit close to Milepost 38; near the I-10 and I-210 junctions	Complete grass cover and no trees	Not considered for this study because the sample depth is too shallow to be equilibrium, and the site is irrigated
5	San Antonio, TX	3.5-5.1	-13.29	CH	22.7	58	31	172.37	3.25	Uncovered median of a	Near the junction of US 90 and FM 1604	Open, rolling terrain, complete	Not considered in this study

Site	Location	Sample depth interval (ft)	TMI	USCS	Moisture content (%)	Liquid Limit	Plasticity Index	Measured Soil Suction (kPa)	Measured Soil Suction (pF)	Surface Covering	Approximate Location beneath the Surface Covering	Vegetative Covering Surrounding Drill Sites, if not Beneath Pavement	Remarks Concerning Equilibrium Soil Suction*
										4-lane roadway		grass cover and no trees	because of shallow sample depth for the respective TMI
6	Vernon, TX	4.8-7.2	-11.12	CL	13.5	34	13	415.60	3.63	Uncovered Right-of-way	1000 feet west of the US 287 and FM 925 junction	No vegetative cover	Not considered for this study as the soil is not expansive
7	Durant, OK	3.5-4.7	25.5	CL	15.8	48	27	30.64	2.49	Uncovered verge slope	Adjacent to the southbound lane of SH 78	Complete grass cover with a sparse tree cover above the cut slope	Not considered for this study because the site is heavily irrigated
8	Hennessey, OK	3.5-5.6	10.53	CL	15.1	47	24	35.43	2.55	Uncovered, open, gently rolling terrain	Near the junction of US 81 and SH 51	Complete grass cover and no trees	Likely too shallow, possibly irrigated
9	Holbrook, AZ (1)	2.5-4.2	-43.34	CL	10.9	34	16	1763.90	4.25	Uncovered relatively narrow median, but bounded by covered	Approximately 60 feet north of the centerline of the eastbound lane	No vegetative cover	Not considered for this study – shallow sample depth for extent of uncovered area
10	Holbrook, AZ (2)	2.0-4.3	-43.34	CH	17.4	54	25	2928.34	4.48	Uncovered Right-of-way, cut section	Approximately 4 miles east of the junction of US 180 and Petrified Forest National Park Road, 50 feet south of the centerline	Sparse grass and no trees	Not considered for this study – shallow sample depth for extent of uncovered area
11	Price, UT	1.2-3.2	-36.03	CL	9.1	46	26	2281.00	4.37	Uncovered, west verge	Approximately ½ mile south of	Sparse grass and no trees	Not considered

Site	Location	Sample depth interval (ft)	TMI	USCS	Moisture content (%)	Liquid Limit	Plasticity Index	Measured Soil Suction (kPa)	Measured Soil Suction (pF)	Surface Covering	Approximate Location beneath the Surface Covering	Vegetative Covering Surrounding Drill Sites, if not Beneath Pavement	Remarks Concerning Equilibrium Soil Suction*
										slope, adjacent to improved shoulder	the junction of SH 10 and SH 155		for this study because the sample depth is too shallow to be equilibrium
12	Hayes, KS	1.4-3.4	-1.97	CH	26.6	75	51	172.37	3.25	Uncovered, south verge slope of the eastbound lane	Adjacent to I-70, 750 feet east of milepost 165	Full grass cover and no trees	Not considered for this study because the sample depth is too shallow to be equilibrium
13	Ellsworth, KS	2.0-4.3	7.69	CL	17.2	49	21	273.87	3.45	Uncovered median	1.5 miles west of the junction of I-70 and US 156	Nearly full grass cover and no trees	Not considered for this study because the sample depth is too shallow to be equilibrium
14	Limon, CO (1)	4.2-6.3	-15.8	CH	25.7	56	31	749.80	3.88	Uncovered, I-70 shoulder, 33 feet north of the centerline of the westbound lane	I-70, Approximately 0.5 mile east of I-70 and US 24 junction	Partial grass cover and no trees	Not considered for this study because the sample depth is too shallow to be equilibrium
15	Limon, CO (2)	3.4-5.0	-15.8	CH	38.0	63	39	172.37	3.25	Uncovered, north verge slope, 22 feet north of the centerline of the westbound lane	I-70, approximately 0.5 mile west of the I-70 and SH 86 junction	Partial grass cover and no trees	Not considered for this study because the sample depth is too shallow to be equilibrium

Site	Location	Sample depth interval (ft)	TMI	USCS	Moisture content (%)	Liquid Limit	Plasticity Index	Measured Soil Suction (kPa)	Measured Soil Suction (pF)	Surface Covering	Approximate Location beneath the Surface Covering	Vegetative Covering Surrounding Drill Sites, if not Beneath Pavement	Remarks Concerning Equilibrium Soil Suction*
16	Denver, CO	5.7-7.8	-19.6	CL	15.2	38	19	1571.42	4.21	Uncovered, north right-of-way, prior to complete construction	SH 48, 1.8 miles east of the junction of SH 8 and SH 74	Partial grass cover and no trees	Not considered for this study because the sample depth is too shallow to be equilibrium
17	Newcastle, WY (1)	3.0-5.2	-17.1	CH	26.9	55	30	375.38	3.58	Uncovered, east right-of-way, 35 feet from the pavement centerline	Approximately 0.5-mile northwest of the junction of US 16 and SH 451	Full grass cover and no trees	Not considered for this study – shallow sample depth for extent of uncovered area
18	Newcastle, WY (2)	1.6-3.8	-17.1	CH	15.5	50	22	2938.87	4.48	Uncovered, 90 feet east of the centerline	Approximately 5.5 miles north of the Weston-Niobrara County Line on US 85	Sparse grass cover and no trees	Not considered for this study – shallow sample depth for extent of uncovered area
19	Billings, MT	3.1-4.6	-25.3	CH	17.9	69	45	121.62	3.09	Uncovered, north verge slope, approximately 18 feet north of the centerline	I-94, approximately 5 miles east of the Hyaham Interchange and about 1.5 miles east of the Sarpy Creek Interchange	Full grass cover and no trees	Too shallow - Soil suction is very low for expected for CH soil at 17.9% moisture – possibly an error
20	Reliance, SD	1.7-3.9	-3.04	CH	33.8	80	46	192.48	3.29	Uncovered, right-of-way, 210 feet east of the centerline	SH 47W, between Big Ben Dam and Reliance	Full grass cover and no trees	Not considered for this study because the sample depth is too shallow

Site	Location	Sample depth interval (ft)	TMI	USCS	Moisture content (%)	Liquid Limit	Plasticity Index	Measured Soil Suction (kPa)	Measured Soil Suction (pF)	Surface Covering	Approximate Location beneath the Surface Covering	Vegetative Covering Surrounding Drill Sites, if not Beneath Pavement	Remarks Concerning Equilibrium Soil Suction*
													to be equilibrium

*Depth to equilibrium suction as determined by Figure 6.52.

6.1.4. McKeen (1981)

The focus of the McKeen (1981) effort was to examine the characteristics of expansive soil subgrades for airport runways, taxiways, access roadways, and aprons. Data were collected to maximum depths of 6.0 m (19.7 ft), including measurements of soil suction by means of filter paper and thermocouple psychrometer methods, accompanied by moisture content. There is ample information in the McKeen (1981) research to suggest that the soil suction data reported may be appropriate for consideration of equilibrium suction conditions, particularly considering the extensive data collection to the 6.0 m (19.7 ft) depth. Although McKeen (1981) did not specifically refer to the soil suction values as equilibrium, it has been relatively easy to determine the equilibrium magnitude because of the available soil suction profile information to depths of 6.0 m (19.7 ft). Suction profiles from McKeen (1981) are provided in Figure 6.5 through Figure 6.7.

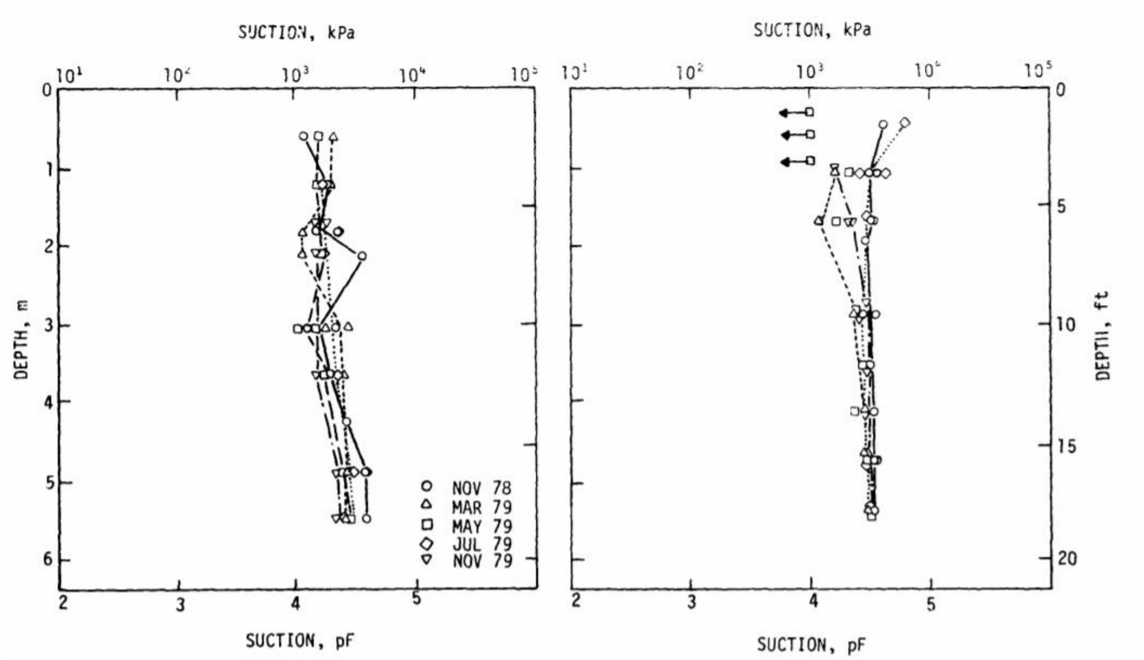


Figure 6.5: Gallup, NM Suction Profiles – Two Sites (McKeen, 1981)

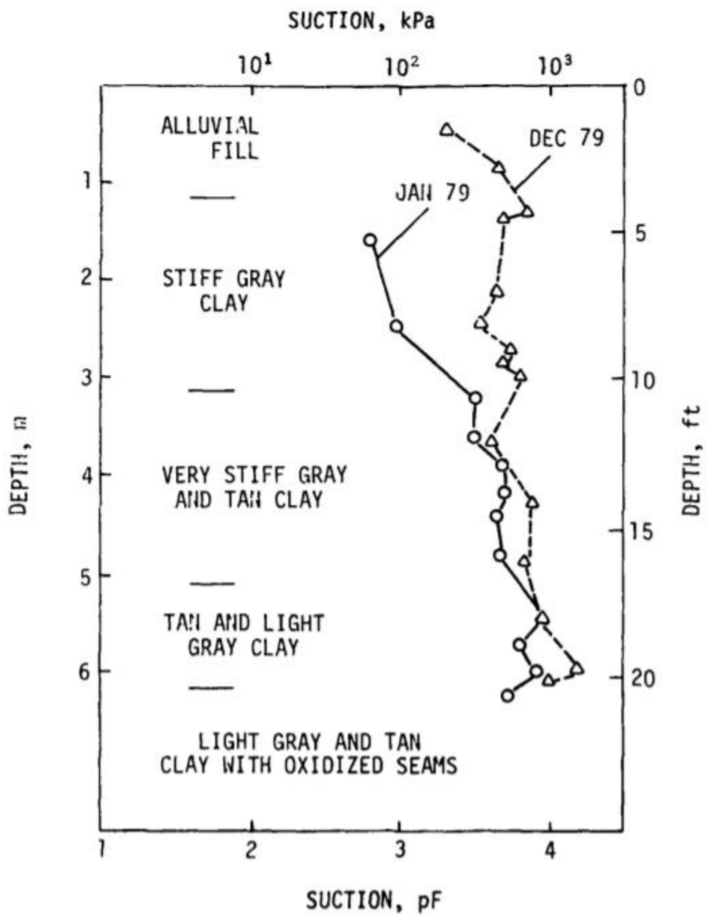


Figure 6.6: Jackson, MS Suction Profiles (McKeen, 1981)

Relevant data from four different suction profiles / test borings is presented in Table 6.4.

Table 6.4: Relevant Data from Four Suction Profiles (McKeen, 1981)

Location	**TMI** 2006	**Covered or Uncovered**	**Soil Data**	**Anticipated Depth to Equilibrium Suction using Figure 6.52 (m)**	**Equilibrium Soil Suction Recommended for Use in this Study, Based on Suction Profile (pF)**
Gallup, New Mexico – Site 1	-29.94	Uncovered	LL ranges from 49 to 95 Moisture ranges from 18 to 35%	4.0	4.2

Location	TMI 2006	Covered or Uncovered	Soil Data	Anticipated Depth to Equilibrium Suction using Figure 6.52 (m)	Equilibrium Soil Suction Recommended for Use in this Study, Based on Suction Profile (pF)
Gallup, New Mexico – Site 2	-29.94	Uncovered	LL ranges from 49 to 95 Moisture ranges from 18 to 35%	4.0	4.4
Jackson, Mississippi	39.41	Uncovered	LL ranges from 36 to 114 Moisture ranges from 25 to 39%	1.6	3.75
Dallas-Fort Worth, Texas	-1.87	Uncovered	LL ranges from 68 to 76 Moisture ranges from 20 to 28% Note: numerous sand lenses may produce erratic suction profiles	1.9	3.7

Pertaining to the McKeen (1981) data, all four data points from Table 6.4 were utilized in the relationship between equilibrium soil suction and TMI for this study.

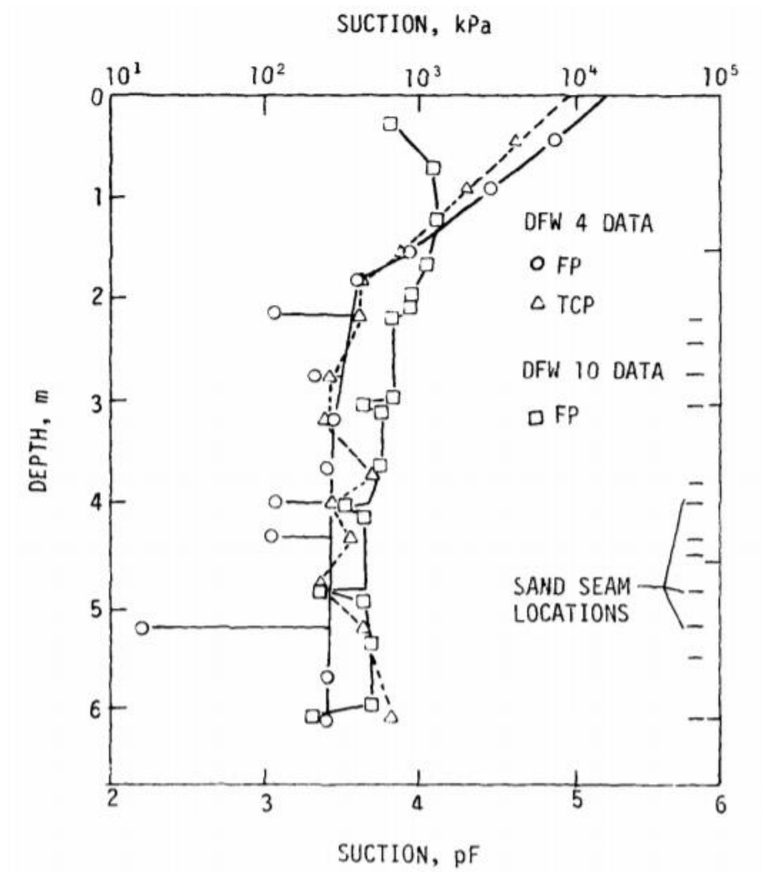


Figure 6.7: Dallas-Fort Worth, TX Suction Profiles (McKeen, 1981)

6.1.5. McKeen (1985)

Suction profiles were obtained for test borings in clay in Murdo, South Dakota, Mesquite Texas, and Dallas (Love Field), Texas. The suction profiles are depicted in Figure 6.8 through Figure 6.10.

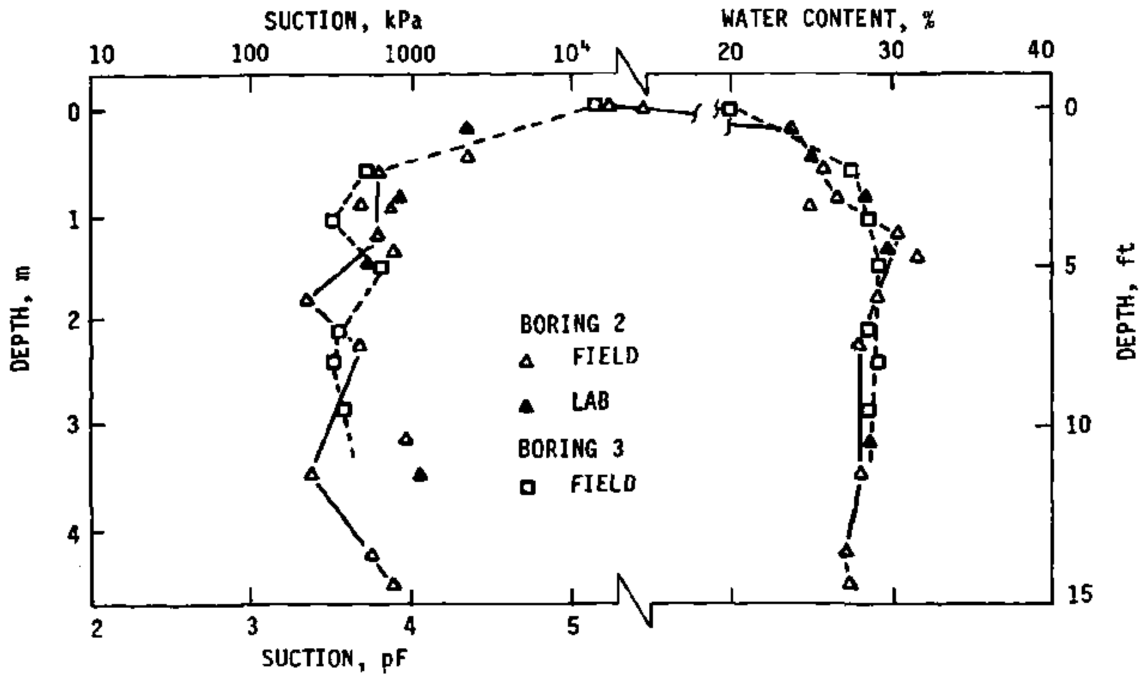


Figure 6.8: Soil Suction Profiles for Two Test Borings in Murdo, South Dakota (McKeen, 1985)

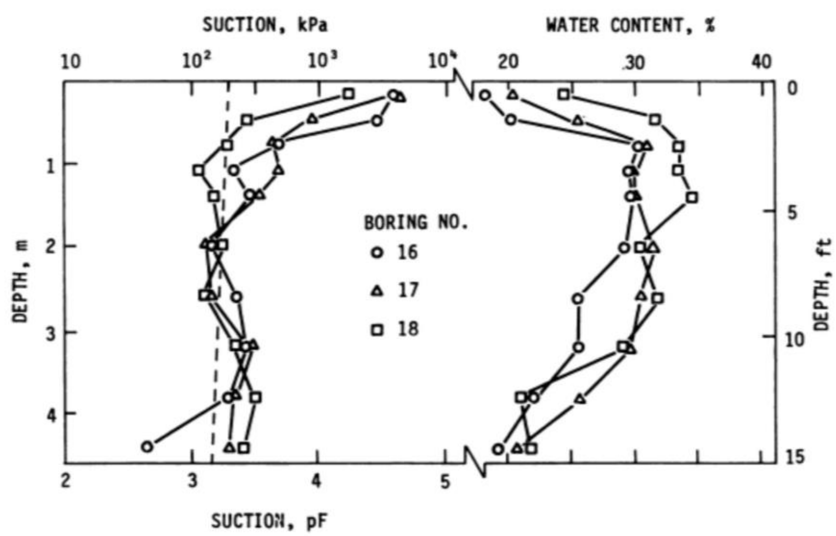


Figure 6.9: Soil Suction Profiles for Mesquite, TX (McKeen, 1985)

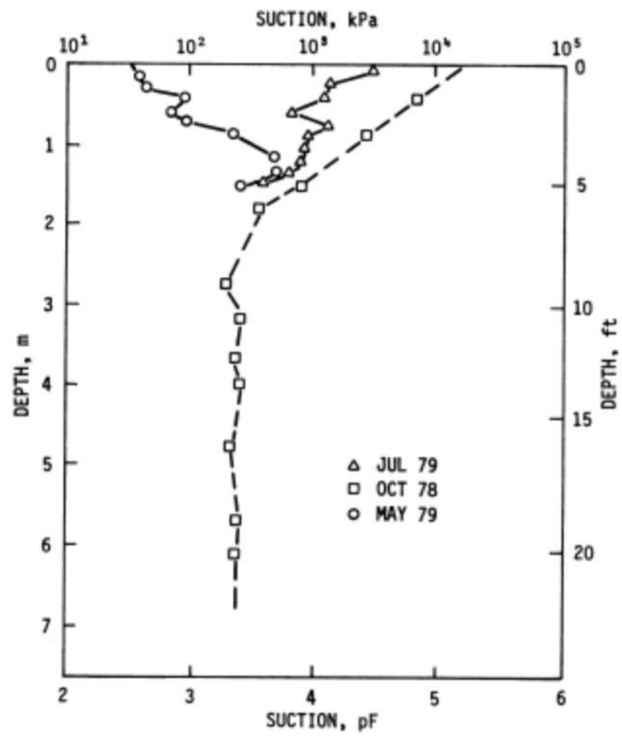


Figure 6.10: Soil Suction Profiles for Dallas (Love Field), TX (McKeen, 1985)

Relevant data from McKeen (1985) is shown in Table 6.5.

Table 6.5: Relevant Data from Three Sites (McKeen, 1985)

Location	**TMI** **2006**	**Covered or Uncovered**	**Anticipated Depth to Equilibrium Suction using Figure 6.52 (m)**	**Equilibrium Soil Suction Recommended for Use in this Study, Based on Suction Profile (pF)**
Murdo, SD – Boring / Site 2	-7.85	Uncovered	2.35	3.8
Murdo, SD – Boring / Site 3	-7.85	Uncovered	2.35	3.9

Location	TMI 2006	Covered or Uncovered	Anticipated Depth to Equilibrium Suction using Figure 6.52 (m)	Equilibrium Soil Suction Recommended for Use in this Study, Based on Suction Profile (pF)
Dallas (Love Field), TX	-2.24	Uncovered	1.9	Not utilized as McKeen (1985) stated that shallow groundwater was controlling the suction profile (cascading in the bore hole at 5.49 m (18 ft)
Mesquite, TX	5.24	Uncovered	1.7	Not utilized as McKeen (1985) stated that shallow groundwater was controlling the suction profile
Mesquite, TX	5.24	Uncovered	1.7	Not utilized as McKeen (1985) stated that shallow groundwater was controlling the suction profile
Mesquite, TX	5.25	Uncovered	1.7	Not utilized as McKeen (1985) stated that shallow groundwater was controlling the suction profile

Because the equilibrium suctions determined by McKeen (1985) for Murdo, SD, are based on suction profiles without groundwater influence, they have been incorporated in this study.

6.1.6. Wray (1989)

Wray (1989) obtained measurements of soil suction at two locations; Amarillo, Texas, and College Station, Texas. The measurements were obtained to a depth of 2.74 m (9.0 ft). Properties of the soils to a depth of 2.74 m (9.0 ft) are presented in Figure 6.11 and Figure 6.12.

DEPTH (ft)	MOISTURE CONTENT (%) Mean	(Range)	PLASTIC LIMIT (%) Mean	(Range)	LIQUID LIMIT (%) Mean	(Range)	PLASTICITY INDEX (%) Mean	(Range)	PERCENT PASSING No. 200 SIEVE (%) Mean	(Range)	PERCENT CLAY (<0.002 mm) (%) Mean	(Range)
0 - 1	8.3	(4.9-9.8)	23.2	(19.8-25.7)	37.3	(35.6-39.8)	14.1	(11.5-16.7)	62	(49-66)	47	(43-50)
1 - 2	10.5	(7.1-13.1)	19.8	(18.4-21.9)	35.0	(32.2-37.1)	15.3	(13.7-18.4)	57	(55-61)	46	(43-47)
2 - 3	13.8	(8.2-18.0)	20.5	(17.7-24.8)	33.9	(32.4-36.8)	14.1	(11.9-15.5)	59	(50-65)	42	(38-47)
3 - 4	17.8	(15.8-19.8)	26.0	(21.8-33.8)	64.3	(57.9-73.3)	38.4	(35.6-40.0)	82	(64-96)	62	(49-70)
4 - 5	19.7	(17.3-22.2)	29.3	(27.1-30.6)	77.2	(67.4-83.1)	54.2	(52.5-56.2)	75	(66-87)	59	(50-68)
5 - 6	21.7	(17.5-24.5)	36.5	(26.9-44.2)	75.8	(69.5-81.3)	39.3	(31.1-54.3)	83	(83-89)	63	(57-67)
6 - 7	24.2	(20.9-27.0)	31.0	(26.3-38.4)	74.3	(72.0-77.3)	43.4	(33.6-49.1)	83	(79-87)	64	(61-66)
7 - 8	22.7	(20.8-25.7)	28.6	(25.4-34.6)	68.7	(64.3-72.9)	40.1	(29.7-47.0)	78	(77-80)	64	(62-66)
8 - 9	23.5	(16.8-26.8)	27.4	(25.8-30.3)	66.3	(54.2-76.9)	34.8	(15.8-51.1)	81	(80-84)	61	(59-64)

Figure 6.11: Soil Properties at the Amarillo, TX Site (Wray, 1989)

DEPTH (ft)	MOISTURE CONTENT (%) Mean	(Range)	PLASTIC LIMIT (%) Mean	(Range)	LIQUID LIMIT (%) Mean	(Range)	PLASTICITY INDEX (%) Mean	(Range)	PERCENT PASSING No. 200 SIEVE (%) Mean	(Range)	PERCENT CLAY (<0.002 mm) (%) Mean	(Range)
0 - 1	6.4	(3.3-14/4)	16.7	(16.2-17.4)	26.1	(23.3-30.9)	9.4	(6.7-15.5)	33	(29-39)	23	(18-28)
1 - 2	8.9	(2.7-23.6)	20.3	(17.9-23.5)	40.0	(21.2-63.1)	19.7	(3.3-39.6)	36	(33-39)	23	(18-29)
2 - 3	18.7	(2.8-29.4)	22.4	(19.5-24.4)	51.9	(46.9-59.7)	29.4	(22.5-36.3)	62	(60-65)	52	(48-56)
3 - 4	17.4	(10.7-31.7)	19.6	(18.7-20.7)	45.1	(40.2-48.2)	25.5	(20.9-28.1)	62	(57-69)	49	(40-57)
4 - 5	16.9	(10.0-21.2)	23.3	(21.6-25.0)	48.0	(40.1-54.5)	24.7	(18.5-31.3)	62	(58-67)	48	(40-61)
5 - 6	17.9	(14.5-20.3)	18.7	(18.6-19.0)	45.5	(36.9-52.8)	26.8	(18.3-33.9)	65	(59-69)	42	(37-48)
6 - 7	20.8	(12.8-26.2)	23.2	(20.5-27.9)	48.8	(42.8-54.4)	25.6	(22.3-28.1)	64	(63-66)	50	(44-53)
7 - 8	23.9	(16.8-30.7)	29.3	(25.9-31.8)	57.6	(50.6-65.8)	28.3	(20.5-39.9)	79	(74-88)	59	(46-68)
8 - 9	29.1	(24.5-30.7)	30.5	(25.4-33.0)	64.4	(46.1-78.5)	34.0	(20.6-45.5)	94	(86-98)	72	(63-82)

Figure 6.12: Soil Properties for the College Station, TX Site (Wray, 1989)

Figure 6.13 presents the moisture content and soil suction measurements to a maximum depth of 2.74 m (9.0 ft) the Amarillo, TX site (Wray, 1989).

DEPTH (ft)	MOISTURE CONTENT (%) Mean	(Range)	FILTER PAPER SOIL SUCTION (pF) Mean	(Range)
0 - 1	8.3	(4.9-9.8)	5.3	(5.0-5.5)
1 - 2	10.5	(7.1-13.1)	5.0	(4.9-5.1)
2 - 3	13.8	(8.2-18.0)	5.0	(4.7-5.8)
3 - 4	17.8	(15.8-19.8)	4.8	(4.7-4.9)
4 - 5	19.7	(17.3-22.2)	4.7	(4.5-4.8)
5 - 6	21.7	(17.5-24.5)	4.6	(4.4-5.0)
6 - 7	24.2	(20.9-27.0)	4.4	(4.2-4.7)
7 - 8	22.7	(20.8-25.7)	4.4	(4.2-4.7)
8 - 9	23.5	(16.8-26.8)	4.3	(4.1-4.7)

Figure 6.13: Amarillo, TX In-Situ Moisture and Soil suction Data

Figure 6.14 presents the moisture content and soil suction measurements to a maximum depth of 2.74 m (9.0 ft) the College Station, TX site (Wray, 1989).

DEPTH (ft)	MOISTURE CONTENT (%) Mean	(Range)	FILTER PAPER SOIL SUCTION (pF) Mean	(Range)
0 - 1	6.4	(3.3-14.4)	4.9	(4.6-5.1)
1 - 2	8.9	(2.7-23.6)	4.5	(3.0-4.9)
2 - 3	18.7	(2.8-29.4)	4.3	(2.3-4.8)
3 - 4	17.4	(10.7-31.7)	4.3	(4.0-4.7)
4 - 5	16.9	(10.0-21.2)	4.3	(3.9-4.5)
5 - 6	17.9	(14.5-20.3)	4.3	(4.2-4.4)
6 - 7	20.8	(12.8-26.2)	4.3	(4.0-4.5)
7 - 8	23.9	(16.8-30.7)	4.3	(4.1-4.6)
8 - 9	29.1	(24.5-30.7)	4.2	(4.1-4.5)

Figure 6.14: College Station, TX in-situ moisture and soil suction data

Using a series of test borings at each of the two sites, Amarillo and College Station, soil suction measurements versus depth were obtained to depth of 2.74 m (9.0 ft). Figure 6.15 is a plot of soil suction versus depth for the Amarillo site. Figure 6.16 is a plot of soil suction versus depth for the College Station site. To determine the equilibrium soil suction and depth to constant soil suction for the Amarillo site, the data is extrapolated until it becomes vertical. A fitted curve becoming vertical corresponds to the approximate depth of equilibrium soil suction per Cuzme (2018). The point at which it becomes vertical defines both the magnitude of constant soil suction and depth to constant soil suction for purposes of the Cuzme study and this current study.

Interpretation of the field soil suction profile indicated an equilibrium soil suction of about 4.3 pF at the Amarillo site. Using Figure 6.52 to approximate the depth to equilibrium soil suction for the Amarillo data suggests that soil suction measurements should be obtained to a depth of at least 3.2 m (10.5 ft). Furthermore, a magnitude of equilibrium soil suction at or near this depth should be obtained through a fit of data that extends below the depth to equilibrium soil suction and avoids the need to extrapolate. However, because there exists a suction profile that clearly defines the magnitude of equilibrium suction, the Amarillo site can be represented by an equilibrium soil suction magnitude of 4.3 pF.

The field soil suction profile for College Station is shown in Figure 6.16. A best fit line was plotted for the entire data set, yielding an equilibrium soil suction value of approximately 4.2 pF with a depth to constant soil suction of approximately 1.83 m (6.0 ft).

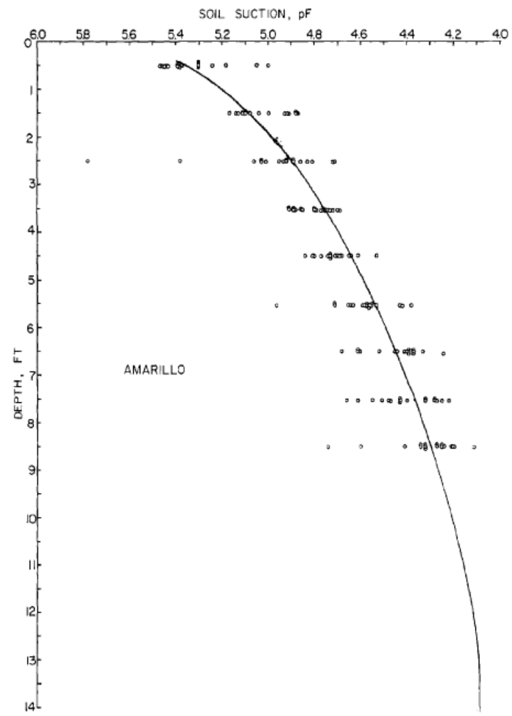


Figure 6.15: Soil Suction Profile for Amarillo (Wray, 1989) Showing Extrapolation to Obtain the Magnitude of Equilibrium Soil suction

Based on the Wray (1989) data, the data considered by this study is presented in Table 6.6.

Table 6.6: Equilibrium Soil suction Magnitudes from Wray, 1989

Location	**TMI**	**Anticipated Depth to Equilibrium Suction using Figure 6.52 (m)**	**Soil suction (pF)**	**Comments**
College Station, TX	8.89	1.65	3.8	Both data points have been considered by this study as being representative values for the magnitude of constant soil suction
Amarillo, TX	-17.11	3.2	4.1	

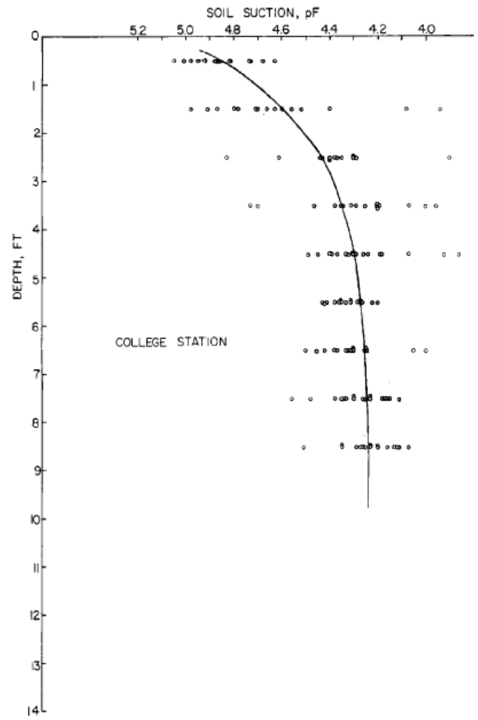


Figure 6.16: Soil suction Profile for College Station (Wray, 1989)

6.1.7. McKeen and Johnson (1990)

McKeen and Johnson (1990) presented magnitudes of equilibrium soil suction for seven cities in the USA. Three sites discussed by McKeen and Johnson (1990) were previously discussed in McKeen (1981); Jackson, MS, Gallup, NM, and Dallas, TX. Other sites including Denver, CO, San Antonio, TX, Dallas, TX, and Houston, TX, were analyzed to predict the magnitude of equilibrium suction based on dispersion coefficients. The site from Amarillo, TX Presented by McKeen and Johnson (1990) was presented by Wray (1989). As no new suction profiles were presented by McKeen and Johnson (1990), no data from this paper were utilized in this study.

6.1.8. Jayatilaka, Gay, Lytton and Wray (1992)

Research related to pavements was completed for the work completed by Jayatilaka, Gay, Lytton, and Wray (1992). Nine sites were investigated as summarized in Table 6.7.

Table 6.7: Relevant Data Summary for Jayatilaka et al. (1992)

Site	TMI 2006	Test Boring	Sample Depth m (ft)	LL	PI	P200	Water Content (%)	Measured Soil Suction (pF)
Dallas 1	1.38	BH1	0.00 (0.0)	74	44	99	21.9	4.15
Dallas 1	1.38	BH1	1.22 (4.0)	74	46	99	24.0	3.83
Dallas 1	1.38	BH1	2.13 (7.0)	76	48	99	21.3	3.98
Dallas 1	1.38	BH2	0.61 (2.0)	78	48	97	25.1	3.82
Dallas 1	1.38	BH2	1.83 (6.0)	74	45	99	25.3	3.6
Dallas 1	1.38	BH2	3.35 (11.0)	77	49	98	21.1	4.0
Ennis 1	5.81	BH3	0.30 (1.0)	46	29	79	20.1	4.11
Ennis 1	5.81	BH3	1.22 (4.0)	51	34	76	24.2	3.77
Ennis 1	5.81	BH3	2.74 (9.0)	46	27	79	31.7	3.36
Ennis 1	5.81	BH4	0.00 (0.0)	71	40	97	45.6	2.43
Ennis 1	5.81	BH4	1.52 (5.0)	72	42	97	49.4	2.18
Ennis 1	5.81	BH5	0.00 (0.0)	67	38	97	31.8	3.46
Ennis 1	5.81	BH5	1.22 (4.0)	66	43	96	29.4	3.55
Ennis 1	5.81	BH5	1.83 (6.0)	43	23	92	22.0	3.67
Ennis 1	5.81	BH6	0.91 (3.0)	79	49	95	27.5	3.68
Ennis 1	5.81	BH6	1.83 (6.0)	60	34	99	17.8	3.94
Ennis 1	5.81	BH6	3.35 (11.0)	60	39	99	20.6	3.80
Seguin	-6.16	BH7	0.61 (2.0)	77	47	87	25.2	3.17
Seguin	-6.16	BH7	2.13 (7.0)	80	47	94	25.8	3.14
Seguin	-6.16	BH7	3.05 (10.0)	57	34	94	18.5	3.88
Seguin	-6.16	BH8	0.61 (2.0)	55	34	95	25.2	3.39
Seguin	-6.16	BH8	1.22 (4.0)	58	33	91	29.6	3.44
Seguin	-6.16	BH8	1.83 (6.0)	71	38	92	30.4	3.74
Seguin	-6.16	BH9	0.76 (2.5)	66	41	82	22.1	3.54
Seguin	-6.16	BH9	1.22 (4.0)	50	29	86	19.7	3.91
Seguin	-6.16	BH9	3.35 (11.0)	77	52	99	22.1	3.98
Converse	-5.72	BH10	0.91 (3.0)	64	39	84	24.8	3.26
Converse	-5.72	BH10	1.52 (5.0)	44	27	79	14.1	4.12
Converse	-5.72	BH10	2.74 (9.0)	42	26	78	14.3	4.06

Site	TMI 2006	Test Boring	Sample Depth m (ft)	LL	PI	P200	Water Content (%)	Measured Soil Suction (pF)
Converse	-5.72	BH11	0.00 (0.0)	50	32	83	11.9	4.18
Converse	-5.72	BH11	0.91 (3.0)	77	49	91	28.8	3.67
Converse	-5.72	BH11	2.13 (7.0)	98	64	93	42.5	2.96
Converse	-5.72	BH12	0.91 (3.0)	90	59	89	32.1	3.47
Converse	-5.72	BH12	1.52 (5.0)	98	64	98	31.0	3.54
Converse	-5.72	BH12	3.05 (10.0)	89	49	95	32.7	3.66
Snyder 1	-19.43	BH13	0.00 (0.0)	40	22	78	18.2	3.51
Snyder 1	-19.43	BH13	0.30 (1.0)	42	19	76	16.9	3.72
Snyder 1	-19.43	BH13	0.61 (2.0)	40	21	73	20.8	3.73
Snyder 1	-19.43	BH13	0.91 (3.0)	41	19	82	19.3	3.70
Snyder 1	-19.43	BH13	1.22 (4.0)	36	20	78	13.8	3.68
Snyder 1	-19.43	BH13	1.52 (5.0)	49	30	63	16.7	3.70
Snyder 1	-19.43	BH13	1.83 (6.0)	54	35	70	18.2	3.92
Snyder 1	-19.43	BH13	2.13 (7.0)	41	24	61	12.1	4.10
Snyder 1	-19.43	BH13	2.43 (8.0)	34	20	64	10.6	4.10
Snyder 1	-19.43	BH13	2.74 (9.0)	38	17	63	10.1	4.09
Snyder 1	-19.43	BH13	3.05 (10.0)	34	19	58	9.4	4.03
Snyder 1	-19.43	BH13	3.35 (11.0)	35	20	63	11.0	4.19
Snyder 2	-19.43	BH14	0.30 (1.0)	46	16	52	24.3	3.60
Snyder 2	-19.43	BH14	0.61 (2.0)	50	24	67	21.3	3.80
Snyder 2	-19.43	BH14	0.91 (3.0)	43	15	60	21.7	3.70
Snyder 2	-19.43	BH14	1.22 (4.0)	44	17	69	20.0	3.70
Snyder 2	-19.43	BH14	1.52 (5.0)	43	16	59	19.7	3.80
Snyder 2	-19.43	BH14	1.83 (6.0)	45	18	42	20.0	3.70
Snyder 2	-19.43	BH14	2.13 (7.0)	54	23	61	19.0	3.60
Snyder 2	-19.43	BH14	2.43 (8.0)	44	16	83	21.7	3.80
Snyder 2	-19.43	BH14	2.74 (9.0)	44	15	85	20.0	3.80
Snyder 2	-19.43	BH14	3.05 (10.0)	42	14	26	18.7	3.90
Snyder 2	-19.43	BH14	3.35 (11.0)	48	18	60	19.0	3.90
Snyder 2	-19.43	BH14	3.66 (12.0)	43	14	49	19.0	4.00
Snyder 2	-19.43	BH14	3.96 (13.0)	46	16	54	19.5	4.00
Snyder 2	-19.43	BH14	4.27 (14.0)	45	16	38	19.0	3.90
Snyder 3	-19.43	BH15	0.30 (1.0)	40	16	75	6.5	3.30
Snyder 3	-19.43	BH15	0.61 (2.0)	49	24	61	23.7	3.40
Snyder 3	-19.43	BH15	0.91 (3.0)	58	30	52	20.0	3.50

Site	TMI 2006	Test Boring	Sample Depth m (ft)	LL	PI	P200	Water Content (%)	Measured Soil Suction (pF)
Snyder 3	-19.43	BH15	1.22 (4.0)	61	35	53	21.3	3.50
Snyder 3	-19.43	BH15	1.52 (5.0)	57	35	52	21.0	3.60
Snyder 3	-19.43	BH15	1.83 (6.0)	69	39	79	27.3	3.70
Snyder 3	-19.43	BH15	2.13 (7.0)	65	37	78	27.3	3.70
Snyder 3	-19.43	BH15	2.43 (8.0)	67	39	69	28.7	3.70
Snyder 3	-19.43	BH15	2.74 (9.0)	55	26	76	26.0	3.80
Snyder 3	-19.43	BH15	3.05 (10.0)	56	24	69	26.7	3.80
Snyder 3	-19.43	BH15	3.35 (11.0)	52	24	59	21.0	3.70
Wichita Falls 1	-9.72	BH16	0.00 (0.0)	34	18	79	16.3	3.91
Wichita Falls 1	-9.72	BH16	0.30 (1.0)	37	19	78	15.3	4.00
Wichita Falls 1	-9.72	BH16	0.61 (2.0)	38	19	86	14.0	4.20
Wichita Falls 1	-9.72	BH16	0.91 (3.0)	42	23	89	14.1	4.38
Wichita Falls 1	-9.72	BH16	1.22 (4.0)	39	19	91	13.5	4.32
Wichita Falls 1	-9.72	BH16	1.52 (5.0)	43	19	97	15.6	4.00
Wichita Falls 1	-9.72	BH16	1.83 (6.0)	41	22	95	15.7	4.13
Wichita Falls 1	-9.72	BH16	2.13 (7.0)	44	23	85	16.1	4.02
Wichita Falls 1	-9.72	BH16	2.43 (8.0)	41	20	87	12.7	4.14
Wichita Falls 1	-9.72	BH16	2.74 (9.0)	50	29	95	14.3	4.38
Wichita Falls 1	-9.72	BH16	3.05 (10.0)	37	16	98	12.1	4.11
Wichita Falls 1	-9.72	BH16	3.35 (11.0)	39	14	98	12.1	3.99
Wichita Falls 1	-9.72	BH16	3.66 (12.0)	45	21	94	12.2	4.20
Wichita Falls 1	-9.72	BH16	3.96 (13.0)	58	35	94	14.4	4.29

Site	TMI 2006	Test Boring	Sample Depth m (ft)	LL	PI	P200	Water Content (%)	Measured Soil Suction (pF)
Wichita Falls 1	-9.72	BH16	4.27 (14.0)	52	31	92	16.1	4.41
Wichita Falls 2	-9.72	BH17	0.00 (0.0)	22	0	23	11.0	3.65
Wichita Falls 2	-9.72	BH17	0.30 (1.0)	28	14	57	13.2	3.37
Wichita Falls 2	-9.72	BH17	0.61 (2.0)	24	10	61	13.6	3.27
Wichita Falls 2	-9.72	BH17	0.91 (3.0)	37	21	77	12.3	3.64
Wichita Falls 2	-9.72	BH17	1.22 (4.0)	34	17	75	13.80	3.70
Wichita Falls 2	-9.72	BH17	1.52 (5.0)	43	21	83	14.4	4.09
Wichita Falls 2	-9.72	BH17	1.83 (6.0)	30	14	85	13.9	4.41
Wichita Falls 2	-9.72	BH17	2.13 (7.0)	36	17	81	15.9	4.00
Wichita Falls 2	-9.72	BH17	2.43 (8.0)	40	18	82	13.8	4.08
Wichita Falls 2	-9.72	BH17	2.74 (9.0)	35	17	85	12.5	4.02
Wichita Falls 2	-9.72	BH17	3.05 (10.0)	39	18	92	13.1	4.20
Wichita Falls 2	-9.72	BH17	3.35 (11.0)	50	26	95	16.1	4.39
Wichita Falls 2	-9.72	BH17	3.66 (12.0)	48	25	95	18.1	3.84
Wichita Falls 2	-9.72	BH17	3.96 (13.0)	51	25	90	19.2	4.02
Wichita Falls 2	-9.72	BH17	4.27 (14.0)	54	30	90	18.4	4.36

The Jayatilaka et al. (1992) data points were used as part of this research to generate suction profiles. Specifically, nine suction profiles were generated from the measured data in Table 6.7. Site designations of the nine sites are Dallas 1, Ennis 1, Seguin, Converse, Snyder 1, Snyder 2, Snyder 3, Wichita Falls 1, and Wichita Falls 2. Figure 6.17 through Figure 6.25 are plots generated as part of this research using the depth and soil suction data from the nine sites.

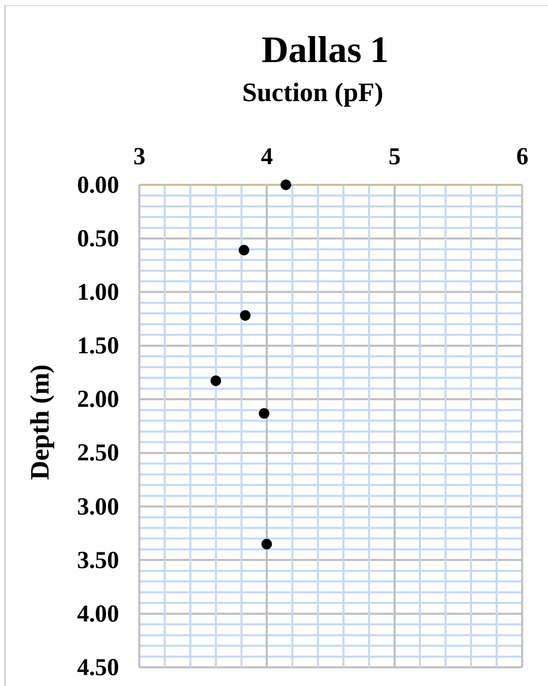


Figure 6.17: Dallas, TX, Depth versus Soil Suction Plot Using Data from Jayatilaka et al. (1992)

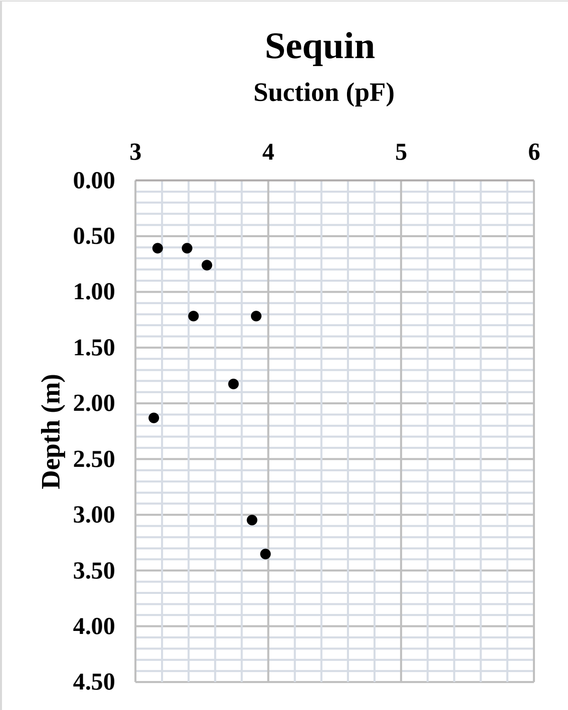


Figure 6.18: Seguin, Texas, Depth versus Soil Suction Plot Using Data from Jayatilaka et al. (1992)

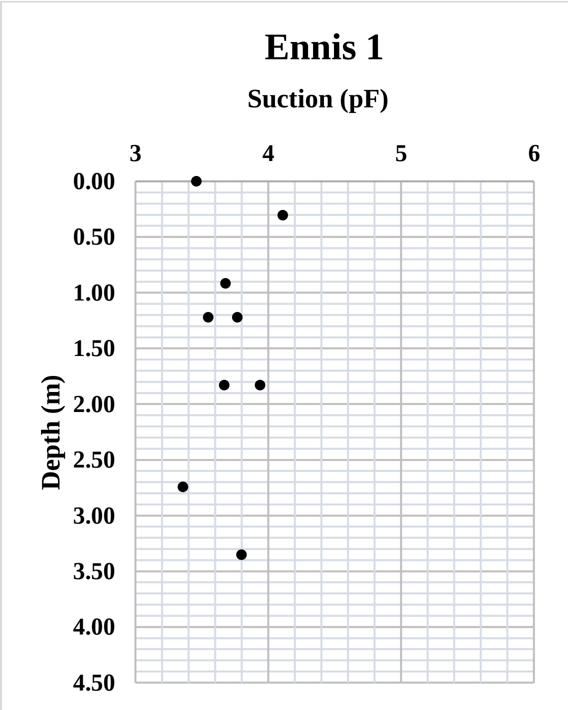


Figure 6.19: Ennis 1, Texas, Depth versus Soil Suction Plot Using Data from Jayatilaka et al. (1992)

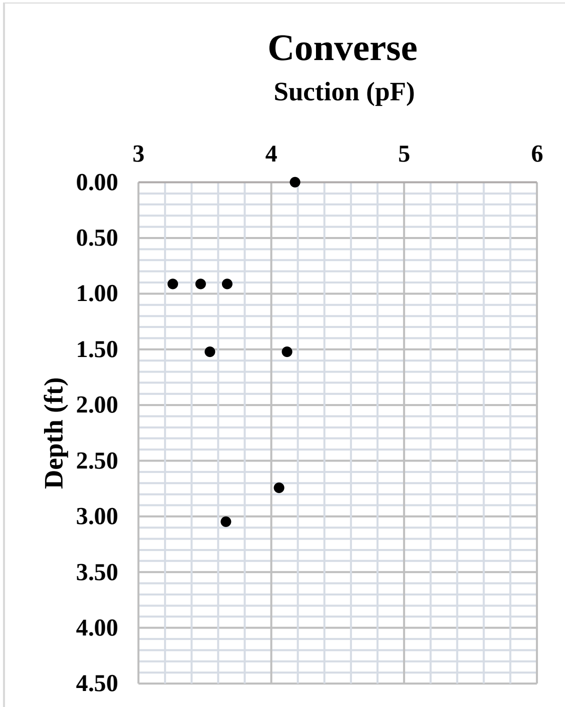


Figure 6.20: Converse, Texas, Depth versus Soil Suction Plot Using Data from Jayatilaka et al. (1992)

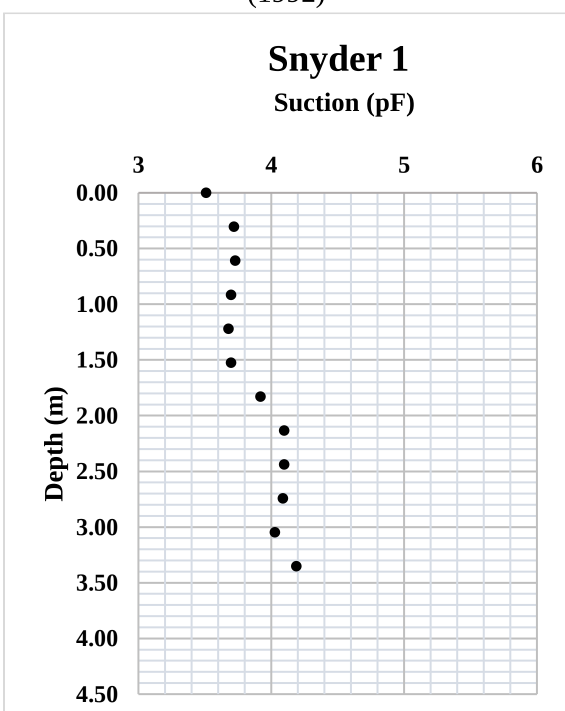


Figure 6.21: Snyder 1, Texas, Depth versus Soil Suction Plot Using Data from Jayatilaka et al. (1992)

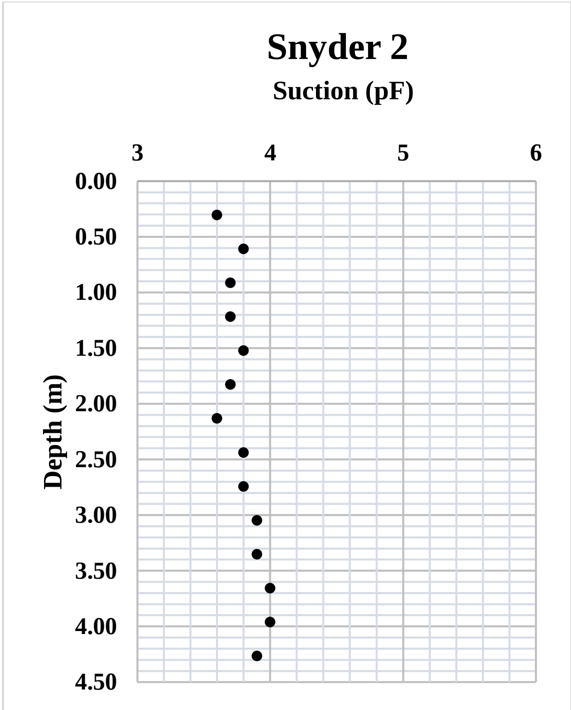


Figure 6.22: Snyder 2, Texas, Depth versus Soil Suction Plot Using Data from Jayatilaka et al. (1992)

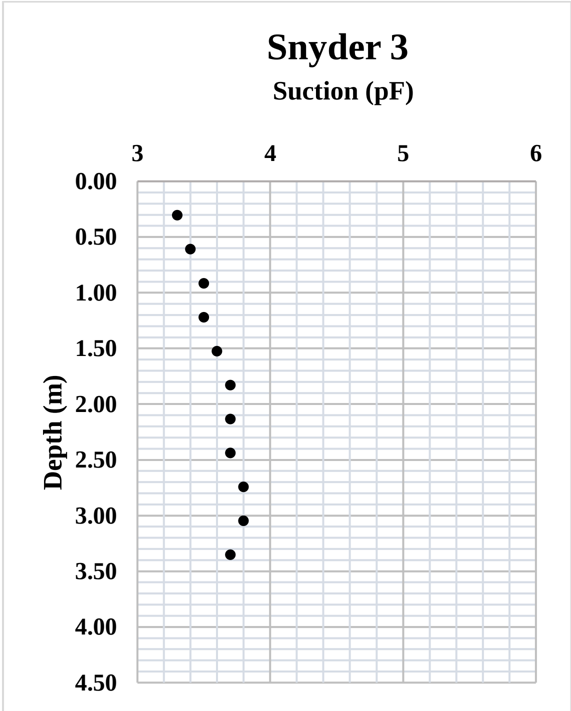


Figure 6.23: Snyder 3, Texas, Depth versus Soil Suction Plot Using Data from Jayatilaka et al. (1992)

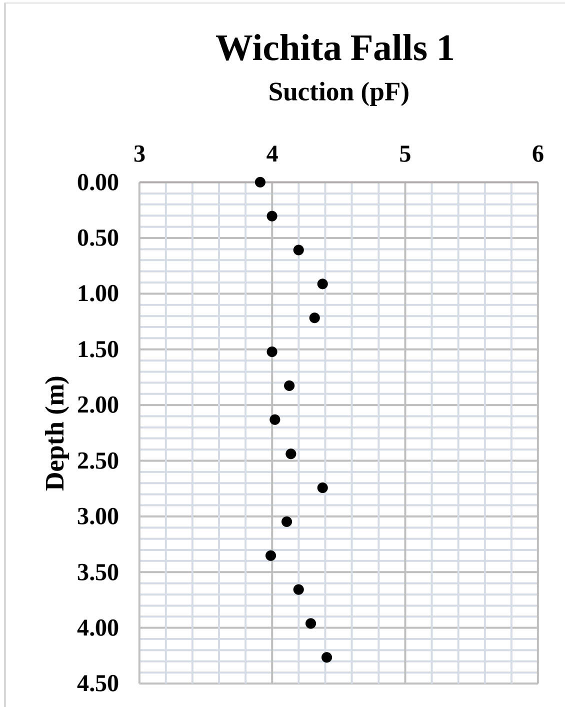


Figure 6.24: Wichita Falls 1, Depth versus Soil Suction Plot Using Data from Jayatilaka et al. (1992)

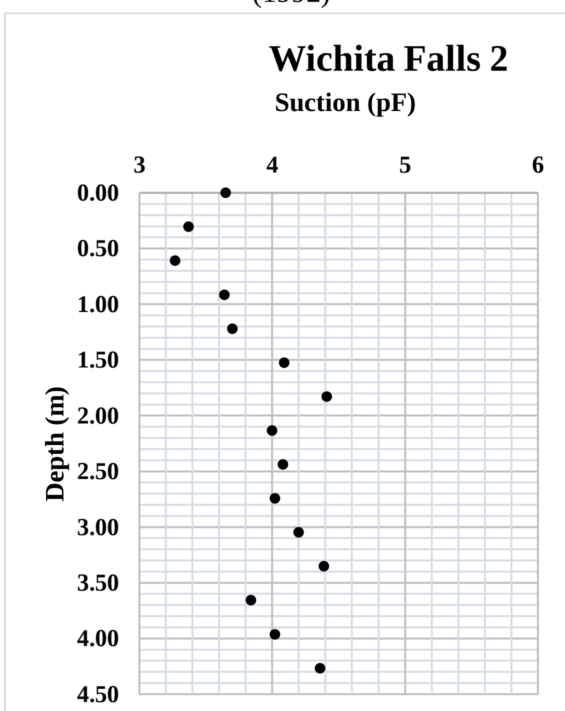


Figure 6.25: Wichita Falls 2, Depth versus Soil Suction Plot Using Data from Jayatilaka et al. (1992)

Using the plots from Figure 6.17 through Figure 6.25, Table 6.8 has been created to show an opinion of the magnitude of equilibrium soil suction and the depth to equilibrium soil suction.

Table 6.8: Equilibrium Soil suction Magnitude (Using Data from Jayatilaka et. al., 1992)

Location	**TMI_{2006}**	**Equilibrium Soil suction from this Research Generated Depth - Dependent Profiles (pF)**	**Comments**
Dallas 1, TX	-11.3	4	All data points have been considered by this study as being representative values for the magnitude of constant (equilibrium) soil suction
Ennis1, TX	5.81	3.82	
Seguin, TX	-7.56	3.95	
Converse, TX	-5.72	3.9	
Snyder 1, TX	-25	4	
Snyder 2, TX	-25	4	
Snyder 3, TX	-25	3.8	
Wichita Falls 1, TX	-9.72	4.1	
Wichita Falls 2, TX	-9.72	4	

6.1.9. PTI 2nd Edition (1996)

In 1996, the 2nd Edition to the PTI design manual was published. A plot relating soil suction (presumed to be equilibrium soil suction) versus TMI was presented. Figure 6.26 was based on the work by Russam and Coleman (1961), with the exception that the lower portion of the curve was moved to become asymptotic to 3.2 to 3.25 pF at high TMI. We can recall the equation that relates soil suction using the pF unit to kPa as Equations (141) and (142).

$$\psi(in\ pF) = log_{10}\left(\frac{\psi(in\ kPa)}{0.098}\right) \tag{141}$$

Or

$$\psi(in\ kPa) = (0.098)10^{\psi(in\ pF)} \tag{142}$$

Research has clearly identified that osmotic soil suction can account for magnitudes in the range of 100 to 245 kPa, or 3.0 pF to 3.4 pF (3.25 pF based on the work of Houston and Houston, 2018). Based on this range, it would appear reasonable to make the lower portion of the curve tend toward being asymptotic at 3.2 to 3.25 pF, as was incorporated in the PTI 2nd edition curve.

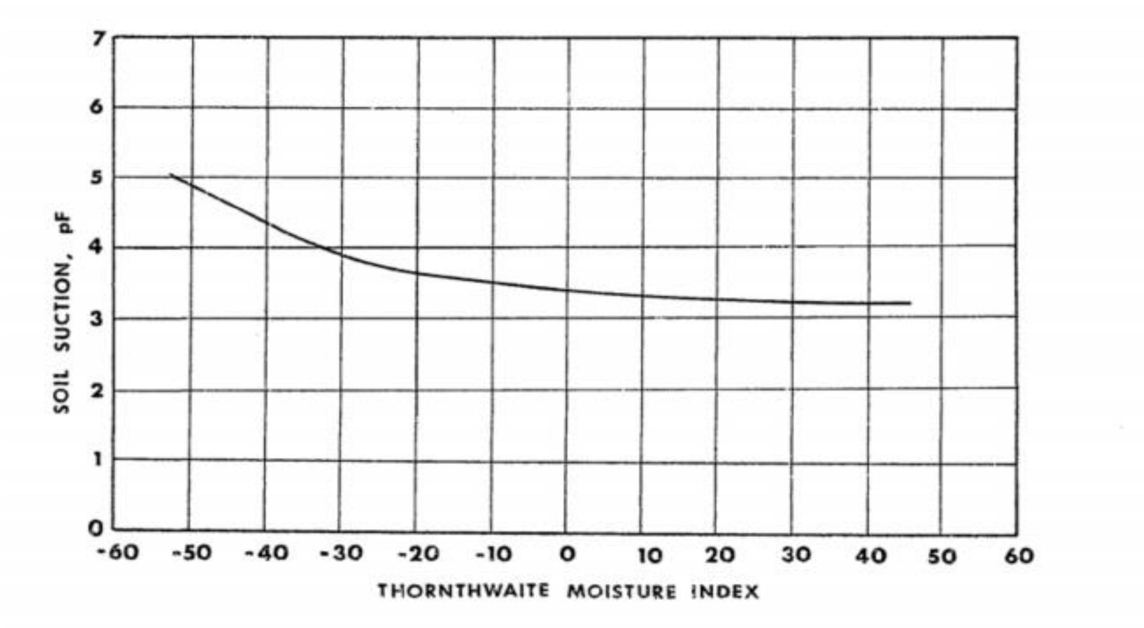


Figure 6.26: Variation of Soil suction with TMI (Post-tensioning Institute 2nd Edition, 1996)

However, as previously presented, the Russam and Coleman (1961) data is not necessarily meant to infer equilibrium soil suction. As such, while the truncation of the lower portion of the curve as a soil suction magnitude of approximately 3.2 to 3.25 pF is approached appears reasonable. Specific data points that formulated the curve are not available.

6.1.10. Bryant (1998)

Bryant (1998) drew a comparison (Figure 6.27) between the Russam and Coleman (1961) data and that presented by the 2nd Edition of the PTI (1996).

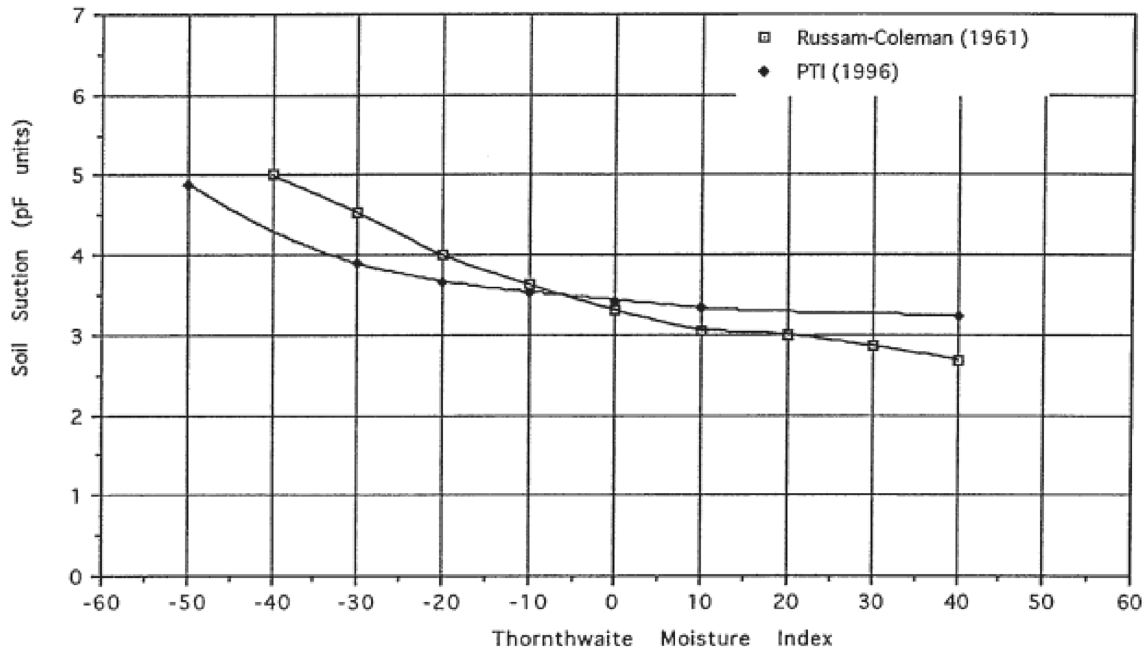


Figure 6.27: Comparison of the PTI 2nd Edition and Russam and Coleman (1961) Soil suction Variation with TMI (Bryant, 1998)

Differences were attributed to soil suction values being measured for differing geologic conditions: residual clay, shale-clay, and soils derived from differing weathered parent material. While the Russam and Coleman (1961) research suggested a soil suction in the Dallas area (presumed to be the constant soil suction) of 3.3 to 3.4 pF (roughly 246 kPa), Bryant (1998) found that the constant soil suction in the Dallas / Fort Worth area was 4.0 pF (roughly 979 kPa); Dallas/Fort Worth has a TMI in the range of -11 to 5.

Future work was recommended by Bryant (1998) in hopes of determining what mechanism is responsible for the differences between the empirical and theoretical predictions of soil suction as a function of TMI. Bryant (1998) postulated that five possible mechanisms contributed to variations between actual measured soil suction magnitudes and empirical predictions; 1) residual clay soils that have resulted from weathering of a parent rock may have a more complete remnant rock fabric and ancillary cementation than clays soils derived from alluvial processes, 2) for alluvial clay soils it is very likely that there is an occurrence of varying fractions of sand and silt, 3) variable plasticity index values may be present in a stratum both horizontally and vertically suggesting that perfect homogeneity may be extremely rare, 4) residual clay soils may exhibit varying amounts of soluble salts in semi-arid climates, and 5) differences in soil suction equilibrium curves may be significant when comparing highly structured residual rock fabric to alluvially deposited clay soils (Bryant, 1998).

The opinions of Bryant (1998) raised questions concerning both the Russam and Coleman (1961) relationship and the relationship suggested by the 2nd Edition of the PTI (1996), for the following reasons. Bryant's opinion was that the average equilibrium soil suction in the Dallas / Fort Worth area is more than 4.0 pF, which is well above the prediction curves by Russam and Coleman (1961) and the PTI, 2nd Edition (1996). Total soil suction measurements collected by Bryant in 1995, 1996 and 1997 are shown in Table 6.9. The Bryant data are not used in this current study because the values cannot be confirmed as equilibrium values from full soil suction profiles and because depths of samples used in determining soil suction are not reported.

Table 6.9: Summary of Measured Soil suction Data from The Dallas / Fort Worth Area Between 1995 And 1997 (Bryant, 1998)

	Precipitation	Average Soil suction (pF)	Minimum Soil suction (pF)	Maximum Soil suction (pF)	Soil suction Range (pF)	Difference Between Average Soil suction and Maximum Soil suction (pF)	Difference Between Average Soil suction and Minimum Soil suction (pF)
1995	Near-normal	4.14	2.75	5.06	2.31	0.92	1.39
1996	Wetter than normal	4.17	2.76	4.82	2.06	0.65	1.41
1997	Wetter than normal	4.25	3.30	4.93	1.63	0.68	0.95

6.1.11. Barnett and Kingsland (1999)

Barnett and Kingsland (1999) provided values for the magnitude of constant soil suction for five climatic ranges that are representative of the New South Wales portion of Australia. The equilibrium soil suction values in Table 6.10 were obtained from samples retrieved below the H_s depth (depth to constant soil suction).

Table 6.10: Climatic Zones Utilized by Barnett and Kingsland (1999)

Classification	TMI	Climatic Zone	H_s m (ft)	$\Delta\psi$ (pF)	Magnitude of Equilibrium Soil suction (pF)
Wet Coastal / Alpine	>40	1	-	-	-
Wet Temperate	10 to 40	2	1.8 to 2.0 (5.9 to 6.6)	1.5	3.8
Temperate	-5 to 10	3	2.3 (7.5)	1.2 to 1.5	4.1
Dry Temperate	-25 to -5	4	3.0 (9.8)	1.2 to 1.5	4.2
Semi-arid	<-25	5	4.0 (13.1)	1.5 to 1.8	4.4

Using a range in TMI suggests some difficulty when plotting a meaningful relationship between TMI and the magnitude of equilibrium soil suction. Nonetheless, there is no appreciable evidence to suggest that the data obtained is not valid. In this study, the Barnett and Kingsland relationship are used for comparison to relationships between TMI and equilibrium suction and depth to constant suction.

6.1.12. PTI 3rd Edition (2004 and 2008)

The 2004 and 2008 PTI manuals present the plot in Figure 6.28 as a relationship between TMI and equilibrium soil suction:

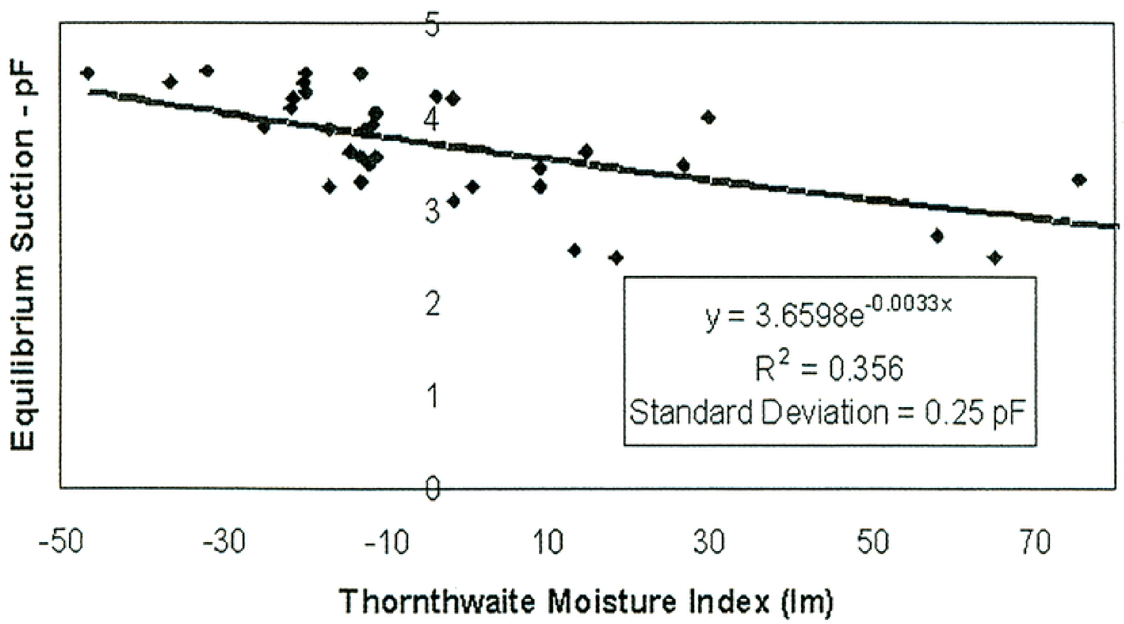


Figure 6.28: Equilibrium Soil suction versus TMI (Post-tensioning Institute 3rd Edition, 2008)

In Figure 6.28, 36 data points are presented as part of the relationship between TMI and the magnitude of equilibrium soil suction. We know through personal communication, that the data points in Table 6.11 were utilized to formulate the above plot (Lytton, 2019). As can be seen, 36 data points are presented in Table 6.11. Each of the data points and their respective sources have been discussed above.

Table 6.11: Data Used for the PTI 3rd Edition Relationship Between Equilibrium Soil Suction and TMI

Location	**Data Source**	**TMI**	**Equilibrium Soil suction Value (pF)**	**Opinion as to Whether the Datapoint Should be Utilized as Part of the PTI 3rd Edition**
Jackson, Mississippi	Snethen (1977)	39.41	3.67	Should be used because the soils were sampled beneath the centerline of a pavement, equilibrium can be assumed to have been reached
Hattiesburg, Miss.	*Snethen (1977)*	*75.6*	*3.32*	*Not considered in this research; reasons presented in 6.1.3*
Monroe, Louisiana	*Snethen (1977)*	*65.1*	*2.5*	*Not considered in this research; reasons presented in 6.1.3*
Lake Charles, La.	*Snethen (1977)*	*58.2*	*2.71*	*Not considered in this research; reasons presented in 6.1.3*
San Antonio, Texas	*Snethen (1977)*	*0.9*	*3.25*	*Not considered in this research; reasons presented in 6.1.3*
Vernon, Texas	*Snethen (1977)*	*-14.3*	*3.63*	*Not considered in this research; reasons presented in 6.1.3*
Durant, Oklahoma	*Snethen (1977)*	*18.4*	*2.5*	*Not considered in this research; reasons presented in 6.1.3*
Hennessey, Okla.	*Snethen (1977)*	*13.4*	*2.56*	*Not considered in this research; reasons presented in 6.1.3*
Holbrook, Arizona	*Snethen (1977)*	*-19.8*	*4.26*	*Not considered in this study; reasons presented in 6.1.3*
Holbrook, Arizona	*Snethen (1977)*	*-19.8*	*4.48*	*Not considered in this study; reasons presented in 6.1.3*
Price, Utah	*Snethen (1977)*	*-36.4*	*4.37*	*Not considered in this study; reasons presented in 6.1.3*
Hays, Kansas	*Snethen (1977)*	*9.1*	*3.25*	*Not considered in this research;*

Location	Data Source	TMI	Equilibrium Soil suction Value (pF)	Opinion as to Whether the Datapoint Should be Utilized as Part of the PTI 3rd Edition
				reasons presented in 6.1.3
Ellsworth, Kansas	*Snethen (1977)*	*9.1*	*3.45*	*Not considered in this research; reasons presented in 6.1.3*
Limon, Colorado	*Snethen (1977)*	*-16.8*	*3.88*	*Not considered in this study; reasons presented in 6.1.3*
Limon, Colorado	*Snethen (1977)*	*-16.8*	*3.25*	*Not considered in this research; reasons presented in 6.1.3*
Denver, Colorado	*Snethen (1977)*	*-3.6*	*4.21*	*Not considered in this research; reasons presented in 6.1.3*
Newcastle, Wyoming	*Snethen (1977)*	*-13*	*3.58*	*Not considered in this research; reasons presented in 6.1.3*
Newcastle, Wyoming	*Snethen (1977)*	*-13*	*4.48*	*Not considered in this research; reasons presented in 6.1.3*
Billings, Montana	*Snethen (1977)*	*-1.6*	*3.09*	*Not considered in this research; reasons presented in 6.1.3*
Reliance, So. Dakota	*Snethen (1977)*	*-12.9*	*3.29*	*Not considered in this research; reasons presented in 6.1.3*
Jackson, Mississippi*	McKeen (1981)	39.41	3.75	Should be used; reasons presented in 6.1.8
Dallas-Fort Worth, Texas*	McKeen (1981)	-1.87	3.7	Should be used; reasons presented in 6.1.8
Gallup 1, New Mexico*	McKeen (1981)	-29.94	4.2	Should be used; reasons presented in 6.1.8
Gallup 2, New Mexico	McKeen (1981)	-29.94	4.4	Should be used; reasons presented in 6.1.8
El Paso, Texas**	Jayatilaka et al. (1992)	-46.5	4.48	Should be used; reasons presented in 6.1.8

Location	Data Source	TMI	Equilibrium Soil suction Value (pF)	Opinion as to Whether the Datapoint Should be Utilized as Part of the PTI 3rd Edition
San Antonio, Texas**	Jayatilaka et al. (1992)	-21.3	4.2	Should be used; reasons presented in 6.1.8
Dallas, Texas**	Jayatilaka et al. (1992)	-11.3	4.04	Should be used; reasons presented in 6.1.8
Houston, Texas**	Jayatilaka et al. (1992)	14.8	3.62	Should be used; reasons presented in 6.1.8
Port Arthur, Texas**	Jayatilaka et al. (1992)	26.8	3.47	Not considered in this research; reasons presented in 6.1.3
Seguin, Texas**	Jayatilaka et al. (1992)	-11.5	3.93	Should be used; reasons presented in 6.1.8
Converse, Texas**	Jayatilaka et al. (1992)	-12.5	3.86	Should be used; reasons presented in 6.1.8
Dallas, Texas**	Jayatilaka et al. (1992)	-11.3	4.01	Should be used; reasons presented in 6.1.8
Ennis, Texas**	Jayatilaka et al. (1992)	-11.3	3.58	Should be used; reasons presented in 6.1.8
Wichita Falls, Texas**	Jayatilaka et al. (1992)	-20	4.38	Should be used; reasons presented in 6.1.8
Snyder, Texas**	Jayatilaka et al. (1992)	-25	3.9	Should be used; reasons presented in 6.1.8
College Station, Texas***	Wray (1989)	-1.6	4.2	Should be used; reasons presented herein, section 6.1.5
Amarillo, Texas***	Wray (1989)	-21.5	4.1	Should be used; reasons presented herein, section 6.1.5

Sources of the above data are cited as part of personal communication

* Data points from McKeen, R. G., (1981), Design of Airport Pavements for Expansive Soils, Report No. DOT/FAA/ RD-81/25, New Mexico Engineering Research Institute, University of New Mexico, Federal Aviation Administration, Washington, D.C.

** Data points from Jayatilaka, R., Gay, D.A., Lytton, R. L., and Wray, W.K., (1992), Effectiveness of Controlling Pavement Roughness due to Expansive Clays with Vertical Moisture Barriers, Report No. FHWA/TX-92/1165-2F, Texas Transportation Institute, Texas A&M University, Texas Department of Transportation, Austin, Texas.

***Data points from Wray, W.K., (1989), Mitigation of Damage to Structures Supported on Expansive Soils, Vols. I, II, and III Texas Tech University, National Science Foundation, Washington, D.C.

All other data points from Snethen, D.R., Johnson, L.D., and Patrick, D.M., (1977), An Investigation of the Natural Microscale Mechanisms That Cause Volume Change in Expansive Clays, Report No. FHWA-RD-77-75, U.S. Army Engineer Waterways Experiment Station, Federal Highway Administration, Washington, D.C.

Of the thirty-six (36) data points that constitute the PTI 3rd Edition (2008) for the relationship between TMI and equilibrium soil suction, Table 6.11 presents those data points considered in this study.

6.1.13. Mitchell (2008)

A compilation of data relating the magnitude of equilibrium soil suction to TMI is presented by Mitchell (2008) in Figure 6.29.

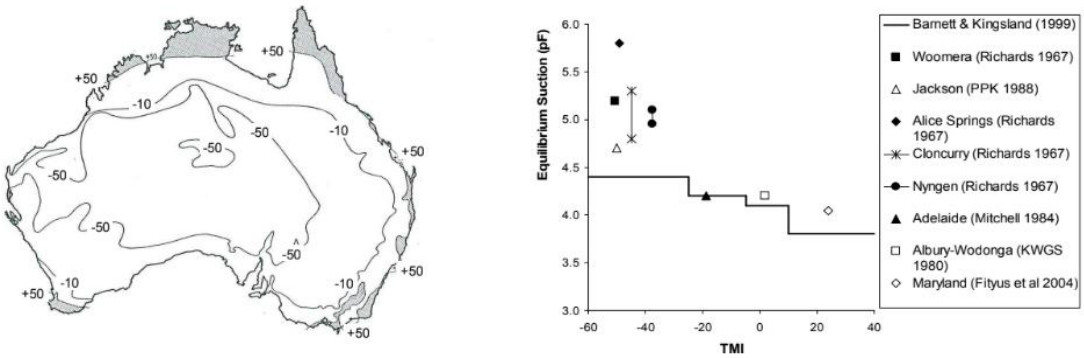


Figure 6.29: Distribution of TMI Through Mainland Australia and the General TMI Versus Equilibrium Soil Suction Relationship

Of particular interest to this study are the two end-points of the Barnett & Kingsland (1999) paper with reflect 4.4 pF and 3.8 pF equilibrium soil suctions for TMIs of -60 and 40, respectively. The end-points establish limits on the range in the magnitude of equilibrium soil suction.

6.1.14. Survey of Constant Soil suction Magnitudes Used by Consultants in Arizona, Colorado, New Mexico And Texas

A survey of geotechnical consultants in various states was conducted to lend an idea of what magnitude of equilibrium soil suction is locally accepted in specific states, or cities. The values in Table 6.12 were obtained by phone or email interview with various geotechnical engineering consultants, and from the author's experience. These data were used in this study in the relationship between TMI and equilibrium soil suction.

Table 6.12: Values of Equilibrium Soil suction Utilized by Consultants

Location	**Consultant**	**Typically Used Magnitude of Equilibrium Soil suction (pF)**
Phoenix, Arizona	Jeff Vann, Vann Engineering, Inc.	4.4
Tucson, Arizona	Jeff Vann, Vann Engineering, Inc.	4.2

Location	Consultant	Typically Used Magnitude of Equilibrium Soil suction (pF)
Flagstaff, Arizona	Jeff Vann, Vann Engineering, Inc.	4.0
Denver, CO	Ron McOmber, Terracon	4.2

6.1.15. Cuzme (2018)

Cuzme (2018) presented Figure 6.30 for the relationship of TMI and the magnitude of equilibrium soil suction. The Cuzme (2018) equation for the relationship between the magnitude of equilibrium soil suction and TMI is shown in Equation (143), with its accompanying R^2 and S.

$$\psi_e = 4.012e^{(-0.001263TMI)} \tag{143}$$

$$R^2 = 0.2411$$

$$S = 0.2865pF$$

Where ψ_e = the magnitude of the equilibrium soil suction

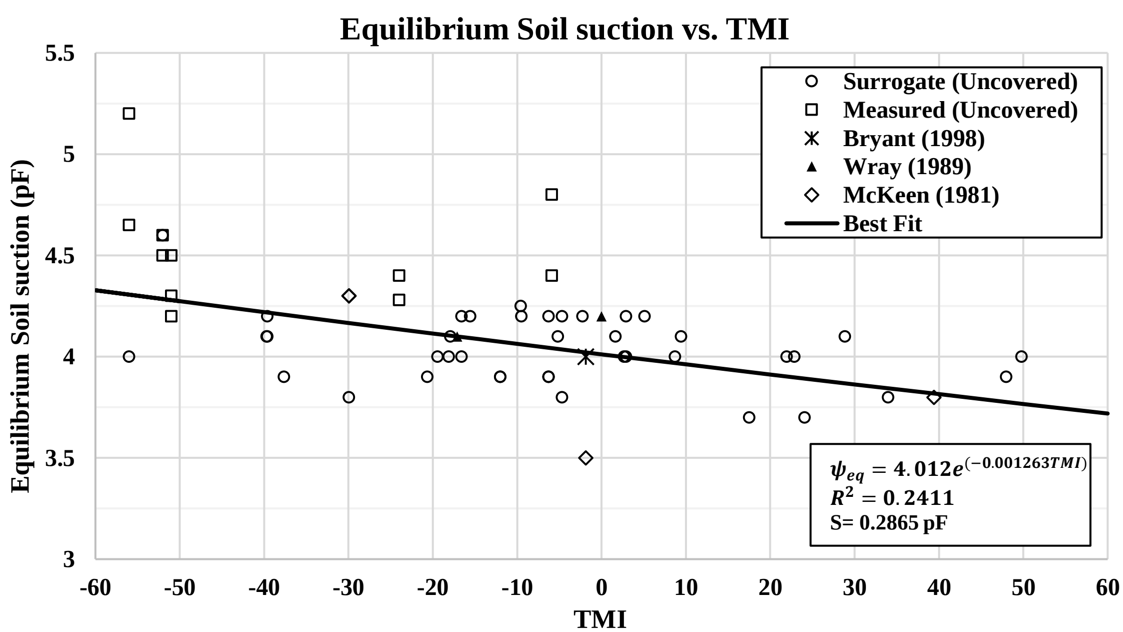


Figure 6.30: Magnitude of Equilibrium Soil Suction vs. TMI (Cuzme, 2018)

Figure 6.30 is based on the usage of Equations (133) through (135), which is the depth-dependent surrogate, where the surrogate was needed. All of the data presented by Cuzme in arriving at equilibrium suction versus TMI relationship were used in this current study because they are based on full soil suction profiles that allow for determination of both equilibrium suction and depth to equilibrium suction.

6.1.16. Discussion and Conclusions Regarding Determination of The Magnitude of Equilibrium Soil Suction

The preceding discussions have demonstrated support for the opinion that the correlation between TMI and the magnitude of equilibrium soil suction could be built on a more appropriate and complete database than used in prior investigations. It is anticipated that use of a more complete database, with focus on ensuring that equilibrium conditions are represented, could improve correlations between TMI and equilibrium soil suction. The PTI 3rd Edition (2008) provides a correlation that is not as strong as needed to be widely used for practitioners (R-square of 0.356). The work by Cuzme (2018) and Singhar (2018) support that, based on the existing data, the correlation between TMI and the magnitude of equilibrium soil suction is relatively weak (R-square of 0.241).

Using the United States data recommended for use in the sections above, a new relationship has been developed for TMI and the magnitude of equilibrium soil suction. This relationship is presented in Figure 6.31. The data contained in Appendix E 2 were analyzed by Excel and Minitab to explore the relationship between TMI and the magnitude of equilibrium suction.

A reasonable relationship has been established between TMI and the magnitude of equilibrium soil suction, described by Equation (144), with its corresponding R^2 and S.

$$\psi_e = 0.00002(TMI)^2 - 0.0053(TMI) + 3.9771 \quad (144)$$

$$R^2 = 0.6539$$

$$S = 0.1959\ pF$$

As shown by the R^2 and S of 0.6539 and 0.1959, respectively, there is geotechnically-speaking statistical credibility for use of Equation (144) in practice.

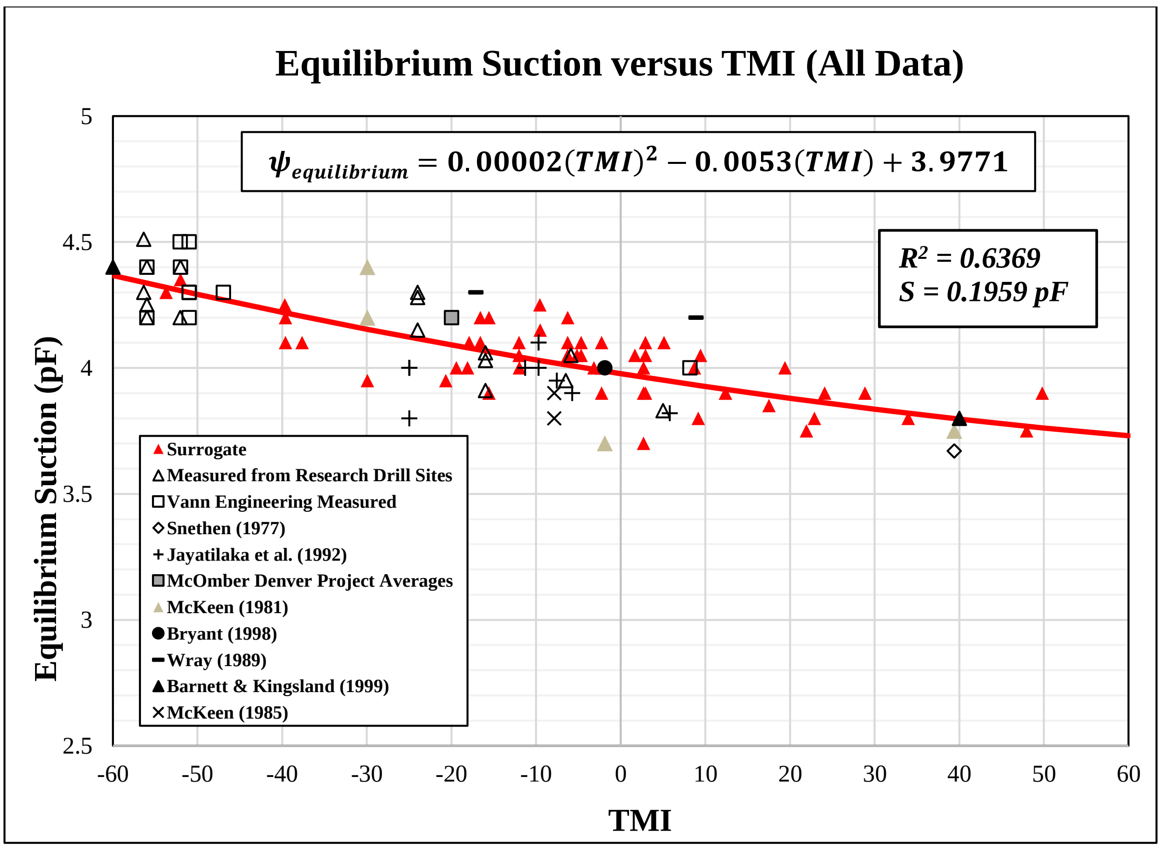


Figure 6.31: Magnitude of Equilibrium Soil Suction Versus TMI

To check the impact of the surrogate-derived data on the TMI versus equilibrium suction relationship, Figure 6.32 has been prepared excluding the surrogate data points.

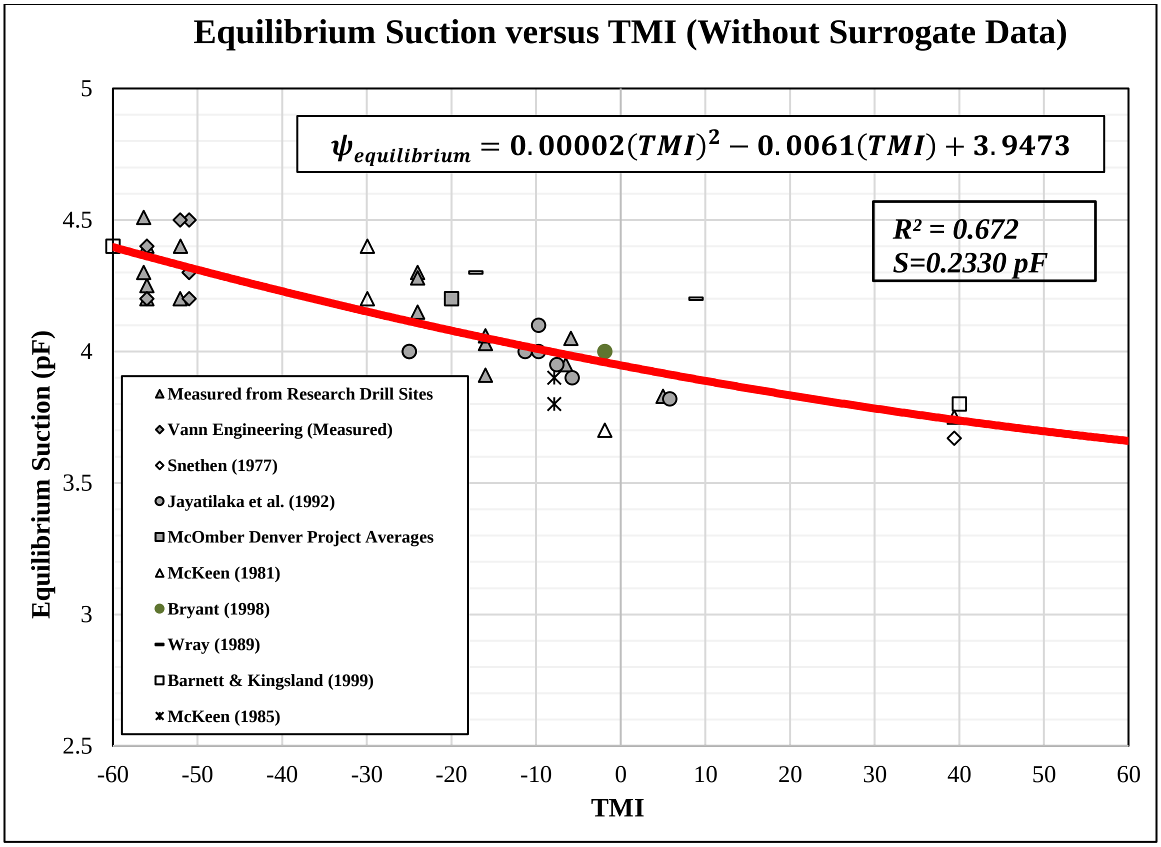


Figure 6.32: Magnitude of Equilibrium Soil Suction vs. TMI without Surrogate Data

Without the surrogate data, the equilibrium soil suction versus TMI Equation (145) is presented with its associated R^2 and S.

$$\psi_e = 0.00002(TMI)^2 - 0.0061(TMI) + 3.9473 \qquad (145)$$

$$R^2 = 0.6720$$

$$S = 0.2330\ pF$$

When comparing Equations (144) and (145), there is reasonable agreement between the plots of the relationship between TMI and magnitude of equilibrium soil suction when both including and excluding the surrogate data as there is no appreciable change in the R^2 value, and the coefficients in Equations (144) and (145) are quite similar.

The comparison, therefore, provides evidence to validate the inclusion of soil suction surrogate data.

Equation (144), therefore, was selected as the most appropriate relationship between TMI and the magnitude of equilibrium soil suction for use in practice where direct suction measurements are not available to aid in determination of equilibrium suction values. Although obtaining measured data is always the most preferred method, the surrogate does provide the practitioner with a reasonable estimate in the absence of measured data. Further research and re-analysis of historical data is, however, encouraged.

While the statistical correlation between TMI and equilibrium suction is stronger than previously presented by others, there remain questions regarding why the relationship between TMI and the magnitude of equilibrium soil suction is not even stronger. Answers may include:

- There are not enough weather stations to capture variability within relatively small regions (e.g. large cities/metropolitan areas)
- Slopes and general topography of the site surface are seldom considered
- Surficial soil type/layer effects
- Cracks and crack patterns
- TMI tracks annual precipitation (P) and annual potential evapotranspiration (PET) and does not capture rainfall intensity or duration.
- Additionally, Singhar (2018) demonstrated that there are multiple ways to calculate PET and it is modeled, rather than measured, in a manner such that PET has only a minor influence on calculated TMI. Figure 6.33 is a plot of the relationship between rainfall and the magnitude of equilibrium soil suction. Figure 6.33, based on

precipitation alone, provides a relationship for the magnitude of equilibrium soil suction that very closely resembles that from the TMI. Figure 6.33 suggests that the potential evapotranspiration (PET) plays a very small role in the calculation of TMI.

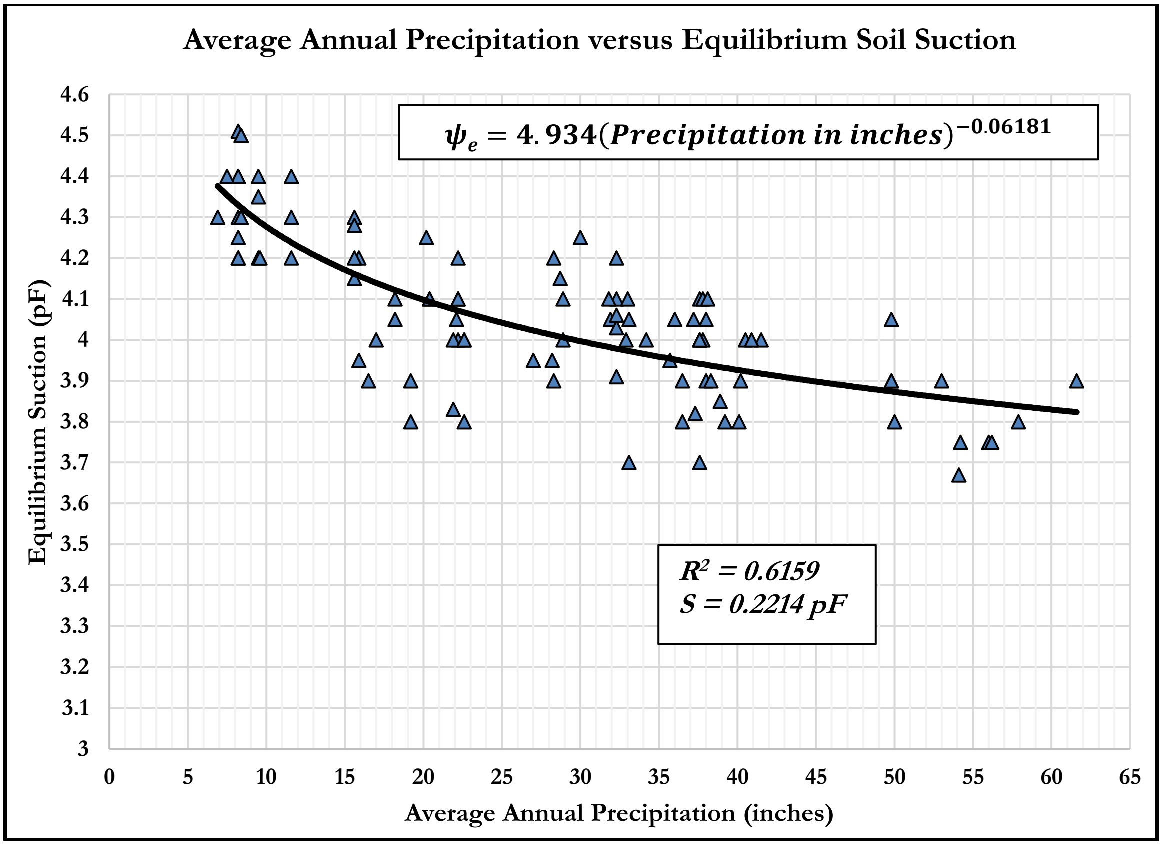


Figure 6.33: Relationship Between the Average Annual Precipitation and the Magnitude of Equilibrium Soil Suction

Equation (146) presents a relationship between the magnitude of equilibrium suction and the average annual precipitation, with its associated R^2 and S.

$$\psi_e = 4.934(Precipitation\ in\ inches)^{-0.06181} \quad (146)$$

$$R^2 = 0.6159$$

$$S = 0.2214\ pF$$

By inference, the data suggests that a location with 5 inches of annual precipitation may have a TMI of -60, with a magnitude of equilibrium suction of 4.4 pF. Likewise, a location that receives on the order of 65 inches of precipitation could have a TMI of +60 and a magnitude of equilibrium suction of roughly 3.7 pF. Denver has a representative TMI of -24, with 15.6 inches of average annual rainfall. The equilibrium suction for Denver based on TMI and annual precipitation is 4.12 pF and 4.16 pF, respectively. San Antonio has a TMI of -16 and an annual precipitation of 32.3 inches. The equilibrium suction for San Antonio based on TMI and average annual precipitation is 4.06 pF and 3.98 pF, respectively. In each case, the equilibrium suction prediction based on the average annual precipitation underestimates the magnitude of equilibrium suction at both the Denver and San Antonio locations. Although the plot of TMI versus the magnitude of equilibrium suction resembles that of precipitation versus equilibrium suction in terms of shape and approximate value, the predicted values are not close enough to rely on if considering precipitation alone. The best conclusion regarding precipitation is that it is the more important variable in calculating TMI as opposed to PET.

Certainly, and subsequent to the plot of precipitation, further research could be considered that explore correlations of the magnitude of equilibrium soil suction with days of rainfall and site slope, to see if correlation improves or to substantiate why TMI may not be as effective in predicting the magnitude of equilibrium soil suction.

6.2 Depth to Equilibrium Soil Suction for Undeveloped Sites

Much work has been completed regarding the determination of the depth to constant soil suction or depth of moisture change. Major contributors typically include authors from Texas and Australia. This section will summarize the key points from various authors since Smith (1993) and progressing forward to Cuzme (2018). For nomenclature clarity, Australian literature, which is presented herein, show the depth to equilibrium suction as H_s. To the extent possible, this research has denoted the depth to equilibrium suction as $\boldsymbol{D_{\psi_e}}$. In many cases, both the H_s and $\boldsymbol{D_{\psi_e}}$ designations are utilized.

6.2.1. Wray (1989)

Sites were investigated in College Station and Amarillo, TX. Suction profiles for uncovered site indicated and were reported to be 1.83 m (6.0 ft) and 3.81 m (12.5 ft) for College Station and Amarillo, respectively. The depths to equilibrium suction are consistent with the predictions provided by this research (Wray, 1989).

6.2.2. McKeen and Johnson (1990)

McKeen and Johnson (1990) presented anticipated depths to equilibrium soil suction for seven cities in the USA. Three sites discussed by McKeen and Johnson (1990) were previously discussed in McKeen (1981); Jackson, MS, Gallup, NM, and Dallas, TX. Other sites including Denver, CO, San Antonio, TX, Dallas, TX, and Houston, TX, were analyzed based on dispersion coefficients. The site from Amarillo, TX Presented by McKeen and Johnson (1990) was originally presented by Wray (1989). As no new suction profiles were presented by McKeen and Johnson (1990), no data from this paper were utilized in this study. McKeen and Johnson (1990) used the Mitchell (1979) equation to derive an estimation of moisture active zone depth, referred to a z_m. The term z_m is discussed in McKeen and Johnson (1990) and Naiser (1997), and subsequently used as part of the PTI 3rd Edition.

6.2.3. Smith (1993)

A correlation between TMI and the depth of moisture change was created, based on field observation, representing three separate regions in Australia. The Smith (1993) correlation is shown in Table 6.13.

Table 6.13: Smith (1993) Correlation Between TMI and the Depth of Moisture Change from Three Regions of Australia

Location	**TMI**	D_{ψ_e} **Depth of Moisture Change m (ft)**
Brisbane, Australia	34	1.5 (4.92)
Melbourne, Australia	-1	2.0 (6.56)
Adelaide, Australia	-26	4.0 (13.12)

The correlation was for only three cities in Australia; Brisbane, Melbourne and Adelaide. From the information contained in Table 6.13, an expanded correlation was made for a wide range in TMI, resulting in the proposed classifications as indicated in Table 6.14. Note that six classifications were proposed.

Table 6.14: Proposed Classification Proposed by Smith (1993) that Relates TMI to the Depth of Moisture Change

Classification	**TMI**	D_{ψ_e} **Depth of Moisture Change m (ft)**
Wet Coastal / Alpine	>40	1.5 (4.92)
Wet Temperate	10 to 40	1.8 (5.91)
Temperate	-5 to 10	2.3 (7.55)
Dry Temperate	-25 to -5	3.0 (9.84)

Classification	TMI	D_{ψ_e} Depth of Moisture Change m (ft)
Semi-arid	-40 to -25	4.0 (13.12)
Arid	<-40	>4.0 (13.12)

6.2.4. AS2870-1996

Initially presented in 1986, the Australian Standard provided a guidance document for construction, addressing the need to consider the adverse effects of expansive clay soils in connection with residential structures. The Australian Standard has expanded through the years. Revisions were made in 1988 and 1990. In 1996, another revision was made with 5 climatic zones and corresponding H_s (D_{ψ_e}) (depth to moisture change) being presented. Figure 6.34 shows the five 1996 code climatic classifications. The difference between Smith (1993) and AS2870-1996 is the absence of a sixth climate zone in the latter.

Climatic Zone & Description		*TMI* range	H_s
1	Alpine / Wet coastal	> +40	1.5m
2	Wet temperate	+10 to +40	1.8m
3	Temperate	-5 to +10	2.3m
4	Dry temperate	-25 to -5	3.0m
5	Semi-arid	< -25	4.0m

Figure 6.34: AS2870-1996 Climatic Zones and Recommended H_s

6.2.5. Fityus et al. (1998)

Based on the work of Smith (1993), Fityus et al. (1998) refined and submitted the correlation shown in

Table 6.15, which relates TMI to the Depth of Moisture Change. Fityus et al. (1998) found that the depth to moisture change of H_s (D_{ψ_e}) should change in a discontinuous stepwise manner as indicated in

Table 6.15.

Table 6.15: Correlation of TMI with Depth of Moisture Change (Fityus et al., 1998)

Classification	**TMI**	$\boldsymbol{D_{\psi_e}}$ **Depth of Moisture Change m (ft)**
Wet Coastal / Alpine	>40	1.5 (4.92)
Wet Temperate	10 to 40	1.5 to 1.8 (4.92 to 5.91)
Temperate	-5 to 10	1.8 to 2.3 (5.91 to 7.55)
Dry Temperate	-25 to -5	2.3 to 3.0 (7.55 to 9.84)
Semi-arid	-40 to -25	3.0 to 4.0 (9.84 to 13.12)
Arid	<-40	>4.0 (13.12)

Figure 6.35: Climatic Zones in Vicinity of Melbourne, Australia as Utilized by AS2870-1996

Figure 6.36: AS2870 Victorian Climate Zones from AS2870-1996

Fityus et al. (1998) provided three data points TMI and Depth to Moisture Change (H_s) (D_{ψ_e}). Table 6.16 presents that data. The data was obtained from measured soil suction versus depth for test borings extending to at least 4.0 m (13.12 ft).

Table 6.16: Fityus et al. (1998) TMI versus H_s ($\boldsymbol{D_{\psi_e}}$)

Location	**TMI**	**Depth of Moisture Change – Hs** (D_{ψ_e}) **m (ft)**
Nelson Bay, Australia	53.7	1.5 (4.92)
Maryville, Australia	24.4	1.5 (4.92)
Scone, Australia	-25.4, -24.3	3.0 (9.84)

6.2.6. Walsh et al. (1998)

Walsh et al. (1998) published maps of Southeast Queensland and Southwest Western Australia in conjunction with AS2870-1996 that are similar to the work of Barnett and Kingsland (1999), Fityus et al. (1998), and Fox (2000) for other portions of Australia.

Walsh et al. (1998) suggested changes in H_s (D_{ψ_e}) for three locations as indicated in Table 6.17.

Table 6.17: Proposed Changes in Hs by Walsh et al. (1998)

Location	**TMI**	**Hs** (D_{ψ_e}) **m (ft)**
Brisbane	40	1.5 (4.92)
Perth	10 to 40	1.8 (5.91)
Ipswich	-5 to 10	2.3 (7.55)

6.2.7. Barnett and Kingsland (1999)

Barnett and Kingsland (1999) presented a change for the soil suction profiles that are linked to the regional climate zones as related to AS2870 for New South Wales (NSW). The climate zone definitions are shown in Table 6.18.

Table 6.18: Climatic Zones Utilized by Barnett and Kingsland (1999)

Classification	**TMI**	**Climatic Zone**	**(D_{ψ_e}) Hs m (ft)**	**$\Delta\psi$ (pF)**	**Magnitude of Equilibrium Soil suction (pF)**
Wet Coastal / Alpine	>40	1	-	-	-
Wet Temperate	10 to 40	2	1.8 to 2.0 (5.91 to 6.56)	1.5	3.8
Temperate	-5 to 10	3	2.3 (7.55)	1.2 to 1.5	4.1
Dry Temperate	-25 to -5	4	3.0 (9.84)	1.2 to 1.5	4.2
Semi-arid	<-25	5	4.0 (13.12)	1.5 to 1.8	4.4

The new map for New South Wales (NSW) is shown in Figure 6.37.

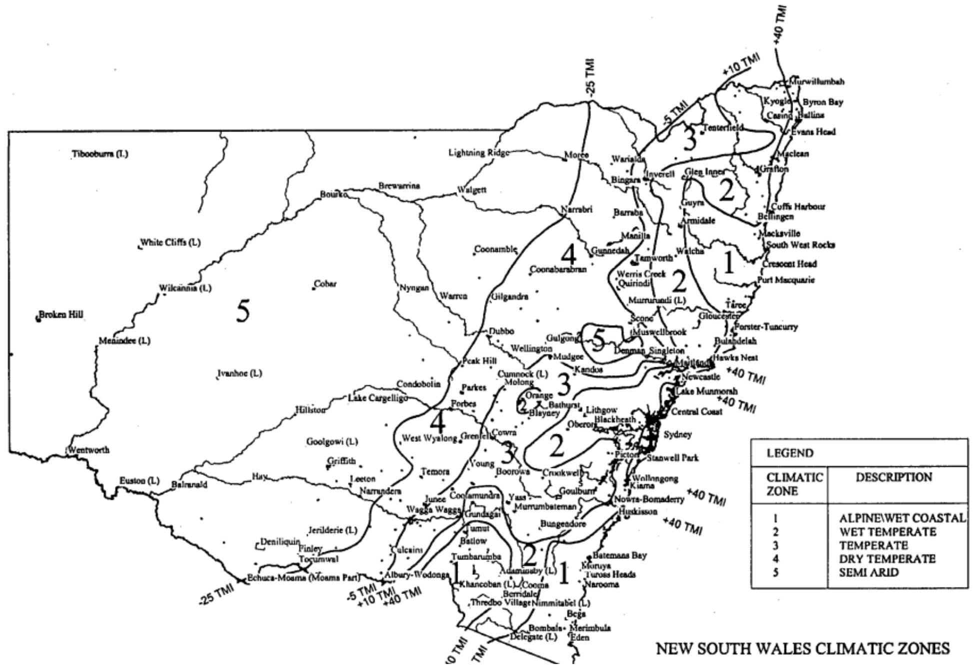


Figure 6.37: New South Wales Climatic Zones (Barnett and Kingsland, 1999)

6.2.8. Fox (2000)

Fox (2000) created a climate-based map of Queensland, Australia, that depicts the design depth of moisture change that could be used to classify sites under AS2870-1996. For the Queensland area only, he presented the use the map in Figure 6.38 and the corresponding values of H_s ($\boldsymbol{D_{\psi_e}}$) contained in Figure 6.39.

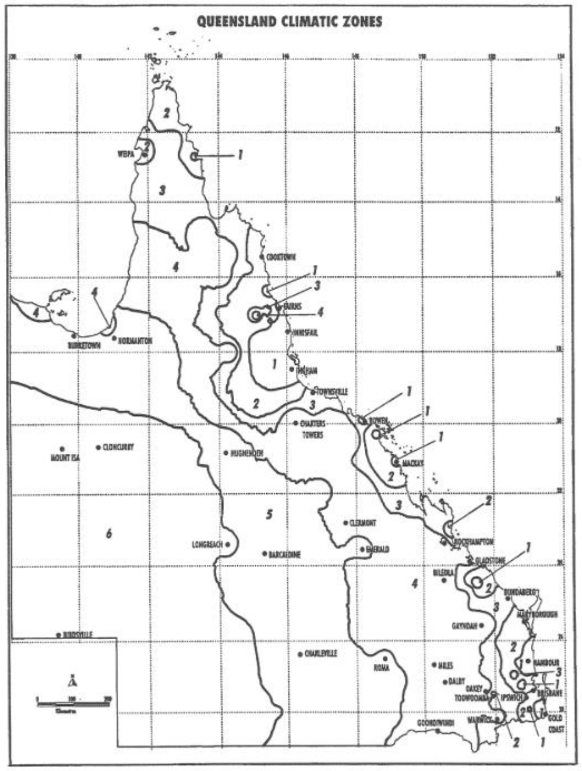


Figure 6.38: Fox (2000) Climate Zone Map of Queensland

Climatic zone	Description	H_s (metres)
1	Alpine/wet coastal	1.5
2	Wet temperate	1.8
3	Temperate	2.3
4	Dry temperate	3.0
5	Semi-arid	4.0
6	Arid	> 4.0

Figure 6.39: Value of H_s ($\boldsymbol{D_{\psi_e}}$) or Climate Zones in Queensland (Fox, 2000)

Climate Zone 6 was added by Fox (2000) to the Queensland climate zone map.

6.2.9. McManus et al. (2004)

Owing to known Australian climate changes, classification changes for portions of Australia were proposed. The TMI associated with each climate zone would remain unchanged; however, the zones themselves would requiring map-wise shifting to keep up with the changing climate. This was particularly important as the climate classification governed the H_s (D_{ψ_e}) depth. Predicated on the Walsh et al. (1998) and Fox (2000) work, a Climate Zone 6 and a corresponding H_s (D_{ψ_e}) > 4.0 m (13.12 ft) are supported for an arid climate with a TMI <-40. Further, Australian researchers were agreed the change in surface soil suction in Australia is 1.0 to 1.5 pF, where no impacts from trees are anticipated. Table 6.19 was proposed by the authors, with the entries in italics representing changes based on new climate conditions.

Table 6.19: McManus et al. (2004) Proposed Surface Soil Suction Variation and Moisture Variation Depth

Climate	**Zone**	**Soil suction Range (pF)**	**Change in Surface Soil suction (pF)**	**Moisture Variation Depth, H_s (D_{ψ_e}) m (ft)**
Alpine / Wet Coastal	1	2.5 to 3.5	1.0	1.5 (4.92)
Wet Temperate	2	2.8 to 4.0	1.2	1.8 (5.91)
Temperate	3	3.0 to 4.2	1.2	2.3 (7.55)
Dry Temperate	4	3.5 to 4.7	1.2	3.0 (9.84)
Semi-Arid	5	4.0 to 5.0	1.0	4.0 (13.12)
Semi-Arid Flood Prone	5	3.5 to 5.0	1.5	4.0 (13.12)
Arid	6	4.0 to 5.0	1.0	6.0 (19.69)
Arid Flood Prone	6	3.5 to 5.0	1.5	6.0 (19.69)

The changes in Table 6.19 were proposed based on the propensity for low-lying dry land in Australia to flood, possibly resulting in quickly alternating wet and dry conditions. The potentially flooding conditions are depicted as "Semi-Arid Flood Prone" and Arid Floor Prone."

6.2.10. PTI 3rd Edition Method

For the PTI 3rd Edition, the depth to equilibrium suction is user input. A default value or iterative method is not an inherent process in the analysis. Figure 6.40 shows the user input, denoted as the "Depth to Constant Suction, cm."

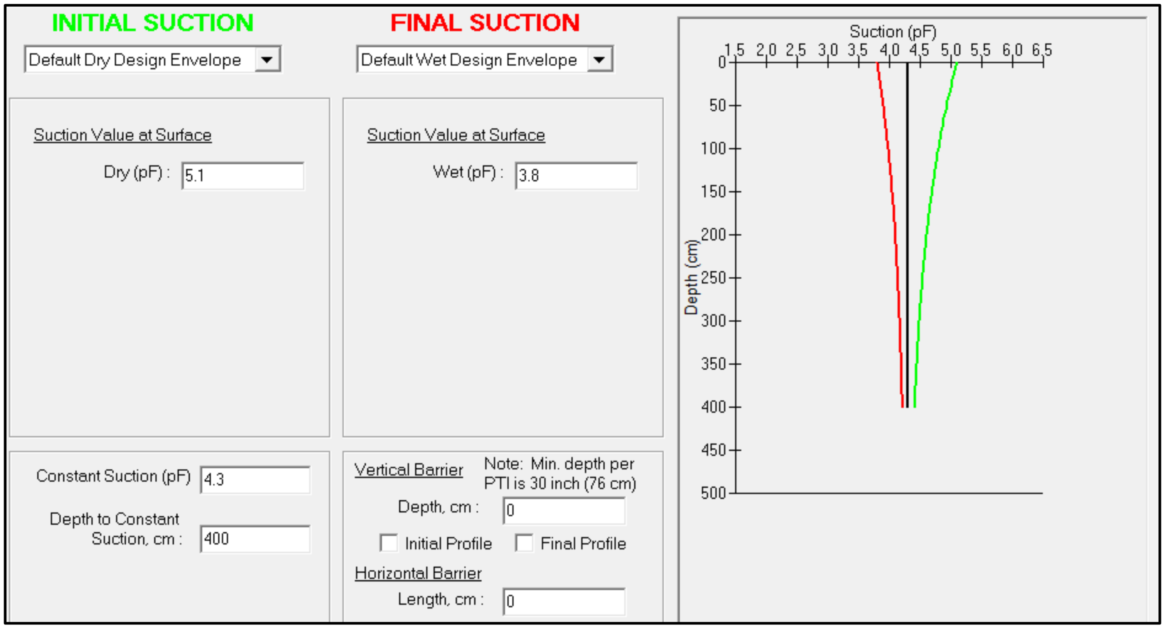


Figure 6.40: Example Input Screen for VOLFLO 1.5 Indicating the Use-Input Depth to Constant Suction Characteristic, i.e. 400 cm for the Example

The example presented is for data representative of a site in Phoenix, Arizona. The site was drilled to an appropriate depth, wherein the depth to equilibrium suction, i.e. 4 m, was determined by interpretation of a plot of the measured suction through the use of a Meter WP4C versus depth. To the maximum extent possible, and to provide an accurate recommendation of the depth of the suction profile, field sampling and appropriate laboratory testing should be performed.

6.2.11. Chan and Mostyn (2008 and 2009)

Chan and Mostyn (2008 and 2009) focused on the effect of climate and H_s ($\boldsymbol{D_{\psi_e}}$) and produced an alternative relationship between TMI and H_s ($\boldsymbol{D_{\psi_e}}$). The plot of the Chan and Mostyn (2008) data is presented also in Mitchell (2008 and 2009). As opposed to most Australian researchers, the Chan and Mostyn (2008 and 2009) relationship is not a stepwise relationship. The Chan and Mostyn (2008 and 2009) relationship are presented in Figure 6.41. A comparison plot with the AS2870 standard relationship is provided.

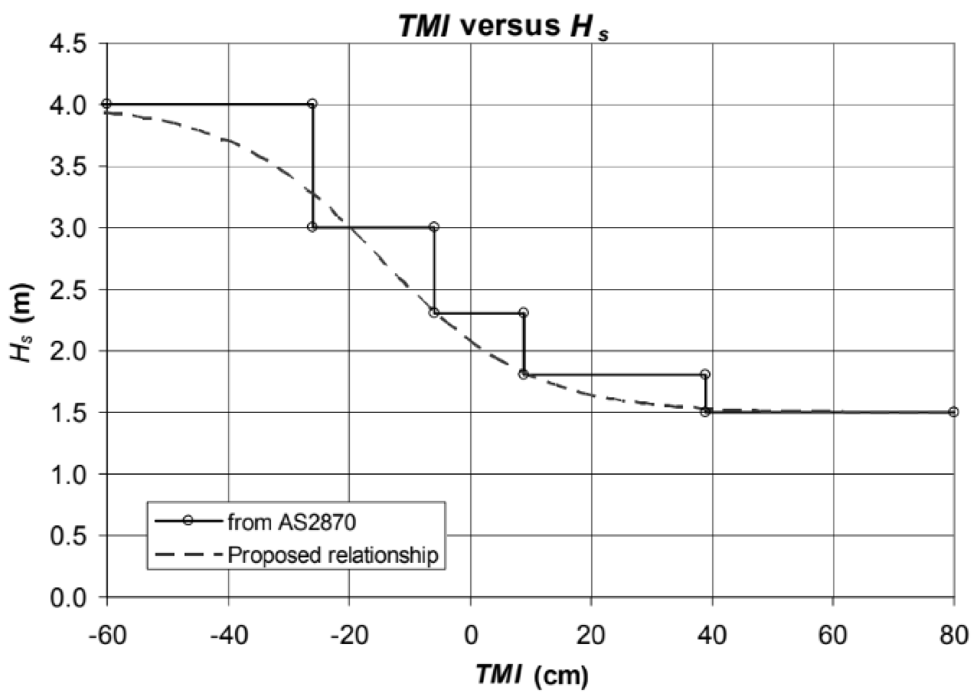


Figure 6.41: Relationship of TMI with H_s ($\boldsymbol{D_{\psi_e}}$) (Chan and Mostyn, 2008 and 2009)

As proposed, the Chan and Mostyn (2008 and 2009) relationship is curvilinear, with the lower bound in H_s (D_{ψ_e})reaching no value shallower than 1.5 m (4.92 ft), while the upper bound not exceeding 3.9 m (12.80 ft).

6.2.12. Mitchell (2008)

Mitchell (2008) focused on arid sites whose TMI < -40. A plot of TMI versus H_s (D_{ψ_e}) was presented by Mitchell (2008). Figure 6.42 is a compilation of seven publications; AS2870-1996, Fityus et al. (1998), Walsh et al. (1998), Barnett and Kingsland (1999), Fox (2000), McManus at al. (2004), and Chan and Mostyn (2008, and subsequently 2009).

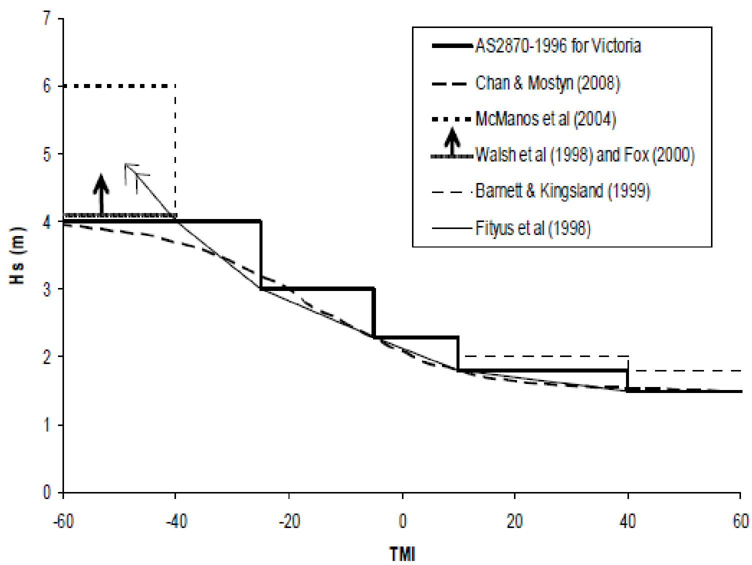


Figure 6.42: Relationship between H_s (D_{ψ_e}) and TMI (Mitchell, 2008)

The box shape in Figure 6.42 with an upward pointing arrow represents the data from Walsh et al. (1998) and Fox (2000) with reference to flood prone areas in semi-arid and arid environments. Mitchell (2008) states that there is little theoretical basis for the relationships shown in Figure 6.42, that can account for the large differences in the recommended values of Hs ($\boldsymbol{D}_{\psi_e}$) in arid climates. Using a diffusion coefficient of 0.004 for an arid climate with an inferred TMI of -50, the calculated Hs ($\boldsymbol{D}_{\psi_e}$) for a site in the Jackson oil field in Queensland is 2.3 m (7.55 ft). For a plot of the diffusion coefficient versus TMI, refer to Figure 6.89 in section 6.3.13.

As an example of using a diffusion coefficient of 0.004 cm^2/sec, the idealized soil suction profiles for a site at Albury Airport, Australia, suggest that the depth to constant soil suction, Hs ($\boldsymbol{D}_{\psi_e}$), and calculated soil suction change at the surface, Δu, are 2.5 m (8.20 ft) and 1.2 pF, respectively. Albury Airport has a TMI of 1.7; a temperate climate zone.

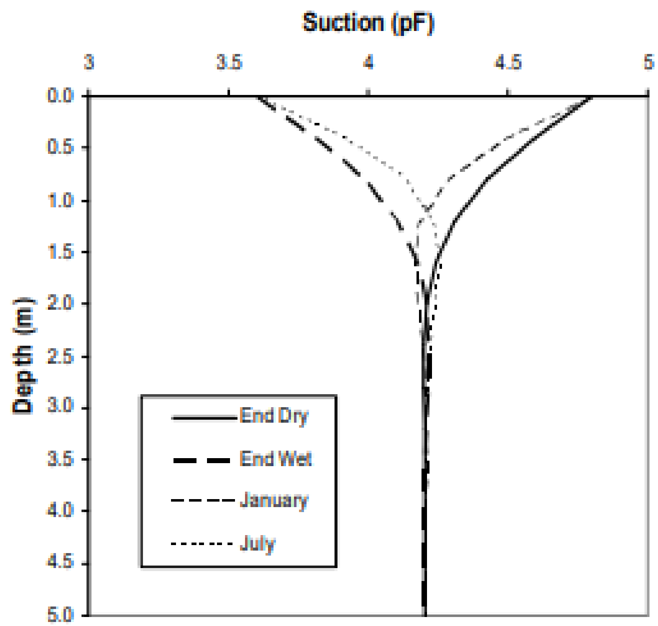


Figure 6.43: Calculated or Idealized Soil Suction Changes with Depth Using a Diffusion Coefficient, α, equal to 0.004 cm^2/sec

Mitchell (2008) provided Figure 6.44 that summarizes the data from five sites representing five climate zones. The values in the final three columns were used as boundary conditions for the diffusion equation to arrive at soil suction changes with depth, such that the diffusion coefficient can be determined to match the magnitudes of Hs (D_{ψ_e}) listed in the table.

Climate Zone	Representative Location	TMI	H_s by AS2870	Δu_s (pF) (wet to dry)	u_{eq} (pF)	Wet /Dry months ratio
Wet coastal	Wilsons Promontory	+51	1.5 m	3.7 to 4.9	4.1	8/4
Wet temperate	Hamilton	+6.3	1.8 m	3.6 to 4.8	4.1	7/5
Temperate	Albury	+1.7	2.3 m to 3.0m	3.6 to 4.8	4.2	6/6
Dry temperate	Horsham	-24.5	3.0 m	3.5 to 4.7	4.2	5/7
Semi-arid	Mildura	-41	4.0 m	3.55 to 4.75	4.5	2½/9½

Figure 6.44: TMI, Hs (D_{ψ_e}), *Δus*, *ueq*, *and* the Wet to Dry Months Ratio Using the Diffusion Equation

One of the results of Mitchell (2008) was that AS2870-1996 may over-estimate the Hs (D_{ψ_e}) for arid sites. This was pointed out by a case history where the Australian Standard (AS2870-1996) indicated that Hs (D_{ψ_e})should be 4.0 m (13.12 ft), whereas further evaluation using the diffusion coefficient indicated that Hs (D_{ψ_e}) should be 2.5 m (8.20 ft). While a theoretical basis is provided, an Hs (D_{ψ_e}) depth based on actual field and laboratory data is not supported.

6.2.13. Fityus and Buzzi (2008)

Fityus and Buzzi (2008) caution the use of TMI-based maps in Australia to serve as an end result to the climate conditions for any site. They state that the map may contain a number of assumptions that could lead to inconsistencies in maps presented by different authors, and for adjacent areas. In order to reconcile the maps, form varying sources, it would serve well to review their paper prior to disembarking on a more site-specific classification of the TMI and most applicable climate zone. Fityus and Buzzi (2008) further state that there is still much research need to quantify different method of computing TMI, methods for r estimating evapotranspiration, confirm and improved upon the relationship between TMI and H_s (D_{ψ_e}), and verify to what extent climate change is having on the realignment of the TMI zones and its significant on future adjustments to H_s (D_{ψ_e}).

6.2.14. AS2870-2011

The most recent version of the AS2870 was published in 2017 and includes the six climate zones as shown in Figure 6.45.

RELATIONSHIP BETWEEN TMI, DEPTH OF DESIGN SOIL SUCTION CHANGE (H_s) AND CLIMATIC ZONE

TMI	Depth of design suction change (H_s), m	Climatic zone
>10	1.5 m	1
≥−5 to 10	1.8 m	2
≥−15 to ≤−5	2.3 m	3
≥−25 to ≤−15	3.0 m	4
≥−40 to ≤−25	4.0 m	5
≤40	>4.0 m	6

Figure 6.45: AS2870-2011 - Adopted Relationship Between TMI, Depth of Design Soil Suction Change (H_s or D_{ψ_e}) and Climate Zone

6.2.15. Mitchell (2013)

Michell (2013) studied the effects of climate change on expansive soil response. The adverse effects on expansive soils because of changing climate can be expressed by a projected change in TMI. Addressing the impacts of climate change relative to H_s (D_{ψ_e}) is in some respects similar to the effect of a group of trees, i.e. there is a shift in the H_s (D_{ψ_e}) plot. Mitchell (2013) provided a graphic relationship of TMI versus H_s (D_{ψ_e}) and H_t (the depth to constant soil suction imposed by a tree group) that is current use. Figure 6.46 shows the relationship between H_s (D_{ψ_e}) and H_t and TMI according to AS2870-2011.

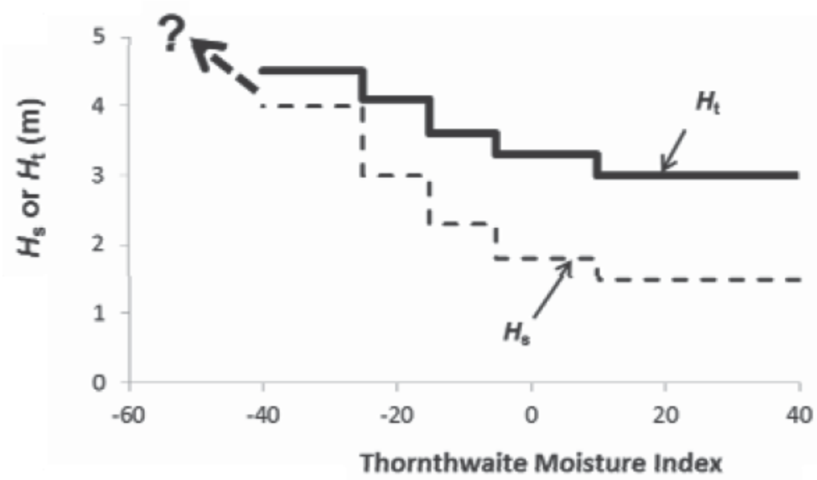


Figure 6.46: Relationship Between Hs (D_{ψ_e}), Ht and TMI to account for a Tree Group or Climate Becoming Drier (Mitchell, 2013)

6.2.16. Sun et al. (2017)

Sun et al. (2017) measured the depth to constant soil suction at three locations in Australia, as presented in Table 6.20.

Table 6.20: Measurements of Hs (D_{ψ_e}) at Three Locations in Western Australia

Location	**Hs (D_{ψ_e}) From Field Measurements m (ft)**	**TMI**
Lake King, Australia (Wheatbelt)	4.0 (13.12)	-39.7
Jerramungup, Australia (Great Southern)	4.0 (13.12)	-22
Ravensthorpe, Australia (Goldfields-Esperance)	4.0 (13.12)	-43.5

6.2.17. Cuzme (2018)

An equation derived by Cuzme (2018) is presented in Figure 6.47 suggesting that TMI can be correlated with the depth to constant soil suction using the surrogate, for uncovered and non-irrigated sites.

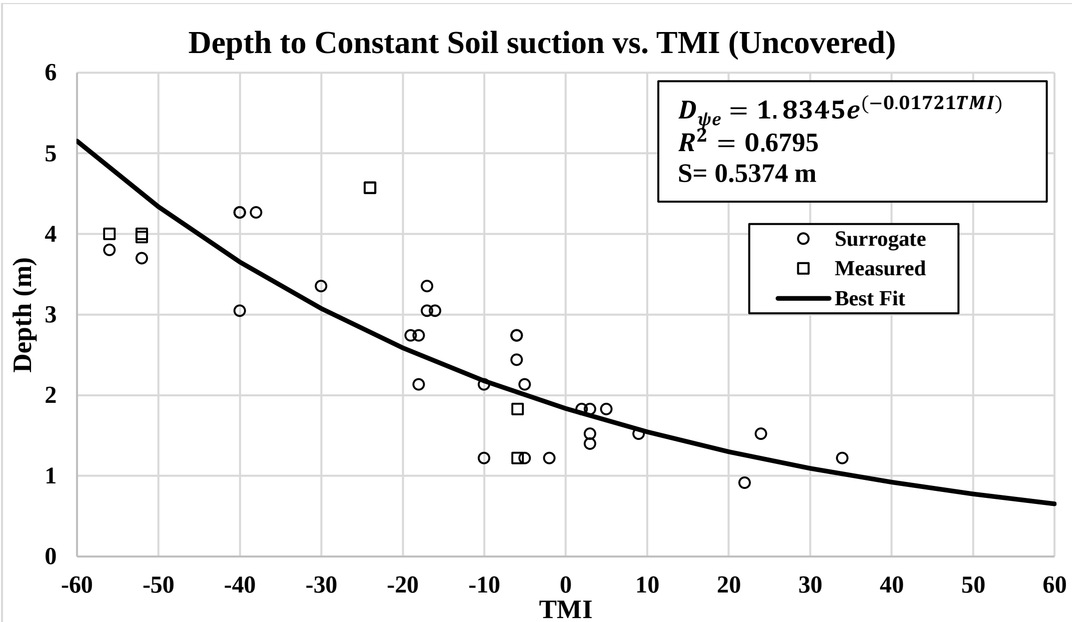


Figure 6.47: Cuzme (2018) Plot of TMI Versus Depth to Constant Soil suction

Equation (147) describes the Cuzme (2018) relationship between the depth to equilibrium soil suction and TMI, with its R^2 and S. The surrogate data utilized in the relationship was obtained using Equations (133) through (135), which incorporate a TMI-depth dependency.

$$D_{\psi_e} = 1.8345e^{(-0.01721TMI)} \tag{147}$$

$$R^2 = 0.6795$$

$$S = 0.5374\ m$$

6.2.18. Research-Related Drilling, Laboratory Testing and Suction Measurement to Verify Suction Equilibrium Magnitude and Depth

The exploratory test drilling and extensive laboratory testing completed as part of this research was examined for the San Antonio site. At the San Antonio site, two test borings were advanced in covered areas where there was at least 3.048 m (10 ft) to the edge of the covering (asphalt), one test boring in an uncovered area that was routinely irrigated, and one test boring in an uncovered area that was not irrigated. Figure 6.48 presents the measured soil suction data using a Meter WP4C. Figure 6.49 shows the plot of soil suction versus depth using the surrogate equation, Equation (139). Although the San Antonio site is associated with former forensic investigations due to expansive-clay related performance issues, at the time of the site investigation for this study, the suction profile show that the equilibrium suction appears unaffected by prior site development/irrigation. The uncovered and non-irrigated location at San Antonio was considered to be outside of the region of prior forensic study.

From the two plots, using measured and surrogate data, Table 6.21 has been prepared.

Table 6.21: Measured and Surrogate Values of the Magnitude of Equilibrium Soil suction and Depth to Equilibrium Soil Suction for the San Antonio Site When Compared to the Predicted Values

San Antonio Dataset	**Magnitude of Equilibrium Soil suction, ψ_e**	**Depth to Equilibrium Soil suction, D_{ψ_e}**	**Predicted Magnitude of Equilibrium Soil suction Using Equation** (144)	**Predicted Depth to Equilibrium Soil suction Using Equation** (148)
Measured Soil suction	4.03 pF	3.66 m (12 ft)	4.1 pF	3.38 m (11.1 ft)

San Antonio Dataset	**Magnitude of Equilibrium Soil suction, $\boldsymbol{\psi_e}$**	**Depth to Equilibrium Soil suction, D_{ψ_e}**	**Predicted Magnitude of Equilibrium Soil suction Using Equation** (144)	**Predicted Depth to Equilibrium Soil suction Using Equation** (148)
Surrogate Soil suction	4.13 pF	3.35 m (11 ft)		

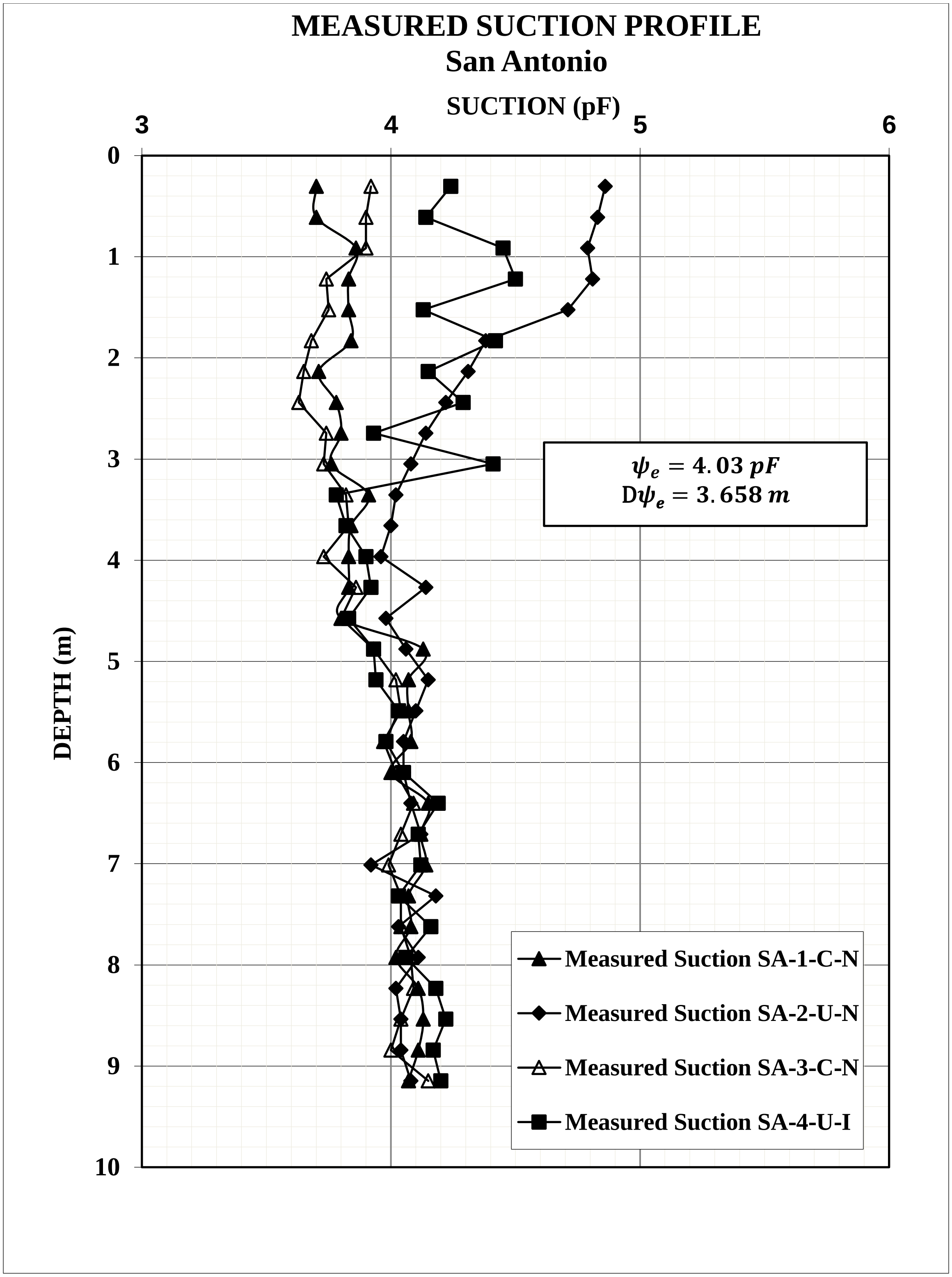


Figure 6.48: Measured Soil suction Data versus Depth for Four Test Borings in San Antonio.

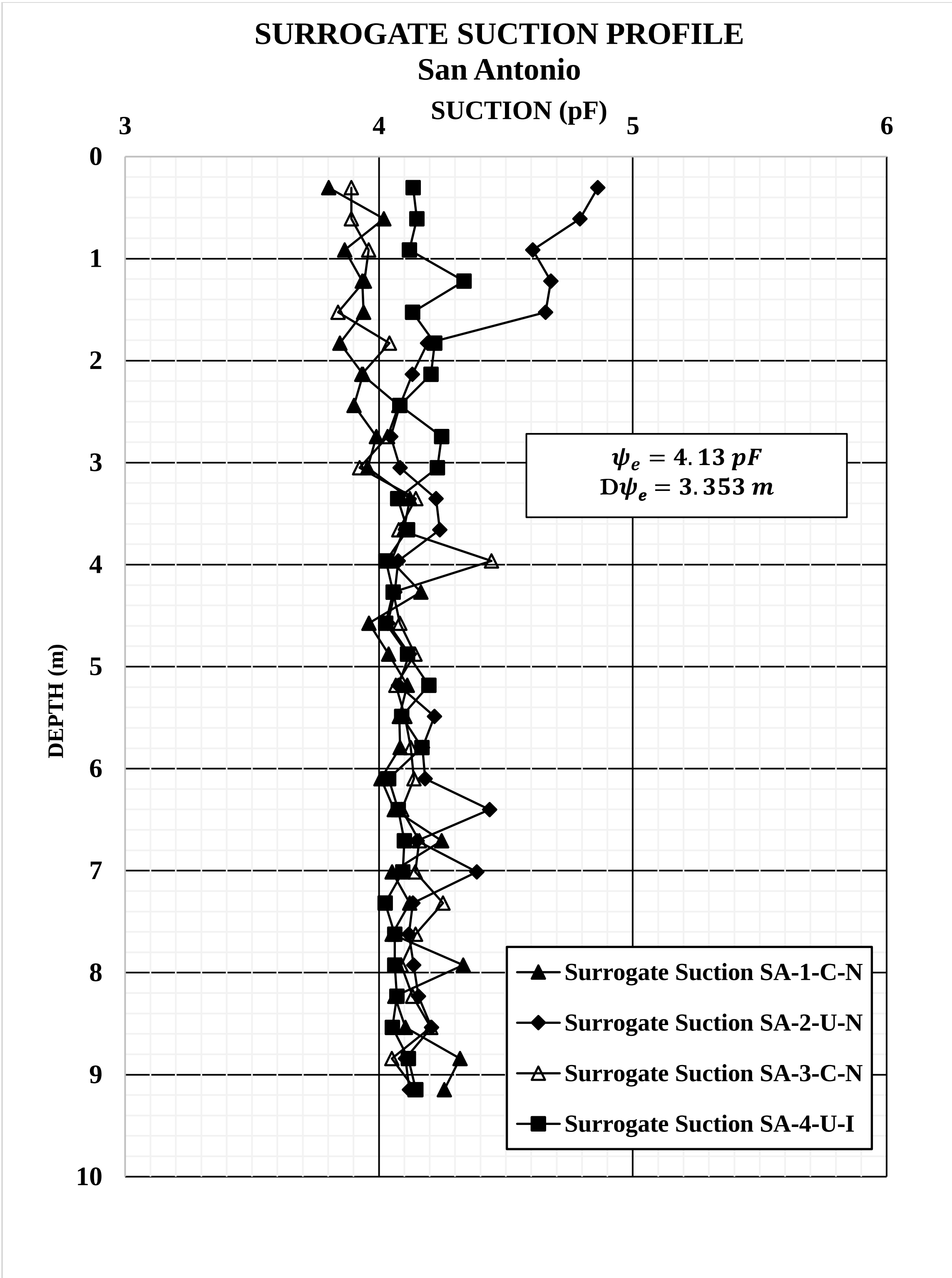


Figure 6.49: Surrogate Soil suction Data versus Depth for Four Test Borings in San Antonio.

For the CH clays at the San Antonio site, and using the soil suction surrogate profile data, there is reasonable agreement with the predicted suction profiles parameters (depth to and magnitude of equilibrium suction) obtained through the use of Equations (144) and (148).

The exploratory test drilling and extensive laboratory testing data for the Denver site was examined. At the Denver site, one test boring was advanced in a covered area where there was at least 3.048 m (10 ft) to the edge of the covering (asphalt), and two test borings were completed in uncovered areas that were not irrigated. Figure 6.50 presents the measured soil suction data using a Meter WP4C. Figure 6.51 shows the plot of soil suction versus depth using the surrogate equation, Equation (139). From the two plots, using measured and surrogate data, Table 6.22 has been prepared.

Table 6.22: Measured and Surrogate Values of the Magnitude of Equilibrium Soil suction and Depth to Equilibrium Soil Suction for the Denver Site When Compared to the Predicted Values

Denver Dataset	**Magnitude of Equilibrium Soil suction, $\boldsymbol{\psi_e}$**	**Depth to Equilibrium Soil suction,** D_{ψ_e}	**Predicted Magnitude of Equilibrium Soil suction Using Equation** (144)	**Predicted Depth to Equilibrium Soil suction Using Equation** (148)
Measured Soil suction	4.31 pF	3.66 m (12 ft)	4.1 pF	3.38 m (11.1 ft)
Surrogate Soil suction	4.2 pF	3.35 m (13 ft)		

For the CH clays at the Denver site, and using the soil suction surrogate, there is reasonable agreement with the predicted features of the suction profile, as recommended through the use of Equations (144) and (148).

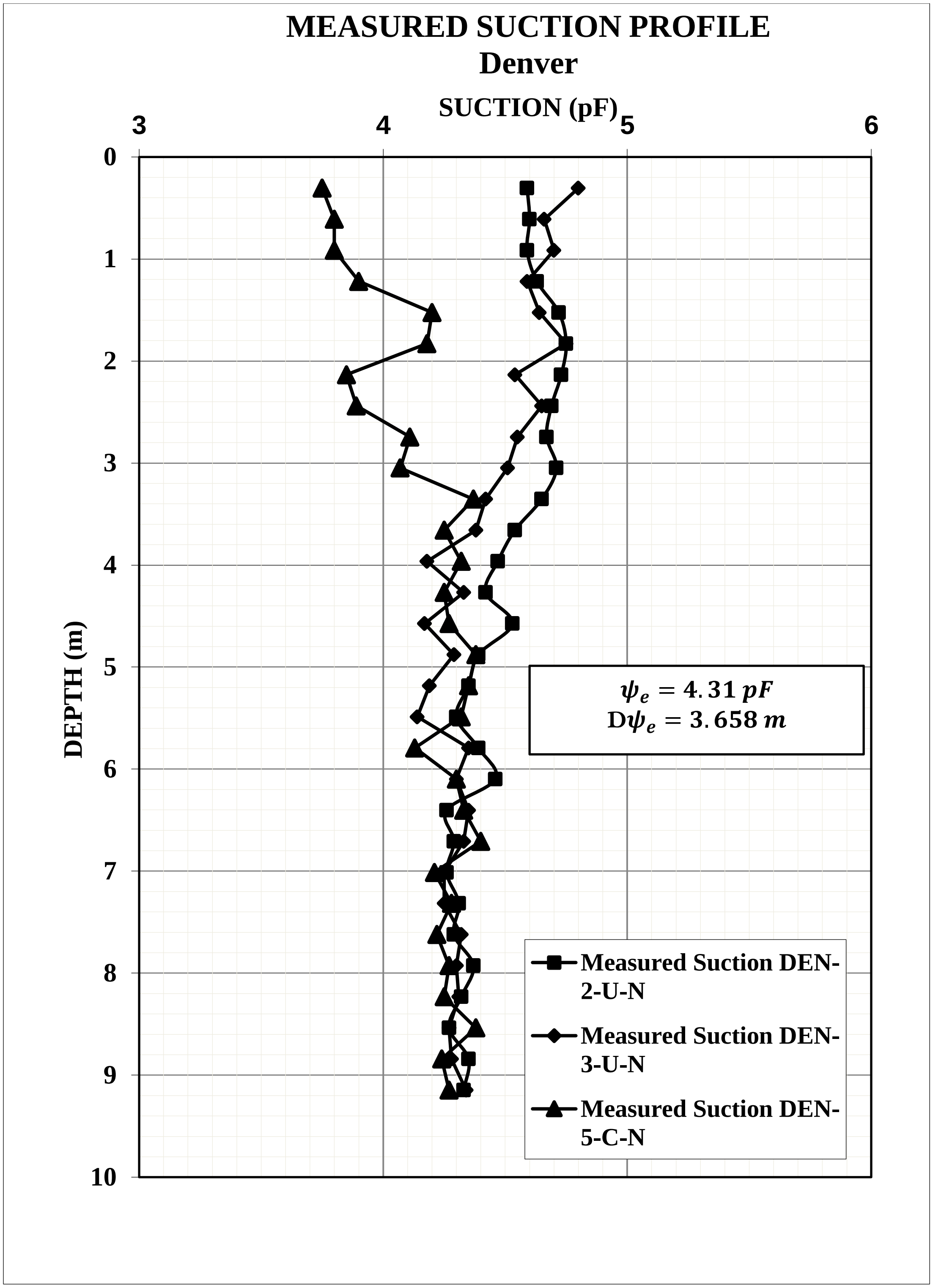


Figure 6.50: Measured Soil suction Data versus Depth for Three Test Borings in Denver.

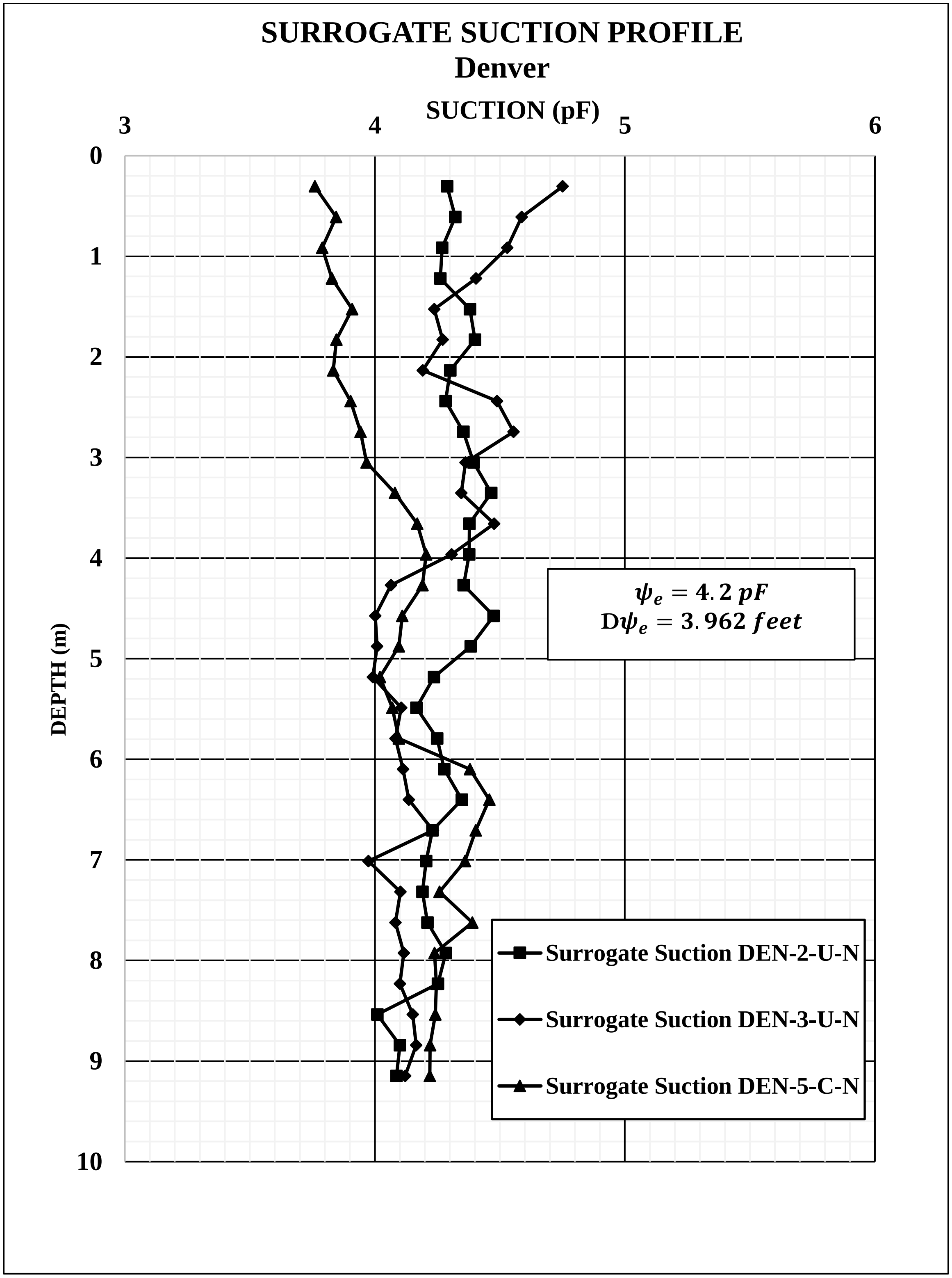


Figure 6.51: Surrogate Soil suction Data versus Depth for Three Test Borings in Denver.

6.2.19. Discussion and Conclusions

A culmination of the depth to constant soil suction (D_{ψ_e} or H_s) versus TMI that can be considered to be added to the Cuzme (2018) data is provided in Table 6.23. The added data for consideration is from Jayatilaka et al. (1992), Smith (1993), Fityus et al. (1998), Walsh et al. (1998), and Sun et al. (2017). Further, the surrogate data has been plotted utilizing Equation (139). The data contained in Appendix E 3 were analyzed to explore the relationship between TMI and the depth to equilibrium soil suction.

Table 6.23: Data Added to the Cuzme (2018) Plot of TMI versus Depth to Constant Soil suction

Location	**H_s (D_{ψ_e}) From Field Measurements m (ft)**	**TMI**	**Data Source**
Lake King, Australia (Wheatbelt)	4.0 (13.12)	-39.7	Sun et al., (2017)
Jerramungup, Australia (Great Southern)	4.0 (13.12)	-22	Sun et al., (2017)
Ravensthorpe, Australia (Goldfields-Esperance)	4.0 (13.12)	-43.5	Sun et al., (2017)
Brisbane, Australia	1.5 (4.92)	34.5	Smith (1993)
Melbourne, Australia	2.0 (6.56)	-1	Smith (1993)
Adelaide, Australia	4.0 (13.12)	-26	Smith (1993)
Nelson Bay, Australia	1.5 (4.92)	53.7	Fityus et al. (1998)
Maryville, Australia	1.5 (4.92)	24.4	Fityus et al. (1998)
Scone, Australia	3.0 (9.84)	-25.4, -24.3	Fityus et al. (1998)
Brisbane, Australia	1.5 (4.92)	40	Walsh et al. (1998)
Perth, Australia	1.8 (5.91)	10 to 40	Walsh et al. (1998)
Ipswich, Australia	2.3 (7.55)	-5 to 10	Walsh et al. (1998)
Seguin, TX	2.74 (8.99)	-6.16	Jayatilaka et al. (1992)
Converse, TX	3.05 (10.01)	-5.72	Jayatilaka et al. (1992)
Dallas, TX	2.13 (6.99)	1.38	Jayatilaka et al. (1992)

Location	H_s (D_{ψ_e}) From Field Measurements m (ft)	TMI	Data Source
Ennis, TX	3.05 (10.01)	5.81	Jayatilaka et al. (1992)
Wichita Falls, TX	3.35 (10.99)	-9.72	Jayatilaka et al. (1992)
Snyder, TX	4.27 (14.01)	-19.43	Jayatilaka et al. (1992)

Using the available data from Table 6.23, the Cuzme (2018), updated with surrogate data using the surrogate from Equation (139), the plot has been augmented as presented in Figure 6.52.

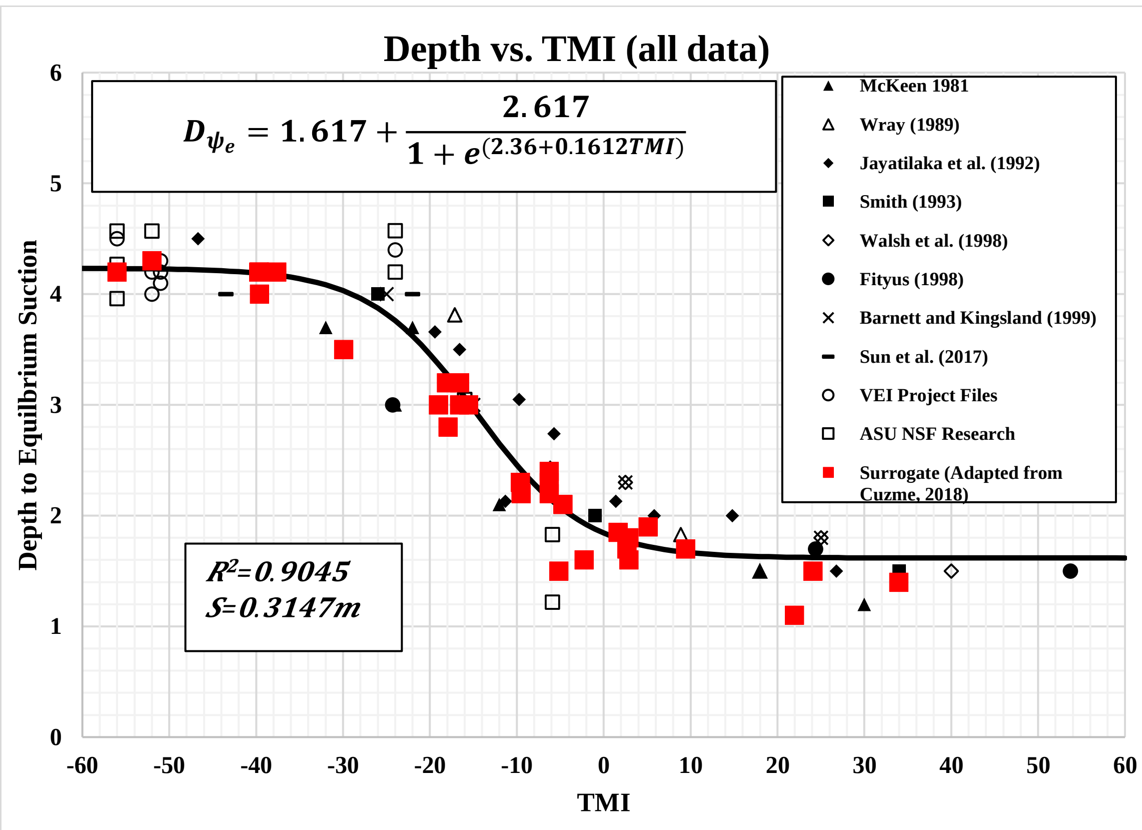


Figure 6.52: Symmetric Sigmoid Plot of the Relationship Between TMI and the Depth to Constant Soil Suction for Uncovered and Non-irrigated Sites

A symmetric sigmoid plot as shown in Figure 6.52, with its R^2 and S, yielded Equation (148).

$$D_{\psi_e} = 1.617 + \frac{2.617}{1 + e^{(2.36+0.1612TMI)}} \tag{148}$$

$$R^2 = 0.9045$$

$$S = 0.3147\ m$$

Where,

D_{ψ_e} is the depth to equilibrium soil suction

The TMI versus depth to equilibrium suction relationship presented is quite compelling and draws positively on all research completed in both the United States and Australia, particularly that of Chan and Mostyn (2008 and 2009) who proposed a sigmoid shape to the relationship. Analyzing the data further by groups of LLs provided further insight into the behavior of the symmetric sigmoid relationship. The data obtained and reviewed as part of this research was divided into two groups, following the general concept of the Unified Soil Classification System (USCS). The first group was comprised of data where the LL was less than 50, corresponding to a CL soil. The second group of data included LLs greater than or equal to 50, corresponding to a CH soil. To confirm the CL and CH classifications, it was verified that none of the data plotted below the A-line. Figure 6.53 presents the symmetric sigmoid plots of the two LL groups.

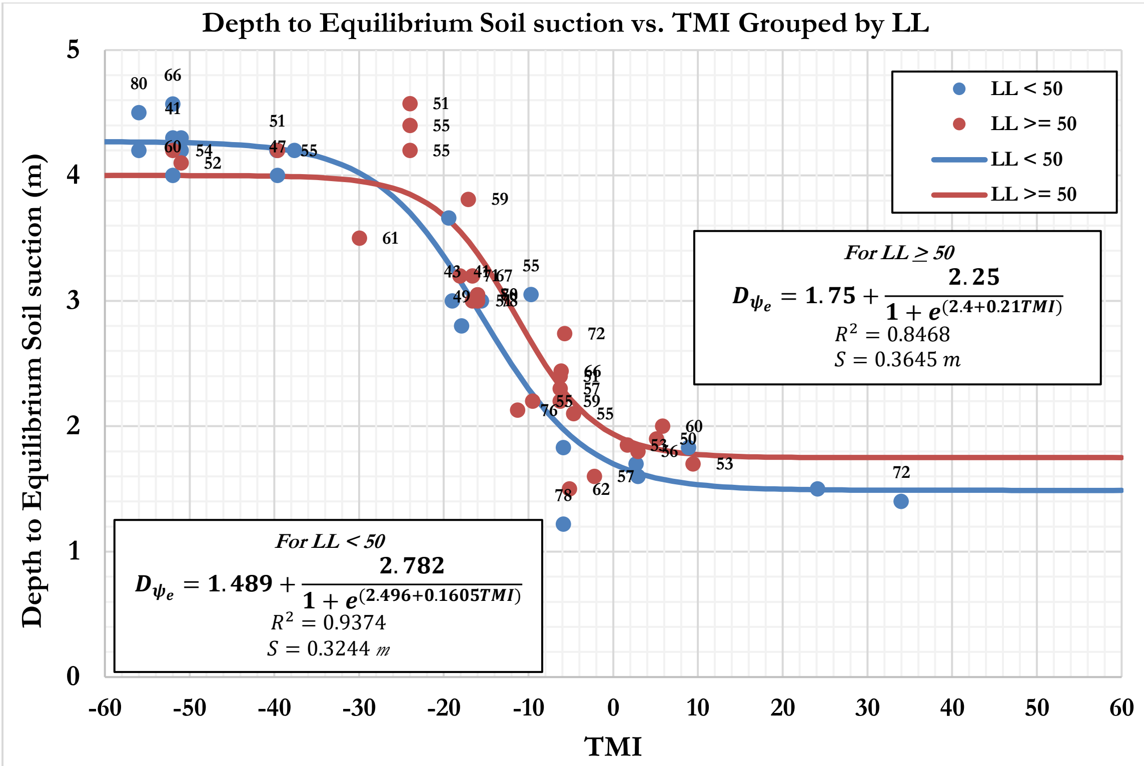


Figure 6.53: Depth to Equilibrium Soil Suction versus TMI, Grouped by Liquid Limit, Indicating the Possibility of Statistical Difference

It is clear from Figure 6.53 that there is an upward shift in the curve as the LL increases. Equations (149) and (150) present relationships for the respective LL groups. Because of the difference in soil types, it is reasonable to expect separate relationships for each, i.e. with further study, statistical difference may be verified.

$$D_{\psi_e} = 1.489 + \frac{2.782}{1 + e^{(2.496+0.1605TMI)}};\ for\ Liquid\ Limits\ < 50 \tag{149}$$

$$R^2 = 0.9374$$

$$S = 0.3244\ m$$

$$D_{\psi_e} = 1.75 + \frac{2.25}{1 + e^{(2.400+0.2100TMI)}};\ for\ Liquid\ Limits\ \geq 50 \tag{150}$$

$$R^2 = 0.8468$$

$$S = 0.3645\ m$$

The LL-dependent curves appear to cross at an approximate TMI of -28. The shape of the LL-dependent curves can be explained by the information contained in Figure 6.54 (Fredlund et al., 2012). In much the same manner that a fine sand can exhibit a lower permeability than a clayey silt where the matric soil suction exceeds a certain magnitude, the same can be asserted for a CL soil as compared to a CH soil. In the case of a CL/CH comparison, the apparent coefficient of permeability of the CL soil decreases as the TMI exceeds -28 and becomes lower than the coefficient of permeability of a CH soil at a TMI greater than -28.

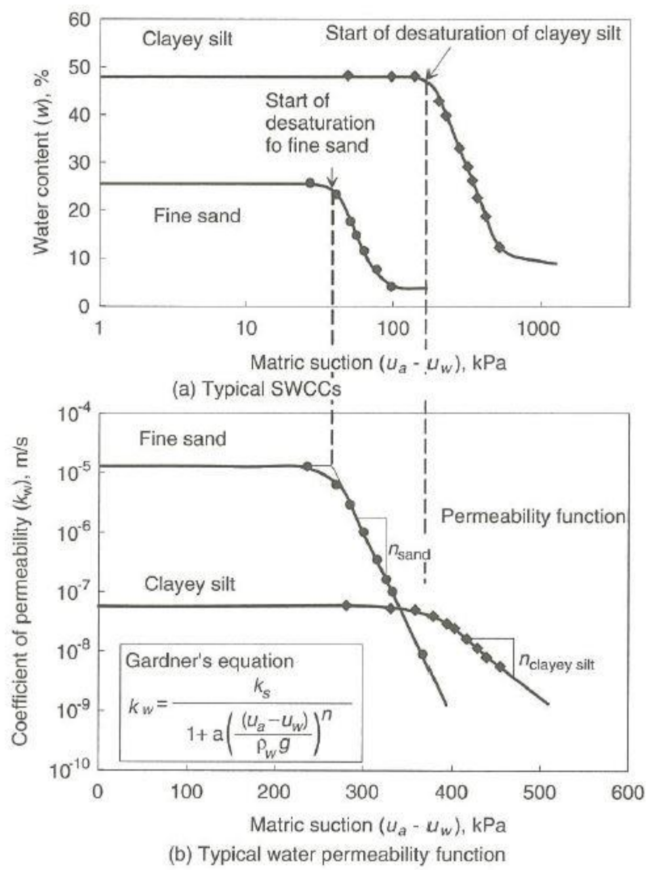


Figure 6.54: Relationship Between SWCCs and Permeability for Sand and Clayey Silt (Fredlund et al., 2012)

Although the arguments associated with the use of Equations (149) and (150) are plausible and thought provoking, a recommendation for their use is premature. A major point that precludes these equations for recommended use is simply attributed to insufficient data with regard to liquid limits greater than or equal to 50, insufficient data with liquid limits less than 50, and an overall set of liquid limit values that cover the complete spectrum of TMIs from -60 to +60. Granted for expansive soil areas, the need for such data could be focused to a greater extent in the TMI range of -60 to +20. Because of the need for more data covering the spectrum of liquid limits in a wider range of TMI, Equations (149) and (150) are not yet ready for recommended use. The current data supports a recommended use for Equation (148).

When determining the depth to constant suction, and its connection to establishing the seasonal suction profiles, Jayatilaka et al. (1992), Naiser (1997), McKeen & Johnson (1990), and Aubeny & Long (2007) have consistently maintained that the depth to equilibrium suction, to adequate engineering accuracy, can be determined with the separation between suction values at the equilibrium depth is no greater than 0.2 pF. This concept has been embraced by the industry and has been utilized in this study.

Because the depth to equilibrium suction will control many aspects of the design process, it will be recommended in Chapter 7.2 to used confidence bands or bounds on the plot of TMI versus the depth to equilibrium suction. As previously presented, the standard deviation is 0.3147. Using a value of twice the standard deviation to create upper and lower bounds on the curve representing the relationship between TMI and the depth to equilibrium suction, Figure 6.55 has been prepared, showing all of the data. A narrowing of the confidence interval band width can be observed, which has verified by Minitab.

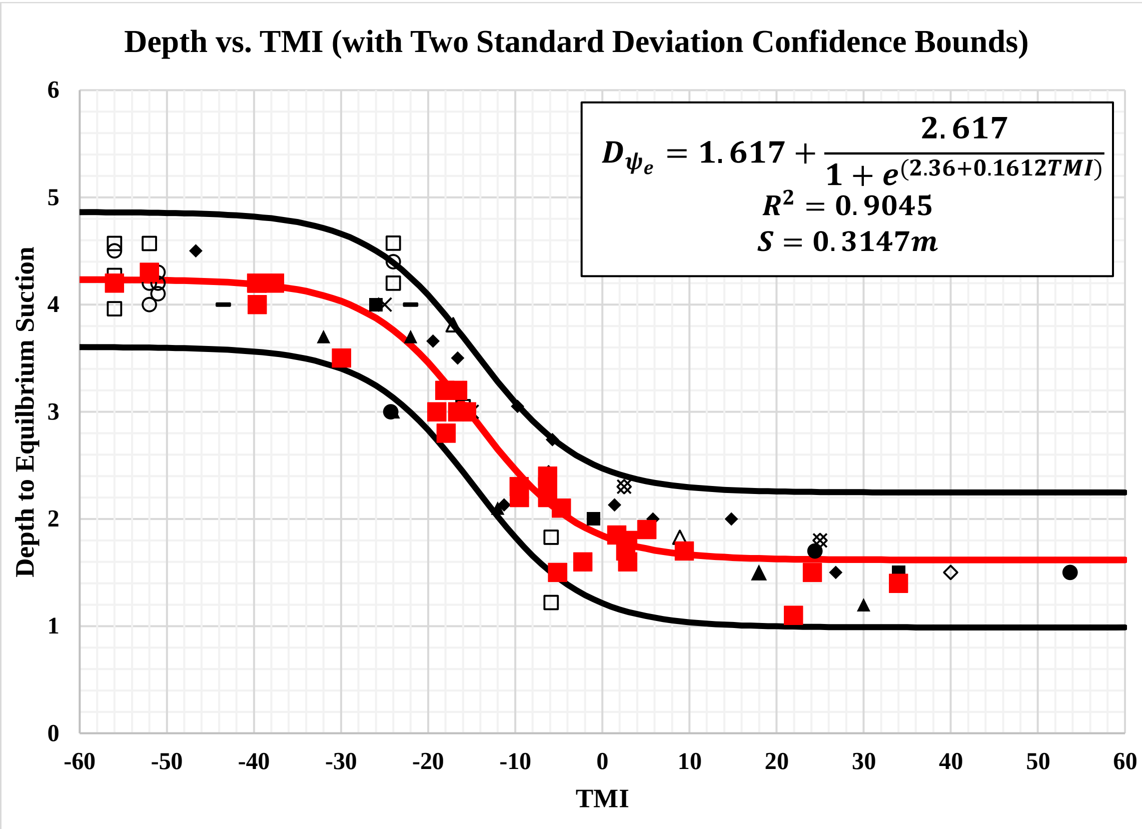


Figure 6.55: Symmetric Sigmoid Plot of the Relationship Between TMI and the Depth to Constant Soil Suction for Uncovered and Non-irrigated Sites, with Confidence Bounds Equal to Two Standard Deviations

To better understand the predictions of the depth to equilibrium suction, it is also important to look at the blow count data versus depth. A significantly high blow count may indicate the presence of a limiting condition that could preclude vertical moisture penetration and hence provide grounds for opining that the depth to equilibrium suction may decrease where a consistently high blow count material is encountered. Figure 6.56 through Figure 6.73 present the available blow count data for eighteen sites whose data were obtained through the data mining effort, i.e. not specifically drilled as part of this research. The blow counts are a combination of Standard Penetration Test (SPT) data and California ring-sample blow counts data. Customary relationships can be used to compare the two types of blow count data. In general, the blow count for an SPT will be less than exhibited for a California ring-sampler. Of specific interest in establishing a potential limiting condition is a blow count equal to 50, for either type of field test. For the geotechnical community, a blow count of 50, whether it is obtained from an SPT or California ring sampler is considered to be indicative of a “hard dig” condition and demarcation of a significant decrease in permeability.

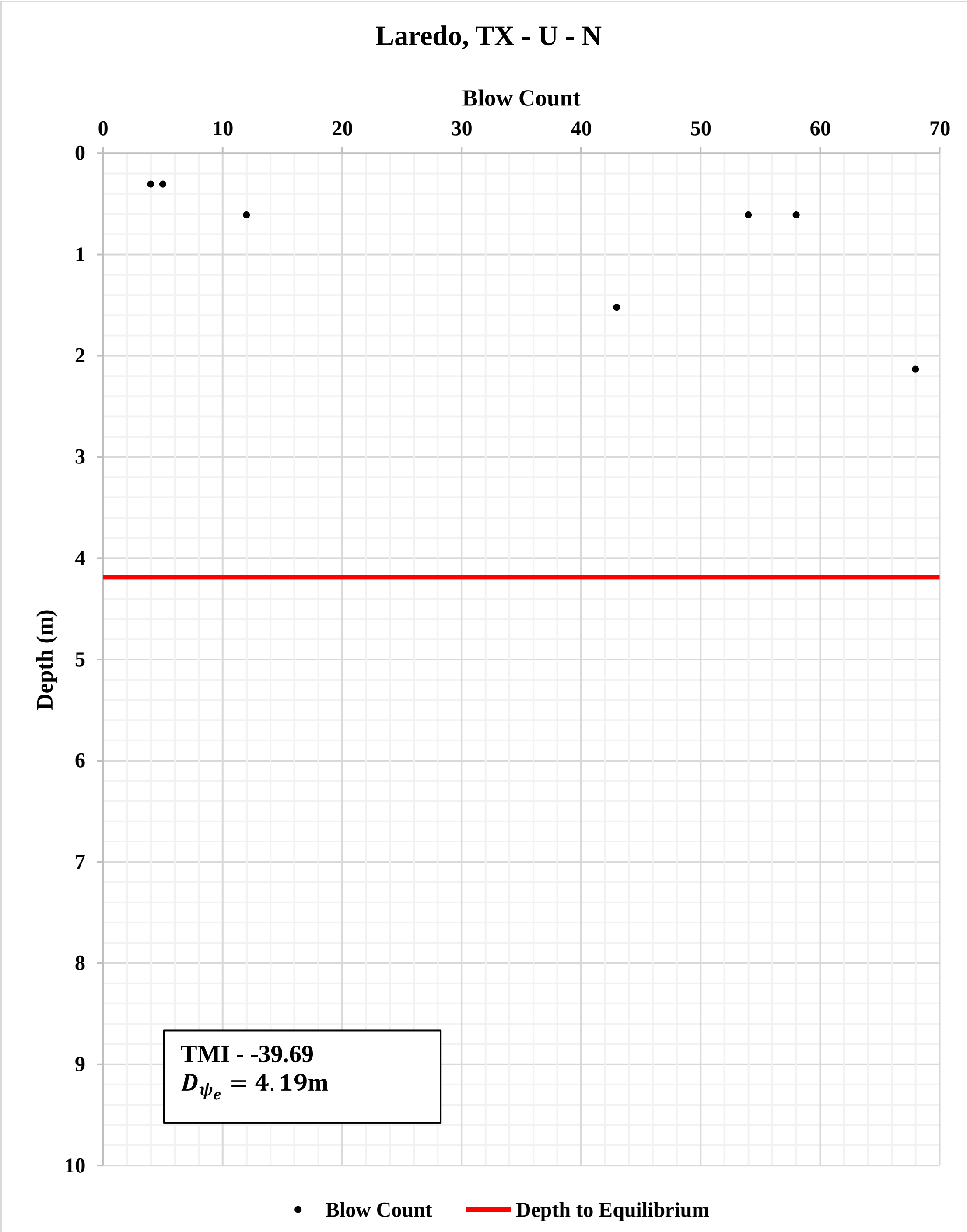


Figure 6.56: Blow Count Versus Depth at Laredo, TX Site

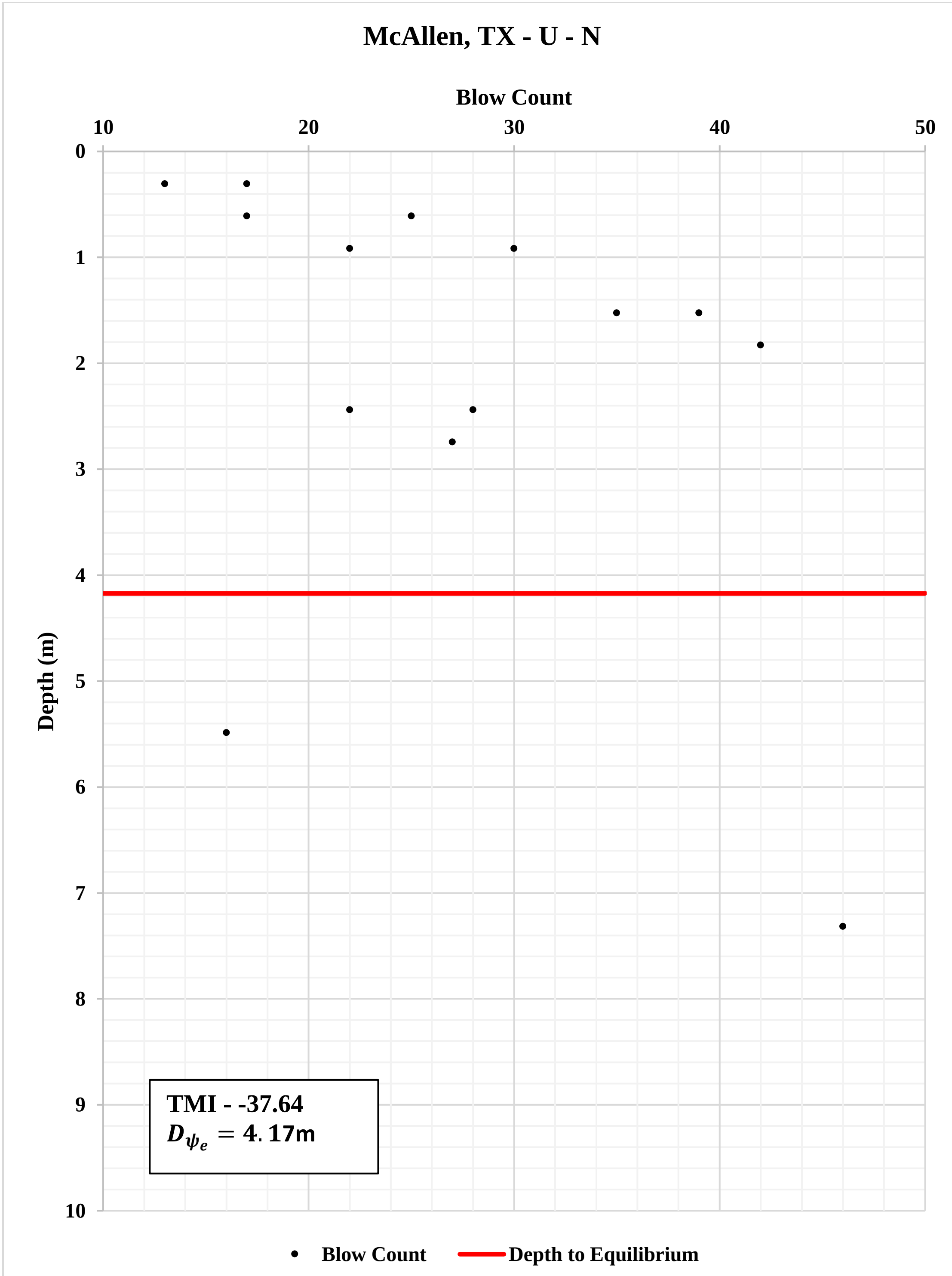


Figure 6.57: Blow Count Versus Depth at McAllen, TX Site

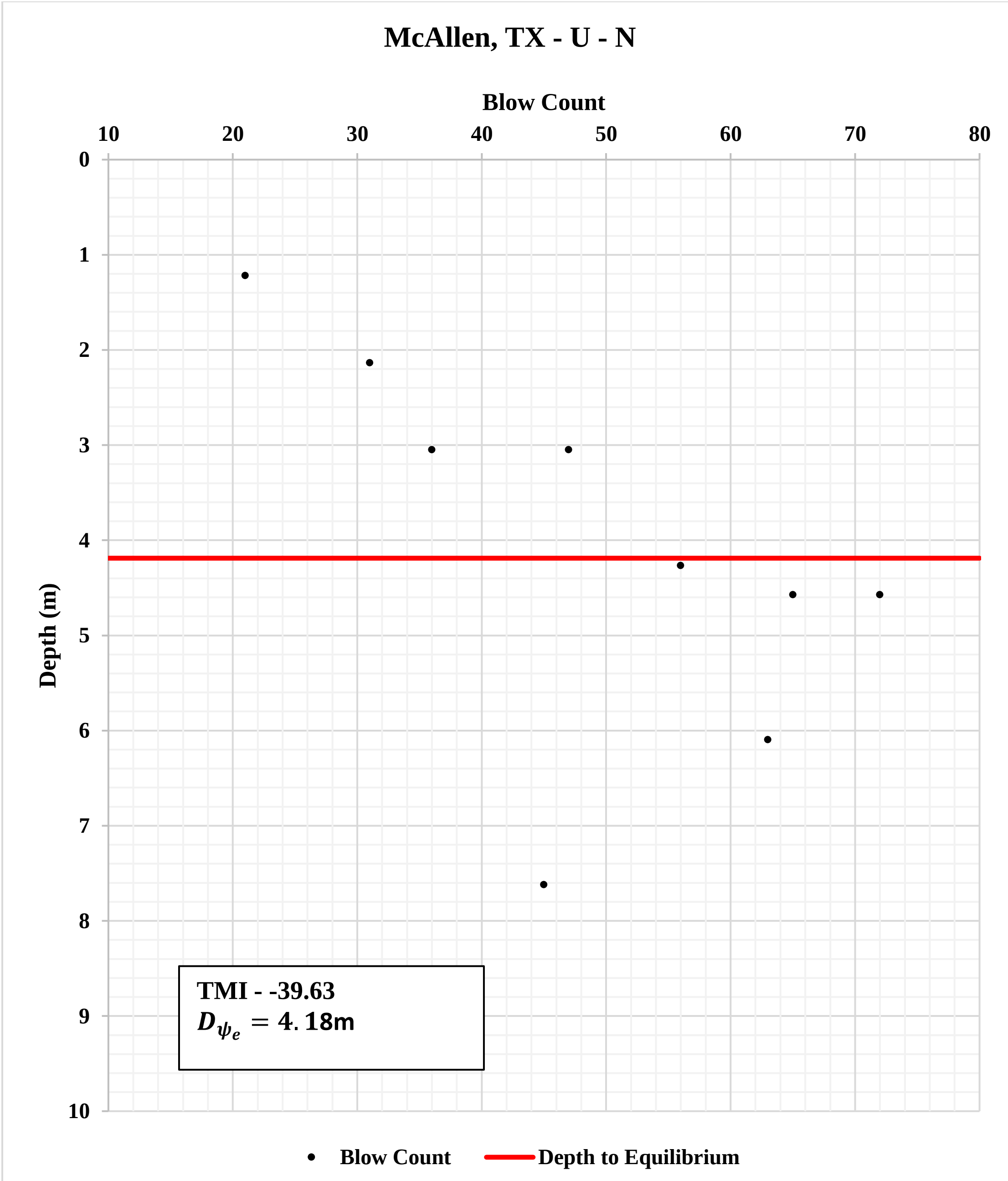


Figure 6.58: Blow Count Versus Depth at McAllen, TX Site

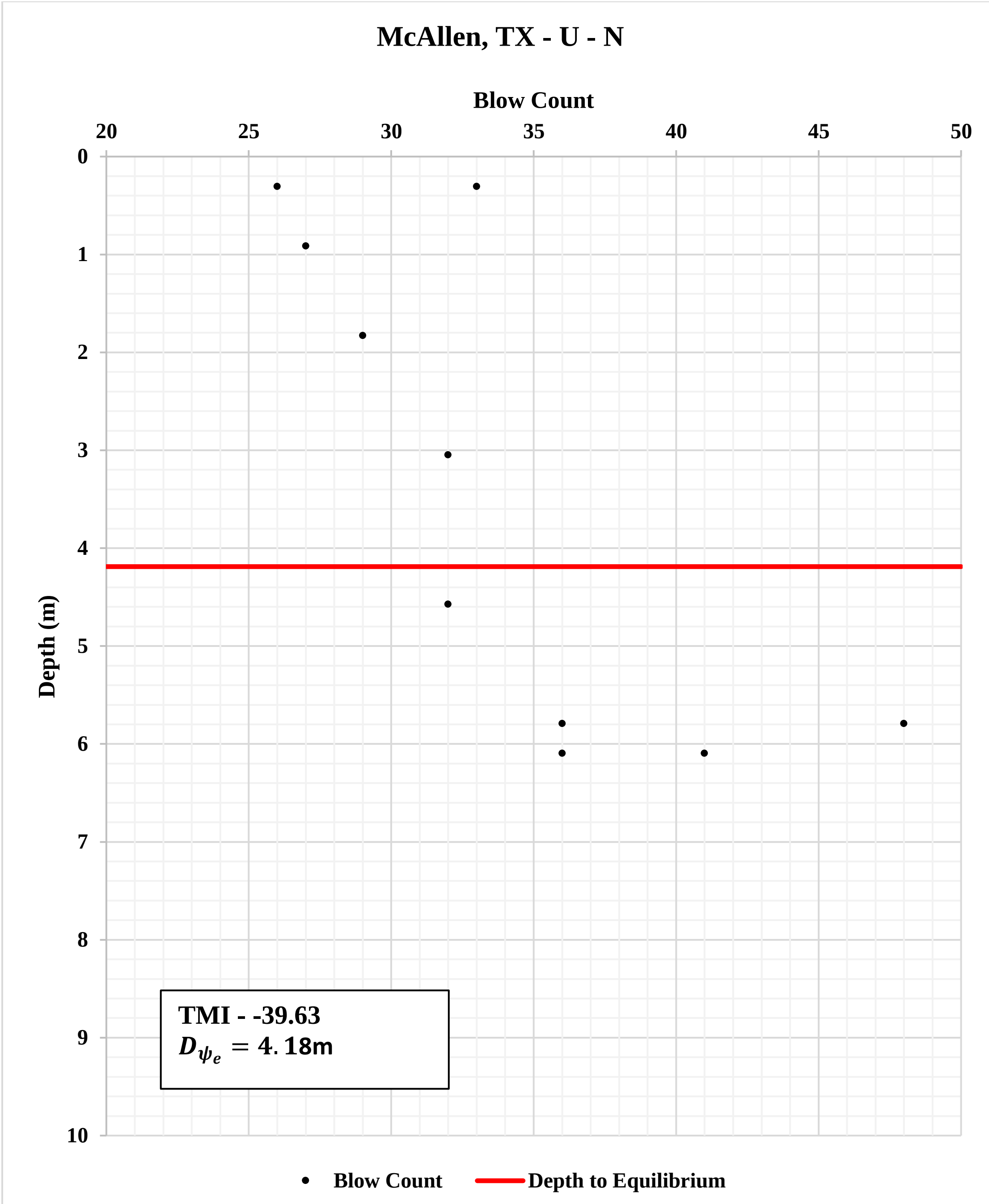


Figure 6.59: Blow Count Versus Depth at McAllen, TX Site

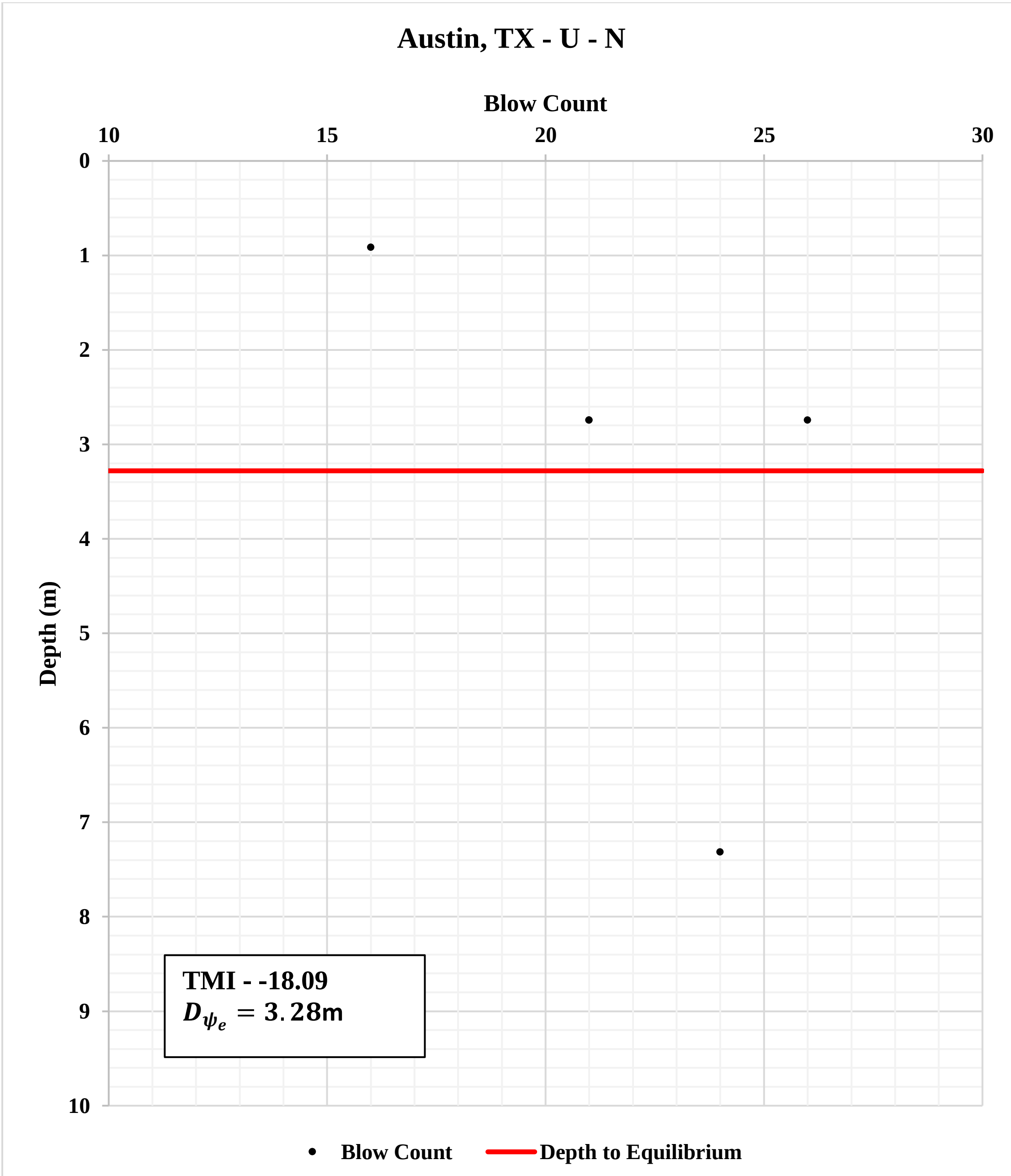


Figure 6.60:Blow Count Versus Depth at Austin, TX Site

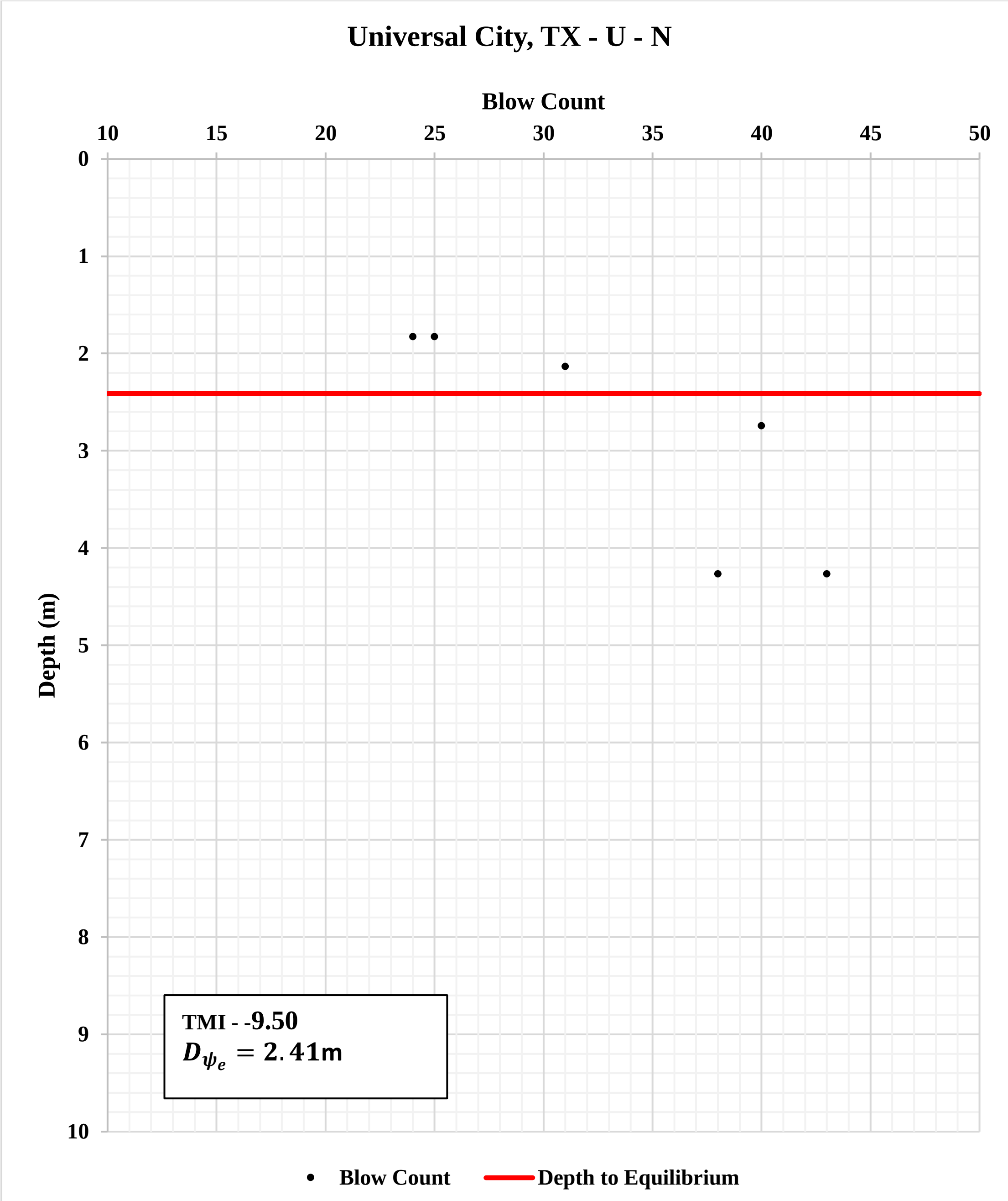


Figure 6.61: Blow Count Versus Depth at Universal City, TX Site

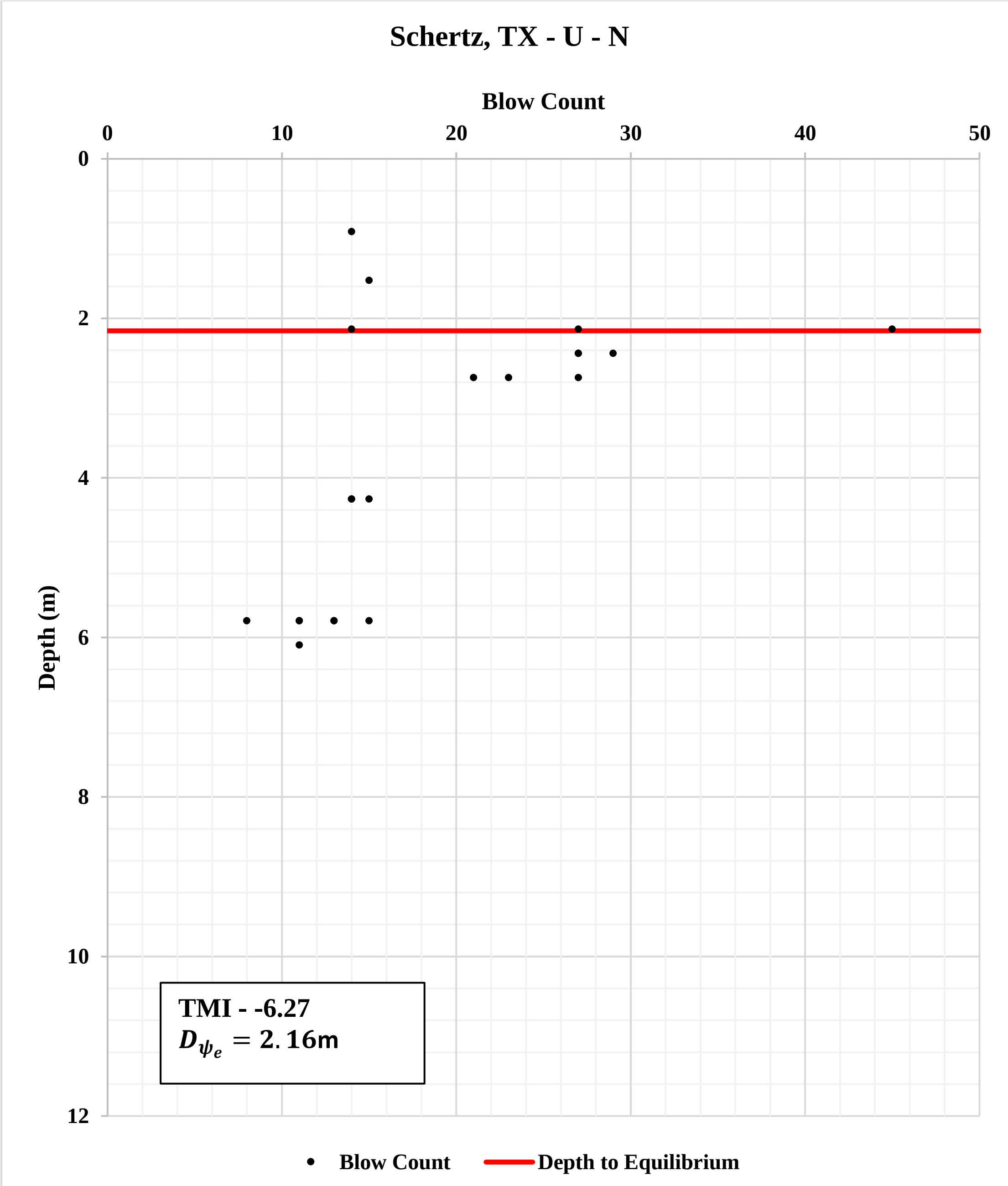


Figure 6.62: Blow Count Versus Depth at Schertz, TX Site

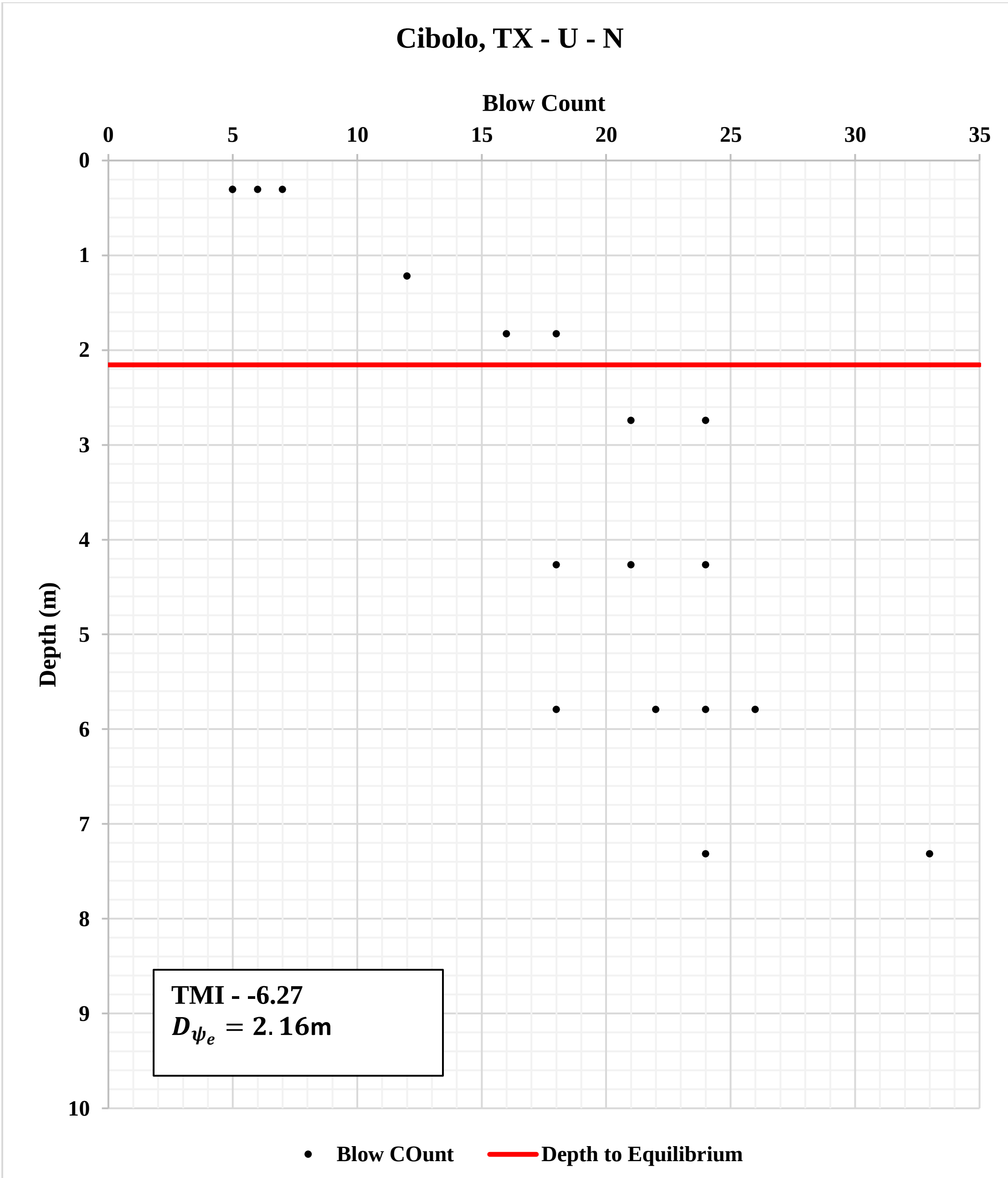


Figure 6.63: Blow Count Versus Depth at Cibolo, TX Site

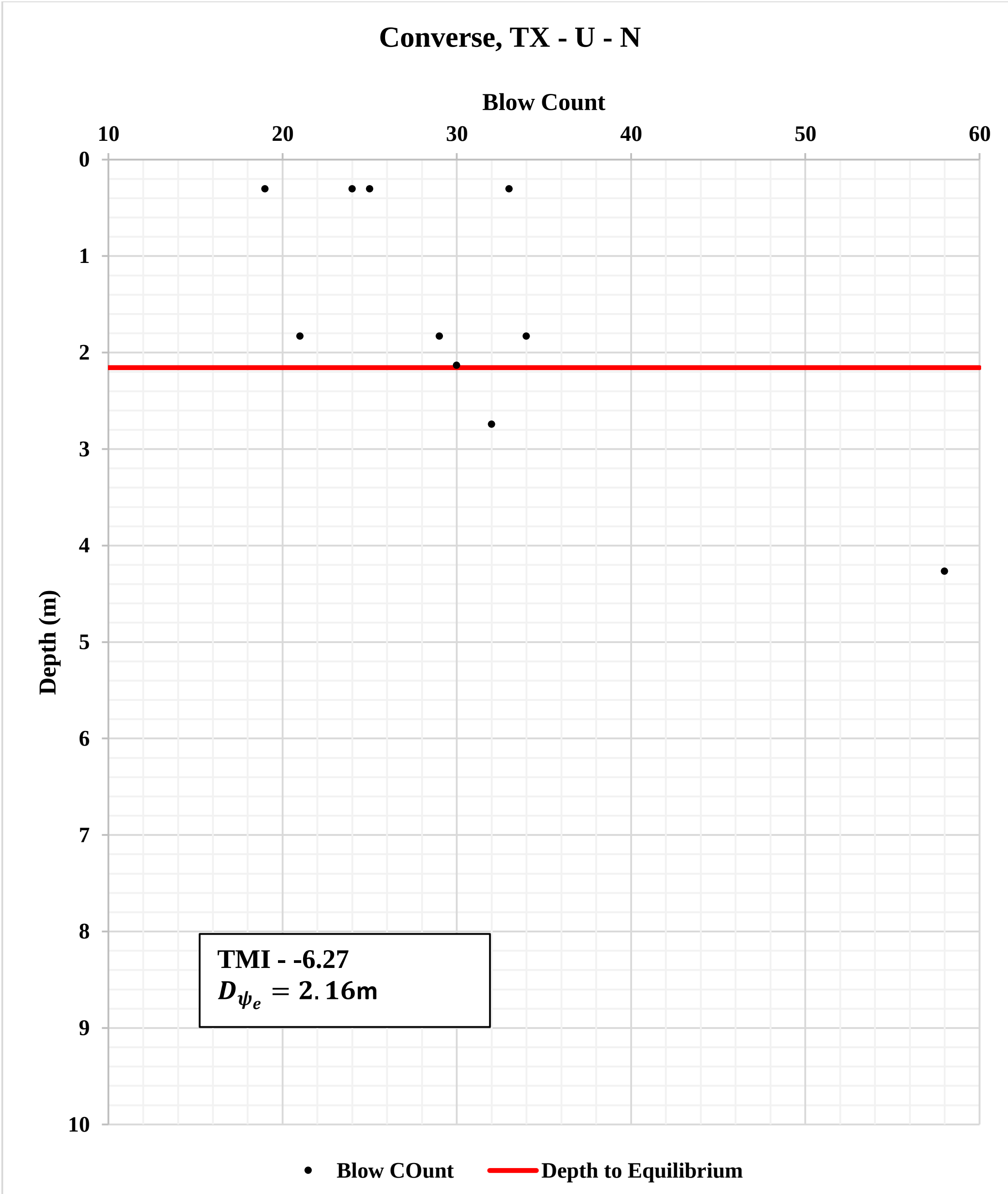


Figure 6.64: Blow Count Versus Depth at Converse, TX Site

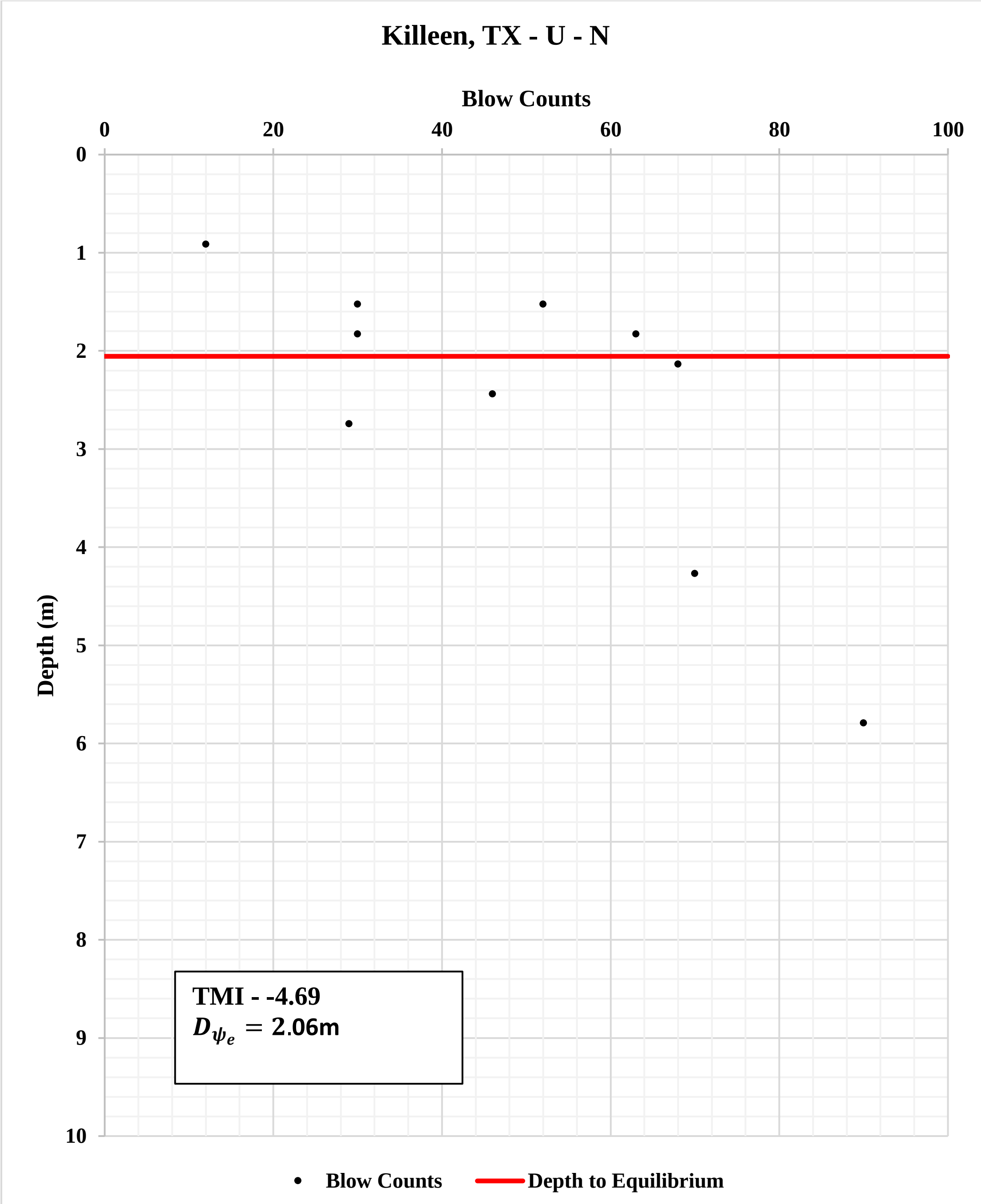


Figure 6.65: Blow Count Versus Depth at Killeen, TX Site

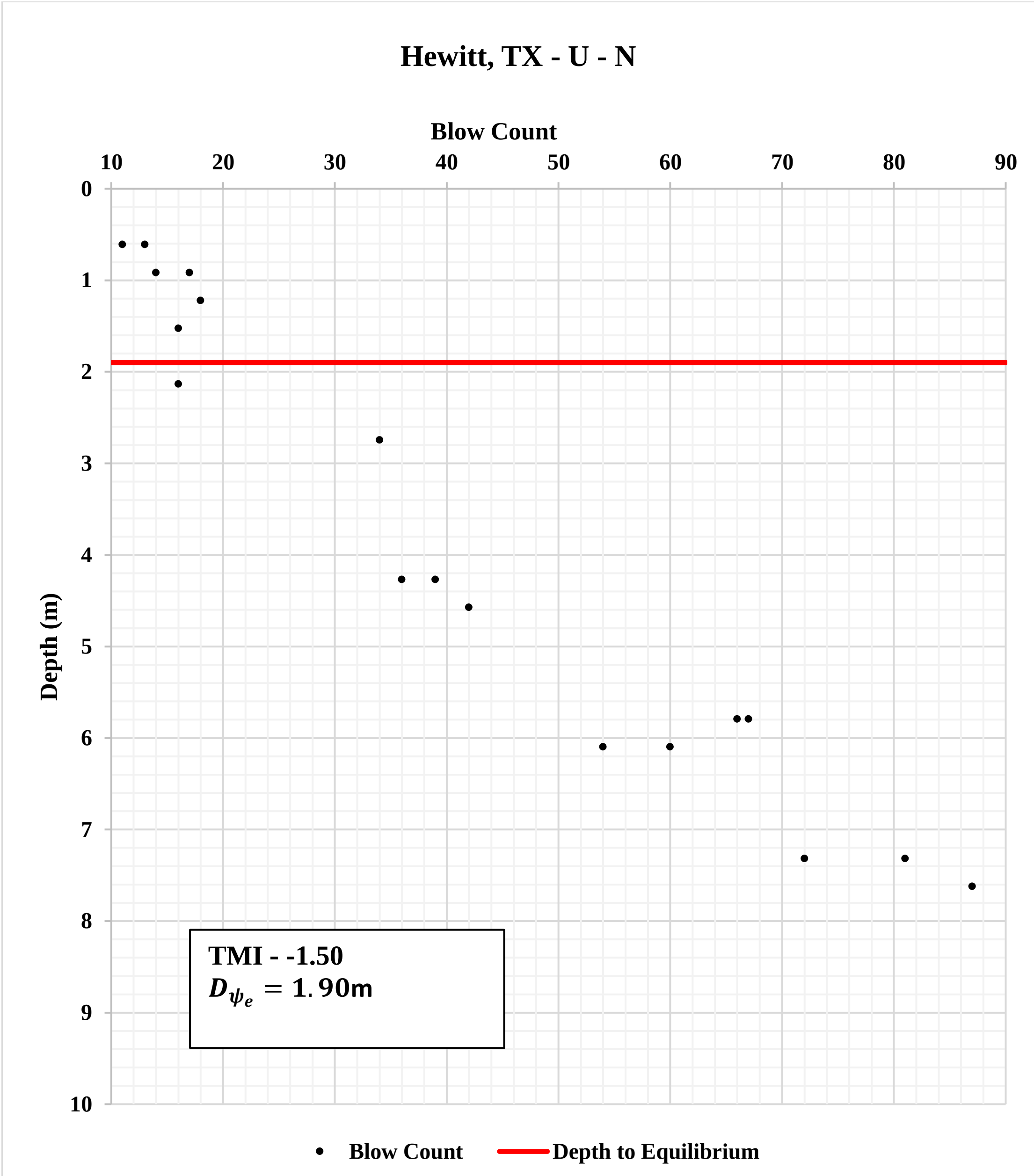


Figure 6.66: Blow Count Versus Depth at Hewitt, TX Site

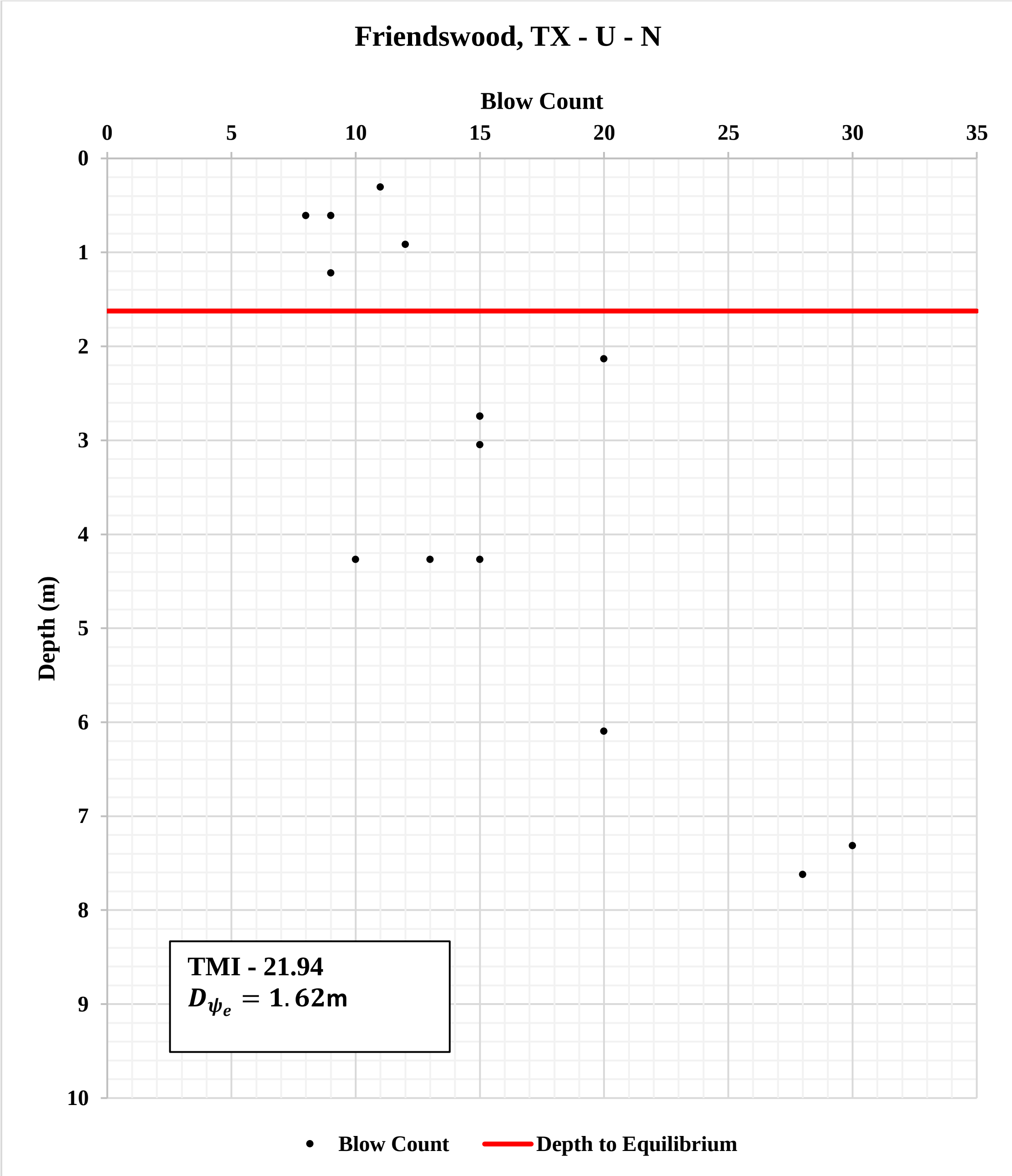


Figure 6.67: Blow Count Versus Depth at Friendswood, TX Site

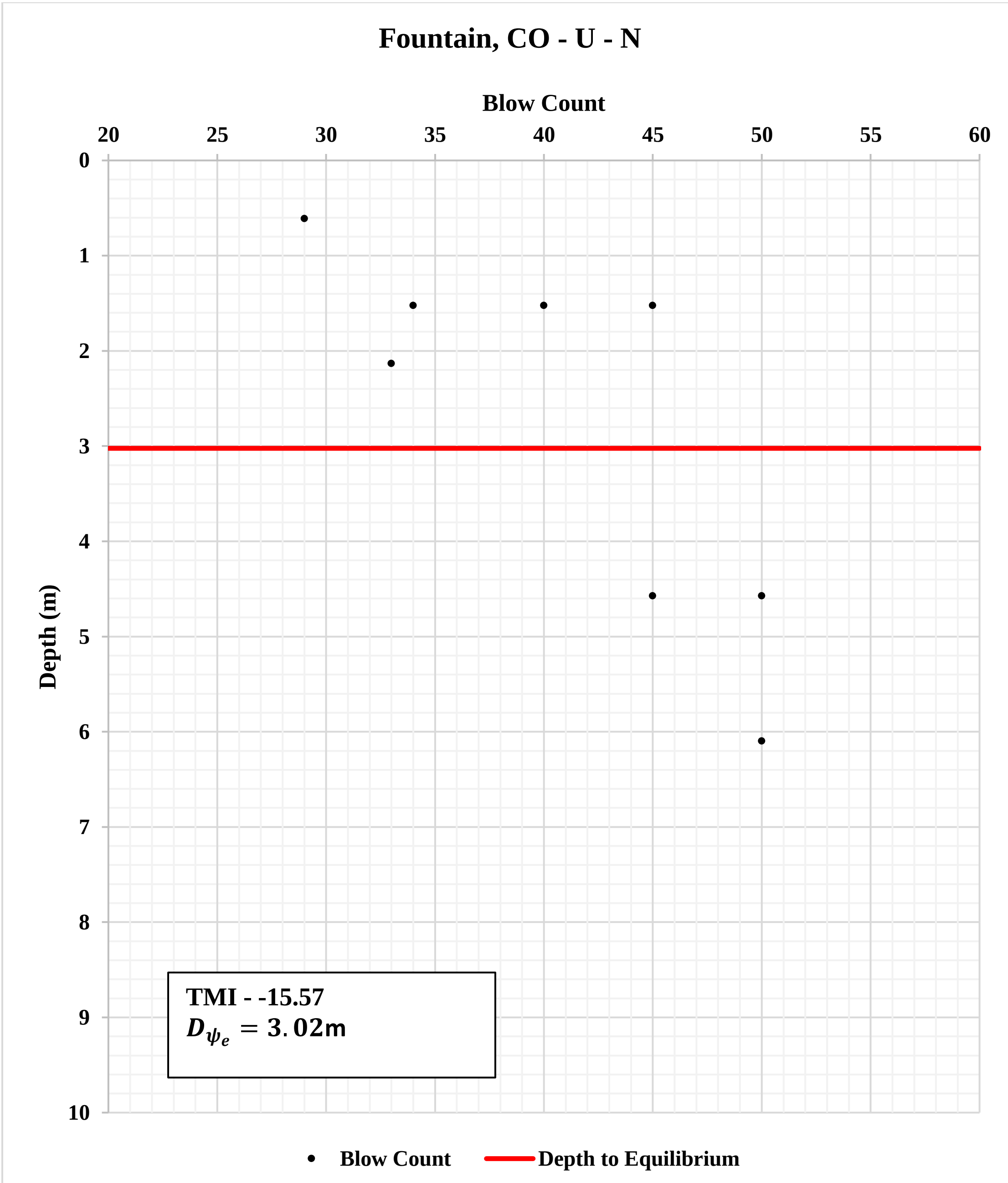


Figure 6.68: Blow Count Versus Depth at Fountain, CO Site

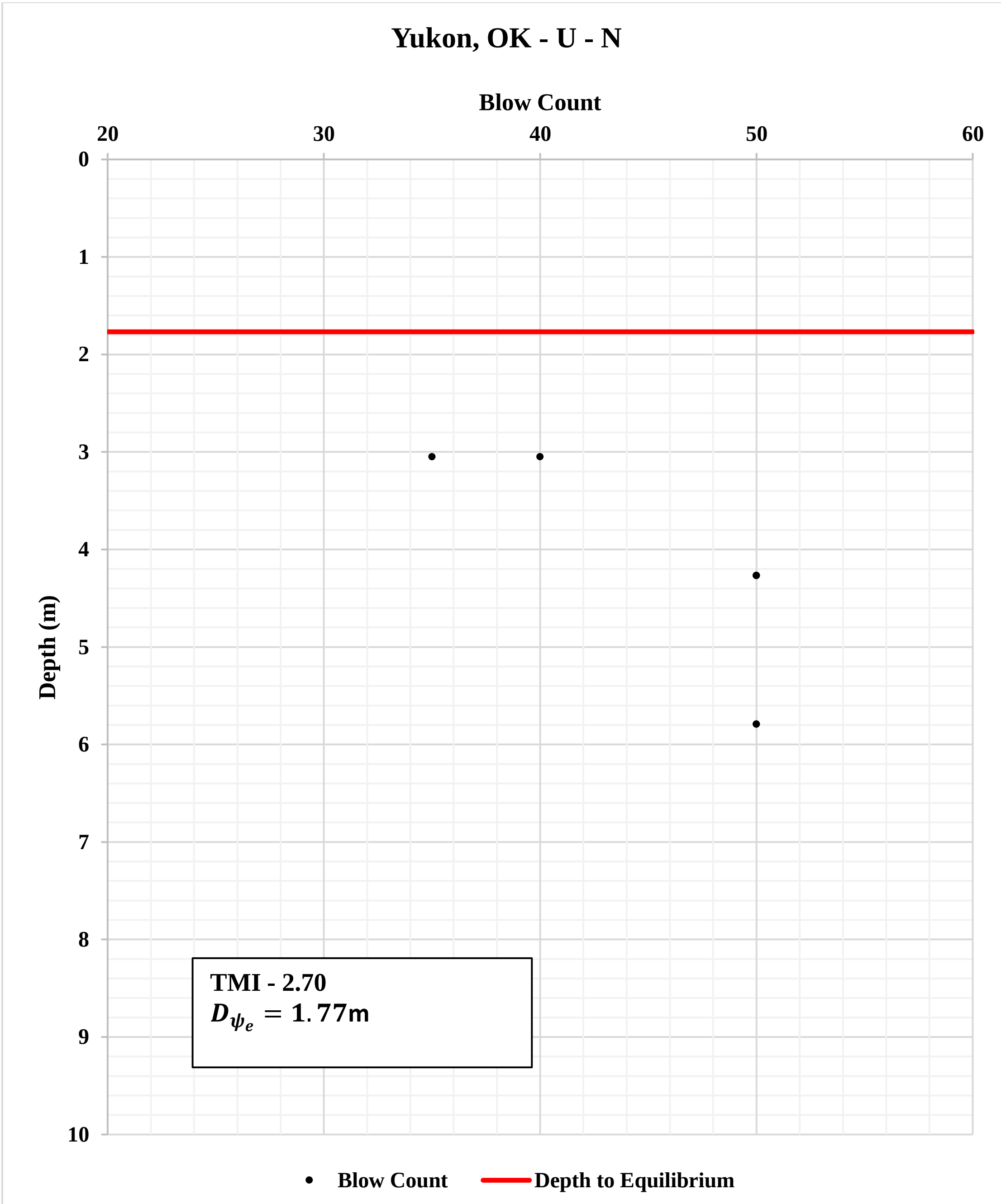


Figure 6.69: Blow Count Versus Depth at Yukon, OK Site

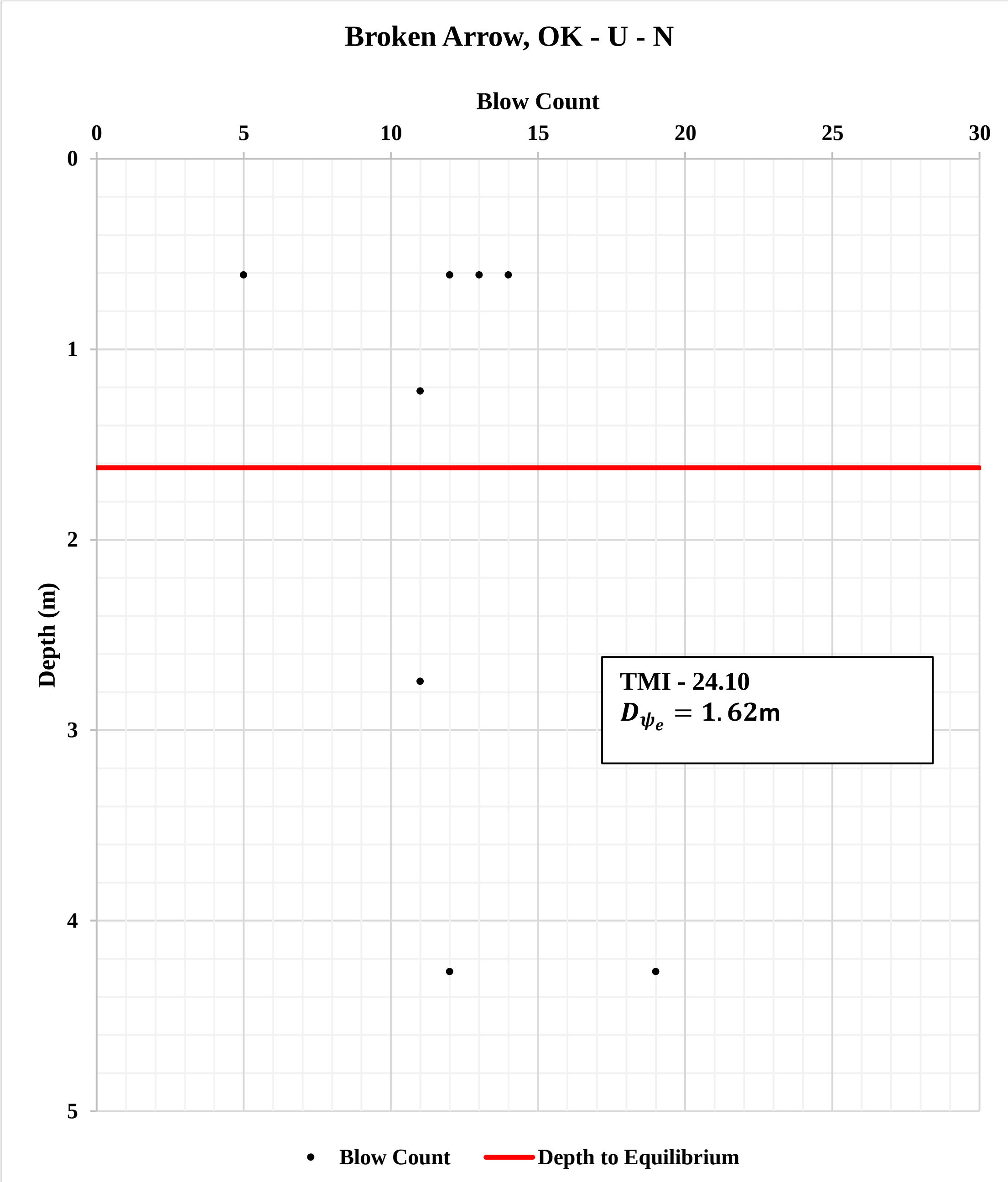


Figure 6.70: Blow Count Versus Depth at Broken Arrow, OK Site

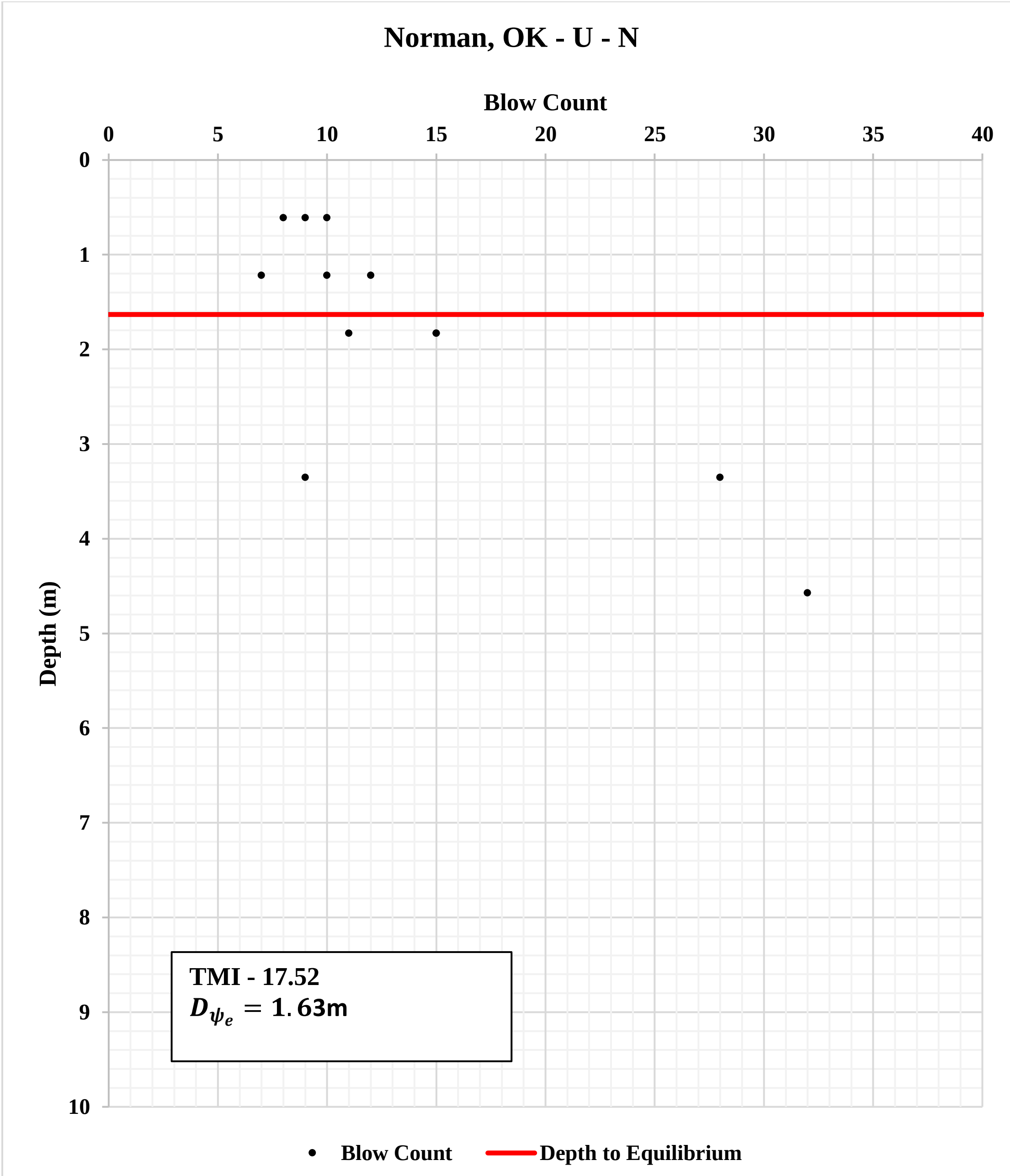


Figure 6.71: Blow Count Versus Depth at Norman, OK Site

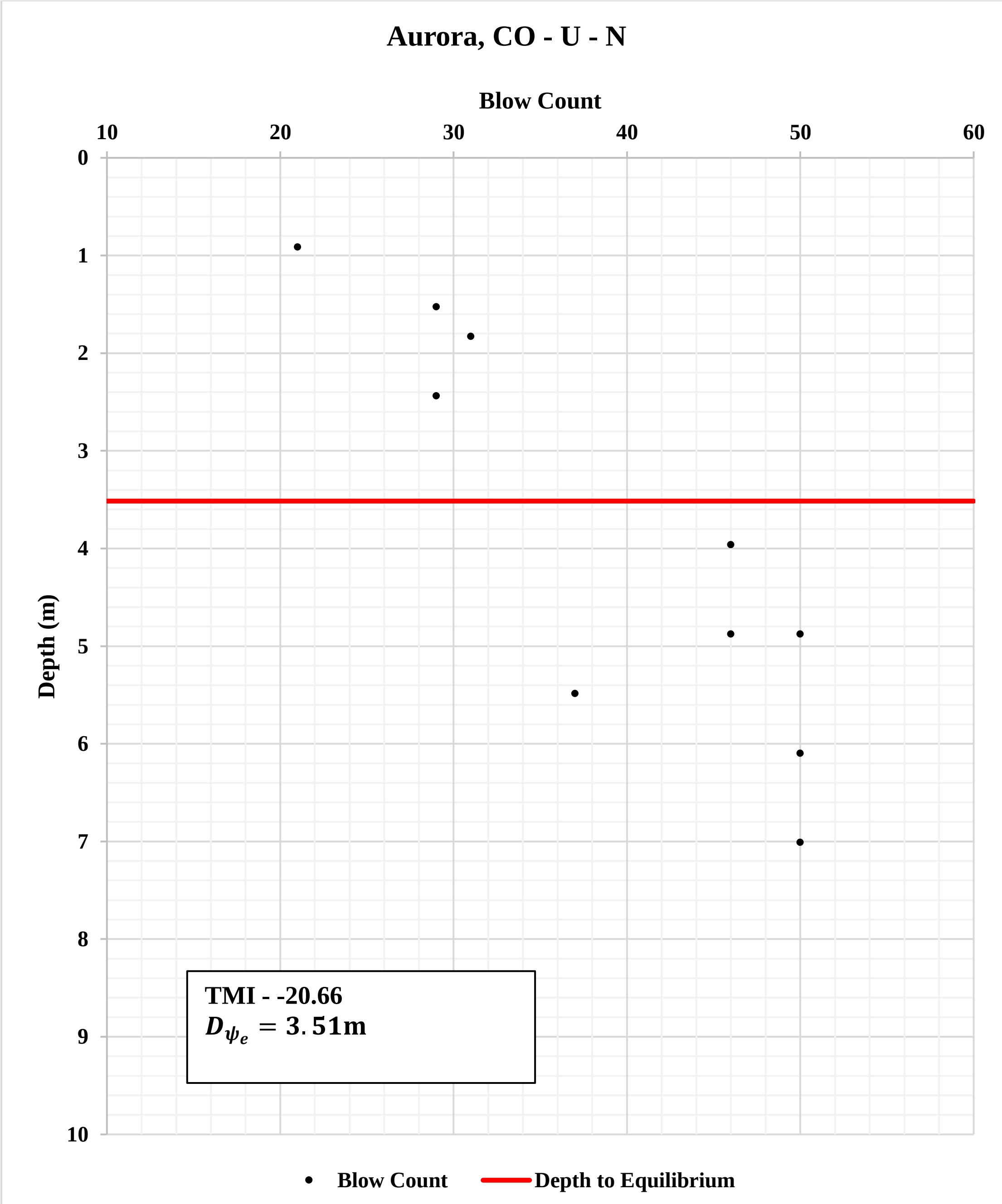


Figure 6.72: Blow Count Versus Depth at Aurora, CO Site

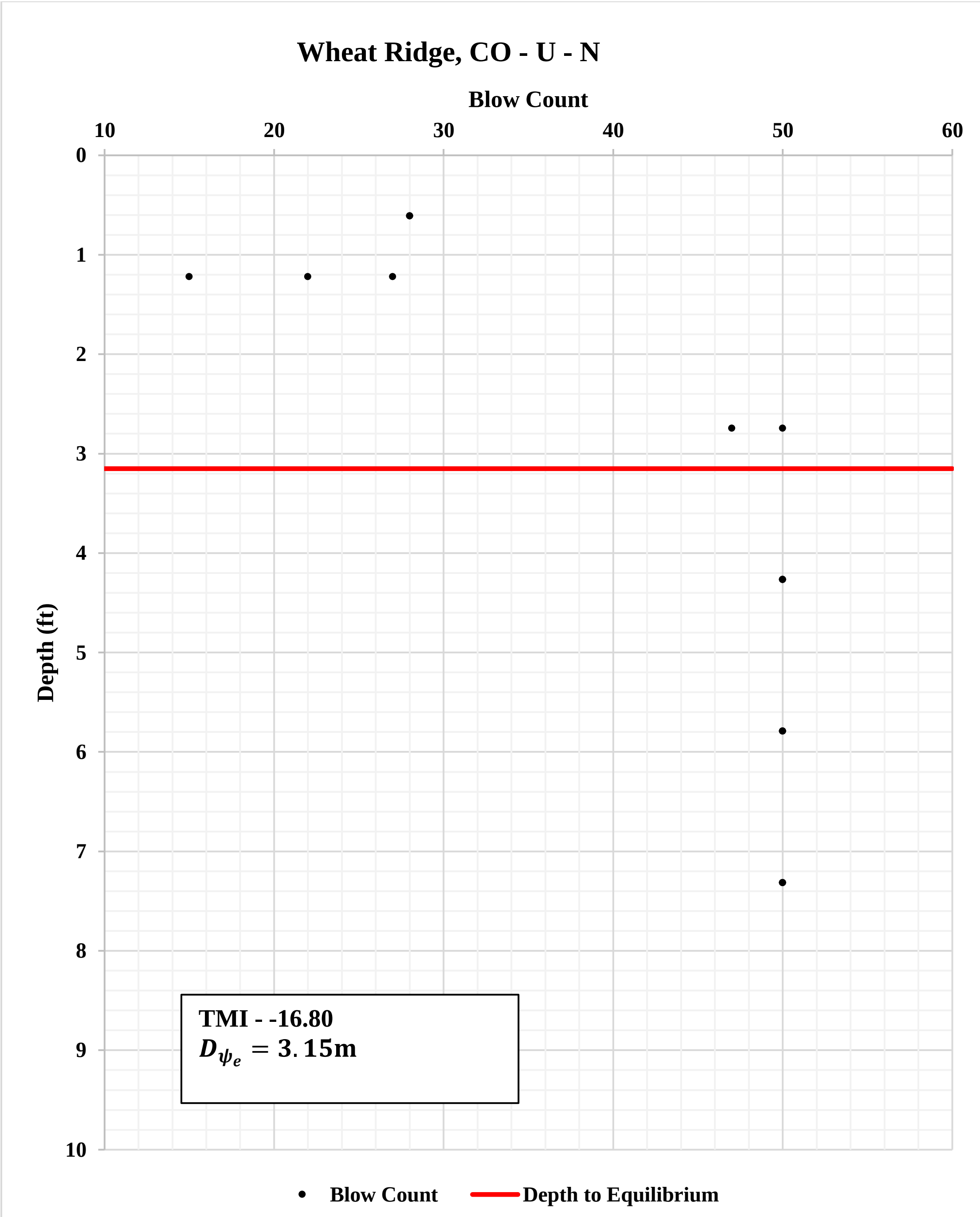


Figure 6.73: Blow Count Versus Depth at Wheat Ridge, CO Site

Based on a review of the blow count plots presented, they can be considered relatively low. The relatively low values suggest that in most cases the depth of wetting limit is a result of reaching a “pseudo equilibrium” state with the surface flux variations, e.g. arising from climatic conditions.

Two sites drilled as part of this research were also examined with respect to blow counts and depth; Denver and San Antonio. Figure 6.74 and Figure 6.75 demonstrate the blow counts versus depth for seven total test borings advanced in Denver and San Antonio.

The test borings were positioned in both covered, C, and uncovered, U, portions of the sites. Further, some borings were located in irrigated, I, and non-irrigated, N, environments.

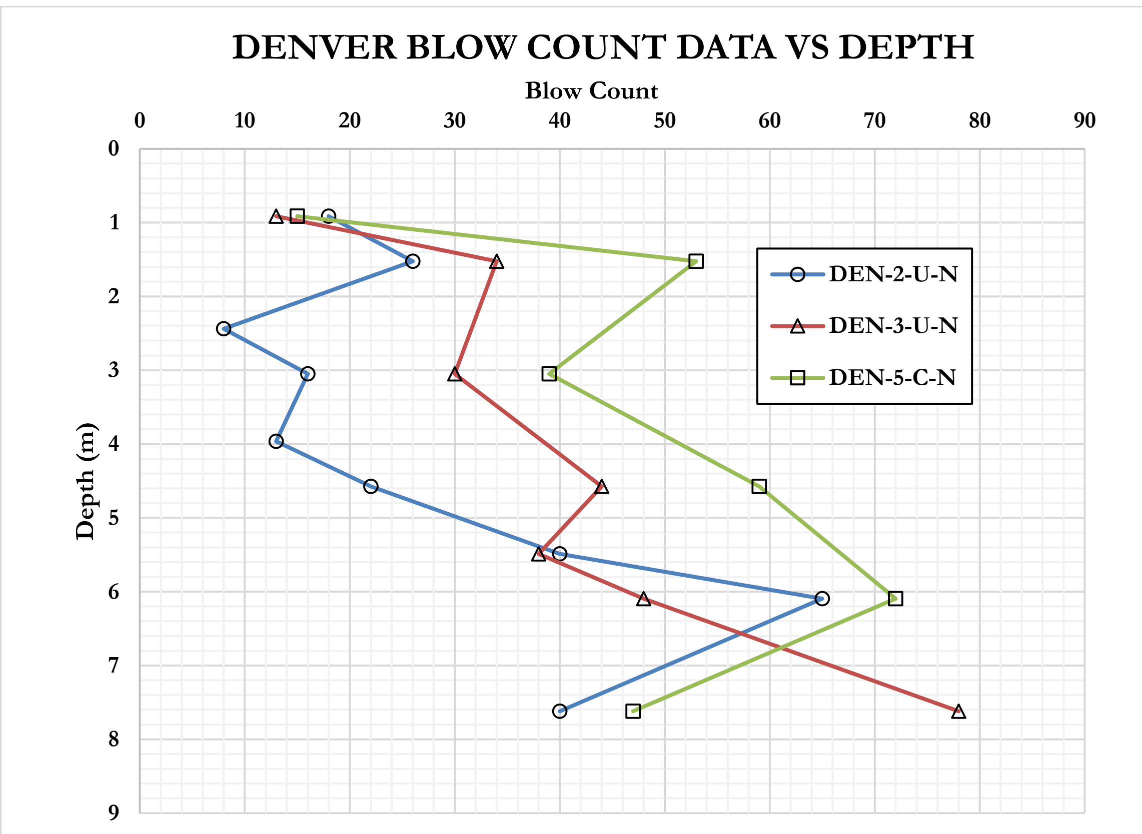


Figure 6.74: Blow Count Data for Three Test Borings at the Denver Research Site

The Denver research drill site suggests that the blow counts become somewhat consistently greater than 50 below an approximate depth of 20 feet. For the Denver area, in general, the depth to equilibrium suction is 3.0 to 3.5 m (9.84 to 11.48 ft), depending on soil classification as depicted in Figure 6.74. The blow count data considered for this study shows a consistent increase below 6.1 m (20 ft), suggesting that the relative blow counts above and below the predicted depth to equilibrium suction show no remarkable difference. Justification is provided that the predictive relationships for the depth to equilibrium suction presented herein are unaffected by a limiting condition attributed to blow count.

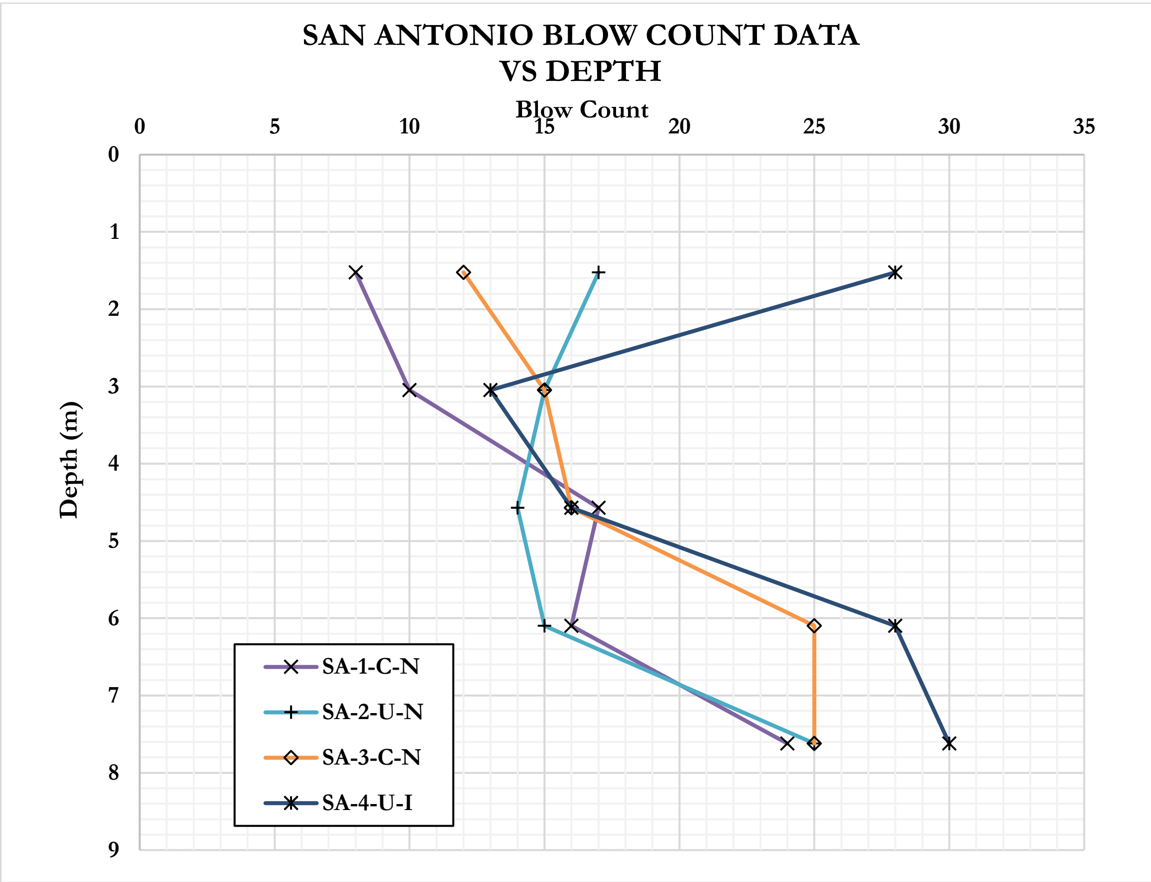


Figure 6.75: Blow Count Data for Four Test Borings at the San Antonio Research Site

The San Antonio research drill site suggests that the blow counts are unaffected by values greater than 50 to a depth of 25 feet below the existing site grade at the time of the test drilling.

6.3 Changes in Soil Suction at the Surface

From the literature review that follows, it is apparent most of the work that can be of use to practitioners has originated from researchers in Australia. Much lesser concern has been expressed in the USA, but that which has been expressed and researched has come from the Texas, Oklahoma and New Mexico sector. The methods that will be presented herein range from zone-wise classifications according to TMI to theoretical modeling to define the soil suction profiles. A great deal of credit goes to all researchers in search of the most appropriate method of determining the range in surface soil suction, referred to herein as $\Delta\psi\ (in\ pF\ units)$. Those that are concerned with climate change and the ramifications on the future modifications to the surface flux concept should be commended, because clearly the soil conditions in the future will not be as they are today. In this paper, the change in soil suction at the surface will be displayed in two fashions; Δu (from Australian nomenclature) and $\Delta\psi\ (in\ pF\ units)$.

6.3.1. Mitchell (1979 and 1980)

Mitchell (1979) developed a procedure to calculate foundation behavior on expansive clay soils through the use of the predicted soil suction variation. The soil suction variation is predicated on the use of the diffusion equation to calculate the vertical soil suction changes.

Mitchell (1980) worked on the premise that soil suction profiles resembled a trumpet shape. The trumpet shape concept such as that depicted in Figure 6.76 was instrumental in arriving at the potential heave of the expansive clay soils. Using the analysis, it is possible to consider a variety of soil suction profile shapes with depth, depending on the seasonal rainfall effects. Considering all of the seasons and associated climate attributes, it became possible to predict the theoretical range in soil suction that could occur at the surface, as well as the determination of the depth to constant or equilibrium soil suction.

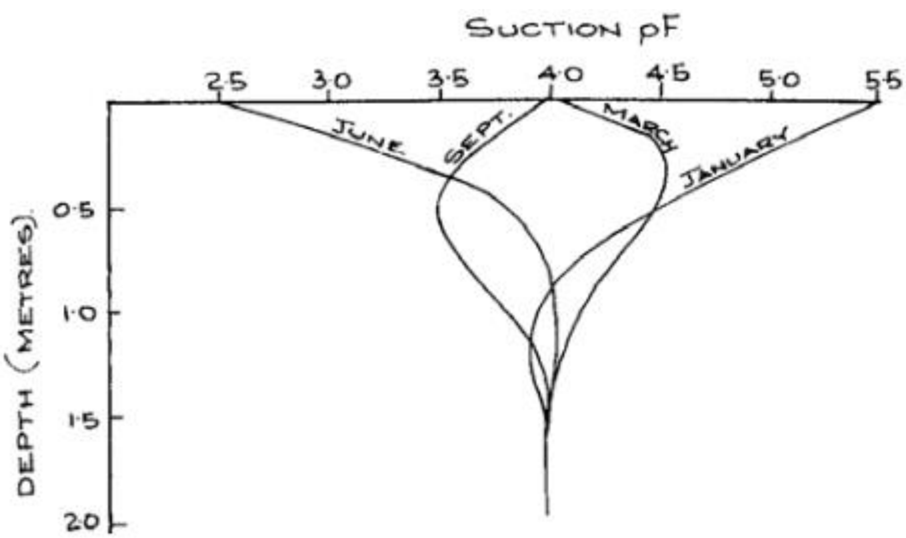


Figure 6.76: Theoretical Soil Suction Profiles as Presented by Mitchell, 1980

The one-dimensional solution for a periodic surface soil suction, developed by Mitchell (1979) varies in a sinusoidal manner in response to climate cycles. The Mitchell (1979) equation is presented as Equation (151).

$$u(y,t) = U_e - U_o exp\left\{-\left[\left(\frac{n\pi}{\alpha}\right)^{0.5}\right]y\right\} cos\left\{2n\pi t - \left[\left(\frac{n\pi}{\alpha}\right)^{0.5}\right]y\right\} \qquad (151)$$

Where,

$u(y, t)$ is the soil suction as a function of space, y, and time, t, in pF or kPa

U_e is the equilibrium soil suction below the active zone depth, in pF or kPa

U_o is the amplitude of the soil suction variation, in pF or kPa

n is the frequency number

α is the diffusion coefficient in cm^2/sec

t is the time coordinate in days

y is the space coordinate for depth in meters or feet

Further discussion regarding the Mitchell (1979 and 1980) work will be discussed in Section 6.4.

6.3.2. Wray (1989)

Wray (1989) investigated two sites with respect to season variations in connection with soil suction profiles. Amarillo and College Station, TX were of focus in the Wray (1989) research. Figure 6.77 and Figure 6.78 present soil suction profiles for the Amarillo and College Station sites that were obtained over a three-year period. Depths to equilibrium suction at the Amarillo site presented by Wray (1989) were 3.81 m (12.5 ft). In comparison, the depth to equilibrium suction as predicted by Equation (150) is 3.5 m (11.48 feet), and with a conservative S=0.3645 m, 3.86 m (12.66 ft).

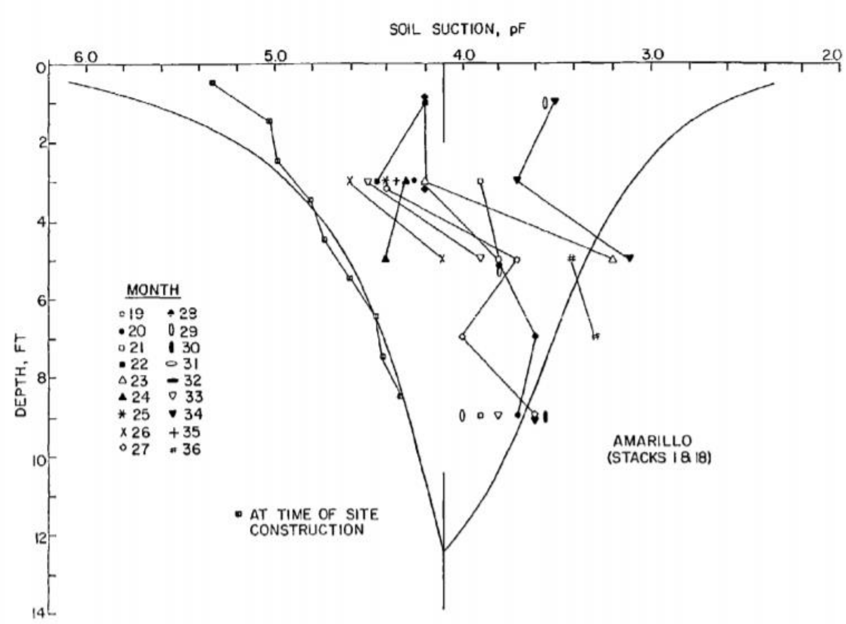


Figure 6.77: Seasonally Measured Soil Suction Profiles for Amarillo, TX Site (Wray, 1989) – Uncovered, TMI= -17.92, Equilibrium Suction=4.1 pF, Depth to Equilibrium Suction=3.5 m (11.48 ft to 12.63 ft) by Equation (150), Δψ (pF)=1.3 pF, ‘r’=0.46

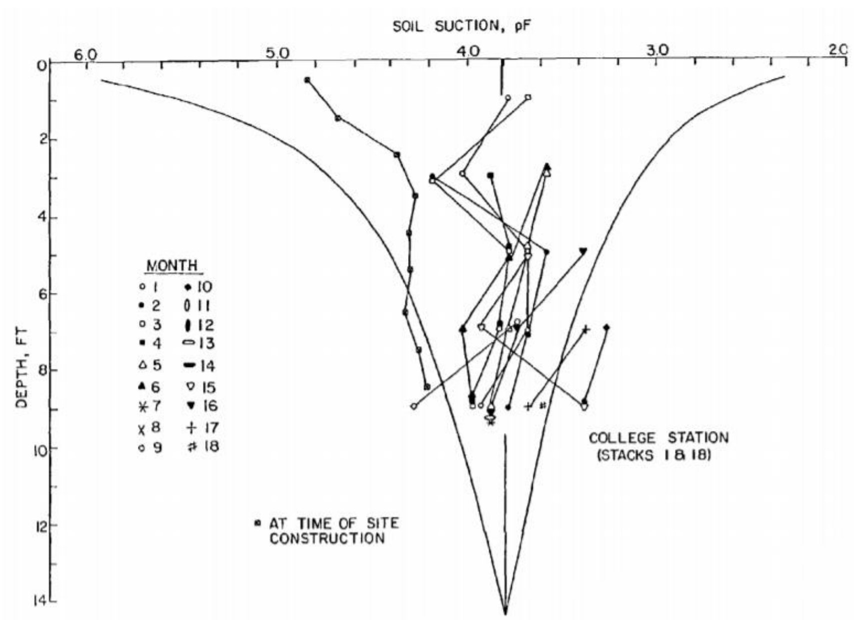


Figure 6.78: Seasonally Measured Soil Suction Profiles for College Station, TX Site (Wray, 1989) – Uncovered, TMI=8.89, Equilibrium Suction=3.8 pF, Depth to Equilibrium Suction=1.83 m (6.0 ft), Δψ (pF)=1.1 pF, ‘r’=0.36

Based on the Wray seasonally measured data, the change in soil suction at the surface is presented in Table 6.24.

Table 6.24: Determination of the Change in Suction at the Surface and Aubeny and Long ‘r’ Parameter for the Wray (1989) Amarillo and College Station, TX, Suction Profiles

Site	$\Delta\psi$ $(in\ pF\ units)$	Aubeny and Long (2007) ‘r’ Parameter
Amarillo, TX	1.3	0.46
College Station, TX	1.1	0.36

6.3.3. McKeen and Johnson (1990)

McKeen and Johnson (1990) provide a quantitative method of determining the active zone depth. The McKeen and Johnson (1990) work is in part based on the work of Mitchell (1979), Mitchell (1980) and McKeen (1981).

The basic character of the equation’s results is indicated in Figure 6.79 and Figure 6.80, with a sinusoidal variation with soil suction at the surface and an exponential decrease in the amplitude with depth. Figure 6.79 depicts the calculated soil suction variation with depth, while Figure 6.80 shows the calculated soil suction variation with time.

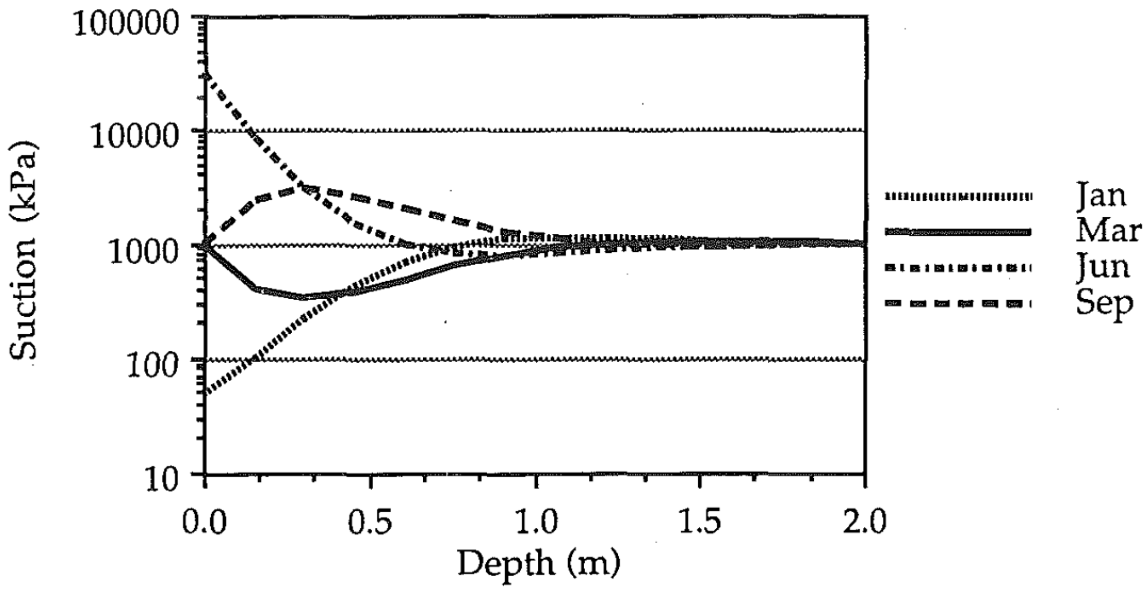


Figure 6.79: Example of the Calculated Soil suction Variation with Depth (McKeen and Johnson, 1990)

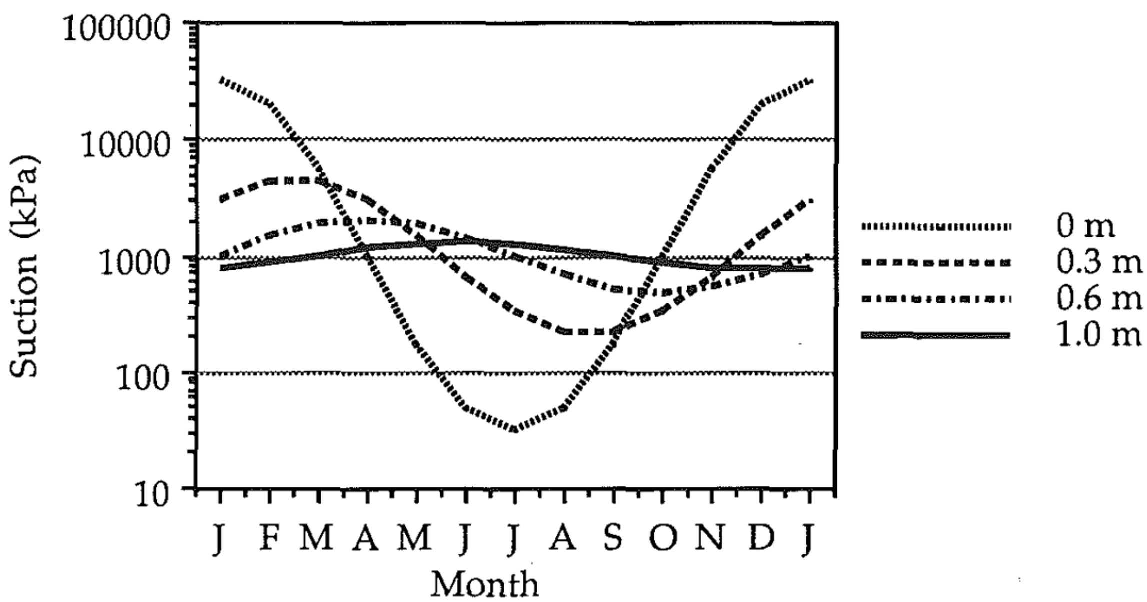


Figure 6.80: Example of the Calculated Soil suction Variation with Time (McKeen and Johnson, 1990)

Soil suction measurements obtained at various depths from the Dallas-Fort Worth (DFW) Airport at specific times were used to demonstrate the back-calculation procedure.

The surface soil suction was assumed to vary at the surface according to the form of Equation (152).

$$u(0,t) = sin(2n\pi t - p\pi)U_o + U_e \qquad (152)$$

Where;

p is a phase shift to match the point utilized to the commence the fitting process

McKeen and Johnson (1990) provide a recommended procedure for estimating the active zone depth and edge moisture penetration distance. The active zone is the depth at which the equilibrium soil suction will occur. As such, the phrase depth to constant soil suction or even H_s may be used. While a determination of the edge penetration distance is not a part of this study, the steps recommended will result in a determination of the value for the change in soil suction at the surface. Five of the six recommended steps are needed to arrive at the depth to constant soil suction and the minimum and maximum soil suction magnitudes at the surface arising from seasonal effects. The five steps are presented below:

1. Measure the plasticity index, clay content, cation exchange capacity, and soil suction of representative samples.

2. Based on the test results, estimate the inverse moisture characteristic (dh/dw) and the soil suction compression index (SCI) from procedures of McQueen and Miller (1968) or McKeen (1985). To develop soil properties, and specifically the SCI, from conventional soil tests:

   A. Data required for soil suction characterization is the Thornthwaite moisture index (TI), the inverse moisture characteristic *(dh/dw)*, and the soil suction compression index (SCI). Since these are not conventional soil parameters, their relation to more conventional data is of interest.

B. TI (or TMI) is determined.

C. The inverse moisture characteristic requires at least one soil suction measurement (McKeen, 1985).

D. The SCI may be measured (McKeen, 1985) or estimate using Figure 6.81 and Figure 6.82. The cation exchange capacity, CEC, may be determined using Equation (153).

$$CEC = \frac{(PL)^{1.17}}{C200} \tag{153}$$

Where,
CEC is the cation exchange capacity
PL is the plastic limit
C200 is the percentage of material passing the number 200 sieve that is finer than 2 μm in site, expressed as a percent

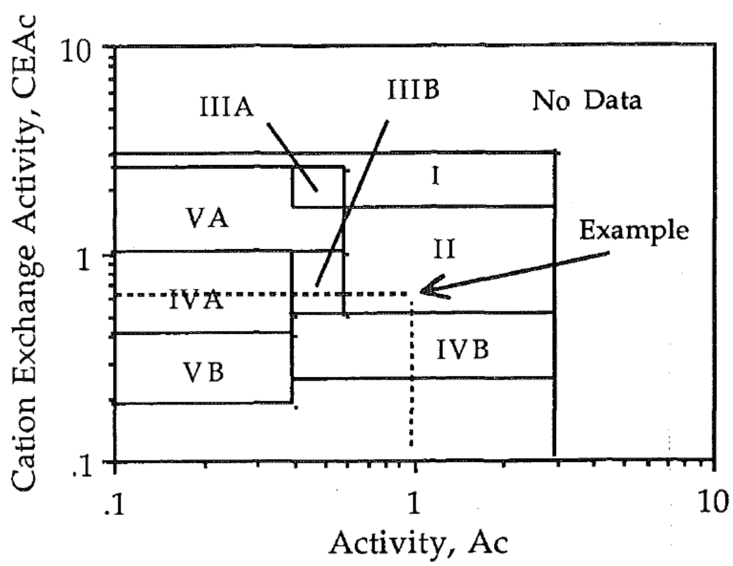


Figure 6.81: Chart for Predicting SCI (McKeen and Johnson, 1990)

Region (1)	SCI for C = 100% (2)	Percentage of Clay Fraction (% < 2 μm)			
		Smectite (3)	Illite (4)	Kaolinite (5)	Vermiculite (6)
I	0.220	>50	N	N	N
II	0.163	>50	Tr–25	Tr–25	N
IIIA	0.096	25–50	10–25	5–10	N
IIIB	0.096	5–50	5–25	Tr–25	N
IVA	0.061	Tr–10	5–25	5–50	N
IVB	0.061	<5	10–25	5–50	N
VA	0.033	N	Tr–25	5–50	Tr–25
VB	0.033	N	N	10–25	<5

Note: N = none; and Tr = trace or less than 5%.

Figure 6.82: Composition of Mineralogical Regions to Arrive at the SCI (McKeen and Johnson, 1990)

3. Estimate the field diffusion coefficient using Equation (154).

$$\alpha = b_o + b_1(TI) + b_2\left(\frac{dh}{dw}\right) + b_3(SCI) \tag{154}$$

Where,

α is the diffusion coefficient

b_o = 0.010134

b_1 = 0.000002

b_2 = 0.05468

b_3 = -0.03509

TI is the TMI

SCI is soil suction compression index

4. Establish criteria for determining the maximum allowable soil suction change below which the movement is considered to be insignificant.

5. Using Mitchell (1979) equation, calculate the minimum and maximum soil suction values for environmental conditions and determine the active zone depth at which the soil suction maintains equilibrium.

The maximum soil suction change and depth to constant soil suction can be accomplished by using the following equations in a spread sheet. The second equation estimates the seasonal active zone depth, or depth to constant soil suction. By using the diffusion coefficient for other wetting conditions, combined with n, Equation (155) can be utilized to investigate long-term wetting.

$$\Delta U_{max} = 2U_o exp\left[-\left(\frac{n\pi}{\alpha}\right)^{0.5}\right]y \tag{155}$$

Where;

ΔU_{max} is the maximum soil suction change; the difference between the maximum and minimum envelopes for a given depth

$$z = \frac{ln\left(\frac{2U_o}{\Delta U_{max}}\right)}{\sqrt{\frac{n\pi}{\alpha}}}$$

Where;

z is the seasonal active zone depth

McKeen and Johnson (1990) concludes that field determined coefficients can be used in estimating soil variation when used with the diffusion equation, soil suction-based parameters can be used to estimate the diffusion coefficient, and the climate cycle characteristics are important in estimating the moisture penetration into the soil profile with depth and predicting soil behavior.

6.3.4. AS2870-1996

Australian Standard (AS2870-1996) presented the recommended soil suction change profiles for specific locations. Figure 6.83 contains the Δu ($or\ \Delta\psi$) data for eleven cites across Australia. Extrapolation was permitted by practitioners to other areas not covered by the listing. As can be observed from Figure 6.83, a relatively uniform value of the change in soil suction at the surface of 1.2 pF covers all of the climate zones, except those areas that have been specifically evaluated to arrive at a Δu=1.5 pF, i.e. Hobart, Hunter Valley and Sydney.

Location	Change in suction at the soil surface (Δu) pF	Depth of design suction change (H_s) m
Adelaide	1.2	4.0
Albury/Wodonga	1.2	3.0
Brisbane/Ipswich	1.2	1.5–2.3 (See Note)
Hobart	1.5	2.0
Hunter Valley	1.5	2.0
Launceston	1.2	2.0
Melbourne	1.2	1.5 to 2.3 (See Note)
Newcastle/Gosford	1.5	1.5
Perth	1.2	3.0
Sydney	1.5	1.5
Toowoomba	1.2	1.8 to 2.3 (See Note)

NOTE: The variation in H_s depends largely on climatic variation.

Figure 6.83: Recommended Soil Suction Change Profiles for Certain Location (AS2870-1996)

6.3.5. PTI 2nd Edition (1996)

The 1996 version of the PTI design procedure called for soil suction testing to be performed on samples obtained from 0.61 m (2.0 ft) increments up to 2.44 m (8.0 ft) to determine both the magnitude of equilibrium soil suction and depth to constant soil suction. Of course, the current state of practice has changed significantly as we have learned the required depth to determine both values may be much greater than 2.44 m (8.0 ft). Relative to the range in soil suction values at the surface, the procedure was not completely defined.

6.3.6. Fityus et al. (1998)

Per Fityus, the surface change of soil suction $\Delta\psi$ $(in\ pF\ units)$ is generally found to be 1.2 pF but for Newcastle a value based on limited data has been adopted of 1.5 pF. Although, there is considerable case for changing the value of $\Delta\psi$ $(in\ pF\ units)$ to a value substantially less than 1.2 pF, which was outside the scope of the paper by Fityus et al. (1998).

6.3.7. Barnett and Kingsland (1999)

Based on AS2870-1996, Barnett and Kingsland (1999) restated that the Australian Standard characterized that design soil suction changes decreased linearly from a maximum value, Δu $(\Delta\psi\ in\ pF\ units)$, at the surface to zero at a depth corresponding to H_s. Below H_s the soil suction maintained at a constant equilibrium value. Scatter plots of soil suction versus depth were analyzed for Climate Zones 2 through 5. Through interpretation of plotted soil suction versus depth data, the equilibrium magnitude was identified. Further, an inverted triangle shaped envelope was drawn to provide a boundary of the high-data point frequency, which was followed by development of an apex of the triangle that was defined as the depth to the design soil suction change, H_s. Using data from four climate zones, the Hs, $\Delta\psi$ $(in\ pF\ units)$, and the magnitude of equilibrium soil suction, ψ_e was presented as indicated in Table 6.25.

Table 6.25: Determination of Hs, $\Delta\psi$ $(in\ pF\ units)$ and ψ_e for Four Climate Zones in Australia (Barnett and Kingsland, 1999)

Classification	**TMI**	**Climatic Zone**	**Hs (or $\Delta\psi_{d_e}$) m (ft)**	$\Delta\psi$ $(in\ pF\ units)$	ψ_e **(Magnitude of Equilibrium Soil suction)**
Wet Coastal / Alpine	>40	1	-	-	-
Wet Temperate	10 to 40	2	1.8 to 2.0 (5.91 to 6.56)	1.5	3.8
Temperate	-5 to 10	3	2.3 (7.55)	1.2 to 1.5	4.1
Dry Temperate	-25 to -5	4	3.0 (9.84)	1.2 to 1.5	4.2
Semi-arid	<-25	5	4.0 (13.12)	1.5 to 1.8	4.4

Table 6.25 was used to arrive at a TMI contour map of New South Wales (NSW). Suction profiles using measured data to formulate Table 6.25 are shown in Figure 6.84.

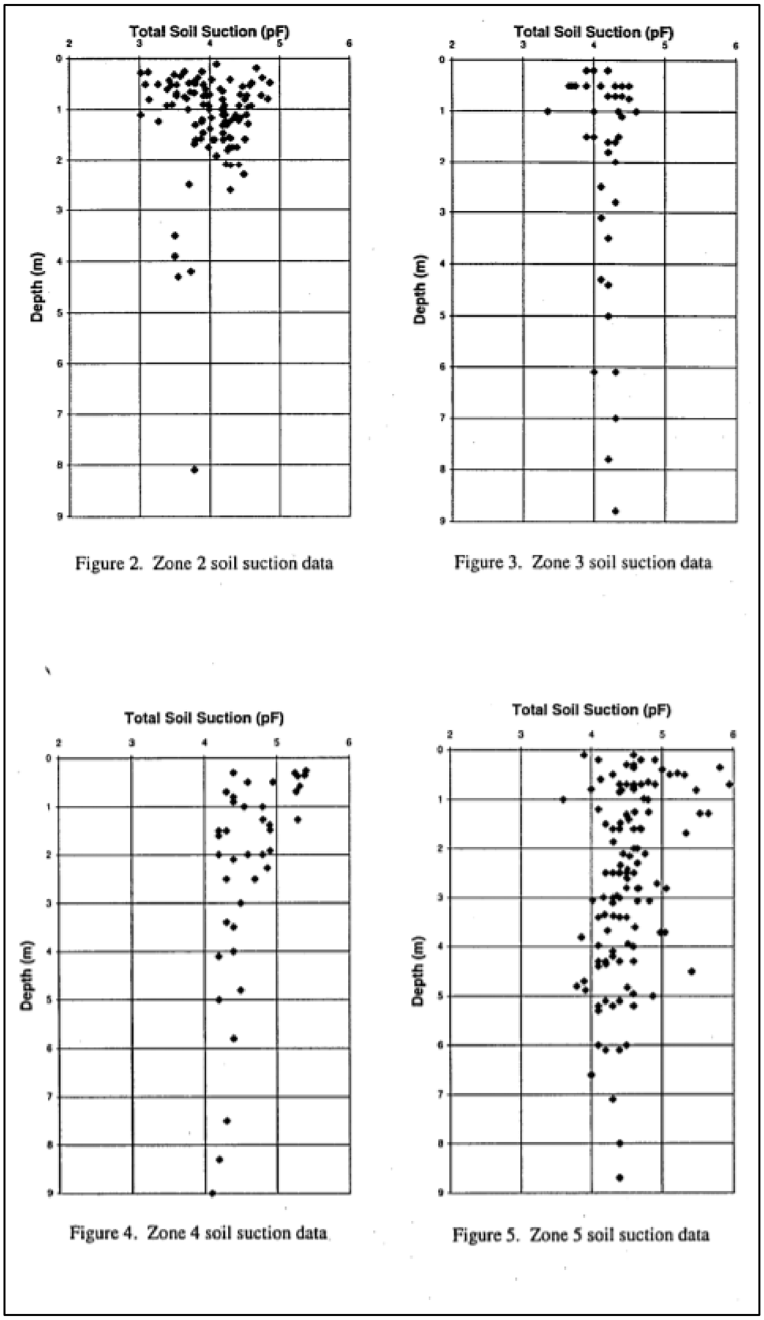


Figure 6.84: Soil Suction Profiles for Four Climate Regions in Australia (Barnett and Kingsland, 1999)

6.3.8. Fox (2000)

Fox (2000) presented Figure 6.85, which was a restatement of a figure from AS2870-1996. The figure shows the accepted Δu=1.2 pF. While the design surface soil suction change,

Δu, is was typically assumed to be 1.2 pF throughout Queensland, Fox (2000) suggested that local practice does vary, and further research was encouraged.

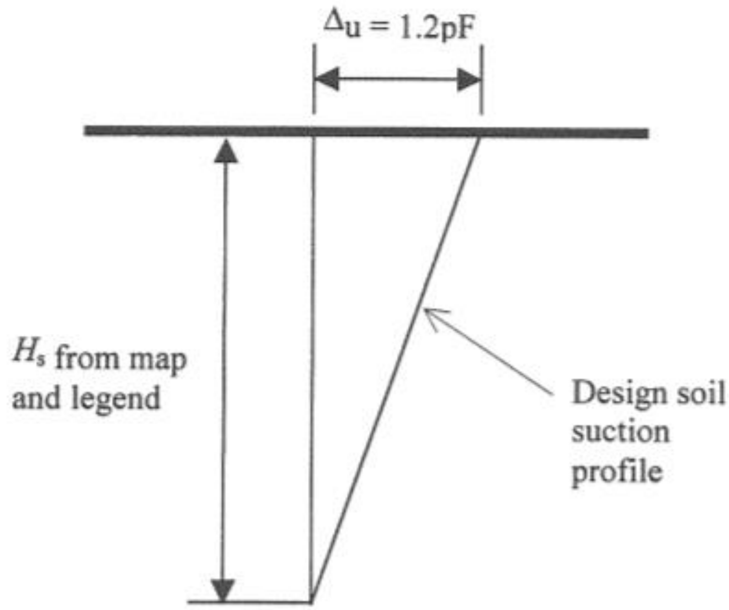


Figure 6.85: Soil Suction Profile (Fox, 2000)

6.3.9. PTI 3rd Edition (2004 and 2008)

The PTI 3rd Edition (2008) states that the typical low or minimum value of soil suction in the wettest condition is 3.0 pF. Conversely, 4.5 pF is the typical high value for the driest condition. However, a value of 6.0 pF may be possible as an extreme upper bound that could result from long-term sunbaked bare ground. The worst-case scenario of 6.0 pF is not recommended for design.

The recommended variation of soil suction at the surface, $\Delta\psi\ (in\ pF\ units)$, is 1.5 pF, which should be utilized for design purposes. A limitation on use of the 1.5 pF surface soil suction change is climate rated to the range of TMI +15 to TMI -15. A post-construction case assumes that that the swell is calculated from the extreme dry profile to the extreme wet profile, i.e. 1.5 pF. The method further states that unless there is compelling evidence as a result of a geotechnical analysis to the contrary of the dry to wet variation swing, the 1.5 pF value is warranted.

6.3.10. McManus et al. (2004)

As presented earlier, McManus et al. (2004) presented proposed change in soil suction values for the Australian climate zones as shown in Table 6.26.

Table 6.26: McManus et al. (2004) Proposed Surface Soil Suction Variation and Moisture Variation Depth

Climate	**Zone**	**Soil Suction Range (pF)**	**Change in Surface Soil Suction, $\Delta\psi$ ($in\ pF\ units$)**	**Moisture Variation Depth H_s m (ft)**
Alpine / Wet Coastal	1	2.5 to 3.5	1.0	1.5 (4.92)
Wet Temperate	2	2.8 to 4.0	1.2	1.8 (5.91)
Temperate	3	3.0 to 4.2	1.2	2.3 (7.55)
Dry Temperate	4	3.5 to 4.7	1.2	3.0 (9.84)
Semi-Arid	5	4.0 to 5.0	1.0	4.0 (13.12)
Semi-Arid Flood Prone	5	3.5 to 5.0	1.5	4.0 (13.12)
Arid	6	4.0 to 5.0	1.0	6.0 (19.68)
Arid Flood Prone	6	3.5 to 5.0	1.5	6.0 (19.68)

6.3.11. Fityus, Smith & Allman (2004)

The study and results by McKeen and Johnson (1990) were employed to arrive at an estimate of the active heave depth for Maryland, a suburb of Newcastle, NSW, in the range of 1.6 to 1.7 m (5.25 to 5.58 ft). The estimated depth is slightly higher that the measured soil suction data depth to moisture change / constant soil suction of 1.3 m (4.27 feet). Even so, the estimated depth range was consistent with the value of 1.6 m (5.25 feet) as indicated by gravimetric and neutron problem water content measurements, and the value of 1.5 to 2.0 m (4.92 to 6.56 feet) as indicated by the measurements of ground movements. The result was that TMI, equal to about +25, was an adequate predictor of the active depth in the Maryland region.

Fityus, Smith and Allman (2004) concluded through a 7-year study (5 years of measured data) of a site roughly 14 km from the Newcastle central business area that the design soil suction changes as suggested by AS2870-1996 in connection with the calculation of open ground movement. AS2870-1996 suggests 1.5 pF as the value of open ground soil suction change at the surface. The results of the study stated that as much 2.0 pF surface soil change is commonly assumed for the Maryland, Newcastle region. According to the study, the measurements of soil suction at the surface ranged from 3.2 pF to 5.2 pF in the topsoil layer (250 mm thick). Discounting the topsoil layer, the range in soil suction at the surface of the clay layer is 3.6 pF to 4.7 pF in the uppermost portion of the clay layer beneath the topsoil. Figure 6.86 presents the soil suction versus depth profile for the study area, which indicates a change in suction at the surface equal to 1.1 pF.

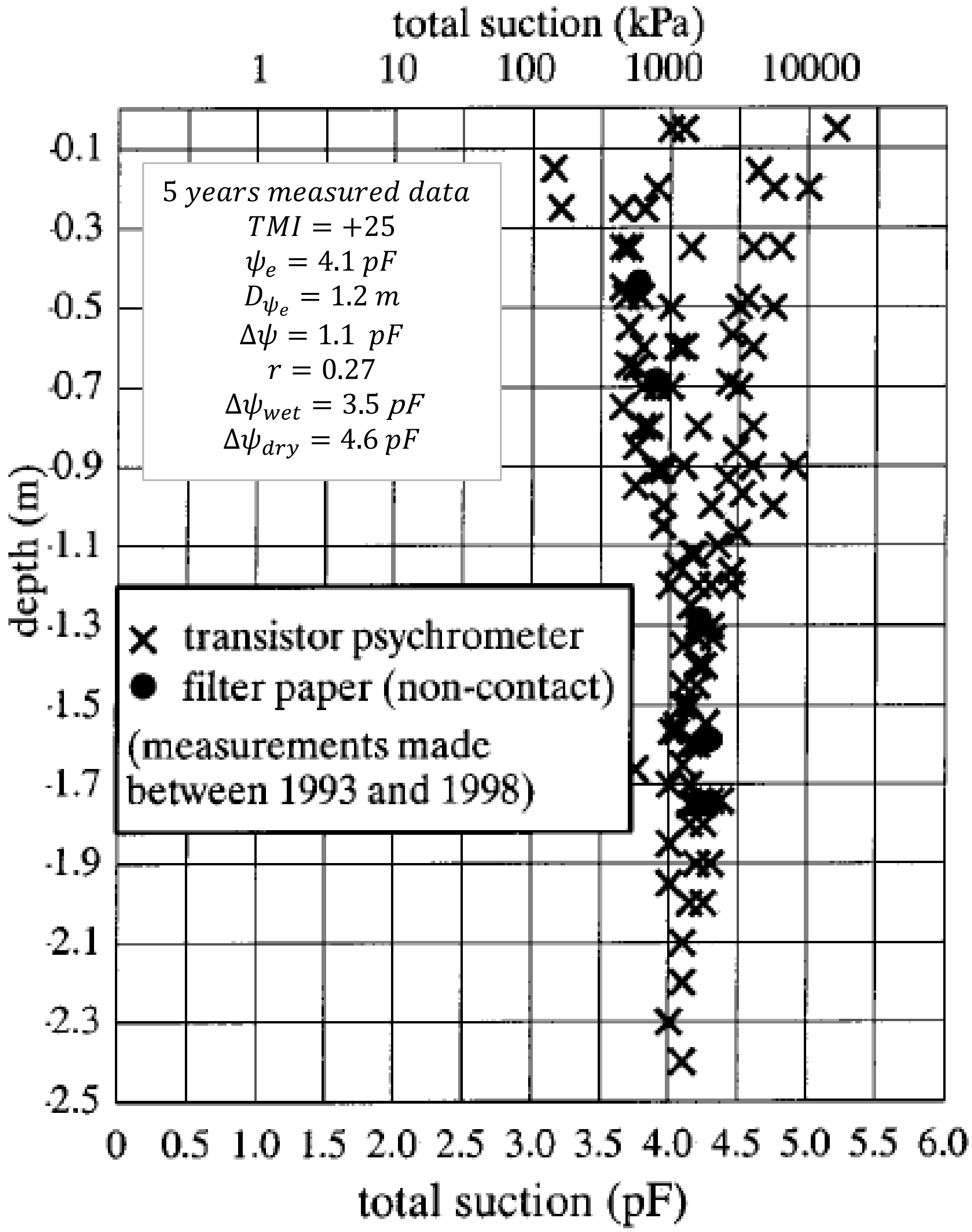


Figure 6.86: Soil Suction Versus Depth for the Maryland, New Castle, NSW Study Area (Fityus, Smith and Allman, 2004)

6.3.12. Aubeny and Long (2007)

In contrast to the McKeen and Johnson (1990) methodology that considered only sinusoidal variations in surface soil suction, the Aubeny and Long (2007) method extends the concepts of McKeen and Johnson (1990) to include non-sinusoidal soil suction variations. The non-sinusoidal variations are obtained using Fourier methods that can provide a more realistic pattern of predicted soil suction variations with depth. The variations in soil suction can attribute to a single diffusion coefficient, α, which is defined in the context of the analytical framework of McKeen and Johnson (1990).

Asymmetric soil suction envelopes can be predicted using two terms, U_o and U_e, where U_e is the average of the wet and dry cycle extremes, U_{wet} and U_{dry}. U_e is also referred to as the equilibrium soil suction. An example of illustration of the predicted asymmetrical soil suction envelop creation is shown in Figure 6.87.

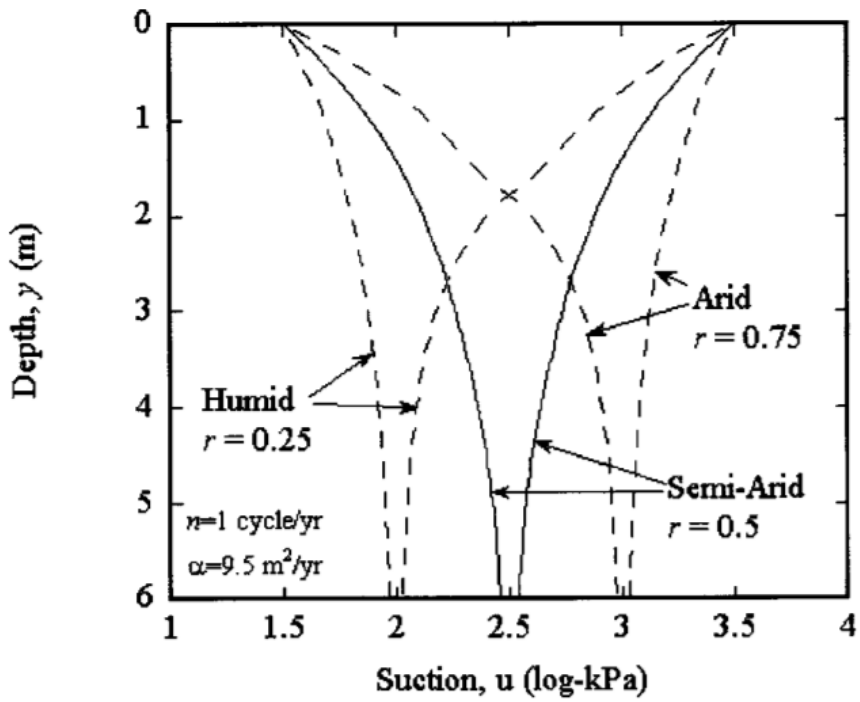


Figure 6.87: Characteristic Soil Suction Envelopes for Arid, Semi-Arid, and Humid Climates Based on the Premise of Possible Asymmetry in Envelope Shape (Aubeny and Long, 2007)

6.3.13. Mitchell (2008)

Mitchell (2008) presents Figure 6.88 that demonstrates a relationship between TMI and the design soil suction change at the surface ($\Delta\psi\ in\ pF\ units$) for various authors. For an arid climate with a TMI of -40 to -50, the recommended values for $\Delta\psi\ (in\ pF\ units)$ range from 1.2 to 1.8 pF when considering the work of the authors comprising the plot.

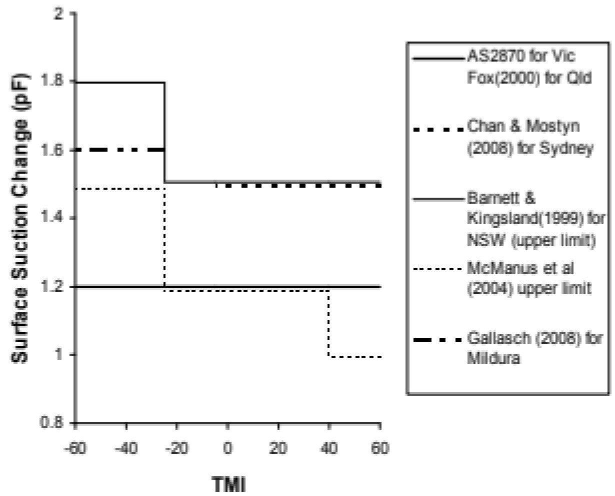


Figure 6.88: Relationship Between the Design Surface Soil Suction Change (Δu) and TMI (Mitchell, 2008)

Mitchell, 2008, recognized that there was little theoretical basis for the values presented in Figure 6.88, which most likely accounts for the large differences in the recommended values for arid climates.

An important element in Mitchell's work in an arid climate was the consideration of the diffusion coefficient, α, when compared to TMI. Figure 6.89 shows the relation between the diffusion coefficient and TMI (Mitchell, 2008). As noted herein, McKeen and Johnson (1990) used the diffusion equation to derive a method to determine the active depth associated with seasonal surface soil suction changes. Using the five back calculated data points from Figure 6.89 Mitchell (2008) inferred a value for the diffusion coefficient for a TMI equal to -50. The inferred value at TMI=-50 was 0.004 cm^2/sec. The inferred value of 0.004 cm^2/sec will be discussed further in Chapter 6.4.

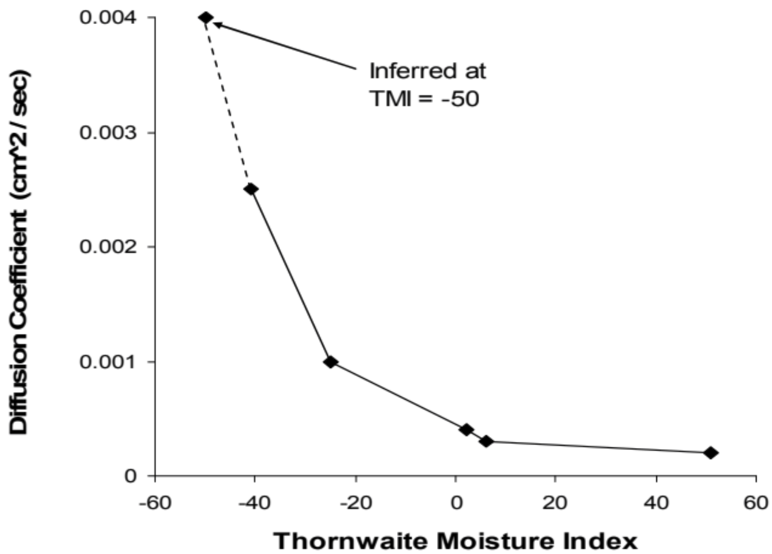


Figure 6.89: Relationship Between Diffusion Coefficient and TMI (Mitchell, 2008)

Using the diffusion coefficient obtained from Figure 6.89 to solve the diffusion equation for a site in an arid climate, it was found that the more appropriate change in soil suction at the surface ($\Delta\psi\ in\ pF\ units$) is 1.8 pF. The value of $\Delta\psi\ (in\ pF\ units)$ was corroborated by a case history of a building in the Jackson oil field that is within an arid climate. A note to a reader of Mitchell (2008) is that the diffusion coefficient mentioned in the example is 0.004 cm^2/sec as opposed to 0.0004 cm^2/sec, which is presented several times.

It can be noted that $\Delta\psi\ (in\ pF\ units)$ for all five of the listed climate zones, not including an arid climate, is 1.2 pF. The previous discussion supports the use of a 1.5 pF $\Delta\psi\ (in\ pF\ units)$ in an arid climate region.

6.3.14. Chan and Mostyn (2008)

Chan and Mostyn (2008) reported that for Sydney, Australia, the Δu was higher there than other areas reported as of that time. Based on accepted calibration as adopted in AS2870, the Sydney $\Delta\psi\ (in\ pF\ units)$ is taken to be 1.5 pF.

6.3.15. AS2870-2011

For specific locations in Australia, Figure 6.90 was made a part of AS2870-2011 to arrive at values of Hs. As can be observed in the figure, all listed cities have a change in soil suction at the surface, $\Delta\psi\ (in\ pF\ units)$, equal to 1.2 pF

Location	Change in suction at the soil surface (Δu) pF	Depth of design soil suction change (H_s) m
Adelaide	1.2	4.0
Albury/Wodonga	1.2	3.0
Brisbane/Ipswich	1.2	1.5–2.3 (see Note)
Gosford	1.2	1.5–1.8 (see Note)
Hobart	1.2	2.3–3.0 (see Note)
Hunter Valley	1.2	1.8–3.0 (see Note)
Launceston	1.2	2.3–3.0 (see Note)
Melbourne	1.2	1.8–2.3 (see Note)
Newcastle	1.2	1.5–1.8 (see Note)
Perth	1.2	1.8
Sydney	1.2	1.5–1.8 (see Note)
Toowoomba	1.2	1.8–2.3 (see Note)

NOTE: The variation in H_s depends largely on climatic variation.

Figure 6.90: Soil Suction Change Profiles for Selected Cities in Australia (AS2870-2011)

For the purpose of calculating the anticipated maximum surface movement, y_s discussed in Section 6.3.15, values of $\Delta\psi\ (in\ pF\ units)$ must equal 1.2 pF.

6.3.16. Li et al. (2013)

Following completion of a forensic analysis in connection with a home in Adelaide, Australia, it was determined that the causative factors that attributed to excessive soil movements included pipe leaks and excessive garden watering. As a result, the soil moisture conditions were heterogeneous. Because of the imposed conditions, the site could not be considered a “normal site” under classification by AS2870-2011. The case study proved that influences on a structure on expansive soils can be far greater from lawn watering and leaking pipes than from changes expected by seasonal fluctuations as suggested by the Australian Standard (Li et al., 2013). The authors believed that an enhanced understanding of the problem of expansive soils could be achieved through analysis of such case studies. The results of three test borings and associated soil suction versus depth data are plotted as indicated on Figure 6.91.

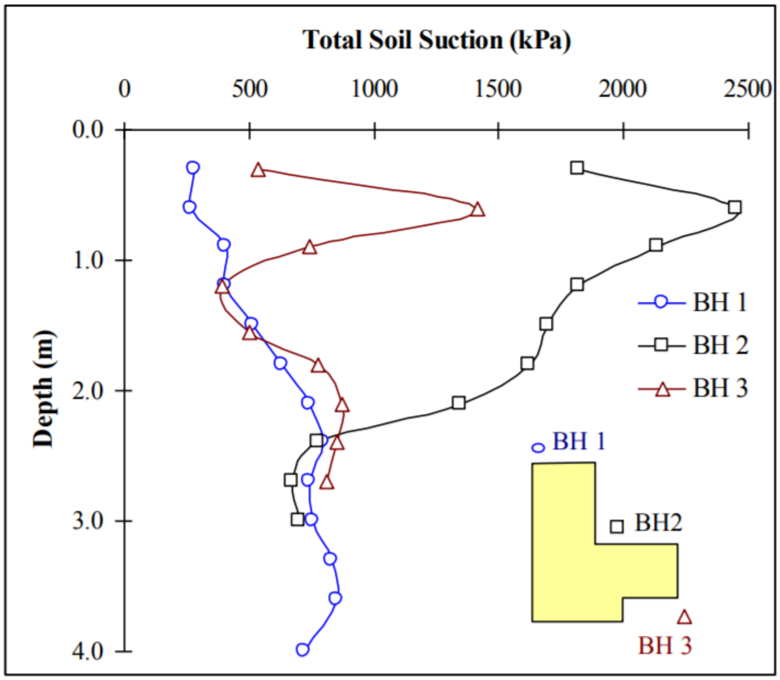


Figure 6.91: Soil Suction Profiles for a Case Study in Adelaide, Australia (Li et al., 2013)

According to AS2870-2011, Adelaide is in Climate Zone 5, with a TMI of $\geq$-40 to $\leq$-25. In this zone, H_s is anticipated to be 4.0 m, while the design $\Delta\psi$ $(in\ pF\ units)$ is 1.2 pF. For the profiles presented in Figure 6.91, the soil suction ranges from to 3.41 pF 4.41 pF, suggesting a 1.0 pF $\Delta\psi$ $(in\ pF\ units)$.

6.3.17. Sun (2017)

Sun (2017) states that AS2870-1996 was adopted to estimate H_s based on 20 years of continuous climate data, while AS2870-2011 recommends 25 years of continuous climate data. Figure 6.92 recaps the original and current versions of AS2870. Sun (2017) notes that the values contained in AS2870 are based more on anecdotal evidence and empirical experience as opposed to an analysis of a significant body of research. Sun opined that further work needed to be completed to investigate a better correlation between TMI and H_s.

Climatic Zone	**Description**	**TMI**		**H_s (m)**
		AS2870(1996)	*AS2870(2011)*	
1	Alpine / Wet coastal	> +40	> +10	1.5
2	Wet temperate	+10 to +40	-5 to +10	1.8
3	Temperate	-5 to +10	-15 to -5	2.3
4	Dry temperate	-25 to -5	-25 to -15	3.0
5	Semi-arid	< -25	-40 to -25	4.0
6	Arid	-	< -40	> 4.0

Figure 6.92: Correlation between Hs, TMI, and climate zone for AS2870-1996 and AS2870-2011 (Sun, 2017)

An additional climate zone was added to the 2011 edition of AS2870. The amendment to the former classification spectrum was needed due to the unlikely event that ground movement would result in wet and humid climates (Lopes and Osman, 2010). Other adjustments as noted in Figure 6.92 were made to accommodate the new climate zone. Radical Hs values can result when transitioning from one TMI range to another. Sun (2017) points out that if the TMI at one site is -15, the H_s is 2.3 m, while for a nearby site whose TMI could be -16, the H_s is 3.0 m. This abrupt change is presented as a shortcoming of the method.

The sharpness of the transitions when moving from one climate zone to another are demonstrated in Figure 6.93. Holding $\Delta\psi\ (in\ pF\ units)$ =1.2 pF constant for all climate zones, H_s varies significantly as the TMI boundary is crossed.

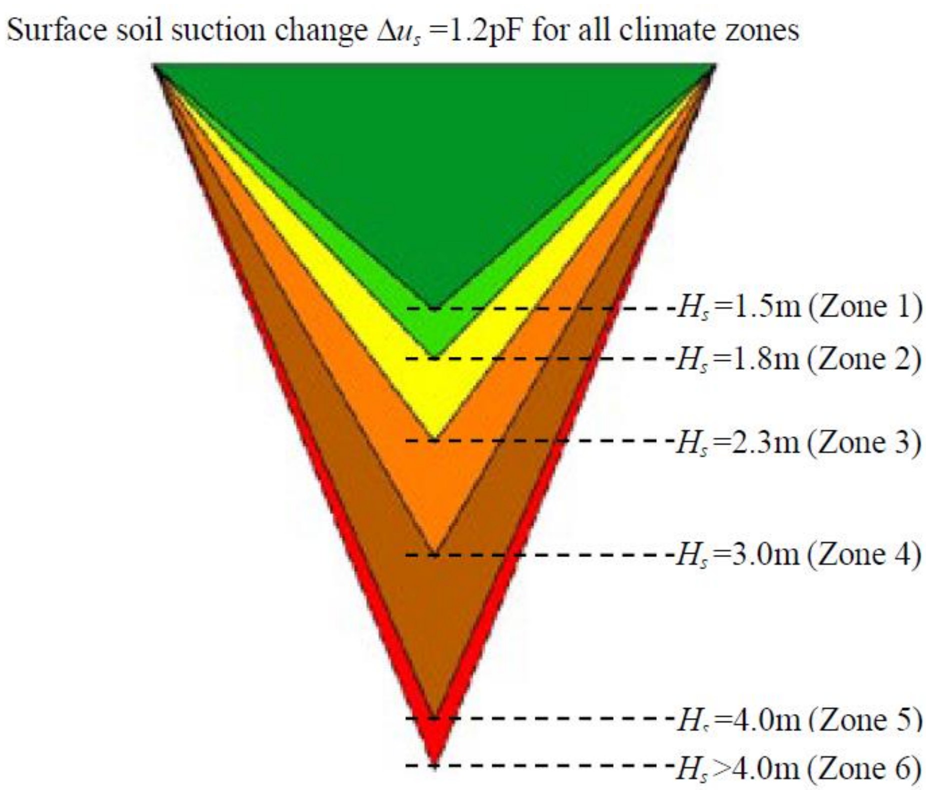


Figure 6.93: Typical Soil Suction Change Profiles per AS2870-2011 (Sun, 2017)

Sun (2017) predicts that will be an expected remarkable decrease in TMI and a significant increase in both H_s and y_s, based on projection models reaching outward to 2070. For example, Melbourne may experience a shift from H_s of 2.1 m in 1990 to 2.93

m in 2070. Likewise, the y_s may increase from 65 mm to 85 mm when fast-forwarding from 1990 to 2070. The changes applicable to Melbourne would be a TMI swing from -11 to -24, from 1990 to 2070. The bottom-line position made by Sun (2017) is that TMI can and will change for a site, depending on a changing climate.

6.3.18. Lopes and Karunarathne (2017)

Lopes and Karunarathne (2017) recommend that the $\Delta\psi\ (in\ pF\ units)$ be increased from 1.2 pF to 1.5 pF for Climate Zone 3 to account for any possible repeat of the radical climates experienced in Australia. Areas of Climate Zone 3 are inundation prone after a severe drought. The change in the predicted $\Delta\psi\ (in\ pF\ units)$ was the result of extensive research associated with the proposed Conditioned Core Shrinkage (CCS) test. The results of the study served as evidence that the AS2870 should be augmented as shown to increase the $\Delta\psi\ (in\ pF\ units)$ to a value greater than 1.2 as currently adopted.

6.3.19. Cuzme (2018)

As part of the work of Cuzme (2018), a listing data was compiled for both surrogate use and measured data. The data compilation is shown in Table 6.27.

Table 6.27: TMI versus $\Delta\psi\ (in\ pF\ units)$ at the Surface

Location	**TMI**	$\boldsymbol{\Delta\psi\ (in\ pF\ units)}$ **at the Surface**
San Antonio, TX	-16.6	1.4
McAllen, TX	-39.69	1.5
DFW	-2.24	1.2

The soil suction profile data from Cuzme (2018) when using the soil suction surrogate are presented in Figure 6.94 through Figure 6.96. In analyzing the scatter of data for regions surrounding a municipality, the work of Walsh et al. (2009) was employed. Walsh et al. (2009) presented a regional shift that accounts for variability in the magnitude of equilibrium from one location to another within a common region. The regional approach was similar to method employed by McOmber and Thompson (2000) and Diewald (2003) wherein all suction data is plotted together, by test boring and season. The site or boring specific suction profiles and be shifted toward a regional value of the equilibrium suction magnitude. In essence, by completing the shift toward the equilibrium value, the data for any suction profile can be normalized to the regional magnitude of equilibrium suction. This method was used in interpretation of the data in Figure 6.94 through Figure 6.96.

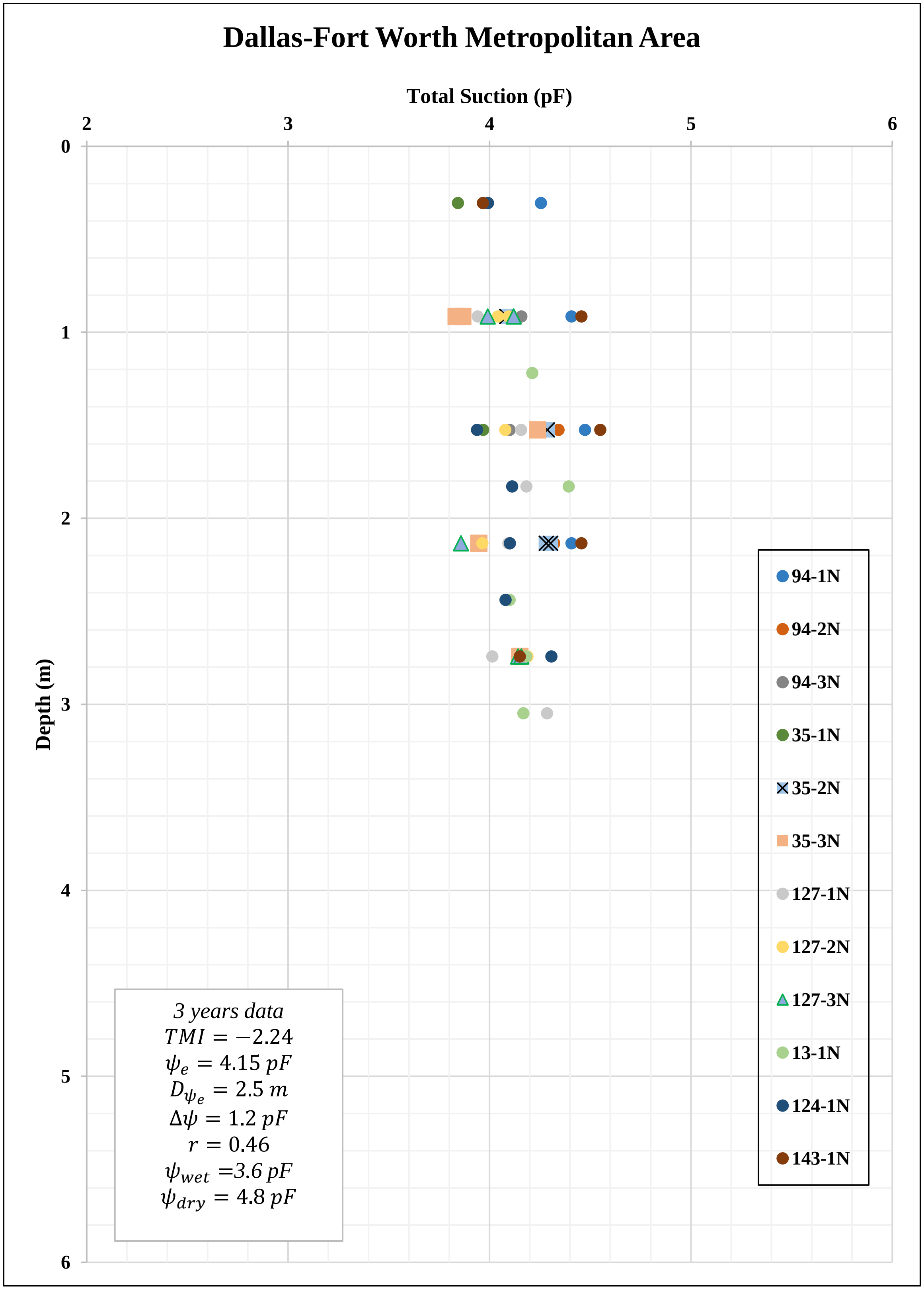


Figure 6.94: Dallas-Fort Worth – Soil Suction versus Depth

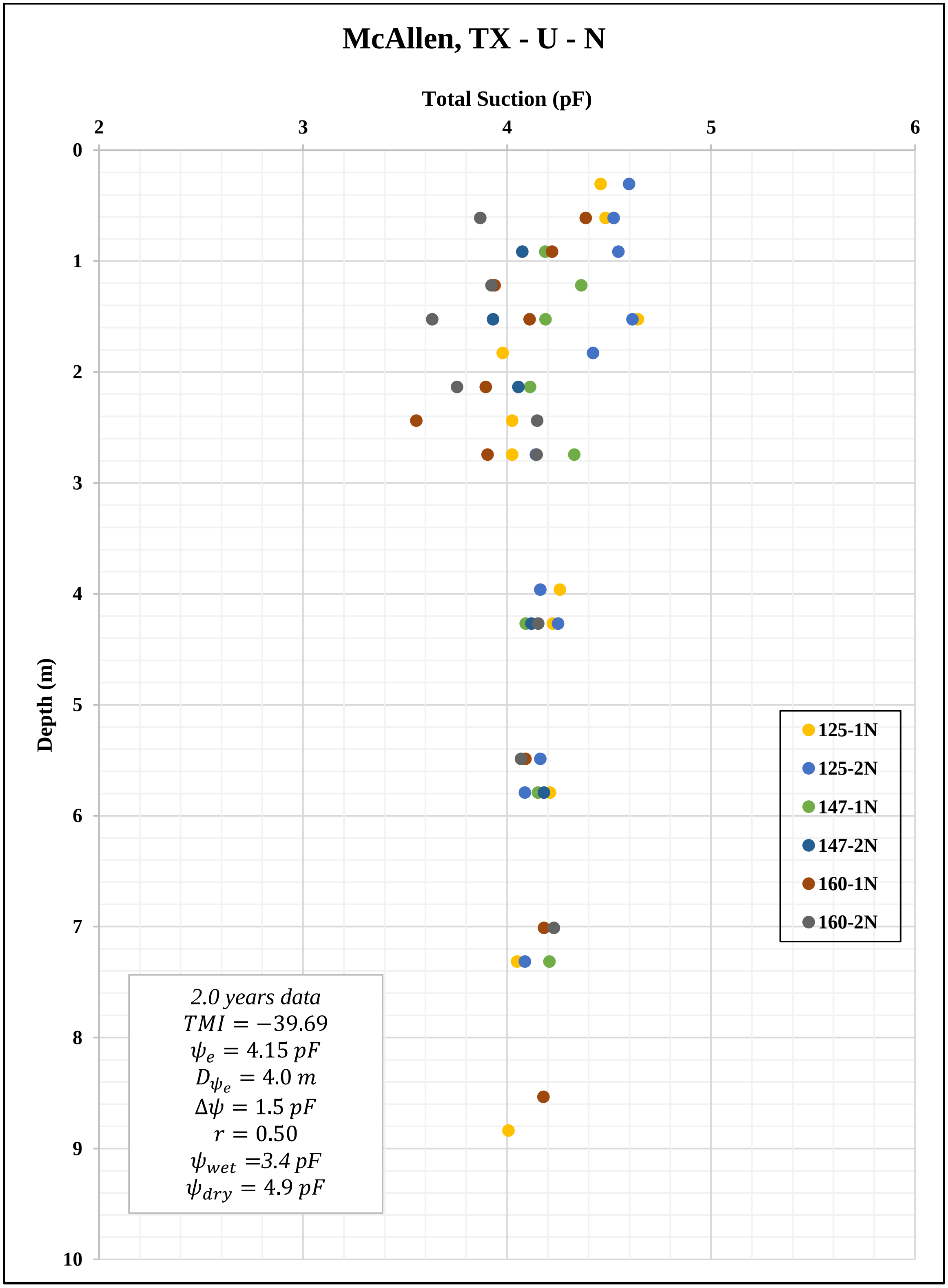


Figure 6.95: McAllen, Texas – Soil Suction versus Depth

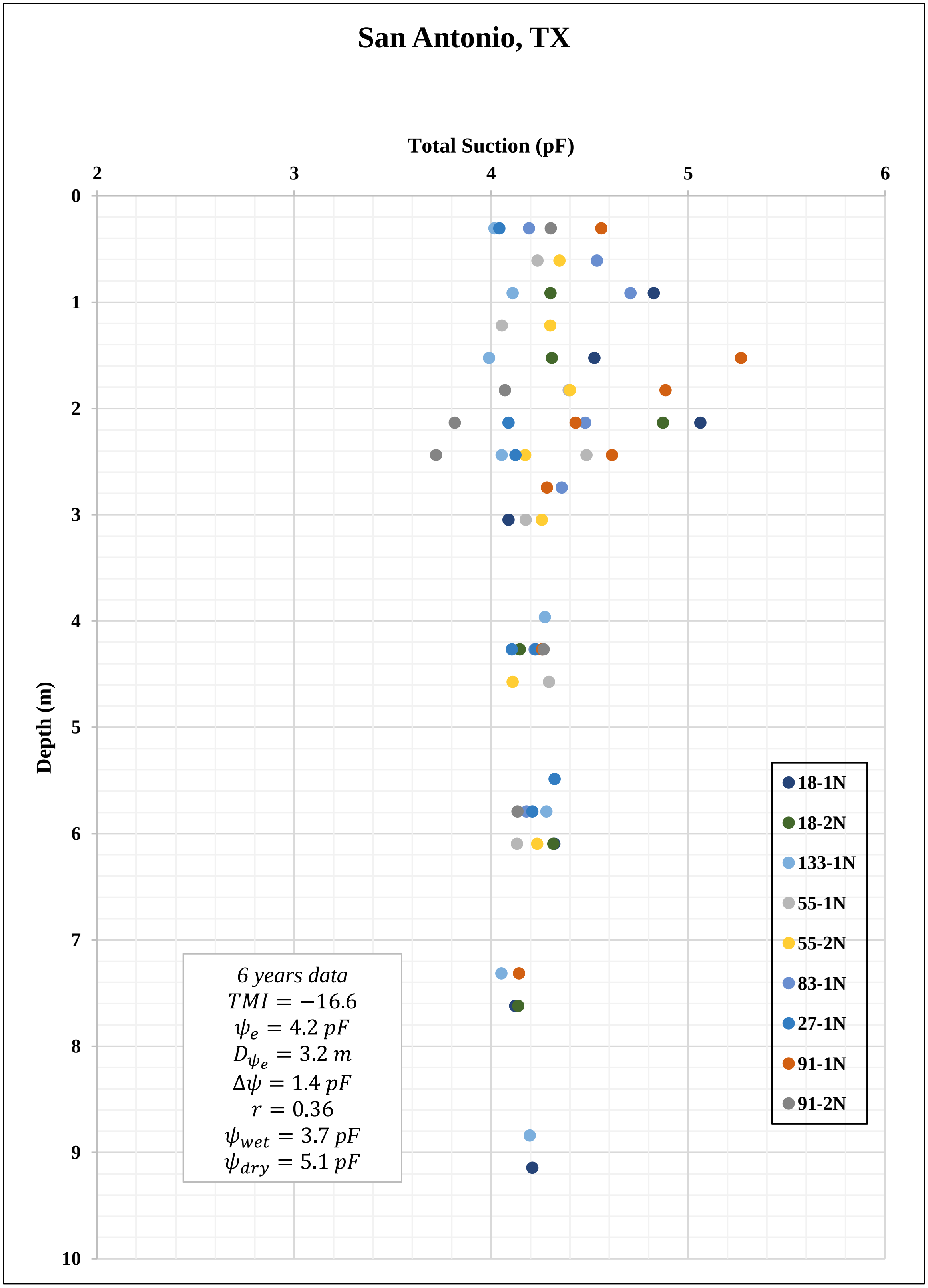


Figure 6.96: San Antonio, Texas – Soil Suction versus Depth

6.3.20. Results from Prior Research – Vann Engineering, Inc. – Peoria, AZ

Between the time interval of February 2006 to November 2007, and prior to construction of a multi-family residential development, downhole Psypro sensors were installed near the northeast corner of the proposed development. Fifteen total test borings, each for a dedicated sensor at a unique depth, were utilized. The sensor depths commenced at 0.3048 m (1 ft) and extended to a maximum depth of 4.572 m (15), the deepest extent of the test borings. The test borings were positioned in a line with an approximate spacing of 0.6096 m (2 ft). Readings were recorded and analyzed until November 2007, when they were discontinued due to the economic downturn. Table 6.28 presents a summary of the data.

Table 6.28: Downhole Psypro Data from Vann Engineering, Inc. Project 18331 from February 2006 to November 2007

	Suction						
Depth (m)	Feb-06	Jul-06	Nov-06	Jan-07	May-07	Aug-07	Nov-07
0.3048	3.34	4.84	4	3.65	4.7	4.89	4.28
0.6096	3.52	4.82	3.77	3.9	4.8	4.72	4.1
0.9144	3.6	4.35	4.18	3.8	4.5	4.63	4.55
1.2192	3.92	4.6	4.06	3.84	4.65	4.46	4.27
1.524	3.85	4.29	4.01	4.15	4.42	4.55	4.44
1.8288	4.28	4.5	4.19	4.03	4.43	4.47	4.32
2.1336	3.9	4.45	3.98	4.18	4.27	4.4	4.45
2.4384	4.14	4.5	4.09	4.22	4.58	4.35	4.34
2.7432	3.99	4.35	4	4.17	4.33	4.38	4.22
3.048	4.08	4.45	4.25	4.35	4.21	4.25	4.13
3.3528	4.09	4.35	4.2	4.11	4.36	4.48	4.38
3.6576	4.06	4.32	4.25	4.41	4.18	4.45	4.41
3.9624	4.2	4.15	4.1	4.28	4.38	4.34	4.29
4.2672	4.15	4.29	4.15	4.4	4.32	4.43	4.23
4.572	4.33	4.38	4.2	4.25	4.14	4.25	4.43

A plot of the data from Table 6.28 is presented in Figure 6.97.

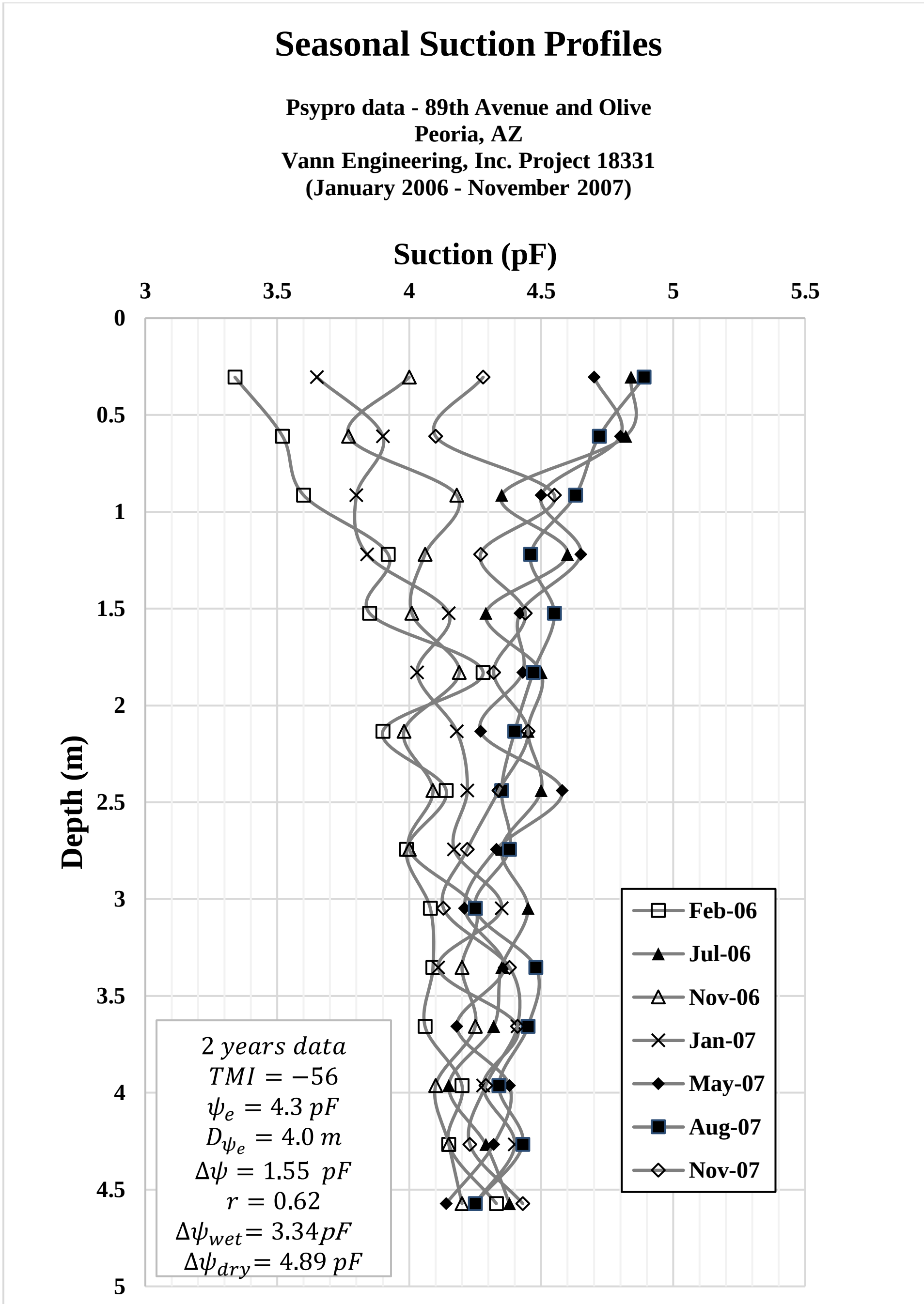


Figure 6.97: Seasonal Suction Profiles from a Site in Peoria, AZ from February 2006 to November 2007

6.3.21. Conclusions and Recommendations Relevant to the Change in Soil Suction at the Surface

Through the years, Australian research has contributed in terms of finding relationships between the change in soil suction at the surface and TMI for expansive soils sites subjected to climatic driven surface flux variations only. An ever-changing climate has and will continue to affect the relationships. Figure 6.98 has been prepared to illustrate the literature, to date. Also added are specifically recommended values for locations in Australia, pre- and post-AS2870-2011. The added data includes recommendations from Mitchell (2008), Fityus et al. (1998), Vann Engineering, Inc. (project file), and Wray (1989). From a practitioner's perspective, using the stair step approach is awkward, arising from ambiguities when transitioning from one zone to another. It would make more sense to utilize a single curve to represent the full range of TMI.

Seven data points, based on measured or surrogate suction profiles, have been included on the plot in Figure 6.98. Locations included College Station, Amarillo, San Antonio, McAllen, Dallas, TX, and Peoria, AZ. Data from Sections 6.3.2, 6.3.11, 6.3.13, 6.3.19, and 6.3.20 were utilized in this study.

The data contained in Appendix E 4 were analyzed to explore the relationship between TMI and the change in soil suction at the surface. The data for the seven sites accounts for tracking of suction variations for durations up to nine years, but also included some sites were seasonally drive suction variations were observed for only 2 years. With time and increased research in the area, additional data can be added to enhance the relationships proposed herein. Nonetheless, the data obtained from the literature and from this research generally support the recommendations made by others, including in particular the recommendations in the AS 2870 and McManus (2004).

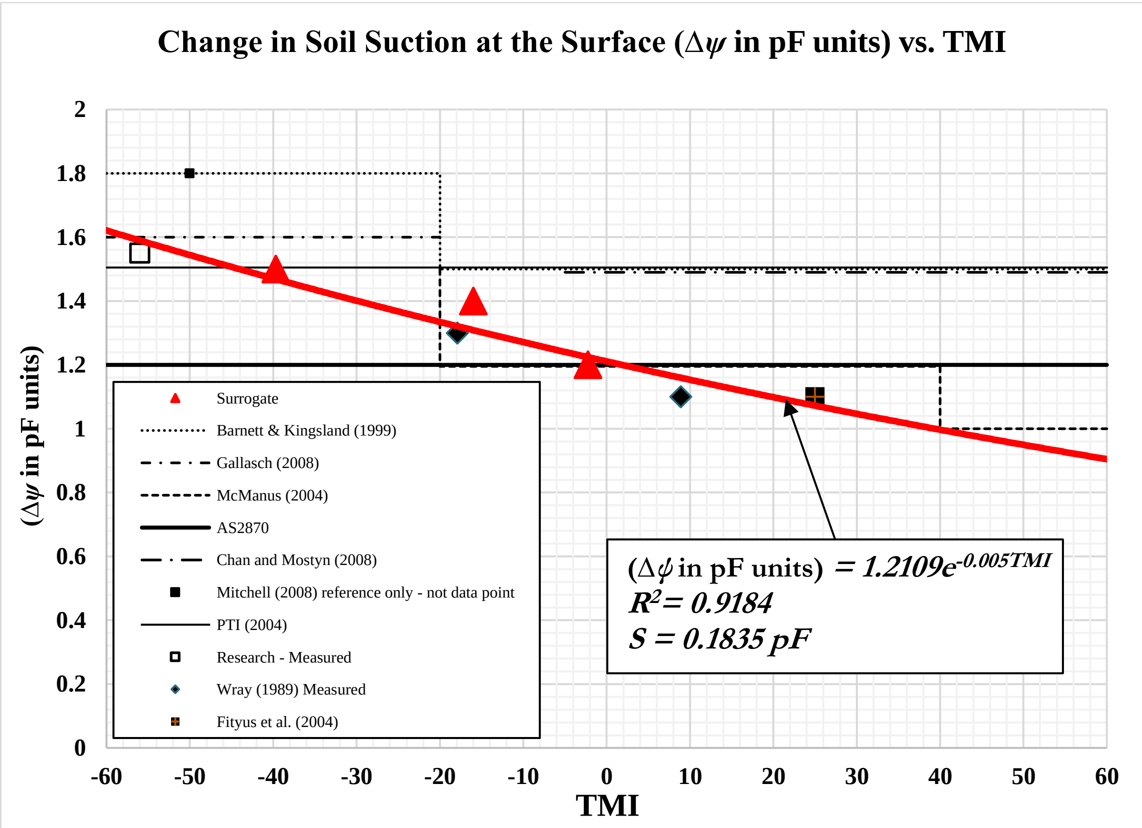


Figure 6.98: Compilation Plot of Change in Soil Suction at the Surface, $\Delta\psi$ in pF units, from Various Authors from Australia and Adapted from Cuzme (2018).

In Figure 6.98, the surrogate was used for four of the data points because of limited available measured data. Based on the data from this research and that of Cuzme (2018), Equation (156) was found to reasonably fit the data obtained.

$$\Delta\psi\ (in\ pF\ units) = 1.2109e^{-0.005TMI} \tag{156}$$

$$R^2 = 0.9184$$

$$S = 0.1835\ pF$$

Figure 6.99 presents a plot with greater clarity by eliminating all background plots and recommendations provided by others. Until and unless further field-based data becomes available, it is recommended that the relationship above be used to estimate the change is soil suction (change in log of soil suction) at (near) the ground surface for seasonal fluctuation boundary conditions for expansive soil profiles.

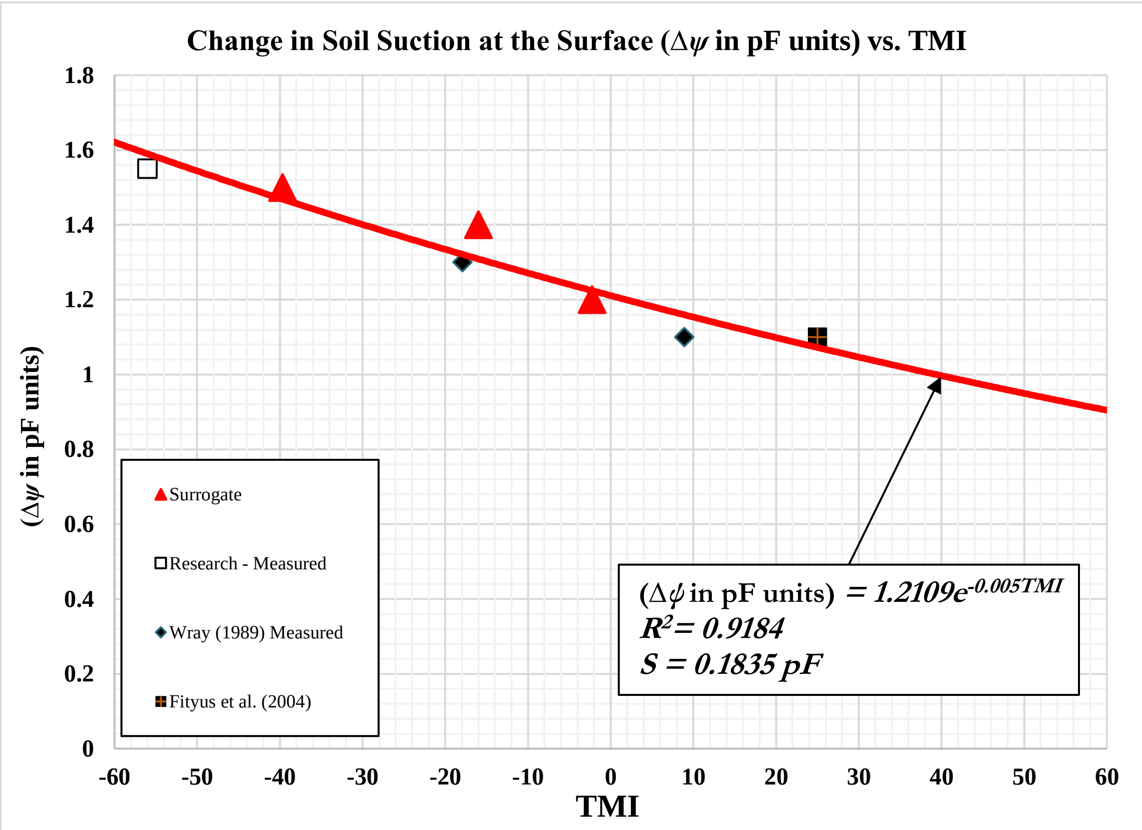


Figure 6.99: Simplified Presentation of the Change in Soil Suction at the Surface, $\Delta\psi$ in pF units

6.4 Symmetry and Asymmetry Associated with the Change in Soil Suction at the Surface Relative to Seasonal Fluctuation Boundary Conditions

Aubeny and Long (2007) presented illustrative suction envelopes, developed from unsaturated flow theory (Mitchell (1980)), to demonstrate that varying climate ranges may experience asymmetrical soil suction profiles. Their arguments originally stem from field measurements by McKeen and Johnson (1990), wherein the implication exists that suction decay is not always symmetrical about the magnitude of equilibrium suction. Three climate examples were given; arid, semi-arid and humid. An ‘r’ parameter (essentially a climate factor) was introduced that is an expression of the percentage of the total anticipated change in log of soil suction at the surface comprising the wet side of suction envelop. Typical values of r=0.25, 0.5, and 0.75 were shown to be characteristic of humid, semi-arid and arid climates. Figure 6.100 is the illustration presented by Aubeny and Long (2007). Aubeny and Long (2007) indicated that the conditions of surface suction are described by three specific suctions; the magnitude of equilibrium suction, the maximum suction representing a dry condition, and the minimum suction representing a wet condition. The climate factor ‘r’ characterizes the surface boundary condition as suggest by Equation (157), where U is the suction in units of pF (log suction).

$$r = t_{dry}n = (U_e - U_{wet})/(U_{dry} - U_{wet}) \tag{157}$$

Mitchell (1979) used the frequency of seasonal suction cycles, *n*, equal to one cycle per year. Subsequent work by McKeen and Johnson (1990) suggested that an *n*=1 does not always provide the best fit for field data. Further, Aubeny and Long (2007) found that in humid climates, the equilibrium suction was closer to the minimum wet suction. Conversely, the maximum dry suction was found to be closer to the equilibrium suction in arid climates.

The basis for the r parameter is that wet and dry seasons of unequal duration can create the resulting asymmetric suction envelop; further the nonlinearly decreasing hydraulic conductivity with increase in soil suction could be a factor in the existence of r values other than 0.5 (i.e. the existence of asymmetric change in log suction, wet to dry about the equilibrium value.

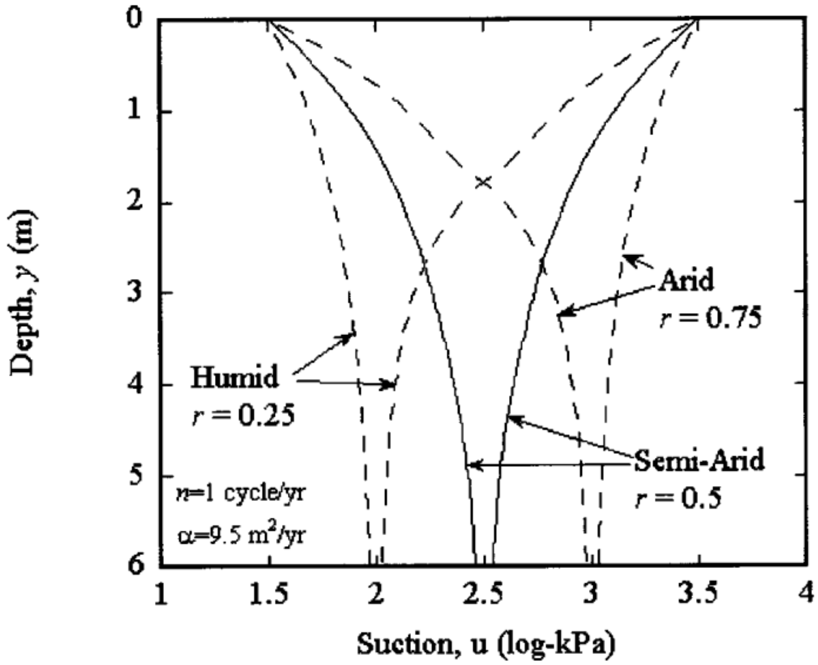


Figure 6.100: Characteristic Soil Suction Envelopes for Humid, Semi-Arid and Arid Climates (Aubeny and Long, 2007)

Using the Cuzme (2018) data (replotted using the suction surrogate of this research), and available literature and file data, together with the relationship between TMI and the change in soil suction at the surface presented above, a relationship was developed to establish the ‘r’ parameter for various TMIs. Figure 6.101 presents the ‘r’ parameter versus TMI fitted to the seven sites where field suction profiles over multiple seasons that were available. The sites considered were those utilized in the development of the TMI versus change in soil suction (in units of pF) at the surface. The data available covered a TMI range of -56 to 12.

Equation (158) is the relationship between the Aubeny and Long (2007) ‘r’ parameter and TMI for the data relative to this study. The data contained in Appendix E 4 were also analyzed to explore the relationship between TMI and the change in soil suction at the surface. Equation (158) is a reasonable function that a practitioner can utilize in determining the relative asymmetry of the suction profile when considering seasonal effects.

$$climate\ parameter\ 'r' = 0.3725e^{-0.009TMI} \tag{158}$$

$$R^2 = 0.7998$$

$$S = 0.1132$$

The importance of an understanding that all sites do not necessarily exhibit a perfectly symmetrical plot for an uncovered site relative to the wet and dry soil suction profiles extending downward to the equilibrium condition.

In comparing the ‘r’ parameters obtained from Figure 6.101 to those suggested by Aubeny and Long (2007), the ‘r’ parameters in connection with the research data for an arid climate range from 0.53 to 0.64(TMI less than -40). A TMI less than or equal to -40 follows the typically adopted range for an arid climate (AS2870-2011). The value suggested by Aubeny and Long (2007) is 0.75 for the same interval. However, the value presented by Aubeny and Long (2007) was intended to be illustrative. For a semi-arid climate, -40 < TMI $\leq$ -25, Aubeny and Long (2007) present an ‘r’ equal to 0.5. Figure 6.101 presents a range of 0.46 to 0.53 which encompasses the Aubeny and Long (2007) value, i.e. 0.5.

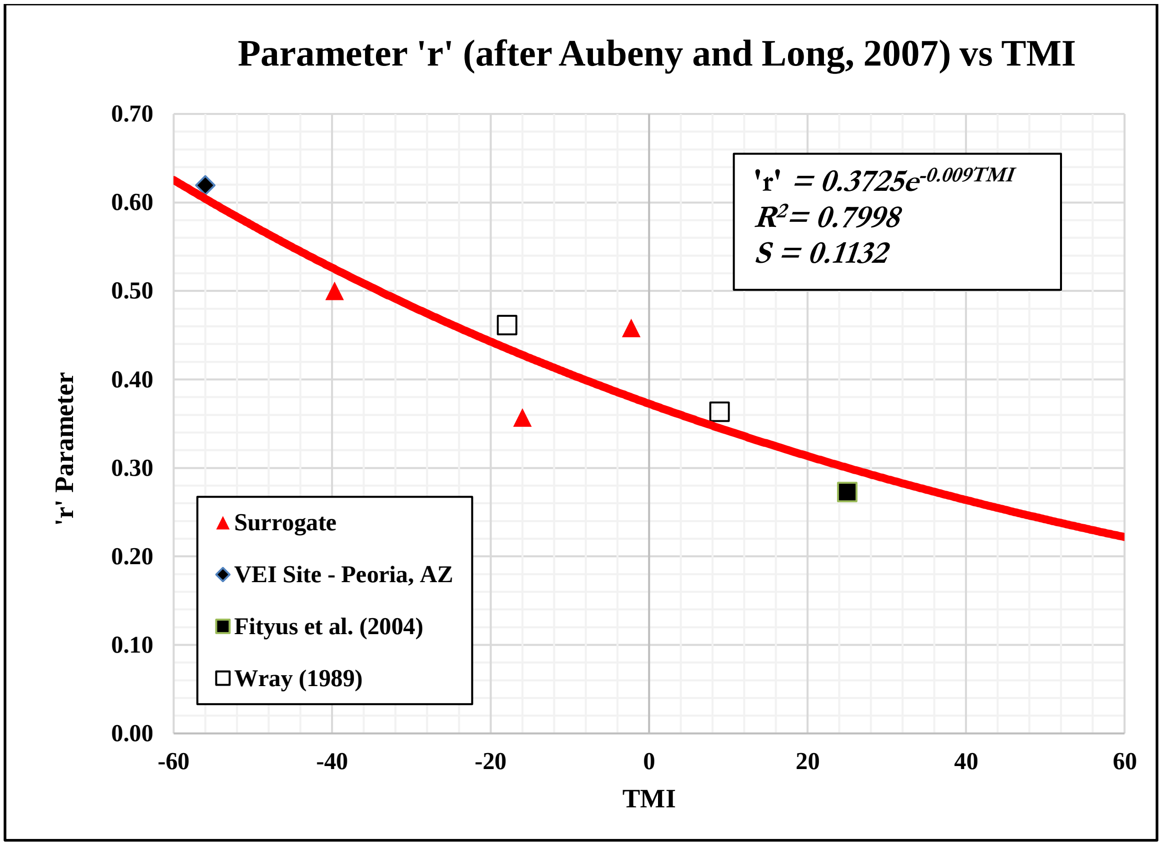


Figure 6.101: Relationship between the Aubeny and Long (2007) 'r' Climate Parameter and TMI for Sites Considered as Part of This Research

For a humid climate, which can be thought of in terms as wet-temperate (AS2870-2011), the TMI has the range of 10 to 40. At present, there are only one datapoint that is greater than 10, suggesting an 'r' parameter 0.27, which is close to the Aubeny and Long (2007) value of 0.25.

Using Figure 6.101 with an understanding of the work from Aubeny and Long (2007) will assist practitioners in formulating the final shape of the soil suction profile. Further, it reasonable that the value of the parameter 'r' should change according to variations in TMI. For the practitioner, it will be easy to reconcile that the 'r' parameter will have a unique value for every TMI, without being limited to three values.

To explain the reason for the asymmetry associated with soil suction envelopes, there are several factors that contribute to a potentially skewed envelope shape. It should be kept in mind that the change in suction in units of pF is actually a change in log of suction. Previous discussion has addressed the commentary by Aubeny and Long (2007) wherein they opine a basis for asymmetric suction envelopes arising from wet and dry seasons of unequal duration. In a humid climate, a plot of precipitation versus time will reveal long wet periods that are separated by short dry periods. Conversely, an arid climate will exhibit long to extremely long dry periods that are separated by short term wet periods. Further, Aubeny and Long (2007) found that in humid climates, the equilibrium suction was closer to the minimum wet suction. Conversely, the maximum dry suction was found to be closer to the equilibrium suction in arid climates. Therefore, the periods of wetting and drying are contributing factors to the skewed envelop shape. Another factor is that connected with the non-linearity of the unsaturated coefficient of permeability. Figure 6.54, previously presented, shows the overall extremely non-linear characteristic of k_{unsat}. There exists a prominent straight-line portion of the relationship, along which most of the relationships between suction and unsaturated permeability are measured, and it is this straight-line on semi-log suction plot that is assumed in Michell's formulation for unsaturated flow. During wet seasons, the unsaturated conductivity is highest, and during dry seasons, the conductivity is reduced. When the surface soil becomes very dry, the conductivity becomes quite low, approaching that of vapor transport, and flow out of or into the subsurface is essentially cut off during these very dry times. The higher conductivity of surficial soils during the wet season, requires a greater change in soil suction during dry times of year to achieve pseudo-equilibrium conditions about the suction value at depth. If the time of wetting and drying each year were identical (in terms of time of infiltration and evaporation), one would expect the shift in log suction at the ground surface to be equally balanced wet to dry side to the extent that the Mitchell assumption of K_{unsat} variation linearly with log suction was valid. Also, the climate 'r' parameters suggested by Aubeny and Long (2007), which are based on Mitchell's formulation, would be expected to match well to field-observed climate 'r' parameters if the assumed K_{unsat} linear with log suction relationship were adequately representative of field conductivity values for the range of suction encountered for field conditions. Indeed, Figure 6.101 shows that the field-observed shifts in log suction about equilibrium match quite well to the Aubeny and Long (2007) illustrative estimates.

6.5 Use of Mitchell's Formation to Establish the Shape of Seasonal Envelopes

Flow through unsaturated soils is governed by the non-linear Richard's equation, which is shown for one-dimensional vertical flow below, Equation (159).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z} + 1\right)\right] \tag{159}$$

Where,

K is the hydraulic conductivity
h is the matric head induced by capillary action
z is the elevation above a vertical datum
θ is the volumetric water content
t is time

Considering that the hydraulic conductivity for unsaturated soils decreases rapidly with increase in the suction Mitchell (1980) assumed: (1) the unsaturated permeability is linearly proportional to the reciprocal of suction and (2) the water content is linearly related to the suction in terms of pF unit. In this way, Mitchell transformed the non-linear partial differential equation of Richard's to a linear form, using a substitution of log suction for suction, as shown in Equation (160). Note that the gravity term in Richards' equation is lost in use of this substitution.

$$\alpha \frac{\partial^2 U}{\partial z^2} = \frac{dU}{dt} \tag{160}$$

Where,

U is the matric suction in pF units;

α = diffusion coefficient for the soil;

$$\alpha = \frac{k_0 u_0}{0.4343 \frac{G_s}{1+e_0} C_w}$$

G_s = specific gravity of the soil;

e_0 = initial void ratio;

u_0 = matric suction at the field capacity;

k_0 = saturated permeability coefficient

Solving for log matric suction as a function of depth, Equations (161) and (162) were generated, under an assumption of cyclic surface suction loading function.

$$U = U_H + \frac{4(U_H - U_o)}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{2n-1} e^{\frac{-(2n-1)^2 \pi^2 \alpha t}{4H^2}} cos \frac{(2n-1)\pi z}{2H} \tag{161}$$

$$U(z,t) = U_e + U_o e^{-\sqrt{\frac{n\pi}{\alpha}} z} cos\left(2\pi n t - \sqrt{\frac{n\pi}{\alpha}} z\right) \tag{162}$$

Where,

z = depth

U is the matric suction in pF units;

α = diffusion coefficient for the soil;

$$\alpha = \frac{k_0 u_0}{0.4343 \frac{G_s}{1 + e_0} C_w}$$

G_s = specific gravity of the soil;

e_0 = initial void ratio;

u_0 = matric suction at the field capacity;

k_0 = saturated permeability coefficient

n = the number of season cycles per year; typically, 1 to 2

The Mitchell's 1980 equation for change in suction based on depth and time, simplified by Naiser and Lytton 1997 for only the limited extremes of suction cases (wet and dry), is used to obtain the shape of the suction envelop; Equation (166).

$$\psi(z) = \psi_{eq} + \Delta\psi_{z=0} e^{(-z)\sqrt{\frac{n\pi}{\alpha}}} \tag{163}$$

Where,

$\psi(z)$ is the suction value at any depth *z*

n is the frequency of suction cycles per year

α is the diffusion coefficient

The separation between the wet and dry boundaries of the suction envelopes at the depth of equilibrium suction is of interest. When determining the depth to constant suction, and its connection to establishing the seasonal suction envelopes, Jayatilaka et al. (1992), Naiser (1997), McKeen & Johnson (1990), and Aubeny & Long (2007) have consistently assumed that the depth to equilibrium suction can be determined where the separation between suction values at the equilibrium depth is no greater than 0.2 pF. Lytton has stated that the separation is acceptable when the separation is no greater than 0.2 pF. This concept has been, therefore, embraced by the industry and has been utilized in this study.

The ratio of the diffusion coefficient and number of suction cycles per year (*n*) can be determined by a back-calculation approach using the known equilibrium depth, change in suction at surface, and the 0.2 pF separation between dry and wet suction at the depth of equilibrium.

$$\frac{n\pi}{\alpha} = \left(\frac{\ln\left(\frac{0.2\,pF}{\Delta\psi_{surface}} \right)}{-d_{eq}} \right)^2 \tag{164}$$

It must be pointed out, however, despite prior studies completed to evaluate the back-calculated diffusion coefficient, α, and the number of seasonal cycles per year, *n*, the need for these values, separately, is a result of the absence of some key features of field suction envelopes. These key features include the magnitude of equilibrium suction, depth to equilibrium suction, expected change in suction at the surface, and the climatic ‘r’ parameter. Where these four key parameters are known, the need to determine α or *n* separately, can be bypassed in developing the shape of the suction envelop. With this research, we have developed the full suite of needed parameters for establishment of the shape of the suction envelopes. In fact, this research has determined that by inputting the four key parameters (r, $\Delta\psi, \psi_e, and\ D_{\psi_e)}$ into the Mitchell (1979) formulation, that the separate values of α and n are not required to establish the seasonally-driven suction envelopes.

6.6 Developed / Covered-Site Soil Suction Envelopes

The preceding discussions have addressed, for the most part, a method to arrive a soil suction profiles for uncovered sites subjected to seasonal fluctuations only. All of these covered site suction profiles were obtained from existing geotechnical engineering reports. There are many circumstances that will require an understanding of the suction profile beneath a site that has been covered for at least 5 years. The surface covering may be an asphalt or concrete pavement, or structure. To demonstrate the soil suction profile with depth, the soil suction surrogate was utilized to evaluate the profile at twelve sites with adequate laboratory and drilling data. In all cases, the sites were relatively flat and covered with an asphalt or concrete pavement for at least 5 years, with the perimeter of the pavement subjected to natural climatic conditions only.

Figure 6.102 through Figure 6.113 illustrate the change in soil suction with depth for twelve sites obtained from existing geotechnical engineering reports, all of which are covered and have been covered for at least 5 years. In addition to the 5-year covered criterion, all the test borings were positioned at least 10 m inward from the edge of the covered surface, except those drilled as part of this research. Using the surrogate equation presented herein, which has been demonstrated to give reasonable estimates of soil suction, the practitioner can use the commonly obtained soil test results that comprised a typical geotechnical investigation to determine the suction profile for the obtained data, as was done in the study of covered sites shown above.

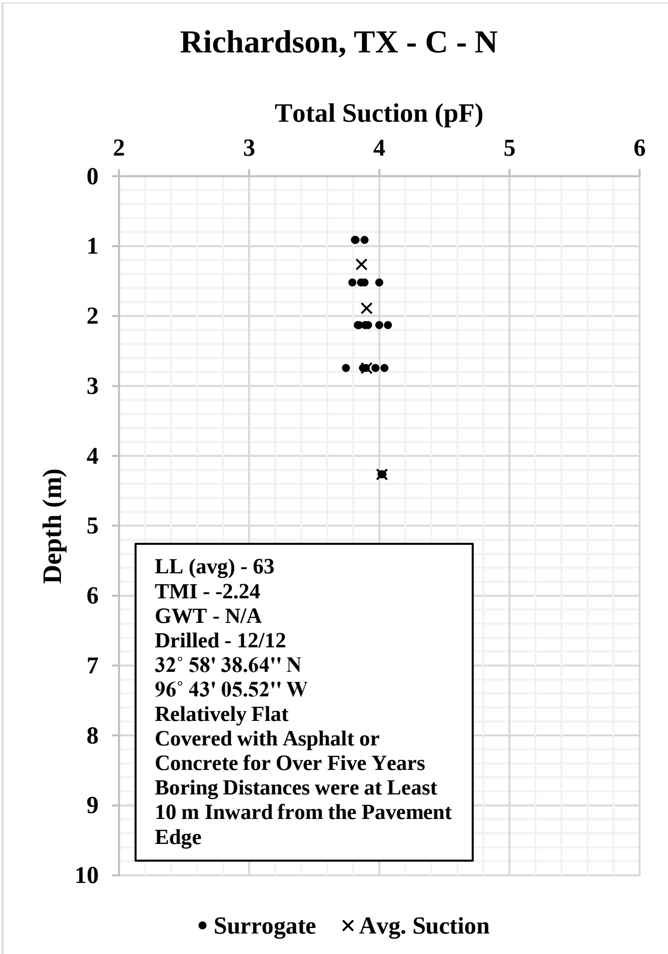


Figure 6.102: Surrogate Soil Suction Profile - Richardson, TX

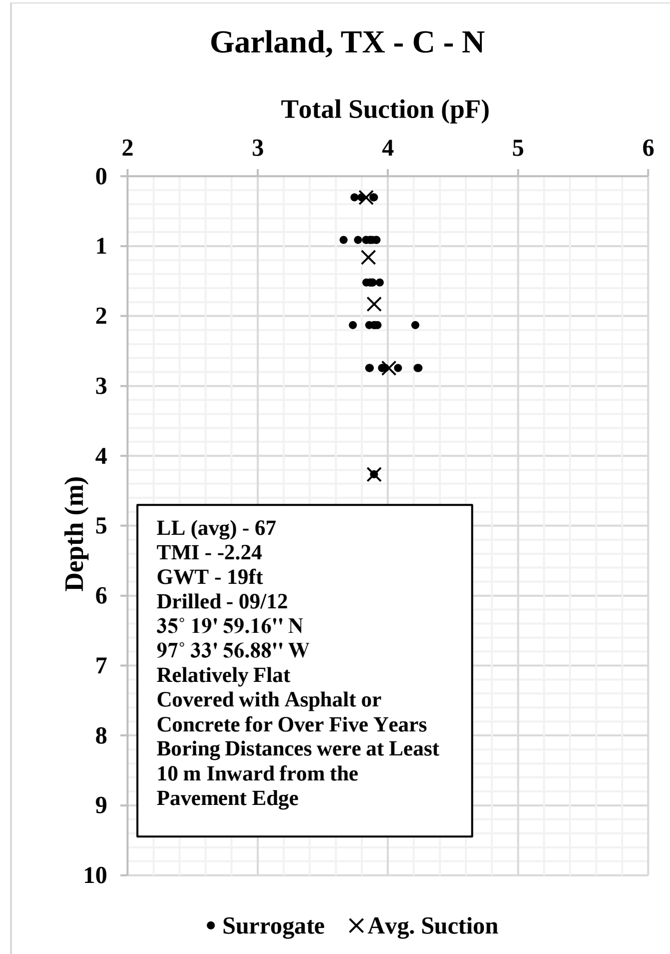


Figure 6.103: Surrogate Soil Suction Profile for Garland, TX

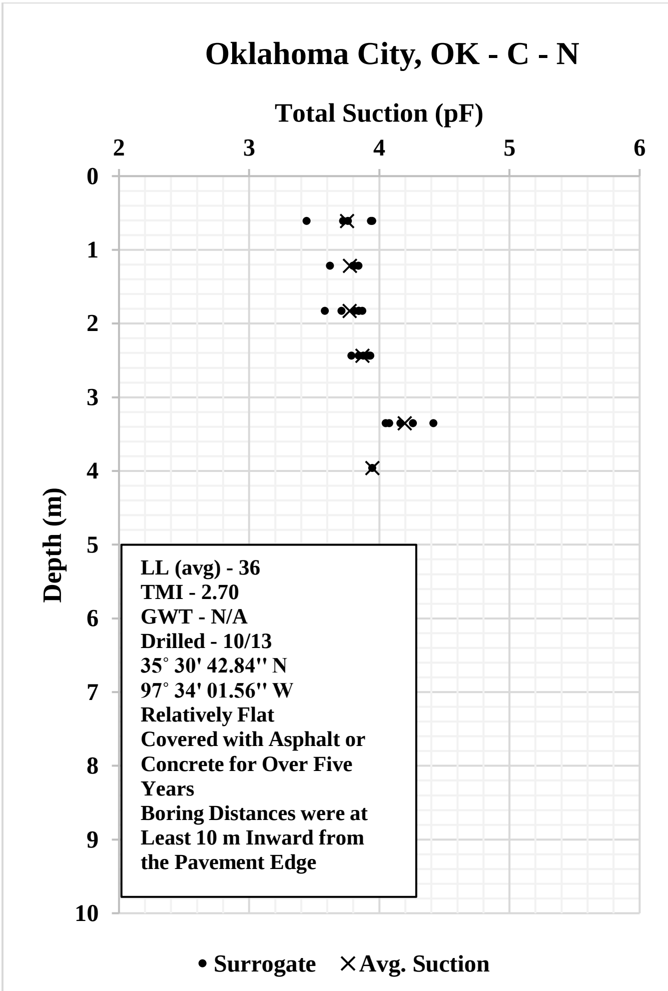


Figure 6.104: Surrogate Soil Suction Profile for Oklahoma City

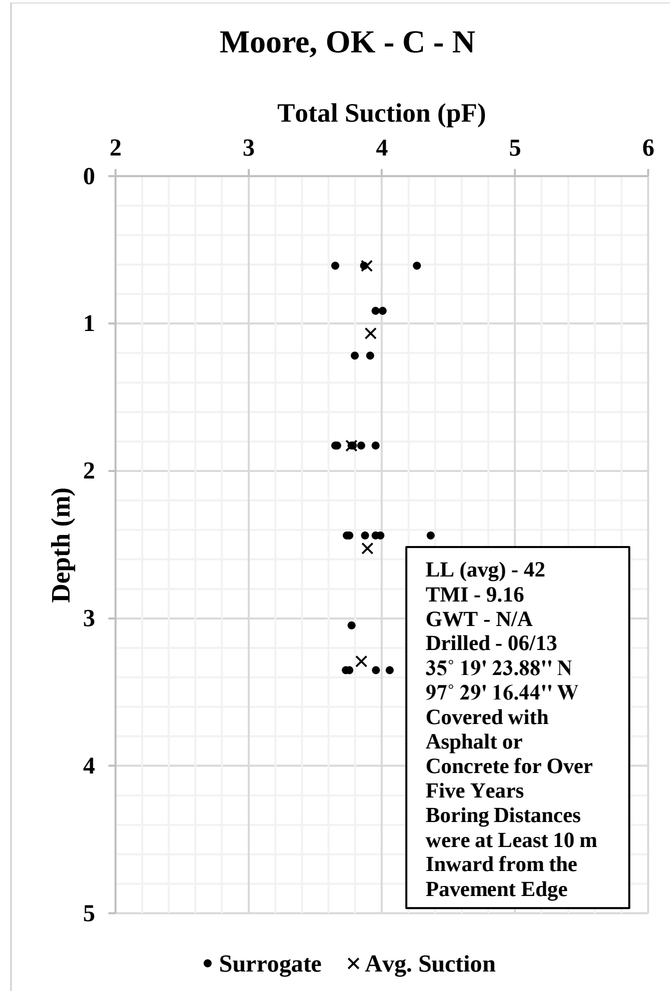


Figure 6.105: Surrogate Soil Suction Profile for Moore, OK

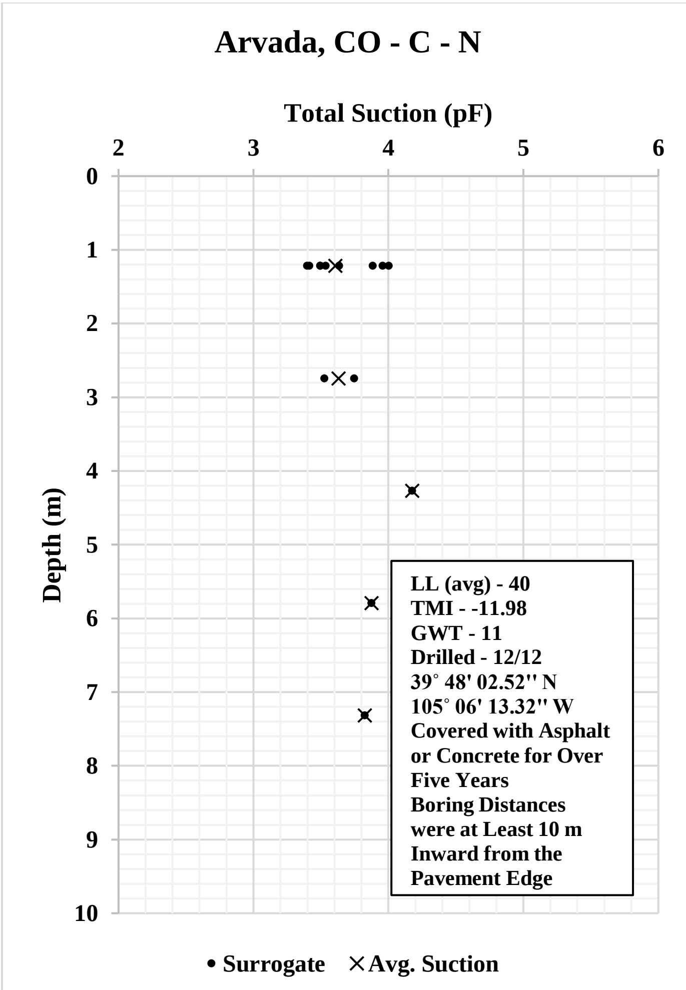


Figure 6.106: Surrogate Soil Suction Profile for Arvada, CO

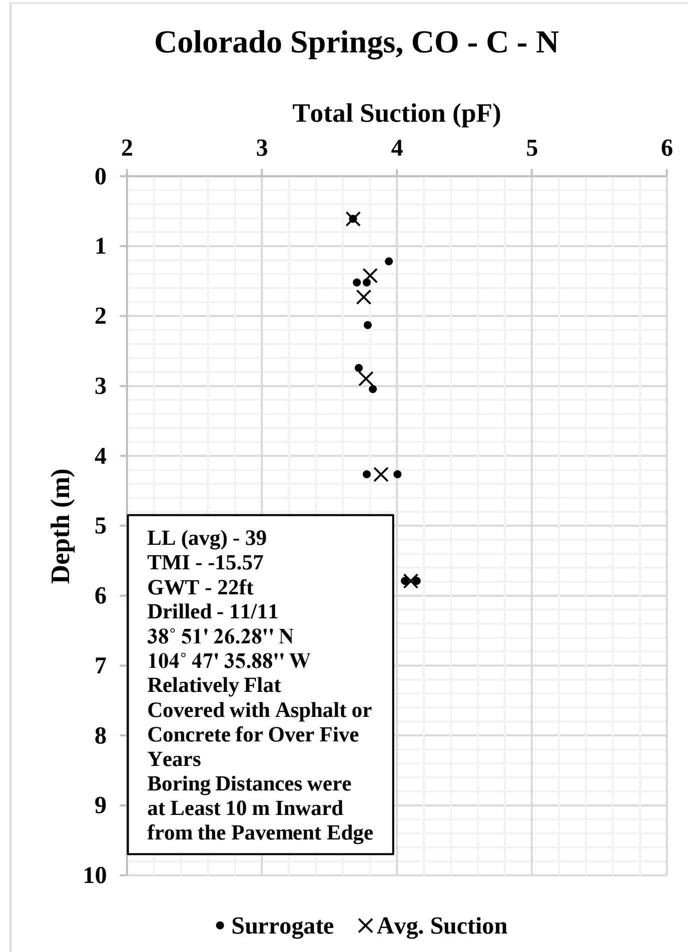


Figure 6.107: Surrogate Soil Suction Profile for Colorado Springs, CO

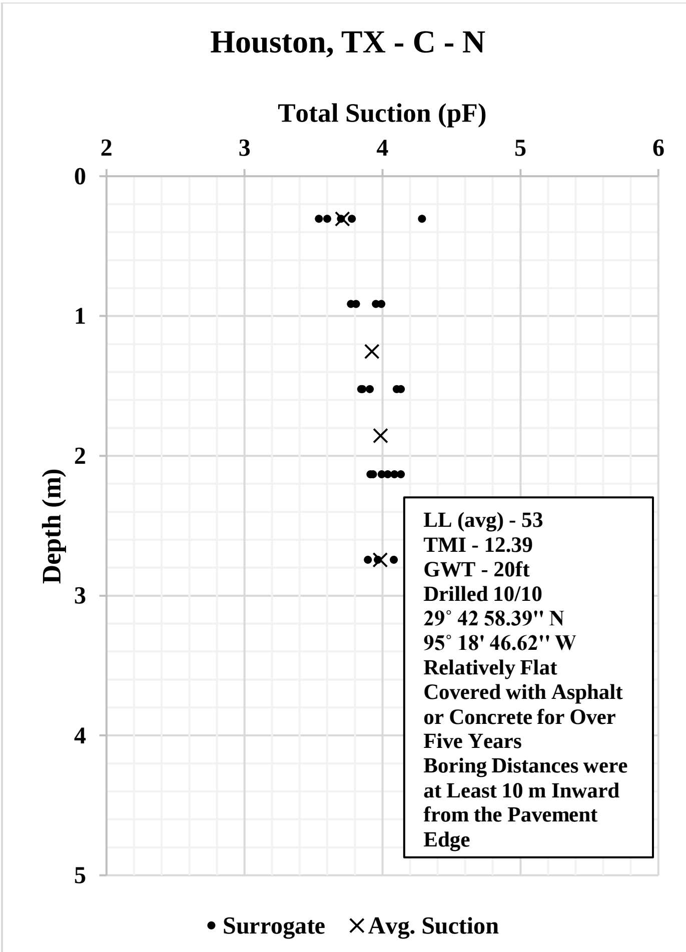


Figure 6.108: Surrogate Soil Suction Profile for Houston, TX

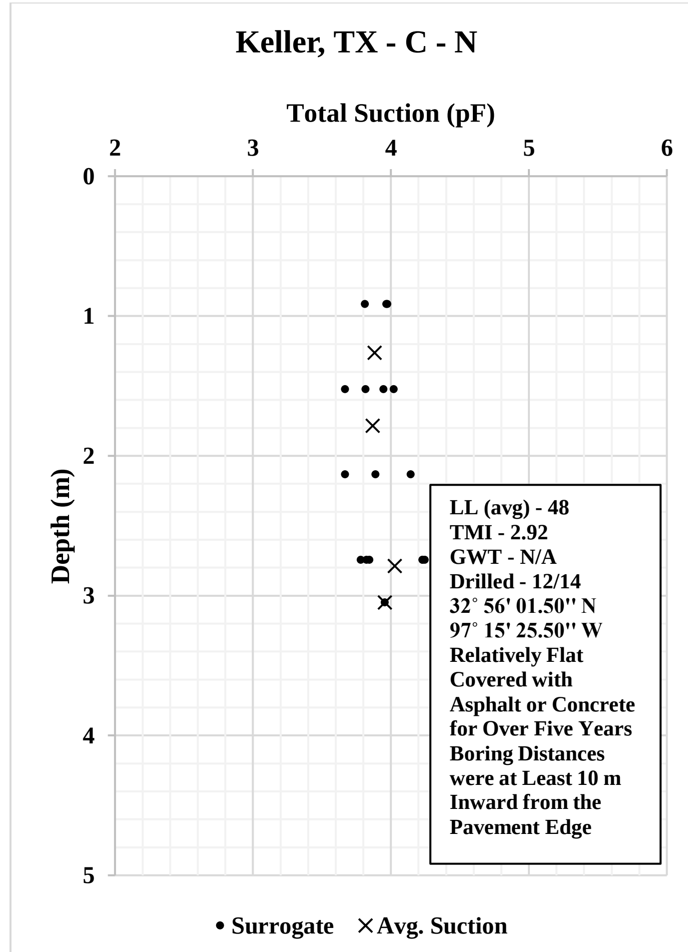


Figure 6.109: Surrogate Soil Suction Profile for Keller, TX

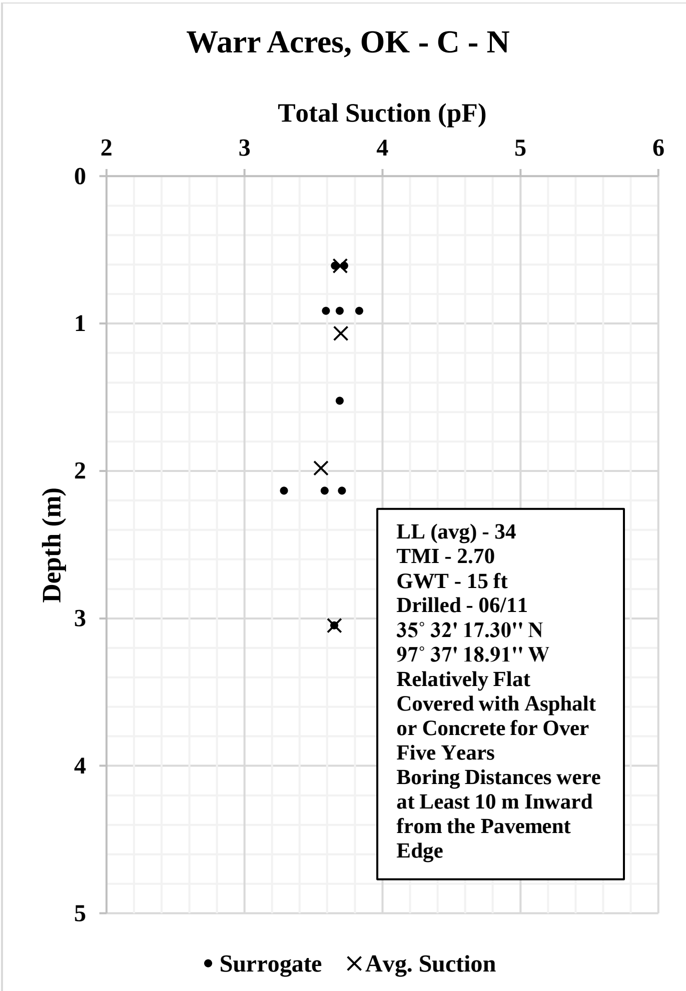


Figure 6.110: Surrogate Soil Suction Profile for Warr Acres, OK

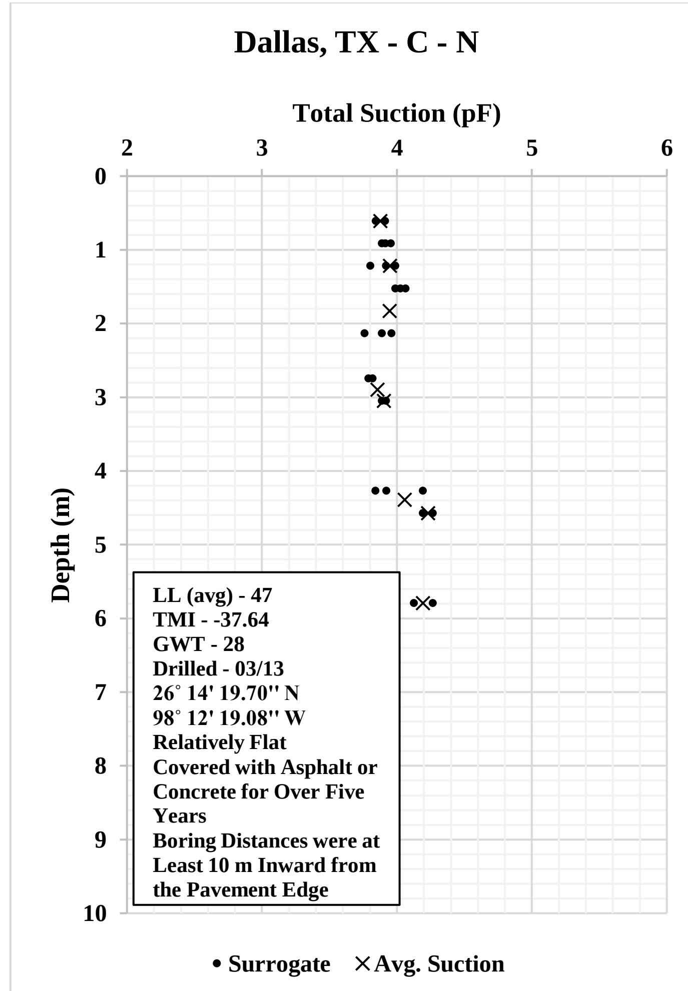


Figure 6.111: Surrogate Soil Suction Profile for Dallas, TX

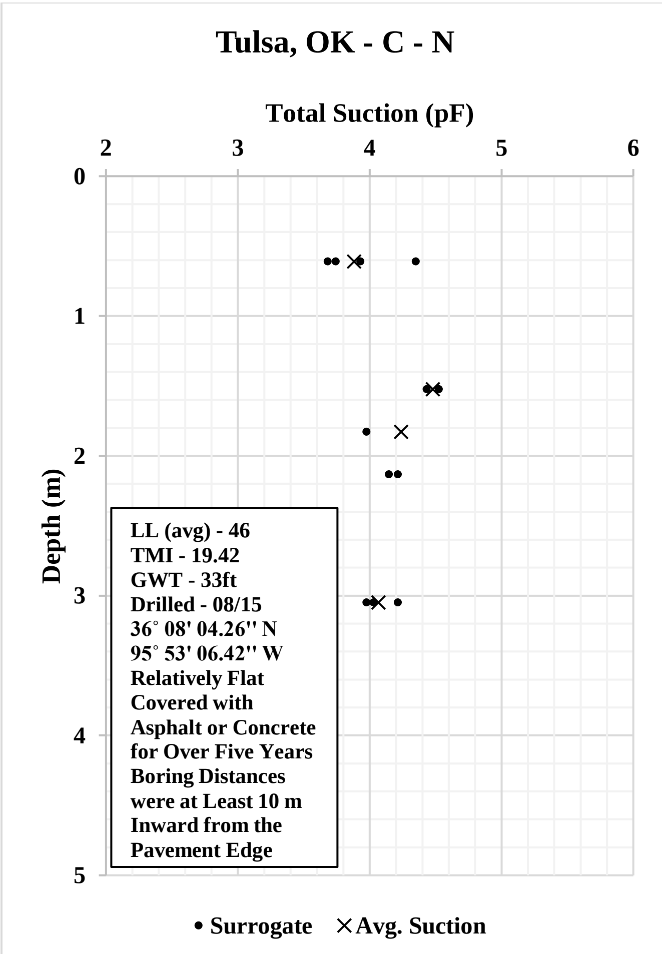


Figure 6.112: Surrogate Soil Suction Profile for Tulsa, OK

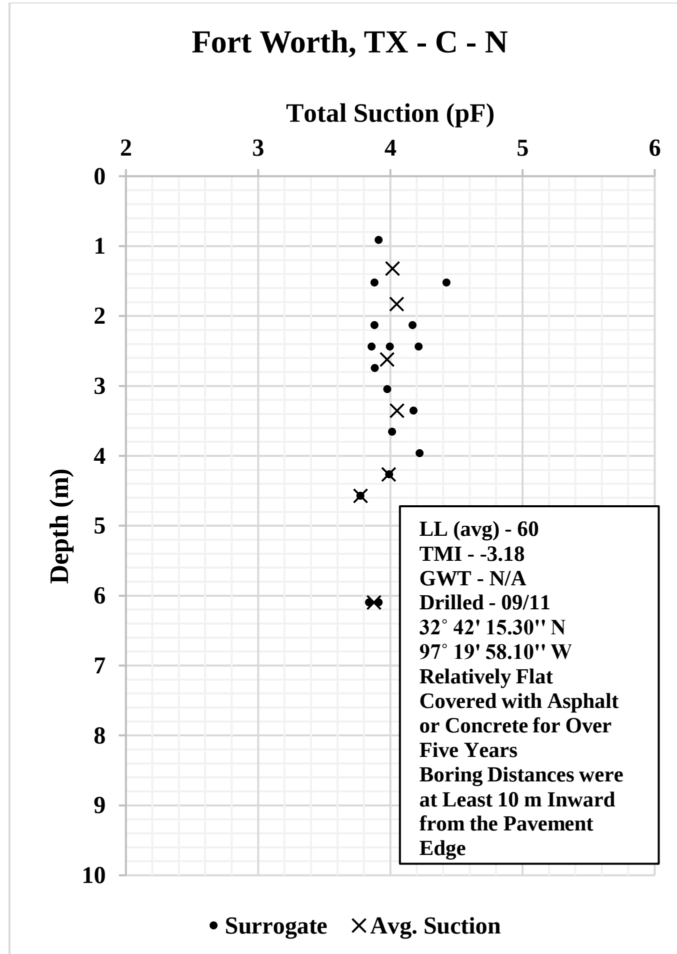


Figure 6.113: Surrogate Soil Suction Profile for Fort Worth, TX

For covered sites that have been verified to be covered for at least 5 years, the magnitude of equilibrium suction is commonly reached directly below the surface covering, as shown in the preceding figures. A benefit of knowing that equilibrium suction is achieved beneath a development after 5 years is important in that it suggests that, where the covering remains intact, the minimum soil suction beneath an existing or proposed structure will equal the magnitude of the equilibrium suction. For the most part, the suction profile beneath an established covered site will approximate somewhat straight line, projected along a magnitude corresponding to the equilibrium suction. Furthermore, the obtained equilibrium suction magnitudes for the twelve sites utilizing the surrogate yield equilibrium suction magnitudes consistent with those presented in this research.

Turning now to the two covered sites drilled as a part of this study, San Antonio and Denver, it was not possible drill more than 10 ft in from the edge of the pavement at these locations. Further, the boundary conditions outside of the paved surface at the San Antonio location corresponded to irrigated, rather than climatic only. Nonetheless, the covered sites drilled as a part of this study offer an opportunity to compare measured and surrogate suction profiles beneath paved surfaces. Examining the measured and surrogate data for the Denver site that was drilled, sampled and laboratory tested as part of this study, a comparison plot, Figure 6.114, was created to contrast the covered-site measured and surrogate soil suction.

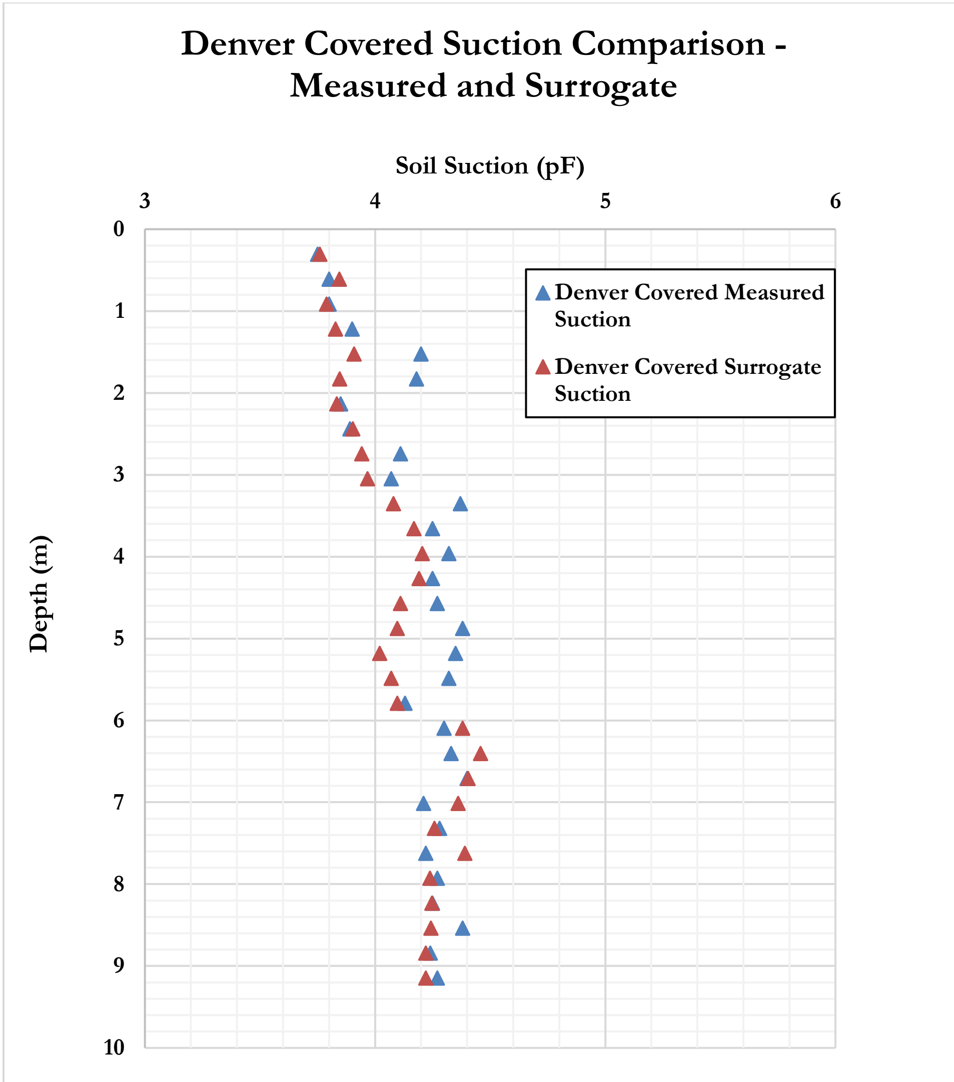


Figure 6.114: Comparison of Measured and Surrogate Soil Suction for the Denver Site Used in this Study, Denoted as DEN-5-C-N

From the plot, a fairly close agreement exists between the measured data and the surrogate. Regarding the covered condition, both sets of data, measured and surrogate demonstrate that the equilibrium suction is 4.23 pF, which is reasonably close to that predicted by Equation (144), i.e. within 0.1 pF of the predicted magnitude.

A second site drilled, sampled and laboratory tested as part of this study was San Antonio. Figure 6.115 depicts a comparison of the measured and surrogate data points for the covered condition. As with the Denver plot, the San Antonio plot demonstrates a reasonable agreement between the measured and surrogate data. The magnitude of equilibrium suction for the plotted data is 4.12 pF, which corresponds to the predicted magnitude using Equation (144).

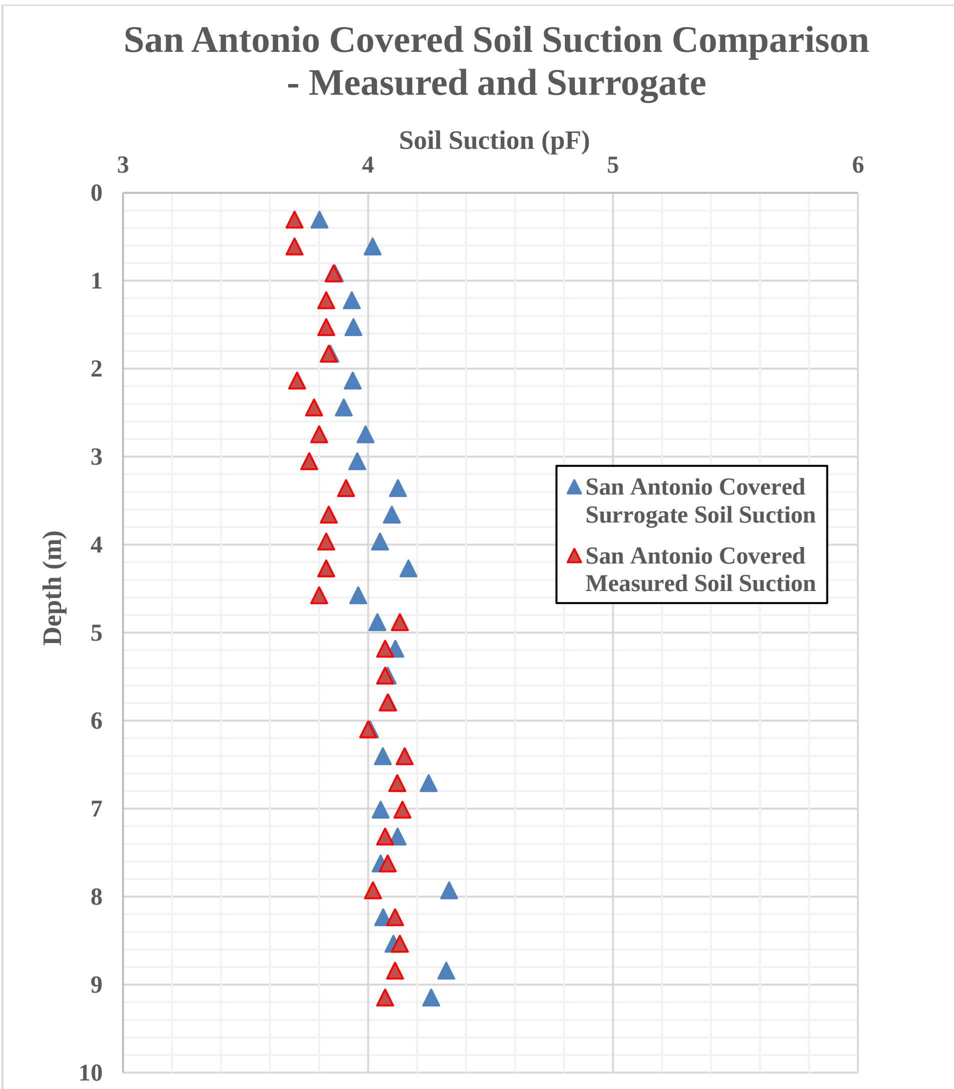


Figure 6.115: Comparison of Measured and Surrogate Soil Suction for the San Antonio Site Used in this Study, Denoted as SA-1-C-N

Both the Denver and San Antonio plots for covered profiles show a slight tilt towards wet in the suction profile as it progresses toward the surface. The character of the covered soil suction profile for Denver suggests that perhaps the pavement structure has not been in-place long enough for the equilibrium condition to have been achieved. For the San Antonio site, while the pavement has been in-place for over 20 years, a significantly irrigated area exists immediately off the edge of the pavement edge. The research test boring was positioned exactly 3.048 m (10 ft) inward from the edge of the pavement for the San Antonio site. As such, there may be some seasonal moisture fluctuations at the distance of 3.048 m (10 ft) arising from the irrigation, i.e. higher moisture contents driving the suction lower than the equilibrium magnitude.

6.7 Discussion of the Effects of Irrigation on the Magnitude of Equilibrium Suction and Depth to Equilibrium Suction

Using the results of moisture content and Atterberg Limits data from four sites, a surrogate suction versus depth profile was created (after Cuzme, 2018). Three of the four sites (Cuzme, 2018) were actively involved with agricultural production, while the fourth was a developed residential area with robust irrigation. Four additional irrigated sites with measured suction profiles were also included in this study. The total number of irrigated sites considered is eight. Aerial photographs and the measured or surrogate suction profiles are provided in Figure 6.116 through Figure 6.121. An aerial photograph of the Denver site was not included due to ongoing litigation; however, the aerial photograph shows residential with green irrigated lawns and closely spaced houses.

Figure 6.116: Aerial Photograph of the Frisco, TX Site

Figure 6.117: Aerial Photograph of the Royce City, TX Site

Figure 6.118: Aerial Photograph of the Hazel Green, AL Site

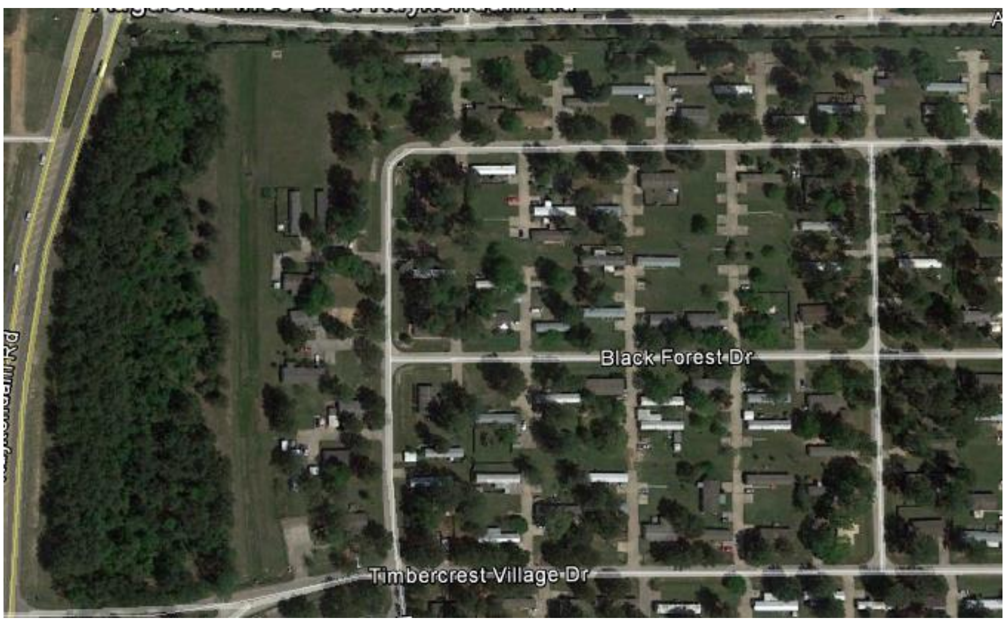


Figure 6.119: Aerial Photograph of The Woodlands, TX Site

Figure 6.120: Aerial Photograph of San Antonio, TX Site

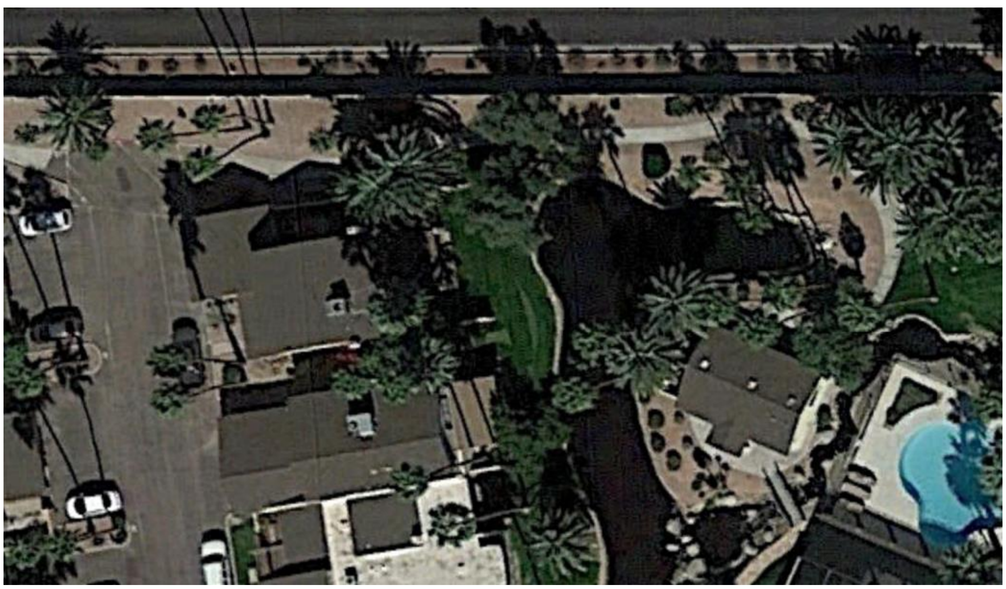


Figure 6.121: Aerial Photograph of Mesa, AZ Site

The measured or surrogate soil suction profiles for the sites shown in Figure 6.116 through Figure 6.121, are presented in Figure 6.122 through Figure 6.129. Added to the suction profiles are the seasonal fluctuation envelopes (assuming no added irrigation) corresponding to the wet and dry sides based on the equilibrium suction and other relationships established in this study in prior sections of Chapter 6. The shape of the envelopes is controlled by the equations associated with the Mitchell (2008) work and the models developed as part of this research.

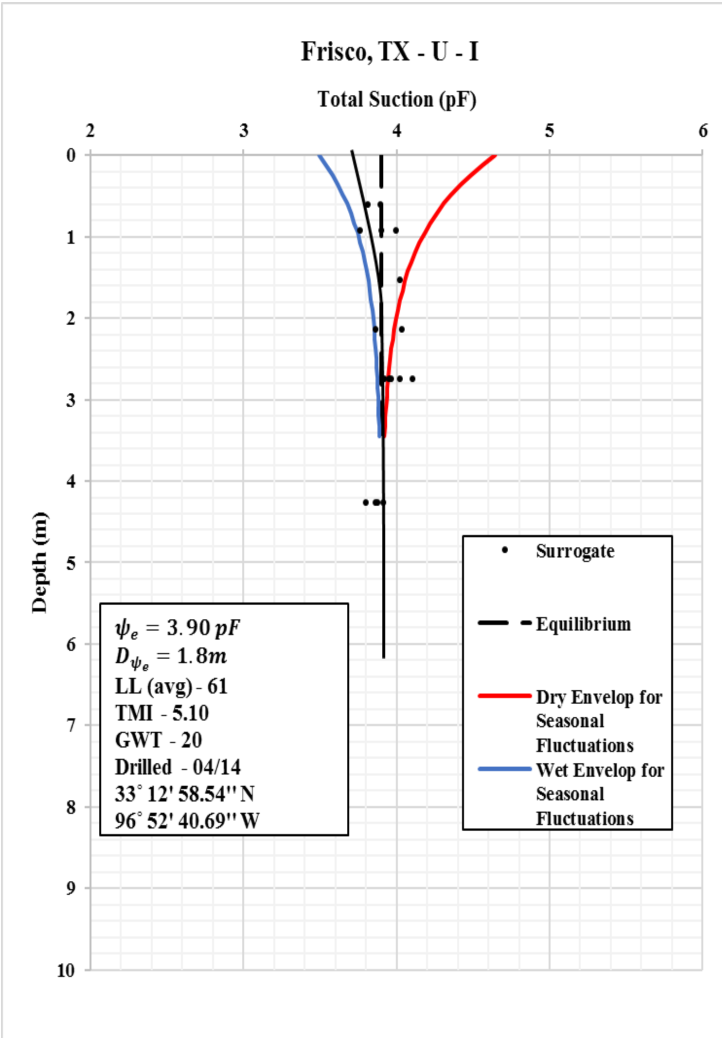


Figure 6.122: Surrogate Suction Profile at Frisco, TX

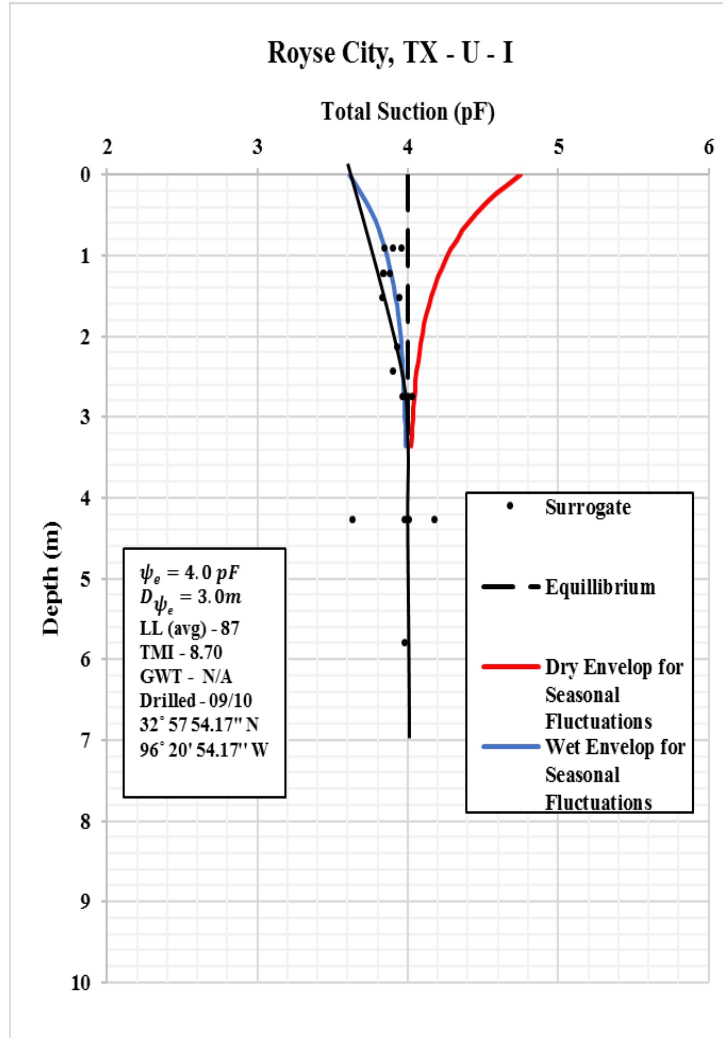


Figure 6.123: Surrogate Suction Profile at Royce City, TX

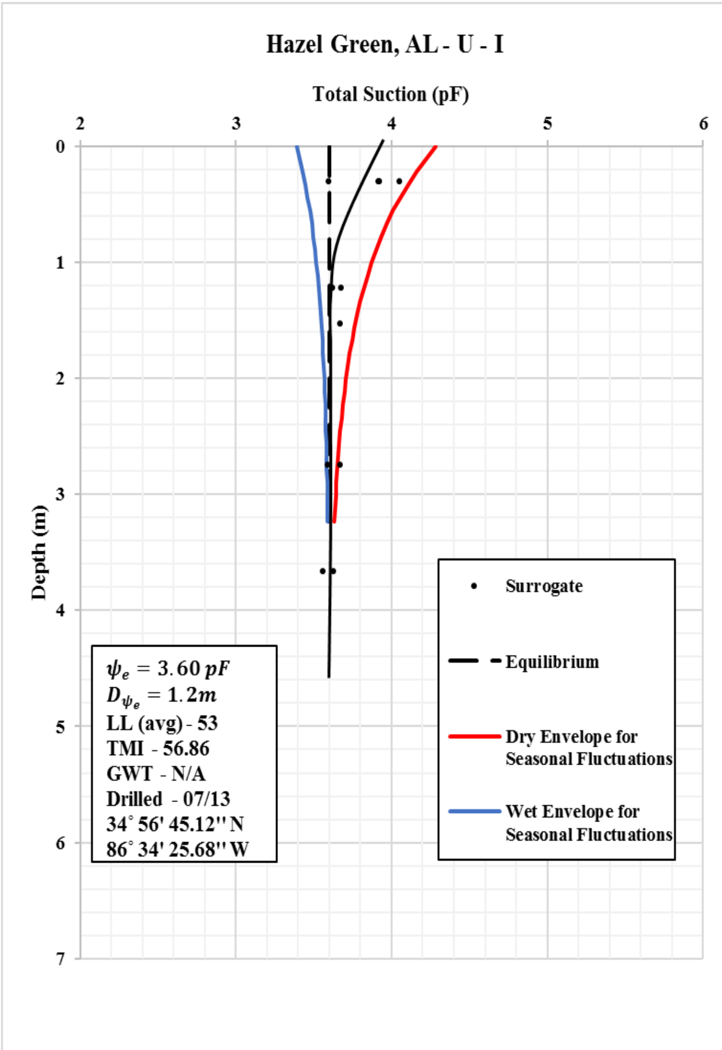


Figure 6.124: Surrogate Suction Profile at Hazel Green, AL

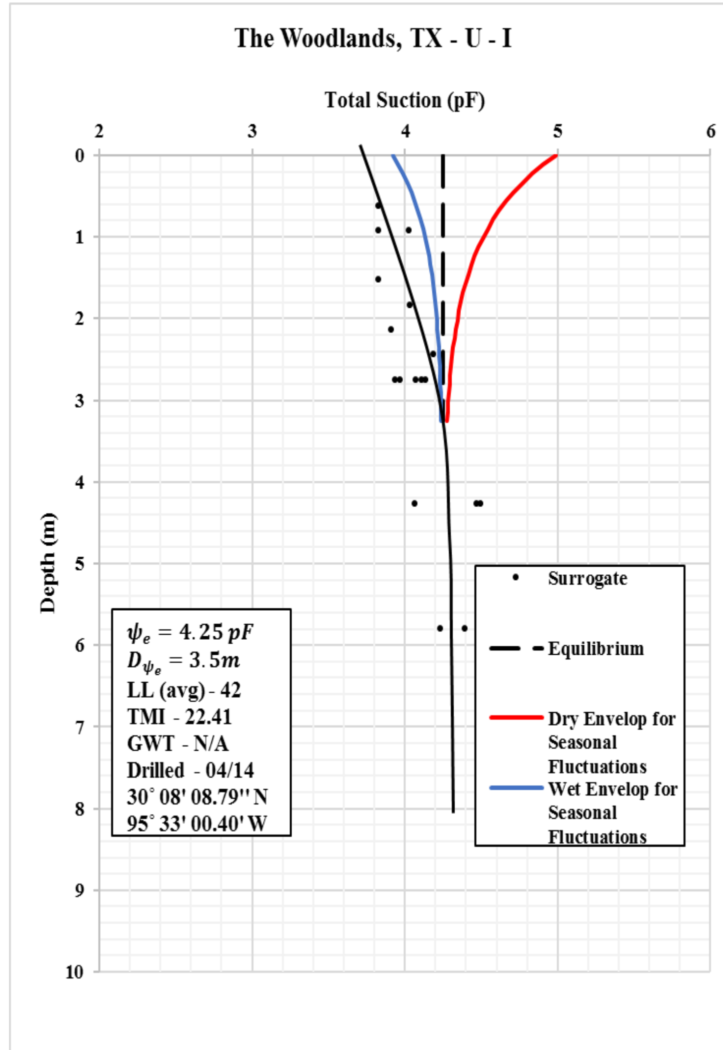


Figure 6.125: Surrogate Suction Profile at The Woodlands, TX

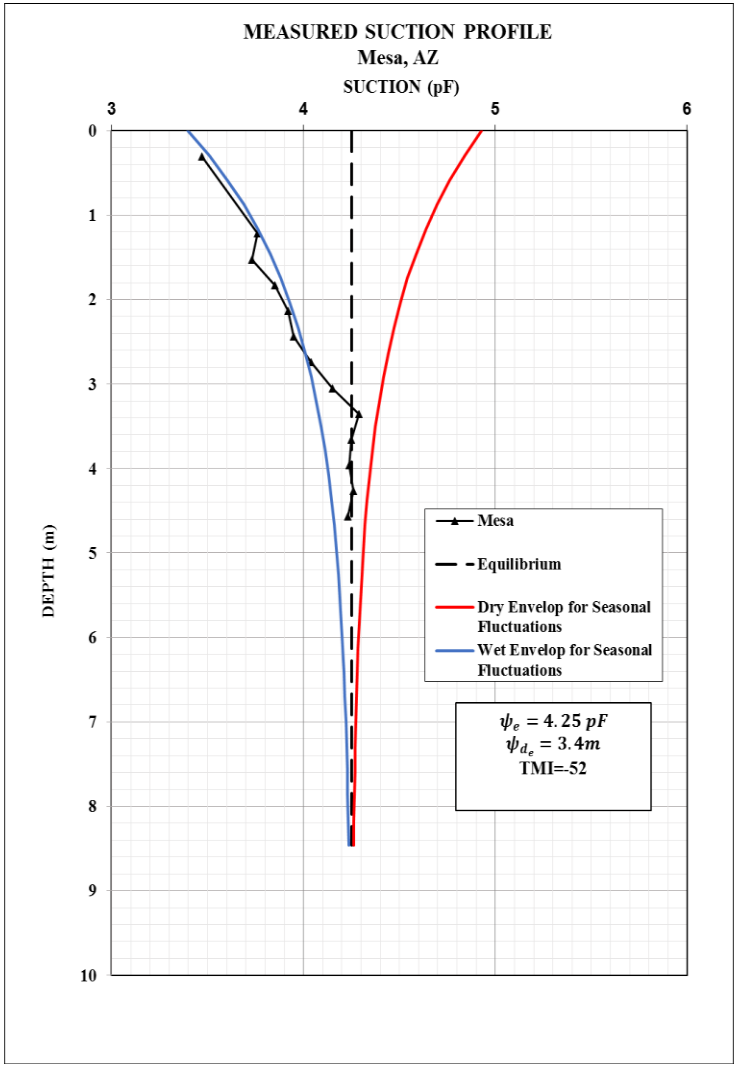


Figure 6.126: Measured Suction Profile at Mesa, AZ

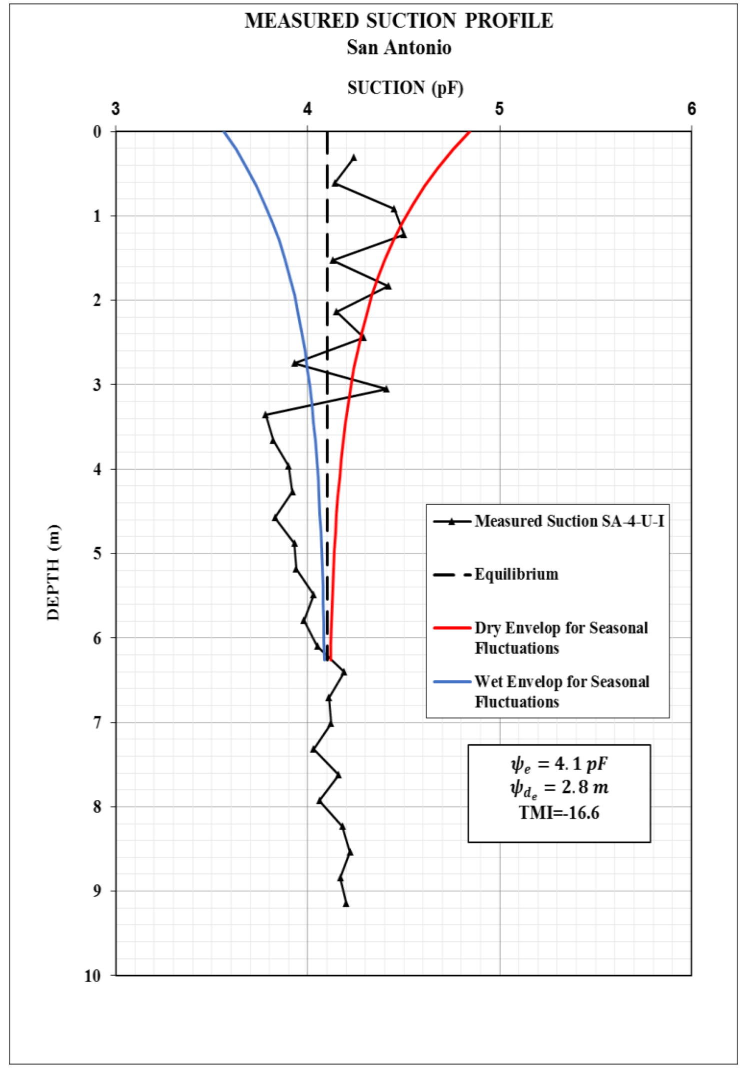


Figure 6.127: Measured Suction Profile at San Antonio, TX

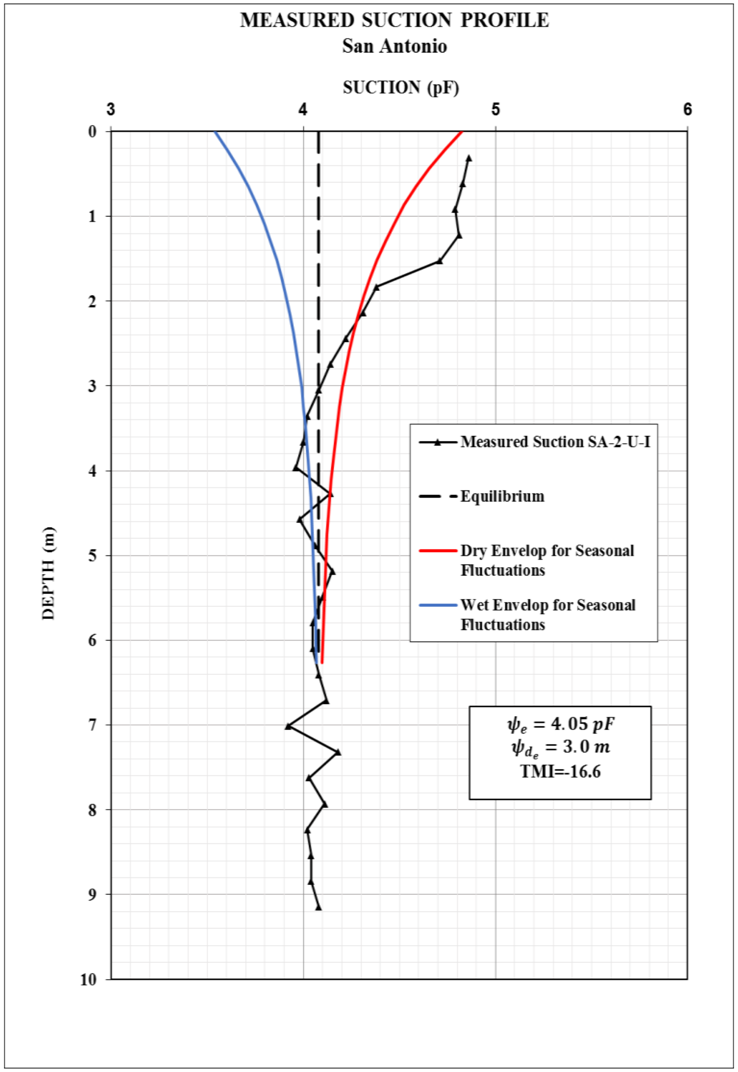


Figure 6.128: Measured Suction Profile at San Antonio, TX

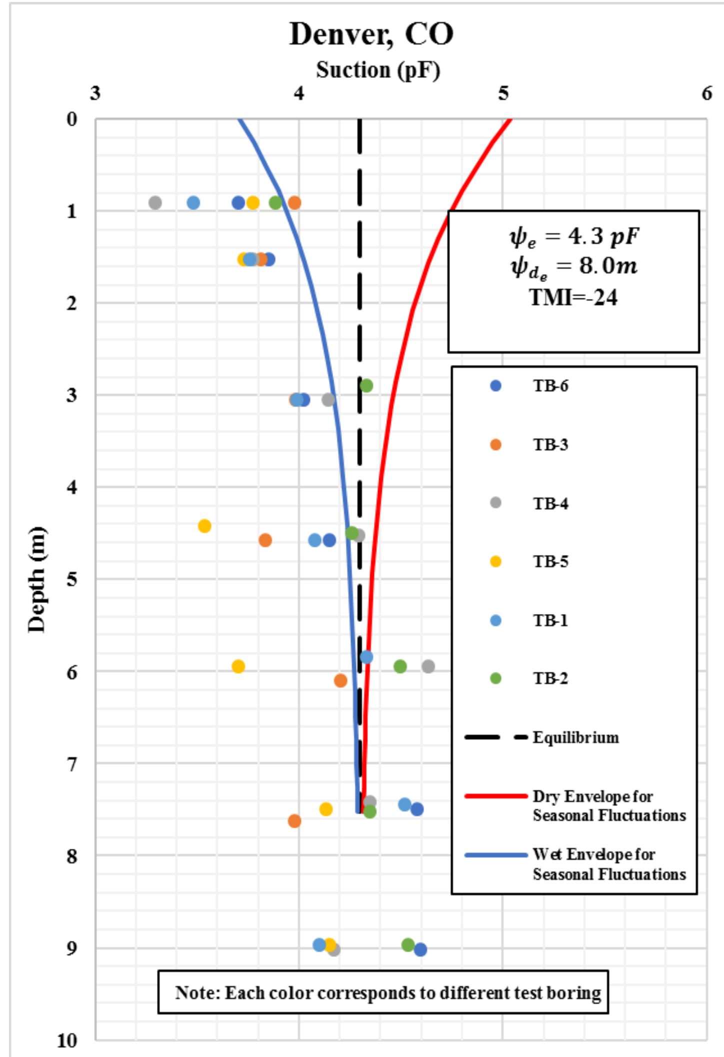


Figure 6.129: Measured Suction Profiles at Denver, CO

Table 6.29 summarizes the TMI, depth to equilibrium suction and magnitude of equilibrium suction for the eight irrigated sites considered.

Table 6.29: Summary of Data Relative to Irrigated Sites in Connection with the Magnitude of Equilibrium Suction and Depth to Equilibrium Suction

Location	**Site Conditions**	**TMI**	**Depth to Equilibrium Suction (m)**	**Equilibrium Suction**
Royse City, TX	Agriculture	8.7	3.0	4
Hazel Green, AL	Agriculture	56.86	1.2	3.6
Frisco, TX	Agriculture	5.1	1.8	3.9
San Antonio, TX	Open Lawn, Forensic	-16.6	3.0	4.05
San Antonio, TX	Open Lawn, Forensic	-16.6	2.8	4.1
The Woodlands, TX	Residential / Developed	22.41	3.5	4.25
Denver, CO	Residential / Developed/ Forensic	-24.76	8.0	4.3
Mesa, AZ	Residential / Developed/ Forensic	-52	3.4	4.25

Based on the limited data on developed/irrigated sites gleaned from this study, and shown in Figure 6.130, whether heavy (e.g. residential, including forensic, or heavy agricultural irrigation) or moderate (residential or agricultural) irrigation occurs at a site does not appear to form a basis for modification to the Equilibrium Suction vs TMI relationship developed for seasonal fluctuations (Figure 6.130). However, as depicted in Figure 6.131, heavy irrigation or ponding of water near-surface, such as occurs often in forensic cases, can result in depth of wetting greater than that determined for seasonal fluctuations alone (Figure 6.131). An exception to these instances of deeper wetting with heavy irrigation may be where the site is quite arid and cracks are prevalent. In such cases, irrigation could result in a closing up of cracks and a reduction in depth of wetting; the

Mesa forensic site depicted above could be such a case. In general, A review of the suction profiles from the developed sites also supports that some irrigation and development, with proper control of site water, can occur with little impact on the suction design profiles relative to those obtained for seasonal. However, heavy irrigation, particularly that associated with residential development and very green and dense vegetation (and possibly near-surface water ponding), can result in a wetted profile that is wet of the wet envelopes established for seasonal fluctuation conditions. These facts speak strongly to the importance of adherence to geotechnical engineering recommendations for control of site water (e.g. surfaces sloped away from structure, roof gutter directed well away from the structure, preferably to enclosed pipes leading to off-site storm drainage, liners for planters and tree root barriers, lined trenches for pressurized water lines, etc.).

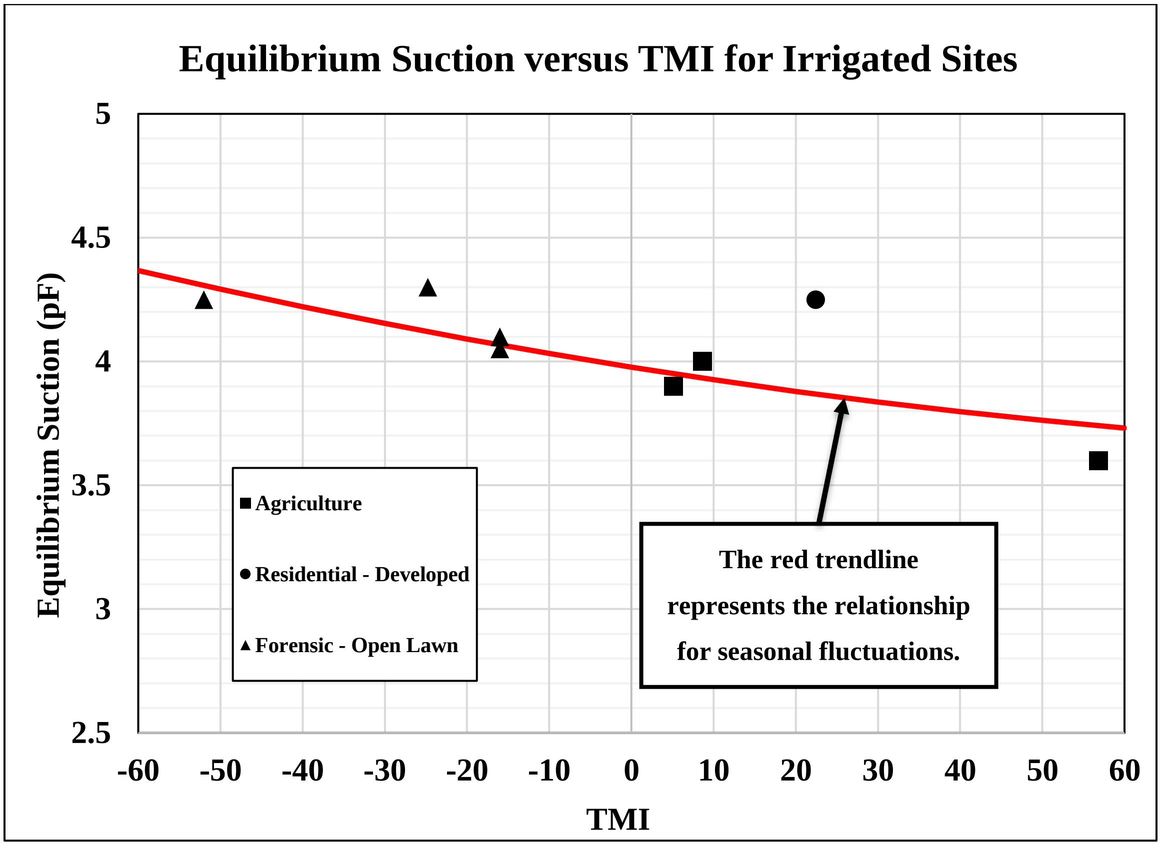


Figure 6.130: Equilibrium Suction Magnitude for Irrigated Sites Plotted on the Relationship of the Magnitude of Equilibrium Suction versus TMI

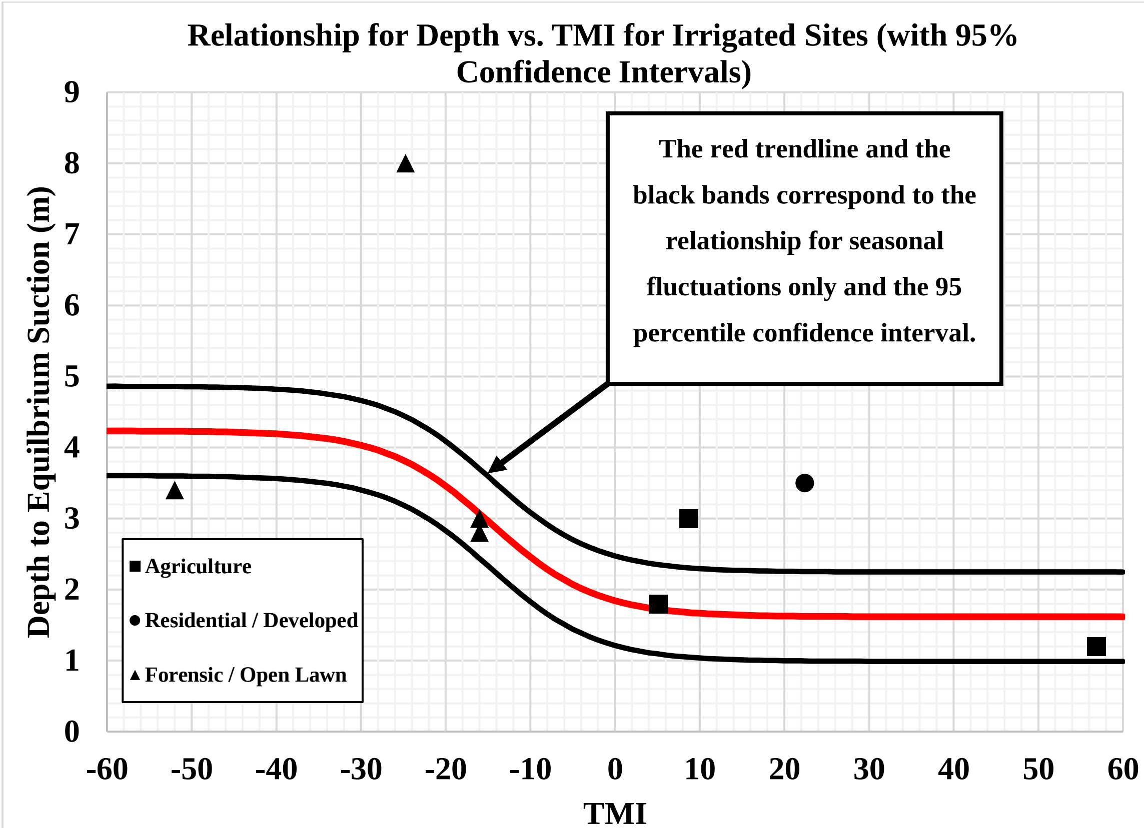


Figure 6.131: Depth to Equilibrium Suction for Irrigated Sites Plotted on the Relationship of the Depth to Equilibrium Suction versus TMI

CHAPTER 7 SUMMARY RECOMMENDATIONS AND ASSOCIATED JUSTIFICATIONS FOR DEVELOPMENT OF INITIAL AND FINAL SOIL SUCTION PROFILES FOR HEAVE ESTIMATION

This chapter summarizes the recommendations for relationships for the magnitude of equilibrium soil suction, depth to equilibrium soil suction and the seasonal change in soil suction at the surface versus TMI that can be utilized by practitioners in design applications where seasonally-driven suction profiles are of concern. Recommendations for soil suction profiles are predicated on:

- Equation (139) for the soil suction surrogate; $\psi = 3.2346\left(\frac{w}{LL}\right)^{(-0.217)}$
- Equation (144) for the magnitude of equilibrium suction; $\psi_e = 0.00002(TMI)^2 - 0.0053(TMI) + 3.9771$
- Equation (148) for the depth to equilibrium suction; $D_{\psi_e} = 1.617 + \frac{2.617}{1+e^{(2.36+0.1612TMI)}}$
- Equation (156) for the change in suction at the surface; $\Delta\psi\ (in\ pF\ units) = 1.2109e^{-0.005TMI}$
- Equation (158) for determination of the Aubeny and Long (2007) concept 'r' climate parameter; $'r' = 0.3725e^{-0.009TMI}$

7.1 Relationship Between TMI and the Magnitude of Equilibrium Soil Suction

The historical studies regarding equilibrium soil suction determination, while all being exceptional work, were focused primarily on pavement studies and on relatively shallow depths. In many cases, soil suction beneath pavements, and not necessarily equilibrium soil suction, was examined in past research on a horizontal basis (from pavement edge) as opposed to vertical (depth-dependent basis that is required for foundation design and analysis where vertical flow dominates. The reason for historical data being of limited use in establishment of TMI versus equilibrium soil suction relationships is simple: in much of the literature the main attention was given to pavement structures and more specifically how the soil suction varied from the edge of the pavement to the center, accompanied by moisture changes or time to stabilization. From the earlier days to the present, the focus of soil suction research has expanded from focus on a horizontal or lateral variation to a greater focus on depth of wetting, or vertical basis, which is consistent with the fact that interest has widened from pavements to structure foundations. Furthermore, as horizontal or lateral moisture change was of most interest in early work focused on pavements, soil suction data, as noted, historically may not have been at an equilibrium magnitude but rather a soil suction corresponding to a specific moisture content and location beneath pavements. In short, soil suction measurement, and magnitudes of equilibrium soil suction, were not viewed historically as they are today, except for much of the research comprising the PTI approach to expansive soils. Researchers in Australia, however, have focused on results obtained generally from adequate depths to correspond to equilibrium soil suction. Much of the Australian research has included drilling and sampling to depths greater than or equal to 4.0 m (13.1 ft).

These results of this study, as well as opinions set forth by previous investigators of expansive soils, including Lytton and colleagues, suggest that TMI may not be the only factor to look at when trying to determine equilibrium soil suction, and in fact, there are likely more factors which affect equilibrium soil suction values, some of which may be difficult to investigate. Factors affecting field soil suction values which are independent of the climate condition (TMI) should be investigated further. It is possible that equilibrium soil suction is so site specific, that rather than looking at TMI for a given region, the site location and site conditions should be accounted for. Walsh et al. (2009) investigated the depth of wetting in residential areas in the Denver metropolitan area and presents a site-specific approach and a regional approach. The regional approach took all data and obtained a single pre-construction soil suction profile for the Denver area. The soil suction profile was then compared to each single site for the site-specific approach. It was found that there was some variation in equilibrium soil suction, which may indicate that there is more to equilibrium soil suction values than only TMI, which is typically taken to be TMI value for a relatively large region rather than a small site-specific region. Degree of homogeneity or layering in the soil profile may also have an influence on the equilibrium soil suction as soil type and layering affects unsaturated flow. Soil weathering and cracking is also a factor. With layering in the profile, there may be variations in “net” hydraulic conductivity of soil profiles within a given TMI region. Recommendations for further study are discussed subsequently.

While site-specific drilling, sampling and laboratory testing is always the preferred way to arrive at the most reliable magnitude of equilibrium soil suction, in the absence of site-specific data, it has been concluded from this study that Equation (144) will yield a reasonable and acceptable magnitude on which the practitioner may rely.

Figure 7.1 is recommended for use by practitioners. The relationship is described by Equation (144). It should be noted, however, that the flatness of the curve relating equilibrium suction to TMI is indicative of a relatively weak relationship, as borne out by field evidence wherein regional shifts in equilibrium suction, relative TMI estimated values, are often required to match measured suction profiles.

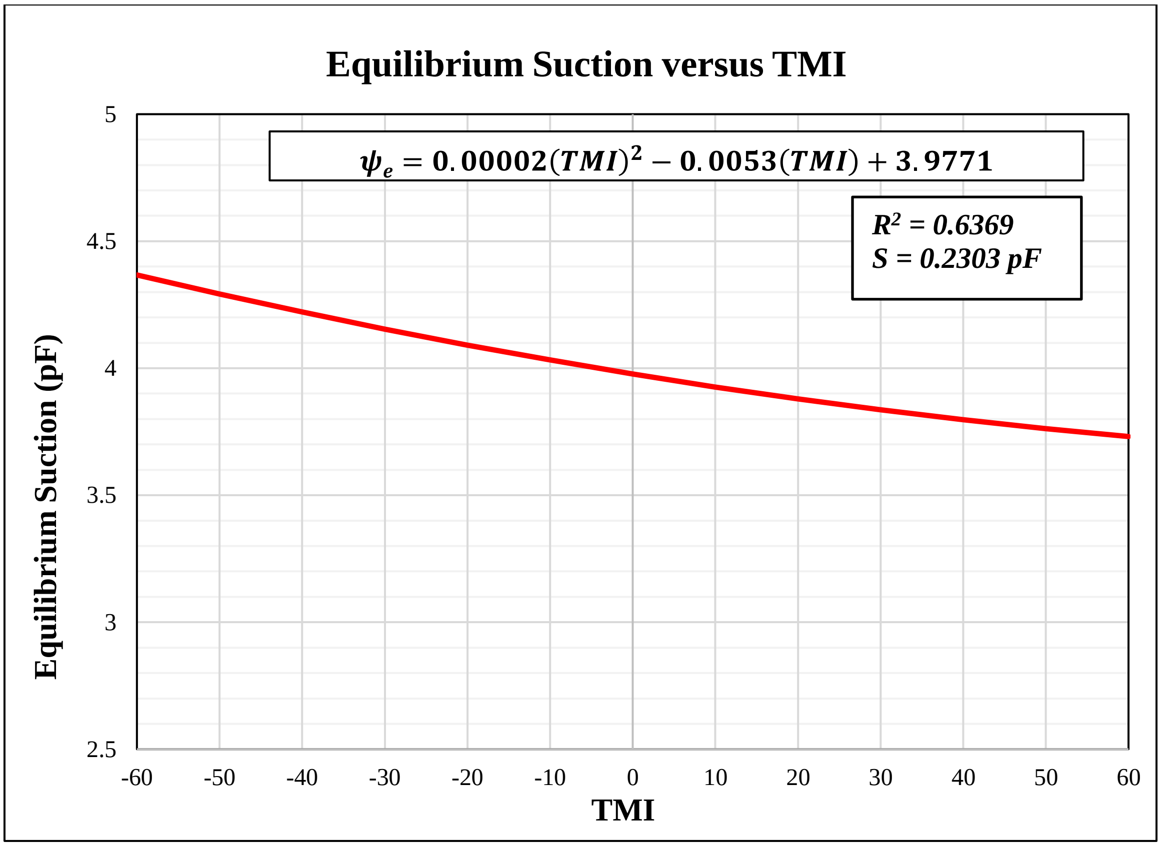


Figure 7.1: Magnitude of Equilibrium Soil suction Versus TMI

7.2 Relationship Between TMI and the Depth to Equilibrium Soil Suction

Practitioners, the apparent controlling factor on the use of unsaturated soil mechanics, need something simple yet reliable to use when estimating the depth to constant soil suction. Of course, the best course of action would be employed during the performance of a geotechnical investigation. Such measures are outlined in this document. Where such data is not available, it has clearly been demonstrated that the use of the soil suction surrogate is a viable tool to predict the depth corresponding to where the soil suction becomes relatively constant. Results of Cuzme (2018) promote the use of a soil suction surrogate to provide a reasonable method to estimate field soil suction profiles from the use of routinely measured liquid limit and moisture content. The surrogate works best when the liquid limit and moisture content are directly measured, and averages are not used (Cuzme, 2018). From the soil suction surrogate profiles, the depth to constant soil suction and equilibrium soil suction values may be obtained, while providing reasonable estimations.

Based on the relationship presented in Figure 6.53, a simple-to-use equation for estimation of depth to equilibrium suction, where direct data is not available, has been developed as indicated in Figure 7.2.

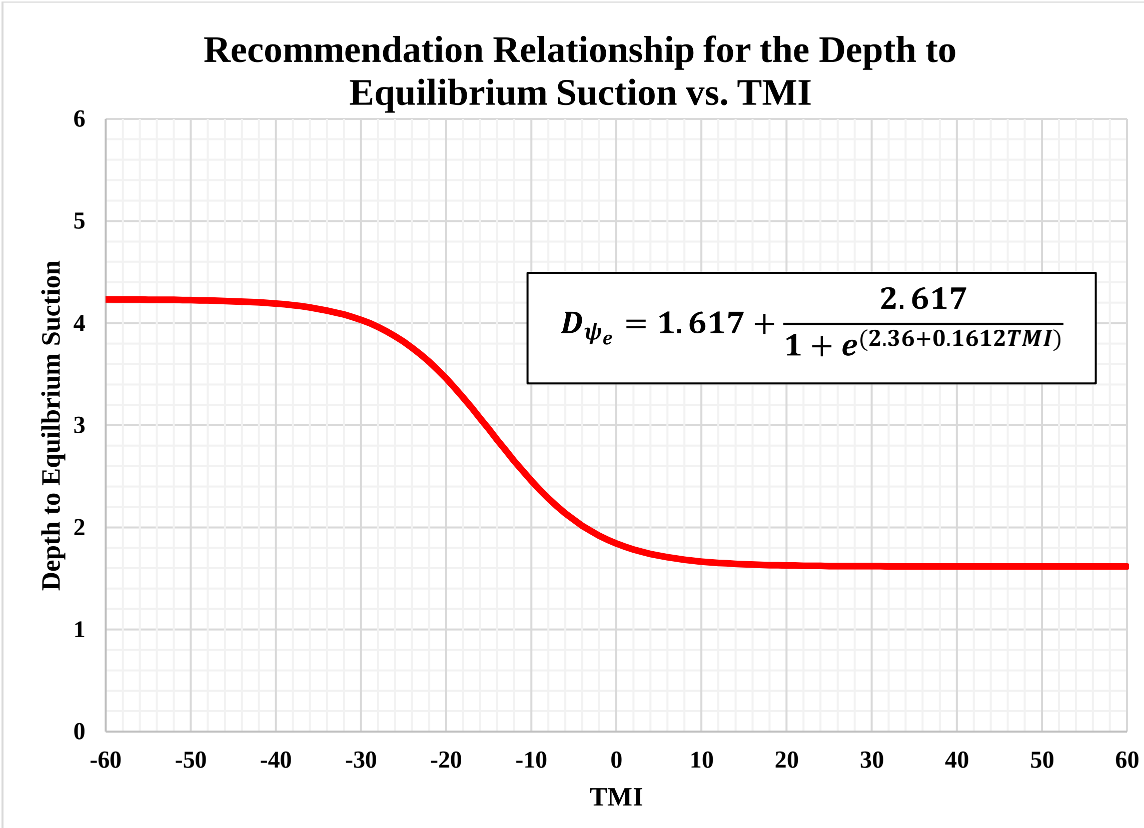


Figure 7.2: Recommended Depth to Equilibrium Soil suction versus TMI

Figure 7.2 presents the recommended form of the equation to relate TMI and the depth to the equilibrium soil suction. Table 7.1 has been presented to demonstrate the coefficients corresponding to the form of the equation for each LL group, previously discussed, along with the corresponding R^2 and S. However, the research completed do date suggests that the amount of data available is currently insufficient to offer the LL based plot and associated equations as recommendations for the practitioner.

Table 7.1: Equation Parameters for the Recommended Relationship Between the Depth to Equilibrium Soil Suction and TMI when Liquid Limit is Grouped

Liquid Limit Group	Equation Form	Shape Corrected Coefficients				S	R^2
		a	b	c	d		
LL<50	$\psi_{d_{eq}} = a + \frac{b}{1 + e^{(c+dTMI)}}$	1.489	2.782	2.496	0.1605	0.3244 m	0.9374
LL≥50		1.750	2.250	2.400	0.2100	0.3645 m	0.8468

Continued research is recommended to incorporate increased sampling of soils with LLs greater than 50 to gain further insight to the behavior of CH clays. Nonetheless, Equation (148) is recommended for use by practitioners, corresponding to the plot in Figure 7.2.

The two standard deviation band for the depth to equilibrium suction relationship is shown in the figure below.

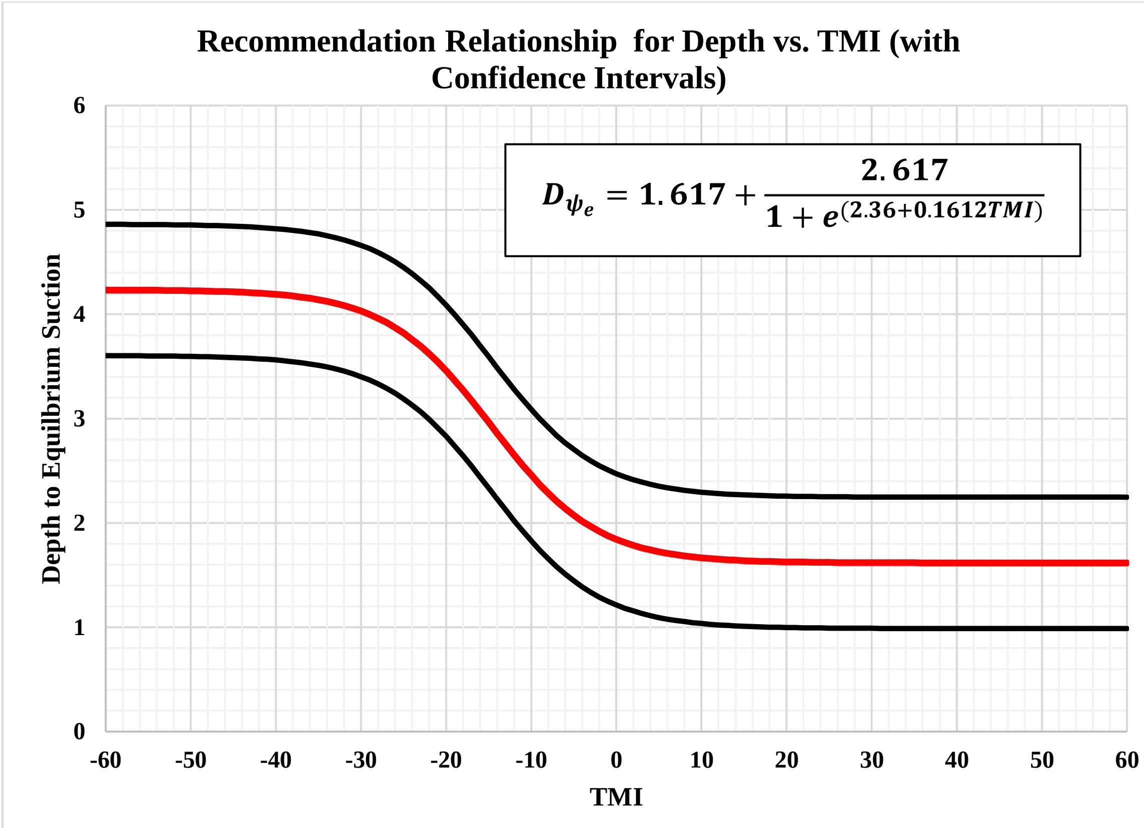


Figure 7.3: Recommended Depth to Equilibrium Soil suction versus TMI, with Confidence Intervals

While the model relationship is recommended to arrive at the depth to equilibrium suction, and its use for most applications, the heave predictions for the calculated depth to equilibrium suction can be compared to those corresponding to an extension of the suction envelopes well below the depth where the separation is no greater than 0.2 pF at the calculated depth. Further, for the practitioner, use of the upper confidence bound could be considered to determine if the heave predictions vary significantly from model estimated depth or the depth extended to that corresponding to two-standard deviations. For some cases, the two-standard deviation depth extension to the suction envelop may prove useful.

7.3 Relationship Between TMI and the Potential Change in Soil Suction at the Surface ($\Delta\psi$ in pF units)

To account for the anticipated soil suction change at the surface, Figure 7.4 is recommended. The curve presented by Figure 7.4 conforms to Equation (156) from the interval of TMI equaling -60 to +35. Beyond and including a TMI value of 30, the recommended change in soil suction at the surface should not be less than 1.0 pF. The reasons for truncating the predictive line such that it does not drop below 1.0 pF include two key points. First, and foremost, there is not sufficient data in the strongly positive TMI range to support recommendations continually decreasing toward the function minimum value of 0.8 pF. In fact, there is only one datapoint with a TMI greater than or equal to 30. Based on the need for further data, there is no basis for assuming that the function remains valid in the TMI region greater than or equal to 30. The second reason for a 1.0 pF truncation draws on the work by McManus (2004) who recommended that no value for the change in suction at the surface be lower than 1.0 pF.

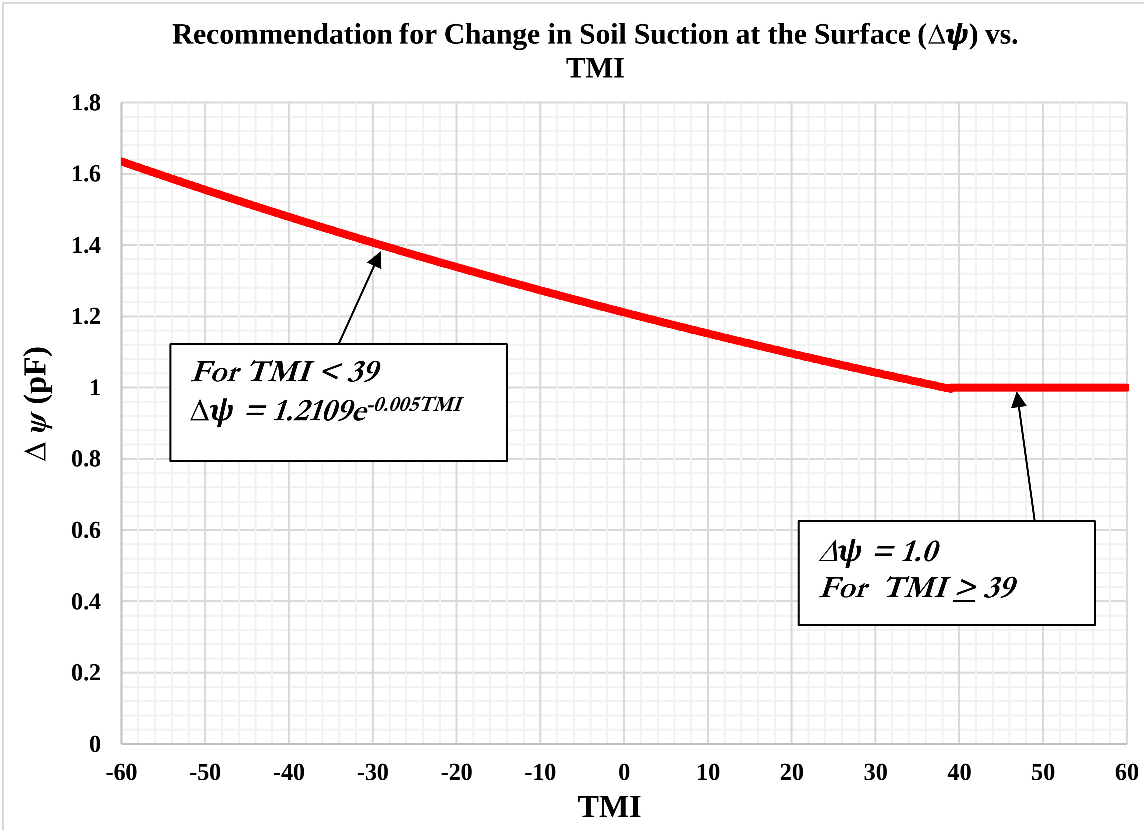


Figure 7.4: Proposed Method of Determining $\Delta\psi$ $(in\ pF\ units)$ Based on TMI

The question for determining $\Delta\psi$ $(in\ pF\ units)$ is partly answered by the recommended relationship. However, the question becomes a matter of determining how symmetrical or asymmetrical the vertical profile is surrounding.

7.4 Relationship Between TMI and the Degree of Asymmetry of the Soil Suction Envelope

Based on the work of Aubeny and Long (2007), the ‘r’ parameter has been expanded upon using the data collected as part of this research. Figure 7.5 presents a reasonable approximation of the expected asymmetry of a soil suction profile.

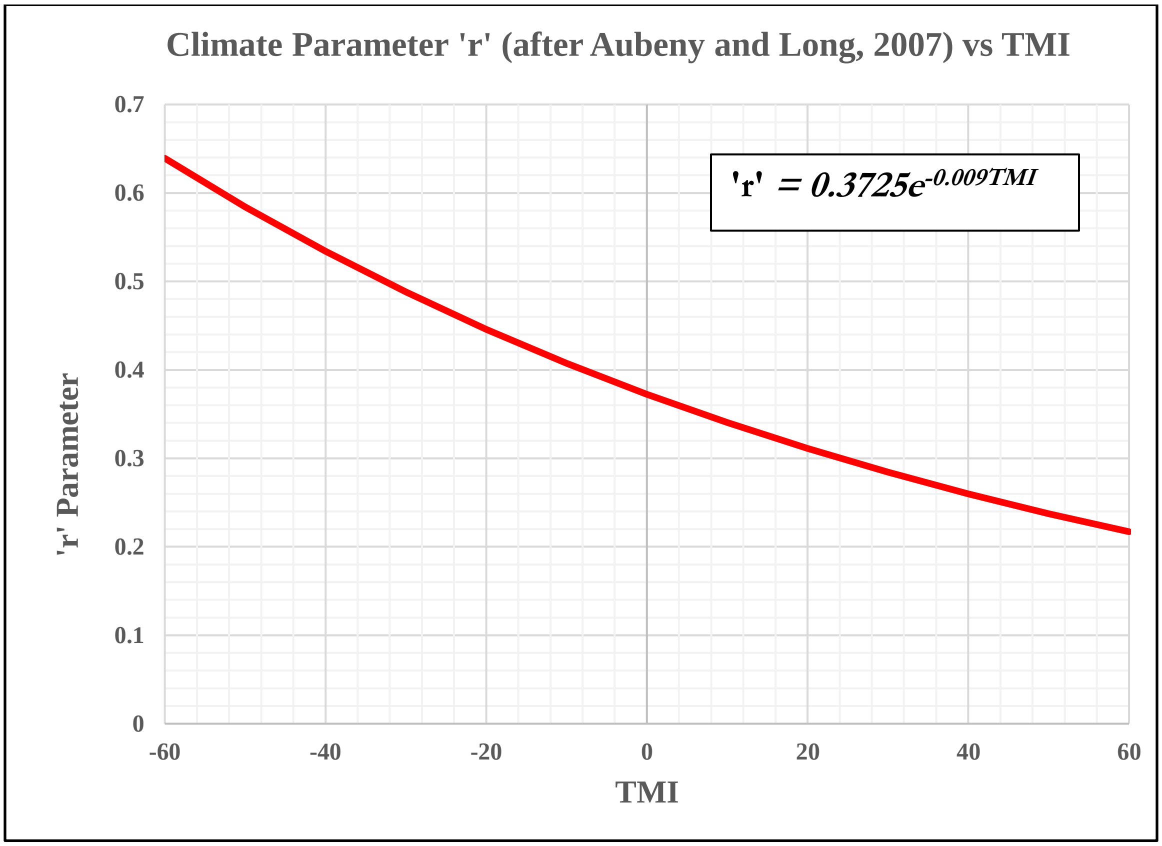


Figure 7.5: Recommended Use of the ‘r’ Parameter (after Aubeny and Long, 2007) for a Specific TMI

Using Figure 7.5 with an understanding of the work from Aubeny and Long (2007) will assist practitioners in formulating the final shape of the soil suction profile. Further, it reasonable that the value of the parameter ‘r’ should change according to variations in TMI. For the practitioner, it will be easy to reconcile that the ‘r’ parameter will have a unique value for every TMI, without being limited to three values as originally proposed by Aubeny and Long.

7.5 Developed Site Considerations

Per Cuzme (2018) for developed sites, the depth to constant suction (depth of wetting) would be expected to deviate from the depth to constant suction for seasonal fluctuations alone. Under an assumption of seasonal moisture fluctuations, the use of TMI to estimate depth to constant suction (depth of seasonal moisture change) is used by the Australians for design purposes of residential slabs on expansive soils and has been adopted into the Australian Standard for Residential Slabs and Footings (Cuzme, 2018).

As a site becomes developed, whether it is used for agricultural purposes or residential, the introduction of water into the soil profile, such as irrigation, may influence the depth to which moisture contents increase. The depth of wetting (depth to constant suction) may also affected by site development, and therefore the relationship between depth to constant suction and TMI for developed sites would, in general, be expected to be different than that for undeveloped and non-irrigated conditions. Development would be expected to increase the depth to constant suction as there is an increase of water migration with depth due to changed surface flux conditions. However, it is also possible that irrigation can result in closing up of cracks, thereby decreasing depth of water infiltration. Thus, it is challenging to predict the impacts of site development on suction profiles in the absence of study of actual field data. An attempt was made in this study to review developed site suction profiles using the suction surrogate.

Cuzme (2018) presents a comparison between non-irrigated and developed irrigated conditions regarding the relationship between depth of wetting (depth to constant suction) and TMI, for the limited amounted of data presented within his study. In his study, it was observed that the depth to constant suction for residential areas with landscaping, where ponding may be more common, resulted in a greater depth of wetting when compared to the trendline for undeveloped sites. For agricultural sites and open lawn irrigation, where there is more controlled irrigation and little ponding, the depths to constant suction observations were closer to the undeveloped non-irrigated trendline. The relationship between depth to constant suction vs. TMI for comparison between irrigated and non-irrigated sites is presented in Figure 28 of Cuzme's thesis. There were also no significant differences in equilibrium suction magnitudes between non-irrigated and irrigated site conditions which is presented in Figure 29 of Cuzme's thesis. In this study, a few additional developed sites were added to the Cuzme data, and the suction profiles for developed sites were compared to the seasonal fluctuation wet and dry envelopes. Heavy irrigation, such as occurs often in forensic cases, can result in wetter soil profiles and depth of wetting greater than that determined for seasonal fluctuations alone. An exception to these instances of deeper wetting with heavy irrigation could be in arid locations where clay profiles are cracked. Irrigation could result in a closing up of cracks and a reduction in depth of wetting, In general, however, it appears (again, based on the limited data available in this study) that some irrigation and development, with proper control of site water, can occur with little impact on the suction design profiles relative to those obtained for seasonal. These facts speak strongly to the importance of adherence to geotechnical engineering recommendations for control of site water (e.g. surfaces sloped away from structure, roof gutter directed well away from the structure, preferably to enclosed pipes leading to off-site storm drainage, liners for planters and tree root barriers, lined trenches for pressurized water lines, etc.).

7.6 Normalization of Suction versus Depth Plots to Account for the Change in Suction at the Surface, Equilibrium Suction Magnitude, and Depth to Equilibrium Suction versus Depth for Varying TMIs

Because of the available models introduced in this research, normalized plots are possible for the practitioners to use. As discussed herein, the shape of the suction envelopes is determined through the use of the magnitude of equilibrium suction, depth to equilibrium suction, change in suction at the surface, and climate ‘r’ parameter, using Mitchell’s 1980 simplifications to the unsaturated flow equation. With the key feature of the suction envelop established, there is no need to estimate the diffusion coefficient, α, and seasonal cycles per year, *n*, to obtain the shape of the suction profiles (needed parameters can simply be back calculated and the diffusion coefficient and number of cycles need not be determined independently). For each TMI, the work of Mitchell when combined with the measured or surrogate suction, magnitude of equilibrium suction, depth to equilibrium suction, change in suction at the surface, and climate ‘r’ parameter can be used to obtain the shape of the suction envelopes, and further simplification for use can be obtained through normalization of the suction envelop plots. Normalized suction envelopes, for TMI of -60 to 10 are shown in Figure 7.6 through Figure 7.9. The soil suction, in pF units, is normalized such that $\psi/\psi_e = 1$ at the value of equilibrium suction. The depth term, $d/D_{\psi e}$, denotes the normalized depth term. Where the depth, d, of the measured or surrogate suction equals the predicted depth to equilibrium suction, $d/D_{\psi e}=1$. The presented charts are for use with suction expressed in pF units.

The TMI curves progress in succession for the wet side of the suction envelop. In Figure 7.6, note that the curves cross over on the dry side of the suction envelopes. Furthermore, the cross-over occurs at about a TMI=-30. For the dry side of the suction envelop, the TMI curves proceed in succession to a TMI=-30, where they commence to cross to some extent. The dry-side curve crossing may be attributed to the non-linearity of the relationship between k_{unsat} and the matric suction.

Use of the normalized curves will enable the practitioner to develop the suction envelop, including both wet and dry sides, with the models presented herein and without the requirement for direct use of Mitchell's equation to obtain the shape of the suction envelopes; Mitchell's equation was used in establishment of the shapes of the normalized suction envelopes.

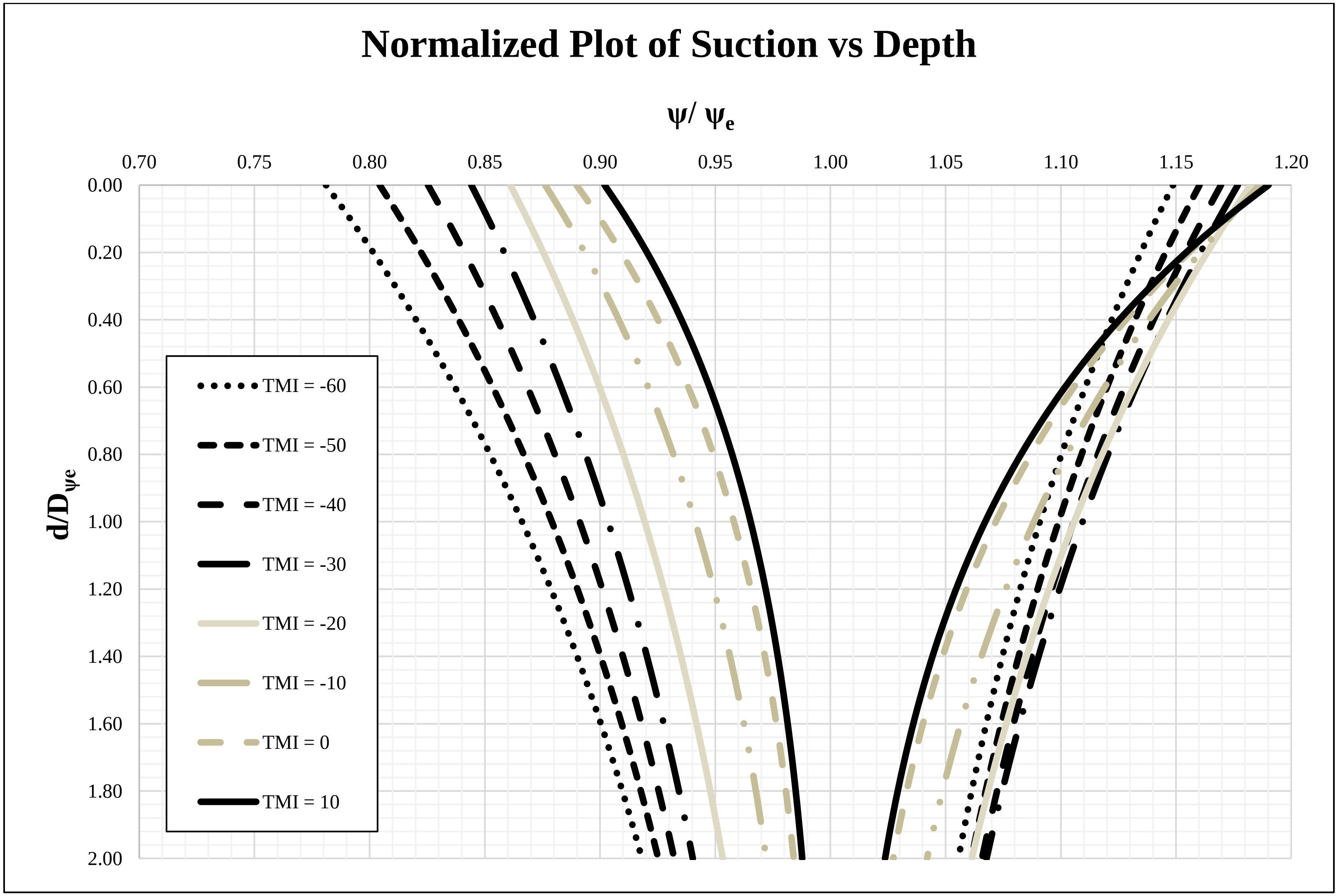


Figure 7.6: Normalized Plots of Suction and Depth for TMIs of -60 to +10 for Both the Wet and Dry-Sides of the Suction Envelop (Suction Expressed in pF)

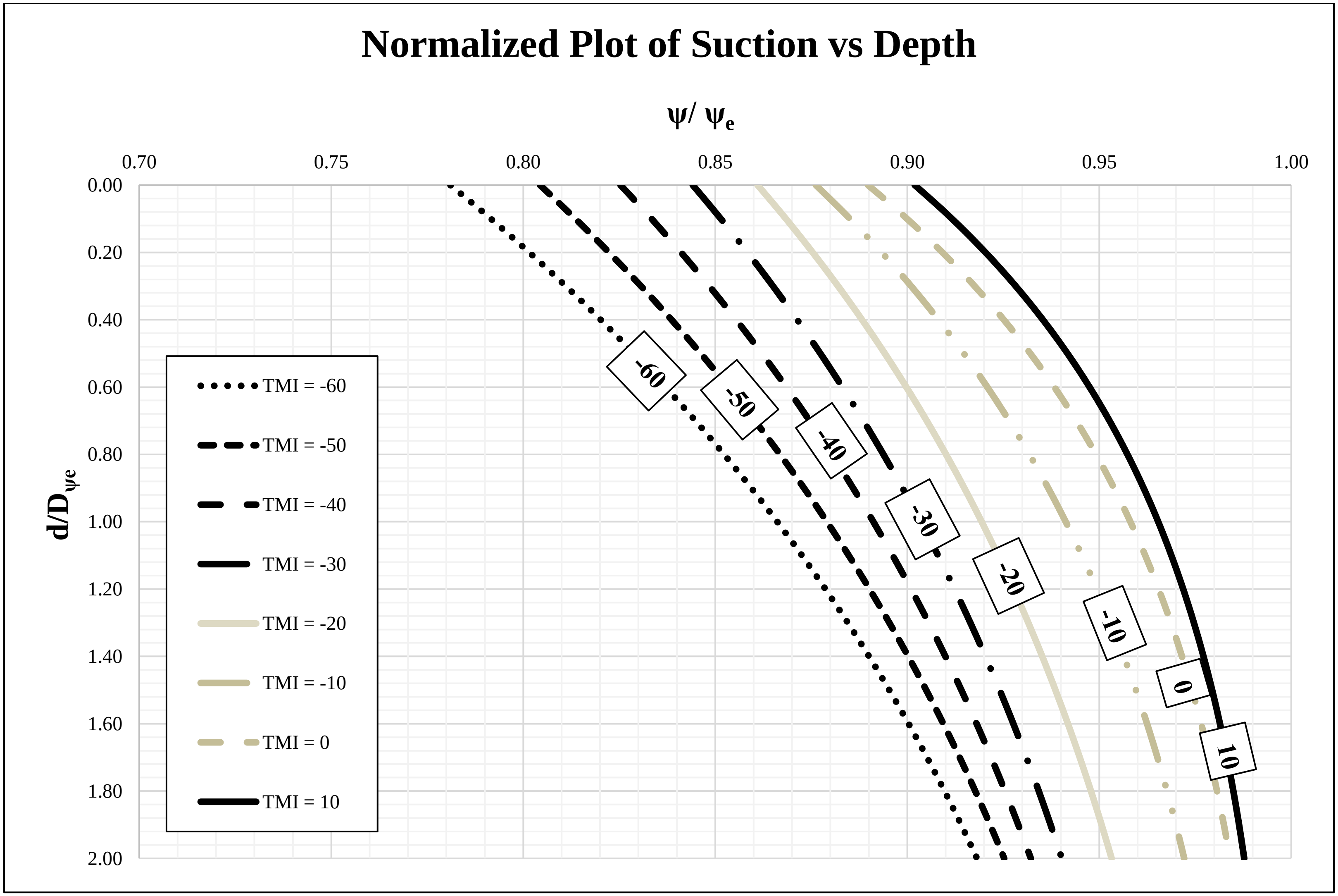


Figure 7.7: Normalized Plots of Suction and Depth for TMIs of -60 to +10 for the Wet-Side of the Suction Envelop (Suction Expressed in pF)

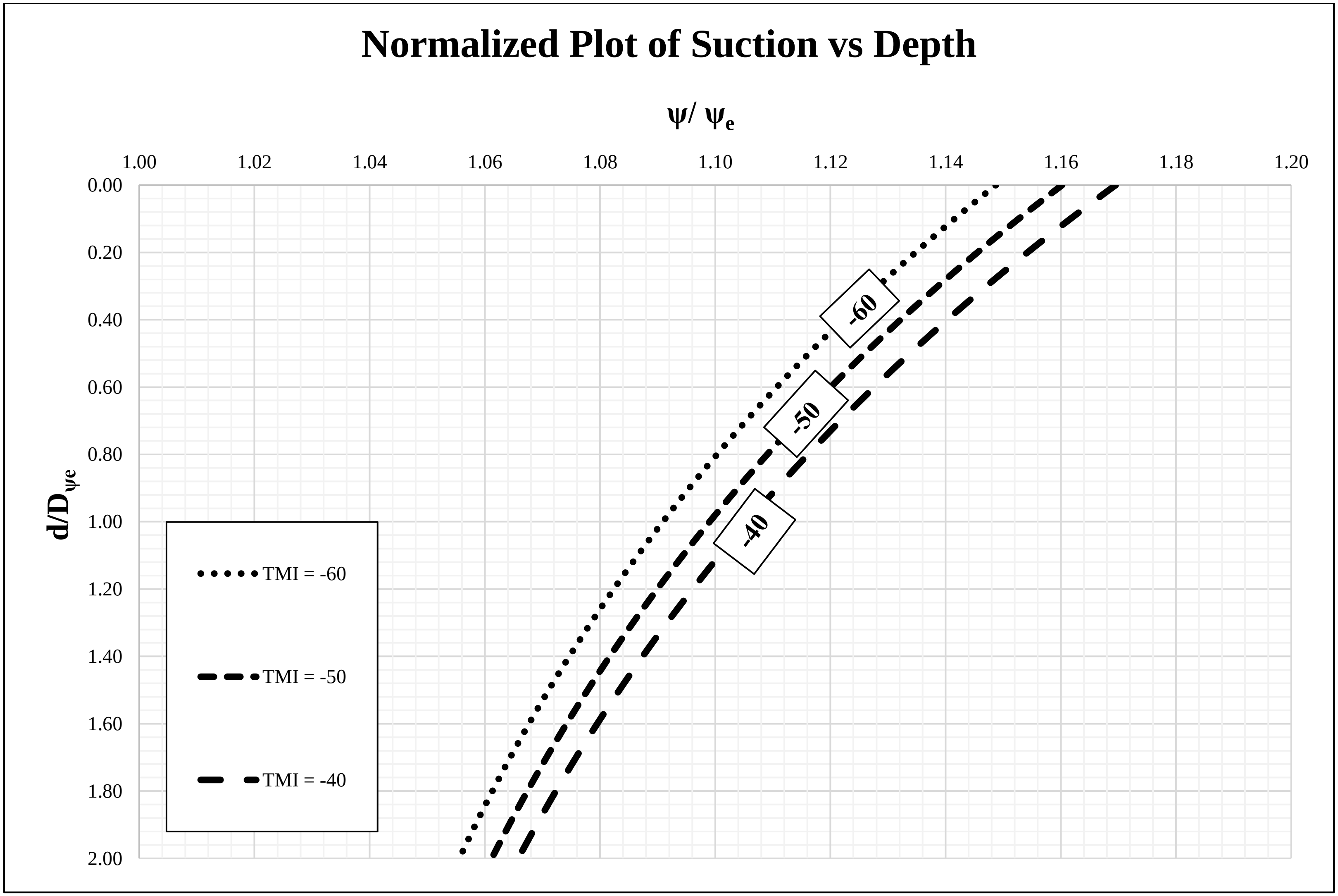


Figure 7.8: 7 (Suction Expressed in pF)

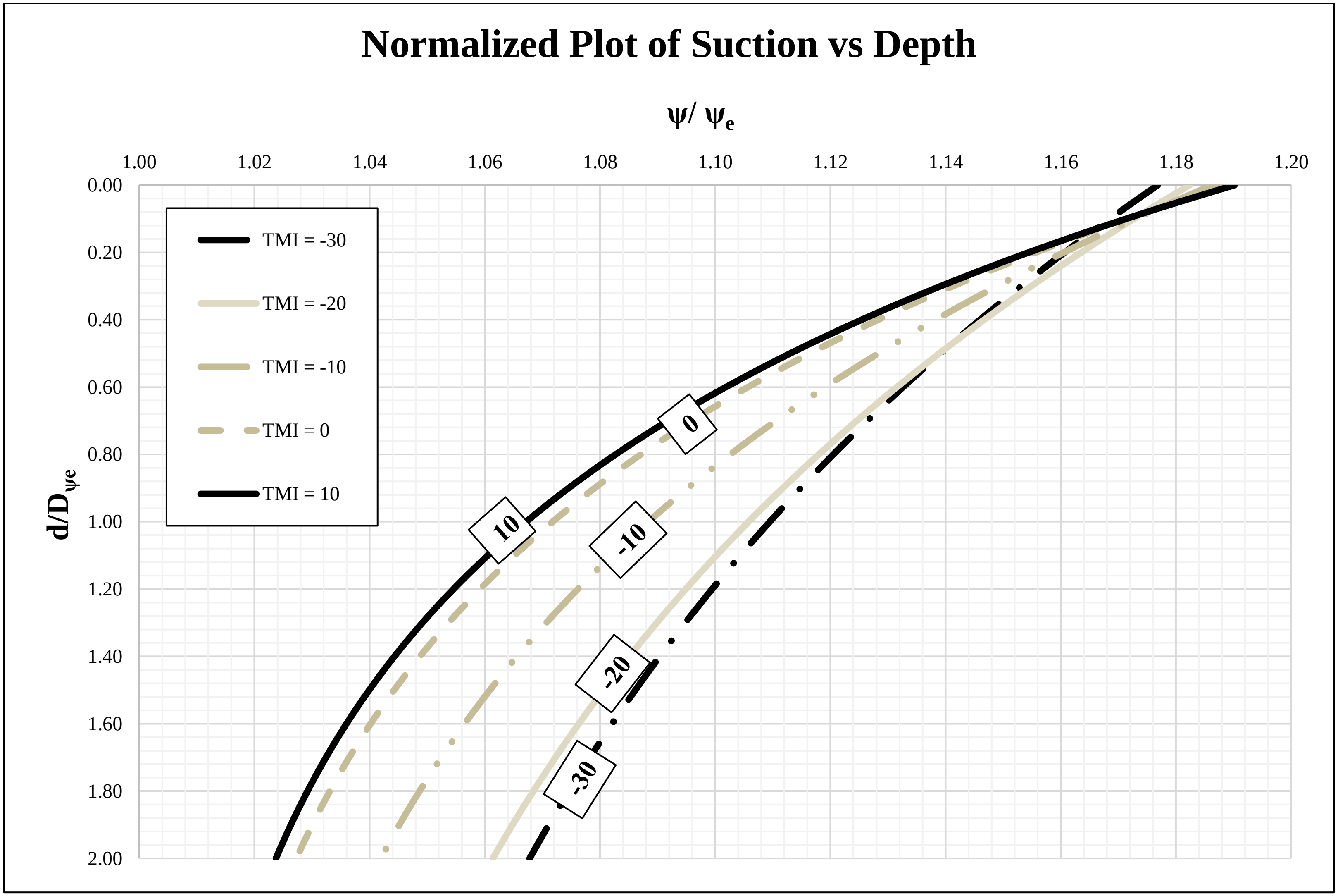


Figure 7.9: Normalized Plot of Suction and Depth for TMIs of -30 to +10 for the Dry-Side of the Suction Envelop (Suction Expressed in pF)

7.7 Suction Profiles for Design

It is assumed that initial, preconstruction water content and a suite of index tests will be a part of all routine site investigations. These data will be used to establish the beginning point for the field wetting or drying process for the soil suction surrogate-based approach. The final soil suction profiles will depend on the major surface boundary conditions. It should be noted that this study does not cover all conceivable boundary conditions but is limited to unirrigated/non-developed covered or uncovered surface conditions. Although developed areas were not studied extensively, it appears the it is possible to control site water such that suction profiles do not deviate from or only modestly deviate from those corresponding to seasonal fluctuation; it is also clear, however, that excessive irrigation and/or ponding of water can push the wetted suction profile outside of the range obtained for seasonal fluctuations. Each condition considered below holds an underlying assumption that appropriate measures have been taken to protect against ponding of water at the ground surface and lateral flow of water from on or off site; further it has been assumed that protections have been put in place against major accidental subsurface leaks (e.g. lining of pressurized utility lines), such that seasonal fluctuations are the primary driver of suction change. Under these controlled conditions, the seasonal fluctuation suction envelopes are useful guides in the selection of final suction profiles for design. The major boundary condition cases for design can be considered to be: (I) uncovered, or subject to seasonal fluctuations in soil suction, or (II) covered sites, protected from seasonal fluctuation suction swings. Case I corresponds to structures located close to the edge of the pavement and pavement (parking and roadway) outer paths, corresponding to regions within the edge distance. Case II corresponds to large commercial structures, such as Target Stores, Home Depots, or Walmart Stores, wherein the pavement footprint is large, and the structures are set back from the edge of the pavement some substantial distance. This setback generally well exceeds the edge distance, where the edge distance is the distance inward from the edge of the pavement within which seasonal moisture content changes occur. Case I is for a narrow shoulder, such that seasonal variations in moisture content occur not only adjacent to the paved surface but also under the pavement (e.g., for roadways under the traveled lanes). Case II is assigned to a design of a roadway wherein the paved shoulder is essentially as wide as the edge distance. In selection of design suction profiles, the initial suction profiles should be measured or estimated using the suction surrogate and measured field data. For case I, the suction will cycle between the wet and dry suction envelopes, which can be estimated using the relationships presented in this dissertation. It should be noted that the maximum heave or shrinkage will be associated with suction change from the initial measured state to the wet side (heave) or dry side (shrinkage). It is not appropriate, in general, to estimate heave or shrinkage using the full range of soil suction, wet envelop to dry envelop- the initial condition must be established to estimate field movements. The final suction profiles for Case II will be the equilibrium suction value. In other words, when pavement (or other moisture barrier such as plastic) protects the structure to some substantial lateral distance (note vertical barriers can also be used to accomplish protection of the structure), the soil suction will tend to move from the initial condition to the equilibrium suction value. The equilibrium suction value can be estimated from the TMI, as detailed in this study, or preferably, measured during site investigation. In dealing with developed sites, it is the typical trend in the USA that development results in wetting of soils compared to conditions at time of construction. In this case, with good control of site water to avoid excessive wetting, based on the limited developed site data of this study, it appears that the final wet suction profiles might reasonably be expected to be the wet envelop obtained in this study for seasonal fluctuation conditions. However, consideration of the two standard deviation depth of wetting on establishment of a final suction profile could also be explored in making final recommendations. Ultimately, the final suction profile for developed site rests heavily on the successive measures put in place to control infiltration of water into the subsurface, but it appears such measures can be successful in keeping suction profiles within the seasonal wet envelop range.

7.8 Recommendations for Site Drilling, Sampling and Laboratory Testing to Determine Magnitude of Equilibrium Suction and Depth to Equilibrium Suction

Notwithstanding, the past research when combined with good engineering practice strongly suggests that when a magnitude of equilibrium soil suction is needed, e.g. design-related recommendations for post-tensioned slabs, one or more test borings should be completed following the criteria below.

- The test boring should extend to a depth that is sufficiently below the calculated depth to equilibrium soil suction as presented by Equation (148). In general, the minimum test boring depth should be 5 m (16.40 ft).
- Bulk disturbed samples should be retrieved throughout the entire test boring depth at regular intervals, i.e. every 0.762 m (2.5 ft) maximum spacing and

approaching one-foot intervals in critical cases. The uppermost sample should be obtained at a depth of 0.305 m (1 ft), with successive samples every 0.762 m (2.5 ft) retrieved at 1.067 m (3.5 ft), 1.829 m (6.0 ft), 2.591 m (8.5 ft), 3.353 m (11.0 ft), 4.115 m (13.5 ft), and 4.877 m (16.0 ft).

- Relatively undisturbed samples should be obtained at intervals of 1.52 m (5.0 ft), commencing the first sample at 0.610 m (2.0 ft). Subsequent samples should be obtained at 2.134 m (7.0 ft) and 3.658 m (12.0 ft). A minimum of three relatively undisturbed samples should be taken at the above depths. A standard ring-sampler may be utilized, provided that the minimum inside diameter of the ring is 6.147 cm (2.42 in).
- The bulk disturbed samples obtained should be tested for grain-size distribution including the value of P200, Atterberg Limits, moisture content and soil suction, with the soil suction being measured by a device similar to Meter's WP4C. In all, seven samples should be tested at the above-defined depths to arrive at sufficient information with which to define the magnitude of equilibrium suction and depth to equilibrium suction. All of the recommended tests are relatively easy to complete and are tests that should be a part of every geotechnical engineers' capabilities. Additional samples may be obtained for verification, as needed, to verify the relative homogeneity of the soil profile.
- A plot of the measured soil suction versus depth will enable the determination of the magnitude of equilibrium soil suction and depth to

equilibrium suction.

- Response to wetting tests must be performed on the extracted relatively undisturbed samples retrieved from selected depth intervals, i.e. 0.610 m (2.0 ft), 2.134 m (7.0 ft) and 3.658 m (12.0 ft). A test method similar to ASTM D4546 may be used for the relatively undisturbed soil samples. Multiple ring samples may be tested from the same sample depth interval, if needed.
- Data from the response to wetting tests will be used to arrive at the anticipated heave beneath a lightly loaded slab, swell pressure, suction compression index and as part of the SPM, described in Chapter 8.

CHAPTER 8 DUAL APPROACH METHOD: SOIL SUCTION-OEDOMETER BASED (USING MEASURED OR SURROGATE SOIL SUCTION DATA)

8.1 Develop a Method of Computation of Heave that is Based on Sound Unsaturated Soils Principles, Using Suction Surrogate or Measured Suction

The development of a soil suction surrogate-based procedure for estimating expected swell strain (and heave) in the field proceeds parallel to the soil suction-based Surrogate Path Method, SPM, described above. The soil suction surrogate will be quantified for the initial field condition, the expected final condition, and the final fully-wetted condition. These suction surrogate data will then be used to construct a function which yields the proportionality factor, R_w, used in the SPM to interpolate (or extrapolate) swell/shrinkage strain for suction values intermediate between the initial suction and full wetting (matric suction of zero) or between initial suction and shrinkage limit (considered to be the limit of soil shrinkage in the modified SPM presented herein). Obviously, the objective here will be to find a R_w function that produces R_w values that are consistently very close to the R_w values obtained via soil suction values – because the soil suction-based R_w values are the most accurate that can be obtained. The soil suction surrogate approach will be founded on the fully-wetted oedometer test, as was the suction-oedometer approach (Houston and Houston, 2018). The methodology will require that full wetting response oedometer tests be performed on undisturbed (or compacted, as field appropriate) specimens, and that design soil suction surrogate profiles be determined, based on known boundary conditions in the field and regional TMI values.

The final product of the research will be a heave estimation method can be approached by one of two methods: (1) a soil suction-based approach wherein soil suction design envelopes are used together with commonly performed full wetting oedometer tests – the Suction-Oedometer Method, which uses the soil suction-based SPM, or (2) soil suction surrogate design profiles are used, and only the full wetting swell test need be performed- the Suction Oedometer Method using the soil suction surrogate-based SPM for interpolation/extrapolation of oedometer test results. It is intended that the two methods (1) and (2) will give the same estimate of heave; however, in method (2) only commonly determined soil parameters (e.g., w, PI, LL) are required, along with the commonly performed full wetting oedometer swell tests. Under method (2) it is not necessary to measure or control soil suction in the laboratory or the field and it is not necessary to estimate soil suctions in the field as the soil suction surrogate will be used as a substitute for measured suction values.

A major part of the research to was the development of methods for obtaining initial and final soil suction envelopes (Chapters 6 and 7) for use in the Soil suction-Oedometer method. The profiles of soil suction surrogate, developed for hundreds of sites where past geotechnical data are analyzed, were used to shed considerable light on this subject. It is, indeed, the estimation of final field soil suction profiles that represents the most challenging aspect of the heave estimation method, making bench-marking to field data essential.

It should be noted at this point that the word surrogate is being used in two somewhat different ways herein. The first way in which the word surrogate is being used is simply as a substitute for soil suction itself – soil suction surrogate. The second way in which surrogate is used is to refer to an alternate stress path as a surrogate path to reach the final swell strain exhibited by an element of expansive soil subjected to wetting in the field – surrogate path. This "equivalent" path method for estimating soil heave has been dubbed the Surrogate Path Method (SPM). It is intended to use the SPM for this research study.

The suction surrogate developed in this study has been demonstrated to be extremely useful in development of a database of actual field suction profiles (Chapters 6 and 7). The questions embedded in this current chapter is whether the soil suction surrogate can be used to estimate design field suction profiles such that the heave/shrinkage estimates for a given field condition will be the same, or nearly the same, whether measured or surrogate suction values are used in the Suction-Oedometer analysis.

8.2 Overview of the Surrogate Path Method (SPM) for Partial Wetting

Given the extreme difficulty in obtaining an appropriate soil suction compression index, a method for estimating partial wetting strains via the Surrogate Path Method (SPM) has been presented and further investigated by Singhal (2010), Houston and Houston (2018), and Olaiz (2017). The SPM is used within a heave prediction method, the Suction-Oedometer Method, presented by Houston and Houston (2018). The SPM has received some preliminary evaluation, which showed considerable promise, through the work of Arizona State University PhD student Singhal (2010) and the MS thesis work of Olaiz (2017). The surrogate path design method, as originally conceived, was a soil suction-based approach that used a surrogate net normal stress path for estimation of partial wetting swell, as depicted in Figure 8.1. This concept of a surrogate path, wherein an "equivalent net normal stress" path is used to ascertain swell strains resulting from changes in soil suction alone, has been used by others in the past, including Fredlund and Rahardjo, 1993. The method described by Singhal (2010), called the SPM, is like the Fredlund and Rahardjo (1993) method in that it employs a surrogate path along the net normal stress axis. However, it differs from the Fredlund and Rahardjo (1993) method in that the SPM is founded directly on the field stress level (or overburden stress) oedometer test to measure the fully wetted strain which ensues under appropriate net normal stress, and the Fredlund and Rahardjo (1993) method is typically based on token load swell tests.

The SPM methodology portrayed in Figure 8.1 and as described by Houston and Houston (2018), is as follows. The actual stress path followed in the field follows the path of line IF, where point I is at the original in-situ soil suction and point F represents the final soil suction after partial wetting. The existing overburden stress is σ_{ob}. The strain at point I, ε_I, is the desired quantity. If wetting were to proceed to full wetting, the matric soil suction $(u_a\text{-}u_w)$ goes to zero, then the strain would be ε_{ob}. The value of ε_{ob} can be directly measured in a fully wetted oedometer test along the net normal stress path GB, where σ_{ocv} is the constant volume swell pressure, ascertained by initially wetting at $\sigma_{ob.}$ A sufficiently accurate estimate of σ_{ocv} can be obtained by simply performing two swell tests, one at σ_{ob} and one at a substantially higher net normal stress and extrapolating to get σ_{ocv} (Houston and Nelson, 2010). Alternatively, the load-back procedure, with correction, can be used to approximate the constant volume swell pressure, σ_{ocv} (Nelson, et al., 2006; Olaiz, 2017). The strain for partial wetting, ε_I, is obtained by using the proportion of soil suction dissipated by wetting from I to F as a proportionality factor in estimating the "final" net normal stress,

σ_P, at point P. In other words, if R_w is defined as $R_w = (u_a\text{-}u_w)_f / (u_a\text{-}u_w)_i$, where $(u_a\text{-}u_w)_i$= initial soil suction and $(u_a\text{-}u_w)_f$ = final soil suction. Thus $R_w = 1$ for no wetting and $R_w = 0$ for full wetting. Then, $\sigma_P = \sigma_{ob} + R_w (\sigma_{ocv} - \sigma_{ob})$. The strain PQ at point P was compared by Singhal (2010) to the actual strain ε_I for numerous cases and an excellent agreement was found for all cases. In connection with the method just described in the preceding paragraph, the actual path, I to F in Figure 8.1, is replaced with the surrogate path, GQ.

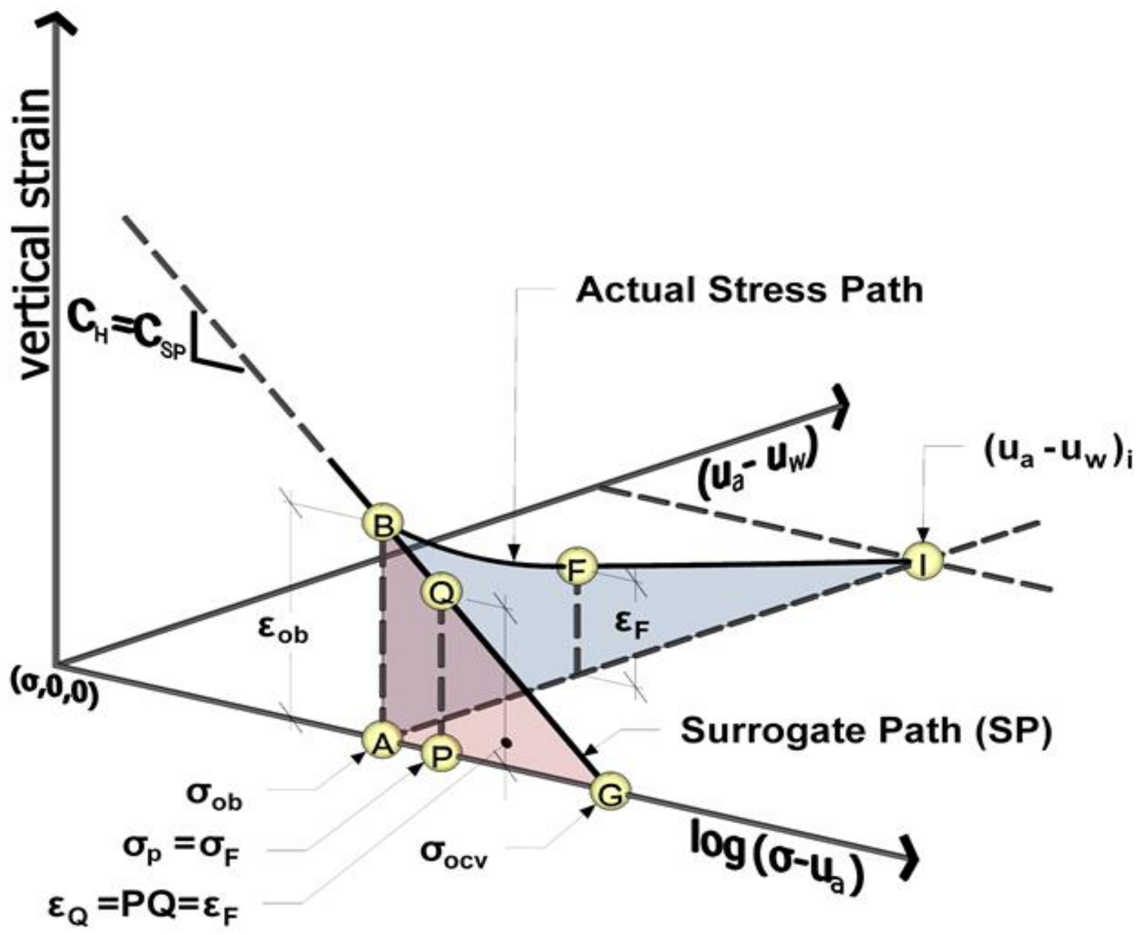


Figure 8.1: Strain-Based "Equivalence" of Reduction of Soil suction from $(U_a– U_w)_I$ to Zero (path IB) to reduction in net normal stress from σ_{OCV} to σ_{ob} (along path GB, the SP)

In the original Suction-Oedometer method, Houston and Houston (2018) outline a method for estimation of shrinkage using the SPM. Houston and Houston (2018) recommended that the amount of shrinkage be limited, for example to no more than would occur for a suction reduction to 30,000 kPa. In this study, the limit placed on shrinkage will be linked to the soil suction surrogate at the soil shrinkage limit (SL). The SL will be estimated from the soil PL using existing literature correlations.

The SPM requires that initial and final soil suction values in the field be estimated, but it does not require that soil suction be measured or controlled in the laboratory and it employs the very familiar oedometer procedure and apparatus. It does not require that the slope of the strain – log soil suction curve, often called the soil suction compression index, be measured or estimated and problems with the nonlinearity of this curve in the low soil suction range are avoided. However, it is noted that the data needed to compute the soil suction compression index is readily available without measuring or controlling soil suction, as will be discussed. For the case of full wetting (R_w=0) the SPM degenerates to a trivial case. For this case the strain is ε_{ob} in Figure 8.1, which is the full wetting strain and is the strain that has been obtained by conventional practice for many decades. However, as is well known to researchers who have delved deeply into the study of equilibrium soil suction values in the field, the assumption of full wetting in the field is almost always overly conservative. The assertion that over-conservatism is costing developers and taxpayers billions of dollars annually will be further supported by the results of the research. Singhal (2010) has pointed out that one of the strengths of the SPM is that it is founded on the full wetting oedometer test and is thus forced to be correct at the endpoints;

no full wetting if the anticipated field condition dictates so. Therefore, all that the SPM is required to do is to provide a reasonable, rational method for interpolation between the endpoints – which it does. As a final characterization of the SPM, it can be said to be a soil suction-based approach in that it requires that initial and final soil suction in the field be estimated and that the proportionality factor, R_w, be computed from numerical values of soil suction.

8.3 Using Measured or Surrogate Soil suction in the Suction-Oedometer Method

In this study, a dual approach will be taken to the development of methods for estimation of expansive soil movements, wherein a soil suction-based approach will be linked to a soil suction surrogate-based approach, to develop a consistent analysis method whether a soil suction-based or surrogate-based path is taken. An ancillary goal is to provide practicing engineers with a sound basis, derived from site-specific measurements, for estimating initial and final moisture conditions for design. Currently, a very large percentage of geotechnical practitioners are simply uncomfortable with direct use of soil suction. Practitioners feel that they do not have the equipment or the experience to measure soil suction reliably and thus they avoid using it and normally do not think about considering its use. This condition will likely change with time, as theory and practice of unsaturated soil mechanics is very gradually adopted into mainstream geotechnical consulting work. In the meantime, a soil suction surrogate-based approach is needed wherein practitioners (and researchers who choose to) can use simple functions of water content and index properties to evaluate expansive soil heave for the general case of partial wetting. This will also allow practitioners and researchers to use the existing extensive database of water content profiles, along with soil index property profiles, to enhance their database for estimating initial and final moisture state conditions that are consistent with unsaturated soil mechanics theory. The soil suction-based approach must be developed simultaneously because soil suction is one of the two stress state parameters that control soil expansion in response to wetting. Thus, the soil suction-based approach represents the benchmark result. Both approaches will use a complete-stress-state analysis, taking into consideration both net normal stress and soil suction, in making the estimate of field heave (or shrinkage).

A primary goal of the research is to simultaneously develop a soil suction surrogate approach that yields essentially the same heave result as does the more rigorous soil suction-based approach, and which allows geotechnical engineers to take advantage of their vast experience base from a more fundamental perspective. This will require the development of a deeper understanding of the relationship between soil matric soil suction and more commonly used measures of soil moisture content, as was done in this study via development of the soil suction surrogate (Chapter 5). The study was focused on performance of carefully aligned field and laboratory studies required for fundamental linking of soil suction to one or more of these soil suction surrogates, toward the goal of development of a better understanding of subsurface soil suction conditions, including equilibrium/pseudo-equilibrium states. The approach to be used in development of a heave/shrinkage prediction method embraces established principles of unsaturated soil mechanics theory by incorporating a complete-stress-state approach yet expands usefulness and applicability through the well-established surrogate parameters. The heave analysis will take into consideration field net normal stress conditions and field-established depth and degree of wetting that occurs under imposed boundary conditions. The heave estimation method will couple moisture profile data with full wetting swell test results, and the surrogate path method (SPM) will be used for estimation of partial wetting swell. Thus, the final products will include both a soil suction-based SPM and a soil suction surrogate-based SPM. It should be noted that while the approach taken here is 1-D, the basic principles and methodologies can be readily extended to 2-D and 3-D field cases but requires the use triaxial and/or K_o-controlled full-wetting swell tests (Noorany, 2013).

8.4 Partial Wetting Swell Strain Estimates Using Soil Suction and Soil Suction Surrogate Using the SPM and Comparisons to those Directly Measured

Undisturbed samples of expansive clay were tested for partial wetting strains using an oedometer pressure plate device (OPPD) which allowed for control of both net normal stress and soil matric soil suction (Olaiz, 2017). A full suite of soil index properties was run on the soil specimens, and initial soil suction values were directly measured using either the OPPD (Fredlund SWCC Device, GCTS, Inc.) or the WP4C device (Meter, Inc.). The OPPD strains observed in response to various changes in soil suction was then compared to those estimated by the SPM procedure using measured soil suction, and then again using soil suction values computed from Equation (139).

The full wetting oedometer test (ASTM D-4546) is typically used in the SPM to determine the slope of the surrogate path (C_H) and to estimate swell pressure. However, even though from the same sample tube, several of the “companion” ASTM D-4546 and

OPPD specimens tested in this study did not show good agreement in strain when fully wetted, likely due to field sample variability. Therefore, the procedure of using companion specimens was not employed in this this study and the conventional swell tests (ASTM D-4546) were used only to estimate swell pressure in the calculations of the partial wetting strains. The OPPD specimens were, in general, taken to low matric soil suction values of 0 to 100 kPa. Where matric soil suction was reduced below 100 kPa, negligible additional swell was observed. Therefore, when specimens were not fully wetted in the OPPD to zero matric soil suction, the largest value of swell strain (e.g., swell strain at 50 kPa matric soil suction), corresponding to the lowest matric soil suction used in the test, was used in lieu of the full wetting strain to avoid errors associated with sample variability. The constant volume swell pressures were estimated using the average ASTM D-4546 C_H slope of the surrogate path, provided by Olaiz (2017). The initial soil matric soil suction for each specimen was either directly measured with the OPPD or calculated from WP4C (Meter, Inc.) total soil suction measurements using the average determined osmotic soil suction for each site.

Comparison of the soil suction-based SPM partial wetting swell strains and the soil suction surrogate-based SPM partial wetting strains to the OPPD directly measured partial wetting swell strains are summarized in Table 8.1. Initial soil suction values corresponded to field conditions, and final soil suction values for the partial wetting tests ranged from 1400 kPa to 200 kPa for the results in Table 8.1. For each partial wet-ting result shown in Table 8.1, the soil matric soil suction was decreased from the initial field value to some lower soil suction (e.g. 800 kPa). The Sample ID in Table 8.1 indicates the location where the specimen was obtained, D for Denver and SA for San Antonio. Note that suction surrogate estimates have been revised from the Houston and Houston (2018) study to use the updated suction surrogate developed in this current study (Chapter 5).

The SPM partial wetting strains obtained from measured initial and final soil suction values showed very good agreement, on average, with the directly measured OPPD partial wetting strains. The soil suction surrogate-based SPM partial wetting strains also provide reasonable estimates of measured strains on average, with only a few exceptions of very good match shown for individual tests in the Table 8.1 data.

Where measured soil suction values are available better estimates of partial wetting strains are expected, in general. This is a result, in part, of inherent error associated with use of a soil suction surrogate (e.g. errors due to hysteresis and soil structure/density, use of estimated osmotic soil suction in computation of matric soil suction). In addition, the final water content values used here to obtain the final soil suction surrogate were not directly measured for the Table 8.1 comparisons, but rather the water contents were inferred from OPPD tube out-flow readings. The out-flow tube water content determinations have some error associated with use of estimated evaporation losses in computation of water content. Such OPPD water content error increases with test duration, and long equilibration times were required for the clays of this study. However, for application to the field, these uncertainties associated with long term laboratory testing do not negatively affect quality of surrogate estimates, and better agreement, in general, would be expected between field partial wetting strains and surrogate-based SPM estimates of partial wetting strains.

Nonetheless, because a soil suction surrogate is subject to errors from hysteresis, for example, use of directly measured soil suction values is recommended, where possible. Initial soil suction profiles can generally be obtained by direct measurement, for example by using the WP4C device to get total soil suction, together with measured or estimated osmotic soil suction for estimation of matric soil suction profiles. Final soil suction profiles for design are best obtained from regional experience where a data base of post-construction directly measured soil suction profiles have been collected for application-specific boundary conditions. An example of such a database is that collected over years of study by the Colorado Association of Geotechnical Engineers (CAGE), and which was used by Walsh et al. (2009), in a study of depth of wetting for residential construction in the Denver front range (Vann et al., 2018). In the absence of a large local database on initial and final field suction profiles, recommendations presented in Chapter 7 can be used for estimation of suction design envelopes were surface boundary conditions are consistent with those presented in Chapter 7 (climatic conditions and/or paved or covered surface conditions, where the area surrounding the pavement is subject to climatic variations only).

Table 8.1: Comparison of measured and predicted partial wetting strain for the updated dataset final proposed surrogate

Sample ID	**εOPPD MEASURED**	**εSPM WITH MEASURED SUCTION**	**εSPM FINAL PROPOSED SURROGATE**
D-1	0.32	0.41	0.50
	0.63	0.55	0.49
	0.62	0.69	0.52
D-2	0.12	0.12	0.10
D-3	0.73	0.85	1.03
	0.94	1.03	1.06
	1.20	1.23	1.10
D-4	0.42	0.35	0.14

Sample ID	εOPPD MEASURED	εSPM WITH MEASURED SUCTION	εSPM FINAL PROPOSED SURROGATE
D-5	0.21	0.32	0.25
	0.76	0.67	0.34
D-6	-1.95	-1.36	-0.95
	-1.69	-1.61	-0.83
D-7	0.1	0.16	0.23
	0.2	0.23	0.24
D-8	0.41	0.46	0.32
	1.38	1.23	0.54
D-9	0.1	0.34	0.51
	0.81	0.69	0.55
	1.32	1.23	0.69
D-10	0.32	0.24	0.49
	0.63	0.51	0.52
	0.84	0.83	0.57
SA-1	0.21	0.26	0.35
	0.81	0.56	0.41
SA-2	0.1	0.12	0.31
	0.52	0.48	0.36
SA-3	0.52	0.57	0.71
	1.08	1.18	0.84
	1.5	1.44	0.88
SA-4	0.21	0.26	0.53
	0.88	1.06	0.67
SA-5	0.21	0.19	0.22
	0.32	0.30	0.24
SA-6	0.21	0.24	0.24
SA-7	0.47	0.36	0.33
SA-8	0.21	0.26	0.26
SA-9	0.61	0.53	0.73
	1.12	1.13	0.85
SA-10	0.32	0.39	0.39
SA-11	0.32	0.35	0.36
	0.89	0.88	0.43
Mean	**0.46**	**0.48**	**0.43**
σ	**0.65**	**0.58**	**0.39**

Table 8.1 has been prepared for the complete dataset and final proposed soil suction surrogate; $\psi = 3.2346\left(\frac{\omega}{\mathrm{LL}}\right)^{-0.217}$. Figure 8.2 presents a plot of the strains from Table 8.1 for comparison of measured field suction data versus the use of the proposed surrogate, showing reasonable agreement.

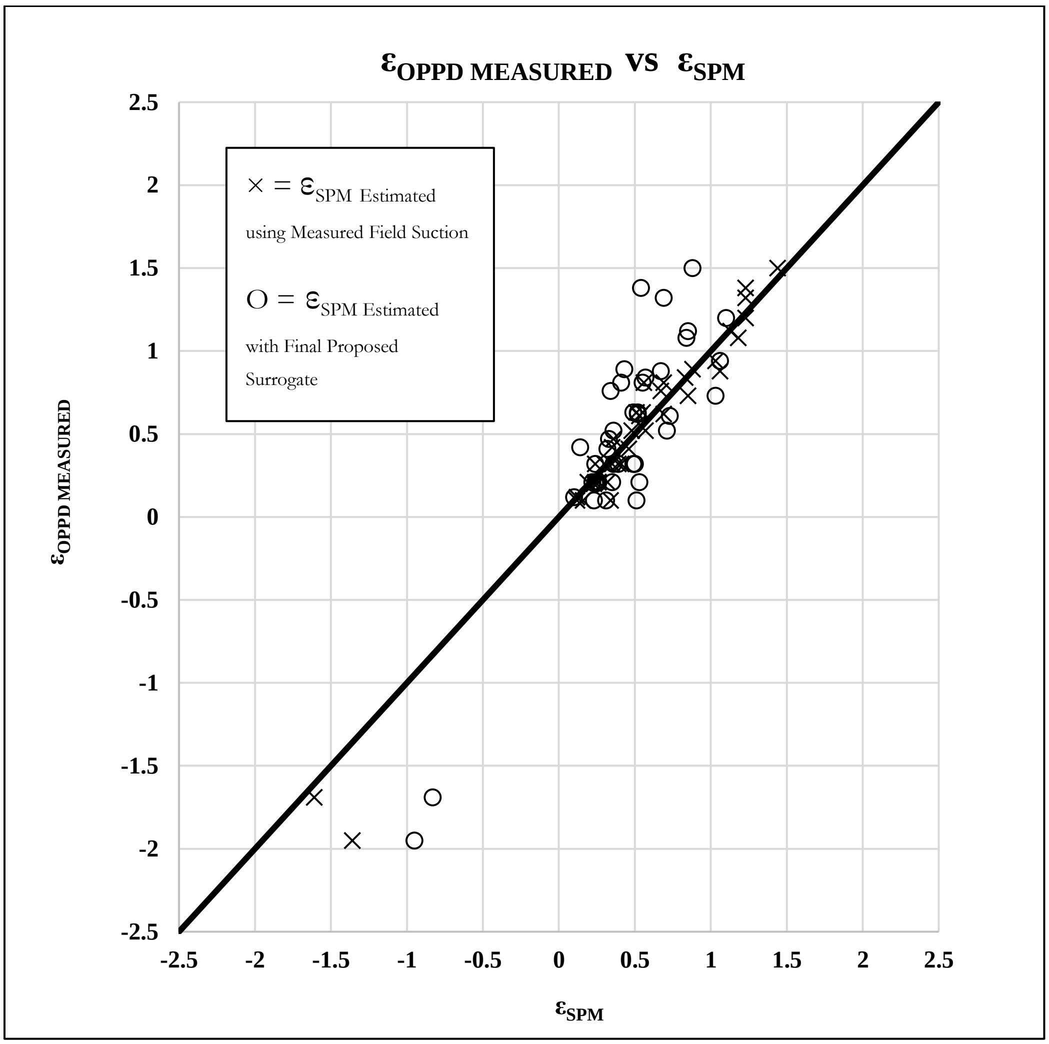


Figure 8.2: Comparison of the Strains Using Measured Field Data and the Final Proposed Surrogate with the Actual Measured Strains

Furthermore, Figure 8.3 and Figure 8.4 present the OPPD measured strains due to the change in soil suction compared to the SPM estimated strains, using measured and surrogate suctions, on a strain vs. log suction plot for one random Denver and one random San Antonio sample presented in Table 8.1. Such plots are typically used to determine the suction compression index of the soil.

For both sites, there is close agreement between the OPPD measured strains and the SPM strains using the measured suctions. For the Denver site, the SPM using the surrogate slightly underestimated the measured strains, while for the San Antonio site, the SPM using the surrogate slightly overestimated the measured strains, however both still provided estimations within a reasonable degree of engineering certainty.

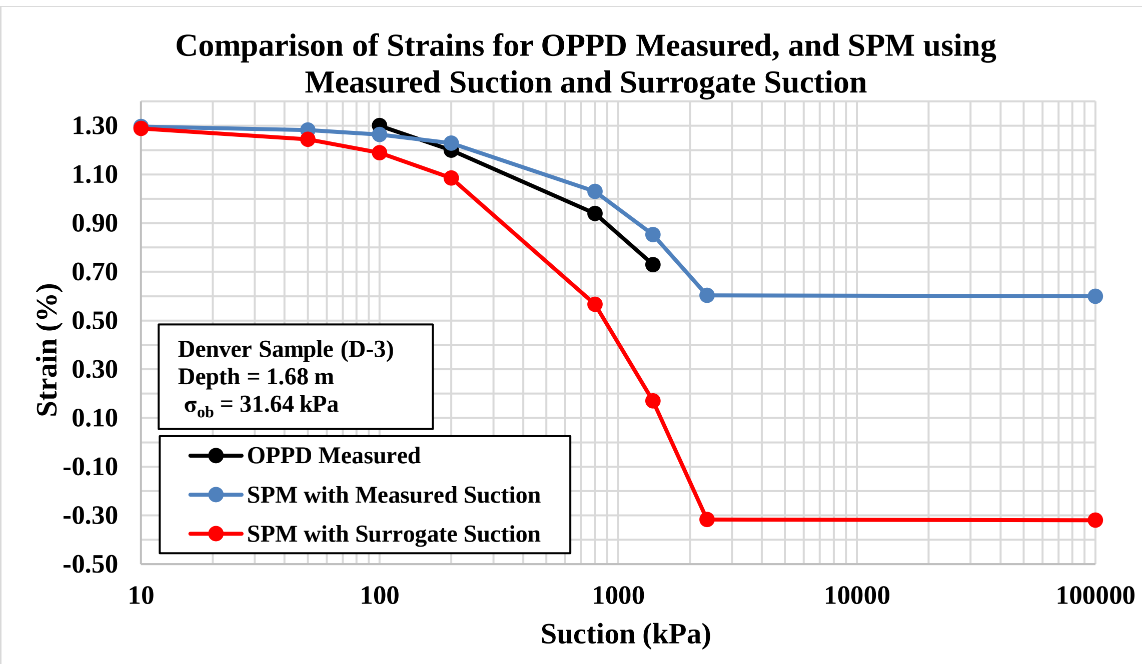


Figure 8.3: Comparison of Strains for OPPD Measured, and SPM using Measured Suction and Surrogate Suction for Denver Sample D-3

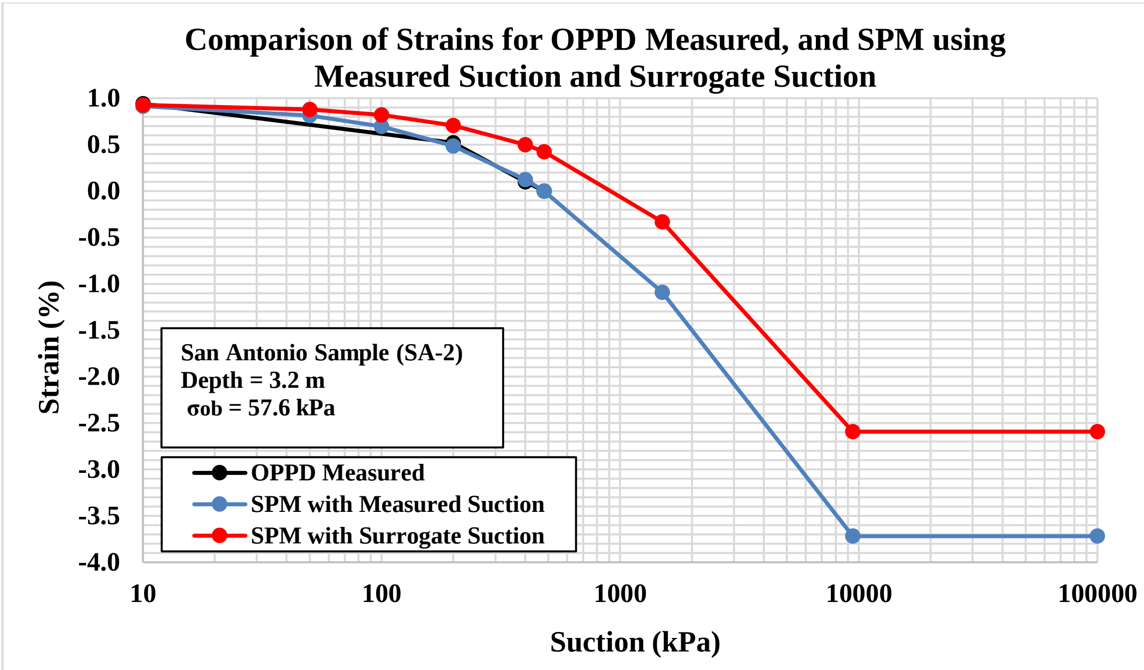


Figure 8.4: Comparison of Strains for OPPD Measured, and SPM using Measured Suction and Surrogate Suction for San Antonio Sample SA-2

Note that the SPM estimated curve is truncated to limit the volume change at the shrinkage limit of the soil. The shrinkage limit (SL) of the soil was estimated using procedure suggested by Casagrande in his lectures at Harvard University, which is summarized in Holtz, Kovacs, and Sheahan (2011). Casagrande's procedure suggests that a line drawn on a Plasticity Chart, from the intersection point of the U-Line and the A-line (-43.5, -46.4) to the point representing the PI and LL of the sample, can be used to infer the SL. The SL will be the point at which that line intersects the x-axis, as illustrated in Figure 8.5. This procedure has been accepted to produce a reasonable estimation of the shrinkage limit which falls within the accuracy of the shrinkage limit test itself.

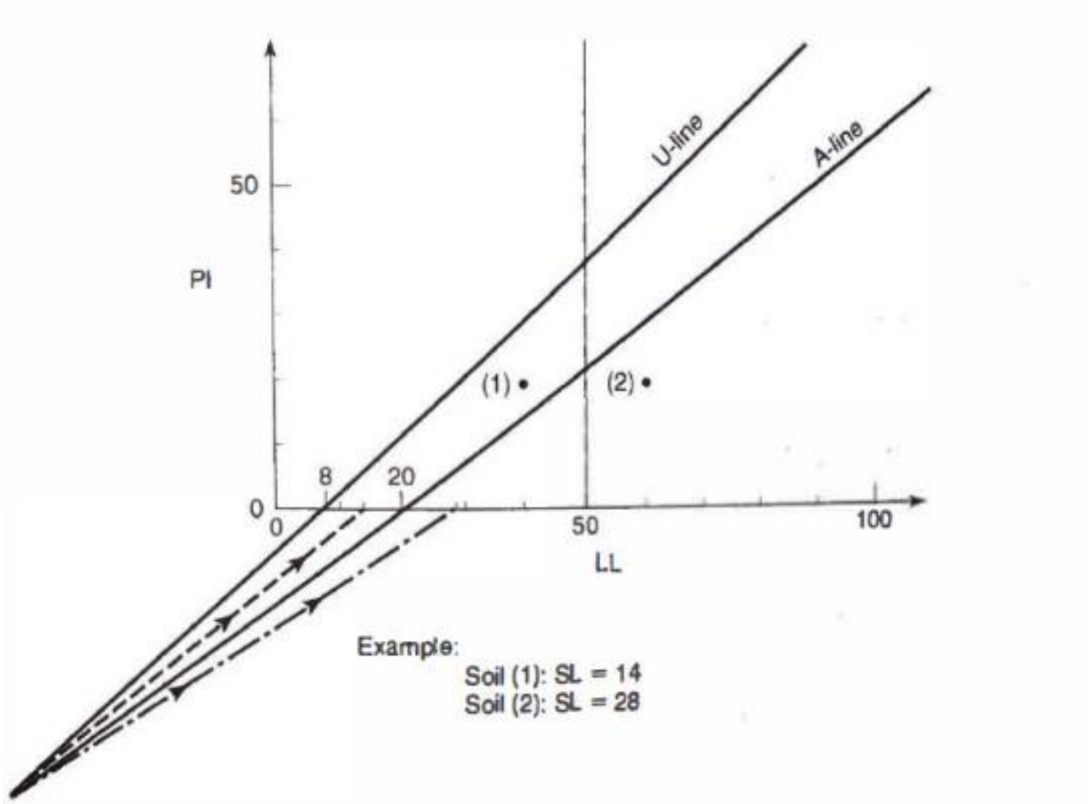


Figure 8.5: Casagrande Procedure for Estimating the Shrinkage Limit (Holtz, Kovacs, and Sheahan, 2011)

Casagrande's graphical procedure to estimate the SL can be converted to a mathematical expression using the Point-Slope Formula.

$$SL = \frac{46.4}{\left(\frac{PI + 46.4}{LL + 43.5}\right)} - 43.5 \tag{165}$$

Where,

PI is the Plasticity Index of the soil sample,
LL is the Liquid Limit of the soil sample.

Table 8.2 presents the estimated shrinkage limit water content and the associated shrinkage limit surrogate suctions for the Denver and San Antonio samples presented in Table 8.1 using the Casagrande approach presented above.

Table 8.2: Estimated Shrinkage Limits for Denver and San Antonio Samples

ID	w	LL	PL	PI	SL per Casagrande	Surrogate at SL (pF)	Surrogate at SL (kPa)
D-1	10.1	38	16	22	11.8	4.2	1450
D-2	9.1	42	16	26	11.3	4.3	1961
D-3	9.9	36	12	24	8.9	4.4	2355
D-4	23.12	51	24	27	16.2	4.1	1373
D-5	22.62	64	27	37	16.3	4.4	2203
D-6	15.9	58	20	38	12.3	4.5	3310
D-7	27.27	56	21	35	13.2	4.4	2606
D-8	24.4	65	18	47	10.4	4.8	6387
D-9	20.6	65	10	55	6.1	5.4	24378
D-10	16.3	55	19	36	12.0	4.5	3125
SA-1	28.2	69	15	54	8.5	5.1	12233
SA-2	23.54	67	16	51	9.1	5.0	9438
SA-3	28.06	77	20	57	10.6	5.0	9286
SA-4	22.74	67	16	51	9.1	5.0	9438
SA-5	32.8	82	17	65	8.8	5.3	17572
SA-6	23.23	67	15	52	8.6	5.0	10978
SA-7	21.24	58	16	42	9.8	4.8	5641
SA-8	23.25	81	16	65	8.4	5.3	19340
SA-9	20.2	66	16	50	9.2	5.0	8934
SA-10	19.7	75	17	58	9.2	5.1	12451
SA-11	29	70	16	54	9.0	5.1	11092

8.5 Procedure for estimating Partial Wetting Swell using the Suction-Oedometer Method with Measured or Surrogate Suction Profiles

To aid with the understanding of the complete computational process for partial wetting heave using the soil suction-oedometer-based approach, examples of the calculation procedures are presented for the San Antonio, TX and Denver, CO sites which were drilled and tested as part of this study. The examples also present a comparison of the heave computation using the field estimated (surrogate) suction to the actual field measured suction. The TMI (Witczak et al. 2006) for the San Antonio site is -16 and the TMI for Denver site is -24. The soil samples gathered from test boring 2 at San Antonio and test boring 3 at Denver (SA-2-U-I and DEN-3-U-N are provided in Appendix B) and the accompanied laboratory test data is presented in Table 8.3 and Table 8.4. Note that the soil properties listed below are not the complete set of data from the test borings. For the example calculations, six bulk samples were gathered at 0.305 m (1ft), 1.524 m (5 ft), and 2.286 m (7.5 ft), and one relatively undisturbed ring sample at 1.524 m (5 ft) below the existing grade. Three of the bulk samples were gathered below the estimated depth of equilibrium suction using Figure 6.31 for the purposes of determining the site-specific equilibrium suction. The average suction (surrogate or measured) was obtained for the three samples below the depth of equilibrium suction.

Table 8.3: Soil Parameters from SA-2-U-I for Example Computation

Depth (m)	Sample Type	w (%)	LL	γ (g/cm^3)	ε_{ob} (%)	σ_{LB} (kPa)
0.305	Bulk	11.1	52	-	-	-
1.524	Undisturbed & Bulk	19.7	65	1.45	2.17	215.1
2.286	Bulk	19.1	59	-	-	-
3.353	Bulk	25.7	88			

Depth (m)	Sample Type	w (%)	LL	γ (g/cm^3)	ε_{ob} (%)	σ_{LB} (kPa)
3.658	Bulk	24.7	86			
3.962	Bulk	28.6	83			

Table 8.4: Soil Parameters from DEN-3-U-N for Example Computation

Depth (m)	Sample Type	w (%)	LL	γ (g/cm^3)	ε_{ob} (%)	σ_{LB} (kPa)
0.305	Bulk	9.7	39	-	-	-
1.524	Undisturbed & Bulk	9.9	36	1.75	1.86	114.7
2.286	Bulk	10.9	36	-	-	-
3.0480	Bulk	12.1	48			
3.9624	Bulk	13.9	52			
4.2672	Bulk	18.5	53			
4.572	Bulk	19.5	52			

Note that for the Denver, CO site an extra bulk sample was gathered at 3.048 m (10.0 feet).

8.5.1. Development of the Suction Envelop

The soil suction profile is determined per this research and Mitchell 1981. Development of the suction profile encompasses five main components:

1. The magnitude of equilibrium suction (ψ_e)
2. The depth to equilibrium suction (D_{ψ_e})
3. Determination of the most appropriate diffusion coefficient (α)
4. The change of suction at the surface ($\Delta\psi\ in\ pF\ units$)
5. The shape of the suction envelope (defined by the climate parameter 'r' and the magnitude of suction variation at the depth of equilibrium)

This research presents five models for determining the magnitude of equilibrium based on TMI (Figure 8.6), the depth to equilibrium suction (Figure 8.7), the suction change at the surface (Figure 8.8), and the climate parameter 'r' (Figure 8.9). However, the magnitude of equilibrium for the example problems was determined using the field data as recommended herein (the average suction of the samples gathered below the depth of equilibrium). The magnitude of suction variation at the depth of equilibrium is assumed to be 0.2 pF as recommended herein.

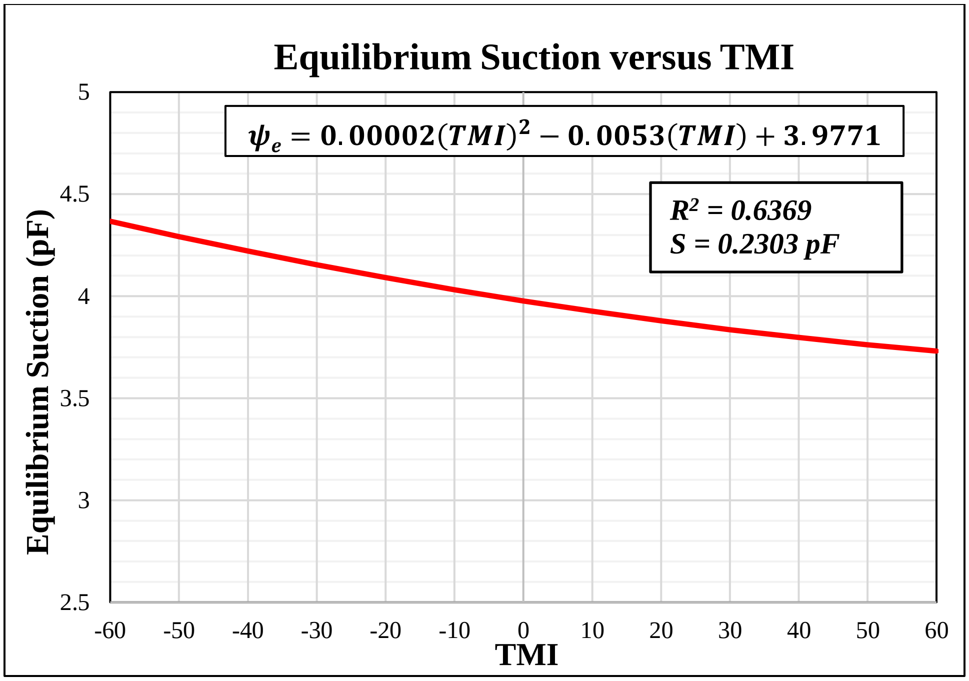


Figure 8.6: Equilibrium Suction vs. TMI

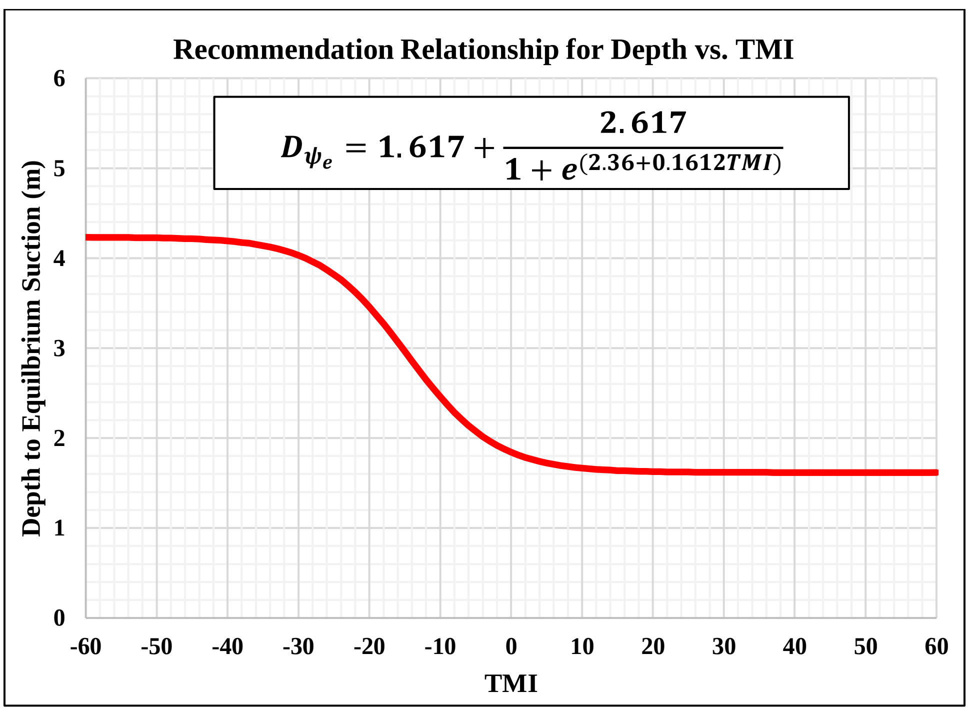


Figure 8.7: Depth to equilibrium suction per TMI

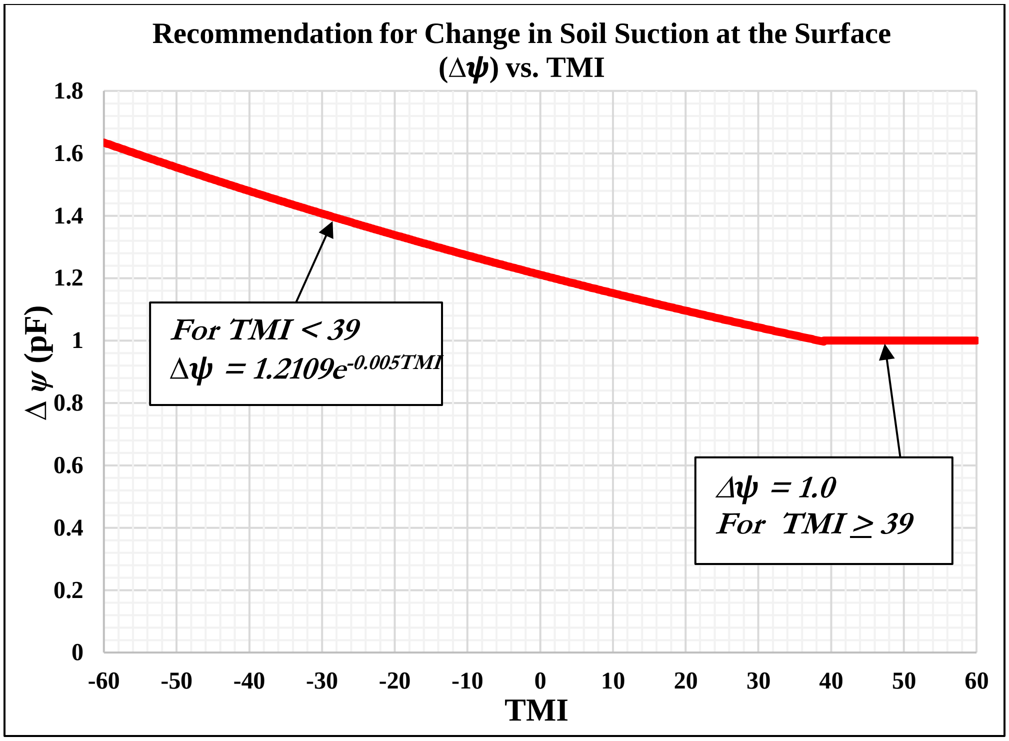


Figure 8.8: Change in suction at the surface per TMI

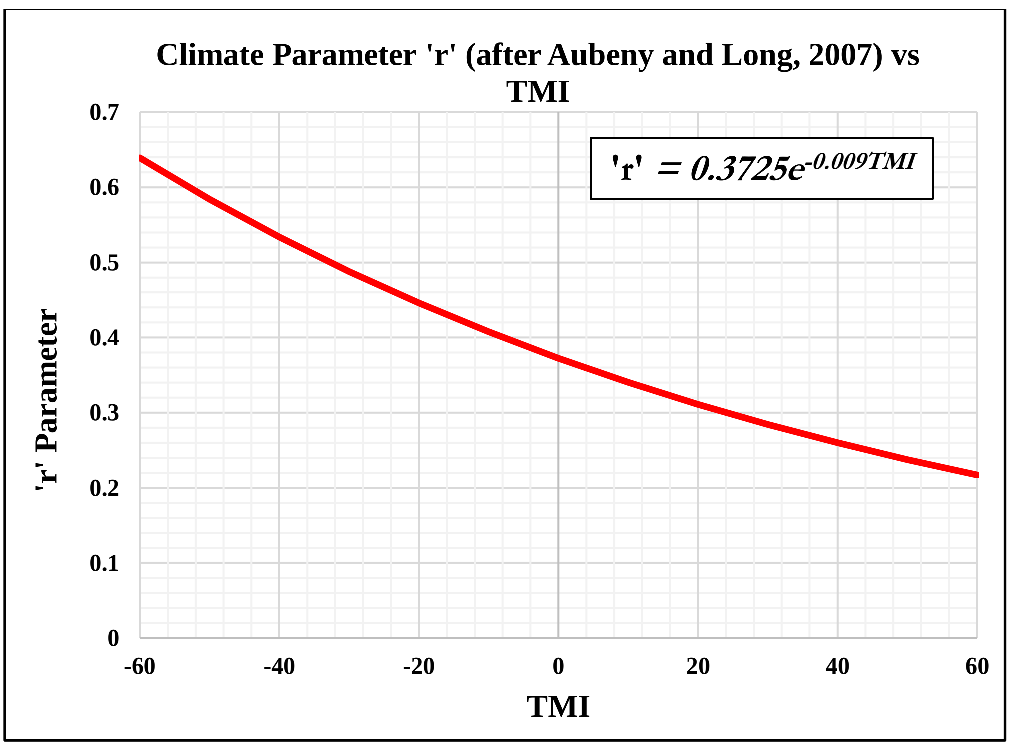


Figure 8.9: ‘r’ Parameter per TMI

First, the initial field suction at each bulk sample depth is determined using the suction surrogate equation per this research.

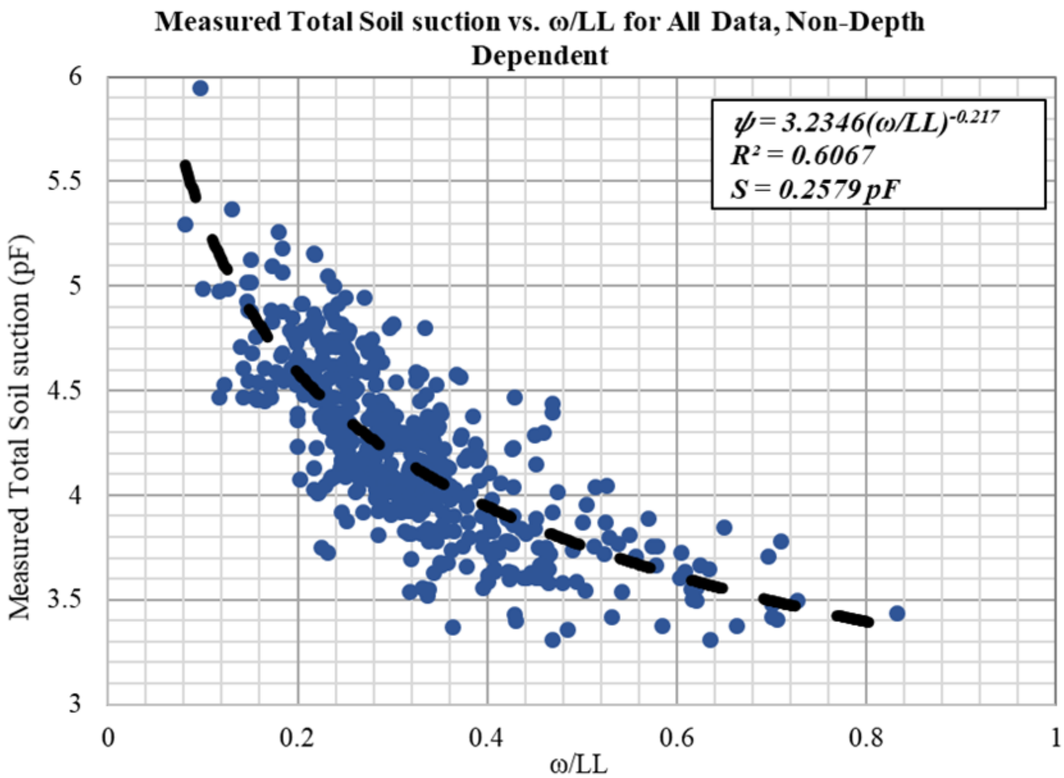


Figure 8.10: Equilibrium suction model (This Research)

The balanced of the heave computation method is presented in the following sections.

8.5.2. Example Suction-Oedometer Heave Computations Using Suction Surrogate

In lieu of a step-by-step computation procedure, the suction oedometer method with be demonstrated through the detailed examples presented in this section. The design suction envelopes developed in this research study are used in establishment of final suction profile conditions, and initial suction profiles are established by measurement. Initial and final suction profiles are represented by either suction surrogate or measured suction in these examples. As a part of the suction oedometer method, the SPM is used to estimate partial-wetting strains from ASTM D4546 data.

The examples presented are for two sites: 1) San Antonio, TX, and 2) Denver, CO. The surrogate suction (ψ_{sur}) values for bulk sample depths for the example location sites are summarized in Table 8.5. The in-situ surrogate suction profile is assumed to be the initial suction profile in the computations. The initial suction profiles are shown, along with seasonal fluctuation suction envelopes in Figure 8.11 and Figure 8.12.

Table 8.5: Field Suction for the Example Sites

San Antonio, TX		Denver, CO	
Depth	ψ_{sur}	Depth	ψ_{sur}
0.305 m	4.7215 pF	3.0480 m	4.5867 pF
1.524 m	4.1911 pF	3.9624 m	4.2381 pF
2.286 m	4.1315 pF	4.2672 m	4.1920 pF
3.353 m	4.2249 pF	4.572 m	4.3620 pF
3.658 m	4.2403 pF	3.0480 m	4.3068 pF
3.962 m	4.0760 pF	3.9624 m	4.0645 pF
		4.2672 m	4.0018 pF

The average equilibrium suction using the surrogate suctions below the depth of equilibrium suction is 4.1804 pF.

Using the calculated TMI, the suction envelope components per this research, for the example San Antonio, TX site are presented in Table 8.6.

Table 8.6: Seasonal Fluctuation Suction Envelope Parameters for the Example Sites

Location	TMI	$\Delta\psi\ in\ pF\ units$	D_{ψ_e}	ψ_e	r
San Antonio, TX	-16.6	1.3157 pF	3.13 m	4.1804 pF	0.4325
Denver, CO	-24	1.3653 pF	3.76 m	4.1244 pF	0.4623

8.5.2.1. Suction Profile Generation

The Mitchell (1981) equation for change in suction based on depth and time, simplified by Naiser and Lytton 1997 for only the extreme suction cases (wet and dry), is used to obtain the shape of the envelopes; Equation (166).

$$\psi(z) = \psi_{eq} + \Delta\psi_{z=0} e^{(-z)\sqrt{\frac{n\pi}{\alpha}}} \tag{166}$$

Where,

$\psi(z)$ is the suction value at any depth z

n is the frequency of suction cycles per year

α is the diffusion coefficient

The suction change with depth is a function of change in suction at the surface ($\Delta\psi\ in\ pF\ units$) and the equilibrium suction (ψ_e). The n, α, π term in the Mitchell (1981) equation, is determined by a back-calculation approach using the known equilibrium depth, change in suction at surface, r, and the 0.2 pF difference, wet to dry, at the depth of equilibrium.

$$\frac{n\pi}{\alpha} = \left(\frac{\ln\left(\frac{0.2\,pF}{\Delta\psi_{surface}} \right)}{-d_{eq}} \right)^2 \tag{167}$$

The suction profile can now be generated using the Mitchell (1981) and previously computed components of the surrogate suction profile (Figure 8.11 and Figure 8.12). The wet and dry limit suction curves are iteratively calculated as the depth (*z*) is increased from 0 (ground surface) to the depth of equilibrium suction, Equations (168) and (169).

$$\psi(z_i)_{dry} = \psi(z_{i-1})_{dry} + (1-r)\Delta\psi_{z=o} e^{\left(-z_i\sqrt{\frac{n\pi}{\alpha}}\right)} \tag{168}$$

$$\psi(z_i)_{wet} = \psi(z_{i-1})_{wet} + r\Delta\psi_{z=o} e^{\left(-z_i\sqrt{\frac{n\pi}{\alpha}}\right)} \tag{169}$$

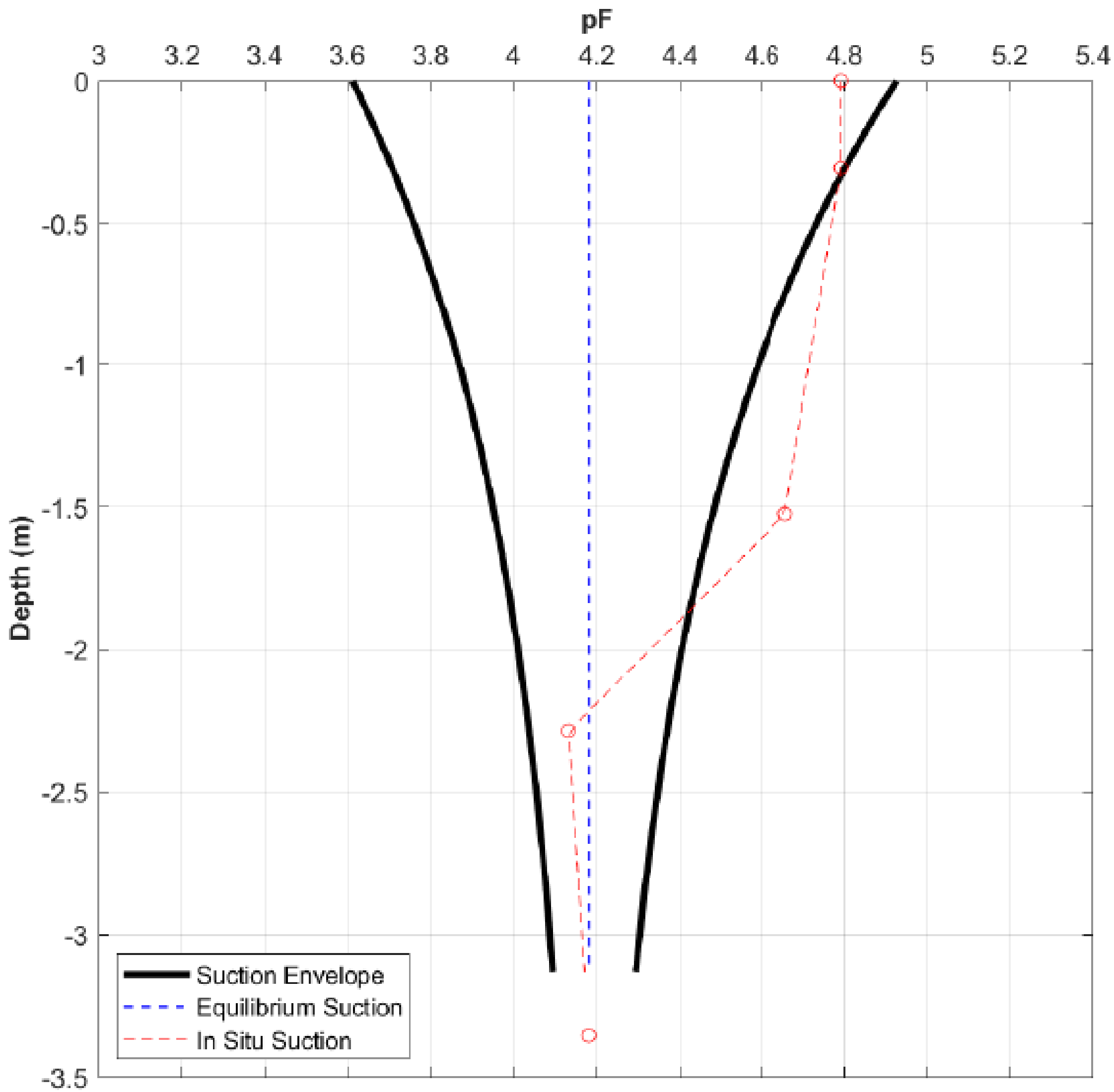


Figure 8.11: Suction envelope with in situ surrogate suction (red) for the example San Antonio, TX site with equilibrium suction determined from the average suction below the depth of equilibrium suction

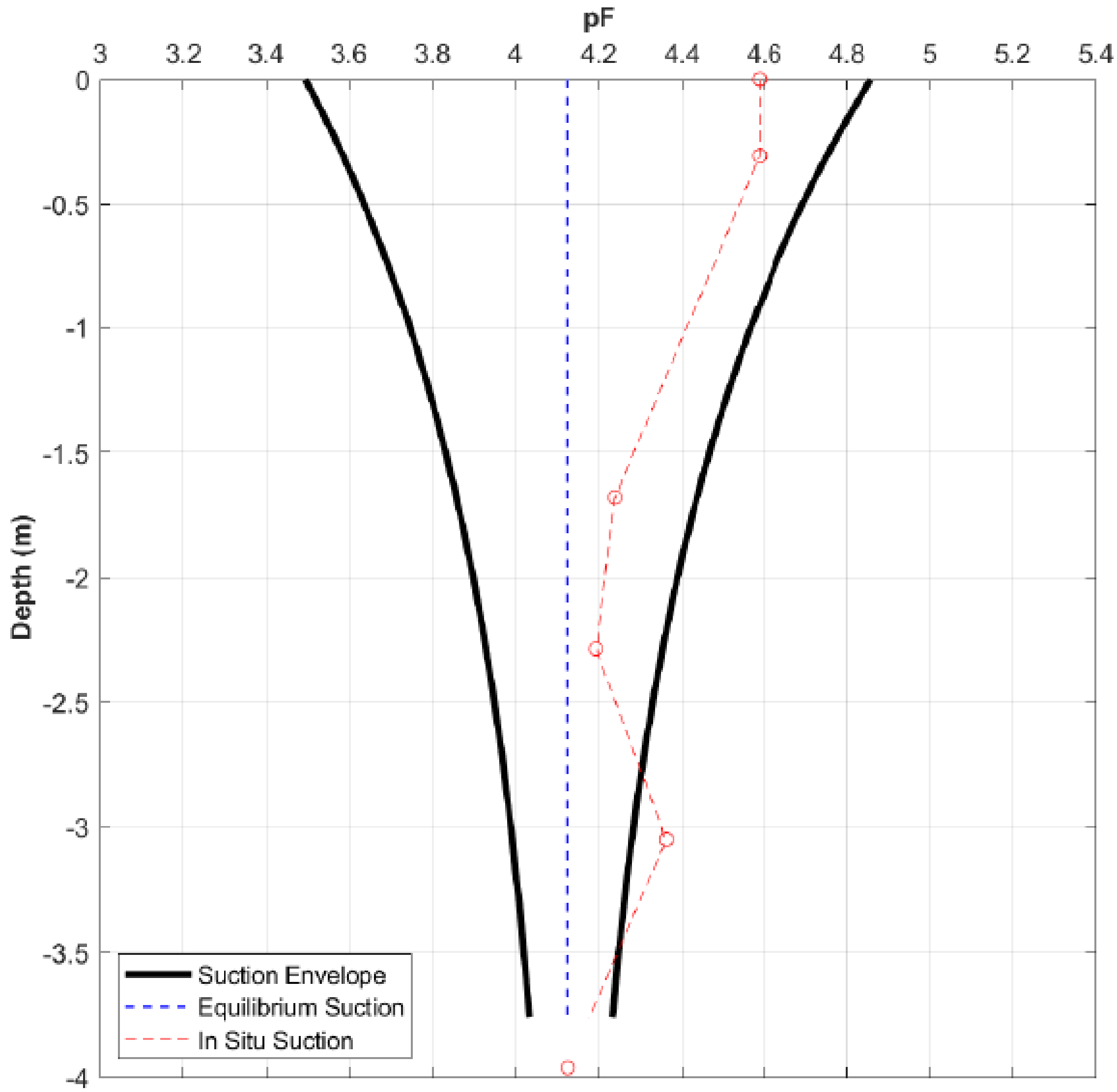


Figure 8.12: Suction envelope with in situ surrogate suction (red) for the example Denver, CO site with equilibrium suction determined from the average suction below the depth of equilibrium suction

Note that in between depths at which samples were collected, the field suction values are linearly interpolated. In the example heave computations presented here, the wet extreme of the seasonal fluctuation suction envelop will be used as the final suction profile condition in the computation of heave.

8.5.2.2. Computation of Heave

Once the initial and final field suction profiles are determined, the partial wetting strain (ε_{pw}) for each incremental depth z is determined for either the shrinking or swelling mode, as appropriate, using the SPM (Singhal, 2010; Houston and Houston, 2018). The heave or shrinkage is calculated by integrating the strain vs depth curve. The ratio (R_w) of the initial suction (ψ_{int}) to the final suction (ψ_f) determined from the suction profiles at the specific depth (subscript *i*) is determined as indicated by Equation (170):

$$R_{w_i} = \frac{\psi_{\text{int}_i}}{\psi_{f_i}} \tag{170}$$

The slope of the surrogate path (C_{SP}) is then calculated with Equation (171) using the fully wetted oedometer strain (ε_{ob}) under the field net normal stress (σ_{ob}) and the constant volume swell pressure (σ_{cv}), determined using ASTM D4546 test results.

$$C_H = C_{SP} = \frac{\varepsilon_{ob}}{\log\left(\sigma_{cv}/\sigma_{ob}\right)} \tag{171}$$

If the load-back swell pressure is obtained during the response to wetting test, it can be corrected using Equation (172) per Nelson et al. (2006) to estimate the constant volume swell pressure.

$$\sigma_{cv} = \sigma_{ob} + \lambda(\sigma_{lb} - \sigma_{ob}) \tag{172}$$

Where,

λ is a proportionality constant.

From experimental data, Nelson et al. (2006) determined that the proportionality constant lies between 0.5 and 0.7. Olaiz (2017) also recommends a proportionality constant of 0.7 based on several response to wetting tests conducted by Singhal (2010). Next, intermediate stress (σ_{p_i}) between σ_{ob_i} and σ_{cv} is determined by Equation (173).

$$\sigma_{p_i} = \sigma_{ob_i} + R_{w_i}\left(\sigma_{cv} - \sigma_{ob_i}\right) \tag{173}$$

Lastly, the partial wetting strain is calculated by Equation (174):

$$\varepsilon_{pw_i} = C_{SP}\log\left(\sigma_{cv} / \sigma_{p_i} \right) \tag{174}$$

Note that the slope of the surrogate path for a given soil layer (a layer wherein an ASTM-D4546 test result is available) is taken to be a constant; only the initial suction, final suction, and overburden stress will be changed as the depth interval increases.

The wetting strain profiles (final suction profiles) with depth for surrogate data for San Antonio, TX and Denver, CO are presented in Figure 8.13 and Figure 8.14. Because the ASTM D4546 test data is only available at limited depth locations, the full wetting strain and swell pressure values are projected to the midpoint between the sample depths, and the overburden pressure used in the SPM computation is calculated at each interval depth.

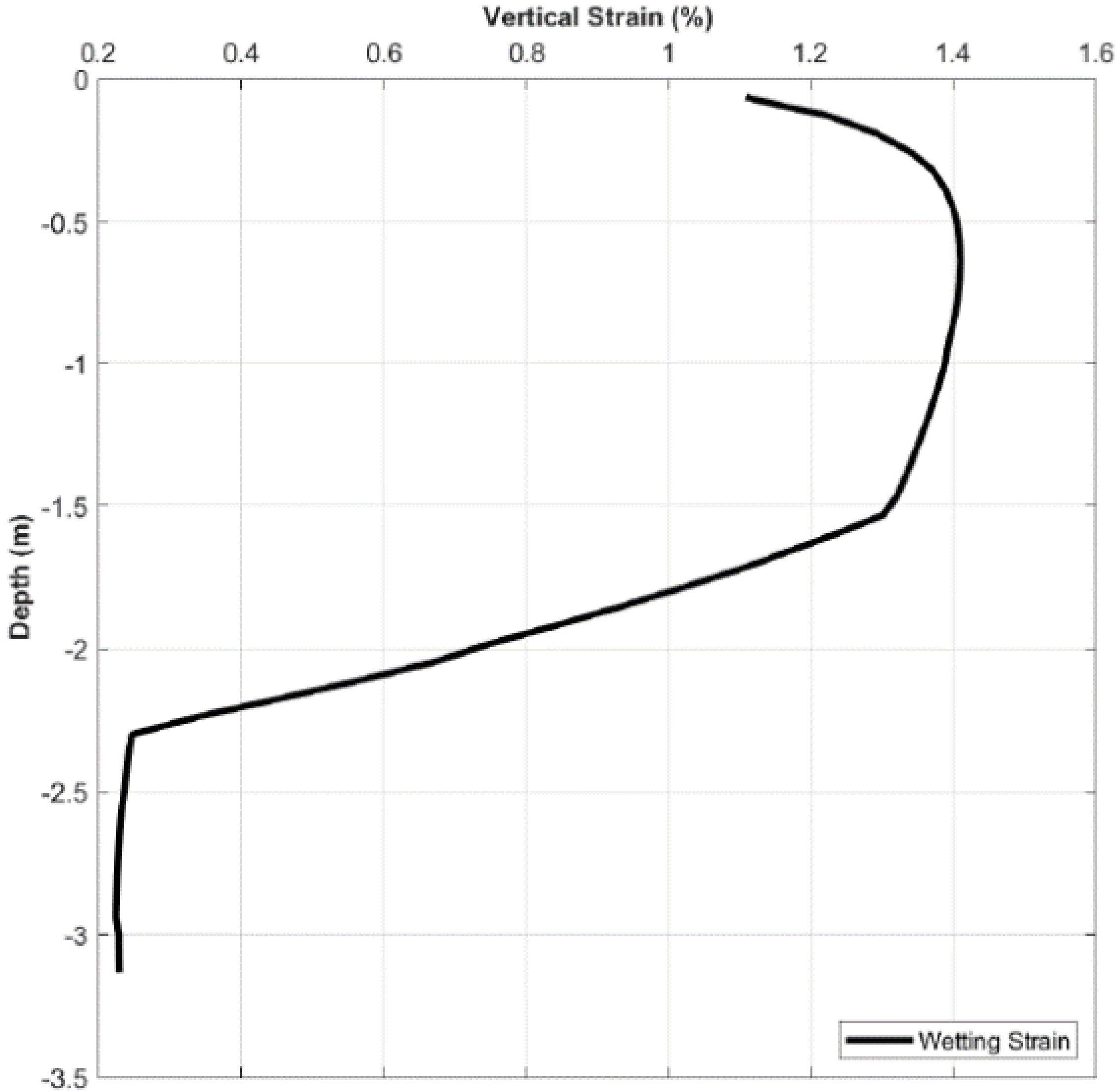


Figure 8.13: Wetting Strain Profile for the San Antonio, TX Site Using Surrogate Field Suction

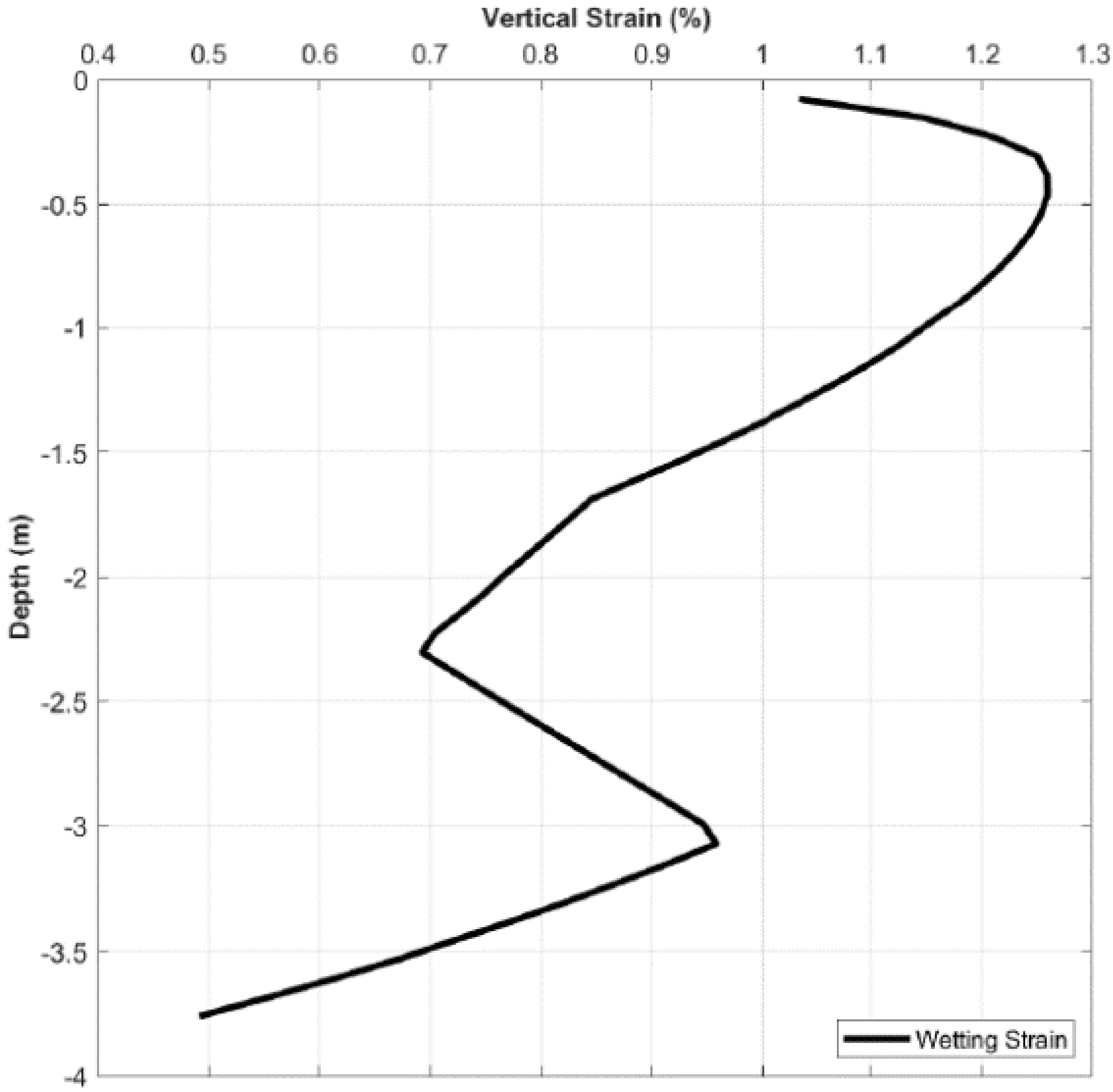


Figure 8.14: Wetting Strain Profile for the Denver, CO Site Using Surrogate Field Suction

To calculate the increment of swell for each depth interval, the strain at each interval is multiplied by the thickness of the layers (*dz*), Equation (175).

$$dz = \frac{d_{eq}}{n_{dz}} \tag{175}$$

Where,

d_{eq} is the depth to equilibrium suction

n_{dz} is the number of layers

Since the total strain is the integration of the strain vs depth profile for a 1-D analysis, the summation of the incremental strains along the depth will result in the total heave (or shrinkage) value. The total amount of swell (assumed to act vertically for 1-D analyses) is calculated by Equation (176).

$$\Delta V = \Delta h = \sum_{i=1}^{d_{eq}} \Delta h_i = \sum_{i=1}^{d_{eq}} \varepsilon_i \Delta z \qquad (176)$$

The calculated soil swell for the example are summarized in Table 8.7.

Table 8.7: Estimated Swells for the Example Sites using Surrogate Field Suctions

Location	$\Delta H_{\mathrm{SWELL}}$ (Surrogate)
San Antonio, TX	2.87 cm
Denver, CO	3.49 cm

Note that the calculations follow a simple algorithmic process that can be easily programmed into a typical spreadsheet software like Microsoft Excel.

8.5.3. Example Suction-Oedometer Heave Computation Using Measured Data

If able to, it is recommended that the suction be directly measured at each sample depth. To compare the differences between the heave computations for field estimated (surrogate) suction using water content and liquid limit, to the actual field measured suction, the WP4C suction measurements for the San Antonio, TX and Denver, CO sites are used.

8.5.3.1. *Suction Profile Generation*

The WP4C suction data are presented in Table 8.8 and Table 8.9. The average of the measured suction data for San Antonio below the estimated depth of equilibrium suction is 3.99 pF, and is used as the equilibrium suction value in the following example. The corresponding average measured equilibrium suction value for Denver is 4.22 pF.

Table 8.8: Soil Parameters from SA-2-U-I for Example Computation

Depth (m)	Sample Type	WP4-C Measured Suction (pF)
0.305	Bulk	4.83
1.524	Undisturbed & Bulk	4.38
2.286	Bulk	4.22
3.353	Bulk	4.02
3.658	Bulk	4.00
3.962	Bulk	3.96

Table 8.9: Soil Parameters from DEN-3-U-I for Example Computation

Depth (m)	Sample Type	WP4-C Measured Suction (pF)
0.305	Bulk	4.66
1.524	Undisturbed & Bulk	4.64
2.286	Bulk	4.65
3.353	Bulk	4.42
3.658	Bulk	4.18
3.962	Bulk	4.33

The initial suction profiles with depth for measured data for San Antonio, TX and Denver, CO are presented in Figure 8.15 and Figure 8.16. The final suction profiles for these sample computations are taken to be the extreme wet limit of the suction envelopes.

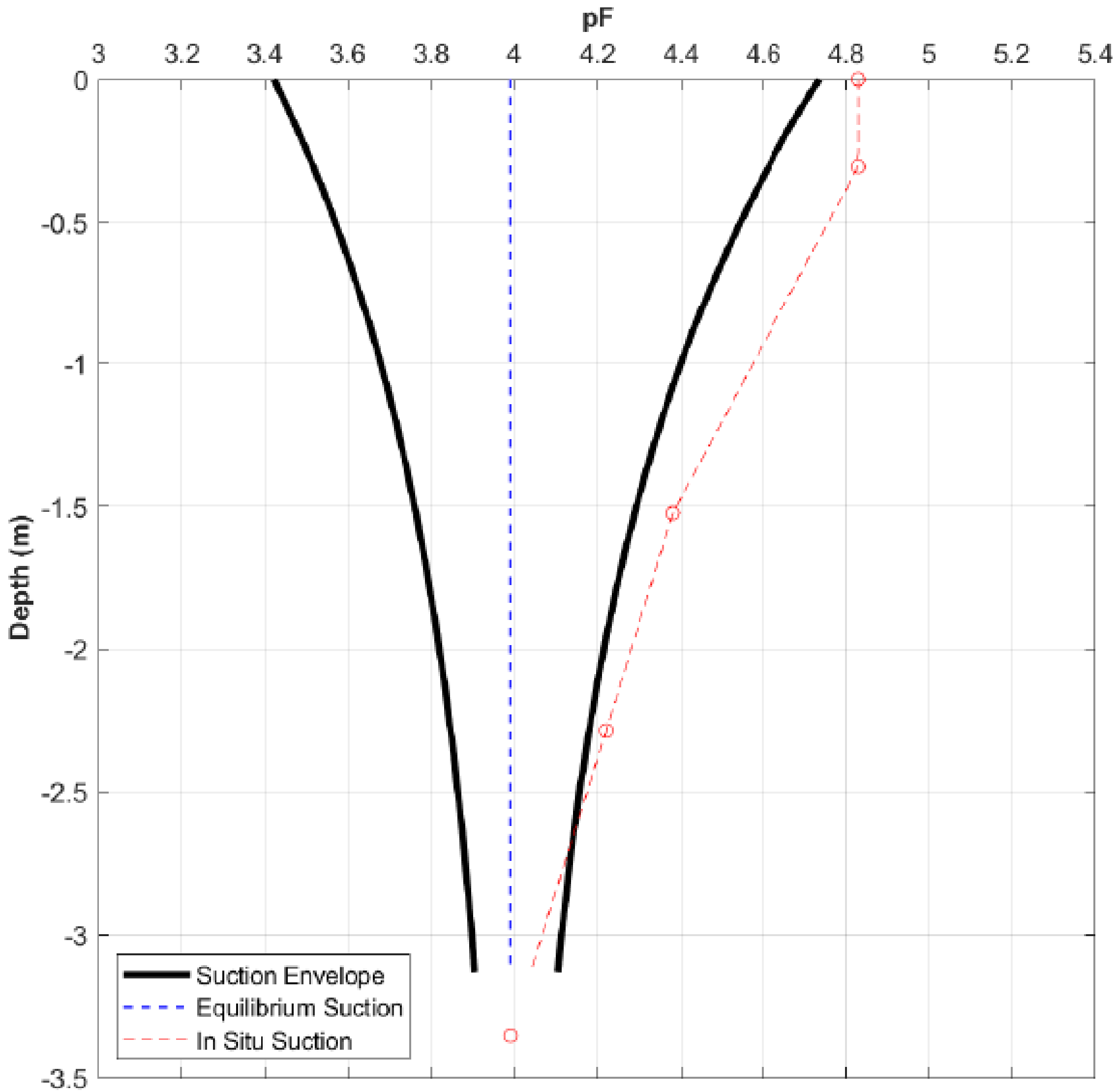


Figure 8.15: Suction envelope with in situ measured suction (red) for the example San Antonio, TX site

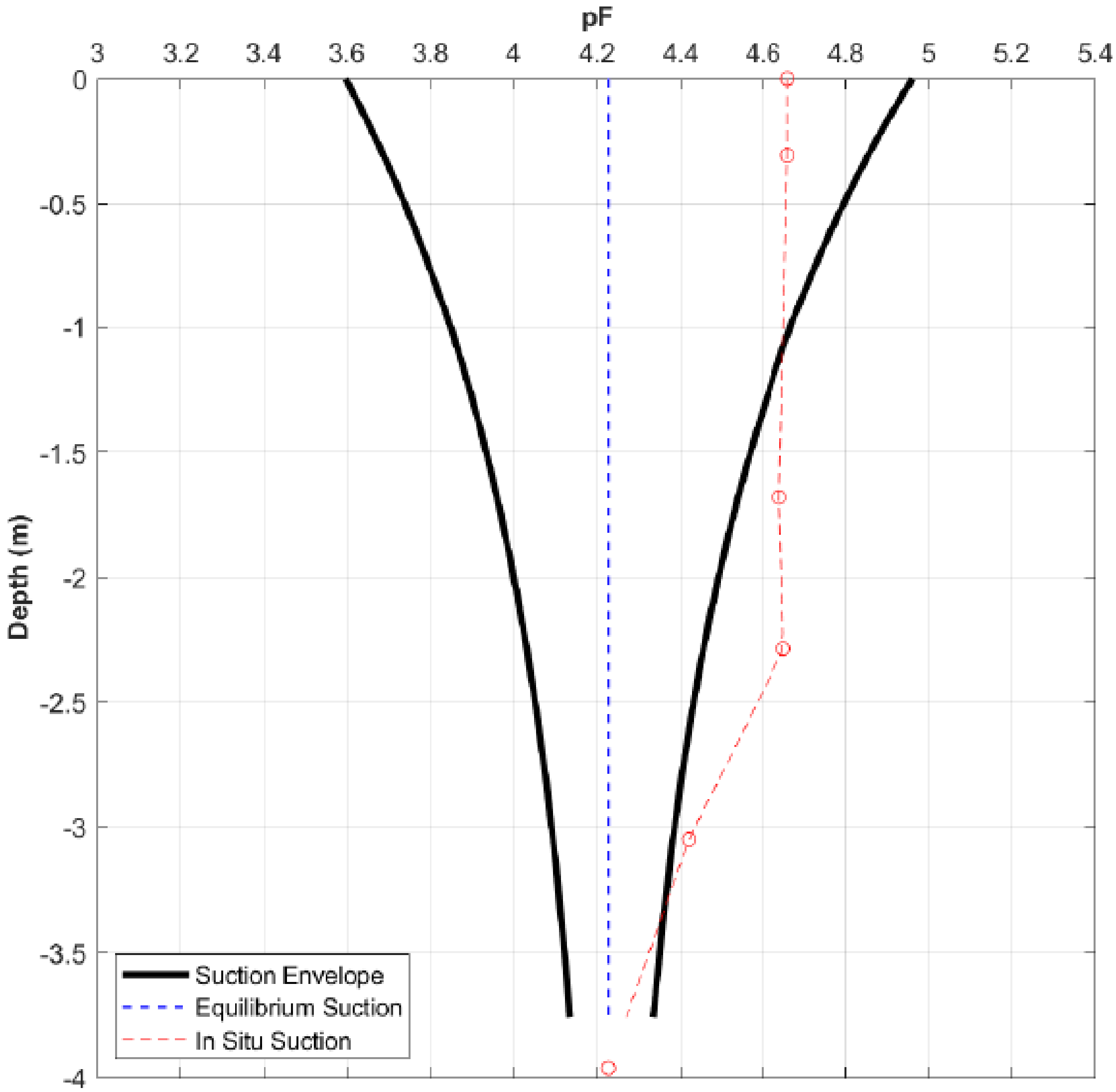


Figure 8.16: Suction envelope with in situ measured suction (red) for the example Denver, CO

8.5.3.2. Computation of Heave

The wetting strain profiles with depth for measured data for San Antonio, TX and Denver, CO are presented in Figure 8.17 and Figure 8.18.

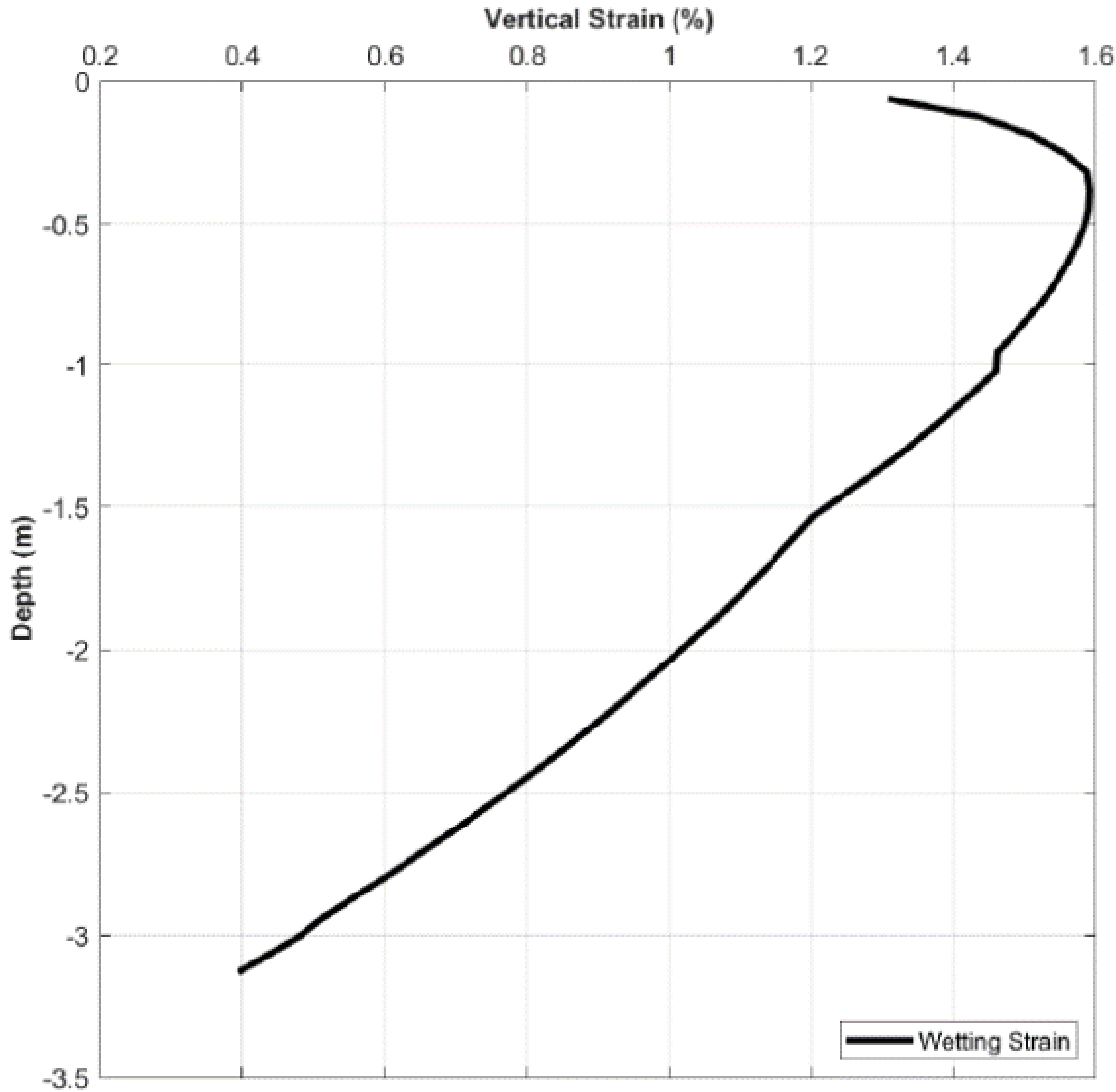


Figure 8.17: Wetting Strain Profile for the San Antonio, TX Site Using Measured Field Suction

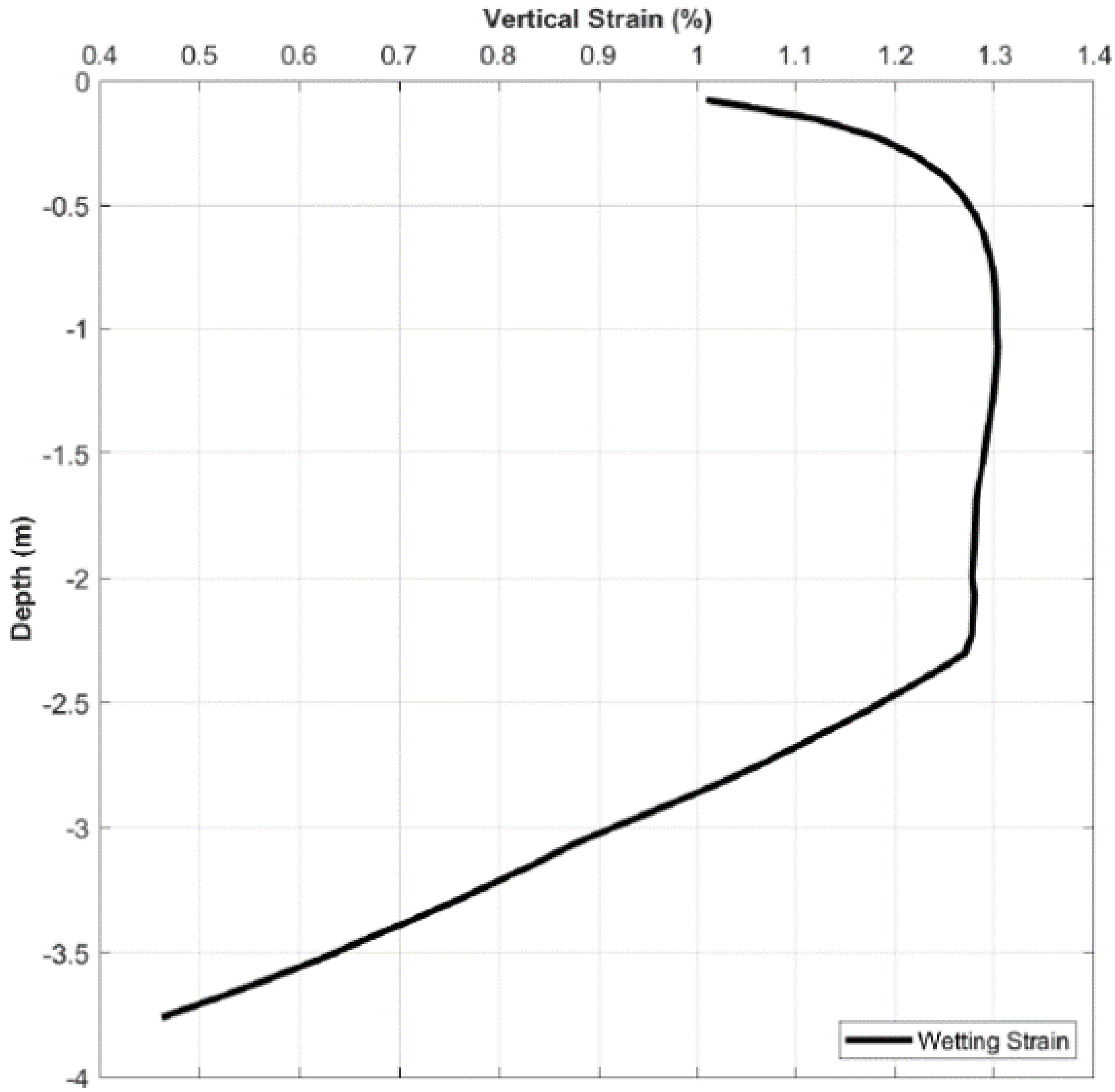


Figure 8.18: Wetting Strain Profile for the Denver, CO Site Using Measured Field Suction

Table 8.10 presents a valuable comparison of heave predictions for the San Antonio, TX and Denver, CO sites using both surrogate and measured suction values.

Table 8.10: Estimated Swells for the Example Sites using Surrogate and Measured Field Suctions

Location	$\Delta H_{\mathrm{SWELL}}$ (Surrogate)	$\Delta H_{\mathrm{SWELL}}$ (Measured)
San Antonio, TX	2.87 cm	3.54 cm
Denver, CO	3.49 cm	4.19 cm

Comparatively, the heave predictions, while appearing variable, should be considered close to one another within a reasonable degree of engineering certainty. For example, using the surrogate the anticipated heave was 2.9 cm, which is 1.14 inches, as opposed to the measured heave of 3.5 cm, which is 1.38 inches. For the practicing engineer, the two heave magnitudes do not represent a significant difference relative to the design process. Likewise, the same argument can be applied to the Denver data.

CHAPTER 9 RECOMMENDATIONS FOR FURTHER STUDY

9.1 Need for Additional Site Drilling and Laboratory Testing

Certainly, a need exists for more sites to be drilled. As the criteria has developed over the course of this research, we know more now than before where and what data is needed. To start, future drill sites need to be in known in areas where the clay stratum extends to at least 9.14 m (30 ft) below the existing site surface. Preferably, site investigations in the future should be comprised of four test borings per site; two test borings in an uncovered area while the two remaining test borings are constraint to a covered area. A covered area must constitute the locations of two of the test borings. The test borings advanced in the covered area must be positioned at least 15 feet inward (on the covered side) from the edge of the covering, whether the covering is comprised of asphalt or concrete. Prior work has been completed on the premise of a 3.048 m (10 ft) distance being adequate to be outside of the edge moisture variation; however, better judgement would dictate a minimum bore hole distance of 4.57 m (15 ft) from the covering edge to account for seasonal moisture variations. Further, the covering (asphalt or concrete) should have been in place for a minimum of 5 years to best-assess the final suction profiles conditions. While each test boring will be advanced to 9.14 m (30 ft), the sampling protocol will vary for each test boring within each area, covered versus uncovered. Standard Penetration Tests (SPTs) should be completed, for one covered and one uncovered test boring, at regularly horizontally spaced intervals, i.e. every 1.52 m (5 ft) at a minimum. The SPTs can commence at minus 1.52 m (5 ft). Also retrieved form the SPT-hole must be regularly spaced undisturbed samples taken by means of a California ring sampler, Shelby Tube or other approved method. The undisturbed samples can commence at minus 0.762 m (2.5 ft) and be repeated vertically every 1.52 m (5 ft). In the second test boring for each covered and uncovered area, bulk disturbed samples must be retrieved for every 0.3048 m (1.0 ft), throughout the entire test boring depth. Undisturbed samples should be laboratory tested for ASTM D4546, moisture content and dry density. Bulk disturbed samples must be tested for Atterberg Limits, grain-size distribution, moisture content, and suction by through usage of the Meter WP4C. When testing with a WP4C, care must be taken with the sample size, placement coverage (ensuring that the sample covered the entire bottom of the cup), prevention of moisture loss, and machine calibration. It is of the utmost concern that these items be addressed as the absence of the above required data in existing geotechnical engineering reports resulted in a much more limited database, even considering use of suction surrogate, for exploration of field suction profiles for expansive soils.

9.2 Enhancement of the Relationship Between TMI and the Depth to Equilibrium Suction

Although the arguments associated with the use of Equations (149) and (150), LL-dependent depth to equilibrium suction (Figure 6.53), are plausible and thought provoking, a recommendation for their use is premature. A major point that precludes these equations for recommended use is simply attributed to insufficient data regarding liquid limits greater than or equal to 50, insufficient data with liquid limits less than 50, and an overall set of liquid limit values that cover the complete spectrum of TMIs from -60 to +60. Granted from expansive soil areas, the need for such data could be focused to a greater extent in the TMI range of -60 to +20. Because of the need for more data covering the spectrum of liquid limits in a wider range of TMI, Equations (149) and (150) are not yet ready for recommended use. There remains a great deal of confidence that with the incorporation of more data, the relationships proposed by Equations (149) and (150), or at least some form of relationship for depth to equilibrium based on both TMI and LL, may be confirmed, refined, and brought to a confidence level where practitioners can rely on their use.

9.3 Enhancement of Database of Suction Profiles Across Multiple Seasons and Years

The relationships between TMI and change in suction at the soil surface ($\Delta\psi$, Figure 6.99) and the relationship between TMI and shifts toward wet or dry (r parameter, Figure 6.101) require the addition of soil profiles across multiple years and seasons at specific locations covering a wide range of TMI. In this study, only seven locations had data for multiple years and seasons, and of these four required combining suction profiles from somewhat distant locations within the region of consideration. Although the relationships for delta pF and r presented in this dissertation show statistical significance, the addition of data is likely to strengthen correlations between TMI and these two parameters.

9.4 Vegetation, Excessive Irrigation, and Lateral Flow Effects

Research pertaining to the effects of vegetation, including trees, and continued excessive irrigation or excessive lateral water contributors on the suction envelopes and profiles should be considered. To date, such modifications of the suction envelopes have been predominantly accomplished according to procedures adopted by the PTI. Alternative methodologies should also be considered in the future to provide design-related options for the practitioner for inclusion of a broader set of boundary conditions. To the extent possible, such recommendation should be based on a database of actual field soil suction profiles.

9.5 Layered Soil Media

Future research could consider the effects of layered clay soil media. Often, clay soil profiles are not homogeneous. In fact, clay mineralogy and structure can change along a vertical profile. During the course of this research, an apparent homogeneous clay layer may have been comprised of multiple CH clay layers, each with a unique clay structure. Perhaps in some cases, a residual clay structure could be dictated by the mineralogy of the subsurface parent rock type, which may vary depending on density and the unsaturated soil permeability. Suction envelop changes when considering heterogeneous layering could prove beneficial to the consultant, particularly when alternating layers of CL and CH clay exist within the zone above the depth to equilibrium suction. The ability to discern where vertical a transition occurs between a residual clay layer overlying a claystone or mudstone is also important as it may have an effect on the suction envelop and profiles perhaps arising from a dramatic change in clay structure, porosity, permeability and diffusion coefficient with depth.

9.6 Long-term Effects / Applications of the Predicted Soil Suction Profiles

It is incumbent that the predictive measures recommended be monitored over time to verify their validity based on benchmarked case studies where heave computations can be compared to heave observed in the field. Of course, this effort will be long-term. The effort will incorporate the design-related measures to arrive at soil suction envelopes, profiles and heave predictions. Following construction, methods can be employed to verify or substantiate the conditions while comparing and contrasting to those predicted. The long-term effects of development can be ascertained including a better understanding of the edge penetration distance, and stabilization of the magnitude of equilibrium suction beneath a structure with time.

9.7 Topography

Future drilling, sampling and testing efforts associated with sites should consider the relative topography of the area. Investigation of a site to determine the suction envelop, profile and heave prediction may depend in part on whether the site is to be elevated or be elevated or be cut substantially. Also, to be considered is the design and constructed site slope in the heave prediction analysis.

9.8 Surface Barriers

For uncovered sites, the soil suction envelopes are obtainable with confidence. Other surface features, such as deep perimeter strip foundation, may affect the suction profiles. Case studies may be initiated to evaluate such features.

9.9 Effects of Soil Improvement or Modification

Invariably, geotechnical practitioners modify the surface of the site as part of the fulfillment of the recommendations contained in their reports. Geotechnical-related measures that are imposed on a site's construction include recompaction of the native soils to a predetermined depth, replacement of the native soils with suitable imported soils to a specified depth, chemical treatment of the native or imported soils to a design-effective depth, and installation of geosynthetic materials. The effects of the above measures could be further examined relative to the alteration of the suction envelopes, profiles and heave prediction.

9.10 Further Review of Mitchell's Formulation for Use in Assessment of Time-Rate Suction Profiles and Effects of Changed Flux Boundary Conditions

In this dissertation the formulation of Mitchell (1980) for estimation of suction profiles was used to estimate the shape of the wet and dry soil suction envelopes for design. Several assumptions were made by Mitchell in simplification of Richards' equation for unsaturated flow. In particular, Mitchell assumed that the hydraulic conductivity of the clay (K_{unsat}) decreased linearly with the log of suction (pF) and that the soil-water characteristic curve (SWCC) varied linearly with the log of suction. These two simplifying assumptions lead to the assumption that the diffusion coefficient (a function of both the slope of the SWCC and the slope of Kunsat versus log suction) remains constant. While the results from Mitchell's solutions appear consistent with the field data obtained here in, further study comparing the Mitchell's formulation to the more rigorous unsaturated flow equation (e.g. Richards' equation) is required to study. Such study would also facilitate the study of time-rate of change of heave/shrinkage. Whereas this particularly study was focused on assessment of design suction envelopes encompassing multiple seasons of wetting/drying or for covered surface flow boundary conditions for field conditions, extreme boundary conditions of excessive irrigation, water ponding, or nearby trees were not evaluated. It is possible that such extreme boundary conditions will push the solution to the unsaturated flow equation into the nonlinear range wherein the assumptions of Mitchell (SWCC slope linear with log suction and Kunsat linear with log suction) as not valid. Further research is required to answer support the use of the simplified Mitchell's formulation over a wider range of boundary conditions. The reason for such study is that to the extent that Mitchell's formulation can be supported/validated, the more time-consuming analyses required by direct use of Richards' equation can be avoided.

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APPENDIX

A SITE PLANS

A 1: Site Plan of the Hobart Drill Area

A 2: Site Plan of the Denver Drill Area

A 3: Site Plan of the San Antonio Drill Area

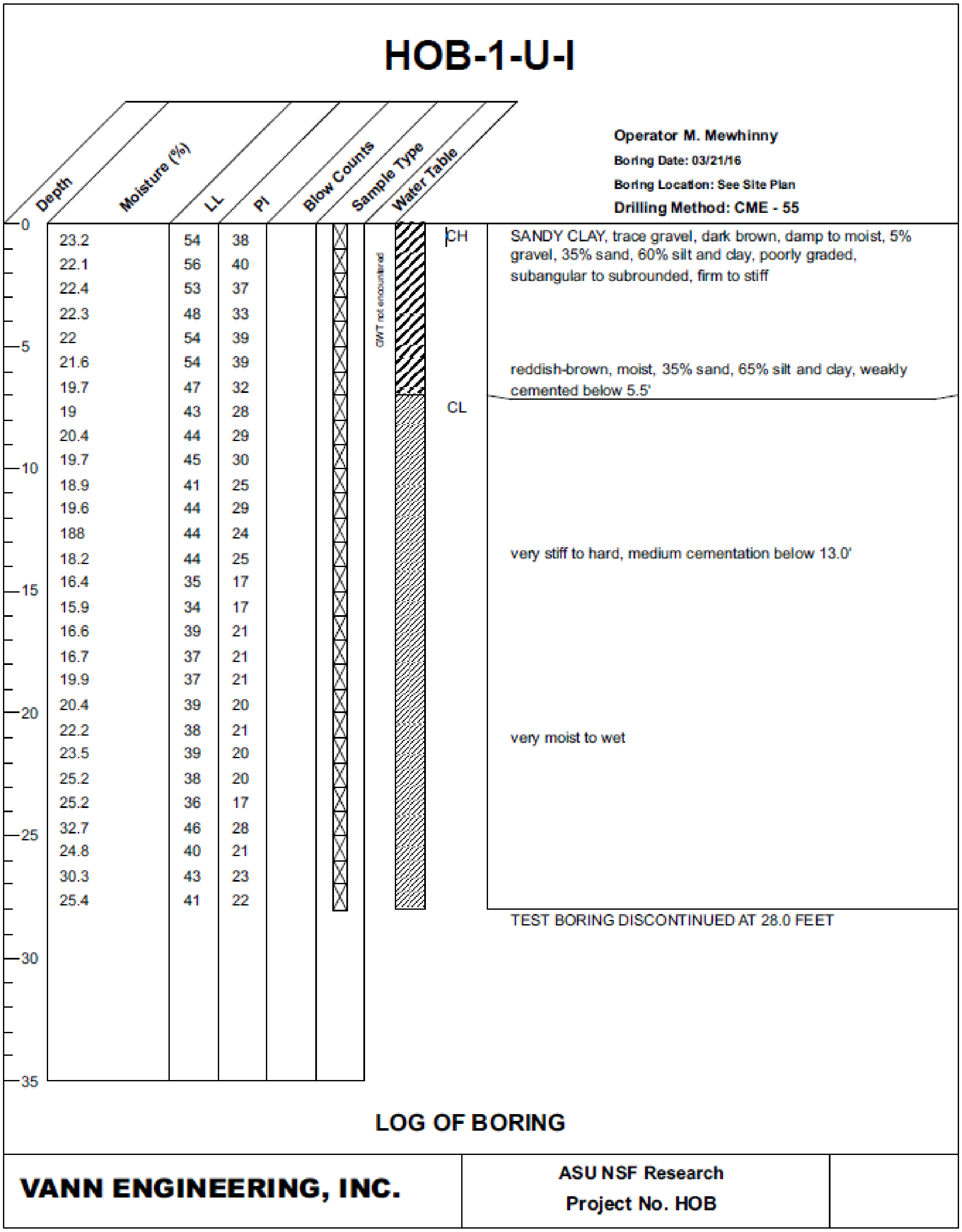
A 4: Site Plan of the Mesa Drill Area

A 5: Site Plan of Phoenix Drill Area

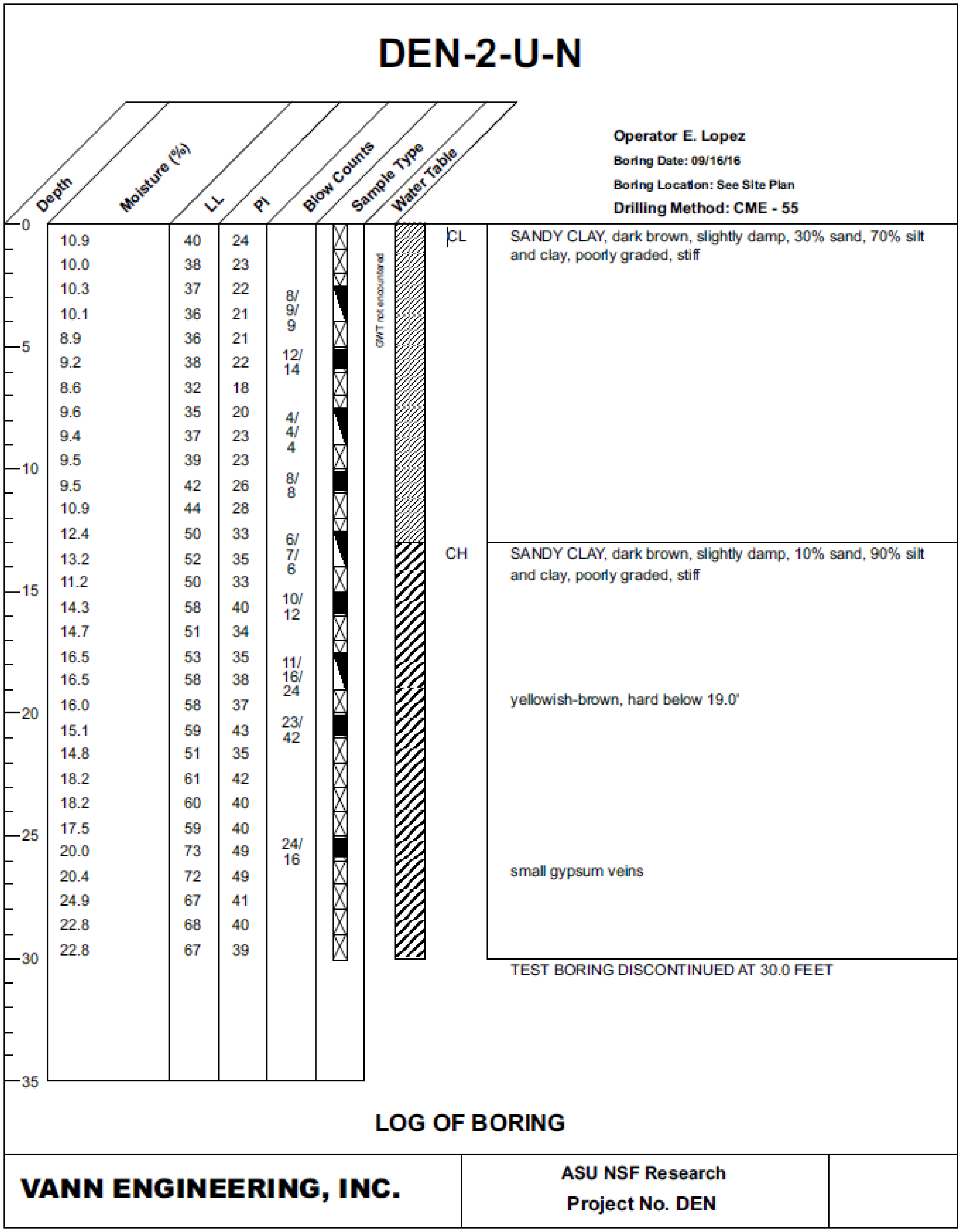
A 6: Site Plan of the Munds Park Drill Area

A 7: Site Plan of the Young Drill Area

B BORING LOGS



B 1: Test Boring Log for Hobart – 1 – U - I



B 2: Test Boring Log for DEN-2-U-N

DEN-3-U-N

Operator E. Lopez
Boring Date: 09/16/16
Boring Location: See Site Plan
Drilling Method: CME - 55

Moisture (%)	LL	PI	Blow Counts
9.4	39	22	
9.7	38	22	
9.8	39	24	
9.4	39	23	8/ 7/ 6
9.5	33	18	
10.0	36	24	14/ 20
10.9	36	24	
8.5	43	27	
8.5	46	28	
12.1	48	32	
13.6	53	33	13/ 17
11.4	51	31	
13.9	52	31	
18.5	53	33	
19.5	52	28	
23.8	64	37	18/ 26
25.4	67	43	
21.0	63	41	14/ 24
21.2	62	41	
20.5	62	41	
21.9	68	41	20/ 28
22.6	78	53	
24.0	62	42	
22.4	67	43	
21.9	64	41	
19.1	58	38	29/ 49
21.8	65	43	
20.9	66	43	
20.9	67	46	
21.3	65	43	

Water Table: GWT not encountered

Depth 0–10: CL — SANDY CLAY, trace gravel, dark brown, slightly damp, 4% gravel, 18% sand, 78% silt and clay, poorly graded, stiff, weak cementation

very stiff below 5.0'

Depth 10–30: CH — SANDY CLAY, yellowish-brown, slightly damp, 20% sand, 80% silt and clay, poorly graded, very stiff, weak cementation

increased in fines

damp below 23.0'

TEST BORING DISCONTINUED AT 30.0 FEET

LOG OF BORING

VANN ENGINEERING, INC. | ASU NSF Research Project No. DEN

B 3: Test Boring Log for DEN-3-U-N

DEN-5-C-N

Operator E. Lopez
Boring Date: 09/16/16
Boring Location: See Site Plan
Drilling Method: CME - 55

Moisture (%)	LL	PI	Blow Counts
14.9	49	31	
20.7	45	29	6/ 8
20.7	45	28	
21.7	44	30	
25.2	56	35	22/ 31
23.3	51	32	
22.3	53	29	
22.9	57	34	
24.6	63	41	
22.3	65	47	15/ 24
20.8	67	46	
19.4	65	46	
19.1	63	45	
19.9	60	42	
21.9	65	45	23/ 36
21.3	58	41	
17.0	49	33	
16.5	49	32	
13.6	55	36	
14.6	64	41	27/ 45
15.2	63	42	
15.9	63	43	
16.9	60	42	
16.4	67	47	
21.3	74	50	20/ 27
21.4	75	50	
23.5	82	47	
22.0	75	47	
22.9	78	47	

Depth: 0, 5, 10, 15, 20, 25, 30, 35

GWT not encountered

AS — 4.5" asphalt

CL — SANDY CLAY, dark brown, moist, 3% gravel, 30% sand, 67% silt and clay, poorly graded, stiff, weak cementation

CH — CLAY, yellowish-brown, moist, 5% gravel, 20% sand, 75% silt and clay, poorly graded, stiff, weak cementation

hard below 5.0'

10% sands, 90% silt and clay, damp below 10.0'

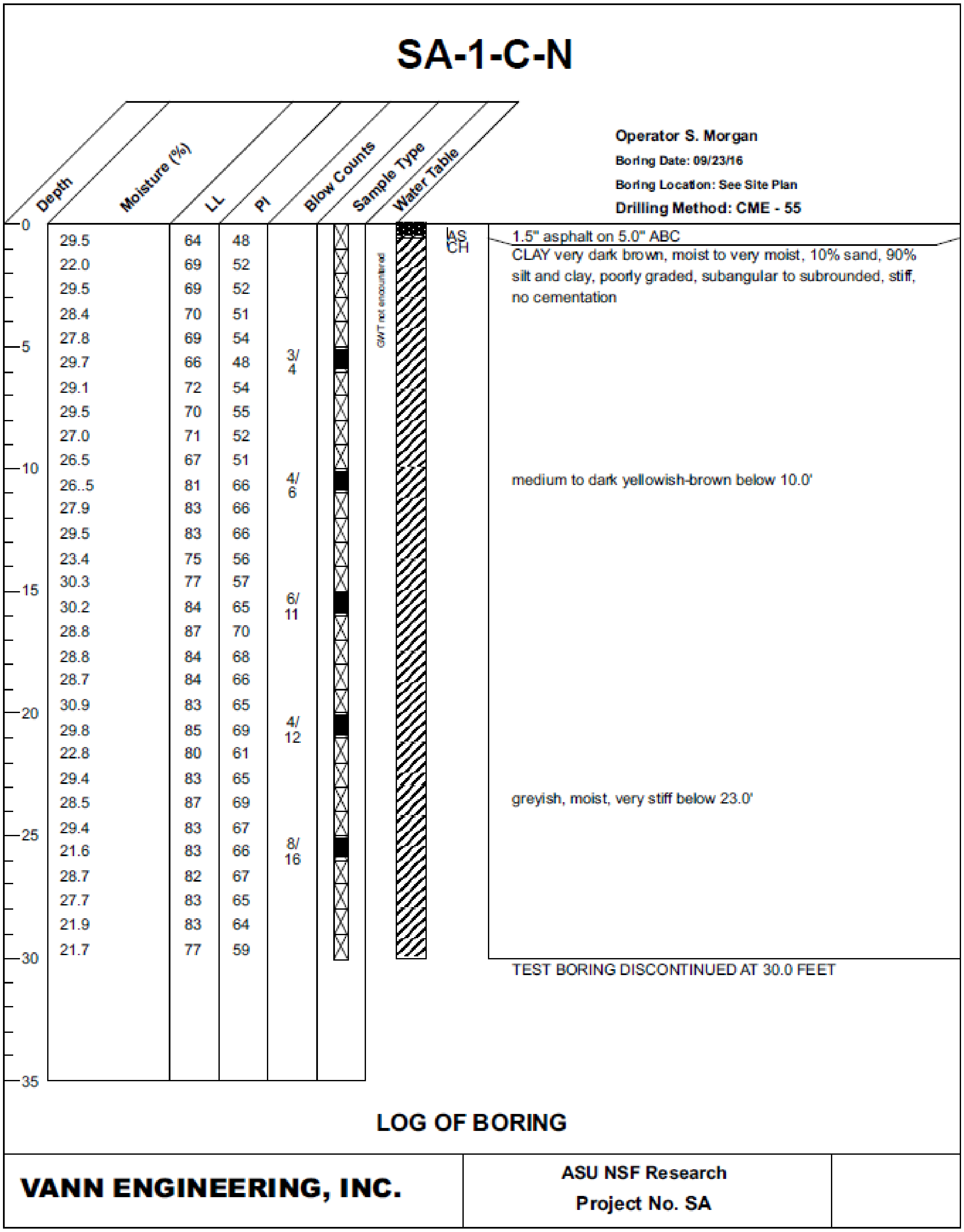
increase in fines

TEST BORING DISCONTINUED AT 30.0 FEET

LOG OF BORING

VANN ENGINEERING, INC.	ASU NSF Research Project No. DEN	

B 4: Test Boring Log for DEN-5-C-N



B 5: Test Boring Log for SA-1-C-N

SA-2-U-I

Operator S. Morgan
Boring Date: 09/23/16
Boring Location: See Site Plan
Drilling Method: CME - 55

Depth	Moisture (%)	LL	PI	Blow Counts
0	11.1	52	36	
	9.1	52	36	
	12.2	52	36	
	9.5	52	37	
	9.7	52	37	
5	19.7	65	50	5/ 12
	19.1	59	44	
	21.9	64	45	
	22.8	64	46	
	22.9	67	51	
10	25.7	88	72	6/ 9
	24.7	86	69	
	28.6	83	67	
	28.7	82	64	
	29.6	82	65	
15	29.5	90	74	5/ 9
	29.6	86	68	
	28.8	98	82	
	28.8	93	77	
	30.0	98	81	
20	21.7	93	77	5/ 10
	28.2	89	73	
	20.9	85	68	
	28.1	87	69	
	28.6	87	70	
25	28.0	87	69	10/ 15
	27.4	87	71	
	25.6	86	69	
	26.7	80	63	
	26.9	82	64	
30				
35				

Sample Type / Water Table: GWT not encountered

FL — Native bleneded with debris

CH — CLAY dark greyish-brown, slightly damp, 10% sand, 90% silt and clay, poorly graded, subangular to subrounded, stiff, no cementation

medium to dark yellowish-brown below 5.0'

greyish, increase in fines below 15

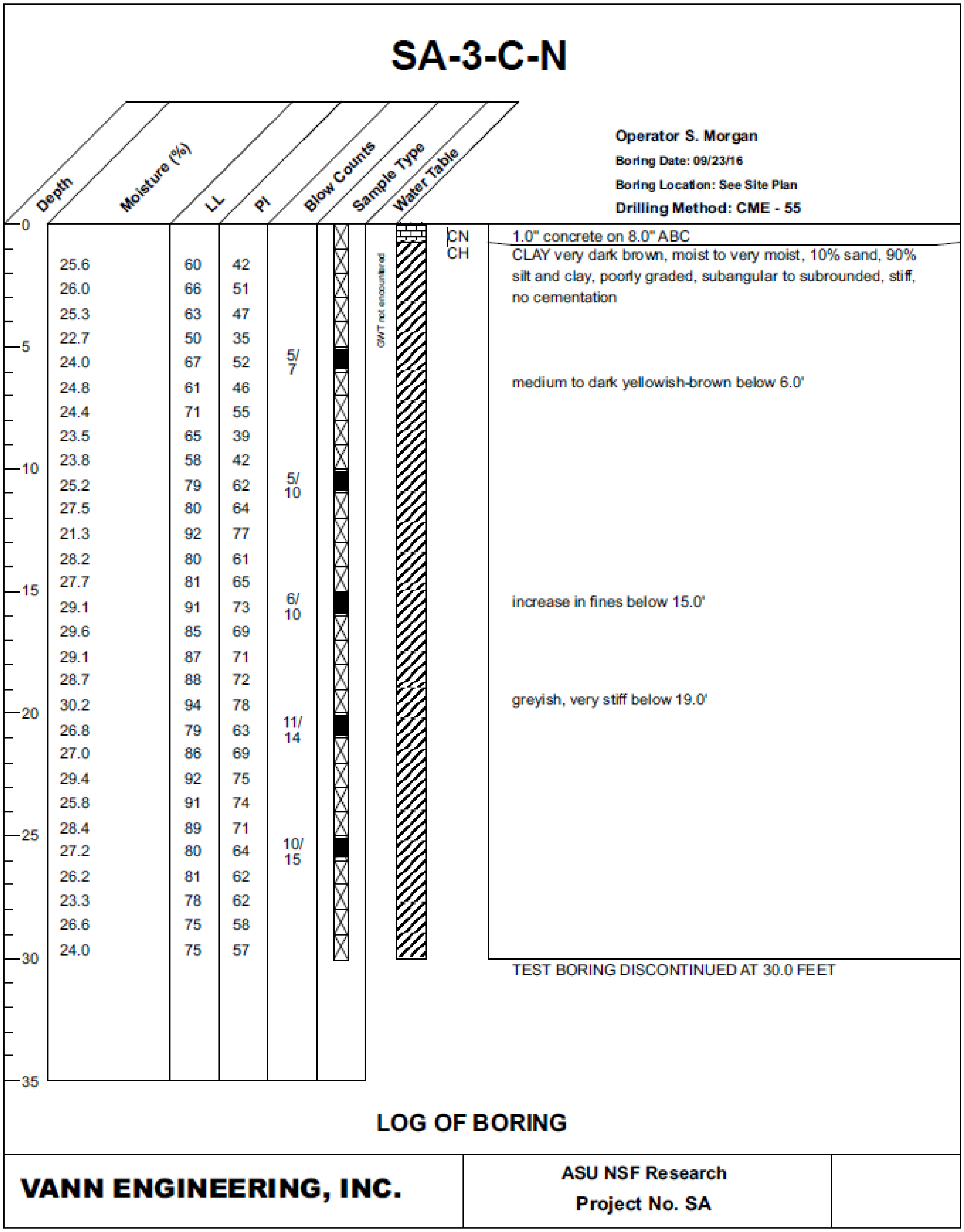
very stiff below 25.0'

TEST BORING DISCONTINUED AT 30.0 FEET

LOG OF BORING

VANN ENGINEERING, INC. | ASU NSF Research Project No. SA

B 6: Test Boring Log for SA-2-U-I



B 7: Test Boring Log for SA-3-C-N

SA-4-U-I

Operator S. Morgan
Boring Date: 09/23/16
Boring Location: See Site Plan
Drilling Method: CME - 55

Depth	Moisture (%)	LL	PI	Blow Counts
0	18.7	58	43	
	18.4	58	43	
	18.7	57	41	
	16.6	64	48	
	20.7	64	48	
5	18.5	63	47	12/ 16
	19.7	66	47	
	19.5	57	41	
	17.1	60	44	
	18.3	63	45	
10	25.9	75	58	4/ 9
	22.8	69	53	
	24.4	67	51	
	22.9	65	37	
	25.5	70	54	
15	28.1	85	69	6/ 10
	23.8	79	64	
	26.8	79	63	
	24.2	78	62	
	29.5	82	65	
20	27.9	81	64	12/ 16
	26.5	79	64	
	27.0	80	64	
	28.5	78	62	
	28.0	80	64	
25	28.7	82	65	14/ 16
	26.7	77	61	
	27.6	78	52	
	25.7	78	61	
	27.1	85	68	
30				
35				

Sample Type | Water Table: GWT not encountered

CH

CLAY very dark brown, moist to very moist, 5% gravel, 10% sand, 85% silt and clay, poorly graded, subangular to subrounded, stiff, no cementation

medium to dark yellowish-brown, 5% sand, 95% silt and clay

greyish, moist, very stiff below 25.0'

TEST BORING DISCONTINUED AT 30.0 FEET

LOG OF BORING

VANN ENGINEERING, INC.	ASU NSF Research Project No. SA	

B 8: Test Boring Log for SA-4-U-I

MESA-1-U-N

Surface Elevation:
Boring Date: 11/16/17
Operator: .M. Mewhinney
Drilling Method: CME - 55

Moisture Content (%)	LL	PI
3.0	31	16
7.1	35	20
9.0	39	21
10.9	45	29
9.0	52	37
10.9	51	34
8.6	53	38
7.8	50	34
7.9	48	31
9.3	43	27
9.6	45	29
10.1	48	34
11.2	51	35
11.6	54	37
11.4	48	32
11.0	64	47
10.0	53	37
7.4	48	33
6.9	42	24
6.6	42	25
6.8	45	29
6.8	46	29
5.2	47	32
8.5	54	38
10.2	53	38
8.0	57	43
7.4	56	40
6.3	53	37
6.7	55	39
6.0	57	41

Columns: Depth (0–35 ft), Moisture Content (%), LL, PI, Blow Counts, Sample Type, Water Table

Water Table: GWT not encountered

USCS	Description
CL	SANDY CLAY, reddish brown, slightly damp to damp, 40% sand, 60% silt and clay, poorly graded, subangular to subrounded, no cementation
CH	CLAY, medium brown, slightly damp, 40% sand, 60% silt and clay, poorly graded, no cementation

TEST BORING DISCONTINUED AT 30.0 FEET

VANN ENGINEERING, INC. | **ASU NSF Research Project No. MESA**

B 9: Test Boring Log for MESA-1-U-N

MESA-2-C-N

Surface Elevation:
Boring Date: 11/16/17
Operator: M. Mewhinney
Drilling Method: CME - 55

Moisture Content (%)	LL	PI
10.7	34	19
16.5	41	25
16.7	37	21
17.1	45	29
16.0	52	37
15.4	44	29
13.7	39	22
12.5	37	22
11.9	36	19
11.0	34	17
11.1	39	21
9.6	48	34
12.1	54	39
12.9	51	35
13.9	58	43
14.2	54	37
13.4	57	40
13.2	52	34
11.6	62	47
11.5	52	36
12.7	44	29
12.4	48	31
14.0	50	33
11.7	54	38
14.5	55	40
12.4	56	39
14.3	60	43
14.2	62	47
14.4	48	32
14.4	51	37

Depth: 0, 5, 10, 15, 20, 25, 30, 35

Blow Counts | Sample Type | Water Table: GWT not encountered

AS — 4" asphalt

CL — SANDY CLAY, reddish brown, slightly damp to damp, 40% sand, 60% silt and clay, poorly graded, subangular to subrounded, no cementation

CH — CLAY, medium brown, slightly damp, 40% sand, 60% silt and clay, poorly graded, no cementation

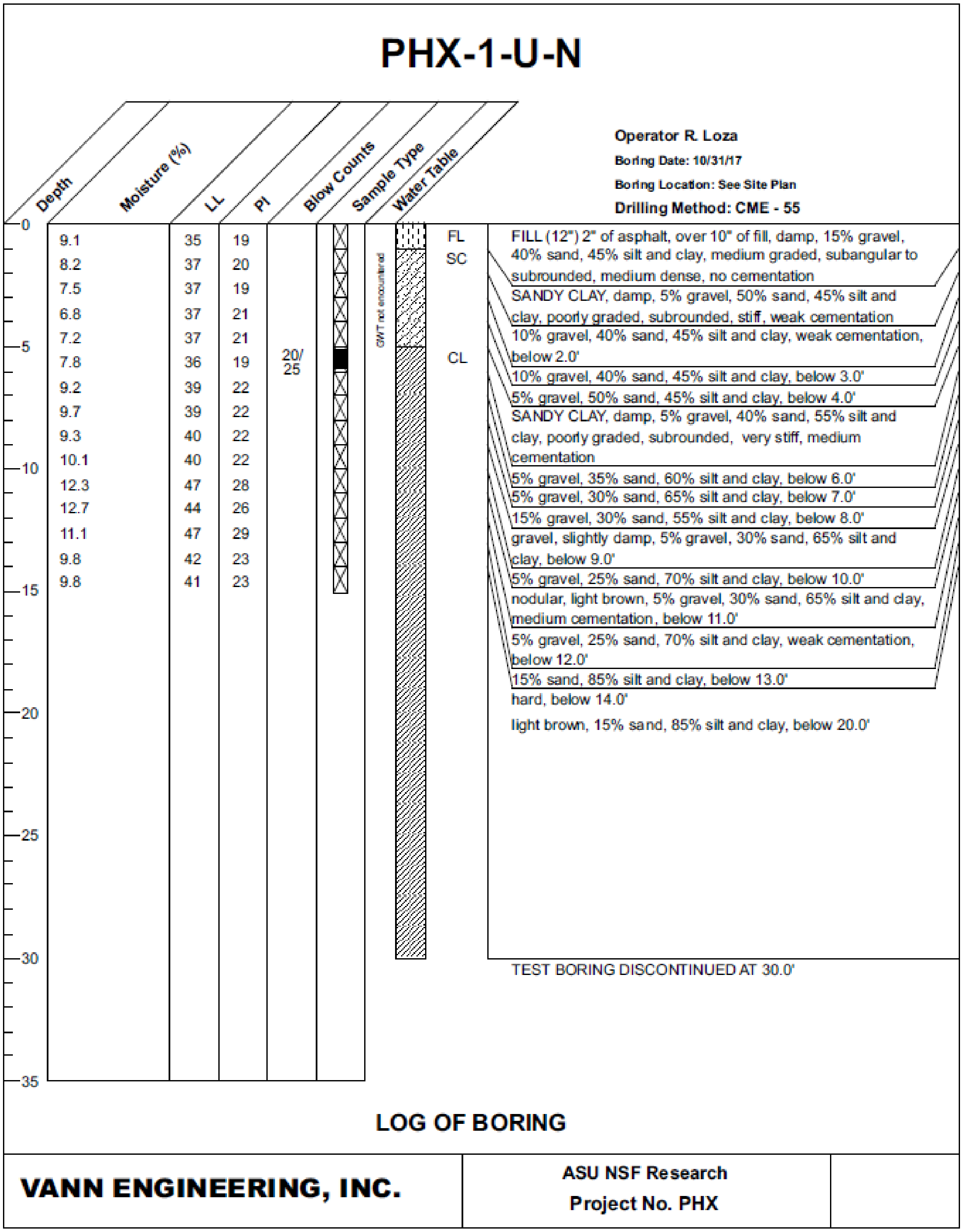
TEST BORING DISCONTINUED AT 30.0 FEET

SuperLog CivilTech Software, USA www.civiltech.com File: L:\Geo_Tools\Boring Logs\Boring Logs\mesa-1-C-N.log Date: 2/14/2018

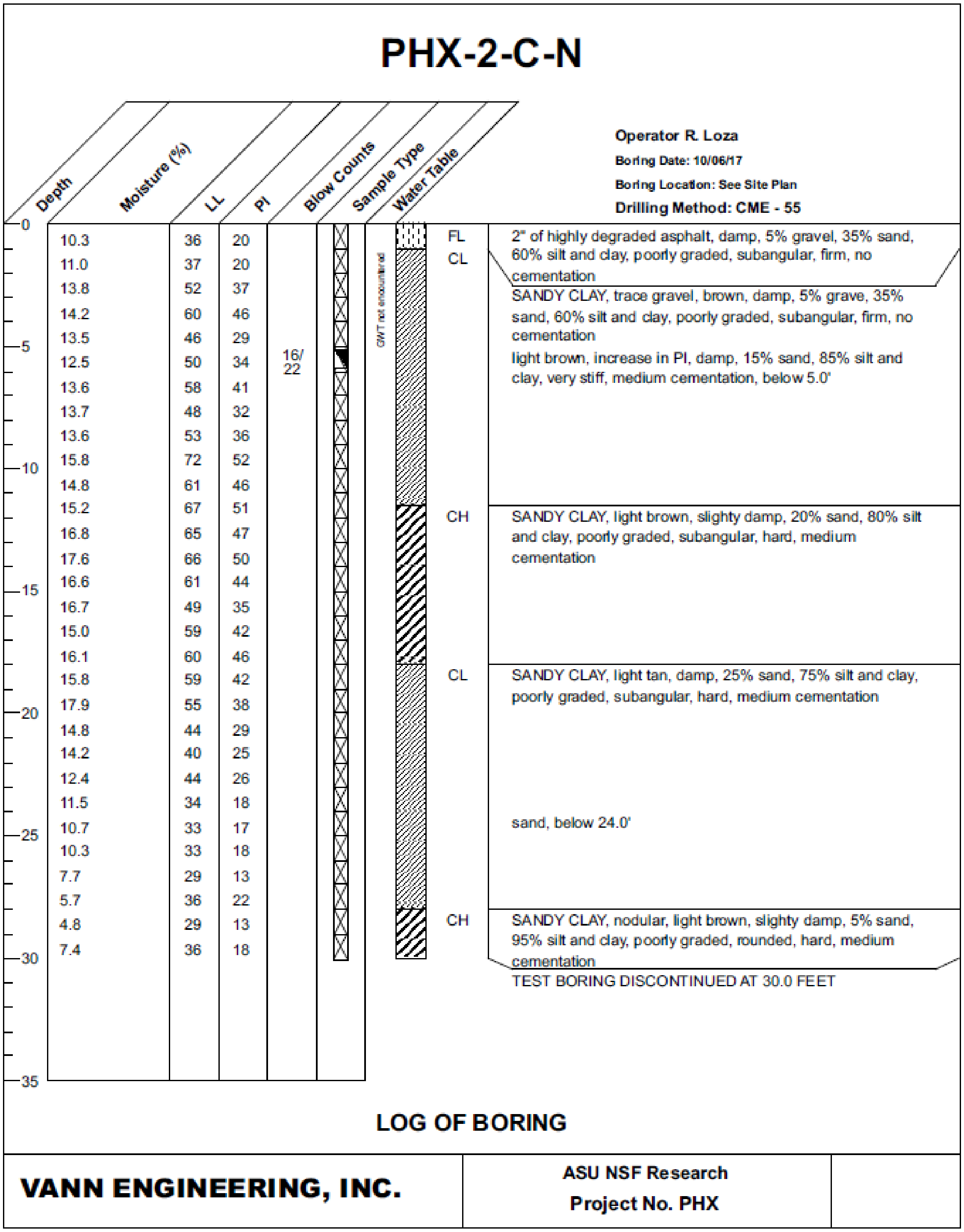
VANN ENGINEERING, INC.

ASU NSF Research
Project No. MESA

B 10: Test Boring Log for MESA-2-C-N



B 11: Test Boring Log for PHX-1-U-N



B 12: Test Boring Log for PHX-2-C-N

MUNDS-1-U-I

Operator R. Loza
Boring Date: 2/20/18
Boring Location: See Site Plan
Drilling Method: CME - 55

GWT not encountered

Moisture (%)	LL	PI
16.7	37	23
15.9	39	22
17.3	38	21
21.1	45	30
18.4	34	18
15.8	35	19
16.3	34	18
15.3	36	19
16.1	38	23
29.2	46	30
30.1	49	33
35.7	51	35
29.2	57	42
31.0	51	35
28.5	57	42
32.0	53	37
28.7	50	35
27.7	55	38
30.6	49	33
33.4	46	30
27.9	43	27
31.2	54	38
31.9	45	31
31.3	45	28
28.6	52	35
27.8	48	33
28.5	50	34
25.6	54	38
25.7	49	35
27.2	53	39

Depth: 0, 5, 10, 15, 20, 25, 30, 35

FL — SPREAD FILL (26'') damp, 25% gravel, 60% sand, 15% silt and clay, poorly graded, subangular coarse-grained particles, medium dense, no cementation

CL — SANDY CLAY, trace gravel, dark brown, damp to moist, 5% gravel, 20% sand, 75% silt and clay, poorly graded, subangular coarse-grained particles, stiff, weak cementation

Light-brown to red below 5.0 feet

20% sand, 80% silt and clay, very stiff, medium cementation below 10.0 feet

Dark reddish, damp to moist below 15.0 feet

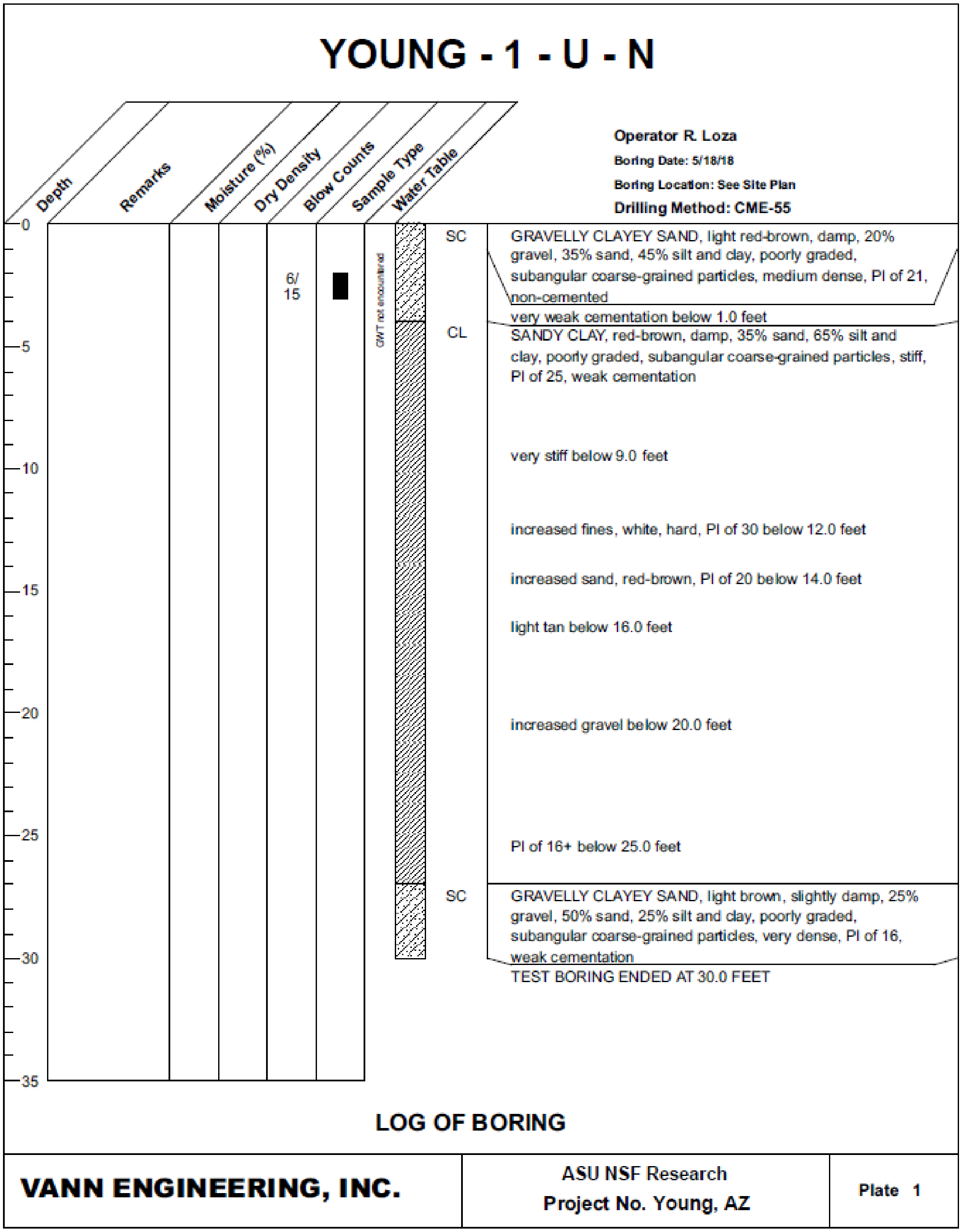
Moist below 25.0 feet

TEST BORING DISCONTINUED AT 30.0 FEET

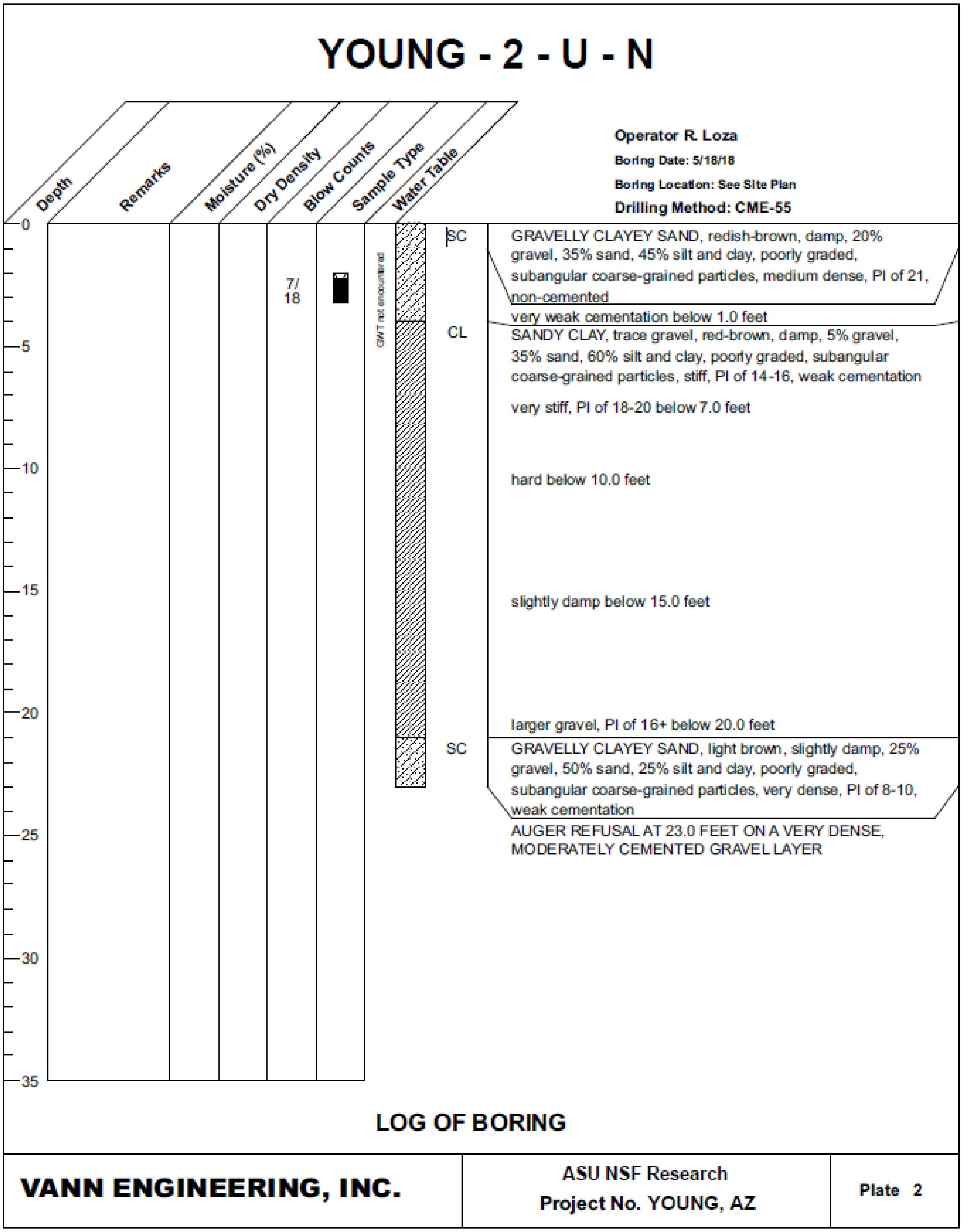
LOG OF BORING

VANN ENGINEERING, INC.	ASU NSF Research Project No. MUNDS PARK, AZ	Plate 1

B 13: Test Boring Log of Munds-1-U-N



B 14: Test Boring Log of Young–1–U-N



B 15: Test Boring Log of Young–2-U-N

C LABORATORY TEST RESULTS

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'	100	100	100	100	98	54	16	38	CH	23.2	3.4
2.0'	100	100	99	98	96	56	16	40	CH	22.1	3.56
3.0'	100	100	100	100	97	53	16	37	CH	22.4	3.6
4.0'	100	100	100	99	97	48	15	33	CL	22.3	3.65
5.0'	100	100	99	98	96	54	15	39	CH	22.0	3.64
6.0'	100	100	100	99	96	54	15	39	CH	21.6	3.59
7.0'	100	99	98	97	94	47	15	32	CL	19.7	3.78
8.0'	100	100	98	96	96	43	15	28	CL	19.0	3.61
9.0'	100	100	99	97	93	44	15	29	CL	20.4	3.58
10.0'	100	96	95	94	90	45	15	30	CL	19.7	3.61
11.0'	100	100	99	98	93	41	16	25	CL	18.9	3.75
12.0'	100	100	100	98	94	44	15	29	CL	19.6	3.63
13.0'	100	100	98	94	86	44	19	24	CL	18.8	4.04
14.0'	100	100	98	92	83	44	19	25	CL	18.2	4.06
15.0'	100	99	96	89	80	35	18	17	CL	16.4	4.4
16.0'	100	100	98	90	82	34	17	17	CL	15.9	4.44
17.0'	100	100	97	93	88	39	18	21	CL	16.6	4.22
18.0'	100	100	98	94	90	37	16	21	CL	16.7	4.15
19.0'	100	100	97	93	87	37	16	21	CL	19.9	3.77
20.0'	100	100	98	96	92	39	19	20	CL	20.4	3.72
21.0'	100	100	99	98	94	38	17	21	CL	22.2	3.38
22.0'	100	100	100	98	93	39	19	20	CL	23.5	3.61
23.0'	100	100	98	92	82	38	18	20	CL	25.2	3.38
24.0'	100	100	94	89	88	36	19	17	CL	25.2	3.42
25.0'	100	99	96	90	82	46	18	28	CL	32.7	3.19
26.0'	100	100	97	90	82	40	19	21	CL	24.8	3.5
27.0'	100	100	99	95	86	43	20	23	CL	30.3	3.41
28.0'	100	98	97	92	85	41	19	22	CL	25.4	3.56
29.0'											
30.0'											

C 1: Laboratory Test Data for HOB-1-U-I

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'	100	100	98	93	71	40	16	24	CL	10.9	4.59
2.0'	100	99	99	95	71	38	15	23	CL	10	4.6
3.0'	100	100	99	95	71	37	15	22	CL	10.3	4.59
4.0'	100	99	99	95	70	36	15	21	CL	10.1	4.63
5.0'	100	98	98	93	67	36	15	21	CL	8.9	4.72
6.0'	100	99	98	93	68	38	16	22	CL	9.2	4.75
7.0'	100	97	96	91	70	32	14	18	CL	8.6	4.73
8.0'	100	99	99	94	61	35	15	20	CL	9.6	4.69
9.0'	100	97	96	90	63	37	14	23	CL	9.4	4.67
10.0'	100	100	99	95	71	39	16	23	CL	9.5	4.71
11.0'	100	100	99	96	77	42	16	26	CL	9.5	4.65
12.0'	100	100	100	97	81	44	16	28	CL	10.9	4.54
13.0'	100	100	99	97	84	50	17	33	CH	12.4	4.47
14.0'	100	100	99	97	86	52	17	35	CH	13.2	4.42
15.0'	100	100	99	96	80	50	17	33	CH	11.2	4.53
16.0'	100	100	100	97	85	58	18	40	CH	14.3	4.39
17.0'	100	100	100	97	84	51	17	34	CH	14.7	4.35
18.0'	100	100	100	97	89	53	18	35	CH	16.5	4.3
19.0'	100	98	95	92	79	58	20	38	CH	16.5	4.39
20.0'	100	100	100	97	84	58	21	37	CH	16	4.46
21.0'	100	100	100	99	82	59	16	43	CH	15.1	4.26
22.0'	100	100	99	97	79	51	16	35	CH	14.8	4.29
23.0'	100	100	100	98	89	61	19	42	CH	18.2	4.26
24.0'	100	100	100	99	91	60	20	40	CH	18.2	4.31
25.0'	100	100	100	99	91	59	19	40	CH	17.5	4.29
26.0'	100	100	100	100	97	73	24	49	CH	20	4.37
27.0'	100	99	98	97	92	72	23	49	CH	20.4	4.32
28.0'	100	100	100	99	94	67	26	41	CH	24.9	4.27
29.0'	100	100	100	99	93	68	28	40	CH	22.8	4.35
30.0'	100	100	100	99	94	67	28	39	CH	22.8	4.33

C 2: Laboratory Test Data for DEN-2-U-N

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'	100	99	98	94	75	40	18	22	CL	6.8	4.8
2.0'	100	99	98	94	69	41	19	22	CL	8.2	4.66
3.0'	100	100	99	96	72	42	18	24	CL	8.9	4.7
4.0'	100	94	93	87	61	39	16	23	CL	9.4	4.59
5.0'	100	98	98	93	65	33	15	18	CL	9.5	4.64
6.0'	100	100	99	95	69	36	12	24	CL	10	4.75
7.0'	100	100	99	96	75	36	12	24	CL	10.9	4.54
8.0'	100	100	99	96	78	43	16	27	CL	9.5	4.65
9.0'	100	100	99	96	78	46	18	28	CL	9.5	4.55
10.0'	100	100	99	96	81	48	16	32	CH	12.1	4.51
11.0'	100	99	98	93	78	53	20	33	CH	13.6	4.42
12.0'	100	100	99	92	76	51	20	31	CH	11.4	4.38
13.0'	100	98	96	88	72	52	21	31	CH	13.9	4.18
14.0'	100	98	95	85	65	53	20	33	CH	18.5	4.33
15.0'	100	94	89	78	57	52	24	28	CL	19.5	4.17
16.0'	100	98	97	94	85	64	27	37	CH	23.8	4.29
17.0'	100	100	99	96	88	67	24	43	CH	25.4	4.19
18.0'	100	100	100	99	90	63	22	41	CH	21	4.14
19.0'	100	100	100	99	90	62	21	41	CH	21.2	4.35
20.0'	100	100	100	99	88	62	21	41	CH	20.5	4.3
21.0'	100	100	100	98	91	68	27	41	CH	21.9	4.35
22.0'	100	100	100	99	94	78	25	53	CH	22.6	4.33
23.0'	100	99	98	98	93	62	20	42	CH	24	4.25
24.0'	100	100	99	98	90	67	24	43	CH	22.4	4.25
25.0'	100	100	100	99	91	64	23	41	CH	21.9	4.32
26.0'	100	100	100	100	89	58	20	38	CH	19.1	4.3
27.0'	100	100	100	100	95	65	22	43	CH	21.8	4.31
28.0'	100	100	100	100	90	66	23	43	CH	20.9	4.27
29.0'	100	100	100	99	90	67	21	46	CH	20.9	4.28
30.0'	100	100	100	99	91	65	22	43	CH	21.3	4.34

C 3: Laboratory Test Data for DEN-3-U-N

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'	100	98	93	86	68	45	17	28	CL	22.5	3.75
2.0'	100	97	95	87	67	49	18	31	CL	22.1	3.8
3.0'	100	98	95	87	64	45	16	29	CL	21.7	3.8
4.0'	100	97	95	87	66	45	17	28	CL	20.7	3.9
5.0'	100	99	95	88	64	45	15	30	CH	18.8	4.2
6.0'	100	96	90	78	61	56	21	35	CH	25.2	4.18
7.0'	100	96	90	62	65	51	19	32	CH	23.3	3.85
8.0'	100	100	100	98	78	53	24	29	CL	22.3	3.89
9.0'	100	100	100	98	81	57	23	34	CL	22.9	4.11
10.0'	100	100	99	98	91	63	22	41	CH	24.6	4.07
11.0'	100	100	100	99	92	65	18	47	CH	22.3	4.37
12.0'	100	100	100	100	92	67	21	46	CH	20.8	4.25
13.0'	100	100	100	99	89	65	19	46	CH	19.4	4.32
14.0'	100	100	100	97	86	63	18	45	CH	19.1	4.25
15.0'	100	100	100	100	90	60	18	42	CH	19.9	4.27
16.0'	100	100	100	99	94	65	20	45	CH	21.9	4.38
17.0'	100	100	100	99	87	58	17	41	CH	21.3	4.35
18.0'	100	100	100	99	78	49	16	33	CH	17	4.32
19.0'	100	100	100	100	76	49	17	32	CH	16.5	4.13
20.0'	100	99	99	98	83	55	19	36	CH	13.6	4.3
21.0'	100	100	100	99	92	64	23	41	CH	14.6	4.33
22.0'	100	100	100	100	94	63	21	42	CH	15.2	4.4
23.0'	100	100	100	100	96	63	20	43	CH	15.9	4.21
24.0'	100	100	100	100	97	60	18	42	CH	16.9	4.28
25.0'	100	100	100	100	95	67	20	47	CH	16.4	4.22
26.0'	100	100	100	99	87	74	24	50	CH	21.3	4.27
27.0'	100	100	100	97	88	75	25	50	CH	21.4	4.25
28.0'	100	100	100	99	91	82	35	47	CH	23.5	4.38
29.0'	100	100	100	100	83	75	28	47	CH	22	4.24
30.0'	100	100	100	98	85	78	31	47	CH	22.9	4.27

C 4: Laboratory Test Data for DEN-5-C-N

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'	100	100	98	96	86	63	15	48	CH	29.9	3.70
2.0'	100	98	97	96	92	68	16	52	CH	25.0	3.70
3.0'	100	99	99	97	89	67	15	52	CH	29.5	3.86
4.0'	100	98	97	94	85	70	19	51	CH	28.4	3.83
5.0'	100	100	99	98	94	69	15	54	CH	27.8	3.83
6.0'	100	100	99	98	93	66	18	48	CH	29.7	3.84
7.0'	100	99	98	97	91	72	18	54	CH	29.1	3.71
8.0'	100	99	98	97	92	70	15	55	CH	29.5	3.78
9.0'	100	100	99	97	93	71	19	52	CH	27.00	3.80
10.0'	100	99	98	97	91	67	16	51	CH	26.5	3.76
11.0'	100	100	99	97	93	81	15	66	CH	26.5	3.91
12.0'	100	100	99	98	95	83	17	66	CH	27.9	3.84
13.0'	100	100	99	98	94	83	17	66	CH	29.5	3.83
14.0'	100	100	99	98	95	75	19	56	CH	23.4	3.83
15.0'	100	100	99	98	95	77	20	57	CH	30.3	3.80
16.0'	100	100	100	99	97	84	19	65	CH	30.2	4.13
17.0'	100	100	100	99	98	87	17	70	CH	28.8	4.07
18.0'	100	100	100	99	97	84	16	68	CH	28.8	4.07
19.0'	100	100	100	99	97	84	18	66	CH	28.7	4.08
20.0'	100	100	100	99	96	83	18	65	CH	30.9	4.00
21.0'	100	100	100	99	98	85	16	69	CH	29.8	4.15
22.0'	100	100	100	99	98	80	19	61	CH	22.8	4.12
23.0'	100	100	100	99	98	83	17	65	CH	29.4	4.14
24.0'	100	100	100	99	98	87	18	69	CH	28.5	4.07
25.0'	100	100	99	99	97	83	15	67	CH	29.4	4.08
26.0'	100	100	100	99	98	83	17	66	CH	21.6	4.02
27.0'	100	99	99	98	97	82	15	67	CH	28.7	4.11
28.0'	100	100	100	99	98	83	18	65	CH	27.7	4.13
29.0'	100	100	100	99	98	83	19	64	CH	21.9	4.11
30.0'	100	100	100	99	98	77	18	59	CH	21.7	4.07

C 5: Laboratory Test Data for SA-1-C-N

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'						52	16	36	CH	8.1	4.86
2.0'									CH	8.5	4.83
3.0'									CH	10.2	4.79
4.0'						52	15	37	CH	9.5	4.81
5.0'									CH	9.7	4.71
6.0'	100	98	96	94	86	65	15	50	CH	19.7	4.38
7.0'	100	97	96	95	90	59	15	44	CH	19.1	4.31
8.0'	100	100	99	98	92	64	19	45	CH	21.9	4.22
9.0'	100	100	99	97	92	64	18	46	CH	22.80	4.14
10.0'	100	99	99	97	92	67	16	51	CH	22.9	4.08
11.0'	100	98	97	95	92	88	16	72	CH	25.7	4.02
12.0'	100	99	98	97	94	86	17	69	CH	24.7	4.00
13.0'	100	98	98	96	93	83	16	67	CH	28.6	3.96
14.0'	100	99	99	96	93	82	18	64	CH	28.7	4.14
15.0'	100	99	98	96	92	82	17	65	CH	29.6	3.98
16.0'	100	100	100	99	97	90	16	74	CH	29.5	4.06
17.0'	100	100	99	99	97	86	18	68	CH	29.6	4.15
18.0'	100	100	100	99	97	98	16	82	CH	28.8	4.10
19.0'	100	100	100	99	96	93	16	77	CH	28.8	4.05
20.0'	100	100	100	99	98	98	17	81	CH	30.0	4.05
21.0'	100	100	100	99	98	93	16	77	CH	21.7	4.08
22.0'	100	100	100	100	99	89	16	73	CH	28.2	4.12
23.0'	100	100	100	99	99	85	17	68	CH	20.9	3.92
24.0'	100	100	100	99	98	87	18	69	CH	28.1	4.18
25.0'	100	100	100	99	97	87	17	70	CH	28.6	4.03
26.0'	100	100	100	99	99	87	18	69	CH	28.0	4.11
27.0'	100	100	100	100	99	87	16	71	CH	27.4	4.02
28.0'	100	99	99	98	97	86	17	69	CH	25.6	4.04
29.0'	100	100	100	99	98	80	17	63	CH	26.7	4.04
30.0'	100	98	98	97	96	82	18	64	CH	26.9	4.08

C 6: Laboratory Test Data for SA-2-U-N

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'	100	98	97	96	92	60	18	42	CH	25.6	3.92
2.0'	100	99	98	95	90	60	18	42	CH	25.6	3.90
3.0'	100	100	98	96	90	66	15	51	CH	26.0	3.90
4.0'	100	99	98	96	90	63	16	47	CH	25.3	3.74
5.0'	100	98	96	93	87	50	15	35	CH	22.7	3.75
6.0'	100	98	96	94	89	67	15	52	CH	24.0	3.68
7.0'	100	100	99	96	92	61	15	46	CH	24.8	3.65
8.0'	100	100	98	95	91	71	16	55	CH	24.4	3.63
9.0'	100	99	98	95	91	65	16	39	CH	23.5	3.74
10.0'	100	100	98	96	91	58	16	42	CH	23.8	3.73
11.0'	100	100	99	98	95	79	17	62	CH	25.2	3.82
12.0'	100	100	99	98	95	80	16	64	CH	27.5	3.83
13.0'	100	100	100	98	95	92	15	77	CH	21.3	3.73
14.0'	100	100	99	97	94	80	19	61	CH	28.2	3.86
15.0'	100	100	99	97	94	81	16	65	CH	27.7	3.80
16.0'	100	100	100	99	98	91	18	73	CH	29.1	3.93
17.0'	100	100	100	99	98	85	16	69	CH	29.6	4.02
18.0'	100	100	100	99	98	87	16	71	CH	29.1	4.04
19.0'	100	100	100	100	98	88	16	72	CH	28.7	3.97
20.0'	100	100	100	100	99	94	16	78	CH	30.2	4.02
21.0'	100	100	99	99	98	79	16	63	CH	26.8	4.09
22.0'	100	100	100	99	98	86	17	69	CH	27.0	4.04
23.0'	100	100	100	99	99	92	17	75	CH	29.4	3.99
24.0'	100	100	100	99	98	91	17	74	CH	25.8	4.04
25.0'	100	100	100	99	98	89	18	71	CH	28.4	4.04
26.0'	100	99	98	97	95	80	16	64	CH	27.2	4.08
27.0'	100	99	98	95	93	81	19	62	CH	26.2	4.09
28.0'	100	99	99	97	95	78	16	62	CH	23.3	4.04
29.0'	100	100	99	98	96	75	17	58	CH	26.6	4.00
30.0'	100	99	99	97	95	75	18	57	CH	24.0	4.15

C 7: Laboratory Test Data for SA-3-C-N

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'	100	91	89	85	79	58	15	43	CH	18.7	4.24
2.0'	100	99	98	96	90				CH	18.4	4.14
3.0'	100	92	90	87	81	57	16	41	CH	18.7	4.45
4.0'	100	96	94	91	85	64	16	48	CH	16.6	4.50
5.0'	100	94	93	92	87				CH	20.7	4.13
6.0'	100	98	96	94	90	63	16	47	CH	18.5	4.42
7.0'	100	99	97	94	90	66	19	47	CH	19.7	4.15
8.0'	100	100	98	96	91	57	16	41	CH	19.5	4.29
9.0'	100	95	94	92	88	60	16	44	CH	17.10	3.93
10.0'	100	91	89	87	83	63	18	45	CH	18.3	4.41
11.0'	100	100	99	97	93	75	17	58	CH	25.9	3.78
12.0'	100	99	99	97	94	69	16	53	CH	22.8	3.82
13.0'	100	100	99	97	93	67	16	51	CH	24.4	3.90
14.0'	100	100	99	98	96	65	18	37	CH	22.9	3.92
15.0'	100	100	99	99	96	70	16	54	CH	25.5	3.83
16.0'	100	100	99	98	95	85	16	69	CH	28.1	3.93
17.0'	100	100	100	99	97	79	15	64	CH	23.8	3.94
18.0'	100	97	97	97	95	79	16	63	CH	26.8	4.03
19.0'	100	100	99	99	96	78	16	62	CH	24.2	3.98
20.0'	100	100	100	99	97	82	17	65	CH	29.5	4.05
21.0'	100	100	99	99	97	81	17	64	CH	27.9	4.19
22.0'	100	100	99	98	97	79	15	64	CH	26.5	4.11
23.0'	100	100	100	99	97	80	16	64	CH	27.0	4.12
24.0'	100	100	100	99	97	78	16	62	CH	28.5	4.03
25.0'	100	100	100	99	97	80	17	64	CH	28.0	4.16
26.0'	100	100	99	98	97	82	17	65	CH	28.7	4.06
27.0'	100	100	100	99	97	77	16	61	CH	26.7	4.18
28.0'	100	100	100	99	98	78	16	52	CH	27.6	4.22
29.0'	100	97	97	96	95	78	17	61	CH	25.7	4.17
30.0'	100	99	99	97	97	85	17	68	CH	27.1	4.20

C 8: Laboratory Test Data for SA-4-U-I

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'	100	94	95	83	51	31	15	16	CL	3.0	5.95
2.0'	100	100	97	87	60	35	15	20	CL	7.1	5.35
3.0'	100	100	98	84	62	39	18	21	CL	9.0	5.05
4.0'	100	100	92	68	93	45	16	29	CH	10.9	4.92
5.0'	100	100	99	81	68	52	15	37	CH	9.0	5.10
6.0'	100	99	97	89	68	51	17	34	CH	10.9	4.82
7.0'	100	98	94	82	59	53	15	38	CH	8.6	4.80
8.0'	100	97	88	71	52	50	16	34	CH	7.8	4.76
9.0'	100	96	86	68	47	48	17	31	SC	7.9	4.61
10.0'	100	98	88	72	47	43	16	27	SC	9.3	4.52
11.0'	100	98	93	80	55	45	16	29	CH	9.6	4.54
12.0'	100	98	94	84	54	48	14	34	CH	10.1	4.55
13.0'	100	98	95	84	55	51	16	35	CH	11.2	4.49
14.0'	100	99	96	83	55	54	17	37	CH	11.6	4.49
15.0'	100	100	97	83	56	48	16	32	CH	11.4	4.47
16.0'	100	99	95	80	59	64	17	47	CH	11.0	4.47
17.0'	100	99	96	81	59	53	16	37	CH	10.0	4.48
18.0'	100	97	89	72	49	48	15	33	SC	7.4	4.47
19.0'	100	98	88	65	43	42	18	24	SC	6.9	4.45
20.0'	100	96	87	63	41	42	17	25	SC	6.6	4.46
21.0'	100	99	92	73	48	45	16	29	SC	6.8	4.65
22.0'	100	99	95	78	52	46	17	29	CH	6.8	4.55
23.0'	100	99	96	82	57	47	15	32	CH	5.2	4.51
24.0'	100	98	94	83	60	54	16	38	CH	8.5	4.54
25.0'	100	100	97	87	64	53	15	38	CH	10.2	4.61
26.0'	100	100	98	88	66	57	14	43	CH	8.0	4.63
27.0'	100	100	98	90	69	56	16	40	CH	7.4	4.51
28.0'	100	100	98	90	69	53	16	37	CH	6.3	4.52
29.0'	100	100	98	90	70	55	16	39	CH	6.7	4.53
30.0'	100	100	97	88	67	57	16	41	CH	6.0	4.68

C 9: Laboratory Test Data for MESA-1-U-N

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'	100	94	86	66	39	34	15	19	CL	10.7	3.01
2.0'	100	97	91	74	49	41	16	25	CH	16.5	2.96
3.0'	100	98	93	77	52	37	16	21	CL	16.7	3.29
4.0'	100	98	93	77	52	45	16	29	CH	17.1	3.22
5.0'	100	99	96	87	67	52	15	37	CH	16.0	3.37
6.0'	100	95	93	85	65	44	15	29	CH	15.4	3.68
7.0'	100	100	97	87	63	39	17	22	CL	13.7	3.67
8.0'	100	100	96	85	57	37	15	22	CL	12.5	3.55
9.0'	100	100	97	83	55	36	17	19	CL	11.9	3.56
10.0'	100	99	94	80	52	34	17	17	CL	11.0	3.45
11.0'	100	98	92	80	54	39	18	21	CL	11.1	3.81
12.0'	100	94	82	65	44	48	14	34	CH	9.6	3.81
13.0'	100	94	86	71	50	54	15	39	CH	12.1	3.75
14.0'	100	98	92	75	53	51	16	35	CH	12.9	3.88
15.0'	100	99	97	86	59	58	15	43	CH	13.9	3.93
16.0'	100	99	94	83	57	54	17	37	CH	14.2	4.03
17.0'	100	100	96	82	56	57	17	40	CH	13.4	4.09
18.0'	100	98	93	77	50	52	18	34	CH	13.2	4.01
19.0'	100	99	94	79	53	62	15	47	CH	11.6	4.05
20.0'	100	98	94	76	51	52	16	36	CH	11.5	4.01
21.0'	100	99	97	85	57	44	15	29	CH	12.7	4.05
22.0'	100	98	92	81	57	48	17	31	CH	12.4	4.08
23.0'	100	99	94	77	52	50	17	33	CH	14.0	4.17
24.0'	100	99	95	80	55	54	16	38	CH	11.7	4.03
25.0'	100	99	97	83	56	55	15	40	CH	14.5	4.09
26.0'	100	99	96	87	62	56	17	39	CH	12.4	4.02
27.0'	100	98	95	85	62	60	17	43	CH	14.3	4.09
28.0'	100	99	95	85	65	62	15	47	CH	14.2	4.05
29.0'	100	100	97	85	65	48	16	32	CH	14.4	4.04
30.0'	100	99	97	86	66	51	14	37	CH	14.4	4.03

C 10: Laboratory Test Data for MESA-2-C-N

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'	100	88	76	59	43	35	16	19	SC	10.3	5.2
2.0'	100	93	78	67	46	37	17	20	SC	11.0	5.01
3.0'	100	92	75	61	44	37	18	19	SC	13.8	4.98
4.0'	100	90	77	59	46	37	16	21	SC	14.2	4.87
5.0'	100	93	80	64	49	37	16	21	SC	13.5	4.85
6.0'	100	97	91	77	57	36	17	19	CL	12.5	4.87
7.0'	100	97	93	81	62	39	17	22	CL	13.6	4.75
8.0'	100	95	91	80	63	39	17	22	CL	13.7	4.64
9.0'	95	87	80	69	55	40	18	22	CL	13.6	4.51
10.0'	100	94	90	78	63	40	18	22	CL	15.8	4.47
11.0'	100	97	93	84	72	47	19	28	CH	14.8	4.41
12.0'	100	94	91	81	66	44	18	26	CH	15.2	4.35
13.0'	100	94	90	81	69	47	18	29	CH	16.8	4.32
14.0'	100	100	100	98	87	42	19	23	CL	17.6	4.39
15.0'	100	100	99	96	83	41	18	23	CL	16.6	4.33

C 11: Laboratory Test Data for PHX-1-U-N

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'	100	95	88	71	51	36	16	20	CL	10.3	4.01
2.0'	100	98	94	77	54	37	17	20	CL	11.0	4.08
3.0'	100	92	87	75	57	52	15	37	CH	13.8	4.18
4.0'	100	97	92	80	59	60	14	46	CH	14.2	4.17
5.0'	100	95	90	78	57	46	17	29	CH	13.5	4.21
6.0'	100	97	92	78	57	50	16	34	CH	12.5	4.24
7.0'	100	98	95	82	60	58	17	41	CH	13.6	4.29
8.0'	100	96	92	81	62	48	16	32	CH	13.7	4.22
9.0'	100	95	90	79	56	53	17	36	CH	13.6	4.35
10.0'	100	97	92	81	63	72	17	52	CH	15.8	4.3
11.0'	100	98	94	85	67	61	15	46	CH	14.8	4.21
12.0'	100	98	94	87	73	67	16	51	CH	15.2	4.22
13.0'	100	99	96	90	76	65	18	47	CH	16.8	4.26
14.0'	100	100	99	95	79	66	16	50	CH	17.6	4.23
15.0'	100	99	96	90	75	61	17	44	CH	16.6	4.40
16.0'	100	100	98	92	79	49	14	35	CH	16.7	4.34
17.0'	100	99	98	93	80	59	17	42	CH	15.0	4.26
18.0'	100	100	98	93	81	60	14	46	CH	16.1	4.26
19.0'	100	97	95	90	80	59	17	42	CH	15.8	4.25
20.0'	100	98	96	92	80	55	17	38	CH	17.9	4.23
21.0'	100	98	95	92	78	44	15	29	CH	14.8	4.23
22.0'	100	99	99	93	76	40	15	25	CH	14.2	4.27
23.0'	100	100	99	95	71	44	18	26	CH	12.4	4.31
24.0'	100	100	99	96	65	34	16	18	CL	11.5	4.34
25.0'	100	100	98	97	64	33	16	17	CL	10.7	4.27
26.0'	100	100	100	97	62	33	15	18	CL	10.3	4.39
27.0'	100	100	100	98	58	29	16	13	CL	7.7	4.34
28.0'	100	94	88	73	40	36	14	22	CL	5.7	4.35
29.0'	100	96	93	72	39	29	16	13	CL	4.8	4.31
30.0'	100	98	94	75	38	36	18	18	CL	7.4	4.29

C 12: Laboratory Test Data for PHX-2-C-N

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'	100	88	83	74	61	37	14	23	CL	16.7	3.89
2.0'	100	100	99	95	88	39	17	22	CL	15.9	3.75
3.0'	100	100	99	96	90	38	17	21	CL	17.3	3.77
4.0'	100	100	99	98	90	45	15	30	CL	21.1	3.92
5.0'	100	99	98	96	76	34	16	18	CL	18.4	3.86
6.0'	100	85	73	60	45	35	16	19	CL	15.8	3.81
7.0'	100	63	54	47	35	34	16	18	CL	16.3	3.88
8.0'	100	89	80	69	54	36	17	19	CL	15.3	3.77
9.0'	100	96	91	81	66	38	15	23	CL	16.1	3.88
10.0'	100	99	98	91	76	46	16	30	CL	29.2	3.81
11.0'	100	100	99	92	76	49	16	33	CL	30.1	3.75
12.0'	100	100	98	88	73	51	16	35	CH	35.7	3.68
13.0'	100	99	97	87	73	57	15	42	CH	29.2	3.76
14.0'	100	97	94	88	73	51	16	35	CH	31.0	3.74
15.0'	100	98	96	86	71	57	15	42	CH	28.5	3.87
16.0'	100	100	98	88	73	53	16	37	CH	32.0	3.73
17.0'	100	99	98	93	80	50	15	35	CH	28.7	3.76
18.0'	100	100	100	94	80	55	17	38	CH	27.7	3.96
19.0'	100	97	96	92	79	49	16	33	CL	30.6	3.87
20.0'	100	99	98	93	77	46	16	30	CL	33.4	3.70
21.0'	100	100	100	96	79	43	16	27	CL	27.9	3.85
22.0'	100	100	99	96	80	54	16	38	CH	31.2	3.77
23.0'	100	100	99	97	82	45	14	31	CL	31.9	3.78
24.0'	100	100	100	97	81	45	17	28	CL	31.3	3.81
25.0'	100	100	100	97	85	52	17	35	CH	28.6	3.81
26.0'	100	100	100	97	85	48	15	33	CL	27.8	3.76
27.0'	100	100	100	97	84	50	16	34	CH	28.5	3.89
28.0'	100	100	100	97	88	54	16	38	CH	25.6	4.02
29.0'	100	100	99	68	85	49	14	35	CL	25.7	3.87
30.0'	100	100	99	96	85	53	14	39	CH	27.2	4.04

C 13: Laboratory Test Data for MUNDS-1-U-N

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'	92	75	72	66	57	37	17	20	CL	3.0	5.30
2.0'	100	95	93	87	76	36	15	21	CL	10.8	4.82
3.0'	100	88	76	62	49	35	15	20	SC	9.0	4.61
4.0'	100	87	75	61	48	37	16	21	SC	5.6	4.68
5.0'	100	66	52	39	28	38	16	22	SC	5.4	4.61
6.0'	100	94	90	82	70	40	16	24	CL	15.4	4.38
7.0'	100	97	93	81	66	41	15	26	CL	12.4	3.62
8.0'	100	99	98	94	83	52	15	37	CH	14.9	3.75
9.0'	100	100	99	96	88	50	17	33	CH	17.3	3.83
10.0'	100	100	100	98	92	55	16	39	CH	19.3	3.69
11.0'	100	100	99	97	91	50	15	35	CH	10.5	3.92
12.0'	100	100	100	98	94	49	13	36	CL	14.5	3.67
13.0'	100	100	100	99	95	58	16	42	CH	16.2	3.99
14.0'	100	100	100	98	93	53	16	37	CH	12.0	4.00
15.0'	100	100	99	97	90	46	17	29	CL	15.4	3.78
16.0'	100	100	98	89	76	45	15	30	CL	9.8	3.82
17.0'	100	99	97	91	82	46	15	31	CL	9.5	4.09
18.0'	100	99	97	93	86	48	16	32	CL	8.8	3.98
19.0'	100	99	98	92	82	46	16	30	CL	11.3	3.89
20.0'	100	96	94	90	81	46	16	30	CL	11.0	4.01
21.0'	100	99	98	93	81	45	14	31	CL	9.8	4.11
22.0'	100	99	97	93	81	46	16	30	CL	9.0	4.06
23.0'	100	99	97	92	80	49	17	32	CL	9.4	4.09
24.0'	100	81	76	71	60	44	16	28	CL	9.7	4.13
25.0'	100	58	51	47	39	38	16	22	SC	5.6	4.19
26.0'	100	49	39	35	28	31	16	15	SC	3.1	4.29
27.0'	100	64	50	42	33	29	15	14	SC	5.3	4.37
28.0'	100	58	47	38	28	29	17	12	SC	5.9	4.22
29.0'	100	95	94	74	48	29	16	13	SC	3.4	4.28
30.0'	100	89	75	62	42	30	16	14	SC	4.2	4.01

C 14: Laboratory Test Data for YOUNG-1-U-N

SAMPLE DEPTH	SIEVE ANALYSIS (% Passing)					ATTERBERG LIMITS			USCS	Moisture Content	WP4C
	1"	#4	#10	#40	#200	LL	PL	PI		%	(pF)
1.0'	100	77	74	64	43	27	15	12	SC	4.5	5.49
2.0'	100	87	76	64	46	29	16	13	SC	6.8	5.10
3.0'	100	84	75	63	47	31	15	16	SC	7.2	4.96
4.0'	100	96	89	79	63	31	15	16	CL	0.8	4.75
5.0'	100	97	92	82	69	32	17	15	CL	12.9	4.81
6.0'	100	94	89	79	66	34	16	18	CL	13.0	4.72
7.0'	100	97	94	85	71	49	16	33	CL	11.6	4.11
8.0'	100	97	95	89	80	36	16	20	CL	13.0	4.16
9.0'	100	97	96	92	84	42	15	27	CL	15.9	3.91
10.0'	100	99	98	95	88	45	16	29	CL	14.6	3.99
11.0'	100	100	99	96	88	49	15	34	CL	11.8	3.90
12.0'	100	98	98	96	91	45	16	29	CL	16.4	3.90
13.0'	100	98	96	92	85	51	16	35	CH	13.0	3.79
14.0'	100	99	97	95	90	47	17	30	CL	12.6	3.95
15.0'	100	100	99	97	92	47	16	31	CL	10.9	3.96
16.0'	100	100	99	96	89	45	16	29	CL	11.7	4.22
17.0'	100	100	100	96	89	45	15	30	CL	11.4	4.10
18.0'	100	100	99	97	90	47	15	32	CL	7.9	4.20
19.0'	100	100	99	97	90	36	16	20	CL	10.9	4.21
20.0'	100	94	93	88	78	46	15	31	CL	8.2	4.30
21.0'	100	66	63	59	52	41	16	25	CL	7.8	4.49
22.0'	100	52	46	44	39	40	16	24	CL	3.3	4.30
23.0'	100	59	51	49	45	43	17	26	CL	4.0	4.29

C 15: Laboratory Test Data for YOUNG-2-U-N

D REPRESENTATIVE SITE PHOTOGRAPHS

D 1: HOBART-1-U-I

D 2: HOBART-2-U-I


D 3: DEN-1-C-N


D 4: DEN-1-C-N

D 5: DEN-2-U-N

D 6: DEN-2-U-N

D 7: DEN-2-U-N

D 8: DEN-2-U-N

D 9: DEN-3-U-N

D 10: DEN-4-C-N

D 11: DEN-4-C-N

D 12: DEN-5-C-N

D 13: DEN-5-C-N

D 14: DEN-5-C-N

D 15: DEN-5-C-N

D 16: SA-1-C-N

D 17: SA-1-C-N

D 18: SA-1-C-N

D 19: SA-1-C-N

D 20: SA-2-U-I

D 21: SA-2-U-I

D 22: SA-3-C-N

D 23: SA-4-U-I

D 24: MESA-1-U-N

D 25: MESA-1-U-N

D 26: MESA-2-C-N

D 27: MESA-2-C-N

D 28: PHX-2-C-N

D 29: PHX-2-C-N

D 30: MUNDS-1-U-I

Figure D.31: MUNDS-1-U-I


D 31: YOUNG-1-U-N


D 32: YOUNG-2-U-N

E DATABASES

E 1: List of Measured Soil suction Data Used in this Research to Develop the Suction Surrogate

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Phoenix	-52		4	1.2192	U	N	6.9	46	4.88
Phoenix	-52		2	0.6096	U	N	18.9	39	3.36
Phoenix	-52		1	0.3048	U	N	8.2	40	4.92
Phoenix	-52		2	0.6096	U	N	5	43	4.47
Phoenix	-52		2	0.6096	U	I	11.9	59	4.08
Phoenix	-52		2	0.6096	U	N	9.2	31	4.31
Phoenix	-52		2	0.6096	C	N	12.3	36	3.83
Phoenix	-52		3	0.9144	U	N	4.8	32	5.02
Kingman	-52		2	0.6096	U	N	6.7	38	4.59
Phoenix	-52		2	0.6096	U	N	9	40	4.51
Phoenix	-52		2	0.6096	U	N	11.3	46	4.82
Phoenix	-52		2	0.6096	U	N	8	34	4.87
Phoenix	-52		3	0.9144	U	N	5.1	34	5.13
Phoenix	-52		2	0.6096	U	N	3.9	30	5.37
Phoenix	-52		3	0.9144	U	I	13.2	33	3.62
Phoenix	-52		2	0.6096	U	I	10.9	33	4.09
Phoenix	-52		3	0.9144	U	N	6.4	35	5.18
Phoenix	-52		3	0.9144	U	N	6.3	43	4.93
Phoenix	-52		2	0.6096	U	N	5.4	43	4.99

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Phoenix	-52		3	0.9144	C	I	17.5	33	3.42
Phoenix	-52		2	0.6096	U	N	20	36	3.71
Phoenix	-52		3	0.9144	U	N	18.9	36	4.05
Phoenix	-52	2	1	0.3048	U	I	26.6	32	3.44
Phoenix	-52	5	4	1.2192	U	N	11	39	4.53
Phoenix	-52		4	1.2192	U	N	11	39	4.53
Phoenix	-52	1	4	1.2192	U	N	7.6	35	4.58
Phoenix	-52		4	1.2192	U	N	7.6	35	4.58
Phoenix	-52	5	3	0.9144	U	N	10	39	4.65
Phoenix	-52		3	0.9144	U	N	10	39	4.65
Phoenix	-52	1	3	0.9144	U	N	8.7	35	4.71
Phoenix	-52		3	0.9144	U	N	8.7	35	4.71
Phoenix	-52	2	3	0.9144	U	N	10.1	26	4.17
Phoenix	-52	2	2	0.6096	U	N	11.1	26	4.23
Phoenix	-52	5	3	0.9144	U	N	15	35	4.47
Phoenix	-52	5	4	1.2192	U	N	14.9	46	4.55
Phoenix	-52	5	2	0.6096	U	N	13	35	4.57
Phoenix	-52	5	5	1.524	U	N	15.2	46	4.58
Phoenix	-52		3	0.9144	U	I	10.5	33	3.54
Phoenix	-52		2	0.6096	U	I	8.3	33	3.88
Phoenix	-52		4	1.2192	C	I	18.9	50	3.66
Phoenix	-52		5	1.524	U	N	9.2	33	4.4

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Phoenix	-52		4	1.2192	U	N	8.5	33	4.53
Phoenix	-52	3	3	0.9144	U	I	5.5	32	4.89
Phoenix	-52		3	0.9144	U	I	6.5	30	5.16
Phoenix	-52	5	4	1.2192	U	N	14.7	32	4.3
Phoenix	-52	11	4	1.2192	U	N	12.7	43	4.38
Phoenix	-52	1	4	1.2192	U	N	14.7	42	4.41
Phoenix	-52	7	4	1.2192	U	N	6	30	4.67
Phoenix	-52	1	3	0.9144	U	N	11.9	42	4.68
Phoenix	-52	7	3	0.9144	U	N	7.6	30	4.79
Phoenix	-52	5	3	0.9144	U	N	10.7	32	4.8
Phoenix	-52	8	4	1.2192	U	N	10	40	4.95
Phoenix	-52	8	3	0.9144	U	N	9.5	40	5
Phoenix	-52	11	3	0.9144	U	N	9.4	43	5.15
Phoenix	-52	4	3	0.9144	U	N	13.9	33	3.64
Phoenix	-52	1	2	0.6096	U	N	16.3	35	3.72
Phoenix	-52	1	3	0.9144	U	N	10.9	40	4.71
Phoenix	-52		3	0.9144	U	N	8.3	34	4.13
Phoenix	-52		3	0.9144	U	N	13.4	39	4.26
Phoenix	-52		4	1.2192	U	N	10.4	32	4.59
Phoenix	-52		5	1.524	U	N	6.8	31	4.76
Phoenix	-52		3	0.9144	U	N	9.5	32	4.8
Phoenix	-52		3	0.9144	U	N	6.3	32	4.59

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Phoenix	-52		3	0.9144	U	I	5.4	30	5.26
Phoenix	-52	2V	3	0.9144	U	N	11.3	42	3.92
Phoenix	-52	2V	1	0.3048	U	N	10.5	42	4.09
Phoenix	-52	2V	2	0.6096	U	N	9.1	42	4.13
Phoenix	-52	8V	1	0.3048	U	N	9.1	35	4.14
Phoenix	-52	8V	2	0.6096	U	N	8.2	37	4.51
Phoenix	-52	8V	3	0.9144	U	N	7.5	37	4.77
Phoenix	-52	8V	5	1.524	U	N	7.2	37	4.85
Phoenix	-52	8V	4	1.2192	U	N	6.8	37	4.88
Phoenix	-52	2V	12	3.6576	U	N	15.3	50	4.3
Phoenix	-52	8V	12	3.6576	U	N	12.7	44	4.45
Phoenix	-52	8V	11	3.3528	U	N	12.3	47	4.51
Phoenix	-52	8V	13	3.9624	U	N	11.1	47	4.62
Phoenix	-52	8V	8	2.4384	U	N	9.7	39	4.64
Phoenix	-52	8V	9	2.7432	U	N	9.3	40	4.71
Phoenix	-52	8V	7	2.1336	U	N	9.2	39	4.75
Phoenix	-52	8V	10	3.048	U	N	10.1	40	4.77
Phoenix	-52	8V	15	4.572	U	N	9.8	41	4.83
Phoenix	-52	8V	6	1.8288	U	N	7.8	36	4.87
Phoenix	-52	8V	14	4.2672	U	N	9.8	42	4.89
Phoenix	-52		2	0.6096	U	N	6.6	45	5.02
Young	-5	1	1	0.3048	U	N	3.0	37	5.30

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Young	-5	1	2	0.6096	U	N	10.8	36	4.82
Young	-5	1	3	0.9144	U	N	9.0	35	4.61
Young	-5	1	4	1.2192	U	N	5.6	37	4.68
Young	-5	1	5	1.524	U	N	5.4	38	4.61
Young	-5	1	6	1.8288	U	N	15.4	40	4.38
Young	-5	1	7	2.1336	U	N	12.4	41	4.32
Young	-5	1	8	2.4384	U	N	14.9	52	4.45
Young	-5	1	9	2.7432	U	N	17.3	50	4.53
Young	-5	1	10	3.048	U	N	19.3	55	4.39
Young	-5	1	11	3.3528	U	N	10.5	50	4.62
Young	-5	1	12	3.6576	U	N	14.5	49	4.37
Young	-5	1	13	3.9624	U	N	16.2	58	4.69
Young	-5	1	14	4.2672	U	N	12.0	53	4.70
Young	-5	1	15	4.572	U	N	15.4	46	4.48
Young	-5	1	16	4.8768	U	N	9.8	45	4.52
Young	-5	1	17	5.1816	U	N	9.5	46	4.79
Young	-5	1	18	5.4864	U	N	8.8	48	4.68
Young	-5	1	19	5.7912	U	N	11.3	46	4.59
Young	-5	1	20	6.096	U	N	11.0	46	4.71
Young	-5	1	21	6.4008	U	N	9.8	45	4.81
Young	-5	1	22	6.7056	U	N	9.0	46	4.76
Young	-5	1	23	7.0104	U	N	9.4	49	4.79

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Young	-5	1	24	7.3152	U	N	9.7	44	4.83
Young	-5	1	25	7.62	U	N	5.6	38	4.89
Young	-5	1	26	7.9248	U	N	3.1	31	4.99
Young	-5	1	27	8.2296	U	N	5.3	29	5.07
Young	-5	1	28	8.5344	U	N	5.9	29	4.92
Young	-5	1	29	8.8392	U	N	3.4	29	4.98
Young	-5	1	30	9.144	U	N	4.2	30	4.71
Hobart	-16	1	1	0.3048	U	I	23.2	54	3.40
Hobart	-6.5	1	2	0.6096	U	I	22.1	56	3.56
Hobart	-6.5	1	3	0.9144	U	I	22.4	53	3.60
Hobart	-6.5	1	4	1.2192	U	I	22.3	48	3.65
Hobart	-6.5	1	5	1.524	U	I	22	54	3.64
Hobart	-6.5	1	6	1.8288	U	I	21.6	54	3.59
Hobart	-6.5	1	7	2.1336	U	I	19.7	47	3.78
Hobart	-6.5	1	8	2.4384	U	I	19	43	3.61
Hobart	-6.5	1	9	2.7432	U	I	20.4	44	3.58
Hobart	-6.5	1	10	3.048	U	I	19.7	45	3.61
Hobart	-6.5	1	11	3.3528	U	I	18.9	41	3.75
Hobart	-6.5	1	12	3.6576	U	I	19.6	44	3.63
Hobart	-6.5	1	13	3.9624	U	I	18.8	44	4.04
Hobart	-6.5	1	14	4.2672	U	I	18.2	44	4.06
Hobart	-6.5	1	15	4.572	U	I	16.4	35	4.40

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Hobart	-6.5	1	16	4.8768	U	I	15.9	34	4.44
Hobart	-6.5	1	17	5.1816	U	I	16.6	39	4.22
Hobart	-6.5	1	18	5.4864	U	I	16.7	37	4.15
Hobart	-6.5	1	19	5.7912	U	I	19.9	37	3.77
Hobart	-6.5	1	20	6.096	U	I	20.4	39	3.72
Hobart	-6.5	1	21	6.4008	U	I	22.2	38	3.38
Hobart	-6.5	1	22	6.7056	U	I	23.5	39	3.61
Hobart	-6.5	1	23	7.0104	U	I	25.2	38	3.38
Hobart	-6.5	1	24	7.3152	U	I	25.2	36	3.42
Hobart	-6.5	1	26	7.9248	U	I	24.8	40	3.50
Hobart	-6.5	1	27	8.2296	U	I	30.3	43	3.41
Hobart	-6.5	1	28	8.5344	U	I	25.4	41	3.56
Denver	-14	1	2	0.6096	C	N	14.3	53	4.95
Denver	-14	1	3	0.9144	C	N	10.8	49	4.74
Denver	-14	1	4	1.2192	C	N	16.8	44	4.02
Denver	-14	1	5	1.524	C	N	14.8	52	4.07
Denver	-14	1	6	1.8288	C	N	14.5	46	4.09
Denver	-14	2	1	0.3048	U	N	10.9	40	4.59
Denver	-14	2	2	0.6096	U	N	10	38	4.6
Denver	-14	2	3	0.9144	U	N	10.3	37	4.59
Denver	-14	2	4	1.2192	U	N	10.1	36	4.63

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Denver	-14	2	5	1.524	U	N	8.9	36	4.72
Denver	-14	2	6	1.8288	U	N	9.2	38	4.75
Denver	-14	2	7	2.1336	U	N	8.6	32	4.73
Denver	-14	2	8	2.4384	U	N	9.6	35	4.69
Denver	-14	2	9	2.7432	U	N	9.4	37	4.67
Denver	-14	2	10	3.048	U	N	9.5	39	4.71
Denver	-14	2	11	3.3528	U	N	9.5	42	4.65
Denver	-14	2	12	3.6576	U	N	10.9	44	4.54
Denver	-14	2	13	3.9624	U	N	12.4	50	4.47
Denver	-14	2	14	4.2672	U	N	13.2	52	4.42
Denver	-14	2	15	4.572	U	N	11.2	50	4.53
Denver	-14	2	16	4.8768	U	N	14.3	58	4.39
Denver	-14	2	17	5.1816	U	N	14.7	51	4.35
Denver	-14	2	18	5.4864	U	N	16.5	53	4.3
Denver	-14	2	19	5.7912	U	N	16.5	58	4.39
Denver	-14	2	20	6.096	U	N	16	58	4.46
Denver	-14	2	21	6.4008	U	N	15.1	59	4.26
Denver	-14	2	22	6.7056	U	N	14.8	51	4.29
Denver	-14	2	23	7.0104	U	N	18.2	61	4.26
Denver	-14	2	24	7.3152	U	N	18.2	60	4.31

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Denver	-14	2	25	7.62	U	N	17.5	59	4.29
Denver	-14	2	26	7.9248	U	N	20	73	4.37
Denver	-14	2	27	8.2296	U	N	20.4	72	4.32
Denver	-14	2	28	8.5344	U	N	24.9	67	4.27
Denver	-14	2	29	8.8392	U	N	22.8	68	4.35
Denver	-14	2	30	9.144	U	N	22.8	67	4.33
Denver	-14	3	1	0.3048	U	N	6.8	40	4.8
Denver	-14	3	2	0.6096	U	N	8.2	41	4.66
Denver	-14	3	3	0.9144	U	N	8.9	42	4.7
Denver	-14	3	4	1.2192	U	N	9.4	39	4.59
Denver	-14	3	5	1.524	U	N	9.5	33	4.64
Denver	-14	3	6	1.8288	U	N	10	36	4.75
Denver	-14	3	7	2.1336	U	N	10.9	36	4.54
Denver	-14	3	8	2.4384	U	N	9.5	43	4.65
Denver	-14	3	9	2.7432	U	N	9.5	46	4.55
Denver	-14	3	10	3.048	U	N	12.1	48	4.51
Denver	-14	3	11	3.3528	U	N	13.6	53	4.42
Denver	-14	3	12	3.6576	U	N	11.4	51	4.38
Denver	-14	3	13	3.9624	U	N	13.9	52	4.18
Denver	-14	3	14	4.2672	U	N	18.5	53	4.33

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Denver	-14	3	15	4.572	U	N	19.5	52	4.17
Denver	-14	3	16	4.8768	U	N	23.8	64	4.29
Denver	-14	3	17	5.1816	U	N	25.4	67	4.19
Denver	-14	3	18	5.4864	U	N	21	63	4.14
Denver	-14	3	19	5.7912	U	N	21.2	62	4.35
Denver	-14	3	20	6.096	U	N	20.5	62	4.3
Denver	-14	3	21	6.4008	U	N	21.9	68	4.35
Denver	-14	3	22	6.7056	U	N	22.6	78	4.33
Denver	-14	3	23	7.0104	U	N	24	62	4.25
Denver	-14	3	24	7.3152	U	N	22.4	67	4.25
Denver	-14	3	25	7.62	U	N	21.9	64	4.32
Denver	-14	3	26	7.9248	U	N	19.1	58	4.3
Denver	-14	3	27	8.2296	U	N	21.8	65	4.31
Denver	-14	3	28	8.5344	U	N	20.9	66	4.27
Denver	-14	3	29	8.8392	U	N	20.9	67	4.28
Denver	-14	3	30	9.144	U	N	21.3	65	4.34
Denver	-14	5	2	0.6096	C	N	6.8	40	3.8
Denver	-14	5	3	0.9144	C	N	20.7	45	3.8
Denver	-14	5	4	1.2192	C	N	20.7	45	3.9
Denver	-14	5	5	1.524	C	N	21.7	44	4.2

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Denver	-14	5	6	1.8288	C	N	25.2	56	4.18
Denver	-14	5	7	2.1336	C	N	23.3	51	3.85
Denver	-14	5	8	2.4384	C	N	22.3	53	3.89
Denver	-14	5	9	2.7432	C	N	22.9	57	4.11
Denver	-14	5	10	3.048	C	N	24.6	63	4.07
Denver	-14	5	11	3.3528	C	N	22.3	65	4.37
Denver	-14	5	12	3.6576	C	N	20.8	67	4.25
Denver	-14	5	13	3.9624	C	N	19.4	65	4.32
Denver	-14	5	14	4.2672	C	N	19.1	63	4.25
Denver	-14	5	15	4.572	C	N	19.9	60	4.27
Denver	-14	5	16	4.8768	C	N	21.9	65	4.38
Denver	-14	5	17	5.1816	C	N	21.3	58	4.35
Denver	-14	5	18	5.4864	C	N	17	49	4.32
Denver	-14	5	19	5.7912	C	N	16.5	49	4.13
Denver	-14	5	20	6.096	C	N	13.6	55	4.3
Denver	-14	5	21	6.4008	C	N	14.6	64	4.33
Denver	-14	5	22	6.7056	C	N	15.2	63	4.4
Denver	-14	5	23	7.0104	C	N	15.9	63	4.21
Denver	-14	5	24	7.3152	C	N	16.9	60	4.28
Denver	-14	5	25	7.62	C	N	16.4	67	4.22

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Denver	-14	5	26	7.9248	C	N	21.3	74	4.27
Denver	-14	5	27	8.2296	C	N	21.4	75	4.25
Denver	-14	5	28	8.5344	C	N	23.5	82	4.38
Denver	-14	5	29	8.8392	C	N	22	75	4.24
Denver	-14	5	30	9.144	C	N	22.9	78	4.27
San Antonio	-16	1	1	0.3048	C	N	29.5	64	3.70
San Antonio	-16	1	2	0.6096	C	N	22	69	3.70
San Antonio	-16	1	3	0.9144	C	N	29.5	69	3.86
San Antonio	-16	1	4	1.2192	C	N	28.4	70	3.83
San Antonio	-16	1	5	1.524	C	N	27.8	69	3.83
San Antonio	-16	1	6	1.8288	C	N	29.7	66	3.84
San Antonio	-16	1	7	2.1336	C	N	29.1	72	3.71
San Antonio	-16	1	8	2.4384	C	N	29.5	70	3.78

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
San Antonio	-16	1	9	2.7432	C	N	27	71	3.80
San Antonio	-16	1	10	3.048	C	N	26.5	67	3.76
San Antonio	-16	1	11	3.3528	C	N	26.5	81	3.91
San Antonio	-16	1	12	3.6576	C	N	27.9	83	3.84
San Antonio	-16	1	13	3.9624	C	N	29.5	83	3.83
San Antonio	-16	1	14	4.2672	C	N	23.4	75	3.83
San Antonio	-16	1	15	4.572	C	N	30.3	77	3.80
San Antonio	-16	1	16	4.8768	C	N	30.2	84	4.13
San Antonio	-16	1	17	5.1816	C	N	28.8	87	4.07
San Antonio	-16	1	18	5.4864	C	N	28.8	84	4.07
San Antonio	-16	1	19	5.7912	C	N	28.7	84	4.08

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
San Antonio	-16	1	20	6.096	C	N	30.9	83	4.00
San Antonio	-16	1	21	6.4008	C	N	29.8	85	4.15
San Antonio	-16	1	22	6.7056	C	N	22.8	80	4.12
San Antonio	-16	1	23	7.0104	C	N	29.4	83	4.14
San Antonio	-16	1	24	7.3152	C	N	28.5	87	4.07
San Antonio	-16	1	25	7.62	C	N	29.4	83	4.08
San Antonio	-16	1	26	7.9248	C	N	21.6	83	4.02
San Antonio	-16	1	27	8.2296	C	N	28.7	82	4.11
San Antonio	-16	1	28	8.5344	C	N	27.7	83	4.13
San Antonio	-16	1	29	8.8392	C	N	21.9	83	4.11
San Antonio	-16	1	30	9.144	C	N	21.7	77	4.07

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
San Antonio	-16	2	1	0.3048	U	N	8.1	53	4.86
San Antonio	-16	2	2	0.6096	U	N	8.5	52	4.83
San Antonio	-16	2	3	0.9144	U	N	10.2	52	4.79
San Antonio	-16	2	4	1.2192	U	N	9.5	52	4.81
San Antonio	-16	2	5	1.524	U	N	9.7	52	4.71
San Antonio	-16	2	6	1.8288	U	I	19.7	65	4.38
San Antonio	-16	2	7	2.1336	U	I	19.1	59	4.31
San Antonio	-16	2	8	2.4384	U	I	21.9	64	4.22
San Antonio	-16	2	9	2.7432	U	I	22.80	64	4.14
San Antonio	-16	2	10	3.048	U	I	22.9	67	4.08
San Antonio	-16	2	11	3.3528	U	I	25.7	88	4.02

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
San Antonio	-16	2	12	3.6576	U	I	24.7	86	4.00
San Antonio	-16	2	13	3.9624	U	I	28.6	83	3.96
San Antonio	-16	2	14	4.2672	U	I	28.7	82	4.14
San Antonio	-16	2	15	4.572	U	I	29.6	82	3.98
San Antonio	-16	2	16	4.8768	U	I	29.5	90	4.06
San Antonio	-16	2	17	5.1816	U	I	29.6	86	4.15
San Antonio	-16	2	18	5.4864	U	I	28.8	98	4.10
San Antonio	-16	2	19	5.7912	U	I	28.8	93	4.05
San Antonio	-16	2	20	6.096	U	I	30.0	98	4.05
San Antonio	-16	2	21	6.4008	U	I	21.7	93	4.08
San Antonio	-16	2	22	6.7056	U	I	28.2	89	4.12

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
San Antonio	-16	2	23	7.0104	U	I	20.9	85	3.92
San Antonio	-16	2	24	7.3152	U	I	28.1	87	4.18
San Antonio	-16	2	25	7.62	U	I	28.6	87	4.03
San Antonio	-16	2	26	7.9248	U	I	28.0	87	4.11
San Antonio	-16	2	27	8.2296	U	I	27.4	87	4.02
San Antonio	-16	2	28	8.5344	U	I	25.6	86	4.04
San Antonio	-16	2	29	8.8392	U	I	26.7	80	4.04
San Antonio	-16	2	30	9.144	U	I	26.9	82	4.08
San Antonio	-16	3	1	0.3048	C	N	25.6	60	3.92
San Antonio	-16	3	2	0.6096	C	N	25.6	60	3.90
San Antonio	-16	3	3	0.9144	C	N	26.0	66	3.90

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
San Antonio	-16	3	4	1.2192	C	N	25.3	63	3.74
San Antonio	-16	3	5	1.524	C	N	22.7	50	3.75
San Antonio	-16	3	6	1.8288	C	N	24.0	67	3.68
San Antonio	-16	3	7	2.1336	C	N	24.8	61	3.65
San Antonio	-16	3	8	2.4384	C	N	24.4	71	3.63
San Antonio	-16	3	9	2.7432	C	N	23.5	65	3.74
San Antonio	-16	3	10	3.048	C	N	23.8	58	3.73
San Antonio	-16	3	11	3.3528	C	N	25.2	79	3.82
San Antonio	-16	3	12	3.6576	C	N	27.5	80	3.83
San Antonio	-16	3	13	3.9624	C	N	21.3	92	3.73
San Antonio	-16	3	14	4.2672	C	N	28.2	80	3.86

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
San Antonio	-16	3	15	4.572	C	N	27.7	81	3.80
San Antonio	-16	3	16	4.8768	C	N	29.1	91	3.93
San Antonio	-16	3	17	5.1816	C	N	29.6	85	4.02
San Antonio	-16	3	18	5.4864	C	N	29.1	87	4.04
San Antonio	-16	3	19	5.7912	C	N	28.7	88	3.97
San Antonio	-16	3	20	6.096	C	N	30.2	94	4.02
San Antonio	-16	3	21	6.4008	C	N	26.8	79	4.09
San Antonio	-16	3	22	6.7056	C	N	27.0	86	4.04
San Antonio	-16	3	23	7.0104	C	N	29.4	92	3.99
San Antonio	-16	3	24	7.3152	C	N	25.8	91	4.04
San Antonio	-16	3	25	7.62	C	N	28.4	89	4.04

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
San Antonio	-16	3	26	7.9248	C	N	27.2	80	4.08
San Antonio	-16	3	27	8.2296	C	N	26.2	81	4.09
San Antonio	-16	3	28	8.5344	C	N	23.3	78	4.04
San Antonio	-16	3	29	8.8392	C	N	26.6	75	4.00
San Antonio	-16	3	30	9.144	C	N	24.0	75	4.15
San Antonio	-16	4	1	0.3048	U	I	18.7	58	4.24
San Antonio	-16	4	2	0.6096	U	I	18.4	58	4.14
San Antonio	-16	4	3	0.9144	U	I	18.7	57	4.45
San Antonio	-16	4	4	1.2192	U	I	16.6	64	4.50
San Antonio	-16	4	5	1.524	U	I	20.7	64	4.13
San Antonio	-16	4	6	1.8288	U	I	18.5	63	4.42

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
San Antonio	-16	4	7	2.1336	U	I	19.7	66	4.15
San Antonio	-16	4	8	2.4384	U	I	19.5	57	4.29
San Antonio	-16	4	9	2.7432	U	I	17.10	60	3.93
San Antonio	-16	4	10	3.048	U	I	18.3	63	4.41
San Antonio	-16	4	11	3.3528	U	I	25.9	75	3.78
San Antonio	-16	4	12	3.6576	U	I	22.8	69	3.82
San Antonio	-16	4	13	3.9624	U	I	24.4	67	3.90
San Antonio	-16	4	14	4.2672	U	I	22.9	65	3.92
San Antonio	-16	4	15	4.572	U	I	25.5	70	3.83
San Antonio	-16	4	16	4.8768	U	I	28.1	85	3.93
San Antonio	-16	4	17	5.1816	U	I	23.8	79	3.94

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
San Antonio	-16	4	18	5.4864	U	I	26.8	79	4.03
San Antonio	-16	4	19	5.7912	U	I	24.2	78	3.98
San Antonio	-16	4	20	6.096	U	I	29.5	82	4.05
San Antonio	-16	4	21	6.4008	U	I	27.9	81	4.19
San Antonio	-16	4	22	6.7056	U	I	26.5	79	4.11
San Antonio	-16	4	23	7.0104	U	I	27.0	80	4.12
San Antonio	-16	4	24	7.3152	U	I	28.5	78	4.03
San Antonio	-16	4	25	7.62	U	I	28.0	80	4.16
San Antonio	-16	4	26	7.9248	U	I	28.7	82	4.06
San Antonio	-16	4	27	8.2296	U	I	26.7	77	4.18
San Antonio	-16	4	28	8.5344	U	I	27.6	78	4.22

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
San Antonio	-16	4	29	8.8392	U	I	25.7	78	4.17
San Antonio	-16	4	30	9.144	U	I	27.1	85	4.20
Phoenix	-56	1	1	0.3048	U	N	3	31	5.95
Phoenix	-56	1	3	0.9144	U	N	9	39	5.05
Phoenix	-56	1	4	1.2192	U	N	10.9	45	4.92
Phoenix	-56	1	5	1.524	U	N	9	52	5.1
Phoenix	-56	1	6	1.8288	U	N	10.9	51	4.82
Phoenix	-56	1	8	2.4384	U	N	7.8	50	4.76
Phoenix	-56	1	9	2.7432	U	N	7.9	48	4.61
Phoenix	-56	1	10	3.048	U	N	9.3	43	4.52
Phoenix	-56	1	12	3.6576	U	N	10.1	48	4.55
Phoenix	-56	1	14	4.2672	U	N	11.6	51	4.49
Phoenix	-56	1	15	4.572	U	N	11.4	48	4.47
Phoenix	-56	1	16	4.8768	U	N	11	64	4.47
Phoenix	-56	1	18	5.4864	U	N	7.4	48	4.47
Phoenix	-56	1	18	5.4864	U	N	7.4	52	4.47
Phoenix	-56	1	19	5.7912	U	N	6.9	42	4.45
Phoenix	-56	1	20	6.096	U	N	6.6	42	4.46
Phoenix	-56	1	22	6.7056	U	N	6.8	46	4.55
Phoenix	-56	1	24	7.3152	U	N	8.5	54	4.54

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Phoenix	-56	1	25	7.62	U	N	10.2	53	4.61
Phoenix	-56	1	29	8.8392	U	N	6.7	55	4.53
Phoenix	-56	2	5	1.524	C	N	16	44	3.37
Phoenix	-56	2	6	1.8288	C	N	15.4	44	3.68
Phoenix	-56	2	7	2.1336	C	N	13.7	39	3.67
Phoenix	-56	2	8	2.4384	C	N	12.5	37	3.55
Phoenix	-56	2	9	2.7432	C	N	11.9	36	3.56
Phoenix	-56	2	11	3.3528	C	N	11.1	39	3.81
Phoenix	-56	2	13	3.9624	C	N	12.1	54	3.75
Phoenix	-56	2	16	4.8768	C	N	14.2	54	4.03
Phoenix	-56	2	17	5.1816	C	N	13.4	57	4.09
Phoenix	-56	2	20	6.096	C	N	11.5	52	4.01
Phoenix	-56	2	23	7.0104	C	N	14	50	4.17
Phoenix	-56	2	24	7.3152	C	N	11.7	54	4.03
Phoenix	-56	2	25	7.62	C	N	14.5	55	4.09
Phoenix	-56	2	26	7.9248	C	N	12.4	56	4.02
Phoenix	-56	2	27	8.2296	C	N	14.3	60	4.09
Phoenix	-56	2	28	8.5344	C	N	14.2	62	4.05
Phoenix	-56	2	29	8.8392	C	N	14.4	48	4.04
Phoenix	-56	2	30	9.144	C	N	14.4	51	4.03
Munds Park	14	1	1	0.3048	U	I	16.7	37	3.89

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Munds Park	14	1	2	0.6096	U	I	15.9	39	3.75
Munds Park	14	1	3	0.9144	U	I	17.3	38	3.77
Munds Park	14	1	4	1.2192	U	I	21.1	45	3.92
Munds Park	14	1	5	1.524	U	I	18.4	34	3.86
Munds Park	14	1	6	1.8288	U	I	15.8	35	3.81
Munds Park	14	1	7	2.1336	U	I	16.3	34	3.88
Munds Park	14	1	8	2.4384	U	I	15.3	36	3.77
Munds Park	14	1	9	2.7432	U	I	16.1	38	3.88
Munds Park	14	1	10	3.048	U	I	29.2	46	3.81
Munds Park	14	1	11	3.3528	U	I	30.1	49	3.75
Munds Park	14	1	12	3.6576	U	I	35.7	51	3.68

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Munds Park	14	1	13	3.9624	U	I	29.2	57	3.76
Munds Park	14	1	14	4.2672	U	I	31	51	3.74
Munds Park	14	1	15	4.572	U	I	28.5	57	3.87
Munds Park	14	1	16	4.8768	U	I	32	53	3.73
Munds Park	14	1	17	5.1816	U	I	28.7	50	3.76
Munds Park	14	1	18	5.4864	U	I	27.7	55	3.96
Munds Park	14	1	19	5.7912	U	I	30.6	49	3.87
Munds Park	14	1	20	6.096	U	I	33.4	46	3.7
Munds Park	14	1	21	6.4008	U	I	27.9	43	3.85
Munds Park	14	1	22	6.7056	U	I	31.2	54	3.77
Munds Park	14	1	23	7.0104	U	I	31.9	45	3.78

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Munds Park	14	1	24	7.3152	U	I	31.3	45	3.81
Munds Park	14	1	25	7.62	U	I	28.6	52	3.81
Munds Park	14	1	26	7.9248	U	I	27.8	48	3.76
Munds Park	14	1	27	8.2296	U	I	28.5	50	3.89
Munds Park	14	1	28	8.5344	U	I	25.6	54	4.02
Munds Park	14	1	29	8.8392	U	I	25.7	49	3.87
Munds Park	14	1	30	9.144	U	I	27.2	53	4.04
Denver	-24	B1 A	5	1.524	U	I	16.1	43.1	3.76
Denver	-24	B1 A	5	1.524	U	I	17.3	43.1	3.88
Denver	-24	B1 A	10	3.048	U	I	23.2	61.3	3.87
Denver	-24	B1 A	10	3.048	U	I	20.7	61.3	3.99
Denver	-24	B1 A	15	4.572	U	I	20	69.2	4.02
Denver	-24	B1 A	15	4.572	U	I	19	69.2	4.08
Denver	-24	B1 A	19.1	5.82168	U	I	13.7	45.5	4.09
Denver	-24	B1 A	19.1	5.82168	U	I	13.5	45.5	4.33

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Denver	-24	B1 A	24.5	7.4676	U	I	12.8	46.9	4.27
Denver	-24	B1 A	24.5	7.4676	U	I	8	46.9	4.52
Denver	-24	B1 A	29.5	8.9916	U	I	17.1	59.7	4.1
Denver	-24	B1 A	29.5	8.9916	U	I	16.6	59.7	4.13
Denver	-24	B1 A	35	10.668	U	I	18.3	45.3	3.98
Denver	-24	B1 A	35	10.668	U	I	17.7	45.3	4.195
Denver	-24	B1 A	39.5	12.0396	U	I	10.7	37	3.95
Denver	-24	B1 A	39.5	12.0396	U	I	10.6	37	4.085
Denver	-24	B1 A	44.5	13.5636	U	I	16	80.2	4.36
Denver	-24	B1 A	44.5	13.5636	U	I	14.5	80.2	4.57
Denver	-24	B1 A	49.5	15.0876	U	I	15.8	61.7	4.26
Denver	-24	B1 A	49.5	15.0876	U	I	14.4	61.7	4.38
Denver	-24	B2 A	9.5	2.8956	U	I	10.1	37.1	4.19
Denver	-24	B2 A	9.5	2.8956	U	I	8.6	37.1	4.33
Denver	-24	B2 A	14.8	4.51104	U	I	12.4	48.9	4.16
Denver	-24	B2 A	14.8	4.51104	U	I	11.6	48.9	4.26
Denver	-24	B2 A	19.5	5.9436	U	I	14.8	61.2	4.38
Denver	-24	B2 A	19.5	5.9436	U	I	15.8	61.2	4.495
Denver	-24	B2 A	24.6	7.49808	U	I	16.7	67.7	4.28
Denver	-24	B2 A	24.6	7.49808	U	I	16.3	67.7	4.35
Denver	-24	B2 A	29.5	8.9916	U	I	16.9	74.8	4.535
Denver	-24	B2 A	29.5	8.9916	U	I	17.4	74.8	4.56

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Denver	-24	B2 A	34.5	10.5156	U	I	18.6	75.4	4.56
Denver	-24	B2 A	34.5	10.5156	U	I	16.8	75.4	4.625
Denver	-24	B2 A	49.3	15.02664	U	I	18.5	84.8	4.46
Denver	-24	B2 A	49.4	15.05712	U	I	17	84.8	4.535
Denver	-24	B6 A	5	1.524	U	I	17.5	41.1	3.63
Denver	-24	B6 A	5	1.524	U	I	17.9	41.1	3.84
Denver	-24	B6 A	29.5	8.9916	U	I	15.9	47.3	3.525
Denver	-24	B6 A	29.5	8.9916	U	I	14.6	47.3	3.92
Denver	-24	B6 A	34.4	10.48512	U	I	15.9	30.1	3.8
Denver	-24	B6 A	39.8	12.13104	U	I	22.4	70.9	3.93
Denver	-24	B6 A	39.8	12.13104	U	I	21	70.9	4.015
Denver	-24	B6 A	44.5	13.5636	U	I	17.2	63.1	4.22
Denver	-24	B6 A	44.5	13.5636	U	I	15.9	63.1	4.31
Denver	-24	B6 A	49.5	15.0876	U	I	17.4	59.6	4.21
Denver	-24	B6 A	49.5	15.0876	U	I	13.3	59.6	4.365
Denver	-24	B7 A	3	0.9144	U	I	22.5	36.5	3.505
Denver	-24	B7 A	3	0.9144	U	I	23.1	36.5	3.65
Denver	-24	B7 A	10	3.048	U	I	11.4	33.8	3.78
Denver	-24	B7 A	10	3.048	U	I	10.7	33.8	3.82
Denver	-24	B7 A	34.8	10.60704	U	I	11.5	45.2	4.35
Denver	-24	B7 A	34.8	10.60704	U	I	12.8	45.2	4.37
Denver	-24	B7 A	40	12.192	U	I	18.5	67	4.18

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Denver	-24	B7 A	40	12.192	U	I	18.9	67	4.2
Denver	-24	B7 A	49.3	15.02664	U	I	16.6	70.1	4.305
Denver	-24	B7 A	49.5	15.0876	U	I	16.3	70.1	4.4
Denver	-24	B8 A	5	1.524	U	I	20.2	40.2	3.545
Denver	-24	B8 A	5	1.524	U	I	19.7	40.2	3.74
Denver	-24	B8 A	20	6.096	U	I	18.7	58.9	4.07
Denver	-24	B8 A	20	6.096	U	I	16.5	58.9	4.265
Denver	-24	B8 A	25	7.62	U	I	20.3	72.8	4.21
Denver	-24	B8 A	25	7.62	U	I	18	72.8	4.25
Denver	-24	B8 A	29.5	8.9916	U	I	9.9	33.3	3.91
Denver	-24	B8 A	29.5	8.9916	U	I	9.4	33.3	3.99
Denver	-24	B8 A	39.5	12.0396	U	I	13.1	28	3.31
Denver	-24	B8 A	39.5	12.0396	U	I	12	28	3.435
Denver	-24	B9 A	5	1.524	U	I	16.9	38.4	3.82
Denver	-24	B9 A	5	1.524	U	I	15.5	38.4	3.85
Denver	-24	B9 A	10	3.048	U	I	20	52.9	3.95
Denver	-24	B9 A	10	3.048	U	I	18.7	52.9	4.02
Denver	-24	B9 A	15	4.572	U	I	17.5	63.3	4.15
Denver	-24	B9 A	15	4.572	U	I	16.4	63.3	4.15
Denver	-24	B9 A	19.5	5.9436	U	I	9.2	46.5	4.73
Denver	-24	B9 A	19.5	5.9436	U	I	8	46.5	4.835
Denver	-24	B9 A	24.5	7.4676	U	I	14.5	68.8	4.58

Location	TMI	Boring	Depth (ft)	Depth (m)	Cover	Irrigation	Moisture	LL	Total Suction (pF)
Denver	-24	B9 A	24.5	7.4676	U	I	12.5	68.8	4.67
Denver	-24	B9 A	29.5	8.9916	U	I	16.5	82.6	4.39
Denver	-24	B9 A	29.5	8.9916	U	I	15.9	82.6	4.595
Denver	-24	B9 A	34.5	10.5156	U	I	13.7	59.7	4.42
Denver	-24	B9 A	34.5	10.5156	U	I	13.6	59.7	4.515
Denver	-24	B9 A	39.5	12.0396	U	I	15.8	76.5	4.48
Denver	-24	B9 A	39.5	12.0396	U	I	15.1	76.5	4.53
Denver	-24	B9 A	44.5	13.5636	U	I	15.3	69.6	4.23
Denver	-24	B9 A	44.6	13.59408	U	I	17.1	69.6	4.17
Denver	-24	B9 A	49.5	15.0876	U	I	13.4	54.6	4.17
Denver	-24	B9 A	49.5	15.0876	U	I	10.9	54.6	4.235

E 2: Databased Utilized to Develop the Relationship Between TMI and Equilibrium Suction

Location	TMI	Equilibrium Suction	Precipitation (inches)	Source
Laredo, TX	-39.69	4.25	20.2	Surrogate - Uncovered Site
McAllen, TX	-39.63	4.2	22.2	Surrogate - Uncovered Site
McAllen, TX	-39.63	4.1	22.2	Surrogate - Uncovered Site
McAllen, TX	-37.64	4.1	22.2	Surrogate - Uncovered Site
Los Fresnos, TX	-29.94	3.95	27	Surrogate - Uncovered Site
Snyder, TX	-19.43	4	22.2	Surrogate - Uncovered Site
Austin, TX	-18.09	4	34.2	Surrogate - Uncovered Site
Amarillo, TX	-17.92	4.1	20.4	Surrogate - Uncovered Site
San Antonio, TX	-16.6	4.1	32.3	Surrogate - Uncovered Site
San Antonio, TX	-16.6	4.2	32.3	Surrogate - Uncovered Site
Fountain, CO	-15.57	4.2	15.9	Surrogate - Uncovered Site
Mesa, AZ	-52	4.35	9.5	Surrogate - Uncovered Site
Breckenridge, TX	-9.57	4.25	30	Surrogate - Uncovered Site
Universal City, TX	-9.5	4.15	28.7	Surrogate - Uncovered Site
Shertz, TX	-6.27	4.05	31.9	Surrogate - Uncovered Site
Cibolo, TX	-6.27	4.1	33	Surrogate - Uncovered Site
Converse, TX	-6.27	4.2	28.3	Surrogate - Uncovered Site
Kyle, TX	-5.16	4.05	37.2	Surrogate - Uncovered Site
Killeen, TX	-4.69	4.05	33.1	Surrogate - Uncovered Site
Dallas, TX	-2.24	4.1	37.6	Surrogate - Uncovered Site
Hewitt, TX	1.66	4.05	36	Surrogate - Uncovered Site

Location	TMI	Equilibrium Suction	Precipitation (inches)	Source
Yukon, OK	2.7	4	32.9	Surrogate - Uncovered Site
Fort Worth, TX	2.92	4.1	37.8	Surrogate - Uncovered Site
Keller, TX	2.92	4.05	38	Surrogate - Uncovered Site
Cross Roads, TX	5.1	4.1	38.1	Surrogate - Uncovered Site
Houston, TX	9.42	4.05	49.8	Surrogate - Uncovered Site
Friendswood, TX	21.94	3.75	56	Surrogate - Uncovered Site
Broken Arrow, OK	24.1	3.9	40.2	Surrogate - Uncovered Site
Vidor, TX	33.98	3.8	57.9	Surrogate - Uncovered Site
Prosper, TX	22.88	3.8	39.2	Surrogate - Uncovered Site
Atascocita, TX	28.87	3.9	53	Surrogate - Uncovered Site
Norman, OK	17.52	3.85	38.9	Surrogate - Uncovered Site
Meridian, MS	47.97	3.75	56.2	Surrogate - Uncovered Site
Harker Heights, TX	-4.69	4.1	31.8	Surrogate - Uncovered Site
Aurora, CO	-20.66	3.95	15.9	Surrogate - Uncovered Site
Hattiesburg, MS	49.81	3.9	61.6	Surrogate - Uncovered Site
Wheat Ridge, CO	-12	4.05	18.2	Surrogate - Uncovered Site
Wheat Ridge, CO	-12	4.1	18.2	Surrogate - Uncovered Site
Wylie, TX	8.7	4	40.5	Surrogate - Uncovered Site
Oklahoma City, OK	2.7	3.9	36.5	Surrogate - Covered Site
Warr Acres, OK	2.7	3.7	33.1	Surrogate - Covered Site
Fort Worth, TX	-3.18	4	37.8	Surrogate - Covered Site
Richardson, TX	-2.24	4	41.5	Surrogate - Covered Site

Location	TMI	Equilibrium Suction	Precipitation (inches)	Source
Dallas, TX	-2.24	4	37.6	Surrogate - Covered Site
Tulsa, OK	19.42	4	40.9	Surrogate - Covered Site
Keller, TX	2.92	3.9	38	Surrogate - Covered Site
Tolleson, AZ	-53.71	4.3	6.9	Surrogate - Covered Site
Colorado Springs, CO	-15.57	3.9	16.5	Surrogate - Covered Site
Garland, TX	-2.24	3.9	38.3	Surrogate - Covered Site
Moore, OK	9.16	3.8	36.5	Surrogate - Covered Site
Arvada, CO	-11.98	4	17	Surrogate - Covered Site
Houston, TX	12.39	3.9	49.8	Surrogate - Covered Site
Houston, TX	12.39	3.9	49.8	Surrogate - Covered Site
Mesa	-52	4.4	9.5	Measured from drilled sites as a part of this research
Hobart. OK	-6.48	3.95	28.2	
Denver	-24	4.3	15.6	
Denver	-24	4.28	15.6	
Phoenix (C & T)	-56	4.25	8.2	
Phoenix (C & T)	-56	4.2	8.2	
Phoenix (C & T)	-56	4.4	8.2	
Young, AZ	-5.89	4.05	22.1	
Mesa	-52.04	4.20	9.50	
San Antonio	-16	4.03	32.3	
San Antonio	-16	3.91	32.3	
San Antonio	-16	4.06	32.3	

Location	TMI	Equilibrium Suction	Precipitation (inches)	Source
Phoenix (C & T)	-56.38	4.51	8.2	
Phoenix (C & T)	-56.38	4.3	8.2	
Munds Park, AZ	5	3.83	21.9	
Denver	-24	4.15	15.6	
Phoenix	-56	4.2	8.2	Vann Engineering Files (measured)
Gilbert, AZ	-51	4.3	8.4	
Phoenix	-56	4.4	8.2	
Chandler, AZ	-51	4.2	9.6	
Gilbert, AZ	-51	4.5	8.4	
Gilbert, AZ	-51	4.3	8.4	
Gilbert	-52.04	4.5	8.4	
Phoenix	-52	4.4	8.2	
Tucson	-46.94	4.3	11.6	
Flagstaff	8.19	4	21.9	
Jackson, MS	39.41	3.67	54.1	*Snethen (1977)*
Dallas 1, TX	-11.3	4	37.6	*Jayatilaka et al. (1992)*
Ennis1, TX	5.81	3.82	37.3	
Seguin, TX	-7.56	3.95	35.7	
Converse, TX	-5.72	3.9	28.3	
Snyder 1, TX	-25	4	22.6	
Snyder 2, TX	-25	4	22.6	
Snyder 3, TX	-25	3.8	22.6	

Location	TMI	Equilibrium Suction	Precipitation (inches)	Source
Wichita Falls 1, TX	-9.72	4.1	28.9	
Wichita Falls 2, TX	-9.72	4	28.9	
Denver	-20	4.2	15.6	*McOmber*
Australia	-60	4.4	7.5	*Barnett & Kingsland (1999)*
Australia	40	3.8	50	
DFW	-1.87	3.7	37.6	*McKeen (1981)*
Gallup 1, NM	-29.94	4.2	11.6	
Gallup 2, NM	-29.94	4.4	11.6	
JSN	39.41	3.75	54.2	
Murdo, SD	-7.85	3.8	19.2	*McKeen (1985)*
Murdo, SD	-7.85	3.9	19.2	
DFW	-1.87	4	37.6	*Bryant (1998)*
College Station, TX	8.89	3.8	40.1	*Wray (1989)*
Amarillo, TX	-17.11	4.1	20.4	

E 3: Databased Utilized to Develop the Relationship Between TMI and the Depth to Equilibrium Suction

Location	Liquid Limit	TMI	Depth to Equilibrium Suction (m)	Data Source
Fountain, CO	36	-15.57	3.0	Surrogate
Snyder, TX	37	-19	3.0	Surrogate
Amarillo, TX	38	-17.92	2.8	Surrogate
Laredo, TX	39	-39.69	4.2	Surrogate
Wichita Falls, TX	41	-9.72	3.1	Jayatilaka et al. (1992)
Young, AZ	41	-5.89	1.2	ASU NSF Research
Phoenix	42	-56	4.5	VEI Project Files
Phoenix, AZ	42	-56	4.2	Surrogate
Young, AZ	43	-5.89	1.8	ASU NSF Research
Yukon, OK	43	2.7	1.7	Surrogate
Broken Arrow, OK	44	24.1	1.5	Surrogate
Chandler, AZ	44	-51	4.2	VEI Project Files
Keller, TX	46	2.92	1.6	Surrogate
McAllen, TX	47	-37.64	4.2	Surrogate
Snyder, TX	47	-19.43	3.7	Jayatilaka et al. (1992)
College Station, TX	48	8.89	1.8	Wray (1989)
Gilbert, AZ	48	-51	4.3	VEI Project Files
Mesa, AZ	48	-52	4.3	Surrogate
McAllen, TX	49	-39.63	4.0	Surrogate
Mesa	49	-52	4.0	VEI Project Files
Mesa	49	-52	4.6	ASU NSF Research
Vidor, TX	49	33.98	1.4	Surrogate
Cross Roads, TX	50	5.1	1.9	Surrogate

Location	Liquid Limit	TMI	Depth to Equilibrium Suction (m)	Data Source
Denver	51	-24	4.6	ASU NSF Research
San Antonio, TX	51	-16.6	3.0	Surrogate
Shertz, TX	51	-6.27	2.4	Surrogate
Gilbert, AZ	52	-51	4.1	VEI Project Files
Hewitt, TX	53	1.66	1.9	Surrogate
Houston, TX	53	9.42	1.7	Surrogate
Gilbert	54	-52	4.2	VEI Project Files
Denver	55	-24	4.2	ASU NSF Research
Denver	55	-24	4.4	VEI Project Files
Killeen, TX	55	-4.69	2.1	Surrogate
McAllen, TX	55	-39.63	4.2	Surrogate
Universal City, TX	55	-9.5	2.2	Surrogate
Fort Worth, TX	56	2.92	1.8	Surrogate
Converse, TX	57	-6.27	2.3	Surrogate
Dallas, TX	57	-2.24	1.6	Surrogate
Amarillo, TX	59	-17.11	3.8	Wray (1989)
Cibolo, TX	59	-6.27	2.2	Surrogate
Ennis, TX	60	5.81	2.0	Jayatilaka et al. (1992)
Los Fresnos, TX	61	-29.94	3.5	Surrogate
Kyle, TX	62	-5.16	1.5	Surrogate
Sequin, TX	66	-6.16	2.4	Jayatilaka et al. (1992)
San Antonio, TX	67	-16.6	3.2	Surrogate
Austin, TX	71	-18.09	3.2	Surrogate
Converse, TX	72	-5.72	2.7	Jayatilaka et al. (1992)

Location	Liquid Limit	TMI	Depth to Equilibrium Suction (m)	Data Source
Dallas, TX	76	-11.3	2.1	Jayatilaka et al. (1992)
San Antonio, TX	78	-16	3.0	McKeen (1981) and McKeen and Johnson (1990)
San Antonio, TX	78	-16	3.0	ASU NSF Research
San Antonio, TX	80	-16	3.0	ASU NSF Research
Adelaide		-26	4.0	Smith (1993)
Amarillo, TX		-22	3.7	McKeen (1981) and McKeen and Johnson (1990)
Breckenridge, TX		-9.57	2.3	
Brisbane		34	1.5	Smith (1993)
Brisbane, Australia		40	1.5	Walsh et al. (1998)
Dallas, TX		-12	2.1	McKeen (1981) and McKeen and Johnson (1990)
Dallas, TX		1.38	2.1	Jayatilaka et al. (1992)
Denver		-24	3.0	McKeen (1981) and McKeen and Johnson (1990)
El Paso, TX		-46.68	4.5	Jayatilaka et al. (1992)
Friendswood, TX		21.94	1.1	
Gallup		-32	3.7	McKeen (1981) and McKeen and Johnson (1990)

Location	Liquid Limit	TMI	Depth to Equilibrium Suction (m)	Data Source
Houston, TX		18	1.5	McKeen (1981) and McKeen and Johnson (1990)
Houston, TX		14.8	2.0	Jayatilaka et al. (1992)
Ipswitch, Australia		2.5	2.3	Walsh et al. (1998)
Jackson, MS		30	1.2	McKeen (1981) and McKeen and Johnson (1990)
Jerramungup, Australia (Great Southern)		-22	4.0	Sun et al. (2017)
Lake King, Australia (Wheatbelt)		-39.7	4.0	Sun et al. (2017)
Maryville		24.4	1.7	Fityus (1998)
Melbourne		-1	2.0	Smith (1993)
Nelson Bay		53.7	1.5	Fityus (1998)
Perth, Australia		25	1.8	Walsh et al. (1998)
Phoenix (C & c)		-56	4.0	ASU NSF Research
Phoenix (C & c)		-56	4.3	ASU NSF Research
Phoenix (C & c)		-56	4.6	ASU NSF Research
Port Arthur, TX		26.8	1.5	Jayatilaka et al. (1992)
Ravensthorpe, Australia (Goldfields-Esperance)		-43.5	4.0	Sun et al. (2017)
San Antonio, TX		-16.6	3.5	Jayatilaka et al. (1992)

Location	Liquid Limit	TMI	Depth to Equilibrium Suction (m)	Data Source
Scone		-24.3	3.0	Fityus (1998)
Australia		25	1.8	Barnett and Kingsland (1999)
Australia		2.5	2.3	Barnett and Kingsland (1999)
Australia		-15	3.0	Barnett and Kingsland (1999)
Australia		-25	4.0	Barnett and Kingsland (1999)

E 4: Database for Determination of $\Delta\psi$ at the Surface and the Aubeny and Long (2007) ‘r’ Parameter

Data Measured or Surrogate	***Source***	***Location***	***TMI***	***Δψ (pF)***	***Climate 'r' Parameter***
Surrogate	File Data Mined as Part of This Research	San Antonio, TX	-16	1.4	0.36
Surrogate	File Data Mined as Part of This Research	McAllen, TX	-39.69	1.5	0.50
Surrogate	File Data Mined as Part of This Research	DFW	-2.24	1.2	0.46
Measured	Drilled and Evaluated Prior to This Research	Peoria, AZ	-56	1.55	0.62
Measured	Fityus et al. (2004)	New Castle, Australia	25	1.1	0.27
Measured	Wray (1989)	College Station, TX	8.89	1.1	0.36
Measured	Wray (1989)	Amarillo, TX	-17.92	1.3	0.46