Estimating Expansive Soil Field Suction Profiles Using a Soil Suction Surrogate

by

Alan J. Cuzme

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved October 2018 by the
Graduate Supervisory Committee:

Sandra Houston, Chair
Claudia Zapata
Leon van Paassen

ARIZONA STATE UNIVERSITY

December 2018

ABSTRACT

Expansive clay soils, when subjected to substantial moisture change, can be extremely problematic causing various types of damage to lightly-loaded structures. Geotechnical engineers are faced with dealing with these types of soils all over the world. Solving these problems requires an understanding of unsaturated soil mechanics. Soil suction, related to moisture content change, is important in the development of unsaturated soil properties and in the assessment of initial and final stress state for heave computation. Direct measurement of soil suction on expansive clays to determine field suction profiles is quite limited due primarily to tradition and related cost-driven geotechnical field investigation practices prioritizing water content measurement over soil suction measurement. This study employs a surrogate equation to estimate soil suction profiles for various sites consisting of clays with a Plasticity Index of approximately 15 to 70. The soil suction surrogate is used to determine soil suction profiles from existing geotechnical engineering expansive clay field investigations.

A database was created through compiling soil profile data from geotechnical investigation reports which have been conducted in a wide range of climatic regions within the United States. Data in these reports, collected by various engineering companies over a number of years, includes index properties, moisture contents, SPT values, and swell test results. A suction surrogate, determined from prior studies, and which is depth, soil-type, and climatic zone dependent, was used to estimate soil suction. The surrogate equations are given in terms of routinely measured index properties, moisture content and liquid limit, and the Thornthwaite Moisture Index (TMI) value for the particular site location. An ArcGIS web-based map with TMI values for the United States was used to determine the

TMI values for the specific site locations. Soil suction profiles were created and a depth to constant suction was determined. Equilibrium suction values, at depth, are also determined. Commonly used heave estimation methods require values of equilibrium suction and the depth to constant suction, together with initial and final suction and net total stress profiles. Surrogate profiles and equilibrium suction values for non-irrigated and uncovered sites are compared to those reported in the literature, and to those obtained by direct measurement at a limited number of locations.

Soil suction profiles obtained by direct measurement and through use of a soil suction surrogate were studied for a range of surface flux boundary conditions: (1) non-irrigated and uncovered (natural); (2) irrigated and uncovered; and (3) non-irrigated and covered. Differences in soil suction profiles for these differing boundary conditions were explored to the extent possible from the available data set on irrigated and covered sites. These soil suction profiles and equilibrium suction values are intended to aid in the development of design suction envelopes which are used to determine shrink and swell potential as needed for engineering applications.

DEDICATION

To my wife, Marie, for her love and understanding, who has always supported me and encouraged me to do my best in my education.

To my son, Bradley, for being a big inspiration.

To my mother, Karen Cuzme, for always showing me in the right direction.

To my father, Jose Cuzme, who has always pushed me to my full potential and has never given up on me.

ACKNOWLEDGMENTS

This work is based in part on research funded by the National Science Foundation under Award No. 1462358. The opinions, conclusions, and interpretations are those of the author and not necessarily the National Science Foundation.

I am truly grateful for my graduate advisor, Dr. Sandra Houston, who had reached out to the veteran community here at Arizona State University and given me the opportunity to be a part of her research. My sincere appreciation for her support, understanding, and guidance as a graduate student. Thank you to the other members on my graduate committee, Dr. Claudia Zapata and Dr. Leon van Paassen, for their patience throughout this research.

My upmost respect and gratitude to Jeff Vann for the support and advice during this research project. Thank you to Austin Olaiz and Sai Singhar for the time and effort that went into data mining, providing data for this study to be completed. Thank you to Vann Engineering Inc. for allowing the use of projects to be included in this project.

TABLE OF CONTENTS

Page

CHAPTER

LIST OF FIGURES

Figure Page

Figure Page

Figure Page

Figure Page

Figure Page

Figure Page

LIST OF TABLES

1.0 INTRODUCTION

1.1 The Problem with Expansive Soils

Expansive soils are one of the most damaging to foundations of lightly loaded structures. Expansive soils are found all over the world and are extremely problematic in the semi-arid and arid regions when subjected to wetting and drying cycles and have caused 10s to 100s of billions of dollars annually of damage due to moisture intrusion (Wray & Meyer, 2004). Change in volume occurs as a result of moisture change and other variables including soil properties, soil suction at the time of construction, the amount of change in moisture, variation of moisture over time and space, and the geometry and stiffness of the structure (Houston, Dye, Zapata, Walsh, & Houston, 2011). In recent decades an extensive amount of research has been focused on unsaturated soil mechanics and expansive soils, more specifically into methods to accurately predict the shrink and swell behavior of expansive soils. There are various methods that have been used to estimate soil heave in the field but currently there is not one particular method that has been adopted in geotechnical engineering practice.

1.2 Objectives

The overall objective of this research study was to investigate field soil suction profiles from a combination of literature review, direct measurements at specific locations, and through the use of a soil suction surrogate to estimate suction profiles from legacy data (i.e. existing geotechnical engineering reports). In addition, the impact of surface flux boundary conditions on field suction profiles is to be studied by sorting the soil profiles on the basis of covered or uncovered and irrigated or non-irrigated. Approximately 400 geotechnical engineering reports from cities throughout the U.S. were reviewed to extract data required for soil suction profile estimates. The soil suction surrogate to be used in this study was developed by others (Vann, et al., 2018) and uses routinely measured soil properties (water content and Atterberg limits) and a climatic parameter (TMI) to estimate total soil suction. Existing geotechnical reports having adequate data and adequate depth of investigation (i.e. well below the active zone) to provide meaningful soil suction profile information were included in this study. The emphasis of the study was on expansive soils with a PI of approximately 15 to 70. Additional goals of the study included the development of a relationship between depth to constant suction and TMI for non-irrigated and uncovered sites, and a comparison of this relationship to those published in the literature. In addition, from the data gathered as a part of this study, the magnitude of equilibrium suction was studied, including the exploration of a relationship between equilibrium soil suction and TMI.

A summary and any recommendations regarding the use of a suction surrogate to estimate depth to constant suction and equilibrium suction are provided herein. Recommendations for future research are provided.

2.0 LITERATURE REVIEW

2.1 Brief Overview of Soil-Suction Based Methods

When dealing with expansive soils, its critical to estimate the amount of movement (shrink or swell volume change) the soil may experience due to variation in soil suction (moisture content) and net total stress. Because net total stress commonly remains more or less constant post-construction, the emphasis in heave estimation methods is on the changes in soil suction. One of the most common methods to estimate swell potential is the Standard Test Method for One-Dimensional Swell (ASTM D4546, 2014) where the sample is fully inundated with water. This method is also used to determine the potential for collapse. However, in the field, soils typically remain unsaturated and will never become fully saturated in the absence of rising groundwater table, and thus, the application of unsaturated soil mechanics is needed in solving expansive soil problems (Houston, 2018).

There are two stress state variables that have been shown to control the mechanical behavior of unsaturated soils, net normal stress (σ-u_a) and matric suction (u_a-u_w) where σ is total stress, u_a is the pore air pressure, and u_w is the pore water pressure (Fredlund & Morgenstern, 1977). The pore air pressure is most commonly assumed to be atmospheric (u_a=0). Changes in the soil suction state variable have the greatest relevance to expansive clay problems. Soil suction can be difficult to measure, however, and is essential in the analysis for predicting expansive soil potential movements. Although newer devices, such as chilled mirror dew point (WP4 C, Meter Group) have improved cost and time requirements for suction measurement, historically and traditionally soil suction is rarely measured in geotechnical site investigations.

Soil suction tends to keep the soil grains together; particularly in clay soils, the higher the soil suction the more tightly bound are the soil particles. The soil suction is a function of moisture content in the soil, as reflected by the soil-water characteristic curve (Fredlund, et al., 2012). Expansive soils, when subjected to variations in moisture contents will undergo shrink and swell movements (volume changes) which causes distress in foundation systems.

2.2 Zone of Matric Suction Change

The unsaturated zone in the subsurface is subjected to various natural and human-induced conditions that will cause the soils to undergo wetting and drying cycles, such as changes in climatic conditions and environmental factors, vegetation, and irrigation. The term active zone depth is often considered to be the zone of soil that contributes to the potential of the soil to both shrink and swell due to changes in moisture contents (Nelson, Overton & Durkee (2001). However, the active zone is also sometimes referred to as the zone of seasonal moisture fluctuation (Post-Tensioning Institute (2008) and AS-2870 (2011)). Another common term for the zone of soil suction changes (and therefore zone of potential heave) is the Depth of Wetting (DOW), which is the depth over which soil suction changes for developed, irrigated surface flux conditions (Walsh, Colby, Houston, & Houston, 2009). The depth of the active zone is influenced by different factors including the climate, the groundwater table (GWT), soil cracking pattern, and the amount of clay minerals within the soil profile (Wray W. K., 1978). It is important to note the climate has a great effect on the active zone depth (depth of wetting or depth of seasonal moisture change). In a very wet climate, or if there is a shallow groundwater table, it is possible for the active zone depth to be negligible (Wray W. K., 1978). In this study, consistent with Wray (1978), there were sites, particularly with high TMI (wet climate) values, where the depth to a more or less constant suction could not be determined and only an equilibrium suction magnitude was able to be determined from the estimated field suction profiles. Estimation of the zone subjected to variation in moisture change (suction) as well as the change in magnitude of the soil suction at the ground surface has an important role in predicting soil movement in expansive soils. In this study, various surface boundary conditions are considered and a review of how a surface boundary condition affects the depth of soil suction change is presented.

Surface boundary conditions that are considered in this study are covered or uncovered and irrigated or non-irrigated conditions. The magnitude of changes in soil suction typically will decrease with depth until a point of essentially constant, or pseudo-equilibrium, suction is reached, below which, for relatively deep groundwater table, there will be no significant suction change within the zone of foundation engineering interest. For an assumption of seasonal moisture fluctuation (non-irrigated and uncovered), during the wet season conditions the soil will experience lowest suction values, while during the dry season the soil suction will exhibit higher suction values.

In the development of design suction envelopes, which are used to predict soil movements, an attempt is made to identify the extreme dry condition and the extreme wet condition (e.g. PTI, 2008). Below the depth where soil suction changes seasonally (i.e. the active zone depth for climate-driven boundary conditions) the soil suction attains an "equilibrium" value which is more or less constant and no longer affected by climatic conditions at the surface (Mckeen & Johnson, 1990). For such design suction envelopes, which are used to predict the total differential soil movements at the surface, depth to constant suction is an important parameter (Fredlund, Rahardjo, & Fredlund, 2012). The amount of differential movement at the surface also depends on factors including the type of clay, how easy water can infiltrate the soil, and subsequent changes in moisture (e.g., seasonal fluctuations and irrigation) (Harris, Davenport, & Lehane, 2013). A theoretical, simplified design suction envelope is presented below in Figure 1, based on the Australian Standard (AS-2870, 2011), where H_s is the active zone depth and Δu is the design surface suction change. The design suction envelopes used in AS-2870 correspond to an assumption of seasonal moisture fluctuations with minimal to no human-induced changes in surface flux boundary conditions.

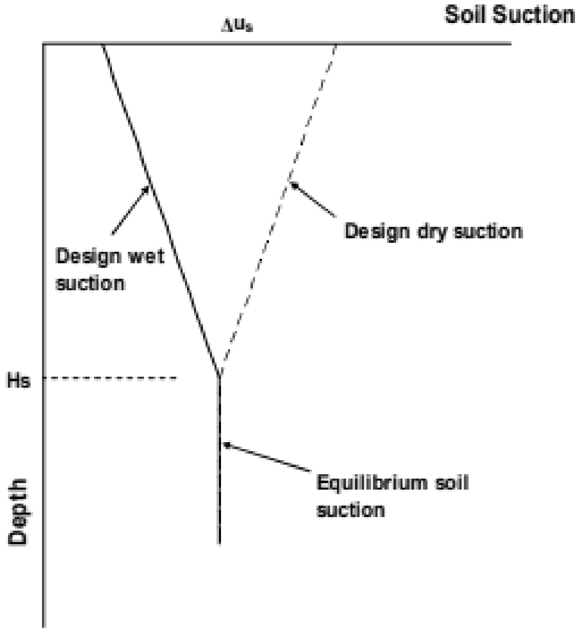


Figure 1: Design Suction Envelope (Mitchell, 2008)

Lytton (1997) has described the active zone depth as the depth in a profile at which there is less than 0.2 pF change in soil suction. It’s important to note when high suctions are present, for example 4.5 pF, a change in 0.2 pF will be much greater in units of kPa than lower suction values such as 4.0 or 3.8 pF. This is because the pF suction scale is logarithmic, corresponding to the log-base 10 of suction in centimeters of water. In this study, to help aid in the determination of the equilibrium suction values and the depth to constant suction, a change of 0.2 pF or less was considered when viewing the estimated field suction profiles from the soil suction surrogate. Profiles of suction are presented in terms of the commonly-used pF scale.

For covered conditions, as when a slab is placed, it is considered post construction or the post development condition and has the possibility to experience high swell and shrink behavior around the slab edges when compared to the center of the slab. When the soil is covered, except near edges (within the “edge moisture distance”), no longer will the surficial soil be subjected to the climatic conditions which greatly affect the swings in soil suction. Surrounding edges of a slab or paved surface, will be subjected to wetting and drying (changes in soil suction) due to seasonal variations, as well as to or other factors such as irrigation or ponding. Changes made during development, such as irrigation and concentration of roof water runoff, can dramatically increase the distance from pavement edge subject to moisture change. Moisture underneath the slab, internal to the edge moisture distance, will eventually come into equilibrium with time as moisture in the soil will either be gained or lost, and the time it takes for the soil to approach equilibrium depends on upon the soils diffusivity and unsaturated hydraulic conductivity (Naiser, 1997), as well as the surface flux conditions.

Extensive research has been done on expansive soils and methods of prediction of differential soil movement. Available methods include consolidation theory-based, water-content based, and soil suction-based methods (Adem & Vanapalli, 2015) and there is no consensus or agreement as to which type of method is the best approach for analyzing expansive soils. Still, all appropriate methods of heave computation require knowledge or estimation of initial and final soil suction profiles (or water content, which is a function of soil suction). When designing foundations or pavements, the amount of shrink or swell over time will have an effect on differential soil movements and related distress to foundations. Soil suction change resulting from moisture flux in or out due to climatic conditions or other human and environmental factors has an important role in predicting the volume change movement in expansive soils.

2.3 Equilibrium Suction

The zone of soil that contributes to the potential of soil heave or shrink is subject to changes in moisture due to climatic conditions and various human and environmental factors. For dry conditions, changes in moisture or suction will typically decrease with depth until eventually the suction will come into a pseudo equilibrium state where there is no longer a significant variation in suction magnitude. Equilibrium suction is defined by the Post-Tensioning Institute (PTI) as the long-term average suction at depth due to the climatic conditions at the surface (Post-Tensioning Institute 3rd Edition, 2008) and is controlled by various factors, including climate. According to the PTI method, the equilibrium suction value can be estimated from literature correlations if the Thornthwaite moisture index (TMI) is known.

Russam & Coleman (1961) presented a study investigating the effect of climatic factors on subgrade moisture conditions where the water table is deep. For climatic conditions (seasonal variation), a correlation with TMI and suction was presented for three different soils, including expansive clays. Results from Russam and Coleman showed equilibrium suction will decrease as the TMI value increases (becomes more wet), and the proposed relationship is presented in Figure 2.

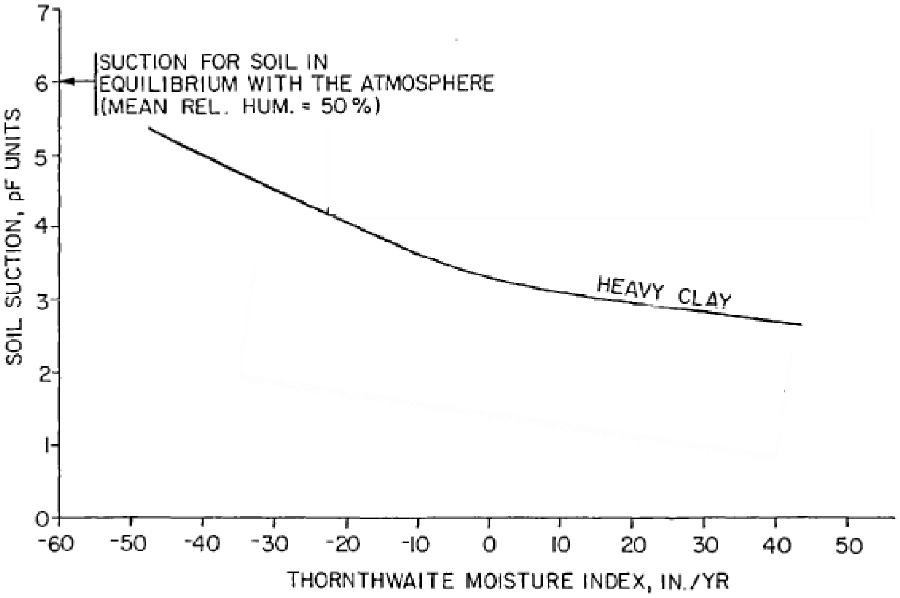


Figure 2: Soil suction vs. TMI (Russam & Coleman, 1961)

The Russam and Coleman relationship was determined from subgrade soils beneath payments. In the paper, it was not explicitly stated that these were measured at equilibrium conditions. It is also unclear as to the time period having been covered by pavement. However, it is believed, that over a significant time period, the soil beneath the slab will come into equilibrium (constant suction). Wray W.K. (1978) first proposed the Russam and Coleman relationship to be equilibrium suction and as such, modified the relationship. The results are later presented in The Post-Tensioning Institute 2nd Edition (1996) and is presented below in Figure 3.

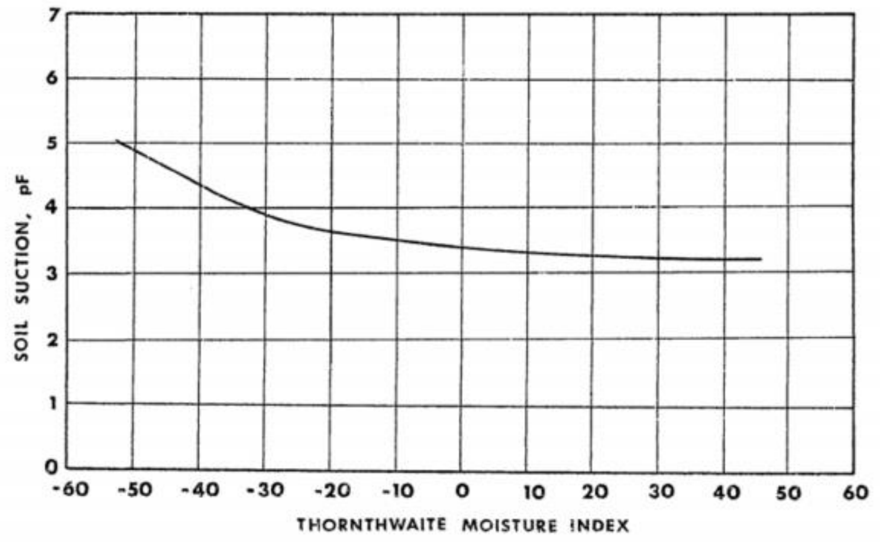


Figure 3: Variation of Constant Soil Suction with Thornthwaite Moisture Index (Modified from Russam and Coleman (1961) (The Post Tensioning Institute 2nd Edition, 1996)

The Post-Tensioning Institute (PTI, 2008) provides detailed procedures for designing slab-on-ground foundation systems on expansive soils and is widely used for residential foundations. VOLFLO is a PTI-developed program that allows user-specified input of initial and final (wet and dry) suction profiles to estimate the amount of soil heave and shrink based on PTI heave computation procedures. The equilibrium suction value is used to aid in the prediction of differential soil movements which affect the foundation systems (Bryant, 1998). The PTI method does not require the user to perform suction measurements, however, the user must select suction design envelopes (wet to dry). When suction measurements are not able to be performed, the equilibrium suction value is commonly estimated from the relationship provided in the PTI design manual, using a known TMI index. Figure 4 presents the equilibrium suction correlation from the Post-Tensioning Institute (2008).

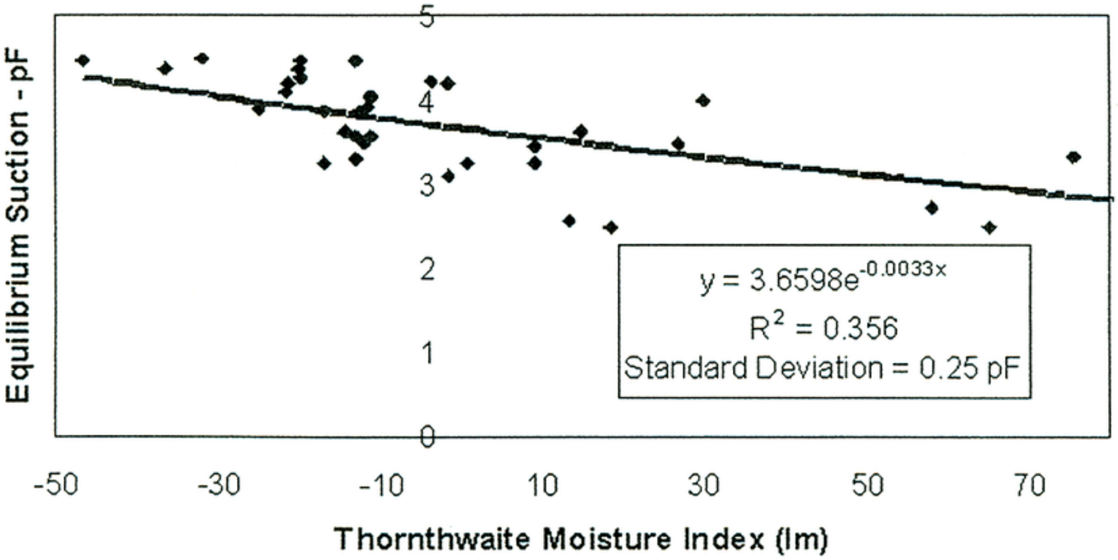


Figure 4: Equilibrium Suction vs. TMI (Post-Tensioning Institute 3rd Edition, 2008)

The Figure 4 correlation by the Post-Tensioning Institute is made on the assumption that the “equilibrium suction is independent of soil type and profile homogeneity” (Dye, Zapata, & Houston, 2006). Presented on the plot is the R^2 squared value for the correlation which is used as a statistical measure of how close the data points fall within the regression, and ranges from 0 to 1. A value of 0.356 shows there is not a strong correlation between equilibrium suction and TMI. The soil suction values were gathered from published literature and were used to determine an updated correlation with TMI. However, there are few correlations with equilibrium suction that exist, which is another reason more research and more field investigations with suction measurements to considerable depth are needed so that improved correlations can be made.

2.4 Methods to Measure Soil Suction

Historically, the soil suction in expansive soils has been shown to be a difficult parameter to measure due to costs and the time to reach equilibrium. However, advances in testing equipment have simplified the measurement of total soil suction in recent years (Toll, Lourenco, & Mendes, 2013) and (Mabirizi & Bulut, 2009). In this study, soil suction profiles which have been established by measuring soil suction with depth, and published data on direct suction measurements have been included. It is the goal to provide a comparison to suction profiles which have been created using suction values which have been determined by the suction surrogate. For suction profiles established from measured suctions, two measurement methods, to be discussed below, were used. These methods have been studied extensively and are: (1) the filter paper method, and (2) the WP4C Dew Point Potentiometer device.

The WP4C is a chilled mirror device that allows for the measurement of total suction and is shown in Figure 5. The device is simple to use and relatively quick to measure total soil suction on expansive clays (within 30 minutes from personal experience with measuring fat clays of high plasticity) while providing accurate suction results. The WP4C has the capability to measure total suction that ranges up to 300,000 kPa and has a lower limit of about 100 kPa. The device uses a chilled mirror dew point technique to measure suction (Meter Group, Inc., 2018). The soil sample is placed into a small stainless-steel container and is then placed into a sealed chamber. The chamber contains a mirror, fan, optical sensor, and infrared sensor. The measurement of total suction is "based on equilibrating the liquid phase of the water in a soil sample with the vapor phase of the water in the air space above the sample" (Bulut & Leong, 2008). A Peltier cooling device reduces the temperature of the mirror until dew forms and the optical sensor detects when the dew forms on the surface. The mirror contains a thermocouple which measures the dew point temperature and the infrared sensor measures the temperature inside the chamber. It is assumed that the temperature in the chamber is the same as the soil sample (Fredlund, Rahardjo, & Fredlund, 2012). Equilibration is complete when the water potential in the air in the headspace and the soil sample are the same.

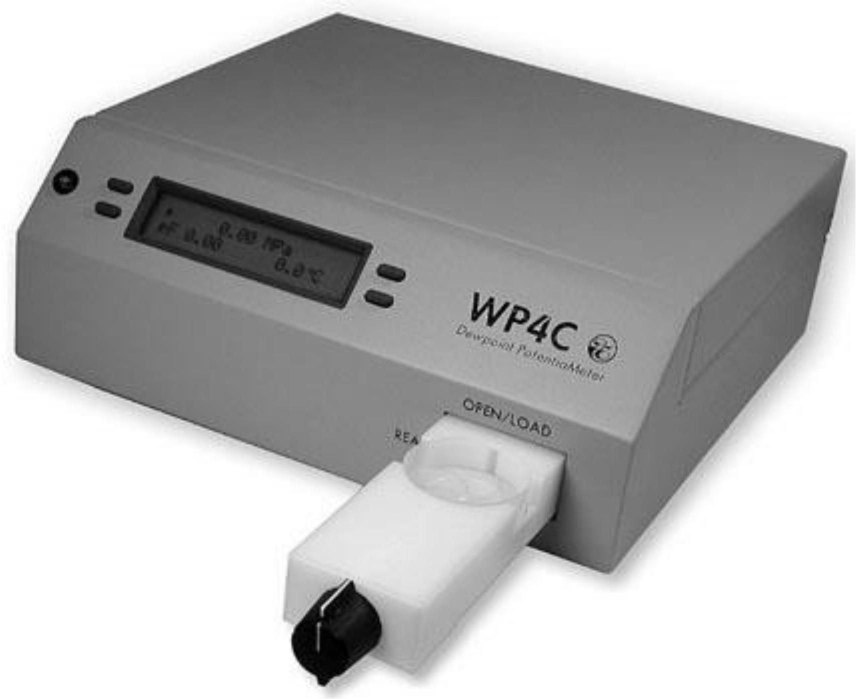


Figure 5: Meter Group Inc. WP4-C Device (Meter Group, Inc., 2018)

The total suction is computed using Kelvin’s equation which can be derived using the ideal gas law. The equation is presented below.

$$\psi = \frac{RT}{M} \cdot ln\left(\frac{p}{p_o}\right) \qquad (1)$$

where ψ is total suction, R is the gas constant (8.31 J/mol$\cdot K$), T is the sample temperature in Kelvin, M is the molecular mass of water, p is the vapor pressure in the chamber, and p_o

is the saturation vapor pressure of the sample (Meter Group, Inc., 2018). Both the temperatures of the dew point and the soil sample are used to determine the vapor pressure in the chamber and the saturation vapor pressure of the soil sample. Relative humidity of the air in the chamber is determined and Kelvin's equation is applied to determine the total suction of the soil sample. The use of the WP4 device has been accepted in part of an ASTM standard procedure, ASTM D6836-16.

The filter paper method to measure soil suction was originally developed in the soil science discipline and was used for agricultural purposes (Fredlund, Rahardjo, & Fredlund, 2012) and has since been adopted into an ASTM standard procedure, ASTM D5298. The filter paper method allows for the measurement of both total and matric suction. Two methods are available for soil suction measurement by the filter paper method, either the contact (matric) or noncontact (total) method. Filter paper is either placed in direct contact with the soil sample or a perforated disk is placed between the soil and the filter paper. The specimen and filter paper are placed into an airtight container at a constant temperature of 20˚ ± 1˚C for a minimum period of seven days to allow for the vapor pressure of pore-water in the specimen, vapor pressure of pore-water in the filter paper, and partial vapor pressure of water in the air to reach equilibrium with the filter paper (ASTM D5298, 2016). Although it is stated that the sample is to be placed into the container for seven days to reach equilibrium, it should be noted equilibration may require a longer amount of time and is dependent upon different factors including material type, type of test performed (contact or noncontact), initial relative humidity of the air, sample size, and the space in the container (Nelson, Chao, Overton, & Nelson, 2015). Marinho (1994) suggested equilibrium time as a function of suction, and for the full range of total suction measurements (0 to 30,000 kPa) an equilibration period of 30 days or greater may be necessary, for the contact filter paper method.

The filter paper method applies the water-absorptive characteristics of the filter paper calibrated through the use of salt solutions producing known relative humidity in the headspace above the solution in an enclosed container. The moisture in the headspace will be absorbed into the filter paper until equilibrium is reached, and this filter paper moisture versus relative humidity relationship is used to estimate total soil suction for the noncontact method (McKeen, 1981). The moisture content of the filter paper is directly related to the matric suction of the soil through relative humidity using Kelvin’s equation (Fredlund, Rahardjo, & Fredlund, 2012). If the filter paper is in contact with the soil, matric suction is measured, as it is assumed that any salts in the pore fluid move into the filter paper such that osmotic suction has no effect on the water content of the filter paper. Total suction is obtained when not in contact with the specimen.

Using the filter paper method, the suction value can be found in published calibration curves for the filter paper. Figure 6 presents the calibration curve suggested by McQueen and Miller (1968) and Figure 7 presents the calibration curve used in ASTM D5298.

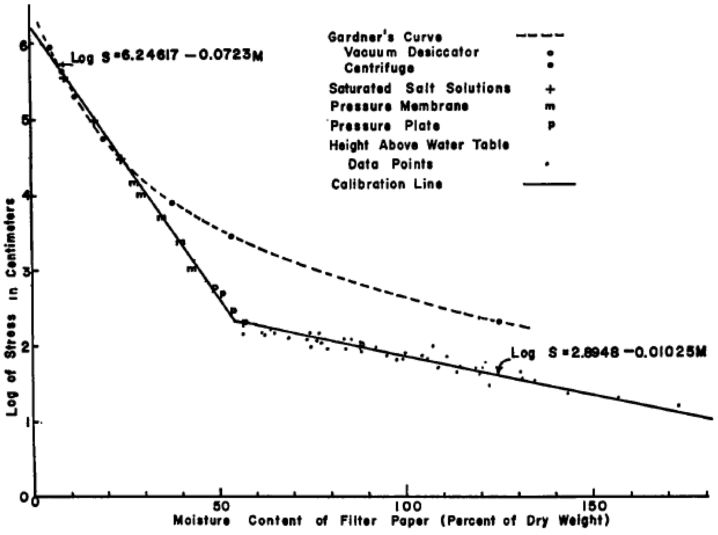


Figure 6: Moisture – Suction Calibration Curve of Schleicher and Schuell No. 589 Filter Paper (McQueen & Miller, 1968)

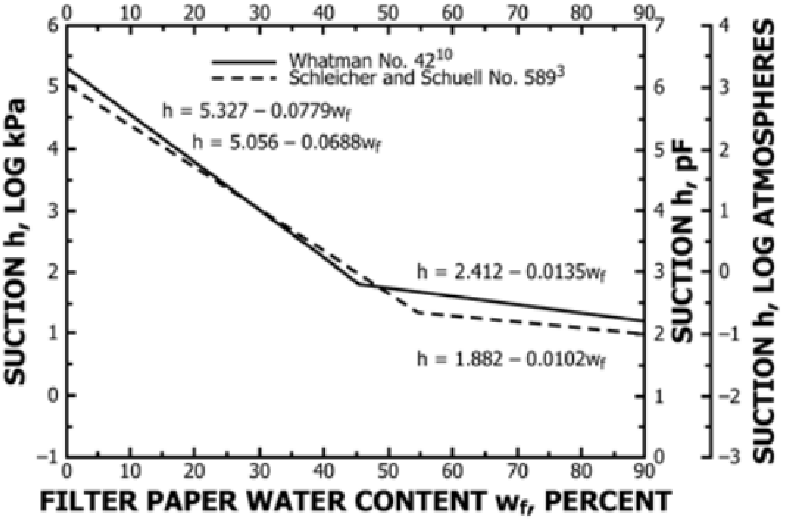


Figure 7: Calibration Suction-Water Content Curve of Filter Paper (ASTM D5298, 2016)

More studies have been conducted presenting filter paper suction calibrations curves, however, for this study, Figure 6and Figure 7 represent the calibration curves used for suction determination for the suction profiles presented herein.

2.5 Estimating Depth to Constant Suction Using TMI

The depth of design suction change or depth to constant suction is most commonly taken to be the depth at which there is no significant seasonal suction changes (i.e., non-irrigated, uncovered surface conditions) (Li & Zhou, 2017). Determination of this depth requires direct suction measurements, with depth, for the best result. However, there is little data in the literature, presenting field suction measurements with depth and the available data is also regionally specific (Sun, 2015). Previous studies have shown TMI to be a climatic index that correlates, at least to some extent, with the depth to constant suction under conditions of undeveloped, seasonal moisture fluctuations. The TMI has become a widely used and accepted climatic parameter in the geotechnical engineering discipline, particularly for expansive soil applications, and is used in the design of pavements and residential foundations. Changes in soil suction at the surface and below are affected by various climatic and environmental conditions, as well as the presence of any structures, irrigation, and the amount of time the structure has been present. Thus, 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 (AS-2870, 2011). Previous studies by Fityus et al. (1998) and Smith (1993) have presented direct correlations between the TMI and the depth of design moisture change (H_s).

Smith (1993) presented a correlation between TMI and the depth of moisture change (H_s) for three different regions in Australia. The correlation was created on the basis of field observation data (Fityus et al., 1998). Three data points were used and are presented in the table below.

Table 1: Relationship between TMI and Depth of Moisture Change (Smith, 1993)

Location	TMI	Depth of Moisture Change (m)
Brisbane	34	1.5
Melbourne	-1	2.0
Adelaide	-26	4.0

From the data presented in Smith's work, a relationship between the climate classifications (wet coastal to arid) and the depth of moisture change was proposed.

Table 2: Climate Classifications and Depth of Seasonal Moisture Change (Smith, 1993)

TMI	Climate Classification	Depth of Moisture Change (m)
>40	Wet Coastal/ Alpine	1.5
10 to 40	Wet Temperate	1.8
-5 to 10	Temperate	2.3
-25 to -5	Dry Temperate	3.0
-40 to -25	Semi-Arid	4.0
<-40	Arid	>4.0

Fityus et al. (1998) noted deficiencies in the way the above correlation is defined and noted that in a map of TMI contours there may be an abrupt change in the depth of moisture change (i.e. a TMI of -24 indicates a depth of moisture change of 3.0m while an adjacent site with a TMI of -26 will have a depth of moisture change of 4.0m). In the work performed by Fityus, a method is presented for the determination of the TMI index which is then used to estimate the depth of design moisture change in reactive clay in the Hunter Valley of Australia. The revised correlation allows for the depth of moisture change to be interpolated between TMI values to ensure continuous H_s values (Li & Zhou, 2017). Three sites with calculated TMI values and H_s values are presented in the table below.

Table 3: Relationship between TMI and Depth of Moisture Change (Fityus et al., 1998)

Location	TMI	Depth of Moisture Change (m)
Nelson Bay	53.7	1.5
Maryville	24.4	1.7
Scone	-25.4, -24.3	3

The revised correlation with climate classifications is presented in Table 4 (Fityus, et al., 1998).

Table 4: Climate Classifications and Depth of Moisture Change (Fityus et al., 1998)

TMI	Climate Classification	Depth of Moisture Change (m)
>40	Wet Coastal/ Alpine	1.5
10 to 40	Wet Temperate	1.8 to 1.5
-5 to 10	Temperate	2.3 to 1.8
-25 to -5	Dry Temperate	3.0 to 2.3
<-25	Semi-Arid	4.0

2.6 Field Suction Profiles found in literature

Previous studies have been published in the literature where field soil suction profiles have been investigated. In particular, equilibrium suction values and depth to constant suction have been studied, with past emphasis on climatic boundary conditions (seasonal fluctuations). Findings from this current study, based primarily on the application of a soil suction surrogate to estimate field conditions, will be compared to published results in the literature. Proposed correlations with TMI will be presented herein with results from the applications of a soil suction surrogate to estimate suction from routinely measured soil properties in the field. There is a limited amount of data found in the literature and part of this study on expansive soils, is to expand the database in the literature of field soil suction profiles for expansive soils.

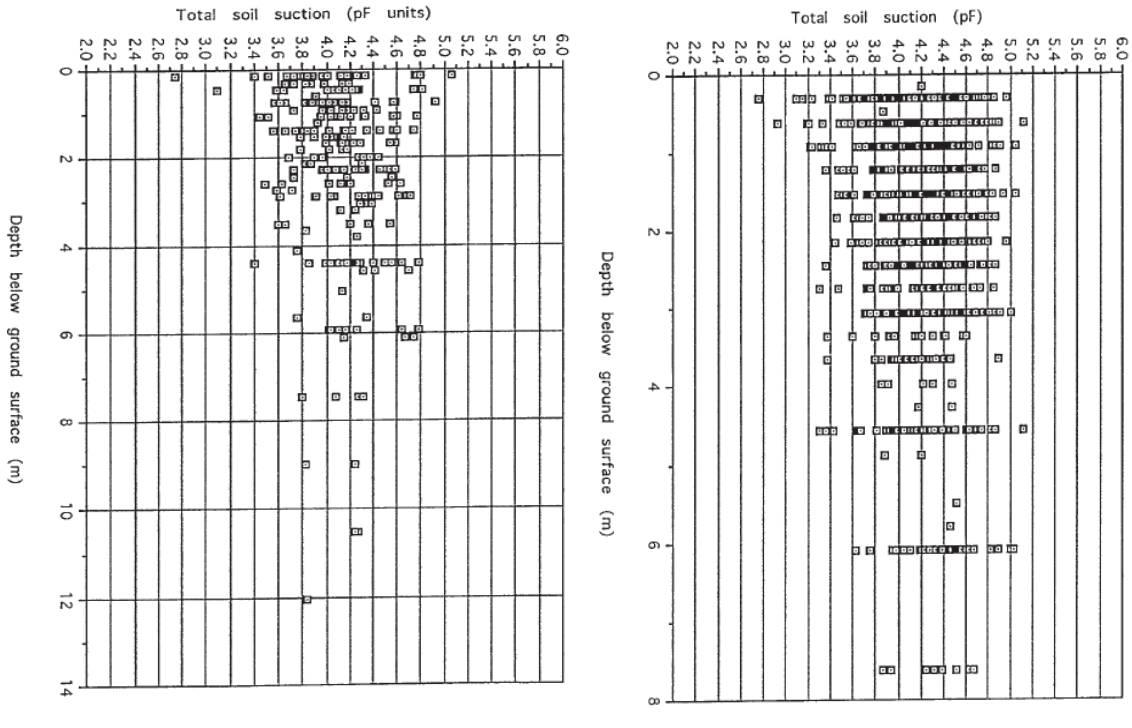
Bryant (1998) investigates the variation of soil suction with depth in the Dallas and Fort Worth, TX area to estimate the equilibrium suction and depth. Bryant presents a comparison with measured equilibrium suction values to empirical curves correlating equilibrium suction with a given TMI index which have been published in the literature. Suction profiles may be used to obtain equilibrium suction and depth to constant suction to aid in the design of vertical moisture barriers for pavement structures and foundations (Bryant, 1998), and as previously stated, to estimate heave which influence shear, deflection, and moments in the slab-on-grade foundations (Post-Tensioning Institute 3rd Edition, 2008). Equilibrium suction values are correlated to the Thornthwaite moisture index (TMI), as presented in the 3rd Edition Post-Tensioning Institute Manual for design of post-tensioned slabs on expansive soils (Post-Tensioning Institute 3rd Edition, 2008) and Russam and Coleman (1961).

In the Bryan study, over 1,200 soil samples were taken to substantial depth from both undeveloped and developed areas between the years of 1995 to 1997. Undisturbed soil samples were extracted using 76-mm diameter tube samples extending to depths ranging from 0.3m to greater than 12m below the surface. Total suction (noncontact) measurements were performed on the undisturbed samples using the filter paper method (ASTM D5298, 2016), and also were allowed for an equilibration period of approximately seven days, where Bryant noted the following deviations from the typical filter paper procedure.

- Whatman No. 42 ashless 55-mm filter paper was used. No special pretreatment of the filter paper was applied.

- A 348-mL polyethylene specimen container was used instead of a metal or glass container. The container had a clamp seal.
- Two wraps of electrical tape, approximately 6-mm wide, were used instead of the flexible plastic electrical tape to further seal the outside lid-container connection.
- Rubber O-rings were used instead of a screen wire of brass discs to separate the filter papers during equilibrium.

Figures 8 and 9 present the results of the study showing the variation of soil suction (units in pF) with depth (m) for the Dallas-Fort Worth area from two different regions within the Dallas-Fort Worth metropolitan area.



(a) (b)

Figure 8: Total Suction Profiles for the Dallas-Fort Worth area in a) 1995 b) 1996 (Bryant, 1998)

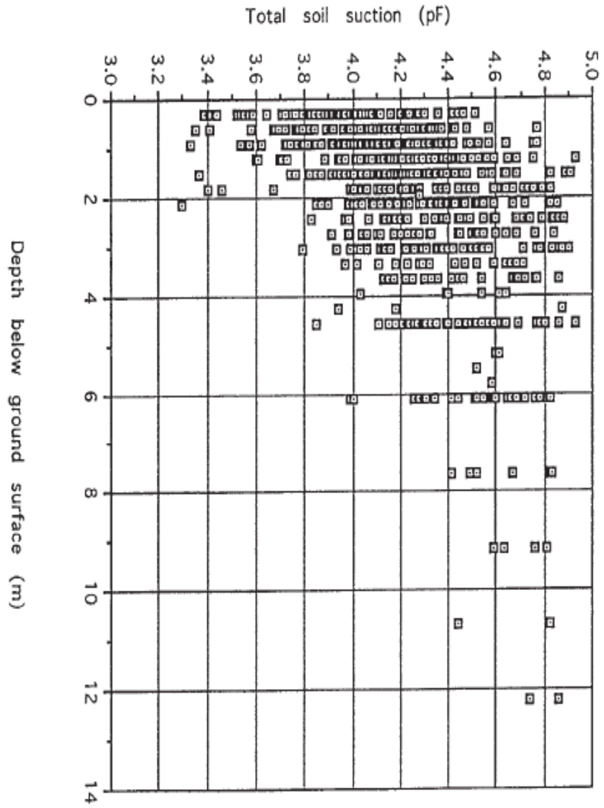


Figure 9: Total Suction Profile for the Dallas-Fort Worth area in 1997 (Bryant, 1998)

It was determined from the data of Figure 8 that an average value of soil suction for the DFW area was 979 kPa (approximately 4.0 pF) and this was taken to be the suction at depth (equilibrium suction). Table 5 below presents the statistical data from the results for each year presented in the study. As seen in the suction profiles, there are a wide range of suction values. The soil samples were taken from undeveloped and developed areas which provide pre-construction and post-construction suction estimations for development of a design suction envelope. Figure 9, also by Bryant (1998), presents much higher suction values, on average, compared to the profiles in 1995 and 1996 (Figure 8). Bryant notes this difference postulates that it may be due to the variability of geology from region to region within the DFW area, which lies within the Upper and Lower Cretaceous sedimentary rock and Quaternary alluvial deposits. Some regions of Dallas-Fort Worth have relatively shallow rock and intermediate geo-materials. The impact of the rock to intermediate material at shallower depth affects the suction measurements (and also possibly the suction values) and the suction values increase due to the internal fabric, lower moisture content, and composition associated with very low conductivity material (Bryant, 1998).

Table 5: Statistical Data from Suction Measurements in the DFW area (Bryant, 1998)

Year	**1995**	**1996**	**1997**
Average	4.1384	4.1675	4.2482
Median	4.15	4.18	4.26
Count	252	308	665
Minimum	2.75	2.76	3.30
Maximum	5.06	4.82	4.93
Range	2.313	2.06	1.63
Std. Deviation	0.3303	0.3606	0.3233

From 1995 to 1997 the range in suction at the ground surface decreased from 2.313 pF to 1.63 pF, which corresponds to an above average amount of annual precipitation in 1997 (Bryant, 1998).

Wray (1989) conducted a field study on shrink/swell characteristics in expansive soils both in a dry climate and a wet climate. Such profiles of suction are needed for slab-on-ground foundation system design. In part of the Wray study, field measurements were conducted on samples collected from different seasons. Changes in soil moisture content were measured in different seasons and soil suction measurements were also conducted. Amarillo, TX and College Station, TX were selected as the location’s representative of dry and wet climates, respectively.

The site soils of Amarillo consisted of silty clay (CL) in the upper 3.0 feet with an average PI of approximately 15. Below a depth of 3.0 feet the profile consisted of stiff, silty clay (CH) and sand clay (CH) soils with an average PI of approximately 42. No groundwater was encountered during the site investigation to a depth of 25 ft. Soil suction measurements were performed on soil samples at every foot extending to a depth of 9.0 feet. Soil suction was measured using the McQueen and Miller (1968) filter paper method. The surface was uncovered at the time of the investigation and soil samples were taken just prior to construction beginning at the site. Following construction, soil suction measurements were taken monthly for 13 months from a location beneath a concrete slab. A thermocouple psychrometer was used to obtain the post-construction suction measurements.

In the Wray (1989) study, soil suction measurements at the ground surface ranged from 5.0 to 5.47 pF, which is considerably dry for a clay soil. At a depth of 9.0 feet, suction values ranged from 4.11 to 4.60 pF, which is also quite dry. Figure 10 presents the field suction profile for Amarillo. Climatic data were also obtained from the National Climatic Data Center, Ashville, NC, in order to determine the associated TMI index. Data was obtained for a 44-year period (1941-1984) and was calculated annually using only 1-year of data (note that TMI is most commonly computed using 30-year average climatic data). A TMI of 2.5 was determined for the wettest year and -41.8 for the driest year experienced within that period. A TMI of -21.3 was determined to be the historical mean for Amarillo using 44 years of climate data. The details of the computation of TMI are provided by Wray (1989). To determine the equilibrium suction and depth to constant suction, a best fit line was plotted and extrapolated to a vertical slope. Interpretation of the field suction profile indicated an equilibrium suction of about 4.1 pF and a depth to constant suction of approximately 12 to 13 feet. An equilibrium suction of 4.1 with the 44-year TMI of -21.3 corresponds well with the correlation established by Russam and Coleman (1961) but is underpredicted by the Post-Tensioning Institute (2008).

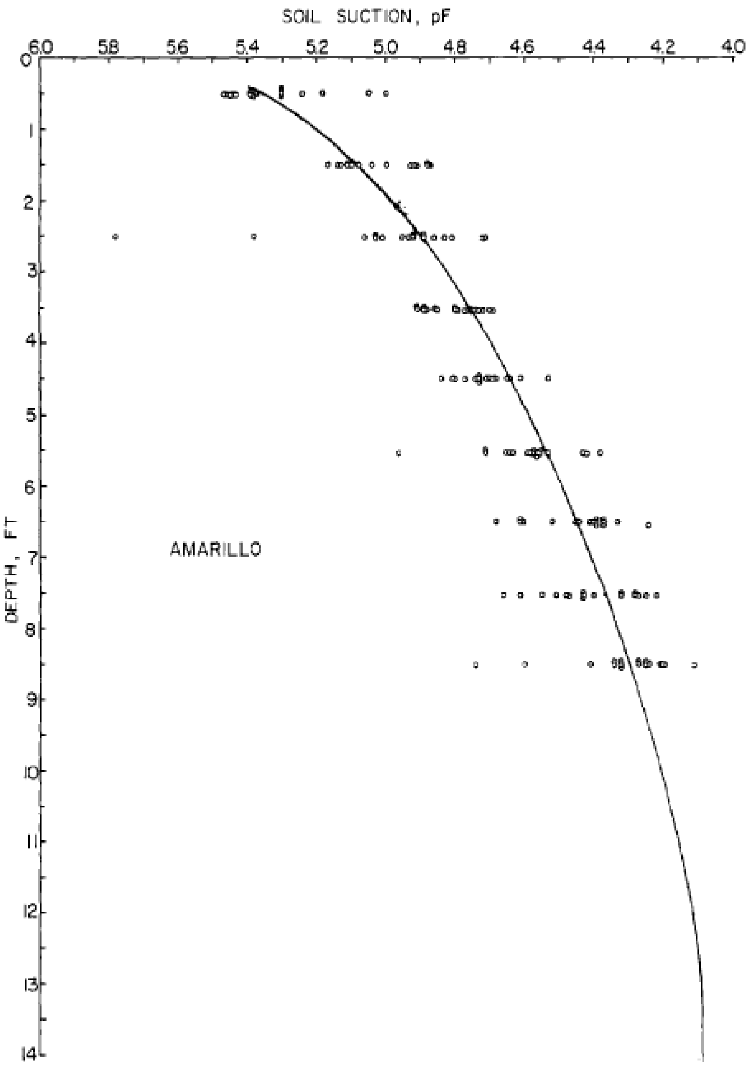


Figure 10: Soil Suction Profile for Amarillo (Wray W. K., 1989)

The subsurface soils at the site in College Station consisted of silty fill material mixed with gravel extending to a depth of 2.0 feet overlying a medium stiff silty clay (CL) extending to a depth of 7.0 feet and silty clay (CH) soils below. No groundwater was encountered during the site investigation to a depth of 25 feet. The upper 2 feet had an average PI of approximately 15 and the soils below a depth of 2 feet had an average PI of approximately 28. Soil samples were taken at every foot extending to 9.0 feet and moisture contents and soils suction measurements were performed. The McQueen and Miller (1968) filter paper method was used to determine soil suction values. Weather data was obtained from the Texas A&M weather station for a 73-year period (1911-1984) to determine the associated TMI index. TMI indices were calculated annually and a value of 37.3 was found for the wettest year and a TMI of -37.4 was determined for the driest year. An average TMI index of 0.1 was determined for College Station. The field suction profile for College Station is shown in Figure 11. A best fit line was plotted for the entire data set and extrapolated to a vertical slope. Interpretation of the suction profile shows an equilibrium suction value of approximately 4.3 pF with a depth to constant suction of approximately 4.0 feet. Russam and Coleman (1961) under predicts the equilibrium suction value with approximately 3.4 pF. Wray noted the difference can be attributed to trees located adjacent to the site, which could affect evapotranspiration rates and also the unusually dry period in the 12 months prior to the site investigation. For those 12 months prior, there was an associated TMI index of -14.6, which suggests an equilibrium suction value of approximately 3.8 pF by Russam and Coleman and Post-Tensioning Institute (2008).

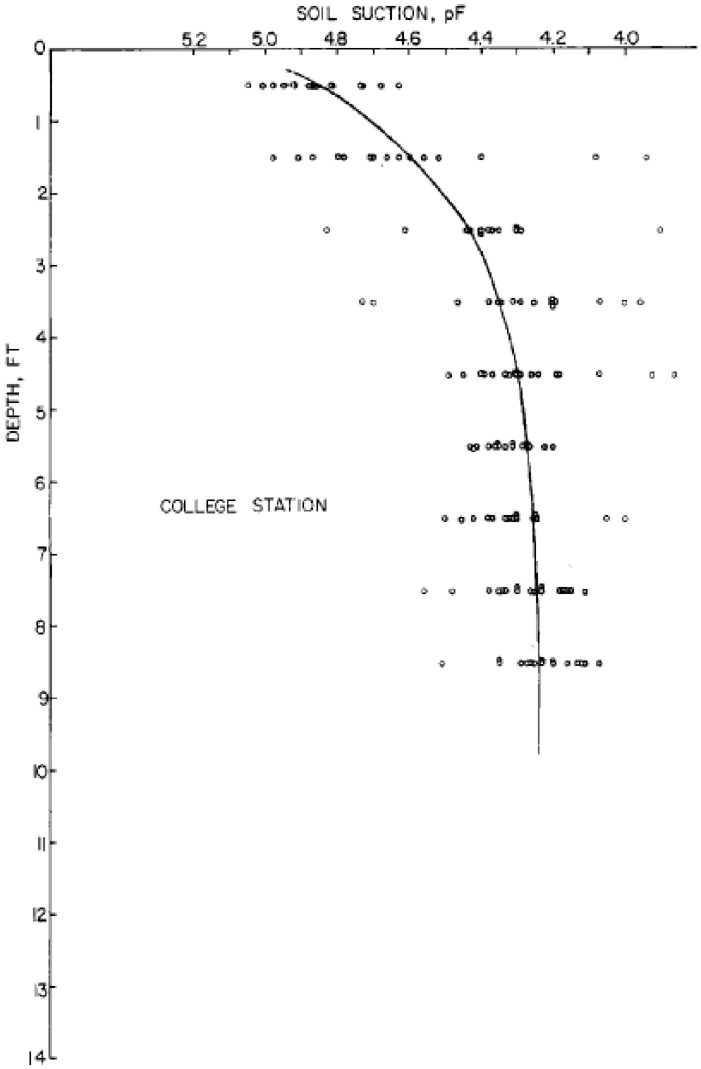


Figure 11: Soil Suction Profile for College Station (Wray W. K., 1989)

More recently, Vann (in progress), as part of continuing research on expansive soils, research sites have been drilled where natural clay soils in the profile exist with depth. Test borings extend to depths of 30 feet with soil samples at every one-foot interval taken for laboratory testing. The laboratory testing included Atterberg Limits, sieve analysis, moisture content, and total soil suction measurements using the WP4C chilled mirror device. Using the suction measurements with depth, soil suction profiles were created.

The sites which have been included in this study are Phoenix, AZ, San Antonio, TX, and Denver, CO. From the measured suction profiles, the equilibrium suction values and depths to constant suction were visually determined and are compared with the findings herein. Sites included both uncovered or covered and non-irrigated or irrigated site conditions.

3.0 APPROACH AND DATA USED IN THIS STUDY

3.1 Data Mining Effort

Before suction profiles were generated, a great effort went into data mining. Approximately 400 geotechnical reports were made available for this project on expansive soils by various geotechnical firms, agencies, and a large retail chain. Geotechnical reports were provided from the Alabama, Arizona, Colorado, Mississippi, Oklahoma, and Texas regions in the United States. Geotechnical reports were reviewed, and an EXCEL database was created as the data mining proceeded containing each site reviewed. The EXCEL database contains the soil profile data collected, including Atterberg limits, depth to groundwater table, water content, and other data relevant to the current study. The use of an EXCEL database allows for the ability to search by certain user-specified criteria. Furthermore, only natural clay deposits, extending to considerable depth, were included in the database. After the completion of the data mining effort, the sites were sorted into two main categories, covered and uncovered; subsequently, a further subdivision of irrigated and non-irrigated was applied to the uncovered sites.

Information pertaining to the type of project, date drilled, covered or uncovered conditions, groundwater table position, geology, and location were all collected and input into the database. A great deal of the data mining effort went into the test boring data, laboratory testing, and identification of locations where the borings conducted were uncovered or covered by asphalt or pavement. Boring logs were compiled to generate a general soil profile for that specific site consisting of natural clay soils. Data was collected with depth and included the following.

- USCS Soil Classification
- Atterberg Limits (LL, PL, PI)
- Moisture Contents
- Wet and Dry Densities
- Swell Potential
- N values from SPT blow counts
- Grain-size distribution
- Proctor data (Optimum moisture content and maximum dry density)

It is important to note that collection of the above data was contingent upon availability in the investigation reports that were provided. It was found that, although these were often fairly large projects with test borings often extending to depths of 20 to 30 feet, soil samples for laboratory testing for index parameters, were not frequently taken at depths below 10 feet, which made it difficult to apply the soil suction surrogate to estimate field suction profiles. Moisture content data, however, were common below depths of 10 feet, and most commonly at intervals of 5 feet. Although the data mentioned above were collected, the most important information needed for estimation of field suction profiles were moisture content and Atterberg Limits, with depth, as these data have been correlated to total soil suction, providing to the soil suction surrogate used in this study (Vann, et al., 2018).

3.2 Thornthwaite Moisture Index Map

To apply the soil suction surrogate to estimate profiles, a value of TMI must be determined for the given site. An interactive TMI map using Arc GIS was used to obtain a value (Olaiz, Singhar, Vann, & Houston, 2018). TMI is a climatic parameter that is widely used and accepted in the geotechnical engineering practice (Fityus & Buzzi, On The Use of The Thornthwaite Moisture Index to Infer Depths of Seasonal Moisture Change, 2008) to determine such values of depth to constant suction and equilibrium suction values.

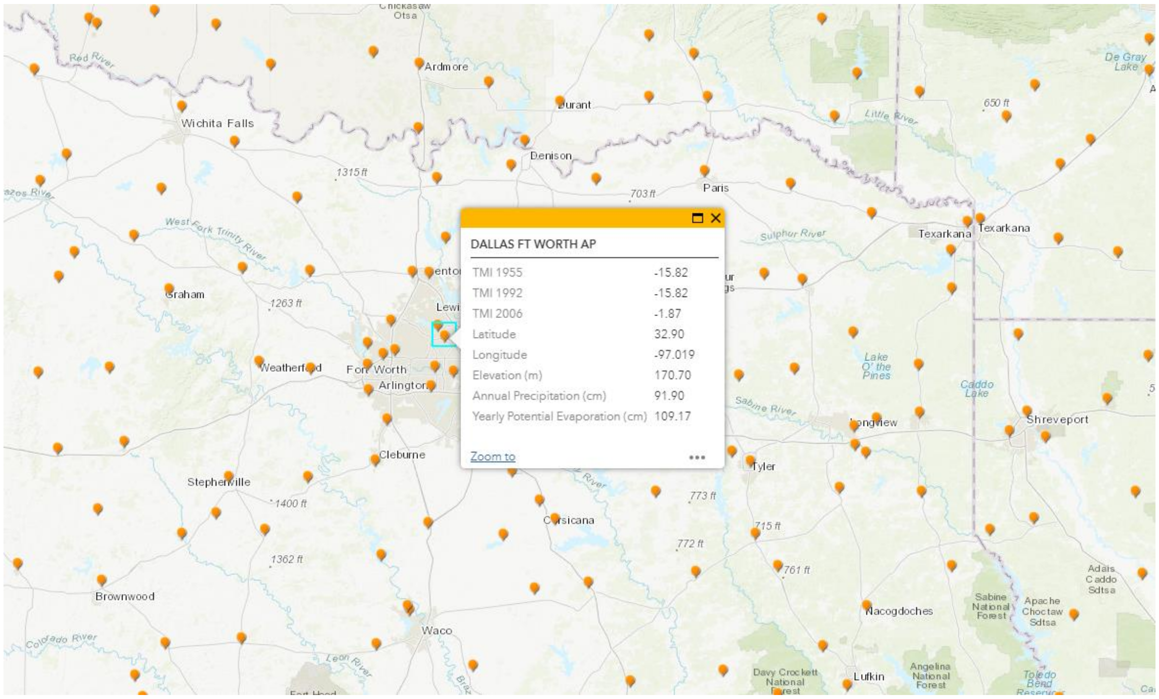
TMI is an empirical value originally developed in 1948 by C.W. Thornthwaite using limited climate data. TMI provides a measure of relative wetness or dryness for a specific region (Olaiz, Singhar, Vann, & Houston, 2018). The original equation (Thornthwaite, 1948) was given in terms of an aridity index (I_a) and humidity index (I_h) and is represented by the following equation.

$$TMI = I_h - 0.6I_a \tag{1}$$

The terms I_a and I_h require climatic data including potential evapotranspiration (PE), which is the potential for evaporation, moisture deficit or quantity of moisture that cannot evaporate from an already dry site, run off or excess amount of moisture that cannot permeate into an already wet site. Since the originally TMI equation, there have been studies to simplify the equation. Following the original work presented by C.W. Thornthwaite, revised TMI equations were presented in the work of Thornthwaite and Mather (1955), Willmott and Feddema (1992), and Witzack et al. (2006).

Olaiz, Singhar, Vann, and Houston (2017) gathered weather data from the National Oceanic and Atmospheric Administration (NOAA) over a period of 1981 to 2010 from

5852 weather stations across the United States. TMI values were calculated using the revised equations from 1955, 1992, and 2006 and an ArcGIS web-based map was created. The map allows the user to click on a given weather station and the 1955, 1992, and 2006 TMI values will be presented along with the latitude, longitude, elevation (m), annual precipitation (cm) and yearly potential evaporation (cm). Shown below is an image from the TMI map with data from a weather station.



DALLAS FT WORTH AP	
TMI 1955	-15.82
TMI 1992	-15.82
TMI 2006	-1.87
Latitude	32.90
Longitude	-97.019
Elevation (m)	170.70
Annual Precipitation (cm)	91.90
Yearly Potential Evaporation (cm)	109.17

Figure 12: Interactive ArcGIS TMI map (Olaiz, Singhar, Vann, & Houston, 2018)

3.3 Soil Suction Surrogate to Estimate Soil Suction

To estimate field suction profiles when the geotechnical engineer is not able to take direct suction measurements in the field, or to use existing geotechnical investigation data, a soil suction surrogate may be used (Vann, et al., 2018). An essential part of this larger study on expansive soils was to develop a soil suction surrogate to be able to provide the practicing geotechnical engineer a means of estimating suction to closely resemble the suction values in the field.

The proposed suction surrogate is a function of moisture content, liquid limit, and the TMI value associated with the site. Measured soil profile data were used to develop a surrogate. Soil samples were taken at every foot extending to depths of 30.0 feet and taken to the laboratory for soil classification testing, to include sieve analysis, moisture content, and Atterberg limits. Soil suction measurements were also taken performed by the WP4-C. A total of 476 soils samples from Denver, Colorado, Hobart, Oklahoma, Phoenix, Arizona, and San Antonio, Texas were used in the development of the suction surrogate. The resulting soil suction surrogate is represented by 3 depth dependent equations shown below:

$$\psi_I = a\left(\frac{w}{LL}\right)^b \quad ; \quad z \leq 3.66m\ (12ft) \tag{1}$$

$$\psi_{II} = \psi_I + \left(\frac{z - 3.66}{5.79}\right)(\psi_{III} - \psi_I) \quad ; \quad 3.66m\ (12ft) \leq z \quad \leq 5.79m\ (19ft) \tag{2}$$

$$\psi_{III} = c\left(\frac{w}{LL}\right)^d + eTMI \quad z \geq 5.79m\ (19ft) \tag{3}$$

where: ψ = Total Suction (pF); w = Moisture Content; LL = Liquid Limit (%); a = 3.0524; b = -0.2663; c = 3.3655; d = -0.2006; e = 0.0068; z = depth in feet. A more detailed description of work that went into the development of the suction surrogate is presented by Vann (Vann J. , in progress). In this current work, the suction surrogate (Vann, et al., 2018) is used to estimate soil suction profiles from existing geotechnical engineering reports.

4.0 ESTIMATING FIELD SUCTION PROFILES FROM FIELD INVESTIGATIONS

The compiled database of the sites used in this study were divided into two main categories considering the surface boundary conditions; covered and uncovered. They were further divided into categories of non-irrigated and irrigated conditions to the best of the author's ability through interpretation of historical aerial photography from Google Earth. The aerial photography analysed were at the time of, or around the time (5-year prior period) of the dated field investigation from the geotechnical investigation report. The uncovered sites were evaluated for being irrigated or non-irrigated; although aerial photographs were observed for the covered sites as well and an insufficient number of covered sites were available for meaningful interpretation of effects of irrigation. For a majority of the uncovered sites, surface soil conditions were determined to be non-irrigated. Where the existence of natural vegetation or bare soil (unimproved) lots were encountered within 5 years prior to development, the assumption was made that the site was non-irrigated. If the proposed site was clearly used for agricultural purposes or was residential with landscaping, the site was considered to be irrigated.

For post construction conditions, where the soil is covered, or if there is irrigation, the changed moisture flux conditions at the ground surface may have an effect on the depth of wetting (depth to constant suction), compared to bare, undeveloped surface conditions. In the case of construction of a slab on the surface the "rate of evaporation and evapotranspiration are reduced significantly" (Durkee, 2000). Durkee (2000) and other researchers have postulated that the soils moisture increases beneath covered areas, and the impact of surface cover on moisture (suction) profiles is a part of this study. As part of this study, comparisons between uncovered and covered conditions were made where data was available to determine a depth of wetting (depth to constant suction). Comparisons between non-irrigated and irrigated sites were also made to the extent possible.

The available data for a given site was exported from the database and individual tables were created in EXCEL with the site number, moisture contents, soil index properties, and the depth to groundwater table if noted in the geotechnical investigation report. TMI values (2006) were determined using the ArcGIS web-based map by searching the location of the site and using the nearest weather station to obtain the TMI value. Using the suction surrogate, field suction values were calculated to generate a field suction profile with depth.

Although hundreds of geotechnical engineering reports were reviewed, only sites where there were available data for the use of the suction surrogate equations and over a depth adequate for determination of depth to equilibrium soil suction, and for soil profiles consisting of natural clay soils with a PI greater than 15, were used for this study. Other limiting conditions were considered when choosing sites that were applicable to the study. Sites with shallow groundwater tables and sites which consisted of shallow limestone or shallow unweathered claystone were not used for this study.

While many geotechnical reports were gathered and reviewed, numerous investigations did not have soil samples taken for Atterberg limit testing below depths of 10 to 15 feet. There were generally moisture contents taken to full depth of boring, at intervals of about every 5 feet below a depth of 10 feet, but other data required for surrogate determination were often unavailable. In some cases, an average Liquid Limit was determined based on measured index properties in the shallower depths and where soil characteristics were judged to be fairly consistent throughout the profile. Boring logs were reviewed for such sites to establish if there was any substantial change in material type. If there was no substantial change, the average liquid limit from shallower depths was used to obtain a suction value, using the suction surrogate, so long as there was an associated moisture content recorded on the boring log to depths of interest. In other cases where only moisture data was available and no Atterberg limit testing was performed at a specific depth, recorded soil property data within ±5 feet was used to determine the soil suction surrogate, provided relative consistency, in soil type indicated on the boring logs (i.e. no substantial change in material type according to visual USCS classifications).

Using the soil suction surrogate equations (Section 3.3), suction values were calculated, and field suction profiles were created for each available site using EXCEL software. The soil profile for each site was divided into 0.762-meter (2.5 feet) layers (intervals of 0-0.762, 0.762-1.524, and 1.524-2.286 meters, etc. (0-2.5, 2.5-5, and 5-7.5 feet) and the average moisture content, depth, and liquid limit were calculated within a given 0.762-meter layer. These values were then applied in the suction surrogate equations to obtain an average soil suction for the given depth interval. If a data point fell directly on a line (i.e. 0.762 meter) the data point was included in the layer above (0-0.762 meter) as well as in the layer below (0.762-1.524 meter). A smooth curve was drawn through the soil suction values using EXCEL, emphasizing on the average suction values to create the smooth curve. The differences of the average soil suction values between each depth were calculated and are included in a table which is presented on the field suction profiles. The differences were calculated to aid in the determination of the equilibrium suction magnitude and the depth to constant suction.

For each site where soil suction profiles were generated, the associated moisture profile was also created, and the averages of soil water content were also plotted and displayed alongside the suction surrogate profiles (Appendix A). A text box was also added to both the field suction profile and the moisture content profile which displays the following information: 1) average LL; 2) TMI value; 3) groundwater table depth if available; 4) date the test borings were drilled; and 5) the coordinates associated with the project site. The soil suction is plotted in units of pF with depth in meters. Figure 13 presents an example field suction profile, which is for McAllen, TX.

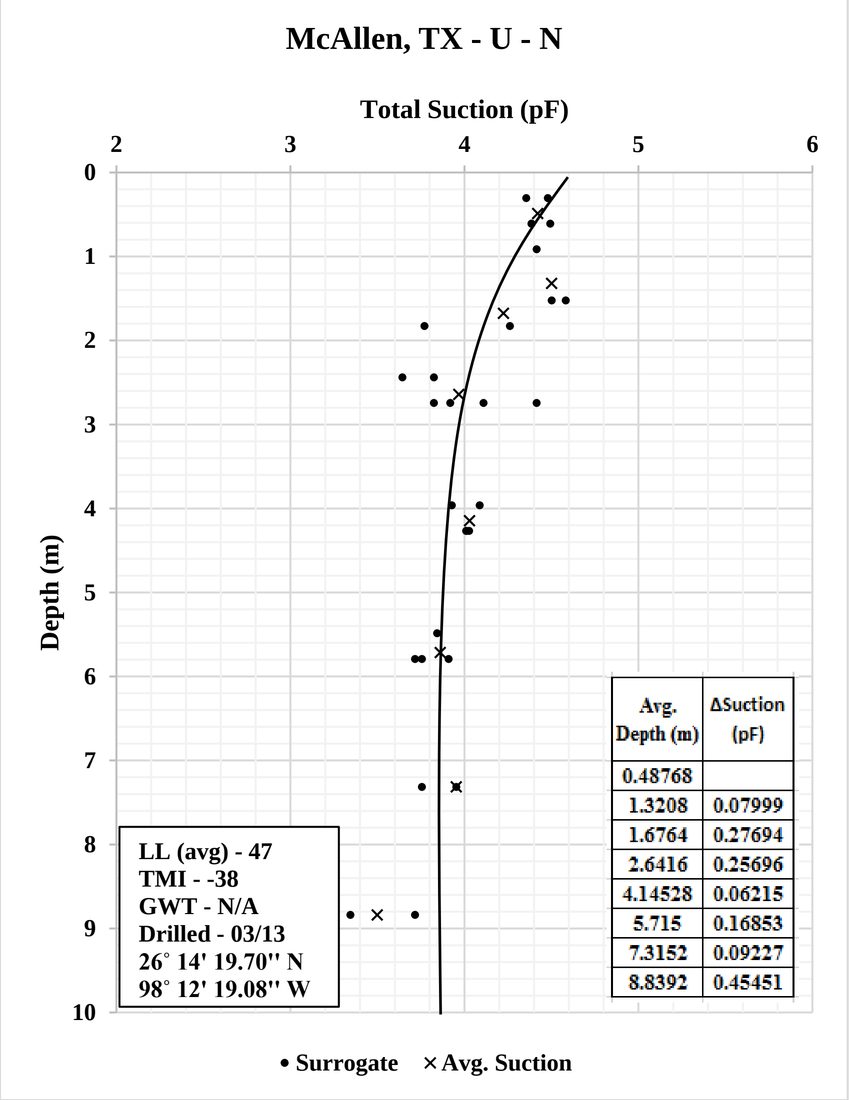


Figure 13: Field Suction Profile for McAllen, TX

The dataset which was included in this study are displayed in Appendix A and presented in Table 11 with the locations and their associated TMI values, average LL for the soil profile, depth to constant suction in meters and feet, and the equilibrium suction magnitudes that were determined from the estimated field suction profiles. Suction profiles are also presented in the appendices. There were some uncovered and non-irrigated sites, where a depth to constant suction was not able to be determined from the field suction profile, although magnitudes of equilibrium suction were established and used for correlations presented herein. Those specific sites where only equilibrium suction values were obtained are noted in Table 11. Shown below in Table 6 are the locations, TMI values, depths to constant suctions, and equilibrium suction magnitudes where suction profiles were directly measured using the WP4-C device, rather than determined from using the soil suction surrogate. These directly measured-suction sites included geotechnical projects provided by Vann Engineering Inc. and sites that are part of on-going research on expansive soils (Vann J. , in progress). For a few sites where suction was directly measured, the depths to constant suction were not able to be determined from the suction profiles.

Table 6: Measured WP4C Suction Data with Depth

Reference	**Location**	**Covered/ Uncovered**	**TMI (2006)**	**Depth to Constant Suction (m)**	**Equilibrium Suction (pF)**
Vann, 2018, in progress	Mesa, AZ	Uncovered	-52	3.048	4.50
Vann, 2018, in progress	Denver, CO	Uncovered	-24	4.572	4.40
Vann, 2018, in progress	Denver, CO	Uncovered	-24	4.572	4.28
Vann, 2018, in progress	Phoenix, AZ	Uncovered	-56	3.3528	4.00
Vann, 2018, in progress	Young, AZ	Uncovered	-6	1.8288	4.40
Vann, 2018, in progress	Young, AZ	Uncovered	-6	1.2192	4.80
Vann Engineering, Inc.	Phoenix, AZ	Uncovered	-56	-	5.20
Vann Engineering, Inc.	Chandler, AZ	Uncovered	-51	-	4.20
Vann Engineering, Inc.	Gilbert, AZ	Uncovered	-51	2.1336	4.50
Vann Engineering, Inc.	Gilbert, AZ	Uncovered	-51	2.1336	4.30
Vann Engineering, Inc.	Gilbert, AZ	Uncovered	-52	3.3528	4.60

Reference	Location	Covered/ Uncovered	TMI (2006)	Depth to Constant Suction (m)	Equilibrium Suction (pF)
Vann, 2018, in progress	San Antonio, TX	Covered	-16	-	3.90
Vann, 2018, in progress	San Antonio, TX	Covered	-16	-	3.82
Vann, 2018, in progress	Mesa	Covered	-52	-	4.00
Vann, 2018, in progress	Phoenix, AZ	Covered	-56	-	4.00
Vann, 2018, in progress	Denver, CO	Covered	-24	-	4.15
Vann Engineering Inc.	Phoenix, AZ	Covered	-56	-	3.90
Vann Engineering Inc.	Gilbert, AZ	Covered	-51	-	4.30

4.1 Approach to Estimate Equilibrium Suction

As part of this current study, equilibrium suction values were determined from estimated field suction profiles and a relationship with TMI is to be explored and compared to studies presented in the literature (Bryant (1998), Russam and Coleman (1961), McKeen (1981), Post-Tensioning Institute (2008), and Wray (1989)). The term equilibrium suction refers to the more or less constant soil suction at depth that develops within a profile in regions of relatively deep groundwater table. The equilibrium suction is believed to be largely controlled by surface flux moisture conditions, as discussed in the literature review section of this thesis. To aid in the determination of the equilibrium suction magnitude, the differences in computed soil suction were calculated between each depth and the smooth fitted curve to average soil suction values; the depth where the suction profile became near vertical, with little significant change in soil suction, was used to determine equilibrium suction values. Profiles were generated where sites had the most available data with depth, and these profiles were used to determine an equilibrium suction magnitude for a given site. For both uncovered and covered sites, equilibrium suction magnitudes were obtained from the estimated field suction profile. The fitted smooth curves of average soil suction were near vertical where it was determined to have reached equilibrium. This depth was determined to be where the average suction values varied less than 0.2 pF, as has been suggested by Lytton (1997), assumed to be where there is no longer a significant change in suction at the at the active zone depth.

Tables 7 and 8 contain the equilibrium suction data for the uncovered and covered sites used in this study which applied the soil suction surrogate. A plot of equilibrium suction vs. TMI, for uncovered sites only, was generated in the attempt to find a correlation and to compare to existing literature correlations. Equilibrium suction values which were obtained for covered sites, were not used in the development of the relationship. Although the sites were covered for a period of at least 5-years prior, verified through interpretation of aerial photography, it cannot be confirmed that the soil profile has reached equilibrium conditions. Therefore, uncovered equilibrium suction values obtained from the suction surrogate and measured equilibrium suction values, from Vann, in progress and Vann Engineering Inc., were used to develop a relationship. The measured suction values are presented in Table 6.

Table 7: Uncovered Data for Equilibrium Suction vs. TMI Relationship

Location	Uncovered/Covered	TMI (2006)	Equilibrium Suction (pF)
Killeen, TX	Uncovered	-5	3.80
Breckenridge, TX	Uncovered	-10	4.25
Snyder, TX	Uncovered	-19	4.00
Fort Worth, TX	Uncovered	3	4.20
Vidor, TX	Uncovered	34	3.80
San Antonio, TX	Uncovered	-17	4.20
Austin, TX	Uncovered	-18	4.00
Universal City, TX	Uncovered	-10	4.20
Los Fresnos, TX	Uncovered	-30	3.80
Shertz, TX	Uncovered	-6	3.90
Cibolo, TX	Uncovered	-6	4.20

Location	**Uncovered/Covered**	**TMI (2006)**	**Equilibrium Suction (pF)**
Kyle, TX	Uncovered	-5	4.10
Friendswood, TX	Uncovered	22	4.00
Converse, TX	Uncovered	-6	4.40
Mesa, AZ	Uncovered	-52	4.60
Phoenix, AZ	Uncovered	-56	4.00
Cross Roads, TX	Uncovered	5	4.20
Laredo, TX	Uncovered	-40	4.10
McAllen, TX	Uncovered	-38	3.90
Dallas, TX	Uncovered	-2	4.20
San Antonio, TX	Uncovered	-17	4.00
Keller, TX	Uncovered	3	4.00
McAllen, TX	Uncovered	-40	4.20
Houston, TX	Uncovered	9	4.10
Hewitt, TX	Uncovered	2	4.10
McAllen, TX	Uncovered	-49	4.10
Amarillo, TX	Uncovered	-18	4.10
Fountain, CO	Uncovered	-16	4.20
Yukon, OK	Uncovered	3	4.00
Broken Arrow, OK	Uncovered	24	3.70
Prosper, TX	Uncovered	23	4.00
Atascocita, TX	Uncovered	29	4.10
Norman, OK	Uncovered	18	3.70
Meridian, MS	Uncovered	48	3.90
Harker Heights, TX	Uncovered	-5	4.20
Aurora, CO	Uncovered	-21	3.90
Hattiesburg, MS	Uncovered	50	4.00
Wheat Ridge, CO	Uncovered	-12	3.90
Wheat Ridge, CO	Uncovered	-12	3.90
Wylie, TX	Uncovered	9	4.00

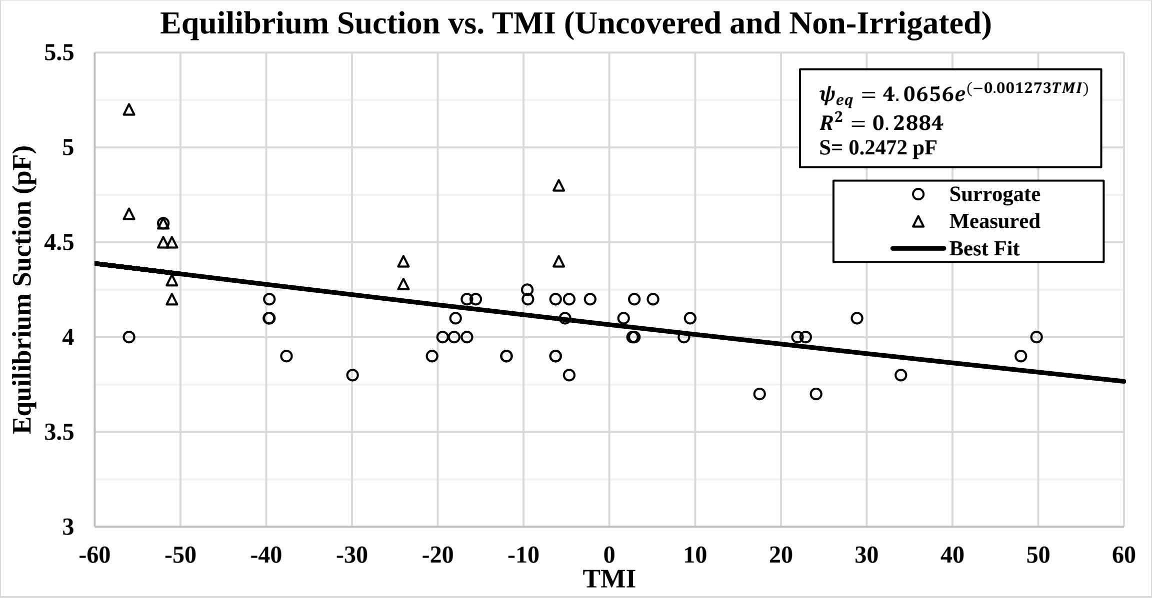
Table 8: Covered Data for Equilibrium Suction vs. TMI Relationship

Location	**Uncovered/Covered**	**TMI (2006)**	**Equilibrium Suction (pF)**
Colorado Springs, CO	Covered	-16	3.90
Arvada, CO	Covered	-12	4.00
Fort Worth, TX	Covered	-3	4.00
Richardson, TX	Covered	-2	4.00
Dallas, TX	Covered	-2	4.00
Garland, TX	Covered	-2	3.90
Oklahoma City, OK	Covered	3	3.90

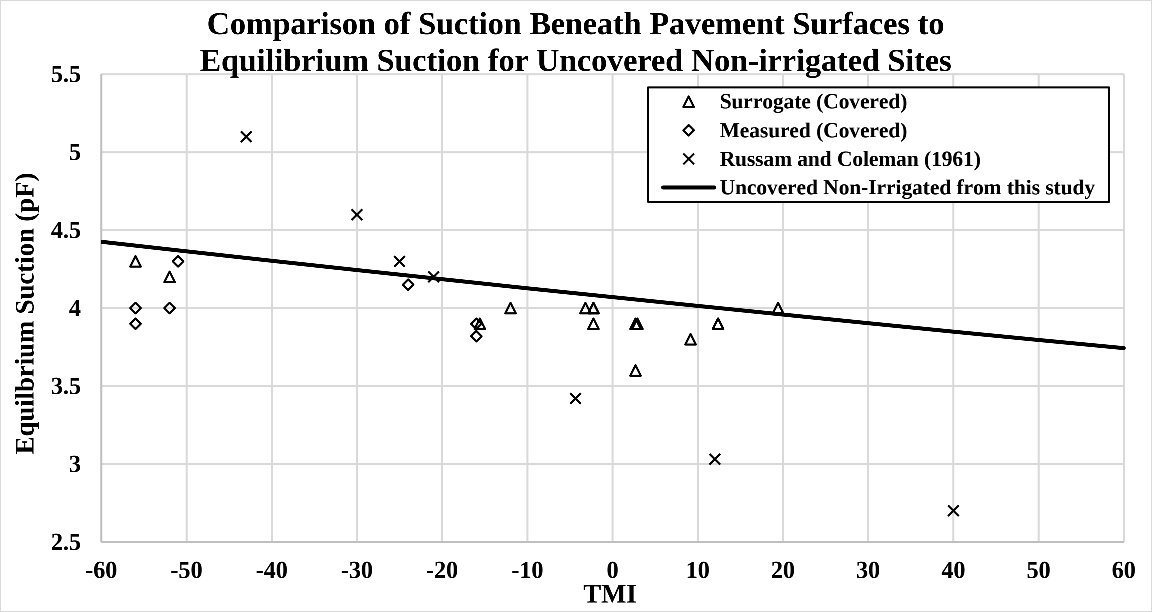
Location	Uncovered/Covered	TMI (2006)	Equilibrium Suction (pF)
Warr Acres, OK	Covered	3	3.60
Keller, TX	Covered	3	3.90
Moore, OK	Covered	9	3.80
Houston, TX	Covered	12	3.90
Houston, TX	Covered	12	3.90
Tulsa, OK	Covered	19	4.00

The entire set of surrogate data provides a range of equilibrium values from 3.60 pF in Warr Acres, OK to 4.25 pF in Breckenridge, TX and TMI values ranged from -52 in the Phoenix metropolitan area to 50 in Hattiesburg, MS. An overall average equilibrium suction value for the range of TMI values associated with the surrogate data was found to be 3.96 pF.

The correlation between equilibrium suction and TMI using the surrogate and measured equilibrium suction values is presented in Figure 14a. The plot includes uncovered locations represented by the data presented in Tables 6 and 7. Figure 14b presents the equilibrium suction values under covered areas for the surrogate and directly measured suctions.



(a)



(b)

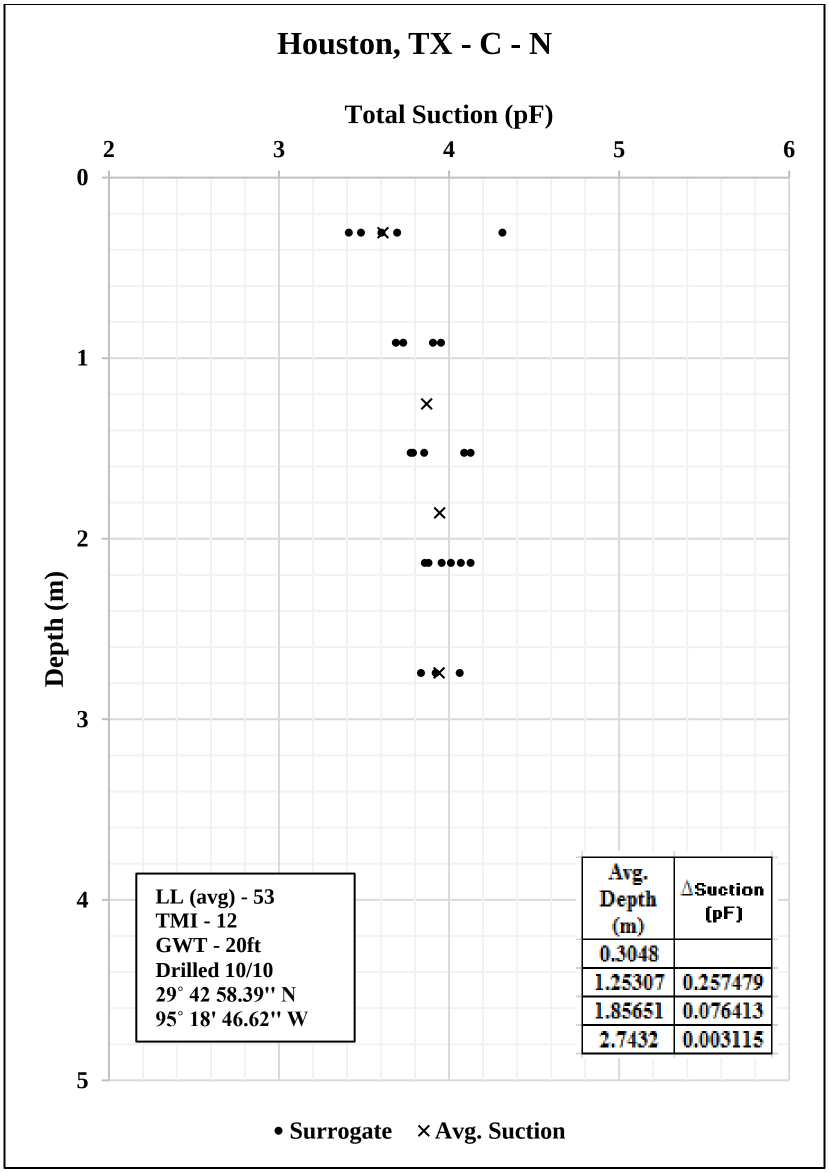
Figure 14: (a) Relationship Between Equilibrium Suction and TMI (Uncovered) Correlation Using Data from this Larger Study and (b) Comparison of Suction Beneath Pavement Surfaces to Equilibrium Suction for Uncovered Non-Irrigated Sites

For the surrogate data, locations where the predicted equilibrium suction values are based on directly measured index properties (i.e. Atterberg limits and moisture content) for input into the surrogate equations were used to have the most accurate suction values. The corresponding values are presented on Figure 14, along with any measured equilibrium suction values (uncovered) provided by Vann Engineering Inc. and Vann, J., in progress. The relationship between equilibrium suction and TMI was determined from a non-linear regression analysis using Minitab software, where equilibrium suction was set as the response variable and the TMI value was set as the predictor. EXCEL was used to plot the results from Minitab and a text box displays the statistics determined from Minitab. The correlation found herein is represented in the following exponential equation.

$$d\psi_{eq} = 4.0656e^{(-0.001273TMI)} \tag{4}$$

The statistical results from Minitab show there is a poor correlation between equilibrium suction and TMI with an associated R^2 value of 0.2884 and a standard error of 0.2472 pF. Previous work by Russam and Coleman (1961) and The Post-Tensioning Institute (2008) have shown that equilibrium suction decreases with an increasing TMI value. Results from the Post-Tensioning Institute (2008) is presented in the manual for the design of slabs-on-ground with an R^2 value of 0.356 between TMI and equilibrium suction. The writer was unable to locate the source of the data and original references for data points shown in the PTI (2008) plot of TMI versus equilibrium suction. Regardless, the results of this study show only very limited statistical significance for the best fit correlation between equilibrium suction and TMI, and the strength of the PTI (2008) correlation is not high, perhaps bringing into question the exclusive use of such correlations in establishment of design suction profiles.

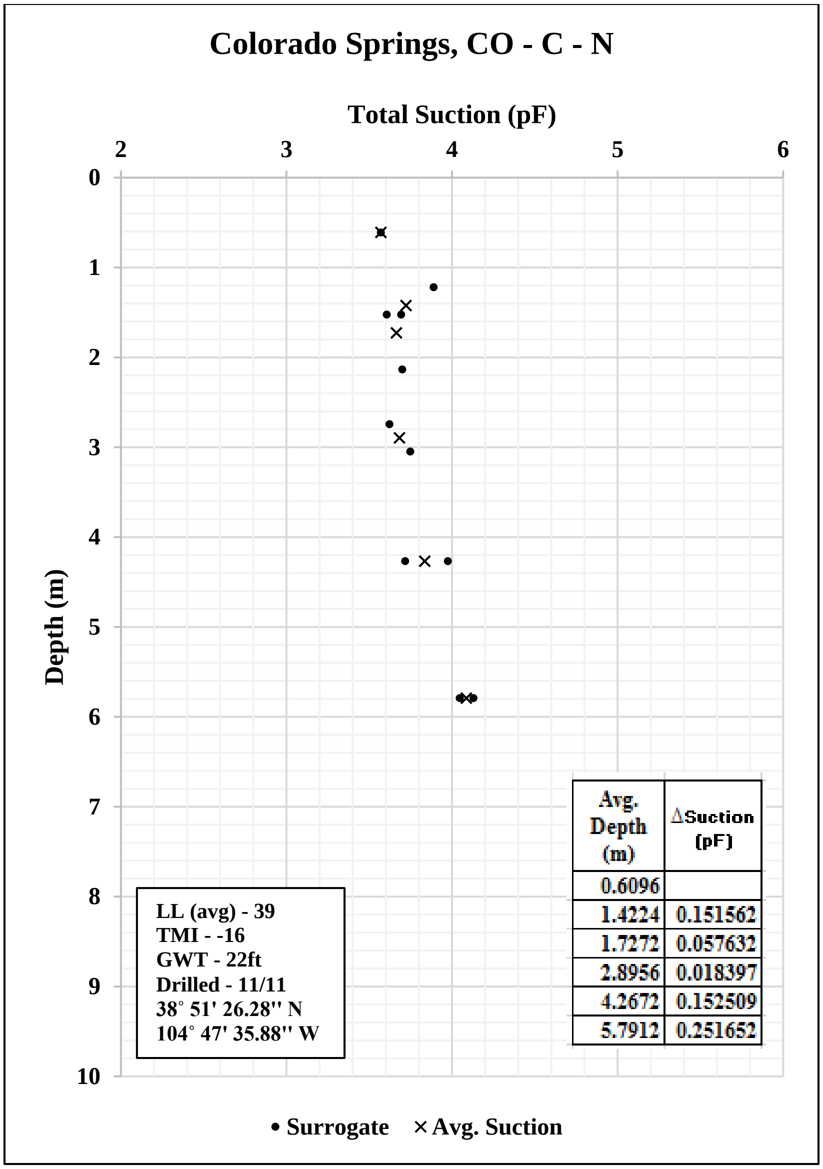
For the covered locations, both the surrogate and measured data, the equilibrium suction values were superimposed on Figure 14b for a comparison with the relationship found from the uncovered data. shows the covered equilibrium suction values, labeled with different symbols. A new correlation was not made with the addition of the covered data. As previously stated, with the geotechnical investigation reports reviewed, for covered areas a majority extended depth of exploration to 10 feet and stopped. It is not confirmed that it is a substantial depth to determine equilibrium suction from the suction profiles. The equilibrium suction values for the covered locations, for the most part, have lower suction values (more wet) and fall below the relationship for uncovered areas. It can be postulated this may be due moisture processing when constructing slabs on ground on expansive soils. Thus, no more allowing for evaporation due to climatic conditions and retaining the moisture underneath the slab. The suction profiles for the covered areas, when compared to profiles in uncovered areas, were generally near vertical. Figures 15, 16, and 17 and three examples of covered suction profiles. Figure 15 and 16 are part of this study and the soil suction surrogate was used to estimate the suction profiles. Figure 17 is the measured suction profile, using the WP4C, and has been provided for comparison (Vann, J., in progress).



LL (avg) - 53
TMI - 12
GWT - 20ft
Drilled 10/10
29° 42 58.39'' N
95° 18' 46.62'' W

Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.25307	0.257479
1.85651	0.076413
2.7432	0.003115

Figure 15: Covered Suction Profile for Houston, TX



LL (avg) - 39
TMI - -16
GWT - 22ft
Drilled - 11/11
38° 51' 26.28'' N
104° 47' 35.88'' W

Avg. Depth (m)	ΔSuction (pF)
0.6096	
1.4224	0.151562
1.7272	0.057632
2.8956	0.018397
4.2672	0.152509
5.7912	0.251652

Figure 16: Suction Profile for Colorado Springs, CO

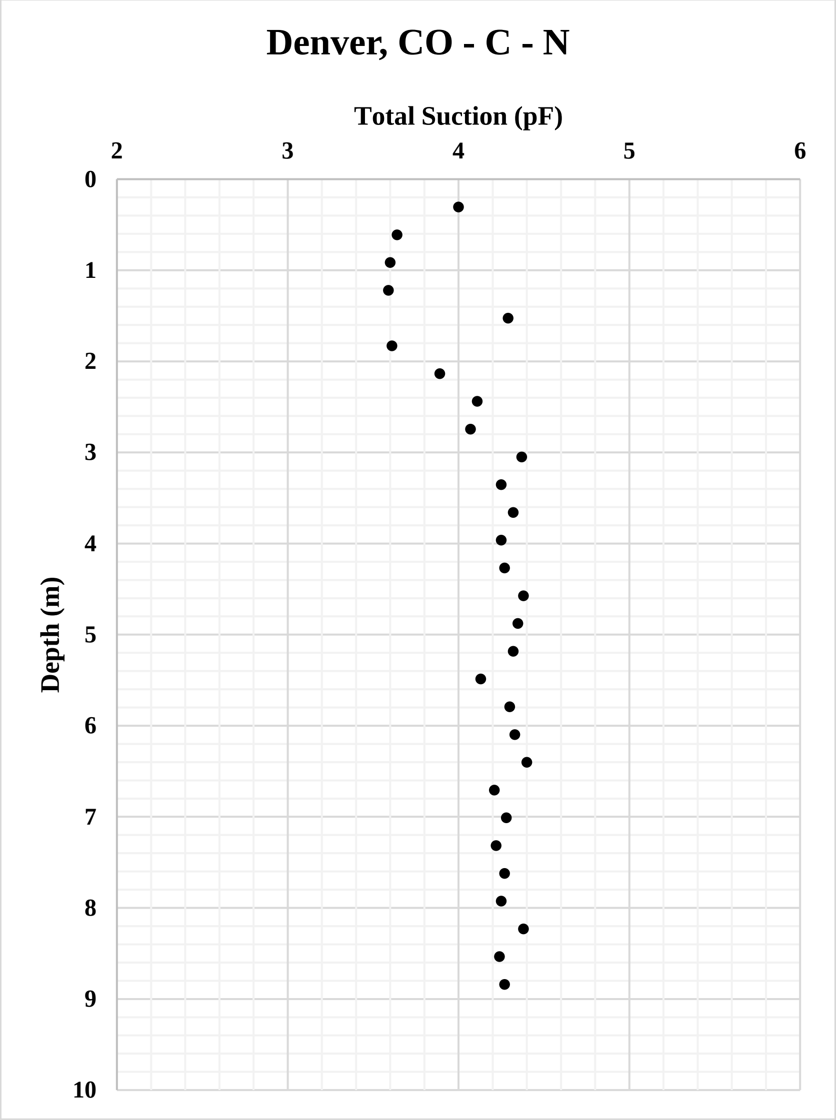


Figure 17: Measured Suction Profile for Denver, CO (Vann, J., in progress)

The soils used in this study consisted of natural clay soils that varied widely in plasticity indices and liquid limits. In terms of liquid limit, the low end was 36 with a high end of 71. An attempt was made to group the sites by their respective average LL values and determine to the extent possible if there is any trend with equilibrium suction and TMI by using liquid limit groupings. Groupings were made going from 30-39, 40-49, 50-59, and extending upward to 70-79. The plot of LL-sorted equilibrium suction versus TMI was made and is presented in Figure 18 below. The data in Figure 18 represents both the surrogate and measured data (Vann, J., in progress and Vann Engineering, Inc.) which were used in the development of the correlation in Figure 14.

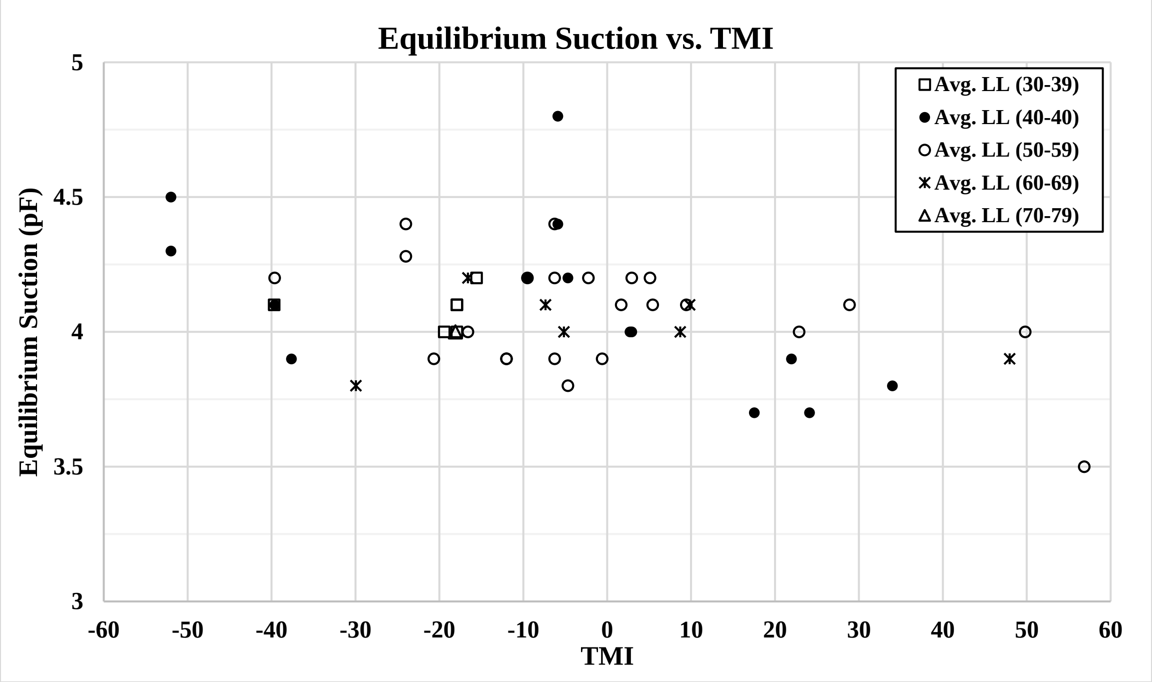


Figure 18: Equilibrium Suction vs. TMI grouped by Liquid Limits

There is no apparent correlation found between equilibrium suction and TMI, even when grouping the data points by their respective liquid limits. The TMI measure of climatic conditions appears to not adequately capture all of the key aspects of site-specific flux boundary conditions that control equilibrium suction values (e.g., slope of ground surface, soil-type layering, sources of lateral water flow, etc.). Further investigation is required to determine whether equilibrium suction values can be estimated from simple parameters such as those related to soil type and climatic conditions, in the absence of direct site-specific or regionally specific measurement.

4.1.1 Equilibrium Suction Comparison with Literature

A comparison is presented herein of the TMI versus equilibrium suction correlations of this study to those existing in the literature, which include work from Bryant (1998), McKeen (1981), Russam and Coleman (1961), Wray (1989), and the Post-Tensioning Institute (2008). For this study, the ArcGIS web-based TMI map (Olaiz, et al., 2018) was used to assign TMI index values for Bryant (1998), McKeen (1981), and Wray (1989). Figure 19 presents the uncovered equilibrium suction values determined in this study, along with the uncovered measured values from Table 6 and equilibrium suctions which have been presented in the literature from McKeen (1981), Bryant (1998), and Wray (1989). The Russam and Coleman and PTI 3rd Edition equilibrium suction values have not been included.

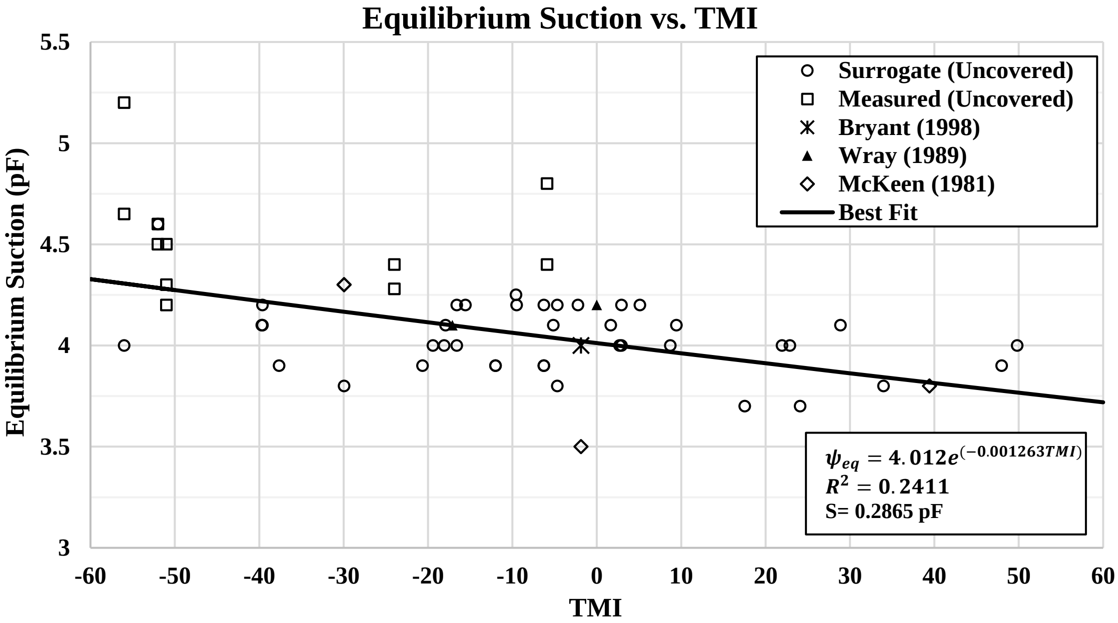


Figure 19: Equilibrium Suction vs. TMI with Literature Suction Values

Only the measurements that are believed to have been taken at depth to determined equilibrium conditions were plotted. A new correlation was attempted. A regression model was found using Minitab. The statistical results show an R-squared value of 0.2411 with a standard error of 0.2865 pF for the model. When compared to the results in Figure 14a, there is a slight decrease in the R-squared value with the addition of more results, and a little more scatter. Therefore, the relationship determined in Figure 19 is of little difference when compared to the relationship in Figure 14a.

Figure 20 presents the correlation resulting from this current study (Figure 14) using the suction surrogate and a limited amount of measured suction values, using the WP4-C device, along with the relationship found by Russam and Coleman (1961) and the Post-Tensioning Institute (2008). Significant differences can be seen when the correlation from this study is superimposed on the same plot of the Russam and Coleman and PTI correlation, Figure 20. As TMI becomes increasingly negative, below approximately -15 to -20, the Russam and Coleman relationship suggests higher equilibrium suction values compared to the PTI curve and the correlation determined in this study. The Russam and Coleman relationship also suggests a wide range of equilibrium suction values, approximately 5.5 pF to 2.5 pF, for TMI values between -50 and 60, while the PTI curve ranges from approximately 4.3 pF to 3.0 pF. The correlation determined from this study presents an almost flat curve on the pF scale, which ranges from 4.1 pF to 3.8 pF over the entire TMI range; the pF scale represents the log of suction in centimeters of water, and therefore the suction range varies from 1259 kPa to 631 kPa, over the full range of TMI.

The Russam and Coleman relationship was found by measuring suction in subgrade beneath pavements at shallow depths. It is also unknown for how long soil beneath has been covered. For this reason, and showing a wide range of suction values, it is not demonstrated that the suction values are in fact at an equilibrium condition. Furthermore, in this study, the Russam and Coleman relationship will not be used to modify or develop an improved correlation. The Post-Tensioning Institute relationship gathered suction data from studies in the literature to present a correlation. For the geotechnical reports reviewed, equilibrium suction values are estimated, and it is known there are directly measured properties to a substantial depth to determine an equilibrium suction magnitude.

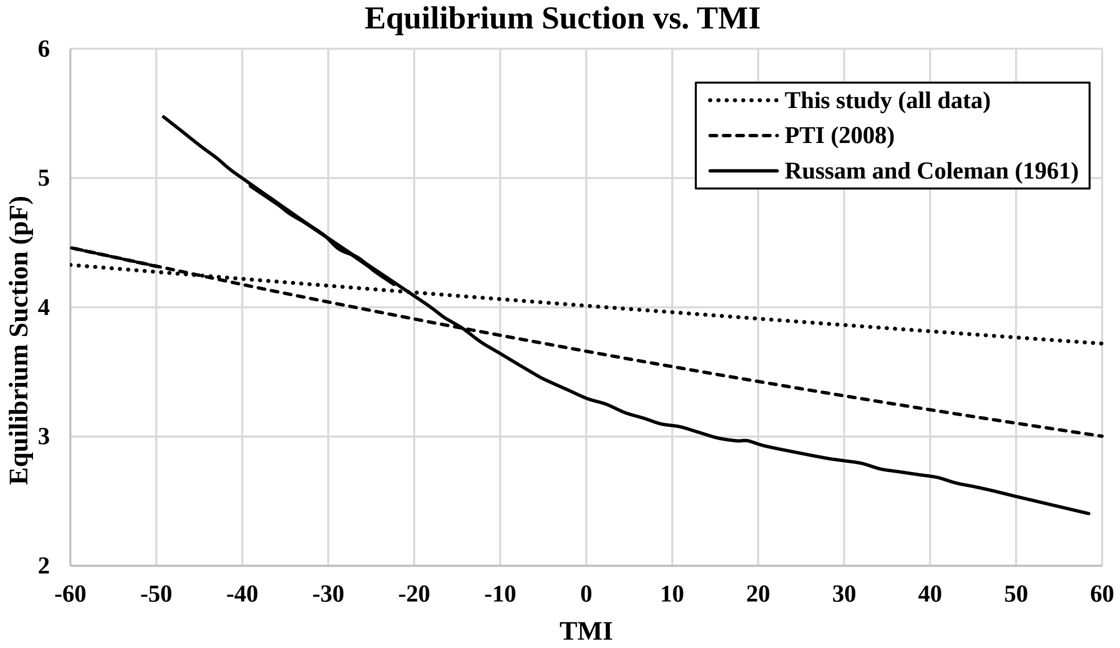


Figure 20: Equilibrium Suction vs. TMI Comparison

Measured equilibrium suction values and equilibrium suction values found in the literature are presented in the following figure, along with the results in the current study. Measured values and the data found in the literature are from uncovered site locations.

As a general observation, there is a slight trend where the equilibrium suction values will decrease as the TMI values become increasingly positive. Intuitively, this seems to be logical, in a wet or humid climate, the soil should be more wet, therefore experiencing lower suction values. However, for the range of TMI, -60 to 60, the majority of equilibrium suction values from this study were between suctions of 3.75 pF and 4.25

pF. For a TMI of 0 and above, the Russam and Coleman curve suggests suction values of approximately 3.3 pF and below. However, the equilibrium suction values presented in this study, and based on surrogate or measured values do not present suction values below 3.5 pF. Both 3.3 pF and 3.5 pF are very low suction values, approaching that which might be expected for osmotic suction (approximately 3.25 pF (175 kPa) is an average osmotic suction value reported by Houston and Houston, 2017). Thus, it is important to keep in mind that the correlations developed are for total suction values rather than matric suction values. For the relationship found in this study, a majority of the data points, both from the surrogate as well as the measured, were from locations with drier climates (low TMI values). When comparing to the Russam and Coleman and PTI relationships, the equilibrium suction values are higher at high TMI values (wet climates). This may be due to not having many data points in the high TMI range.

From the previous figures presenting equilibrium suction vs. TMI, not only is there currently a weak correlation which has been published in existing literature, a poor to insignificant relationship between equilibrium suction and TMI was also found in this study. These results show that TMI is not the only factor to look at when trying to determine equilibrium suction, and in fact, there is likely much more which affects equilibrium suction values, some of which may be difficult to investigate. Factors affecting field suction values which are independent of the climate condition (TMI) should be investigated further. It is possible that equilibrium suction is site specific, and rather than looking at TMI for a given region, the site itself and 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 suction profile for the Denver area. The suction profile was then compared to each single site for the site-specific approach. It was found that there was some variation in equilibrium suction, which may indicate that there is more to equilibrium suction values than only TMI, which is typically taken to be a 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 suction as soil type and layering affects unsaturated flow. 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.

4.2 Depth to Constant Suction for Uncovered/Non-irrigated (natural) Sites

From the estimated field suction profiles, a depth to constant suction was visually determined from the smooth curves fitted using the average suction values. A plot of depth to constant suction vs. TMI was made using results from the estimated field suction profiles in EXCEL. Only depths to constant suction from sites having directly measured index properties and moisture content data with depth were used to determine a correlation between depth to constant suction and TMI. Sites where an average liquid limit was estimated from shallower depths and to apply the suction surrogate equation to deeper depths having moisture contents but no Atterberg limit data were not used in the development of the fitted trend curve. The trend curve for depth to constant suction versus TMI was compared to the trend line applying all measured properties in the suction surrogate equations. Table 9 presents the data used in the development of the correlation and the associated plot of depth to constant suction vs. TMI is presented in Figure 21.

Table 9: Data Used to Formulate Relationship Between Depth to Constant Suction and TMI

Location	TMI (2006)	Average LL	Depth to Constant Suction (m)	Equilibrium Suction (pF)
Laredo, TX	-40	39	4.27	4.1
McAllen, TX	-40	55	4.27	4.2
McAllen, TX	-40	49	3.045	4.1
McAllen, TX	-38	47	4.27	3.9
Los Fresnos, TX	-30	61	3.35	3.8
Snyder, TX	-19	37	2.74	4.00
Austin, TX	-18	71	2.74	4
Amarillo, TX	-18	38	2.13	4.1
San Antonio, TX	-17	67	3.05	4.2
San Antonio, TX	-17	51	3.35	4
Fountain, CO	-16	36	3.05	4.2
Breckenridge, TX	-10	45	1.22	4.25
Universal City, TX	-10	55	2.13	4.2
Shertz, TX	-6	51	2.74	3.9
Cibolo, TX	-6	59	2.74	4.2
Converse, TX	-6	57	2.44	4.4
Kyle, TX	-5	62	1.22	4.1
Killen, TX	-5	55	2.13	3.80
Dallas, TX	-2	57	1.22	4.2
Hewitt, TX	2	53	1.83	4.1
Yukon, OK	3	43	2.13	4.0
Fort Worth, TX	3	56	1.83	4.20
Keller, TX	3	46	1.52	4
Cross Roads, TX	5	50	1.83	4.2
Houston, TX	9	53	1.52	4.1
Friendswood, TX	22	44	0.91	4
Broken Arrow, OK	24	44	1.52	3.7
Vidor, TX	34	49	1.22	3.8

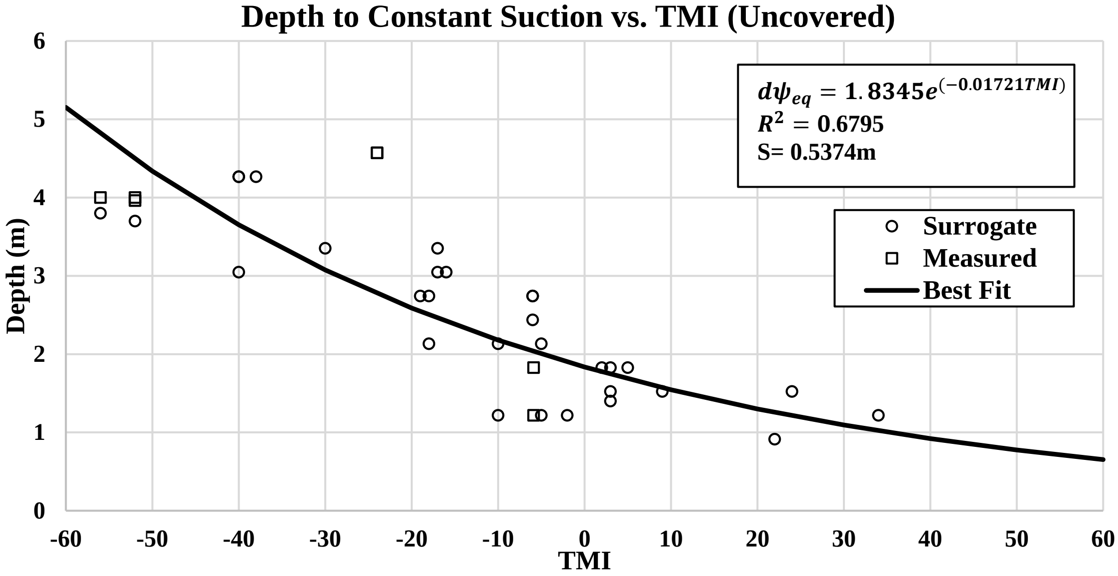


Figure 21: Depth to Constant Suction vs. TMI using Suction Surrogate

TMI values ranged from approximately from -39 in Laredo, TX to 34 in Vidor, TX which provided a wide range of data to formulate a relationship that can be used in different climate zones. Depths to constant suction ranged from 0.91 m in Friendswood, TX (TMI=22) to 4.27 m in Laredo, TX (TMI=-40). In all cases the TMI reported is the 30-year average TMI.

A regression model was determined using Minitab software and applying a nonlinear regression analysis where the depth to constant suction was the response variable and TMI was the predictor. While the analysis was performed using Minitab, EXCEL was used to plot the results. Interpretation of the statistical analysis showed a strong R^2 value of 0.6795 with the regression model between depth to constant suction and TMI. The standard error (S) was determined to be 0.5374 m and the following relationship was found.

$$d\psi_{eq} = 1.8345e^{(-0.01721TMI)} \tag{5}$$

where $d\psi_{eq}$ is the depth to constant suction in meters and TMI is the 2006 Thornthwaite Moisture Index (Witczak, Zapata, & Houston, 2006).

Through application of the suction surrogate to estimate soil suction profiles in the field, depth to constant suction was determined. The results show the depth to constant suction decreasing as the TMI value becomes increasingly positive (climate becomes wetter). The relationship found in this study agrees well with existing correlations and studies which have been published in the literature (Fityus et al. (1998), Walsh et al. (1998), Barnett & Kingsland (1999), Fox (2000), Chan & Mostyn (2008) and AS-2870 (2011)). Mitchell (2008) presents a summary of their findings shown in Figure 22.

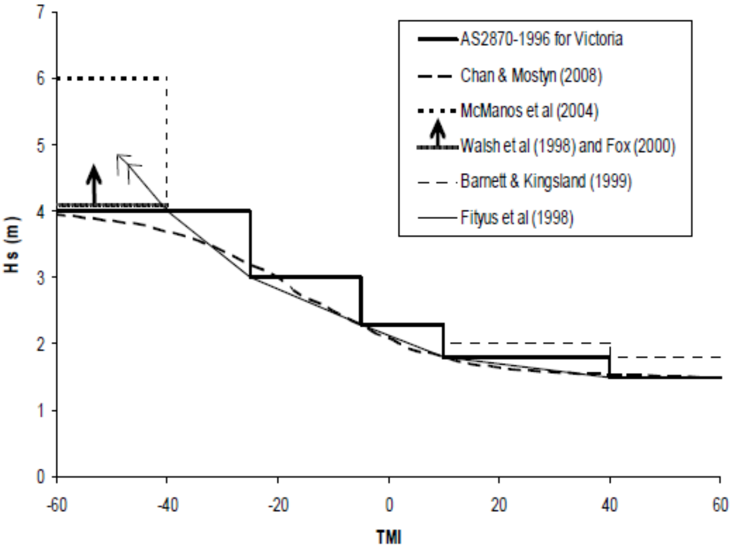


Figure 22: Relationship Between H_s and TMI ((Mitchell, 2008)

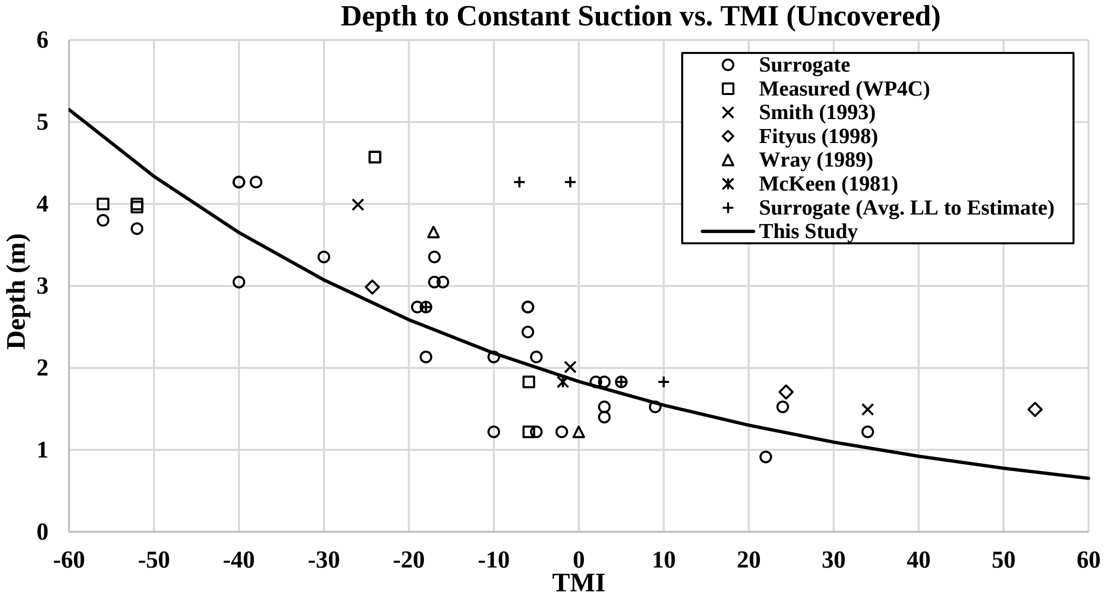


Figure 23: Correlation between Depth to Constant Suction and TMI

Figure 23 shows the regression model from the suction surrogate data, the data which used the average LL from shallow depths to estimate suction from water content at greater depth, published relationships in the literature, findings as part of ongoing research (Vann, J., in progress), and data provided by Vann Engineering, Inc. The symbols are presented in the legend which distinguish between the published, measured, and surrogate data.

The above correlations between equilibrium suction versus TMI and depth to constant suction versus TMI suggest that the use of the suction surrogate profiles provide a reasonable estimate of field suction profiles with regard to depth to constant suction. The suction surrogate data tended to yield suction values and trends in suction profiles that are consistent with measured and existing literature values. However, the suction surrogate works best when directly measured index properties are used in the surrogate equations. For example, two outliers in Figure 23 between TMI values of 0 and 10 were obtained using an average LL from shallow depth to estimate suction at greater depths. These outlying data points would predict substantially greater depth to constant suction than what the overall trend suggests (4.2 m, comparted to 2.0 to 2.3 m).

Comparing the depth to constant suction in the literature to the regression model found using the soil suction surrogate, the correlation agrees well with the trends found in the literature, i.e. with increasing values in TMI, the depth to constant suction will become shallower. For TMI values greater than 20, the regression model in Figure 21, based on the data from this study only, shows the depth to constant suction continuing to decrease to a value of approximately 0.75 m at a TMI of 60. However, for the data used to determine the relationship from Figure 21 by applying the suction surrogate and as well as the published data found in the literature, the depths to constant suction appear to level out at a TMI of 20 with a depth to constant suction of approximately 1.0 m to 1.5 m (Figure 23). The summary of findings in the literature presented by Mitchell (2008), Figure 22, show that at a TMI of 20 and above, the depth to constant suction also levels out at approximately 1.3 to 1.5 m, which is supported by the collective data in Figure 23. Differences between depth to constant suction versus TMI trends shown in Figures 21, 22, and 23 are of little engineering significance.

4.3 Depth to Constant Suction for Uncovered/Irrigated Sites

Few sites within the considerable number of geotechnical reports reviewed for this study were found to be uncovered and irrigated. Nonetheless, for the available irrigated sites, depth to constant suction versus TMI was determined for comparison to non-irrigated sites. 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, influences the depth to which moisture contents increase. The depth of wetting (depth to constant suction) is affected by site development, and therefore the relationship between depth to constant suction and TMI for developed sites would 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.

Walsh et al. (2009) conducted a study of the Denver area on the influence of residential construction and landscape irrigation on the depth of wetting within the soil profile and an approach to determine the depth of wetting was presented. Undisturbed soil samples which had been collected at undeveloped sites were subjected to total suction measurements using the filter paper method. The suction data was compiled to establish an average suction profile for undeveloped conditions. Between 2001 and 2003, 32 sites were drilled which had residential structures present from 7 to 48 years. The drilling was performed at the sides of the residences. Soil samples were taken extending to depths of 12.2 m (40 ft) and total suction measurements were performed using filter paper to create suction profiles for each individual site location. Soil suction profiles for post-development conditions were created and compared with the preconstruction soil suction profile to determine the depth of wetting at each site location. The average depth of wetting (depth to constant suction) 16 sites from Walsh, et al. (2009) were used in this current study as well as the average equilibrium suction values. Not all 32 sites were used. For six of the sites in the study, soil suction data was unusable. Furthermore, there were sites which were influenced by shallow groundwater predevelopment and was not used due to criteria for sites used in this study, and for one site, there was no data at depth to estimate a depth of wetting. The values of the depth to wetting were used from the site-specific approach presented by Walsh et al. (2009). An additional 4 sites were identified from the geotechnical investigation reports reviewed in this current study where covered and uncovered area suction profiles could be directly compared for differences in depth to constant suction.

From the geotechnical investigation reports reviewed in this study, four sites were identified as irrigated, as determined from interpretation of the respective aerial photographs at or around the time of the dated field investigation from their geotechnical investigation reports. They were located in Royse City, TX, Frisco, TX, The Woodlands, TX, and Hazel Green, AL. Figures 24 through 27 are the aerial photographs which depict the site conditions at or around the time of the field effort.

Figure 24: Site conditions at Frisco, TX

Figure 25: Site conditions at The Woodlands, TX

Figure 26: Site conditions at Royse City, TX

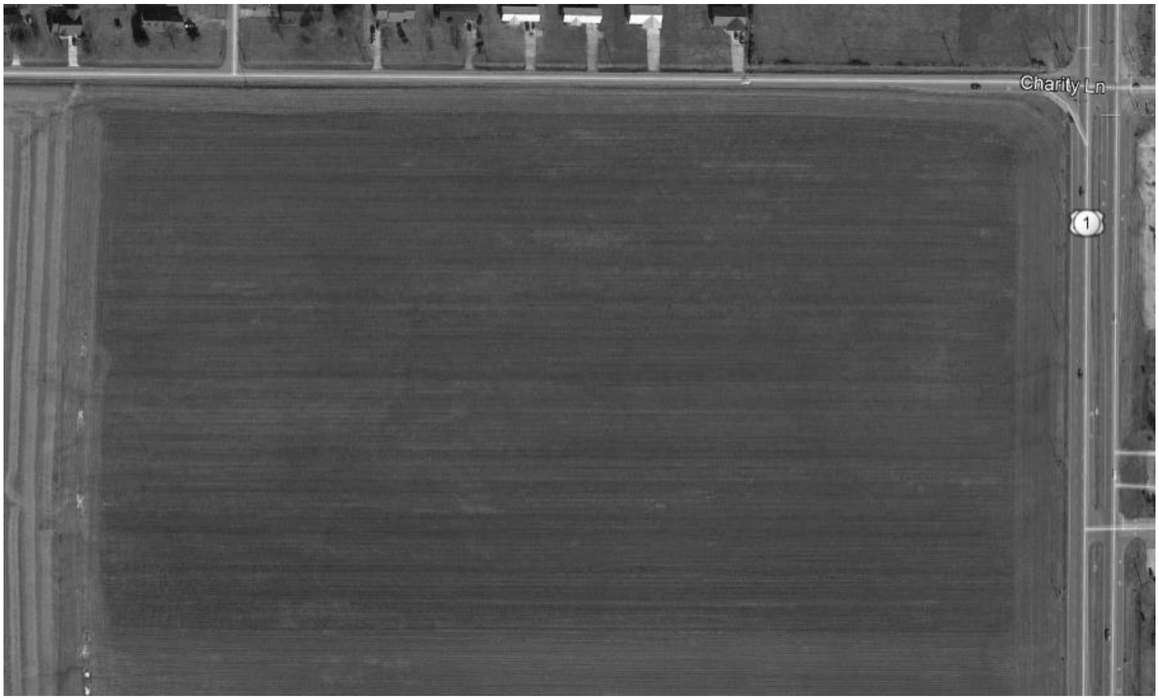


Figure 27: Site Conditions at Hazel Green, AL

Interpretation of the historical aerial photography at the locations of the purposed projects in Royse City, TX and Frisco, TX, and Hazel Green, AL showed that they were used for agricultural purposes. The location in The Woodlands, TX showed that at the approximate time of the field effort, it was developed with residential housing and landscape irrigation within the area of the geotechnical site investigation.

Figure 28 depicts the depth to constant suction vs. TMI from the 4 sites of this study, measured sites provided by Vann Engineering, Inc. and Vann, J., in progress, and shows the best fit correlation between constant suction versus TMI which was found in the results of the uncovered and non-irrigated sites. Interestingly, only the irrigated residential developments exhibited depth to constant suction significantly greater than that indicated by the trendline for undeveloped sites. Agricultural irrigation and open lawn irrigation, where little opportunity for concentration of ponding of surface water is allowed, showed depth to constant suction very close to that suggested by the trendline for unirrigated sites. This suggests a greater depth a wetting (depth to constant suction) with landscaping and residential development, which was also reported by Walsh et al. (2009). Walsh et al. (2009) were able to obtain water use records for some residential homes included in their study and presented a relationship of depth of wetting vs. watering. However, the amount of data available for direct comparison of depth of wetting for developed and undeveloped sites is quite limited; the data available suggests that more severe concentration of water sources, such as occurs commonly in residential development where water is not well controlled, results in depth of wetting in excess of what would be estimated for undeveloped sites; undeveloped sites tend to have depth of wetting that is largely controlled by climatic conditions where groundwater tables are at considerable depth. Figure 28 data also shows that some residential developments had depth to constant suction comparable to that of undeveloped sites, demonstrating that depth of wetting does not necessarily increase for developed sites; control of roof-runoff, well graded slopes away from structure, and other such measures can be used to limit depth of wetting. Table 10:presents the data for the irrigated sites used for this study.

Table 10: Depth to Constant Suction and Equilibrium Suction for Irrigated Sites

Reference	Location	Type	TMI (2006)	Depth to Constant Suction (m)	Equilibrium Suction (pF)
This Study	Royse City, TX	Agricultural	9	2.7432	3.9
This Study	Hazel Green, AL	Agricultural	57	1.2192	3.5
This Study	Frisco, TX	Agricultural	5	1.2192	3.9
This Study	The Woodlands, TX	Residential / Developed	22	3.5052	4.3
Vann, J., in progress	San Antonio, TX	Open Lawn	-16	3.048	4.1

Reference	Location	Type	TMI (2006)	Depth to Constant Suction (m)	Equilibrium Suction (pF)
Vann, J., in progress	San Antonio, TX	Open Lawn	-16	2.5908	4.0
Houston and Houston (2017)	Denver, CO	Residential / Developed	-25	8.0	4.5
Vann Engineering, Inc.	Phoenix, AZ	Residential / Developed	-52	-	3.9
Vann Engineering, Inc.	Chandler, AZ	Agricultural	-52	-	3.7
Vann Engineering, Inc.	Paradise Valley, AZ	Forensic	-52	3.3528	4.25
Vann Engineering, Inc.	Gilbert, AZ	Agriculture	-52	2.4384	3.5
Vann Engineering, Inc.	Gilbert, AZ	Agriculture	-52	-	3.5

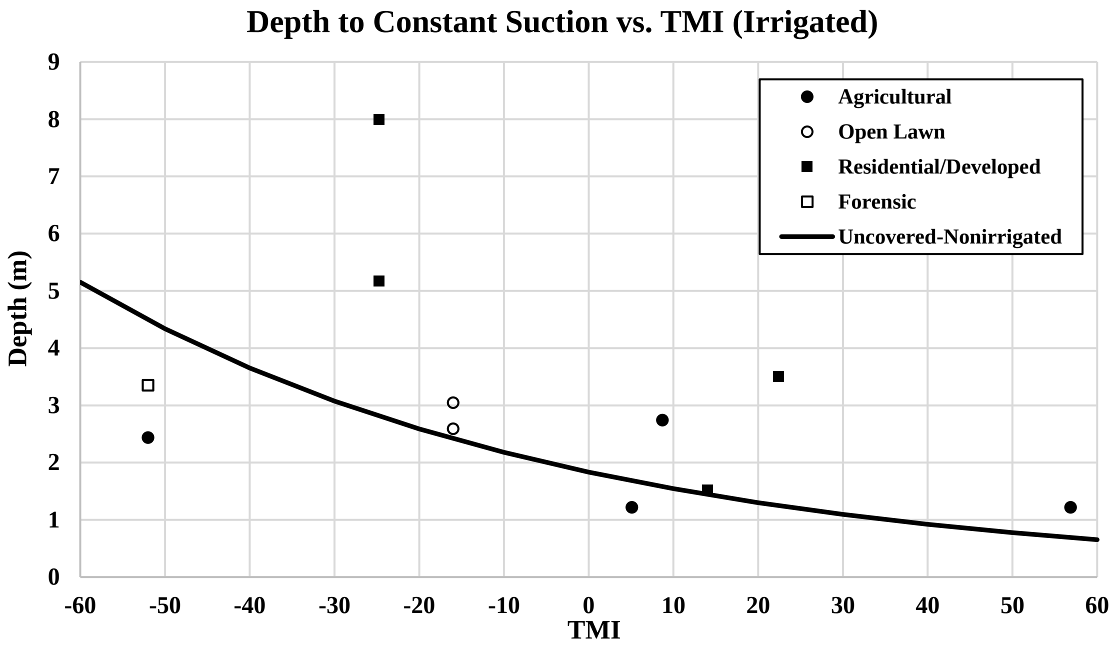


Figure 28: Depth to Constant Suction vs. TMI for Uncovered/ Irrigated Sites Compared to Trend Line for Undeveloped Sites

Equilibrium suction vs. TMI is presented in Figure 29. The data includes the non-irrigated data points, both measured equilibrium suction and equilibrium suction established using the suction surrogate, with the corresponding trend-line (Figure 14a) which had been found for the relationship between equilibrium suction and TMI for non-irrigated site. The trend-line for non-irrigated sites is shown for a comparison between the non-irrigated and irrigated equilibrium suction values. Shown in the plot, there is scatter amongst the irrigated data points similar to the scatter for non-irrigated sites. There is no obvious difference in equilibrium suction values observed for irrigated and non-irrigated sites for the limited amount of irrigated site data of this study.

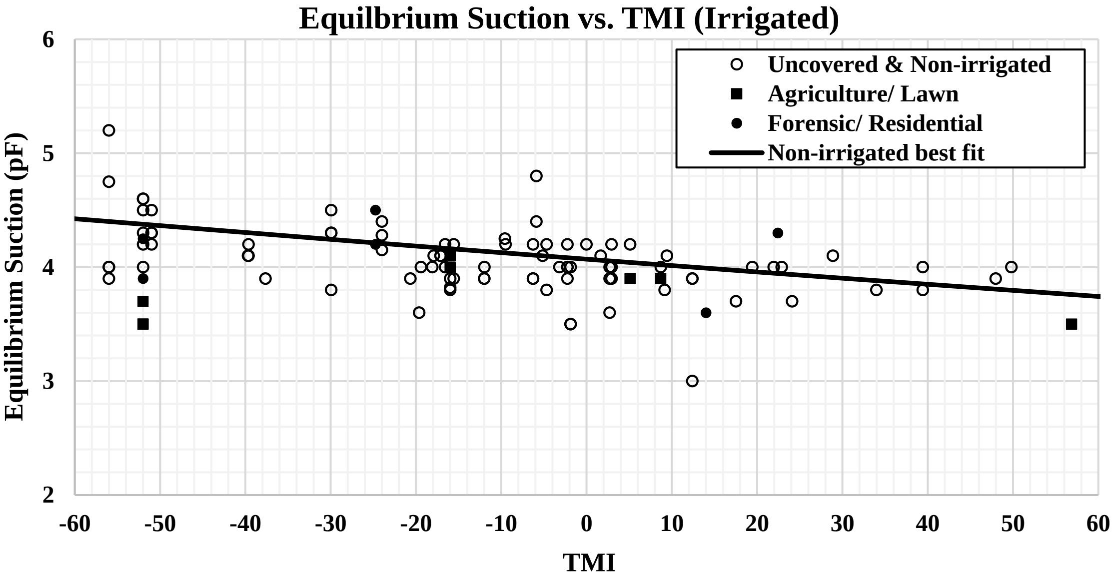


Figure 29: Equilibrium Suction vs. TMI Comparison between Non-irrigated and Irrigated

4.4 Estimated Field Suction Profiles

From the database of this study, suction surrogated estimated field suction profiles and their associated moisture content profiles with depth were created in EXCEL. Index properties, moisture contents, and TMI values were parameters needed for the suction surrogate equations (Vann, et al., 2018). The individual suction profiles for uncovered and non-irrigated, covered and non-irrigated, and uncovered and irrigated are presented in Appendices B, C, and-D, respectively.

The field suction profiles will be used to aid the development of design suction envelopes and/or initial and final suction profiles for design. Design suction envelopes or profiles provide the suction limits that the soil profile will experience (wet to dry conditions) and are required for computation of heave/shrinkage. Design suction profiles are important in the prediction of soil movements (shrink and swell), and such estimates are required in foundation design. For multiple sites within this study, individual field suction profiles were combined for uncovered and non-irrigated sites to generate a suction profile that presents a change in soil suction over seasonal fluctuations alone. Covered profiles, as well as irrigated suction profiles were also added for comparison between developed and undeveloped and irrigated and non-irrigated. Figure 30 presents suction profiles for San Antonio, TX where five individual profiles from this study were combined.

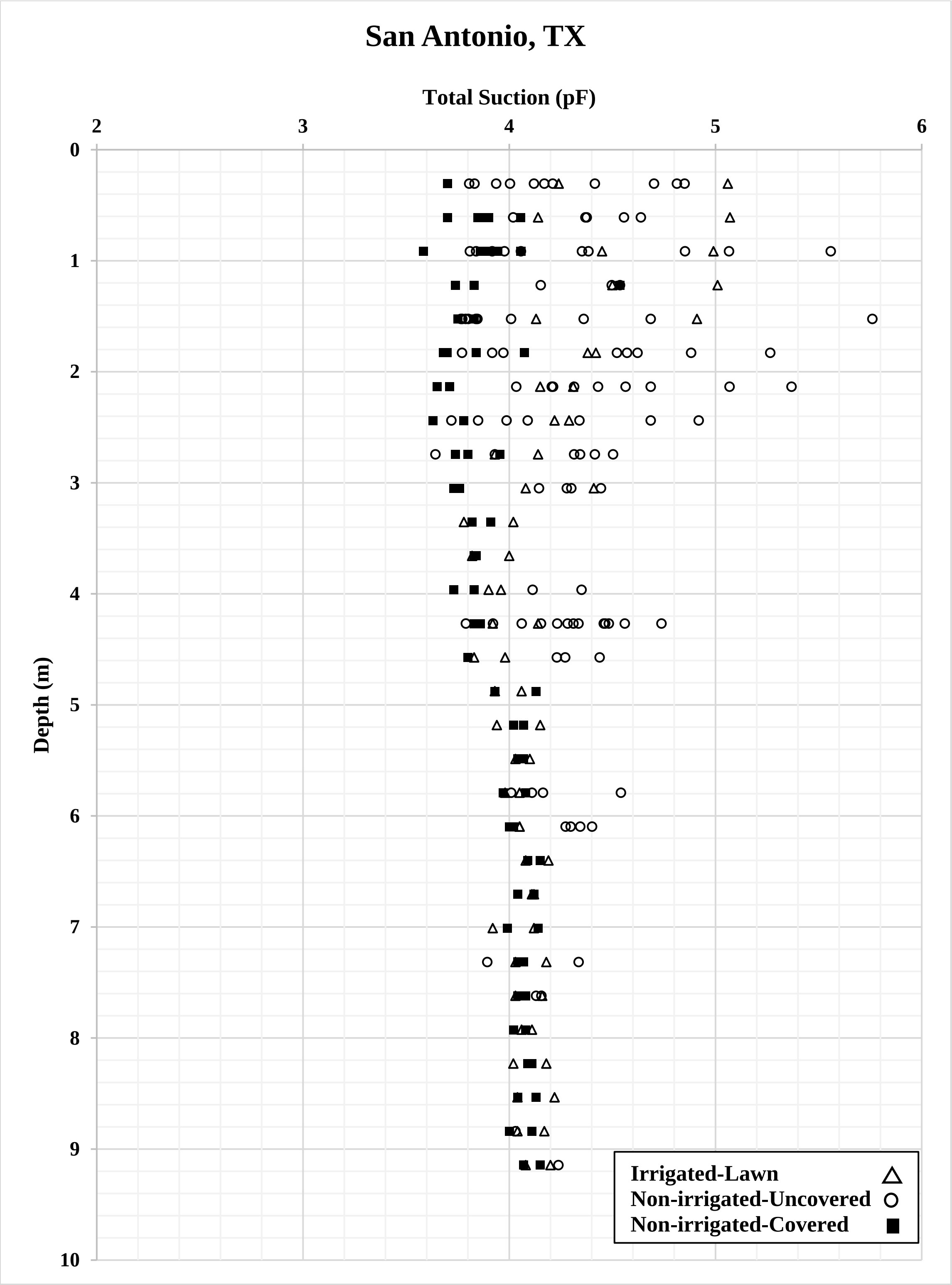


Figure 30: Combined Suction Profiles for San Antonio, TX

For San Antonio, individual field suction profiles were obtained over several years (2007-2016) and for various different months (Feb. to Nov.) throughout the years to present suction variations incorporating seasonal change. In the legend of Figure 30 different symbols are used for the different surface boundary conditions at the time of the field investigations. There were three different site conditions, irrigated with a lawn, non-irrigated and uncovered, and non-irrigated and covered. Converse, TX is located within the San Antonio metropolitan area and was included in the profiles of Figure 30. Interpretation of the Figure 30 suction profiles suggest an equilibrium suction value of approximately 4.2 pF, where the individual suction profiles suggest equilibrium suction magnitudes of 4.0 to 4.2 pF. A review of the suction profiles of Figure 30 suggests that there is not much of an effect on the equilibrium suction value for developed conditions (i.e. irrigation and covered conditions). From the individual suction profiles, depth to constant suction was determined to be 3 to 3.35m, and the combined suction profiles, including developed sites, suggest a depth to constant suction approximately between 4 and 5m. The individual suction profiles, at a specific time period, suggest shallower depths to constant suction, in general, compared to the combined suction profiles.

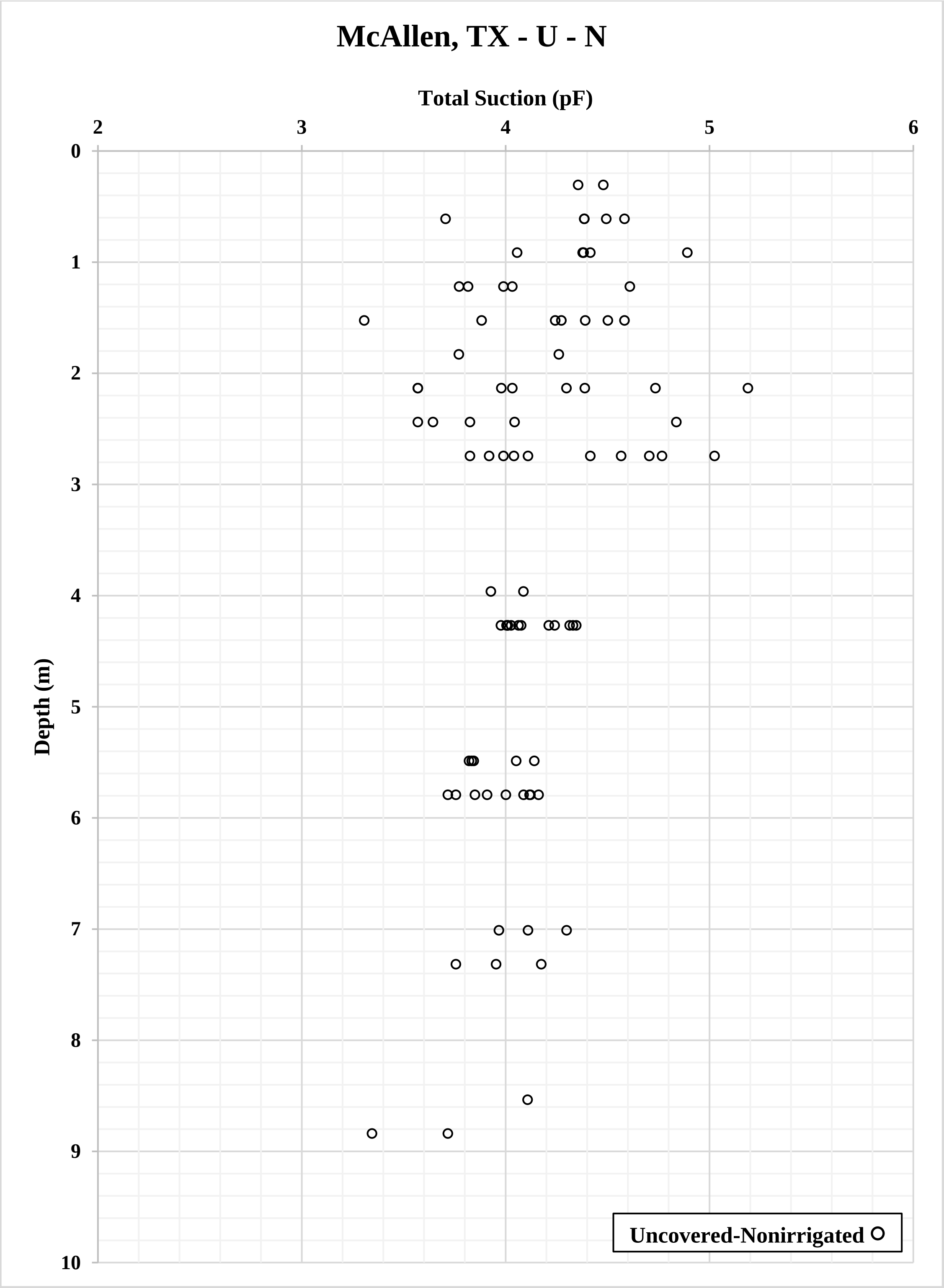


Figure 31: Combined Suction Profiles for McAllen, TX

The combined suction profiles for McAllen, TX are presented in Figure 31. Three individual suction profiles from 2013 and 2014 were combined from months March, May, and August. From the suction profiles, the equilibrium suction is approximately 4 pF at a depth to constant suction of approximately 4m. The individual profiles suggest a depth to constant suction of 3 to 4.2m and an equilibrium suction of 3.9 to 4.2 pF, consistent with the findings for the San Antonio profiles above.

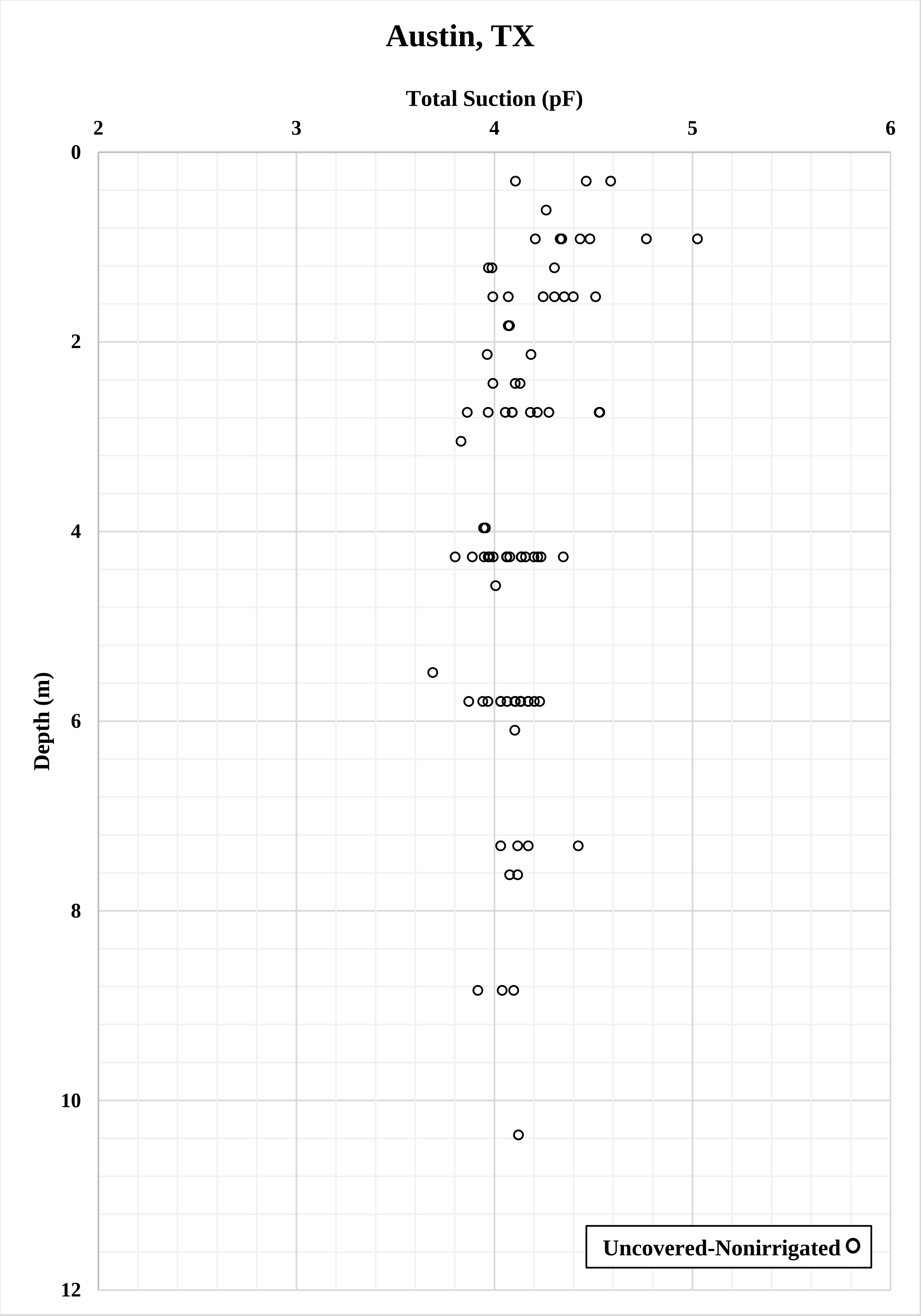


Figure 32: Combined Suction Profile for Austin, TX

Shown below in Figure 33 is a combined suction profile for Houston, TX. The individual field suction profiles ranged from 2010 to 2014 in April, July, October, and November. These sites are of the Houston metropolitan area which include The Woodlands, Atascocita, Friendswood, and Houston itself. Individual field suction profiles suggest an equilibrium suction magnitude of 3.9 to 4.3pF, while an equilibrium suction of approximately 4.2pF can be read from the combined suction profiles. A depth to constant suction of approximately between 3 to 3.5m can be determined for the combined suction profile. The depths to constant suction determined from the individual field suction profiles are shallower than that estimated from the combined plots, at about 1 to 1.5m. The Woodlands, TX individual suction profile, an irrigated residential site at the time of the field investigation, suggested a depth to constant suction of approximately 3.5m with an equilibrium suction magnitude of 4.3 pF.

Additional suction profiles for Dallas-Fort Worth, TX and Denver, CO are provided in Figure 33 and 34. The Dallas-Fort Worth area profiles are for non-irrigated conditions only, whereas the Denver profiles represent a combination of irrigated and non-irrigated sites.

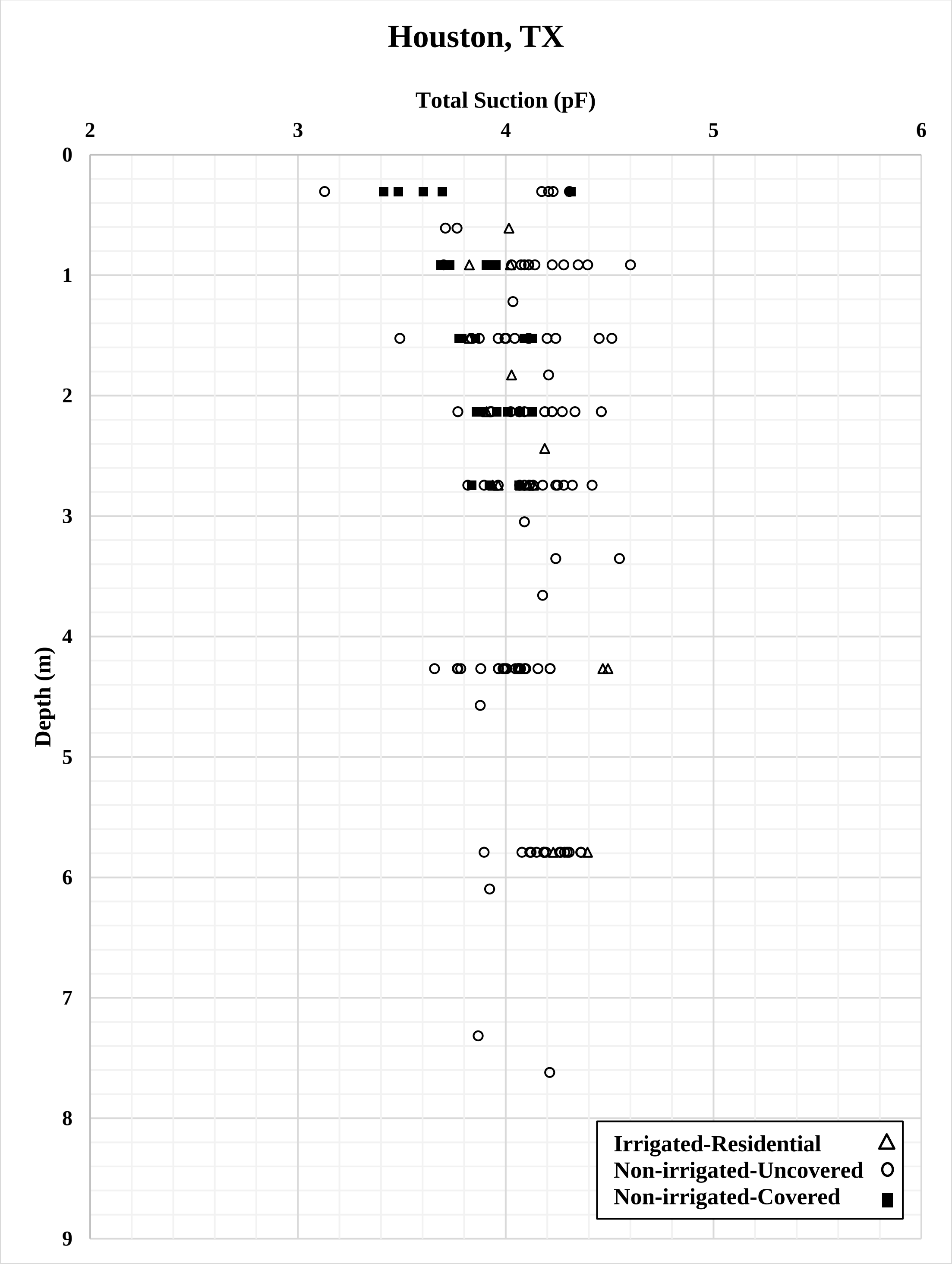


Figure 33: Combined Suction Profile for Houston, TX

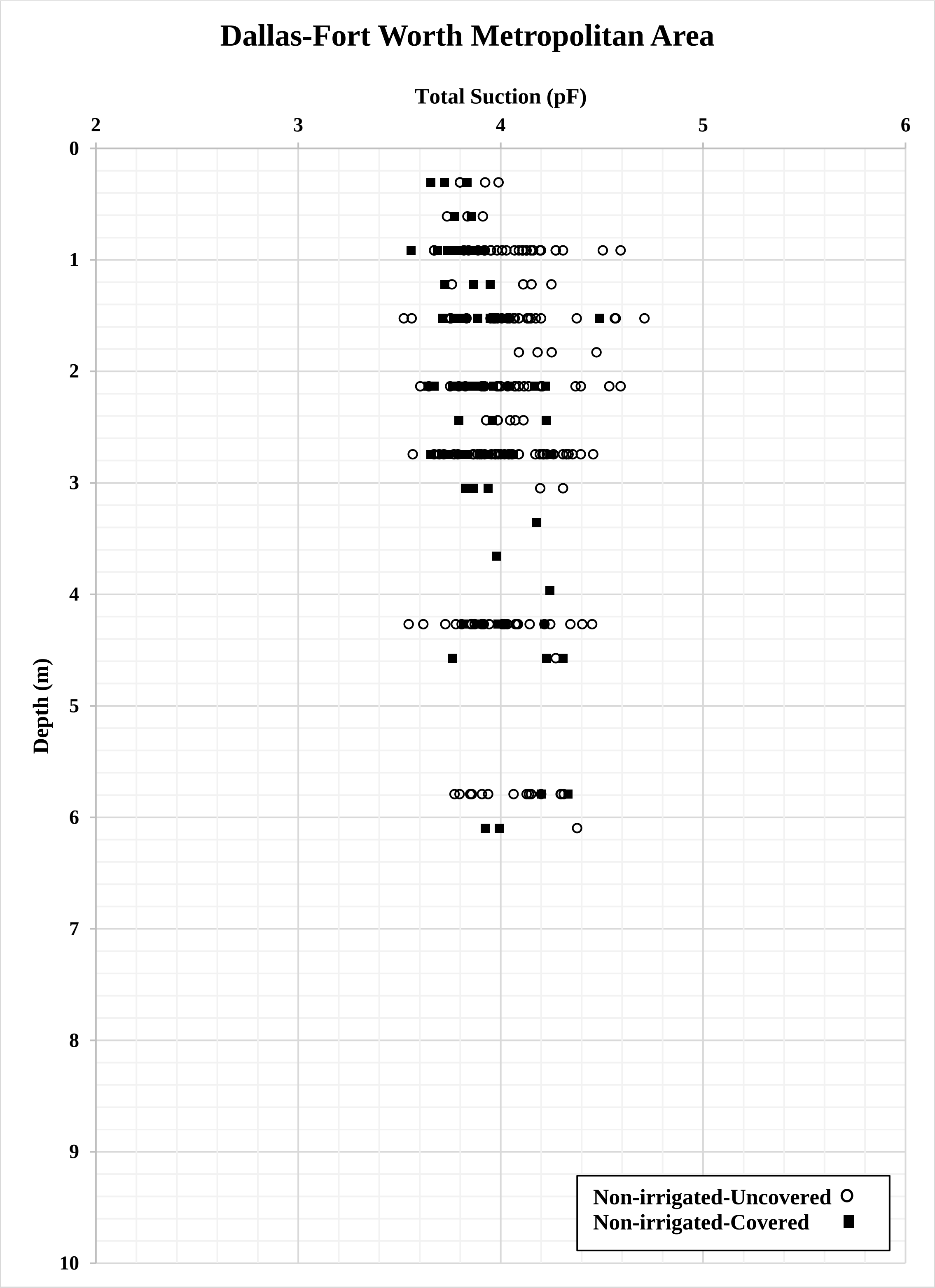


Figure 34: Combined Suction Profile for DFW

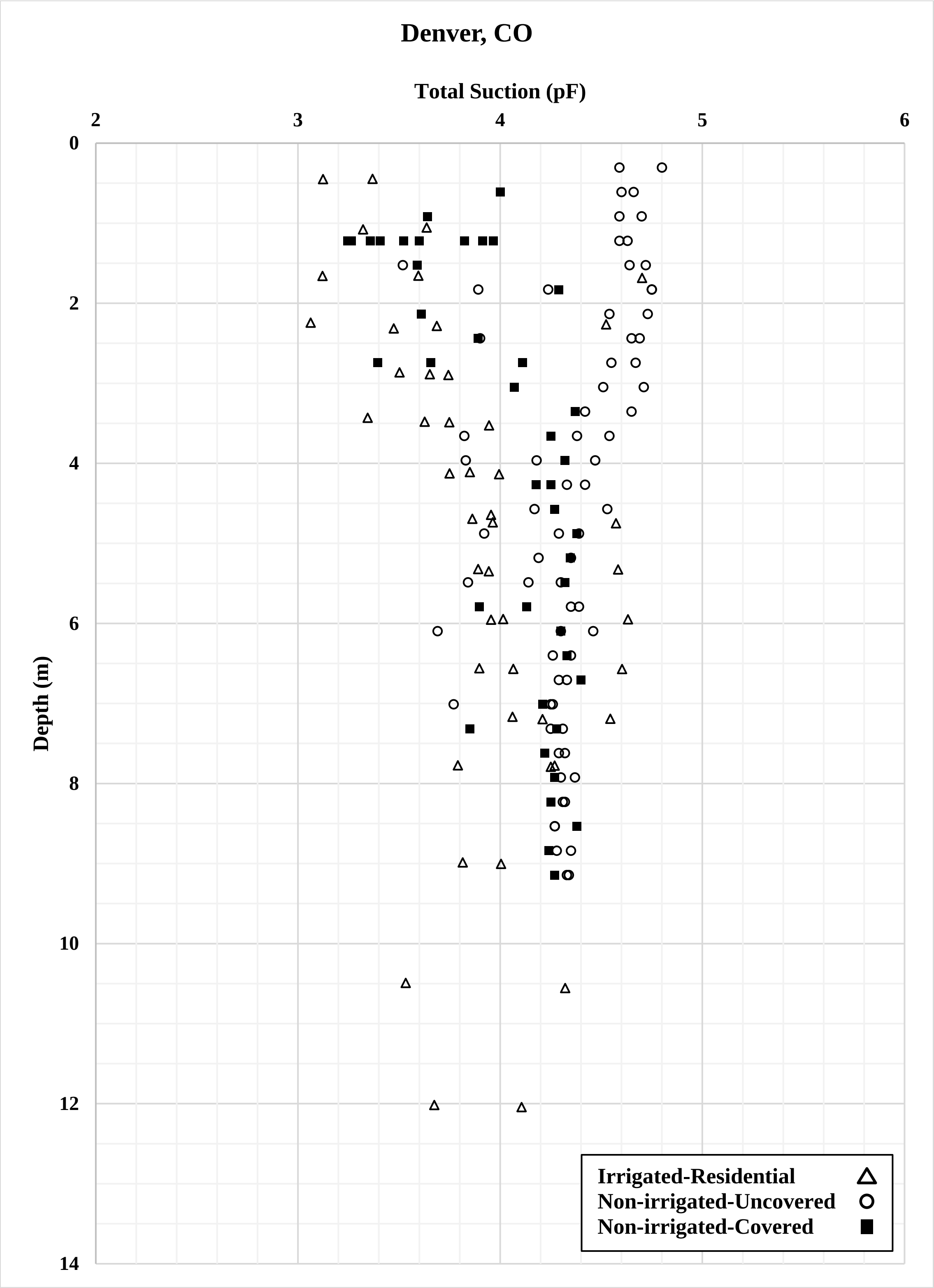


Figure 35: Combined Suction Profile for Denver, CO

These plots of soil suction versus depth, taken all together, show the importance of additional studies on the development of soil suction profiles needed for foundation design analysis. Individual field suction profiles provide the initial suction values, which are required input to computations of heave/shrinkage, while the band of suction profiles developed over time provides information on final suction values which can be used to determine the amount of heave or shrink the soil may experience over time after the development of the infrastructure. Although, the TMI can provide a reasonable estimate for the depth to constant suction, measurements appear to be required for estimation of equilibrium suction value. Note that a suction profile obtained at a single time or over a short period of time, may not be best for use in estimating the depth to constant suction for design, particularly for sites that will be heavily irrigated and where water sources are not well controlled. As such, regionally specific or site-specific review of suction profiles over a period of years, and including more than one season and development type, may be necessary to reliably estimate the final design suction profiles, as suggested by (Sun, 2015) and as done for the Denver, CO region (Walsh, Colby, Houston, & Houston, 2009).

5.0 CONCLUSION

5.1 Summary

Expansive soils are extremely problematic and without proper foundation design, damage occurs due to variation in soil suction (moisture) change which results in volume change. Being able to measure suction in expansive soils can be costly and time consuming to the geotechnical engineer, though there have been advancements in testing equipment to allow for accurate results in a timely manner. Soil suction profiles provide the geotechnical engineer the ability to predict the amount of soil movement at the ground surface to aid in foundation design. There is no accepted method to predict the change in suction with depth and many rely on local experience (Briaud, Zhang, & Moon, 2003). A soil suction surrogate is one needed method to allow for suction estimates.

This study herein presented the use of a soil suction surrogate developed by others (Vann, et al., 2018), which applies water content and routinely measured soil index properties, specifically w/LL, and a climatic parameter (TMI), to estimate suction profiles in the field. Depth to constant suction and equilibrium suction magnitudes were estimated from the suction profiles and correlations were explored with the use of TMI, which has been widely accepted by the Australians (AS-2870, 2011) and in the design of post-tensioned slabs (Post-Tensioning Institute 3rd Edition, 2008). The surface flux boundary conditions (i.e. covered or uncovered and irrigated or non-irrigated) and the differences in the field suction profiles were presented. A strong correlation was found between the depth to constant suction and TMI and agreed with published relationships. A very weak correlation between equilibrium suction and TMI was found in the study herein and requires further study. From the results of this study and the poor existing relationship between equilibrium suction and TMI, it can be seen that there are more factors related to equilibrium suction than TMI alone. TMI is more related to the depth to constant suction, and it is possible that once below a certain depth, climatic conditions at the surface will not have as much of an effect on the equilibrium suction value. Other factors may have more of an affect at depth, such as the layering in the soil profile with changing index properties (i.e. plasticity index and hydraulic conductivity), topography (runoff), and surficial soil type. In this study and previous work of others, it has been presented that the depth to constant suction increases as the TMI becomes more negative. This may be an indication of cracking within the soil profile which allows for moisture infiltration to greater depths.

Results found in this study suggest the use of a soil suction surrogate provides a reasonable method to estimate field suction profiles from the use of routinely measured index properties. The surrogate works best when index properties are directly measured, and averages are not used. From the suction profiles, the depth to constant suction and equilibrium suction values may be obtained, while providing reasonable estimations as seen from the comparisons presented herein. The depth to constant suction provided the best results with regard to correlation with TMI and agrees with studies which have been published in the literature. Regarding equilibrium suction, there was a poor correlation with TMI value for a given site.

5.2 Recommendations

While the measurement of soil suction in expansive clays is difficult to measure and can be costly and time consuming, the use of a soil suction surrogate provides reasonable alternative for estimating suctions in the field with the use of routinely measured index properties. It is important to note that in order to determine an equilibrium suction and a depth, laboratory testing should be done to an adequate depth. The use of test borings extending to a sufficient depth, i.e. well below the active zone, should be completed for every site where expansive soils exist. Based on this study, the minimum depth of test borings for expansive soil sites in expansive soil areas with negative TMI is 5 to 6 meters (16.4 to 19.69 feet). Furthermore, bulk disturbed samples are recommended at regular intervals throughout the entire depth of the test boring, not just toward the surface. For example, it is recommended that such samples be obtained every 0.76 meters (2.5 feet).

Bulk disturbed samples retrieved from the test borings should be tested for moisture content, Atterberg Limits, P200, and total suction by means of the usage of a WP4-C device. Valuable information pertaining to the magnitude of constant suction, suction range with depth, and the probable determination of the depth to constant suction should be obtained for every site.

In addition to that which should be completed in terms of the geotechnical protocol at each site, we recommend further study along the lines presented herein to add to the data points with regard to the magnitudes of equilibrium suction and depths to constant suction for sites covering the entire range of TMIs (60 to -60) and filling in the gaps.

Within the research of expansive soils, further study is needed for the relationship between equilibrium suction and TMI. Currently, there are few relationships, including the relationship presented in this study, and they have shown to be poor correlations with TMI. As part of this ongoing research, Singhar (2018) investigates the use of TMI and attempts to find an improved correlation while comparing TMI values when using 30-year, 5-year, and 1-year weather data to obtain a TMI index. This study benefited greatly from the use of the soil suction surrogate to estimate soil suction in the field from routinely measured index properties. Estimated field suction profiles are able to be added to the overall study regarding soil suction in unsaturated soils. It was noted that the effort that went into developing the soil suction surrogate applied measured suctions from dry climates, as a majority. Further studies to improve the soil suction surrogate from gathering measured suction data, with depth, from wet climates (high TMI ranges), may be warranted. The correlation was poor between equilibrium suction and TMI, as a whole, and overall there were not many data points from high TMI ranges.

This work is based in part on research funded by the National Science Foundation under Award No. 1462358. The opinions, conclusions, and interpretations are those of the author and not necessarily the National Science Foundation.

REFERENCES

Adem, H. H., & Vanapalli, S. K. (2015). Review of Methods for Presidicting In-Situ Volume Change Movement of Expansive Soil Over Time. *Journal of Roch Mechanics and Geotechnical Engineering*, 73-86.

AS-2870. (2011). Residential Slabs and Footings. *Australian Standards*.

ASTM D4546. (2014). Standard Test Method for one-dimensional swell or settlement potential of cohesive soils.

ASTM D5298. (2016). Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper. *American Standards for Testing and Materials*.

Aubeny, C., & Long, X. L. (2007). Moisture Diffusion in Shallow Clay Masses. *Journal of Geotechnical and Geoenvironmental Engineering, Vol. 133, No. 10,* 12411248.

Briaud, J.-L., Zhang, X., & Moon, S. (2003). Shrink Test - Water Content Method for Shrink and Swell Predictions. *Journal of Geotechnical and Geoenvironmental Engineering, Vol. 129, No. 7,* 590-600.

Bryant, J. (1998). Variation of Soil Suction with Depth in Dallas and Forth Worth, TX. *Trasportation Research Record*, 100-104.

Dye, H., Zapata, C., & Houston, S. (2006). Geotechnical Evaluation of the Design of Post-Tensioned Slabs on Expansive Soils Using the PTI Thrid Edition Procedure for Arizona Conditions. *Proceedings, 4th Internations Conference on Unsaturated Soils.* Reston, VA: ASCE.

Fityus, S., & Buzzi, O. (2008). On The Use of The Thornthwaite Moisture Index to Infer Depths of Seasonal Moisture Change. *Australian Geomechanics, Vol. 43, No. 4*, 69-76.

Fityus, S., Walsh, P., & Kleeman, P. (1998). The Influence of Climate as Expressed by the Thornthwaite Index on the design depth of moisutre change of clay soils in the Hunter Valley. Springwood, Australia: Conference on Geotechnical Engineering and Engineering Geology in the Hunter Valley (pp. 251-265). Conference Publications.

Fredlund, D. G., Rahardjo, H., & Fredlund, M. D. (2012). *Unsaturated Soil Mechanics In Engineering Practice.* Hoboken, New Jersey: John Wiley & Sons, Inc.

Houston, S. L., Dye, H. B., Zapata, C. Z., Walsh, K. D., & Houston, W. N. (2011). Study of Expansive Soils and Residential Foundations on Expansive Soils in Arizona. *Journal of Performance of Contructed Faciliities, Vol. 25, No.1*, 31-44.

Li, J., & Zhou, A. (2017). Assessment of the Impact of Climate Change on Exapansive Soil Movements and Site Classification. *Austalian Geomechanics Journal. Vol. 52, No. 3*, 39-50.

Lytton, R. L. (1997). Engineering Structures in Expansive Soils. *Proceedings of the Third Brazilian Symposium on Unsaturated Soils,* (pp. Vol. 2, 550-562). Rio De Janiero, Brazil.

Marinho, F. A. (1994). *Shrinkage Behavior of Some Plastic Soils.* London, U.K.: Ph.D Dissertation, University of London, Imperial College of Science, Technology and Medicine.

Mckeen, G. R., & Johnson, L. D. (1990). Climate-Controlled Soil Design Parameters for Mat Foundations. *Journal of Geotechnical Engineering, Vol. 116, No. 7*, 1073-1094.

McKeen, R. G. (1981). *Design of Airport Pavements for Expansive Soils.* Washington, D.C.: DOT/FAA/RD-81/25. Systems Research and Development Service, Federal Aviation Administration.

McQueen, I., & Miller, R. (1968). Calibration and Evaluation of a Wide Range Gravimetric Method for Measuring Moisture Stress. *Soil Science. Vol. 106*, 225-231.

Meter Group, Inc. (2018). *WP4C Dew Point PotentiaMeter Operator's Manual.* Pullman, WA: Meter Group, Inc.

Mitchell, P. W. (2008). Footing Design for Residential Type Structures in Arid Climates. *Australian Geomechanics. Vol. 43, No. 4*, 51-68.

Naiser, D. D. (1997). Procedures To Predict Vertical Differential Soil Movement for Expansive Soils. College Station, AZ: Thesis, Texas A&M University.

Nelson, J. D., Chao, K. C., Overton, D. D., & Nelson, E. J. (2015). *Foundation Engineering for Expansive Soils.* Hoboken, NJ: John Wiley and Sons, Inc.

Nelson, J. D., Overton, D. D., & Durkee, D. B. (2001). Depth of Wetting and The Active Zone. *Expansive Clay Soils and Vegetative Influence on Shallow Foundations* (pp. 95-109). Houston, TX: ASCE.

Olaiz, A., Singhar, S., Vann, J., & Houston, S. (2017). Comparison and Applications of the Thornthwaite Moisture Index using GIS. *Proceeding of the 2nd Pan American Conference on Unsaturated Soils.* Dallas, TX: Vol. 1, ASCE.

Post-Tensioning Institute. (2004). *Design of Post-Tensioned Slabs-on-Ground.* Phoenix: 3rd Edition, Post-Tensioning Institute.

Russam, K., & Coleman, J. D. (1961). The Effect of Climatic Factors on Subgrade Moisture Conditions. *Geotechnique, Vol. 11, No. 1*, 22-28.

Smith, R. (1993). Estimating Soil Movements in New Areas. *Seminar - Extending the Code beyond Residential Slabs and Footings.* The Institution of Engineers, Australia.

Vann, J. (2018, in progress). A Suction-Oedometer Method and Design Soil Suction Profile Recommendations for Estimation of Volume Change of Expansive Soils. Tempe, AZ: PhD Disseration, Arizona State University.

Vann, J., Houston, S., Houston, W., Singhar, S., Cuzme, A., & Olaiz, A. (2018). A Soil Suction Surrogate and Its Use in the Suction-Oedometer Method for Computation of Volume Change of Expansive Soils. *Pan American Conference on Unsaturated Soils.* Hong Kong.

Walsh, K. D., Colby, C. A., Houston, W. N., & Houston, S. L. (2009). Method for Evaluation of Depth of Wetting in Residential Areas. *Journal of Geotechnical and Geoenvironmental Engineering, Vol. 135, No. 2*, 169-176.

Wray, W. K. (1978). Development of a Design Procedure for Residential and Light Commercial Slabs-on-Ground Constructed Over Expansive Soils. College Station, TX: Ph.D. Dissertation. Texas A&M University.

Wray, W. K. (1989). *Mitigation of Damage to Structures Supported on Expansive Soils.* Final Report., National Science Foundation. Vol. 1.

Wray, W., & Meyer, K. (2004). Expansive Clay Soil. A Widspread and Costly Geohazard. *Geo-Strata*, 24-28.

Yue, E. (2009). *Soil Matric Suction and Active Zone Depth in Oklahoma.* Sillwater, Ok: Thesis. Oklahoma State University.

APPENDIX A

DEPTH OF CONSTANT SUCTION AND EQUILIBRIUM SUCTION VALUES FOR A GIVEN SITE

Table 11: Uncovered and Covered Surrogate data

Location	Covered/ Uncovered	TMI (2006)	Avg. LL	Depth to Constant Suction (ft)	Depth to Constant Suction (m)	Equilibrium Suction (pF)
Killeen, TX	Uncovered	-5	55	7	2.1336	3.80
Breckenridge, TX	Uncovered	-10	45	4	1.2192	4.25
Snyder, TX	Uncovered	-19	9	9	2.7432	4.00
Fort Worth, TX	Uncovered	3	56	6	1.8288	4.20
Vidor, TX	Uncovered	34	49	4	1.2192	3.80
San Antonio, TX	Uncovered	-17	67	10	3.048	4.20
Austin, TX	Uncovered	-18	71	9	2.7432	4.00
Universal City, TX	Uncovered	-10	55	7	2.1336	4.20
Los Fresnos, TX	Uncovered	-30	61	11	3.3528	3.80
Shertz, TX	Uncovered	-6	51	9	2.7432	3.90
Cibolo, TX	Uncovered	-6	59	9	2.7432	4.20
Kyle, TX	Uncovered	-5	62	4	1.2192	4.10
Friendswood, TX	Uncovered	22	44	3	0.9144	40
Converse, TX	Uncovered	-6	57	8	2.4384	4.40
Cross Roads, TX	Uncovered	5	50	6	1.8288	4.20
Laredo, TX	Uncovered	-40	39	14	4.2672	4.10
McAllen, TX	Uncovered	-38	47	14	4.2672	3.90
Dallas, TX	Uncovered	-2	57	4	1.2192	4.20
San Antonio, TX	Uncovered	-17	51	11	3.3528	4.00
Keller, TX	Uncovered	3	46	5	1.524	4.00
McAllen, TX	Uncovered	-40	55	14	4.2672	4.20
Houston, TX	Uncovered	9	53	5	1.524	4.10
Hewitt, TX	Uncovered	2	53	6	1.8288	4.10
McAllen, TX	Uncovered	-40	49	10	3.0480	4.10
Amarillo, TX	Uncovered	-18	38	7	2.1336	4.10
Fountain, CO	Uncovered	-16	36	10	3.0480	4.20
Yukon, OK	Uncovered	3	43	7	2.1336	4.00
Broken Arrow, OK	Uncovered	24	44	5	1.5240	3.70
Hazel Green, AL	Uncovered	57	53	4	1.2192	3.50
Prosper, TX[1]	Uncovered	23	56	-	-	4.00
Atascocita, TX[1]	Uncovered	29	53	-	-	4.10
Norman, OK[1]	Uncovered	18	40	-	-	3.70
Meridian, MS[1]	Uncovered	48	64	-	-	3.90
Harker Heights, TX[1]	Uncovered	-5	45	-	-	4.20

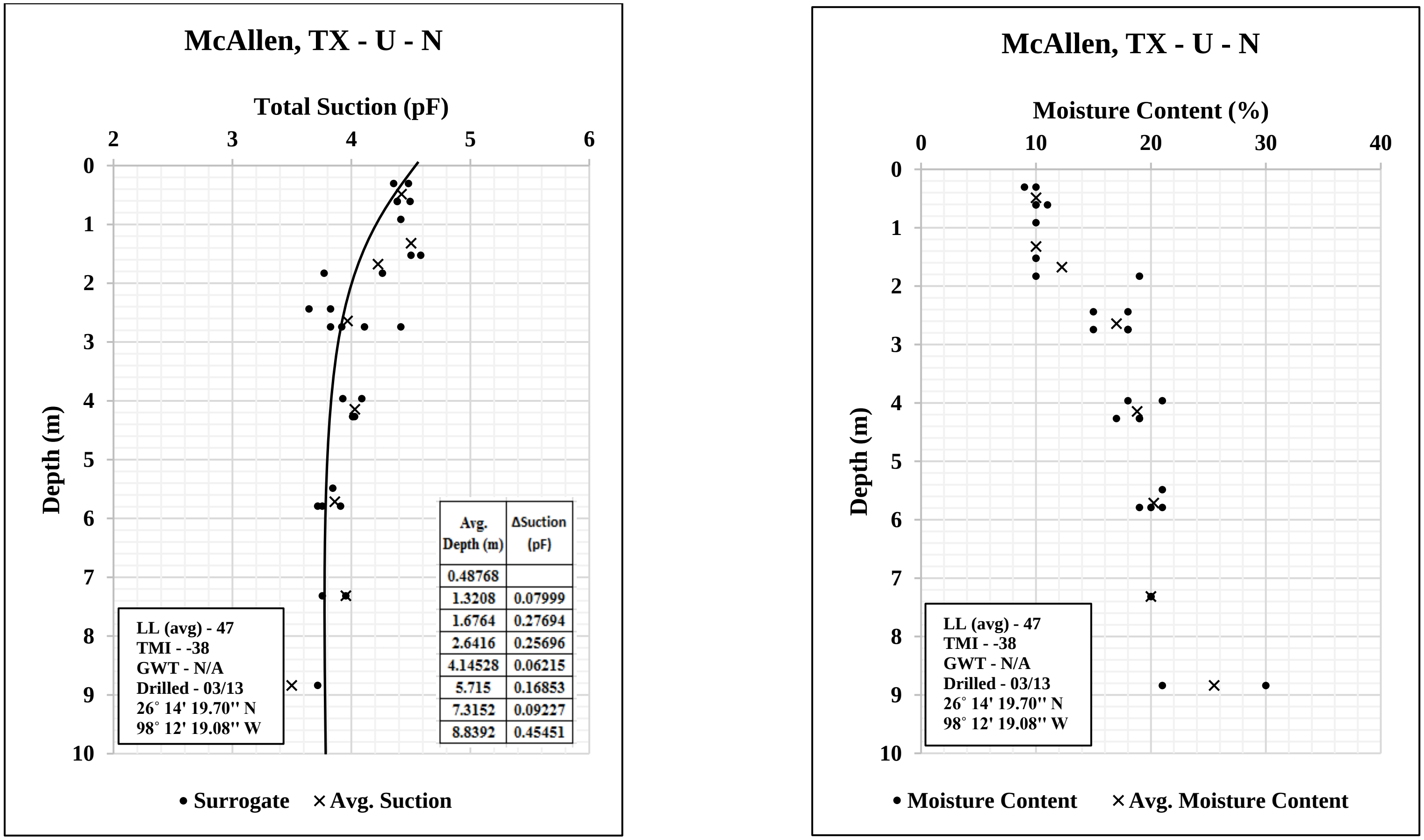
Location	Covered/ Uncovered	TMI (2006)	Avg. LL	Depth to Constant Suction (ft)	Depth to Constant Suction (m)	Equilibrium Suction (pF)
Killeen, TX	Uncovered	-5	55	7	2.1336	3.80
Aurora, CO[1]	Uncovered	-21	55	-	-	3.90
Hattiesburg, MS[1]	Uncovered	50	54	-	-	4.00
Wheat Ridge, CO[1]	Uncovered	-12	52	-	-	3.90
Wheat Ridge, CO[1]	Uncovered	-12	57	-	-	3.90
Wylie, TX[1]	Uncovered	9	69	-	-	4.00
Burleson, TX[2]	Uncovered	5	51	6	1.8288	4.10
Amarillo, TX[2]	Uncovered	-18	39	9	2.7432	4.10
Kaufman, TX[2]	Uncovered	10	69	6	1.8288	4.10
Grand Prairie, TX[2]	Uncovered	-0	55	14	4.2672	3.90
Amarillo, TX[2]	Uncovered	-18	35	9	2.7432	4.00
Elign, TX[2]	Uncovered	-7	68	14	4.2672	4.10
Oklahoma, OK	Covered	3	36	-	-	3.90
Warr Acres, OK	Covered	3	34	-	-	3.60
Fort Worth, TX	Covered	-3	60	-	-	4.00
Richardson, TX	Covered	-2	63	-	-	4.00
Dallas, TX	Covered	-2	55	-	-	4.00
Tulsa, OK	Covered	19	46	-	-	4.00
Keller, TX	Covered	3	39	-	-	3.90
Tolleson, AZ	Covered	-54	39	-	-	3.90
Colorado Springs, CO	Covered	-16	39	-	-	3.90
Garland, TX	Covered	-2	67	-	-	3.90
Moore, OK	Covered	9	42	-	-	3.90
Arvada, CO	Covered	-12	40	-	-	4.00
Houston, TX	Covered	12	53	-	-	3.90
Houston, TX	Covered	12	56	-	-	3.90

[1] Depths to constant suction were not able to be determined

[2] Locations where an average LL from shallower depths was used to apply suction surrogate at deeper depths where index properties were not measured

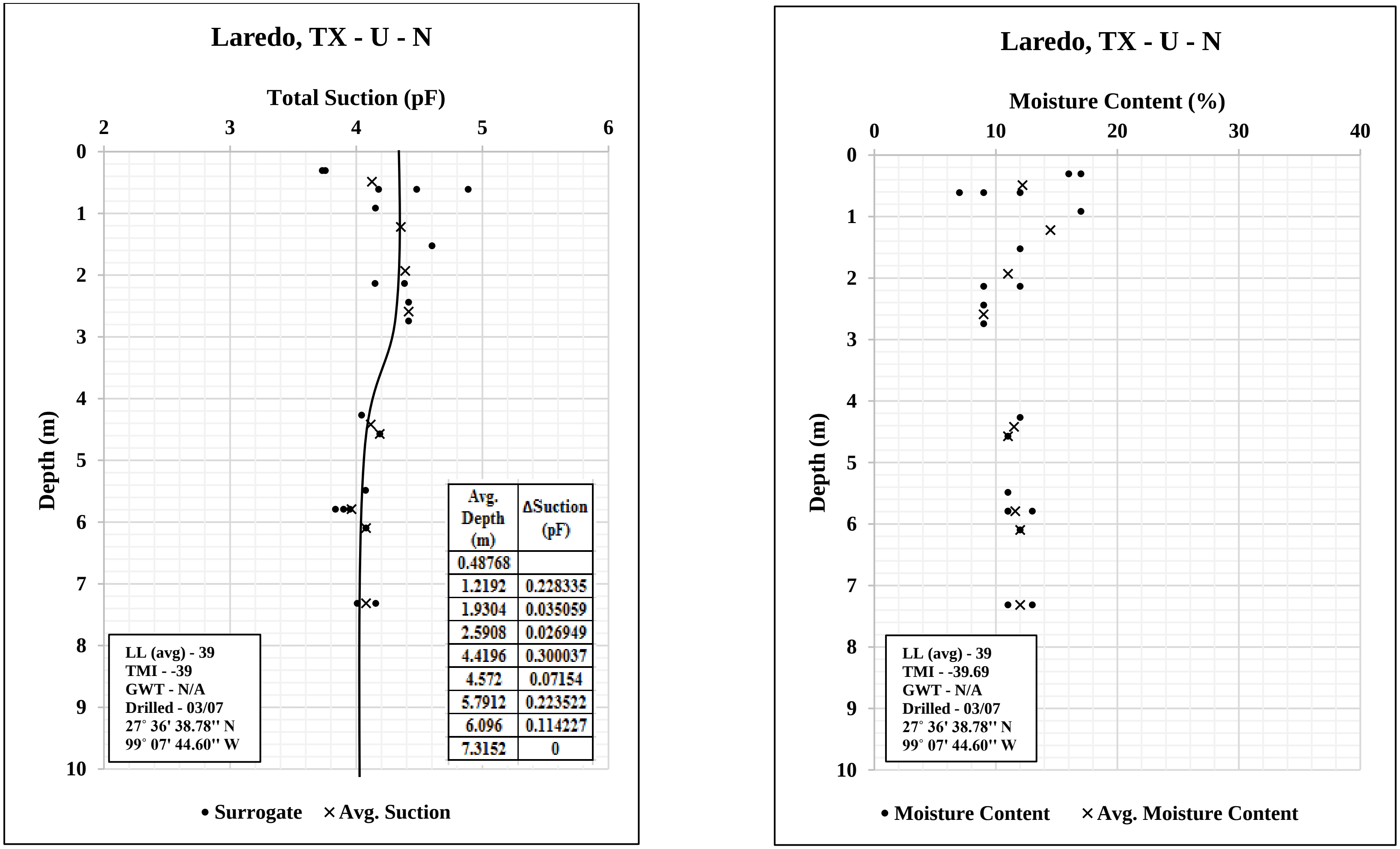
APPENDIX B

UNCOVERED/ NON-IRRIGATED FIELD SUCTION AND MOISTURE PROFILES



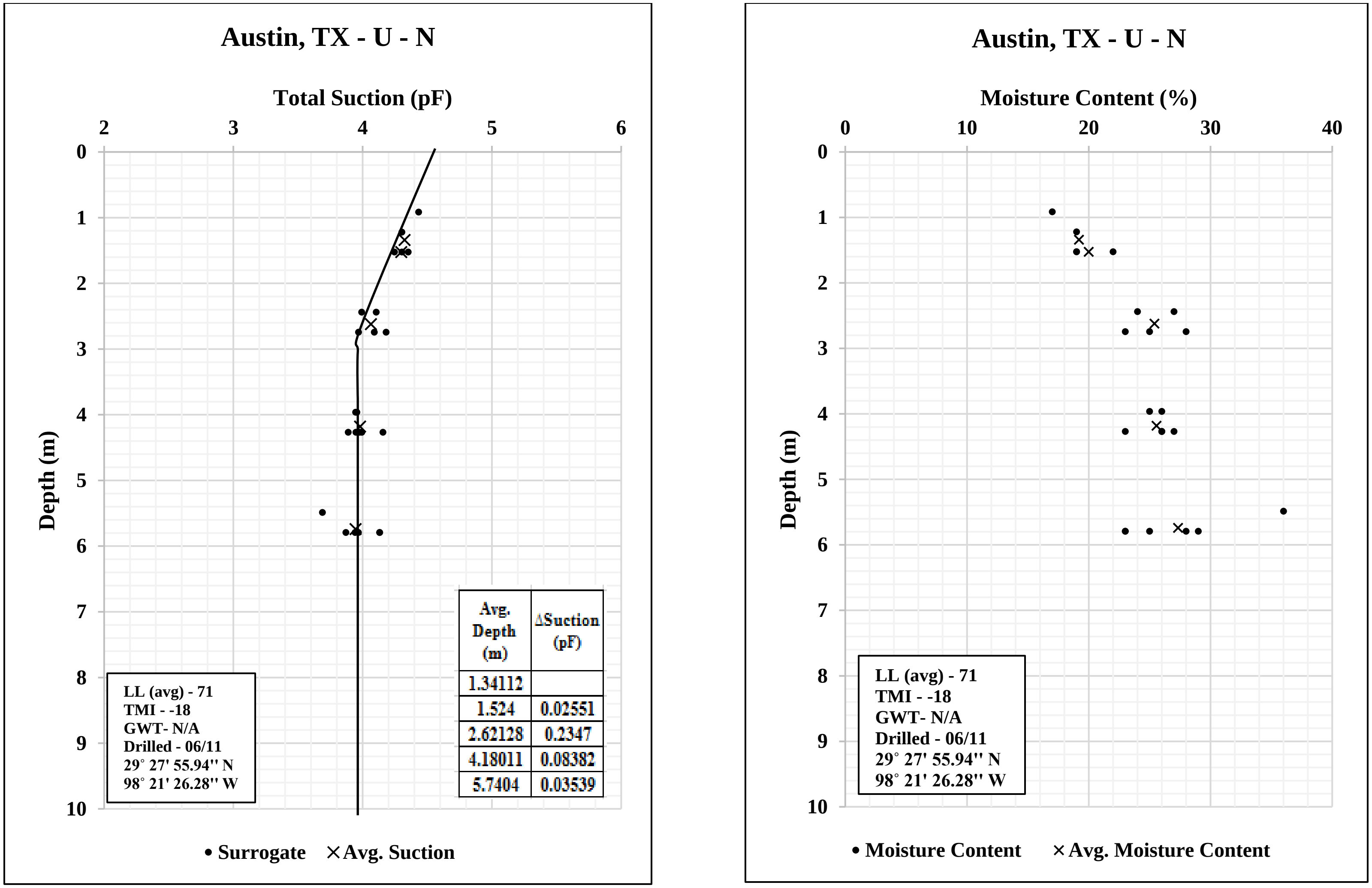
Avg. Depth (m)	ΔSuction (pF)
0.48768	
1.3208	0.07999
1.6764	0.27694
2.6416	0.25696
4.14528	0.06215
5.715	0.16853
7.3152	0.09227
8.8392	0.45451

Figure 36: Field Suction Profile (left) and Moisture Content Profile (right) for McAllen, TX



Avg. Depth (m)	ΔSuction (pF)
0.48768	
1.2192	0.228335
1.9304	0.035059
2.5908	0.026949
4.4196	0.300037
4.572	0.07154
5.7912	0.223522
6.096	0.114227
7.3152	0

Figure 37: Field Suction Profile (left) and Moisture Content Profile (right) for Laredo, TX

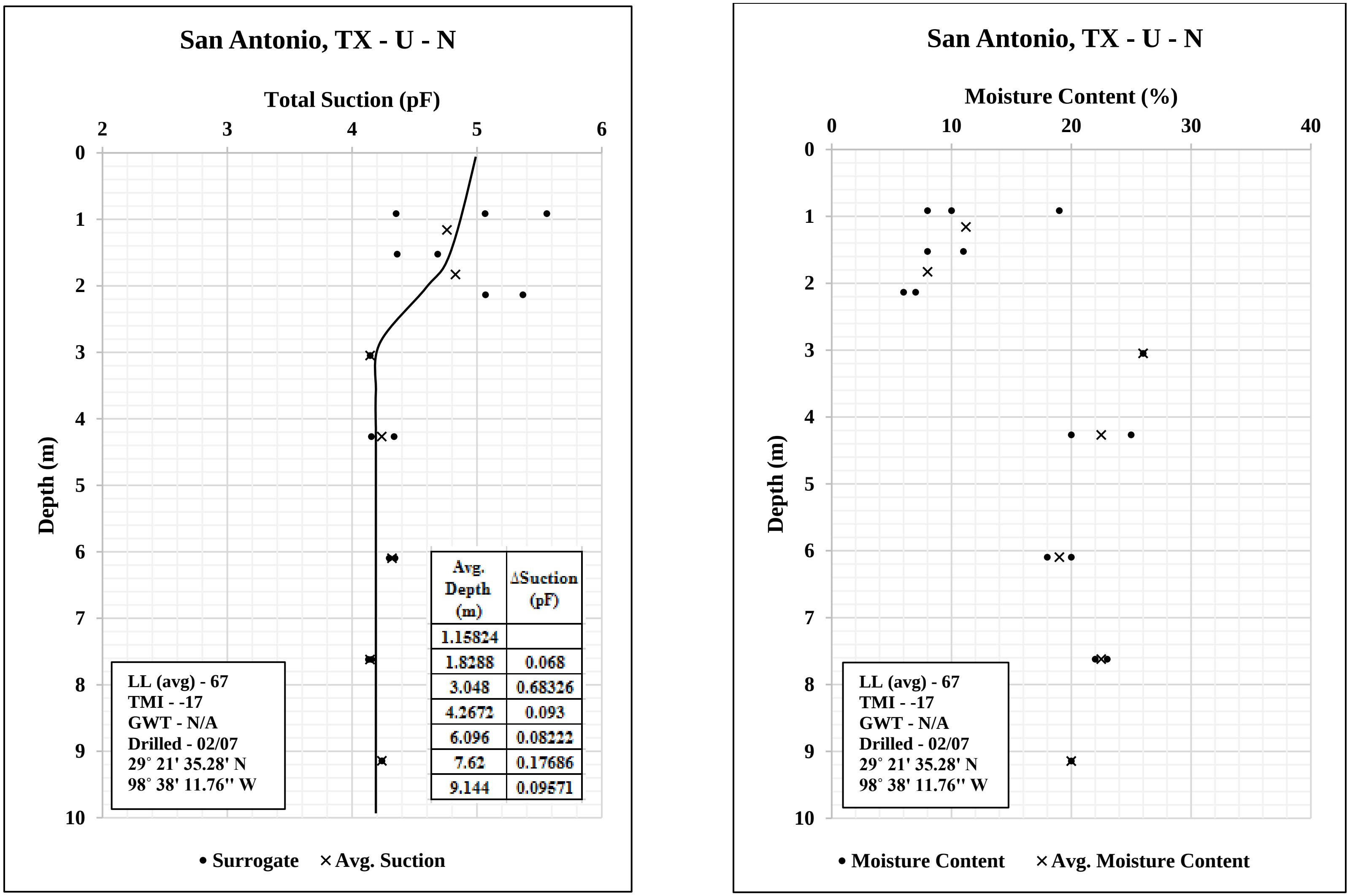


Avg. Depth (m)	ΔSuction (pF)
1.34112	
1.524	0.02551
2.62128	0.2347
4.18011	0.08382
5.7404	0.03539

LL (avg) - 71
TMI - -18
GWT- N/A
Drilled - 06/11
29° 27' 55.94'' N
98° 21' 26.28'' W

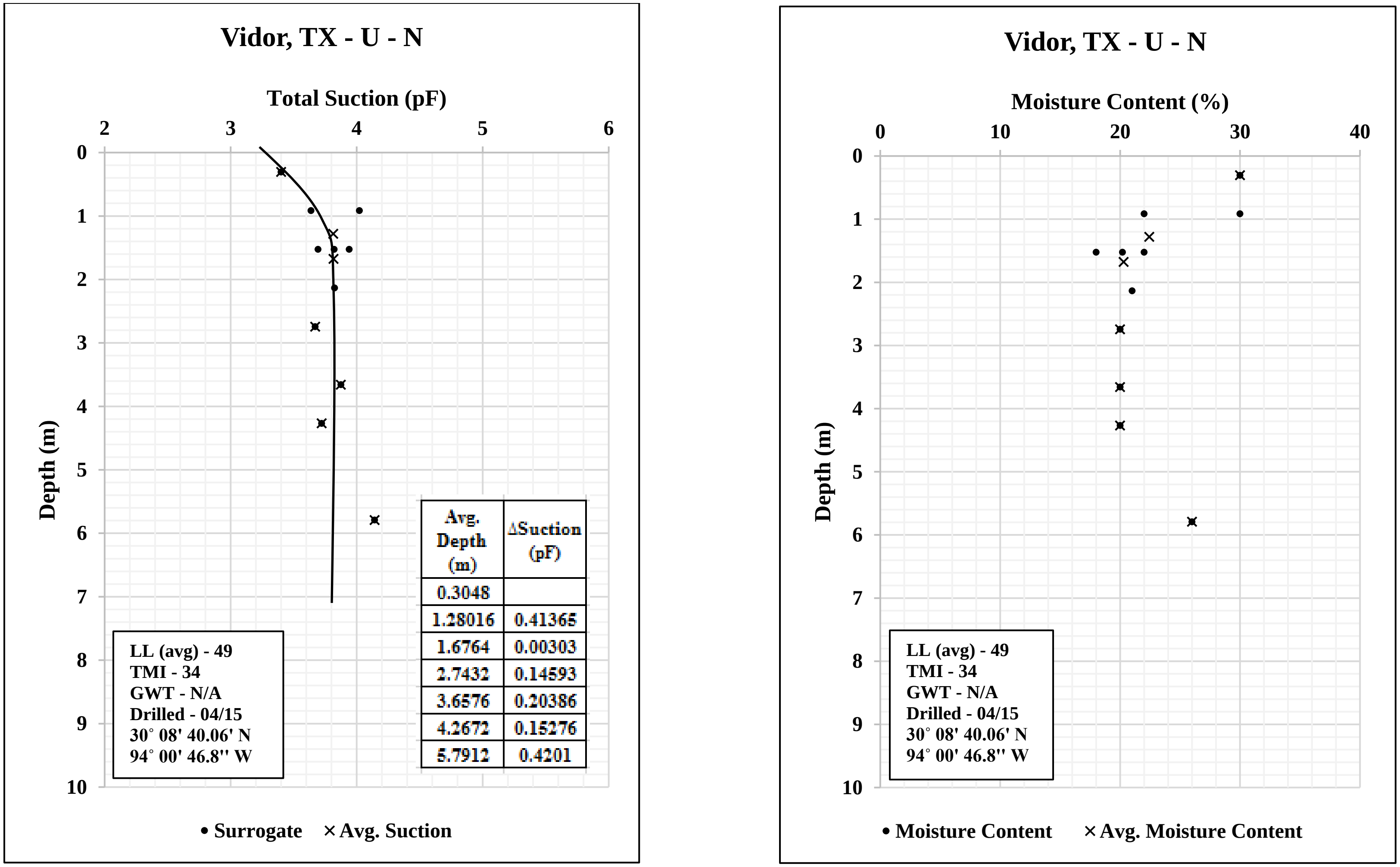
LL (avg) - 71
TMI - -18
GWT- N/A
Drilled - 06/11
29° 27' 55.94'' N
98° 21' 26.28'' W

Figure 38: Field Suction Profile (left) and Moisture Content Profile (right) for Austin, TX



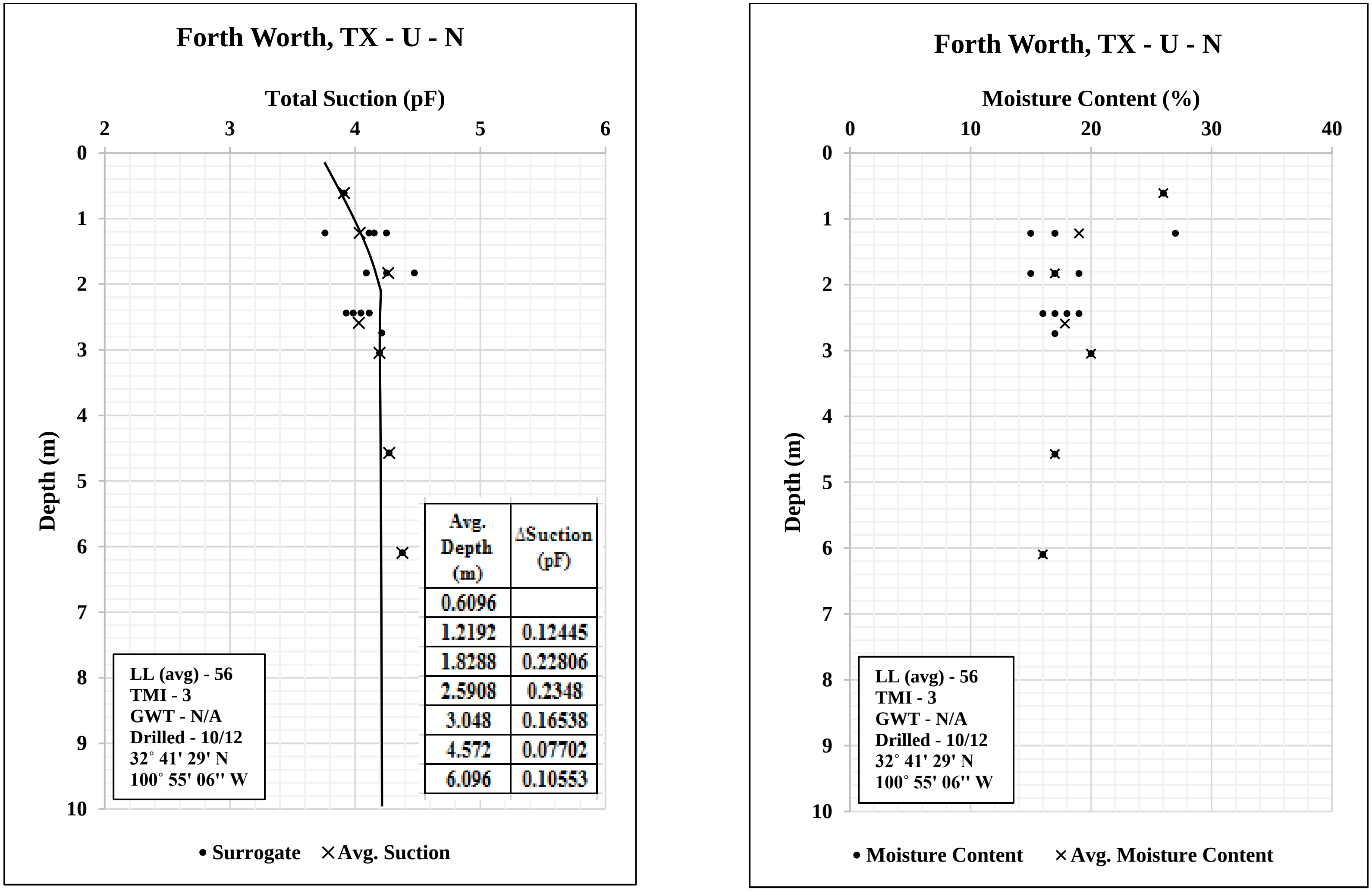
Avg. Depth (m)	ΔSuction (pF)
1.15824	
1.8288	0.068
3.048	0.68326
4.2672	0.093
6.096	0.08222
7.62	0.17686
9.144	0.09571

Figure 39: Field Suction Profile (left) and Moisture Content Profile (right) for San Antonio, TX



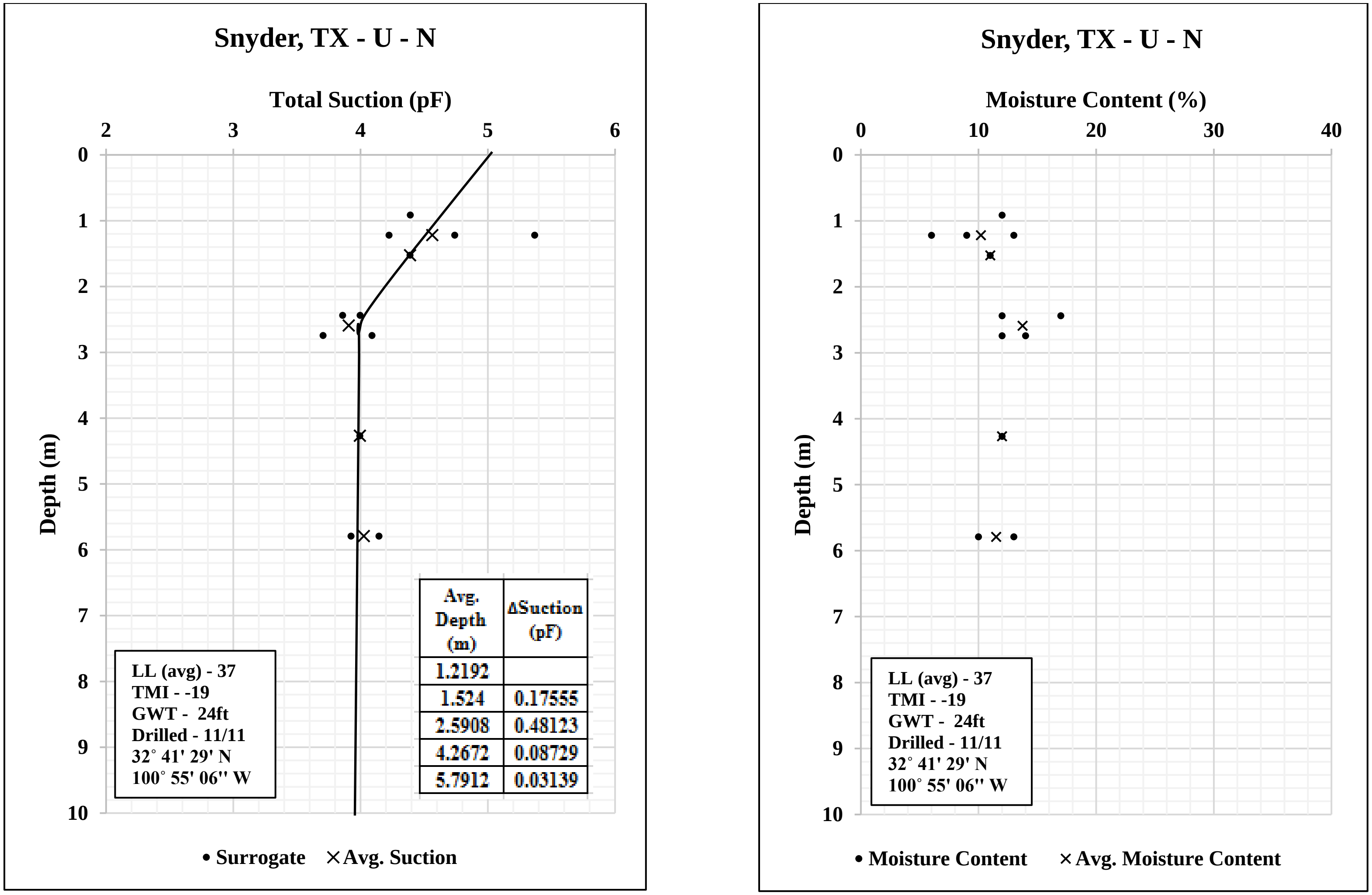
Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.28016	0.41365
1.6764	0.00303
2.7432	0.14593
3.6576	0.20386
4.2672	0.15276
5.7912	0.4201

Figure 40: Field Suction Profile (left) and Moisture Content Profile (right) for Vidor, TX



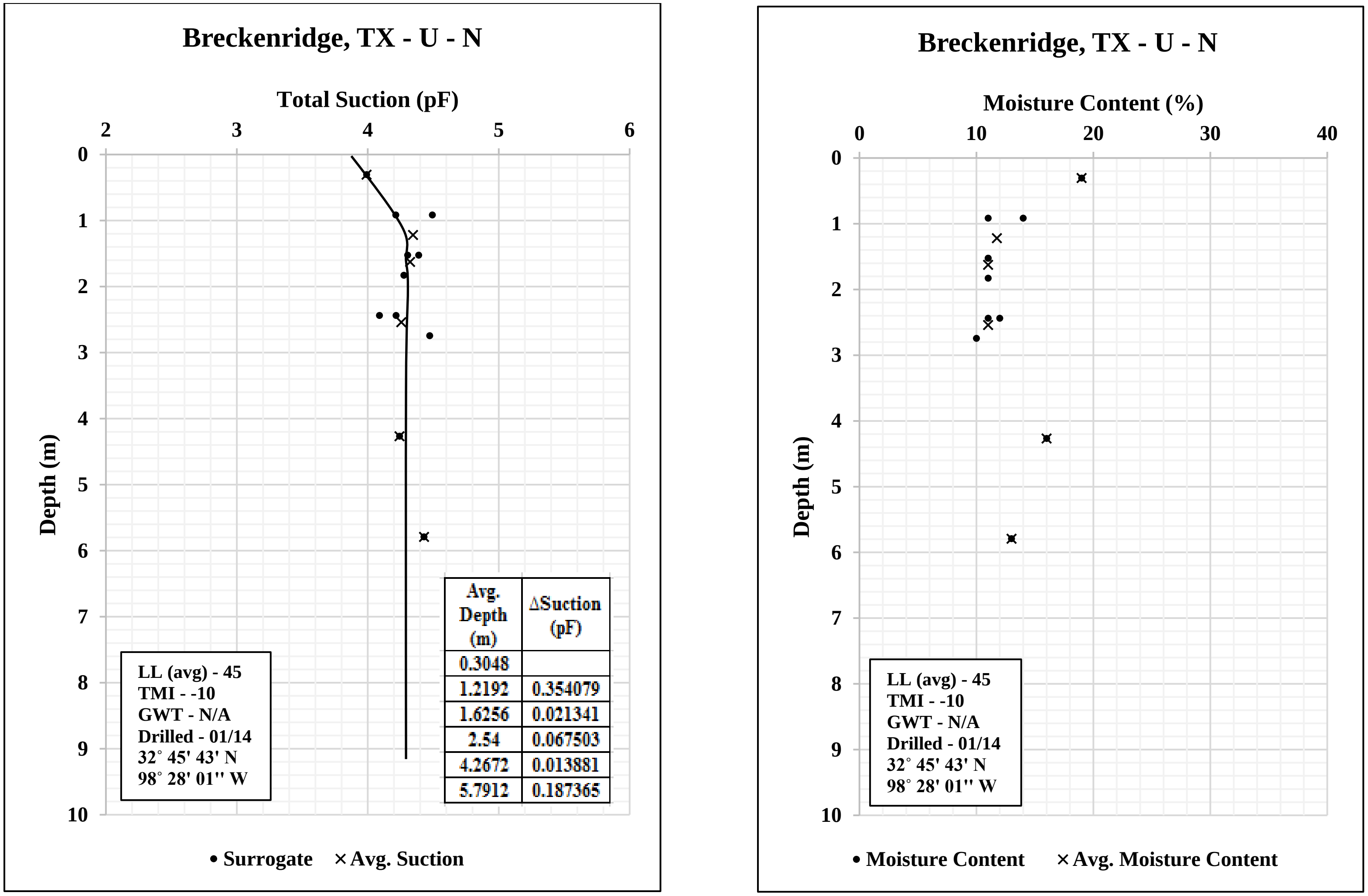
Avg. Depth (m)	ΔSuction (pF)
0.6096	
1.2192	0.12445
1.8288	0.22806
2.5908	0.2348
3.048	0.16538
4.572	0.07702
6.096	0.10553

Figure 41: Field Suction Profile (left) and Moisture Content Profile (right) for Forth Worth, TX



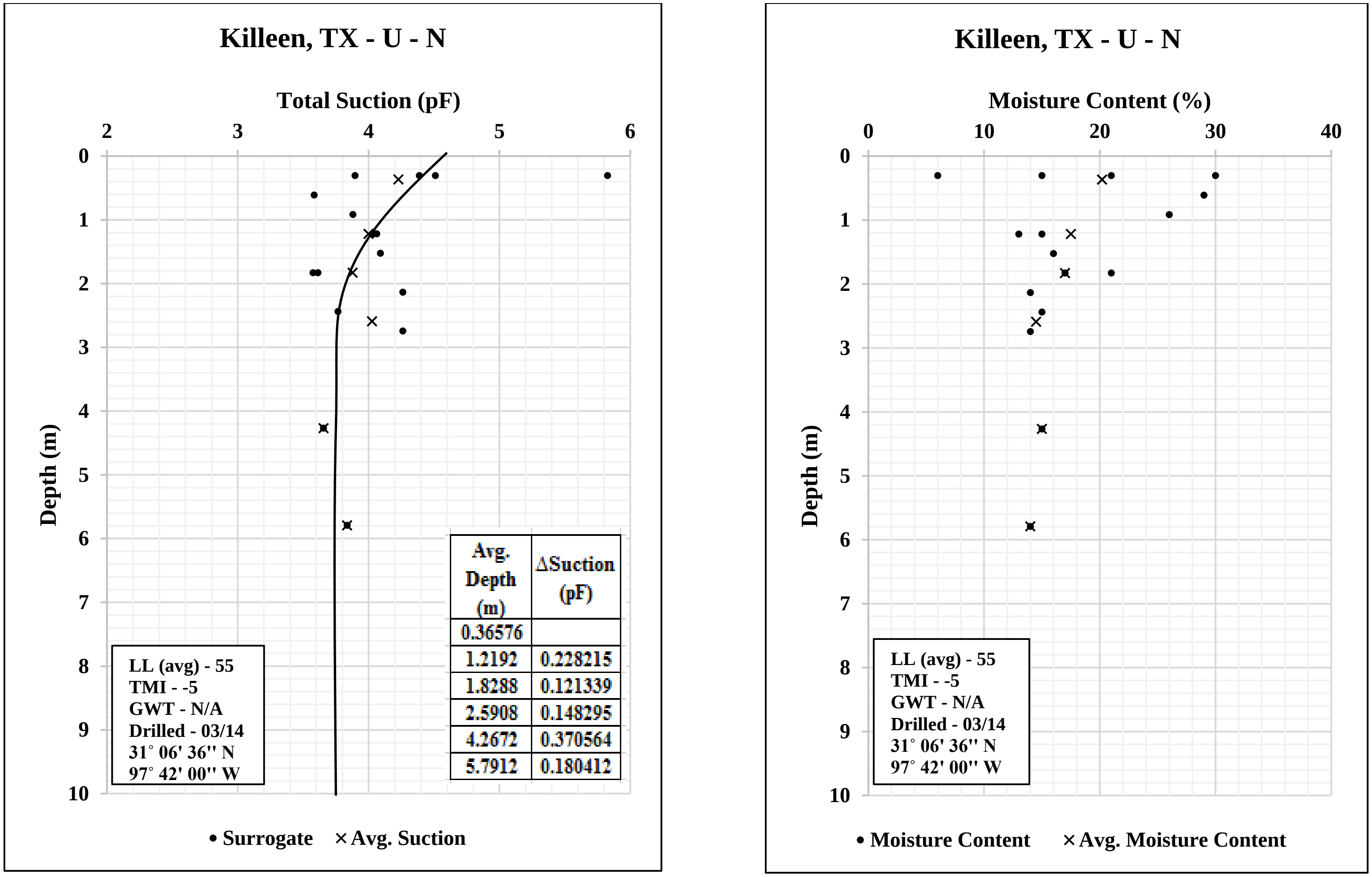
Avg. Depth (m)	ΔSuction (pF)
1.2192	
1.524	0.17555
2.5908	0.48123
4.2672	0.08729
5.7912	0.03139

Figure 42: Field Suction Profile (left) and Moisture Content Profile (right) for Snyder, TX



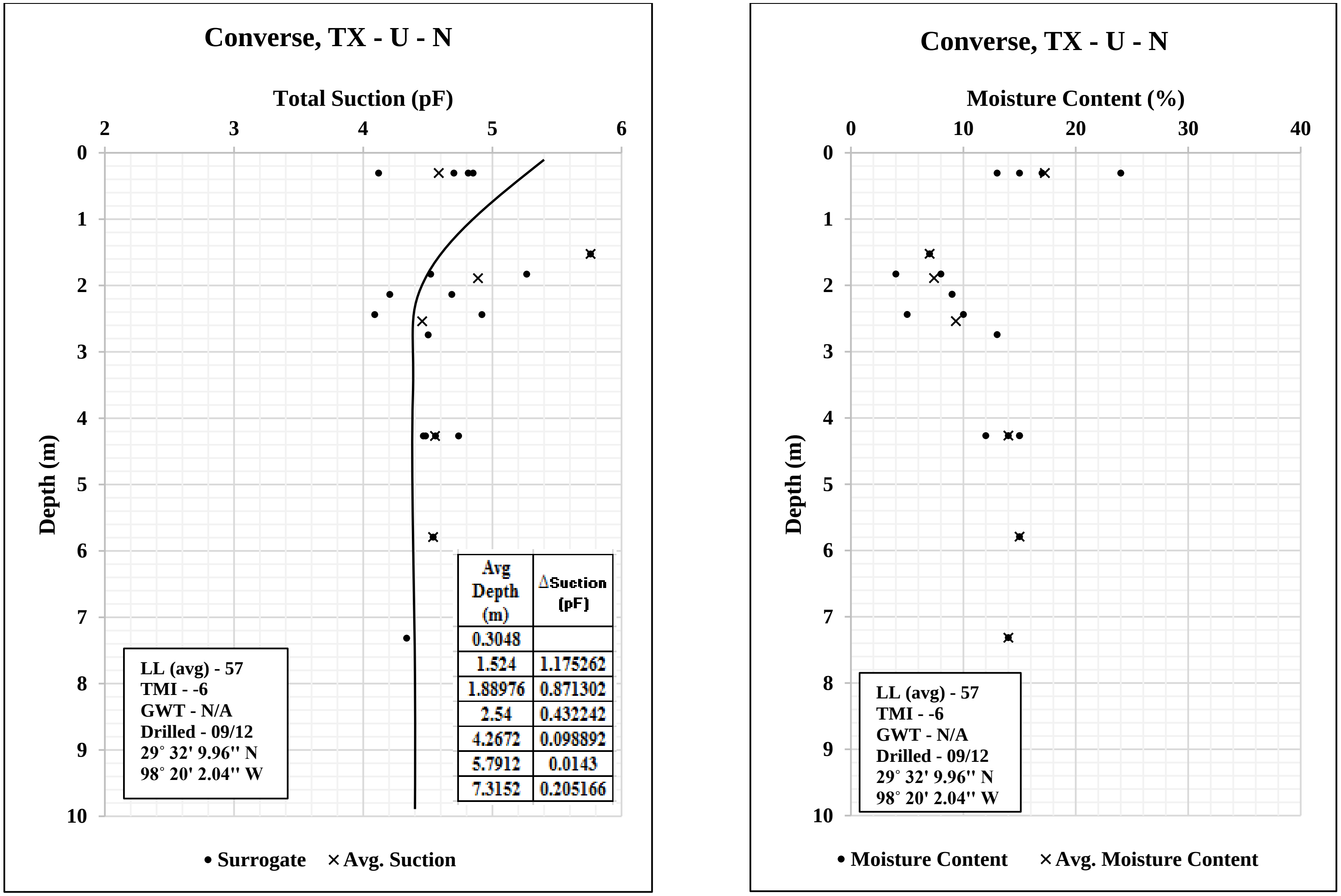
Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.2192	0.354079
1.6256	0.021341
2.54	0.067503
4.2672	0.013881
5.7912	0.187365

Figure 43: Field Suction Profile (left) and Moisture Content Profile (right) for Breckenridge, TX



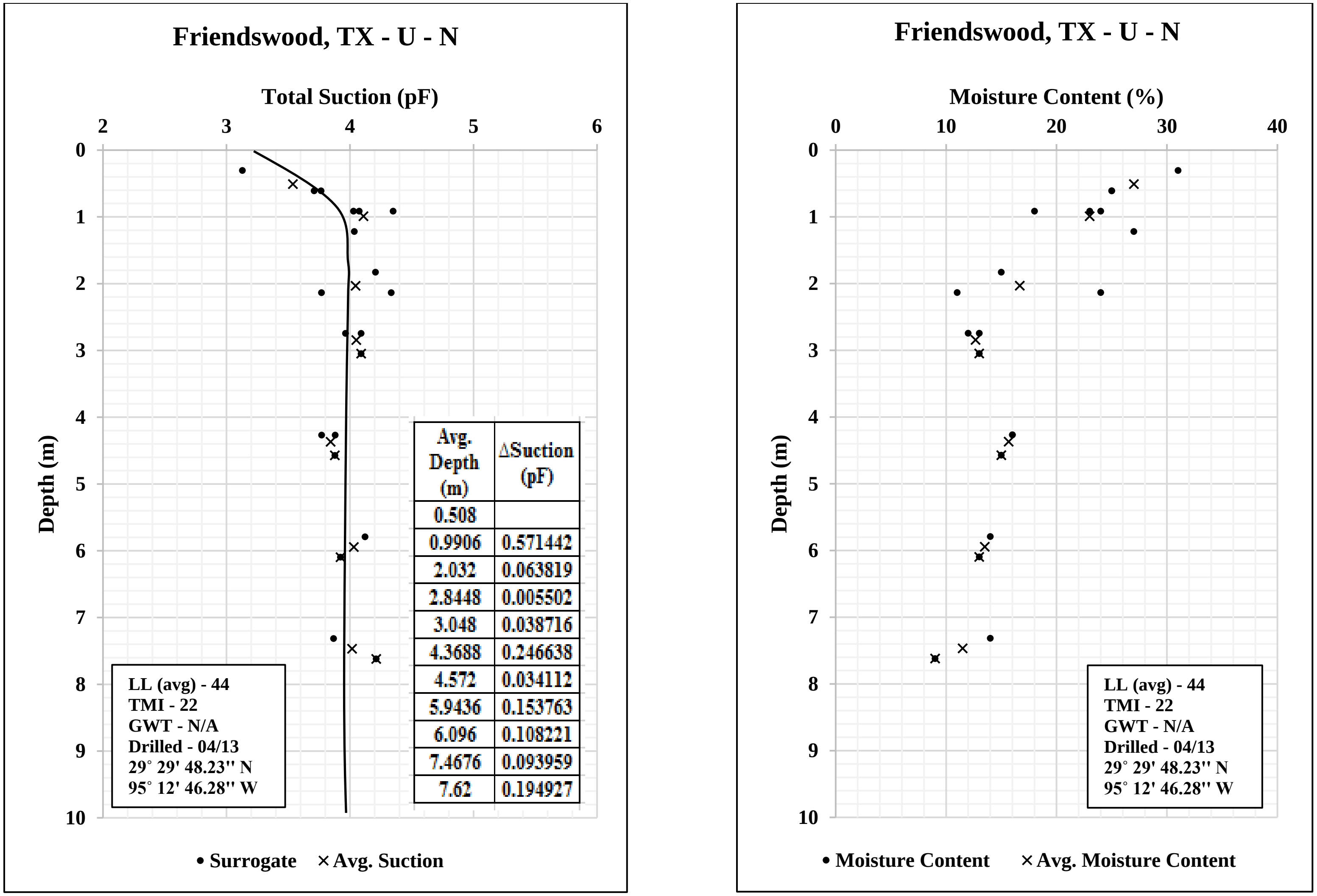
Avg. Depth (m)	ΔSuction (pF)
0.36576	
1.2192	0.228215
1.8288	0.121339
2.5908	0.148295
4.2672	0.370564
5.7912	0.180412

Figure 44: Field Suction Profile (left) and Moisture Content Profile (right) for Killeen, TX



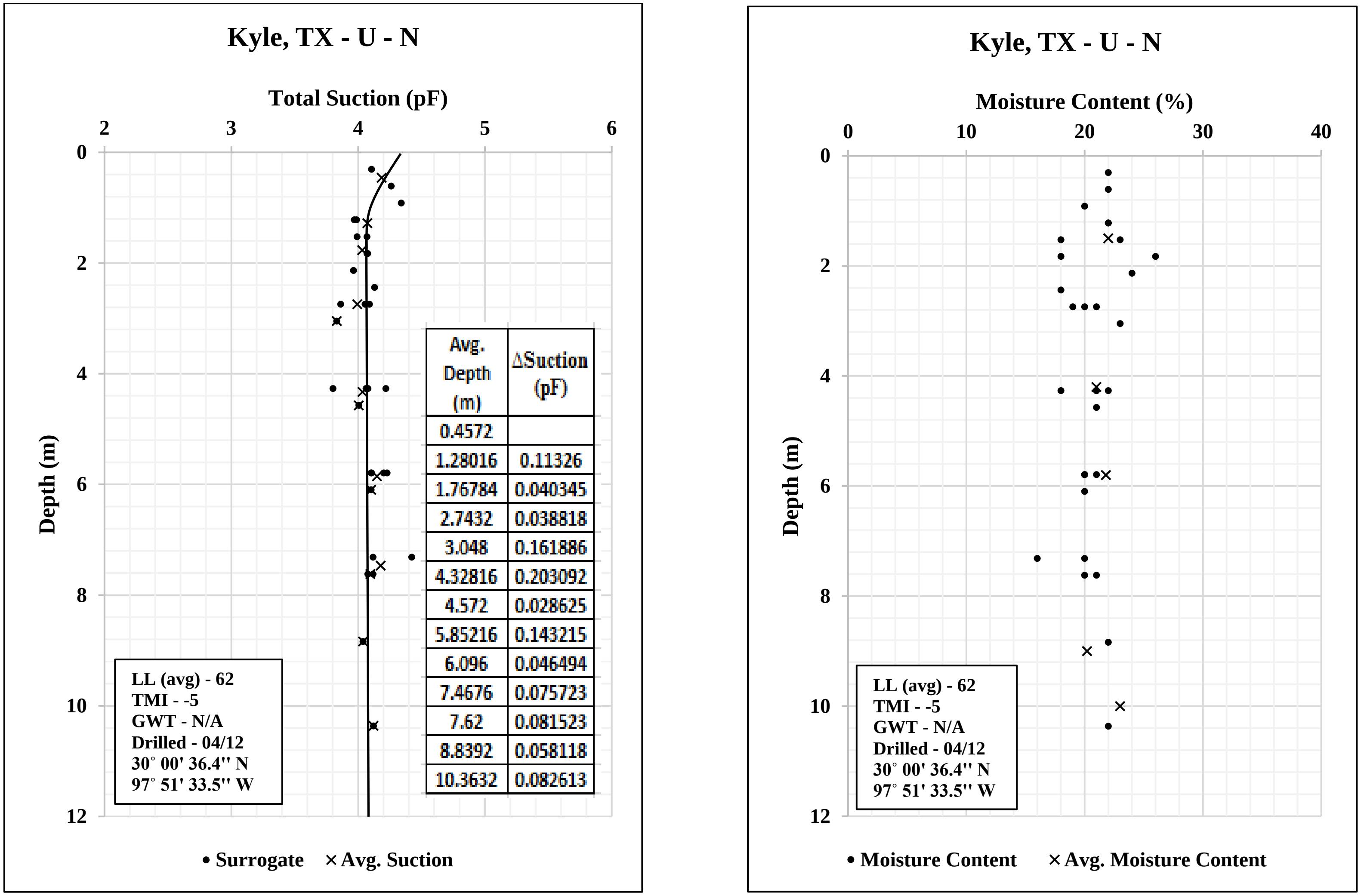
Avg Depth (m)	ΔSuction (pF)
0.3048	
1.524	1.175262
1.88976	0.871302
2.54	0.432242
4.2672	0.098892
5.7912	0.0143
7.3152	0.205166

Figure 45: Field Suction Profile (left) and Moisture Content Profile (right) of Converse, TX



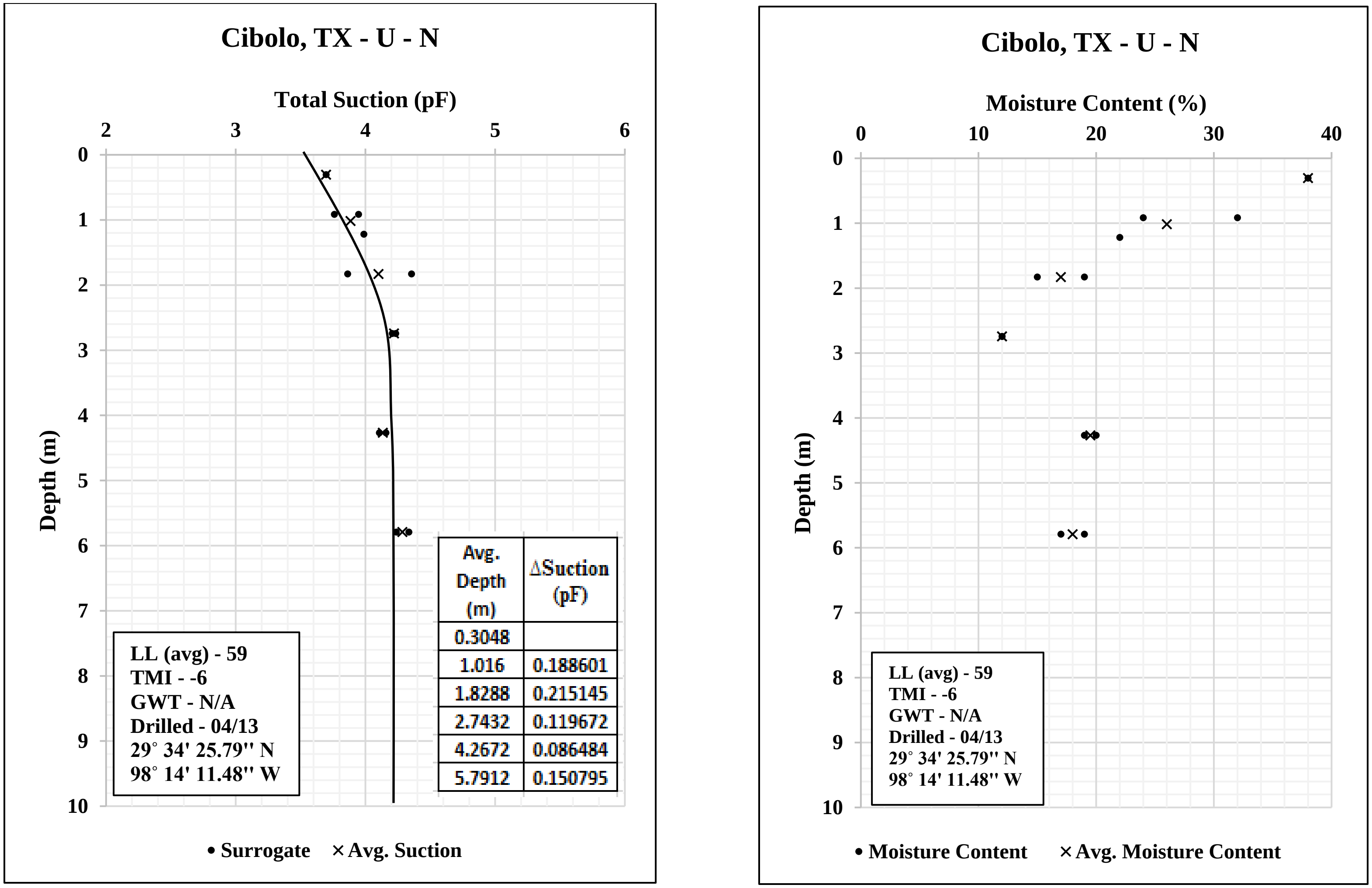
Avg. Depth (m)	ΔSuction (pF)
0.508	
0.9906	0.571442
2.032	0.063819
2.8448	0.005502
3.048	0.038716
4.3688	0.246638
4.572	0.034112
5.9436	0.153763
6.096	0.108221
7.4676	0.093959
7.62	0.194927

Figure 46: Field Suction Profile (left) and Moisture Content Profile (right) for Friendswood, TX



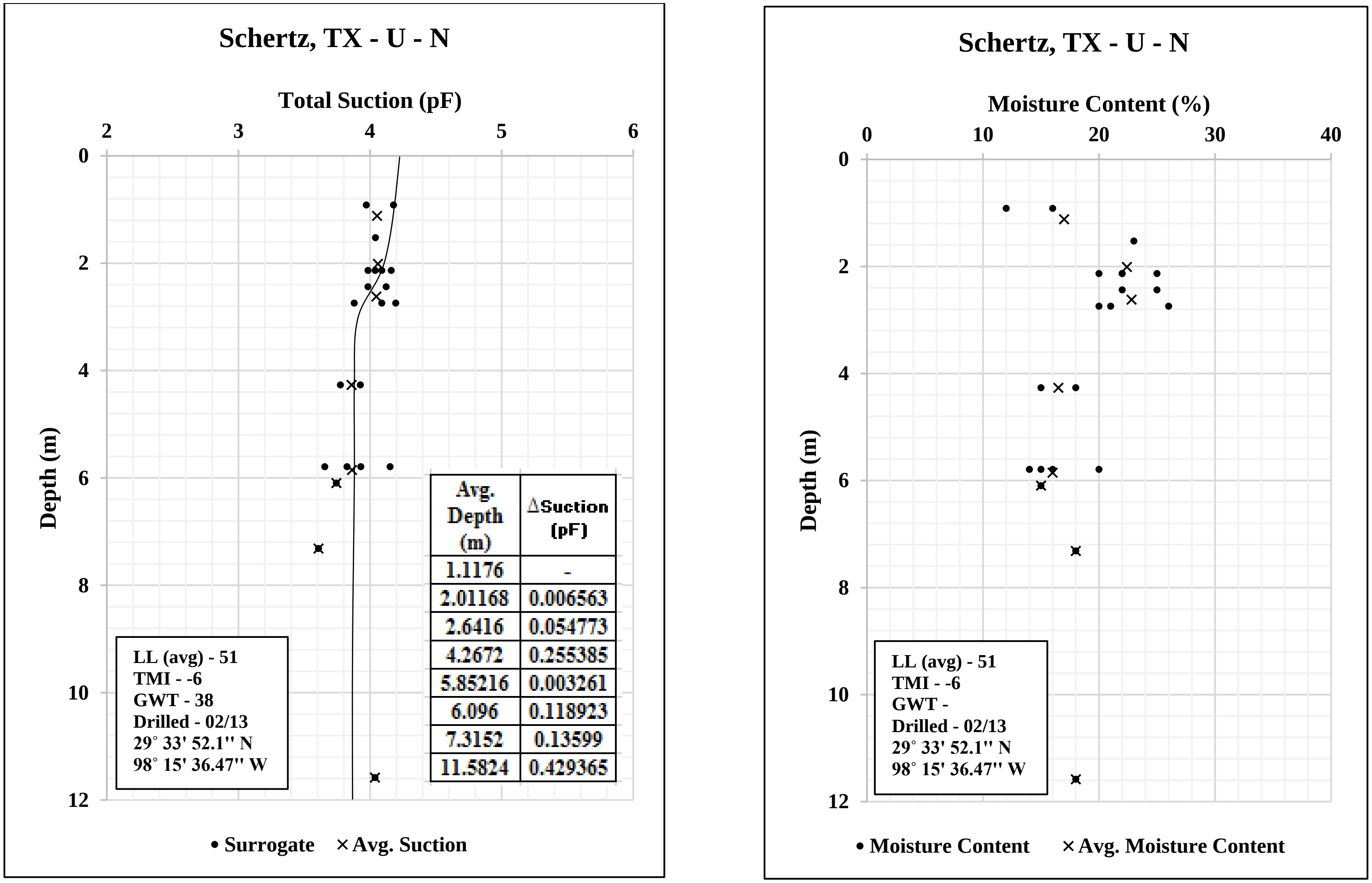
Avg. Depth (m)	ΔSuction (pF)
0.4572	
1.28016	0.11326
1.76784	0.040345
2.7432	0.038818
3.048	0.161886
4.32816	0.203092
4.572	0.028625
5.85216	0.143215
6.096	0.046494
7.4676	0.075723
7.62	0.081523
8.8392	0.058118
10.3632	0.082613

Figure 47: Field Suction Profile (left) and Moisture Content Profile (left) for Kyle, TX



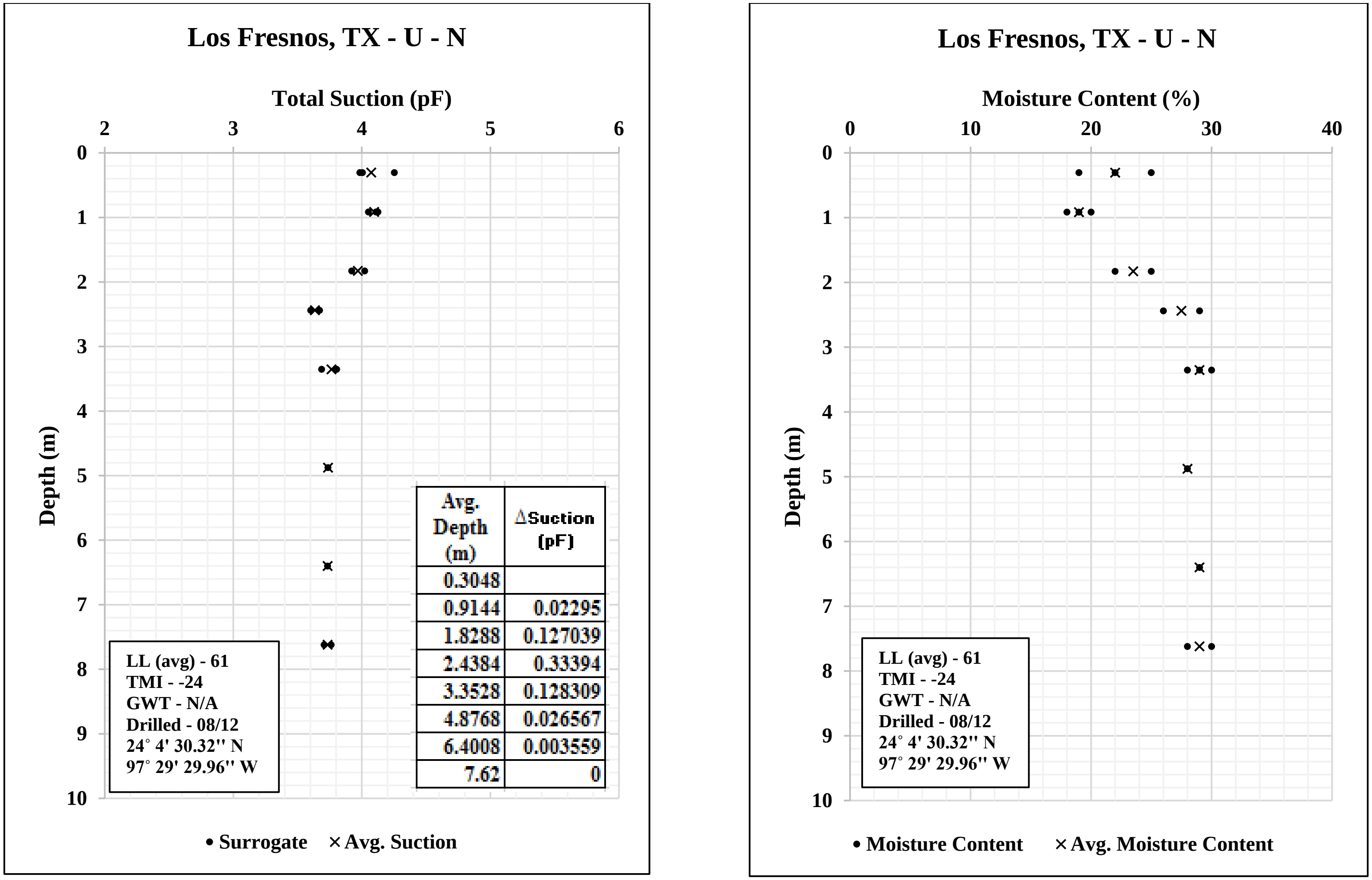
Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.016	0.188601
1.8288	0.215145
2.7432	0.119672
4.2672	0.086484
5.7912	0.150795

Figure 48: Field Suction Profile (left) and Moisture Content Profile (right) for Cibolo, TX



Avg. Depth (m)	ΔSuction (pF)
1.1176	-
2.01168	0.006563
2.6416	0.054773
4.2672	0.255385
5.85216	0.003261
6.096	0.118923
7.3152	0.13599
11.5824	0.429365

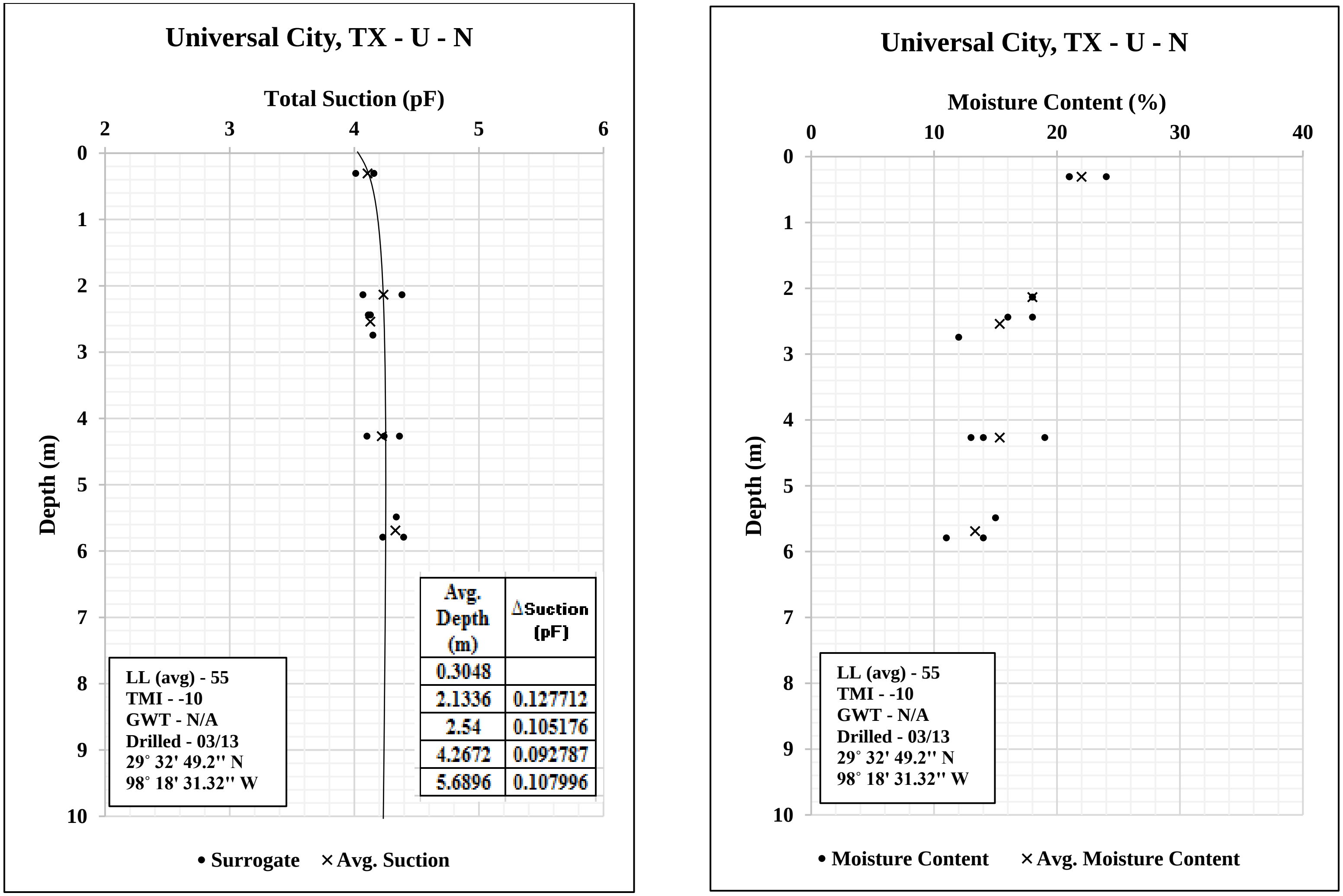
Figure 49: Field Suction Profile (left) and Moisture Content Profile (right) for Schertz, TX



Avg. Depth (m)	ΔSuction (pF)
0.3048	
0.9144	0.02295
1.8288	0.127039
2.4384	0.33394
3.3528	0.128309
4.8768	0.026567
6.4008	0.003559
7.62	0

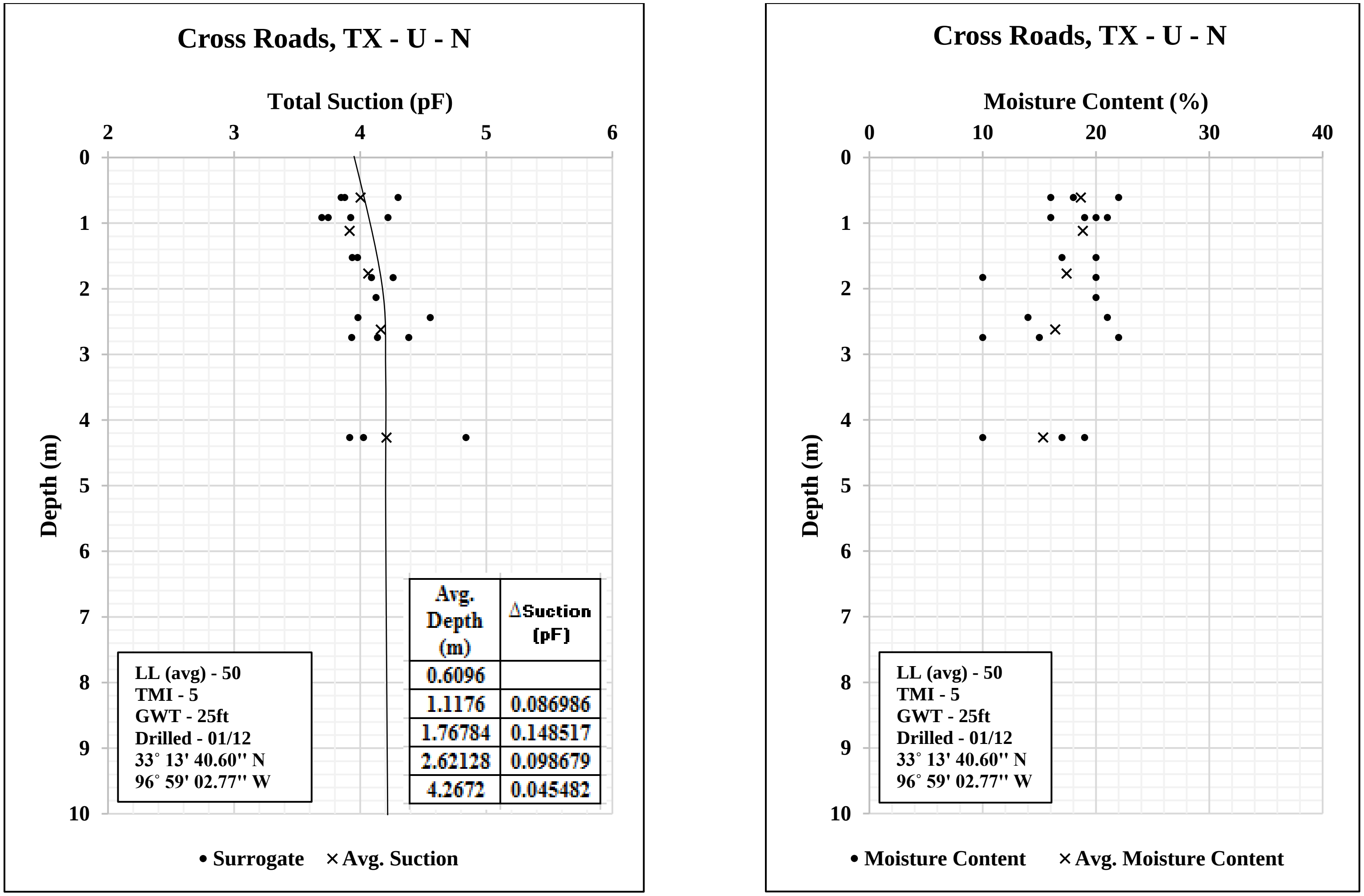
LL (avg) - 61
TMI - -24
GWT - N/A
Drilled - 08/12
24° 4' 30.32'' N
97° 29' 29.96'' W

Figure 50: Field Suction Profile (left) and Moisture Content Profile (right) for Los Fresnos, TX



Avg. Depth (m)	ΔSuction (pF)
0.3048	
2.1336	0.127712
2.54	0.105176
4.2672	0.092787
5.6896	0.107996

Figure 51: Field Suction Profile (left) and Moisture Content Profile (right) for Universal City, TX



Avg. Depth (m)	ΔSuction (pF)
0.6096	
1.1176	0.086986
1.76784	0.148517
2.62128	0.098679
4.2672	0.045482

Figure 52: Field Suction Profile (left) and Moisture Content Profile (right) for Cross Roads, TX

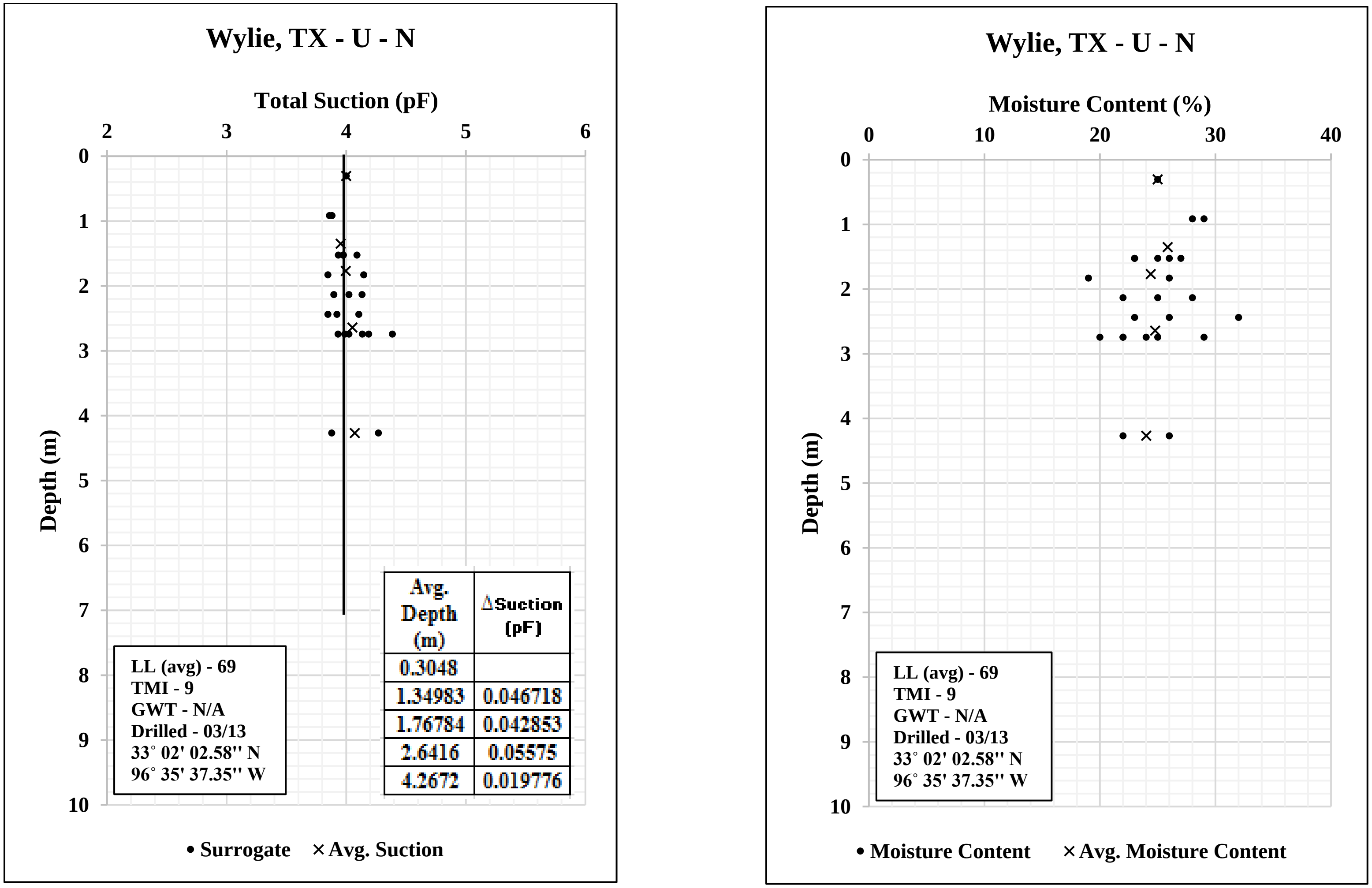


Figure 53: Field Suction Profile (left) and Moisture Content Profile (right) for Wylie, TX

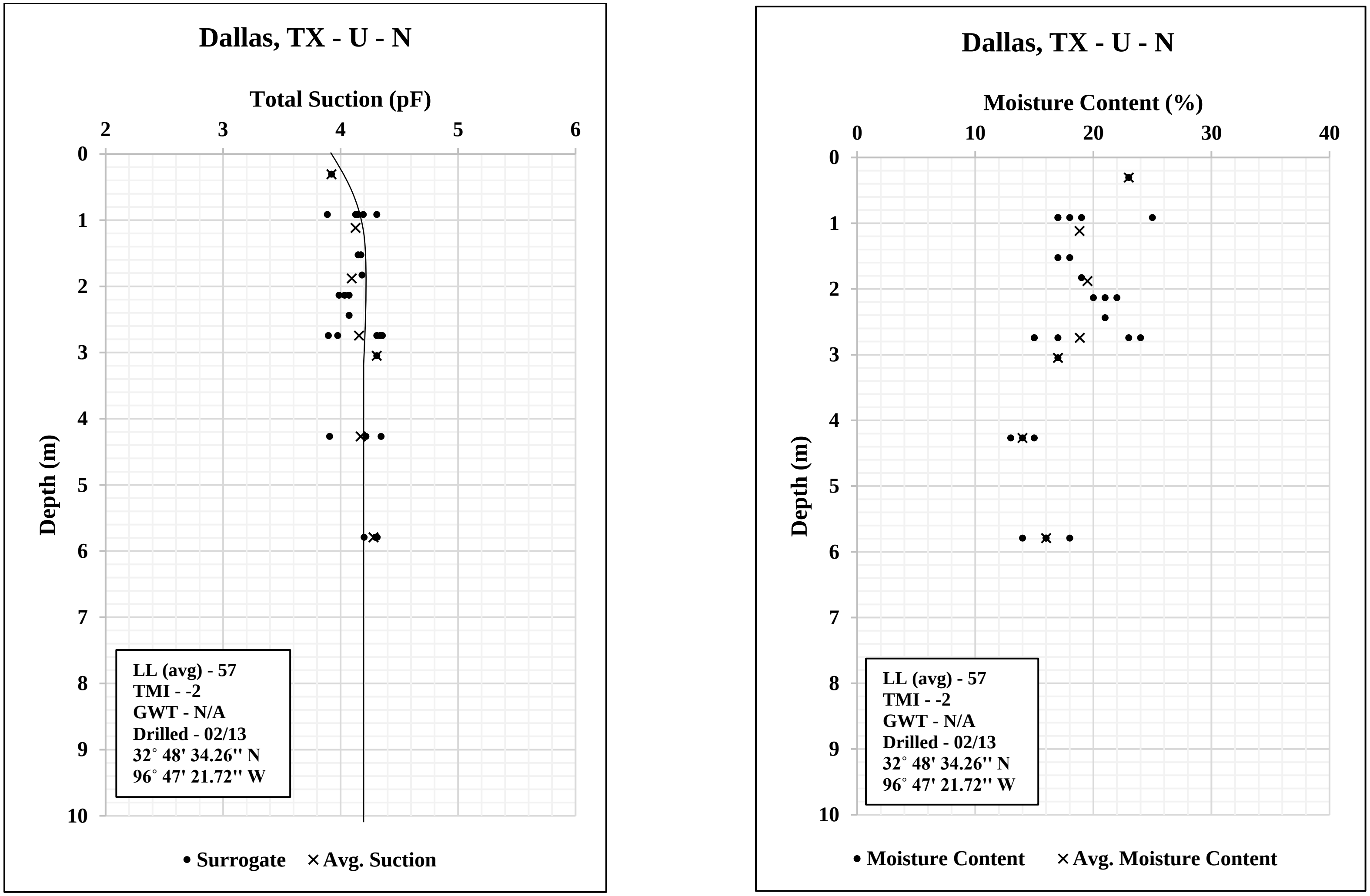
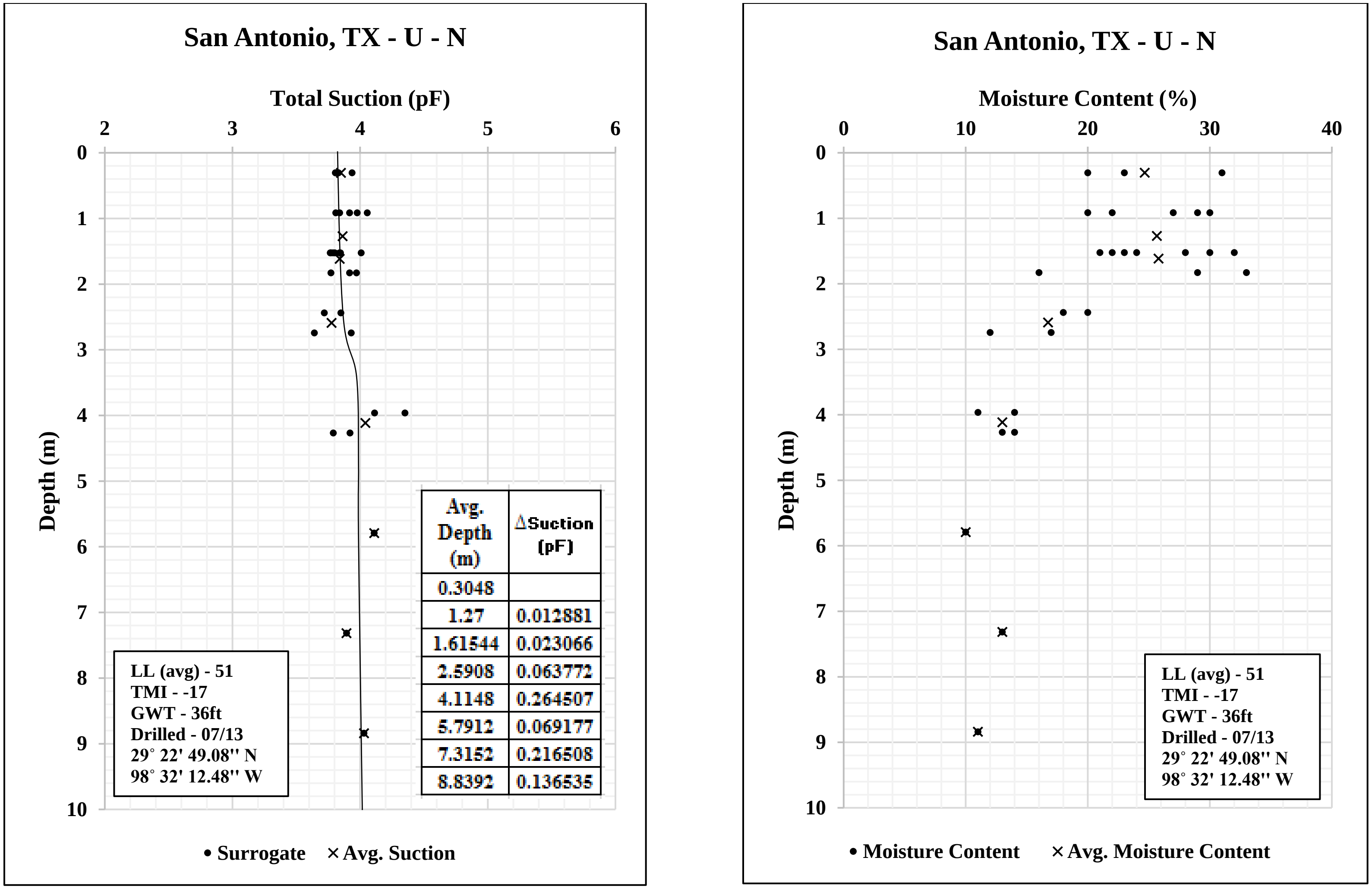


Figure 54: Field Suction Profile (left) and Moisture Content Profile (right) for Dallas, TX



Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.27	0.012881
1.61544	0.023066
2.5908	0.063772
4.1148	0.264507
5.7912	0.069177
7.3152	0.216508
8.8392	0.136535

Figure 55: Field Suction Profile (left) and Moisture Content Profile (right) for San Antonio, TX

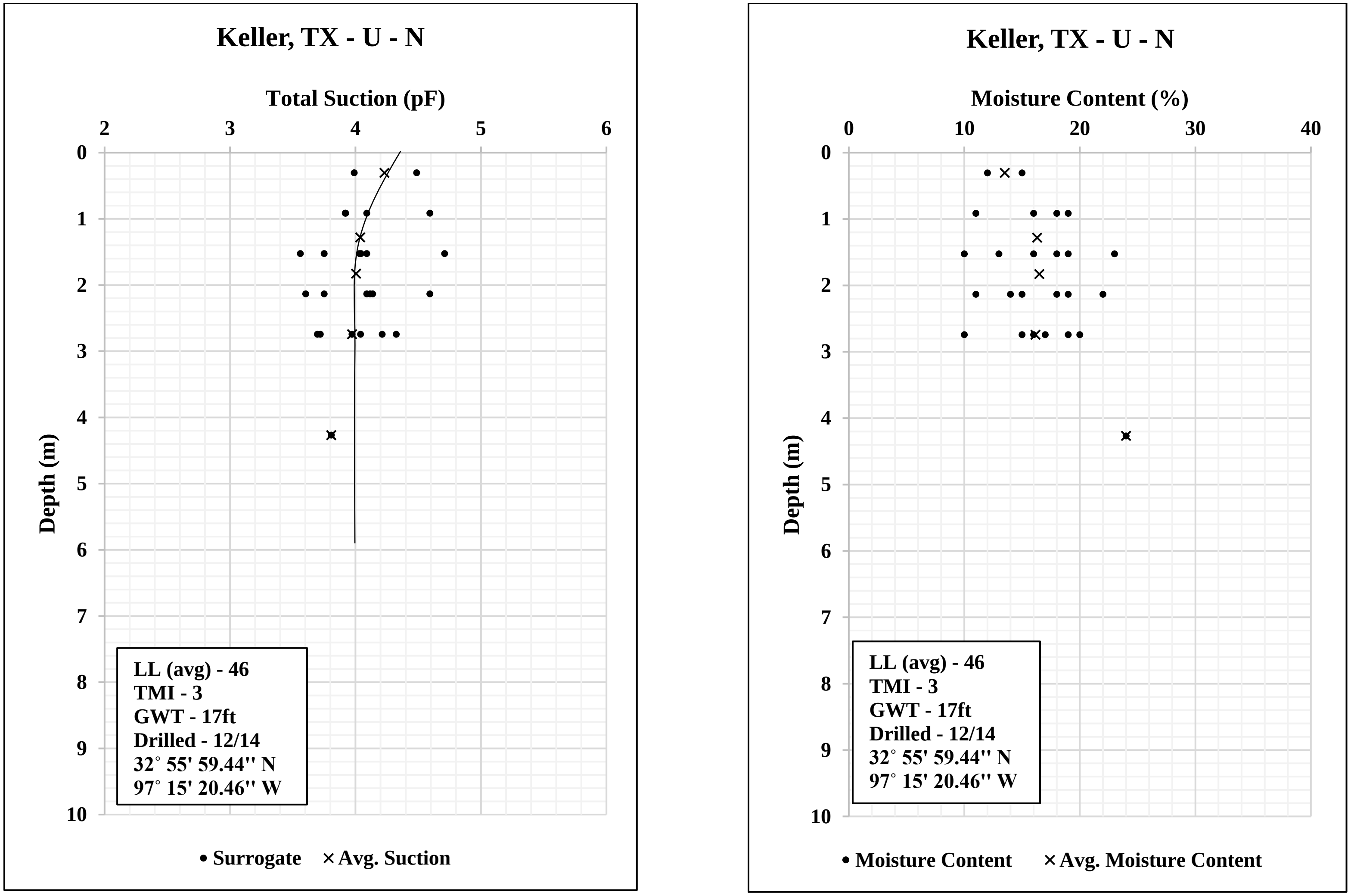
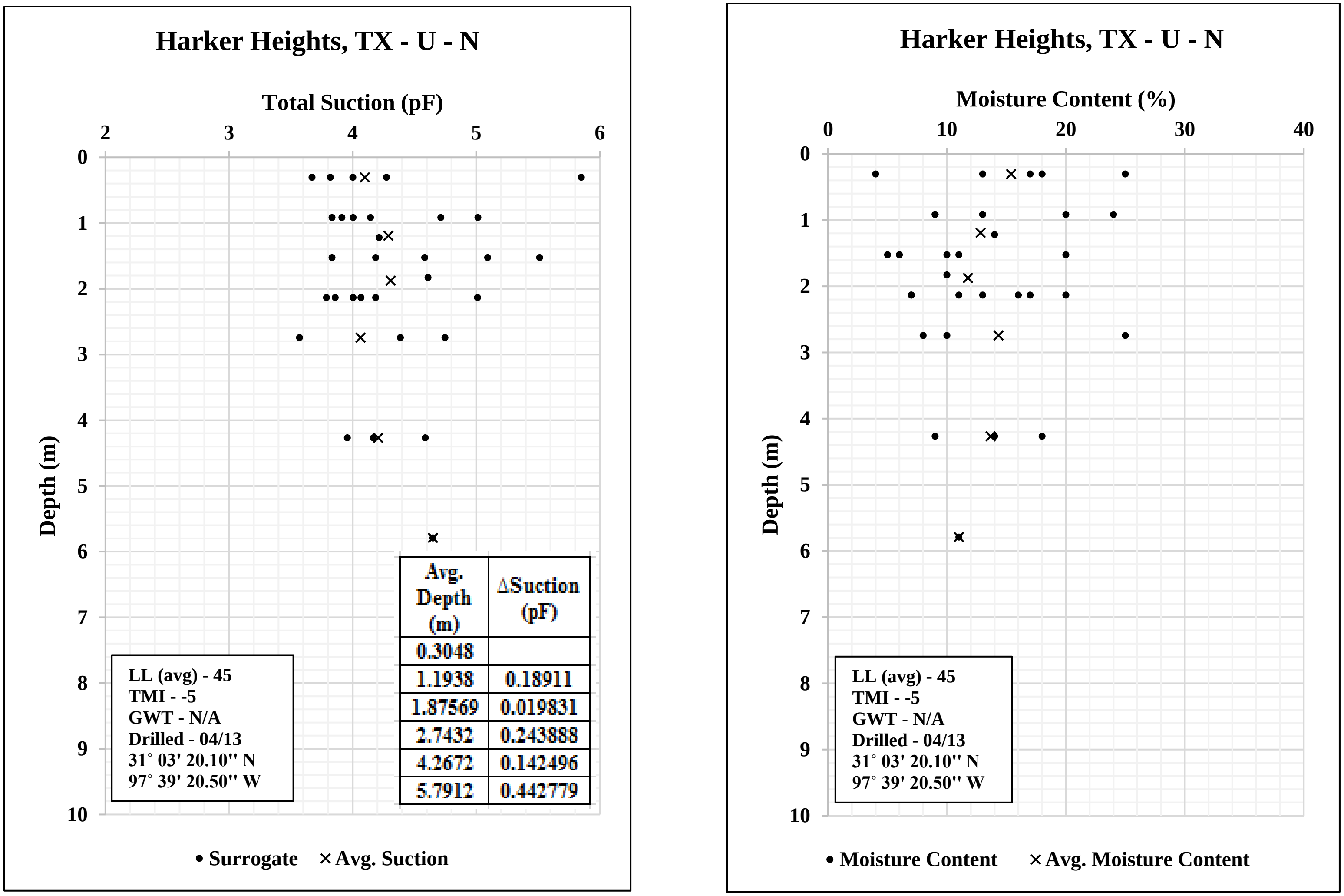
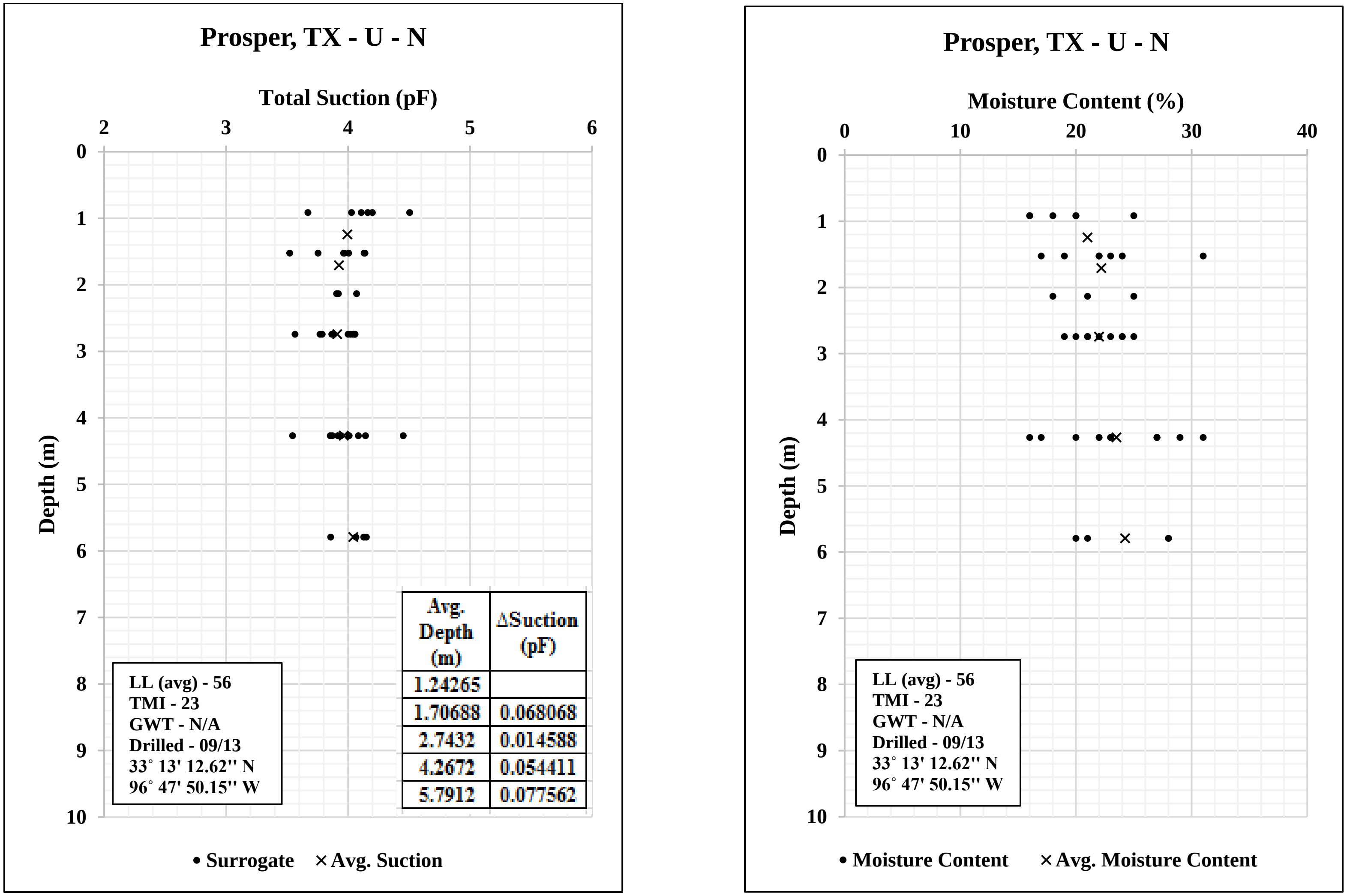


Figure 56: Field Suction Profile (left) and Moisture Content Profile (right) for Keller, TX



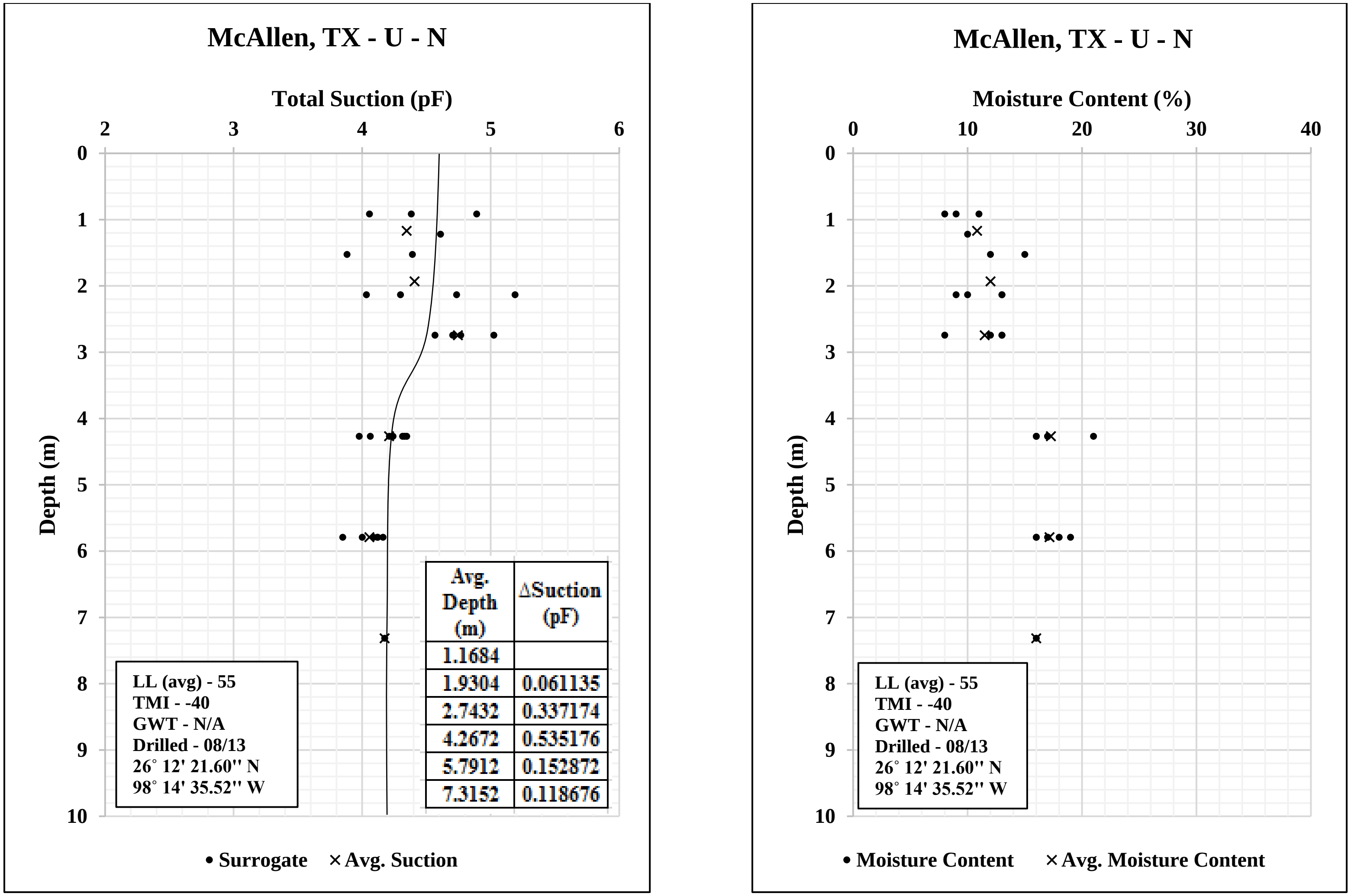
Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.1938	0.18911
1.87569	0.019831
2.7432	0.243888
4.2672	0.142496
5.7912	0.442779

Figure 57: Field Suction Profile (left) and Moisture Content Profile (right) for Harker Heights, TX



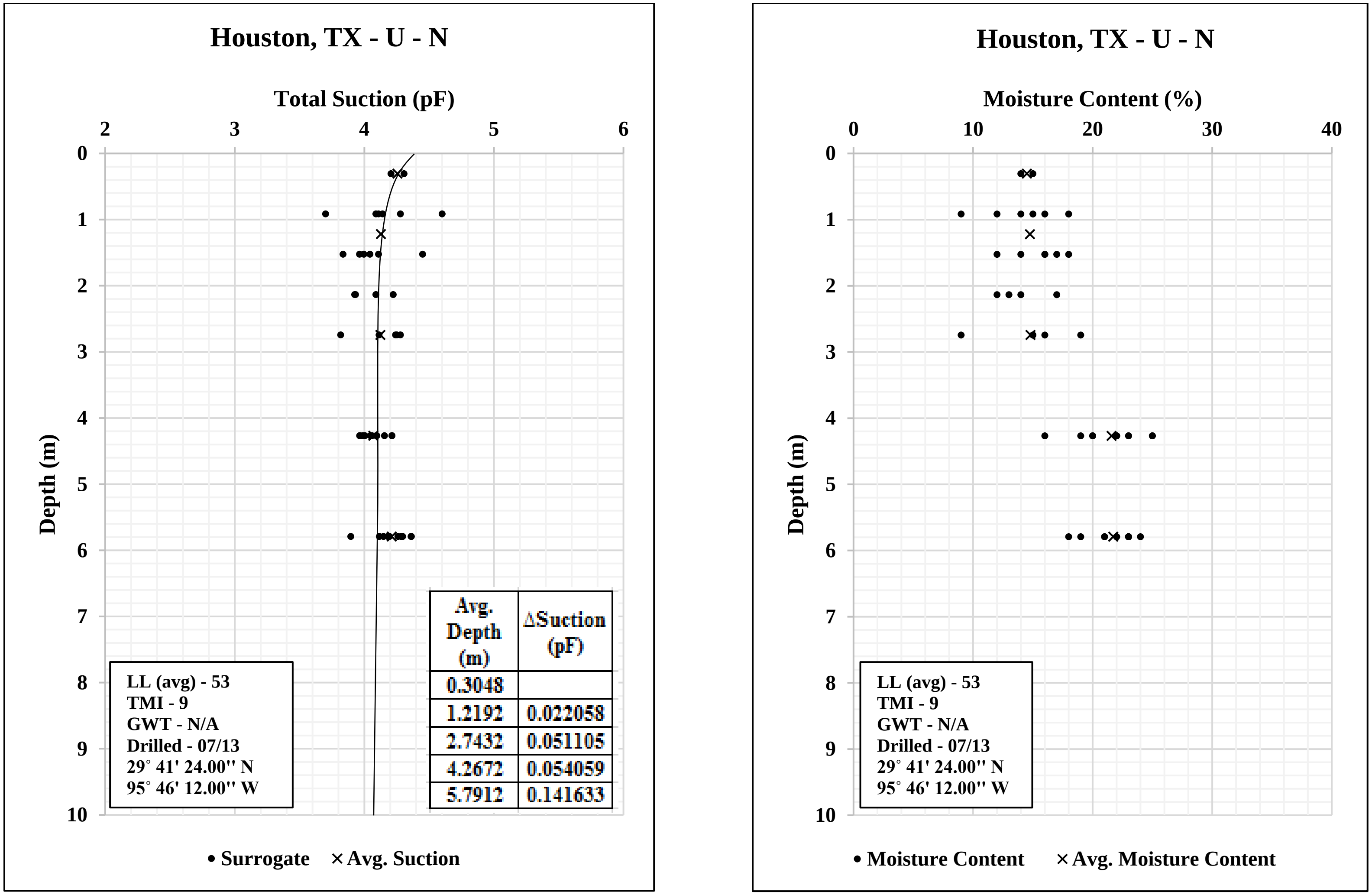
Avg. Depth (m)	ΔSuction (pF)
1.24265	
1.70688	0.068068
2.7432	0.014588
4.2672	0.054411
5.7912	0.077562

Figure 58: Field Suction Profile (left) and Moisture Content Profile (right) for Prosper, TX



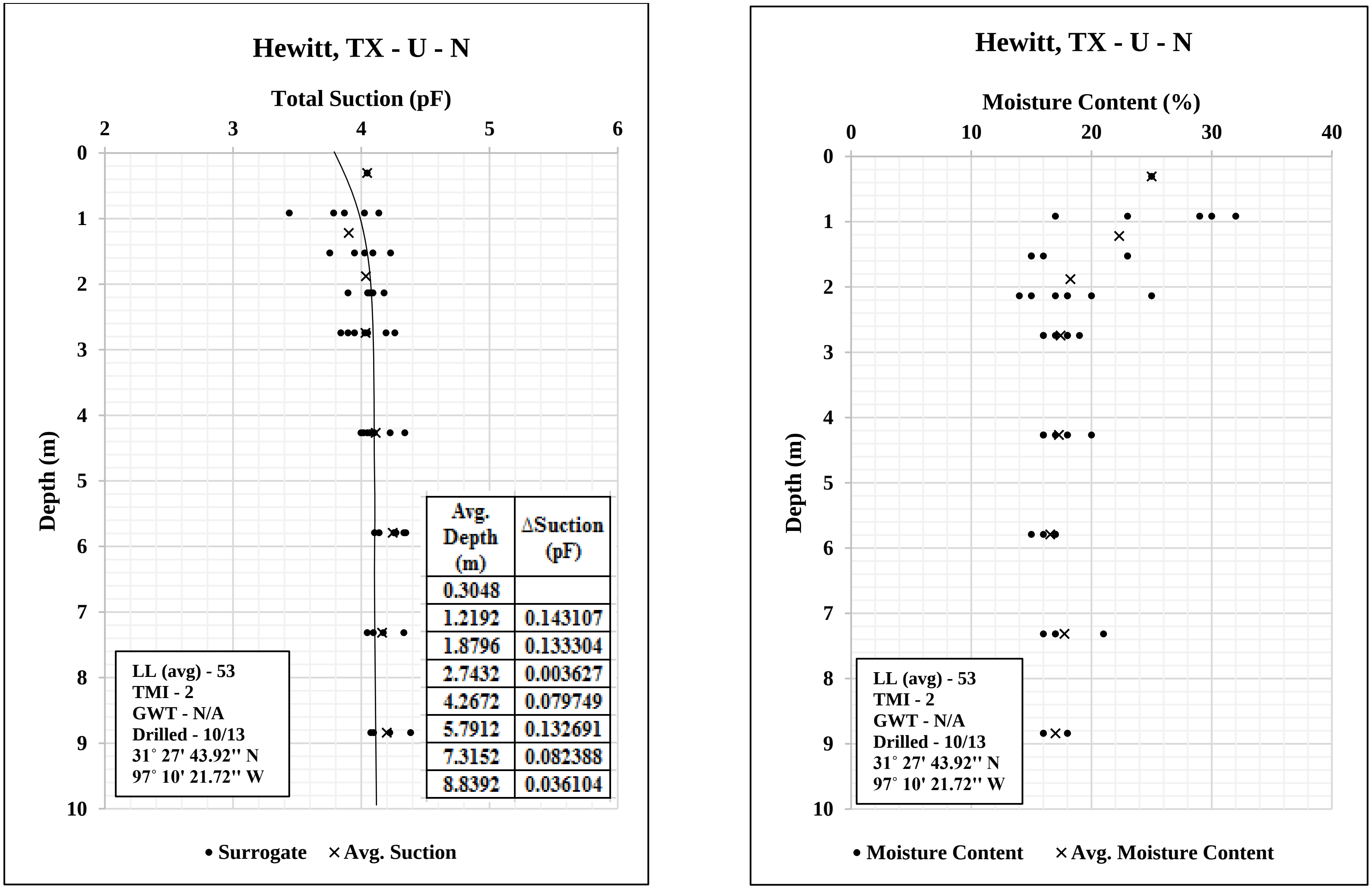
Avg. Depth (m)	ΔSuction (pF)
1.1684	
1.9304	0.061135
2.7432	0.337174
4.2672	0.535176
5.7912	0.152872
7.3152	0.118676

Figure 59: Field Suction Profile (left) and Moisture Content Profile (right) for McAllen, TX



Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.2192	0.022058
2.7432	0.051105
4.2672	0.054059
5.7912	0.141633

Figure 60: Field Suction Profile (left) and Moisture Content Profile (right) for Houston, TX

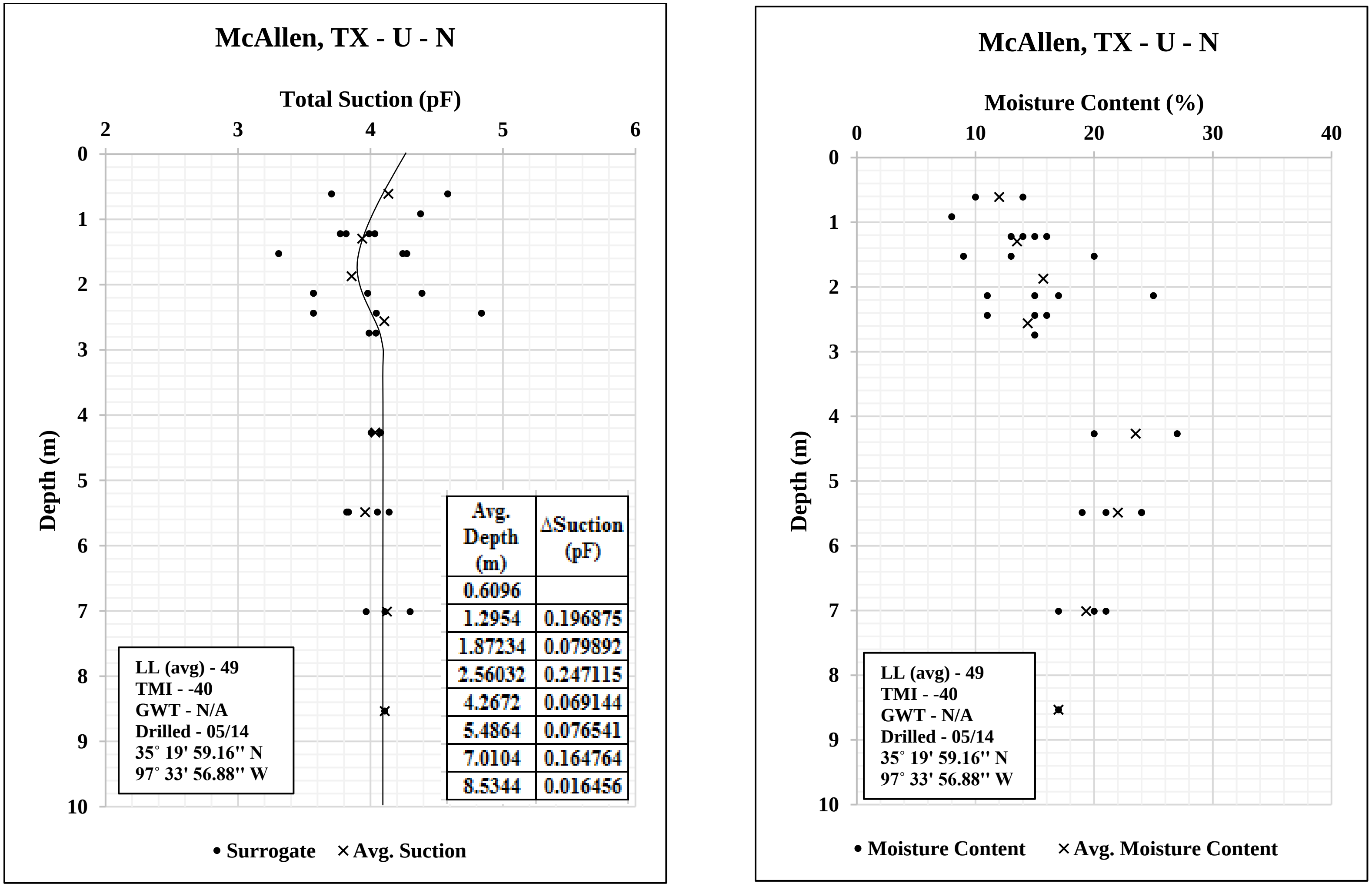


Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.2192	0.143107
1.8796	0.133304
2.7432	0.003627
4.2672	0.079749
5.7912	0.132691
7.3152	0.082388
8.8392	0.036104

LL (avg) - 53
TMI - 2
GWT - N/A
Drilled - 10/13
31° 27' 43.92'' N
97° 10' 21.72'' W

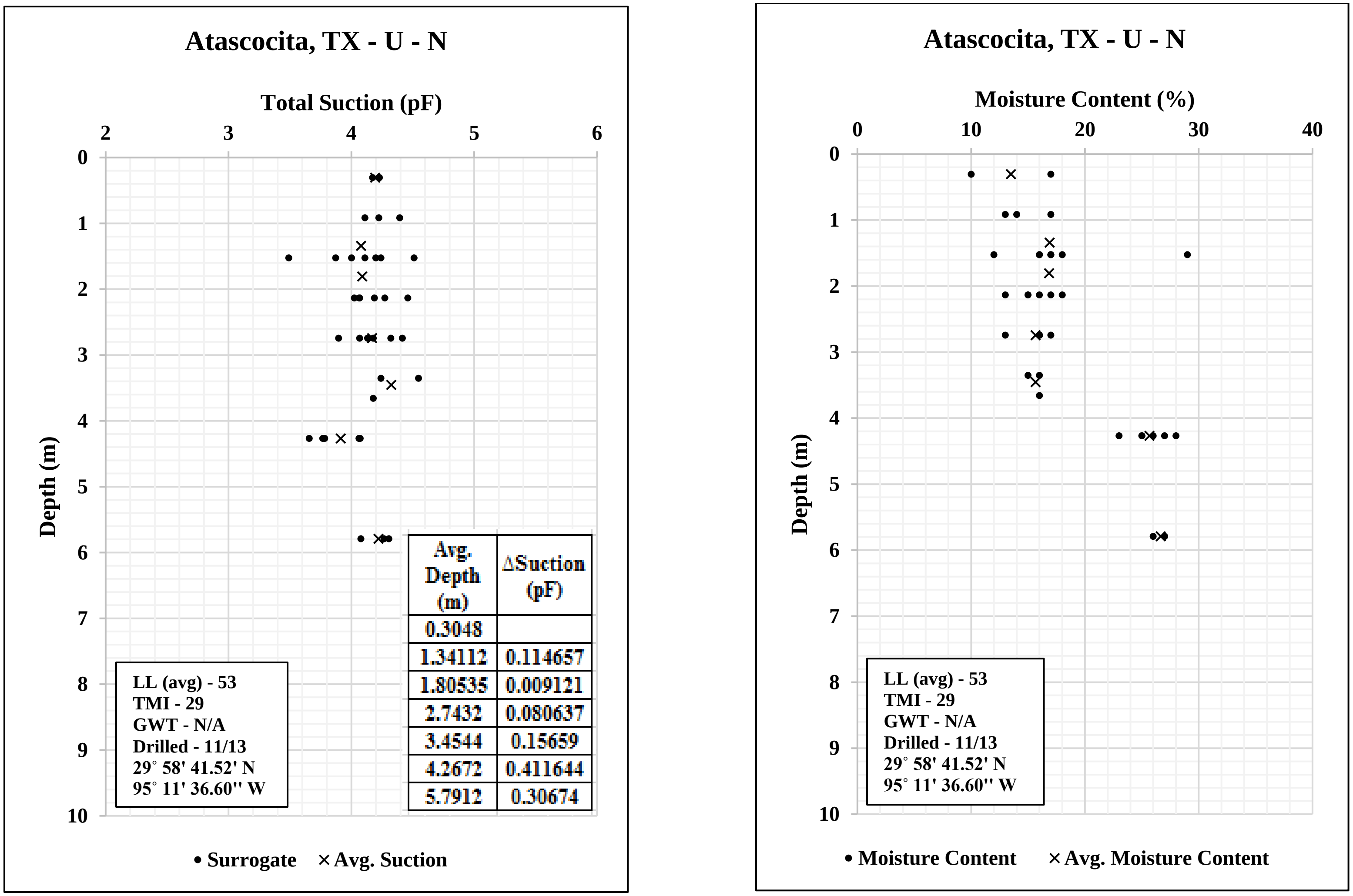
LL (avg) - 53
TMI - 2
GWT - N/A
Drilled - 10/13
31° 27' 43.92'' N
97° 10' 21.72'' W

Figure 61: Field Suction Profile (left) and Moisture Content Profile (right) for Hewitt, TX



Avg. Depth (m)	ΔSuction (pF)
0.6096	
1.2954	0.196875
1.87234	0.079892
2.56032	0.247115
4.2672	0.069144
5.4864	0.076541
7.0104	0.164764
8.5344	0.016456

Figure 62: Field Suction Profile (left) and Moisture Content Profile (right) for McAllen, TX



Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.34112	0.114657
1.80535	0.009121
2.7432	0.080637
3.4544	0.15659
4.2672	0.411644
5.7912	0.30674

Figure 63: Field Suction Profile (left) and Moisture Content Profile (right) for Atascocita, TX

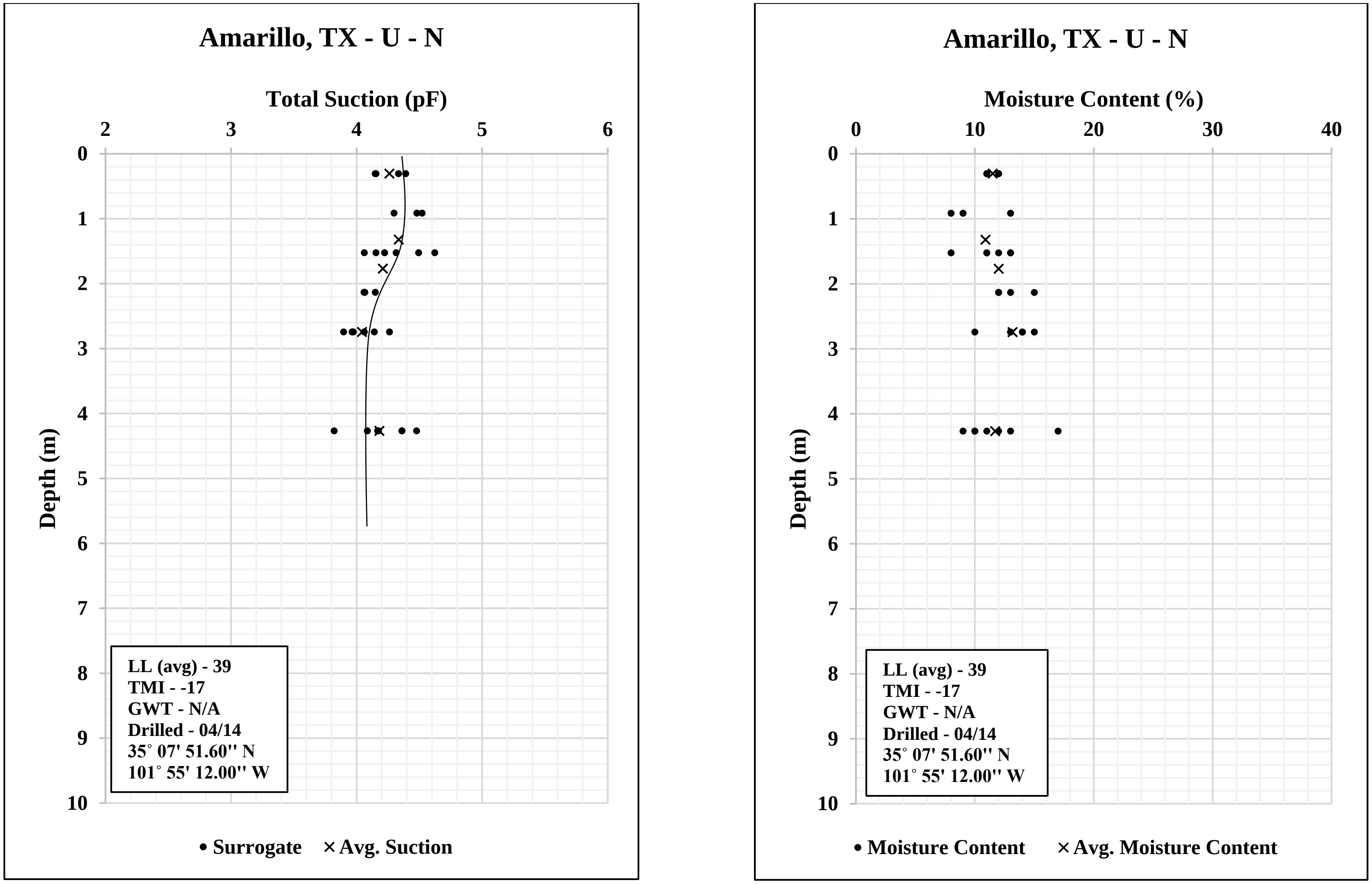
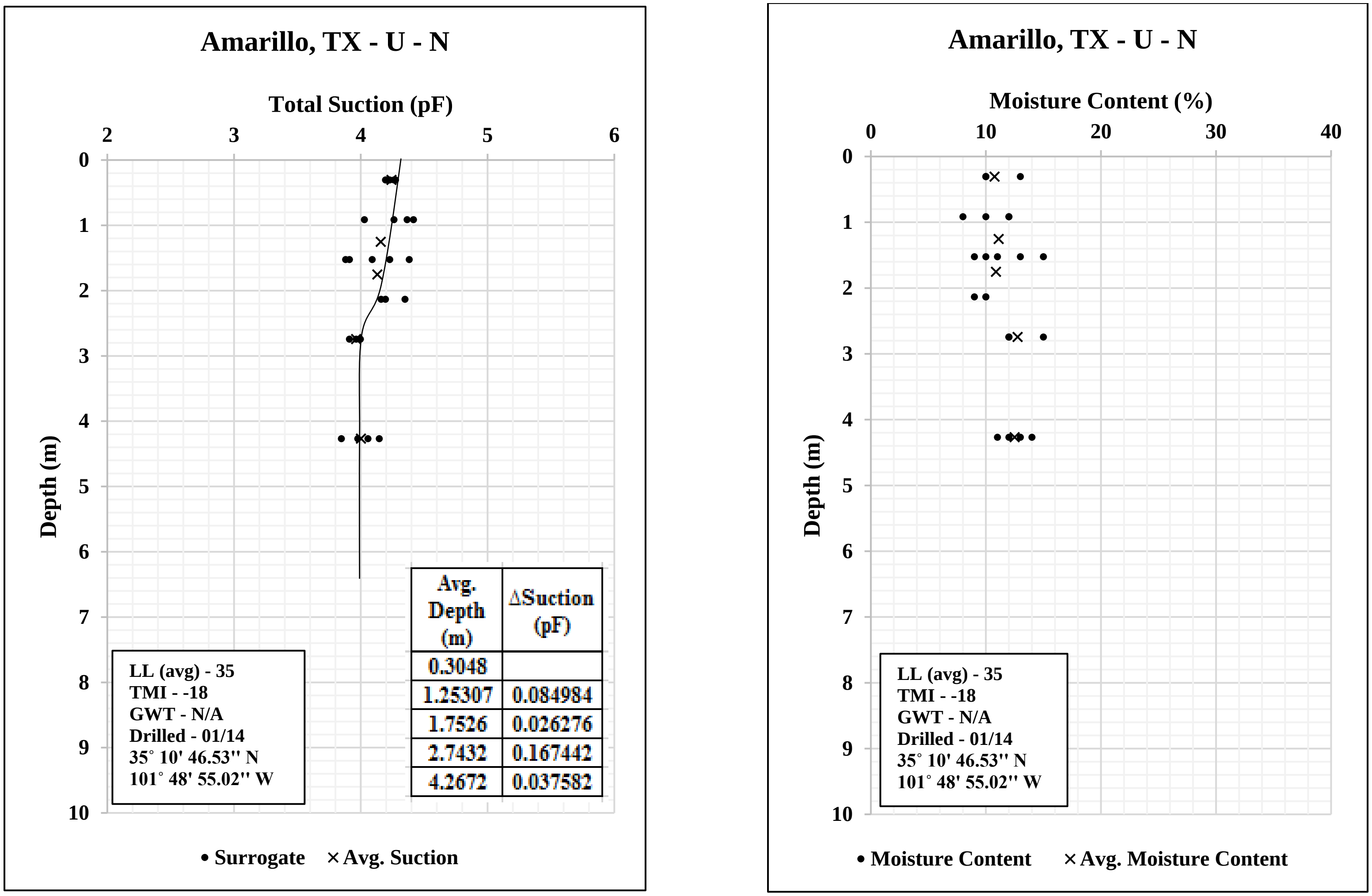
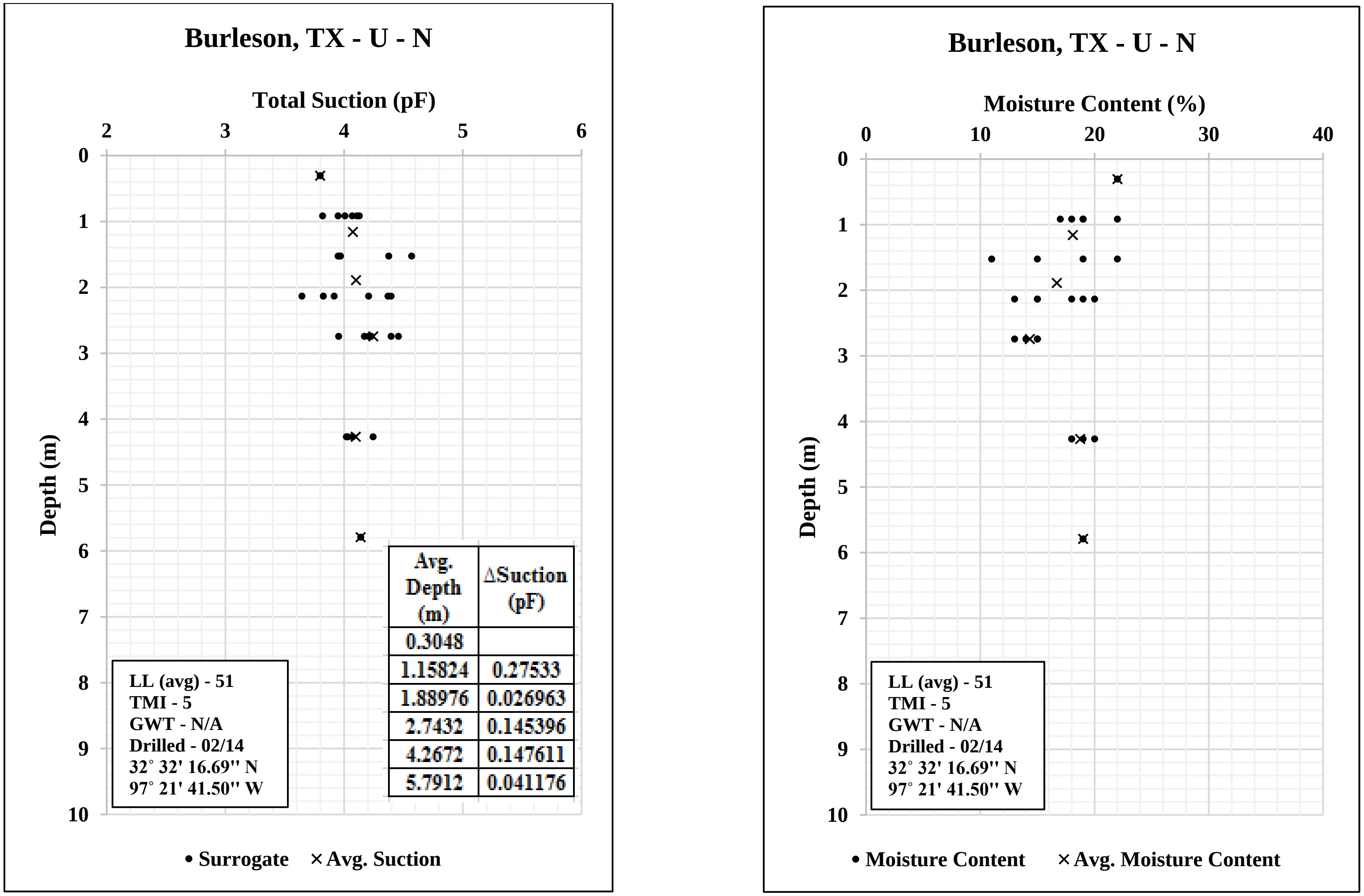


Figure 64: Field Suction Profile (left) and Moisture Content Profile (right) for Amarillo, TX



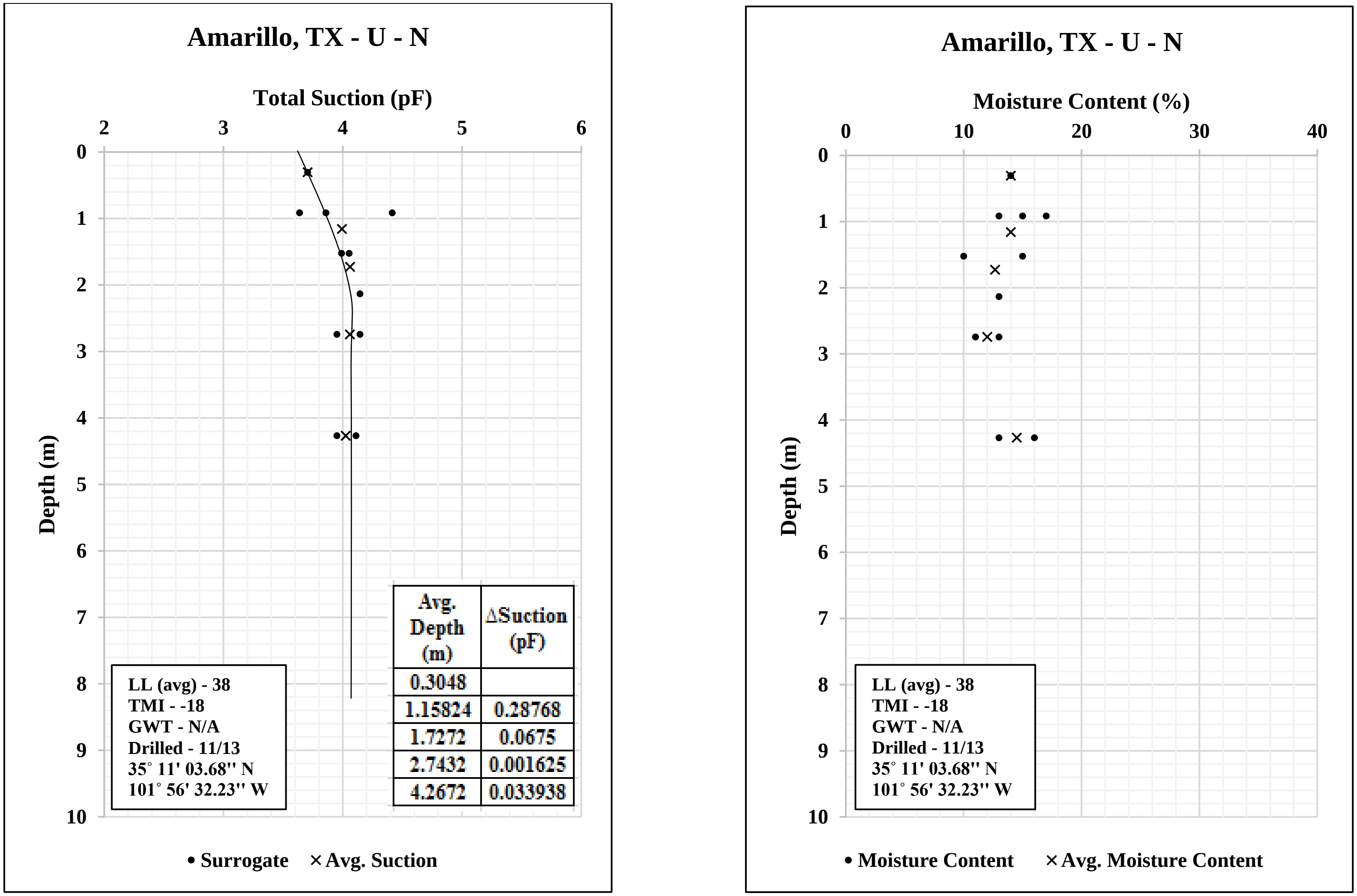
Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.25307	0.084984
1.7526	0.026276
2.7432	0.167442
4.2672	0.037582

Figure 65: Field Suction Profile (left) and Moisture Content Profile (right) for Amarillo, TX



Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.15824	0.27533
1.88976	0.026963
2.7432	0.145396
4.2672	0.147611
5.7912	0.041176

Figure 66: Field Suction Profile (left) and Moisture Content Profile (right) for Burleson, TX

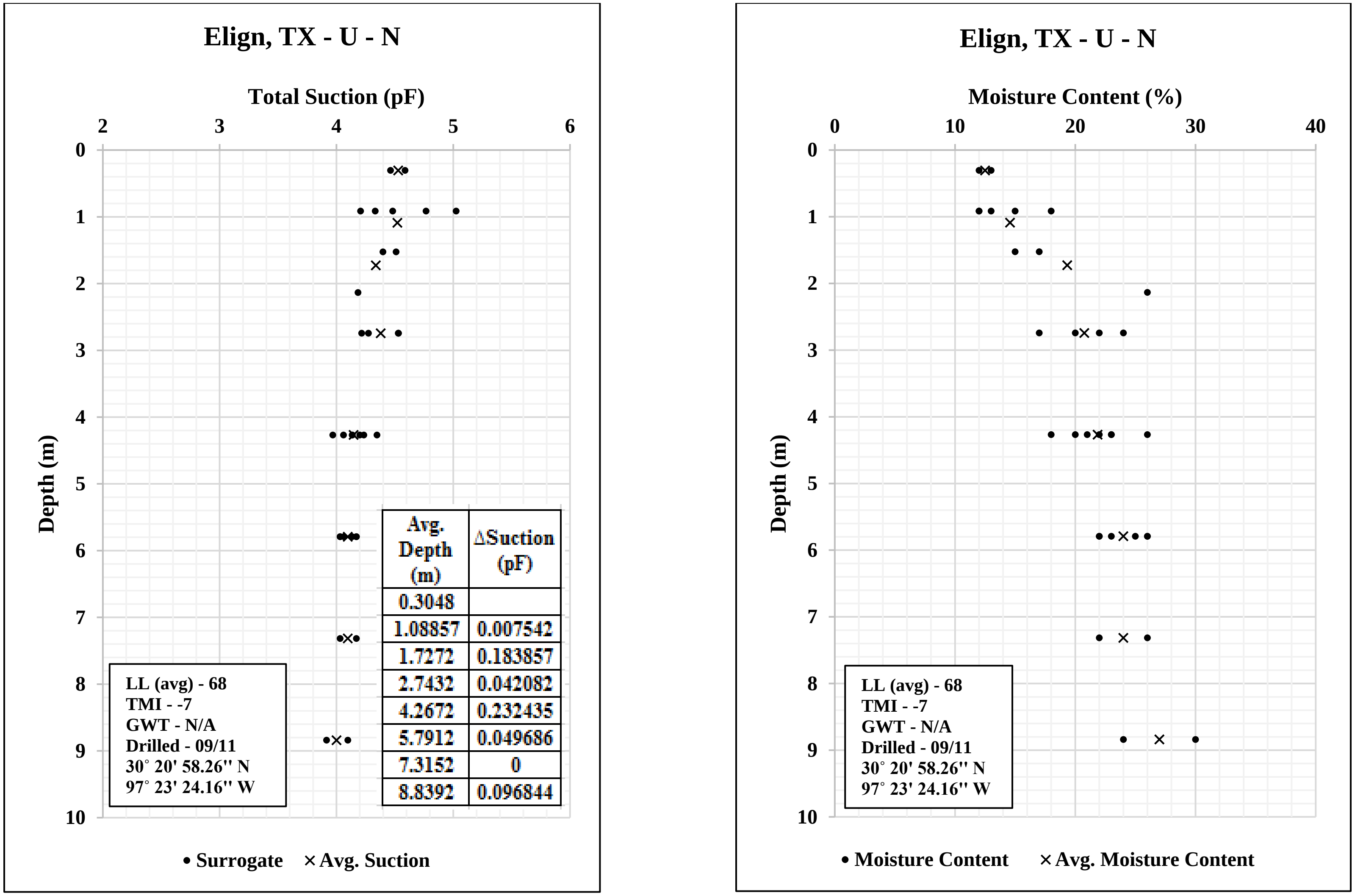


Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.15824	0.28768
1.7272	0.0675
2.7432	0.001625
4.2672	0.033938

LL (avg) - 38
TMI - -18
GWT - N/A
Drilled - 11/13
35° 11' 03.68'' N
101° 56' 32.23'' W

LL (avg) - 38
TMI - -18
GWT - N/A
Drilled - 11/13
35° 11' 03.68'' N
101° 56' 32.23'' W

Figure 67: Field Suction Profile (left) and Moisture Content Profile (right) for Amarillo, TX



Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.08857	0.007542
1.7272	0.183857
2.7432	0.042082
4.2672	0.232435
5.7912	0.049686
7.3152	0
8.8392	0.096844

Figure 68: Field Suction Profile (left) and Moisture Content Profile (right) for Elign, TX

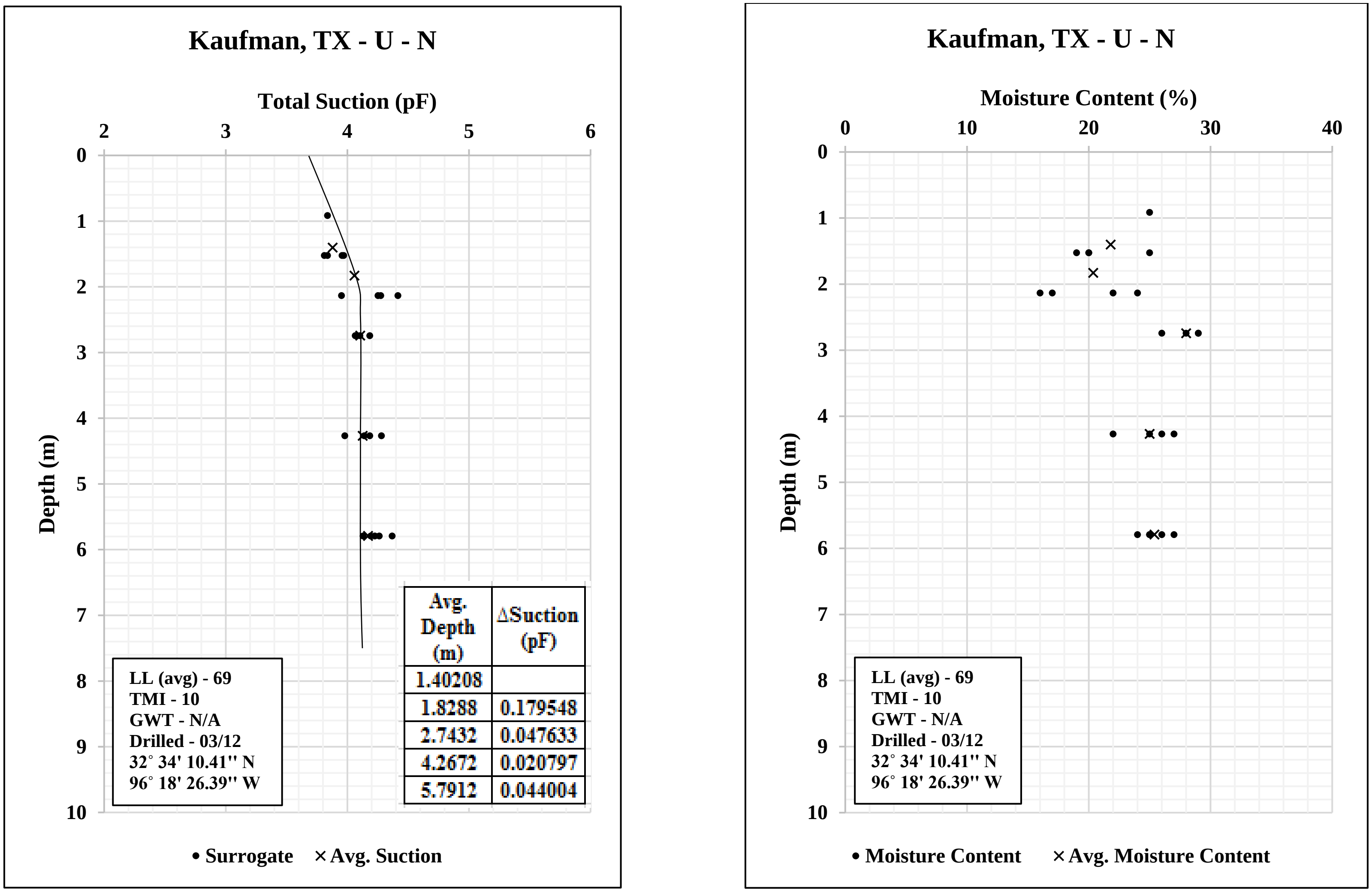


Figure 69: Field Suction Profile (left) and Moisture Content Profile (right) for Kaufman, TX

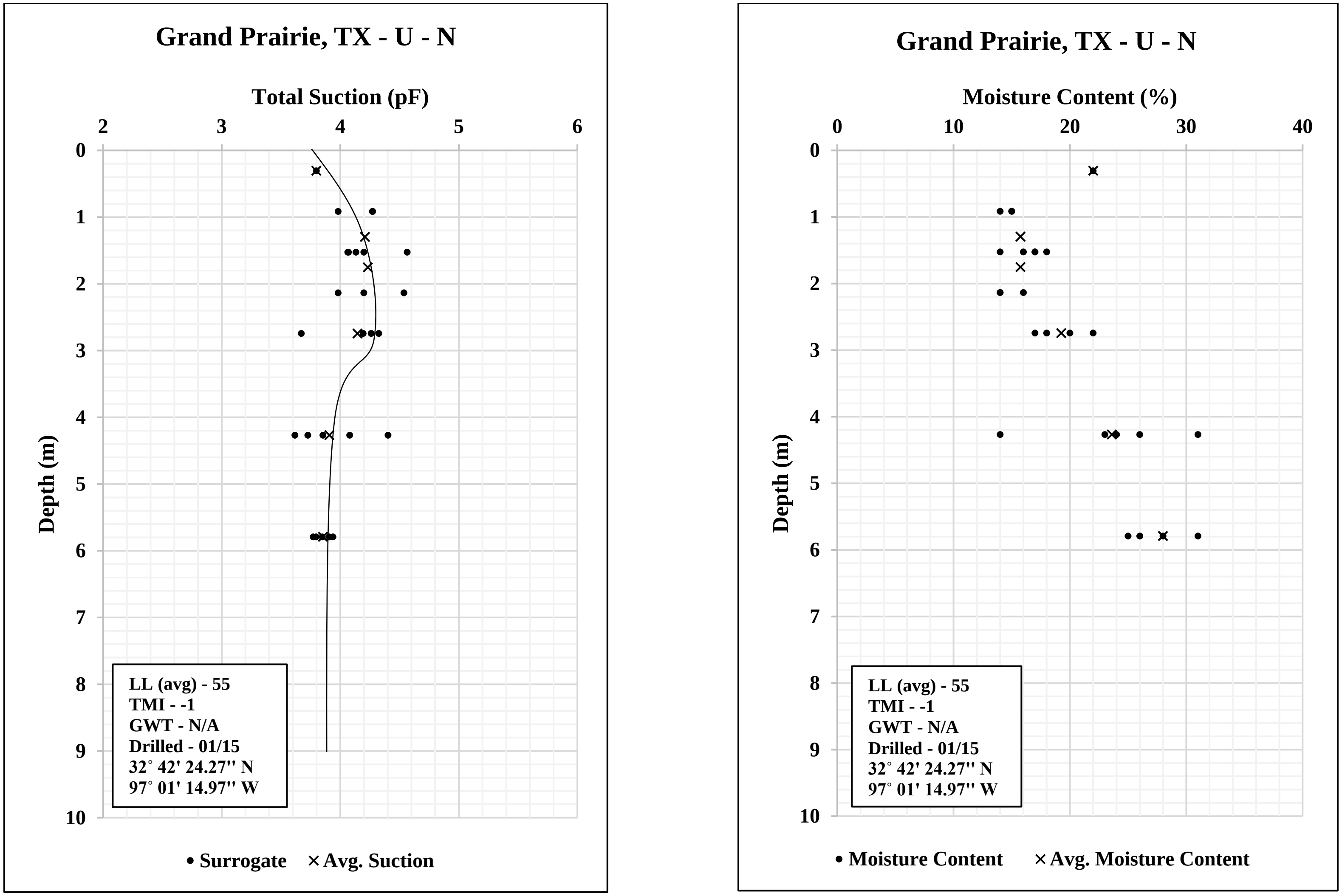
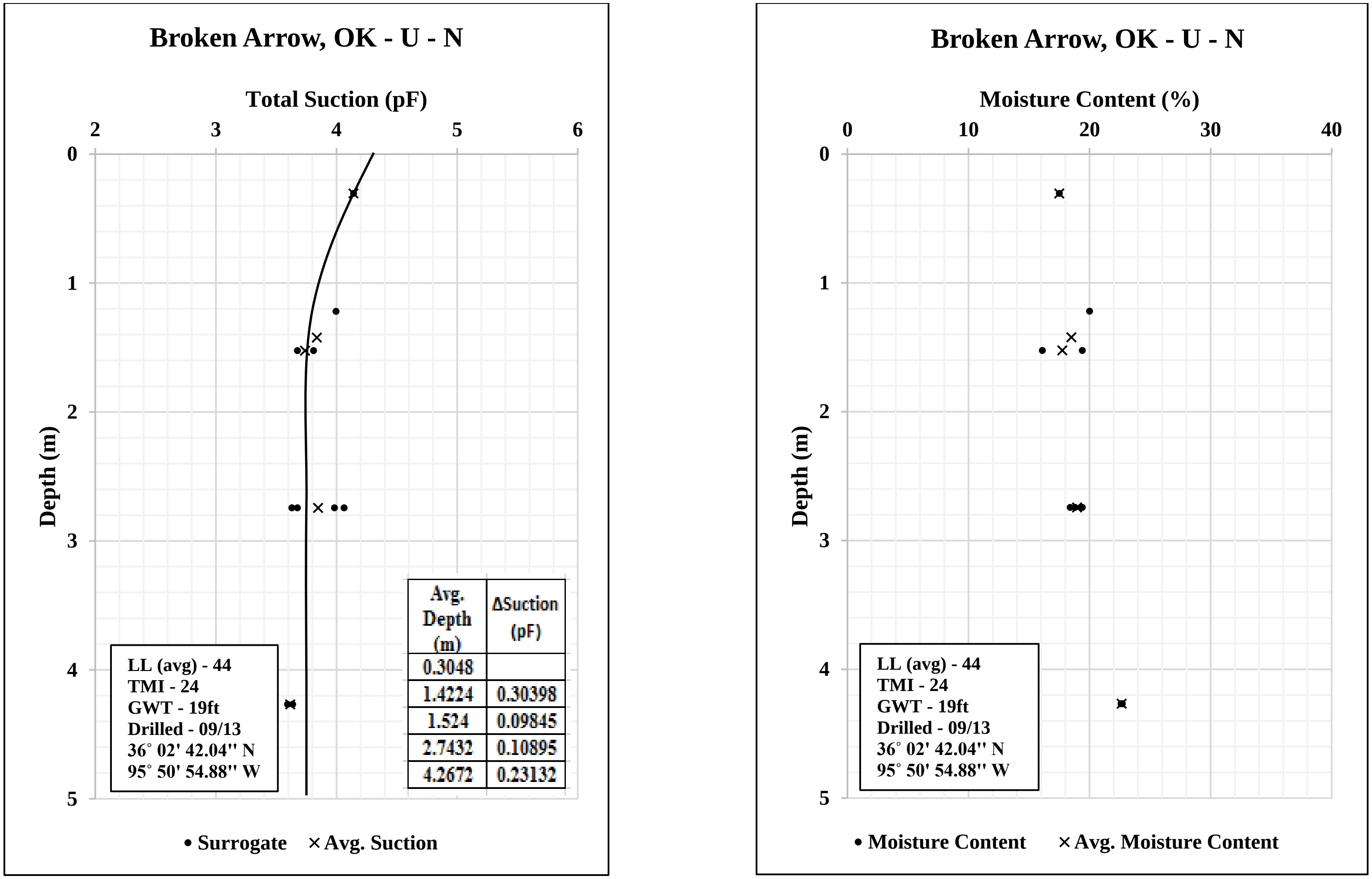
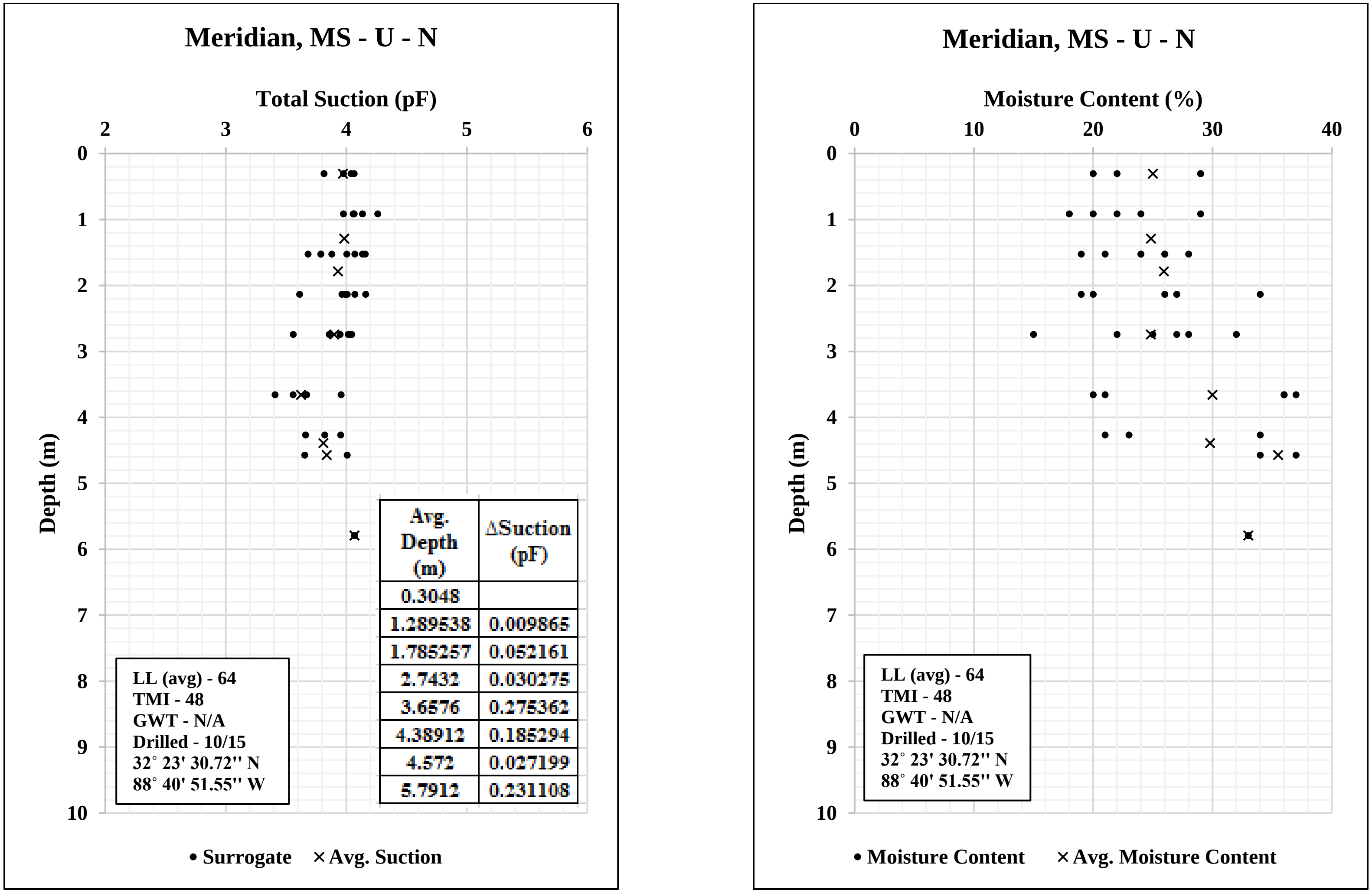


Figure 70: Field Suction Profile (left) and Moisture Content Profile (right) for Grand Prairie, TX



Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.4224	0.30398
1.524	0.09845
2.7432	0.10895
4.2672	0.23132

Figure 71: Field Suction Profile (left) and Moisture Content Profile (right) for Broken Arrow, OK

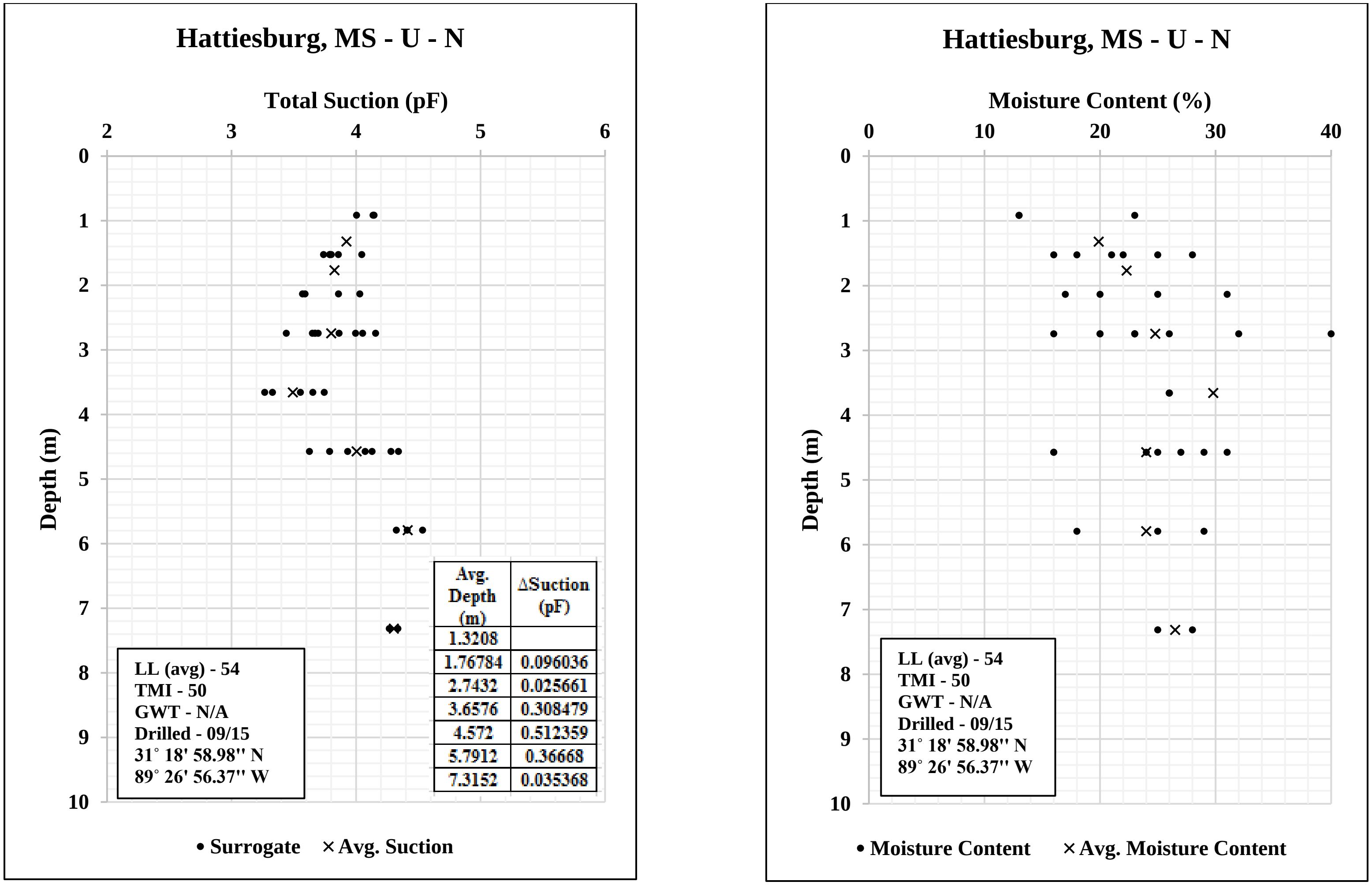


LL (avg) - 64
TMI - 48
GWT - N/A
Drilled - 10/15
32° 23' 30.72" N
88° 40' 51.55" W

Avg. Depth (m)	ΔSuction (pF)
0.3048	
1.289538	0.009865
1.785257	0.052161
2.7432	0.030275
3.6576	0.275362
4.38912	0.185294
4.572	0.027199
5.7912	0.231108

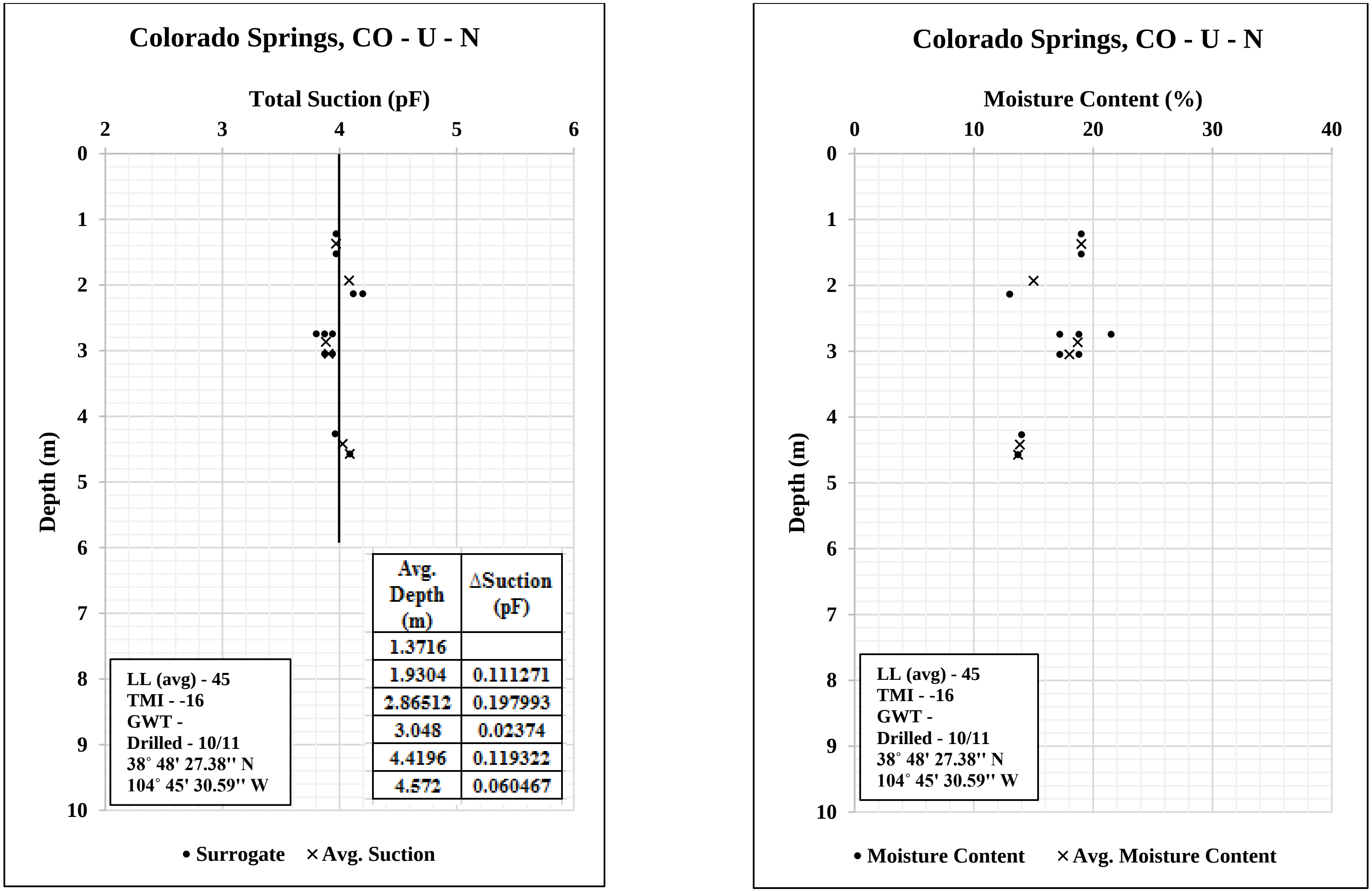
LL (avg) - 64
TMI - 48
GWT - N/A
Drilled - 10/15
32° 23' 30.72" N
88° 40' 51.55" W

Figure 72: Field Suction Profile (left) and Moisture Content Profile (right) for Meridian, MS



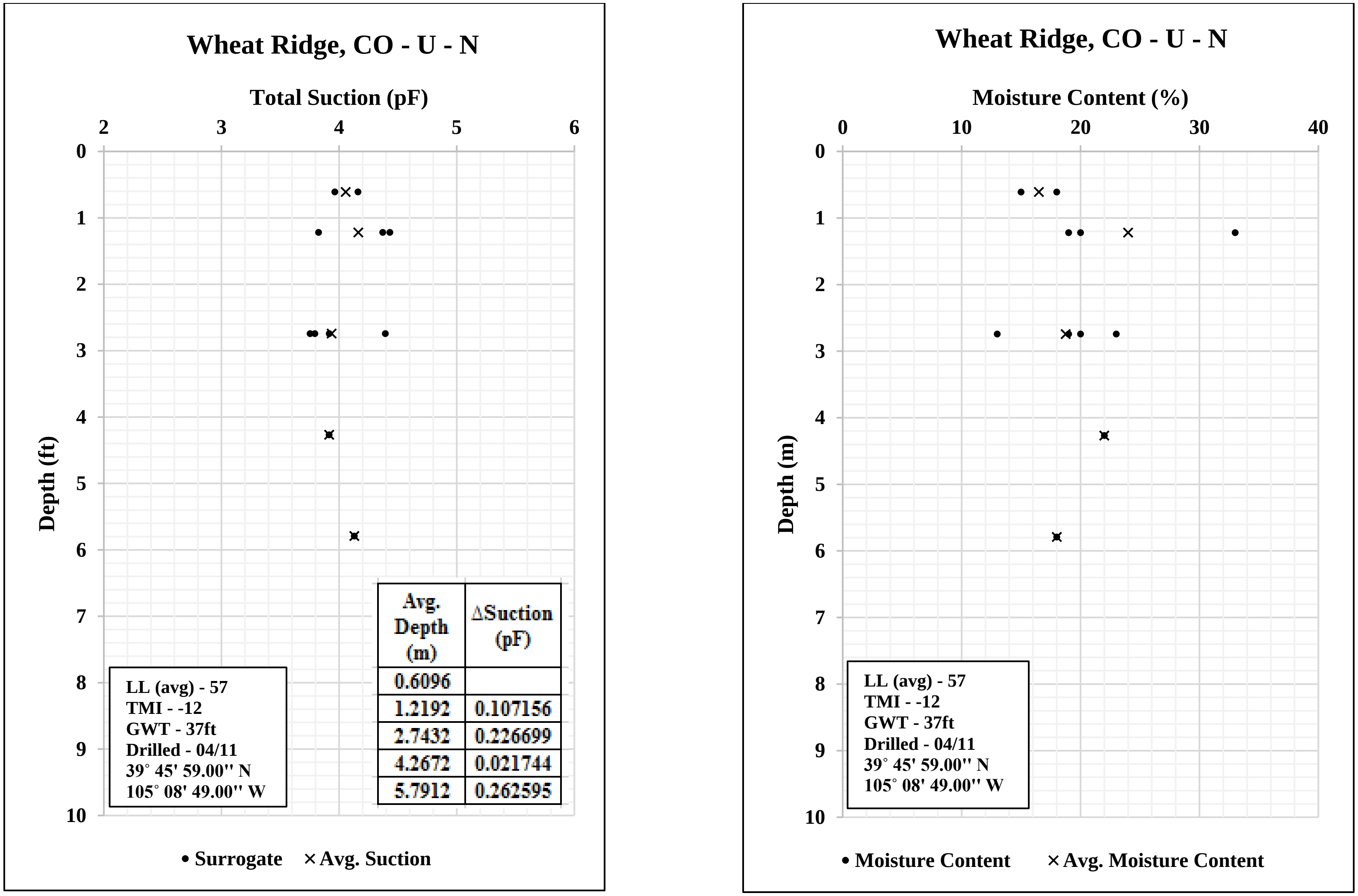
Avg. Depth (m)	ΔSuction (pF)
1.3208	
1.76784	0.096036
2.7432	0.025661
3.6576	0.308479
4.572	0.512359
5.7912	0.36668
7.3152	0.035368

Figure 73: Field Suction Profile (left) and Moisture Content Profile (right) for Hattiesburg, MS



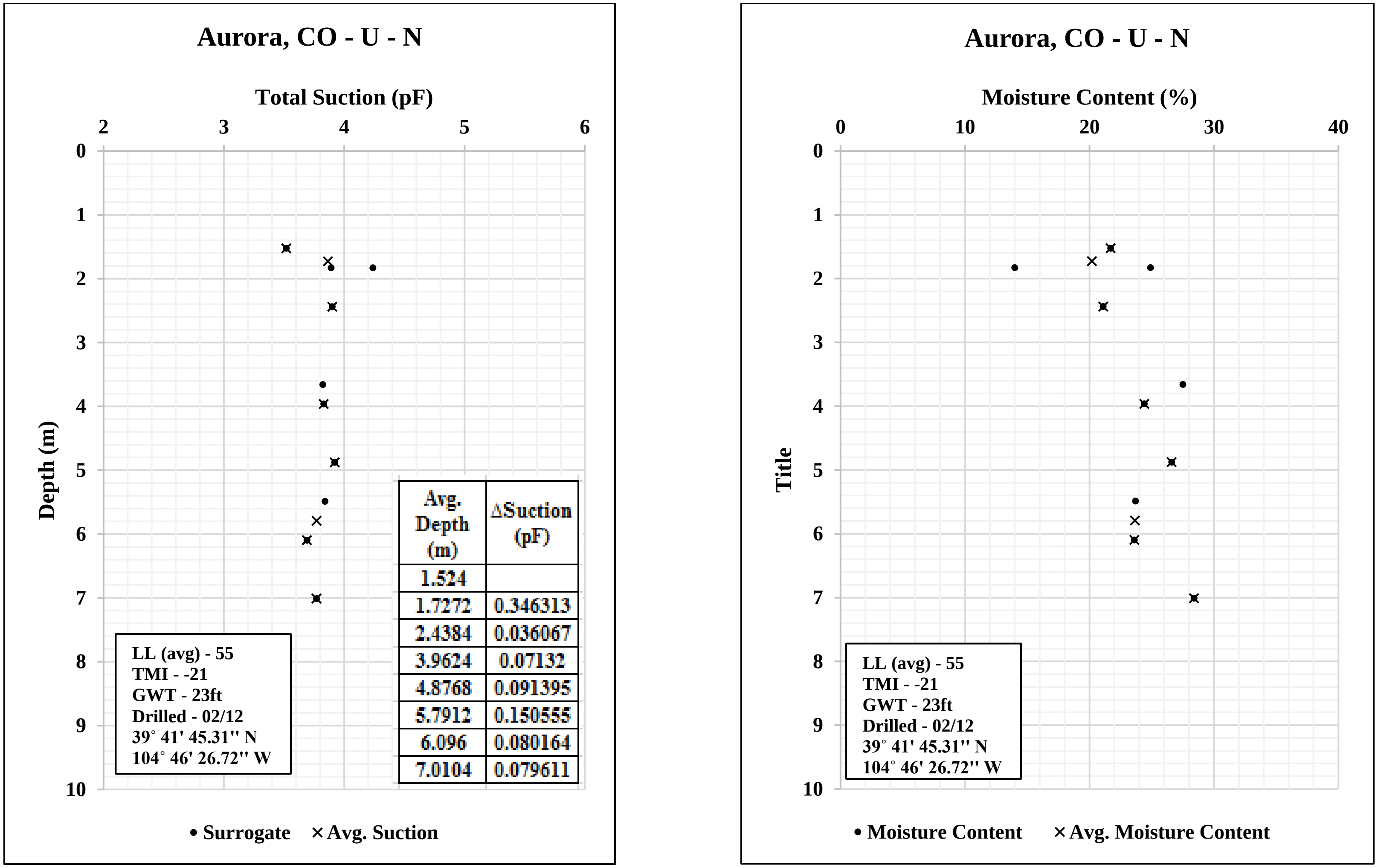
Avg. Depth (m)	ΔSuction (pF)
1.3716	
1.9304	0.111271
2.86512	0.197993
3.048	0.02374
4.4196	0.119322
4.572	0.060467

Figure 74: Field Suction Profile (left) and Moisture Content Profile (right) for Colorado Springs, CO



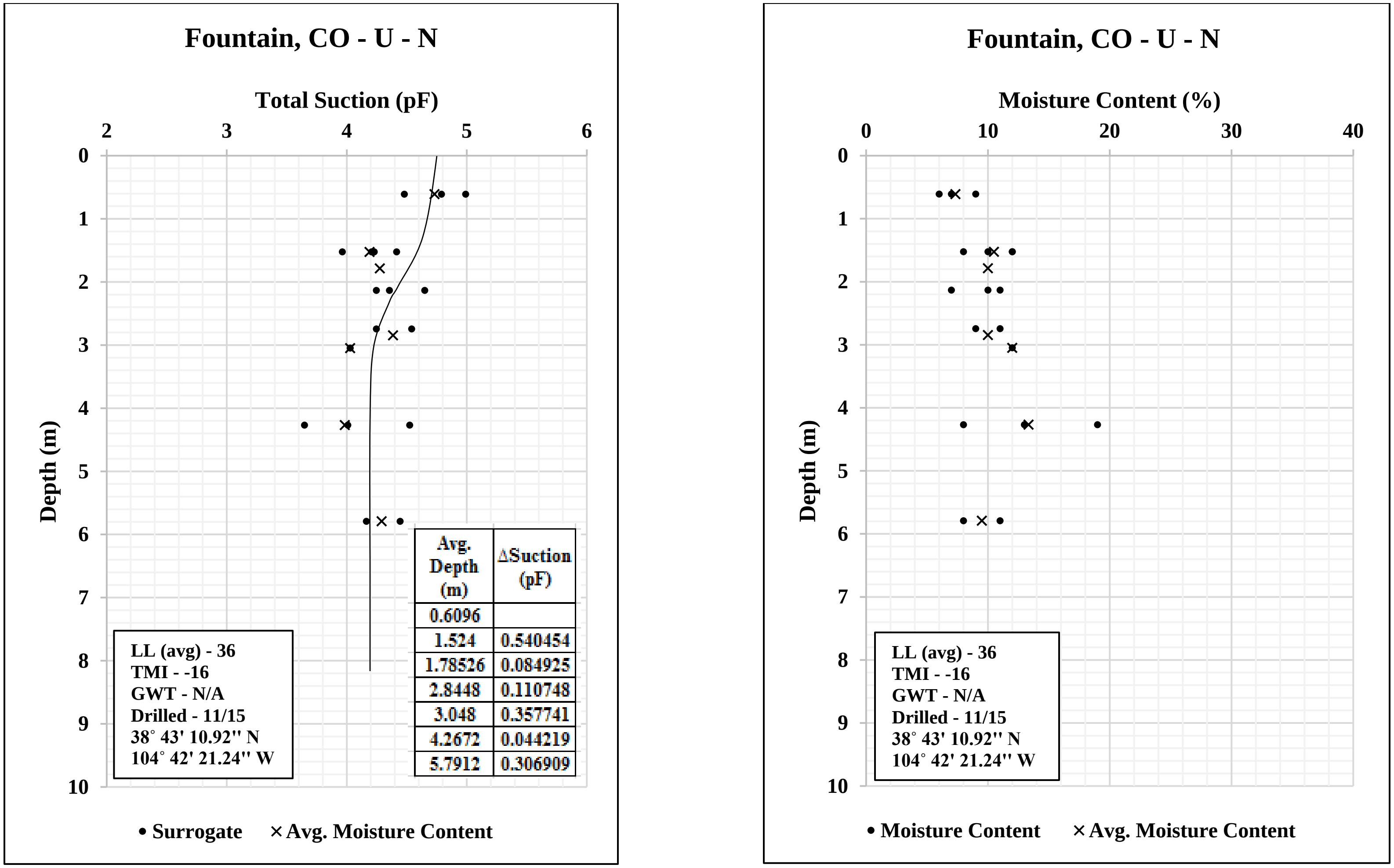
Avg. Depth (m)	ΔSuction (pF)
0.6096	
1.2192	0.107156
2.7432	0.226699
4.2672	0.021744
5.7912	0.262595

Figure 75: Field Suction Profile (left) and Moisture Content Profile (right) for Wheat Ridge, CO



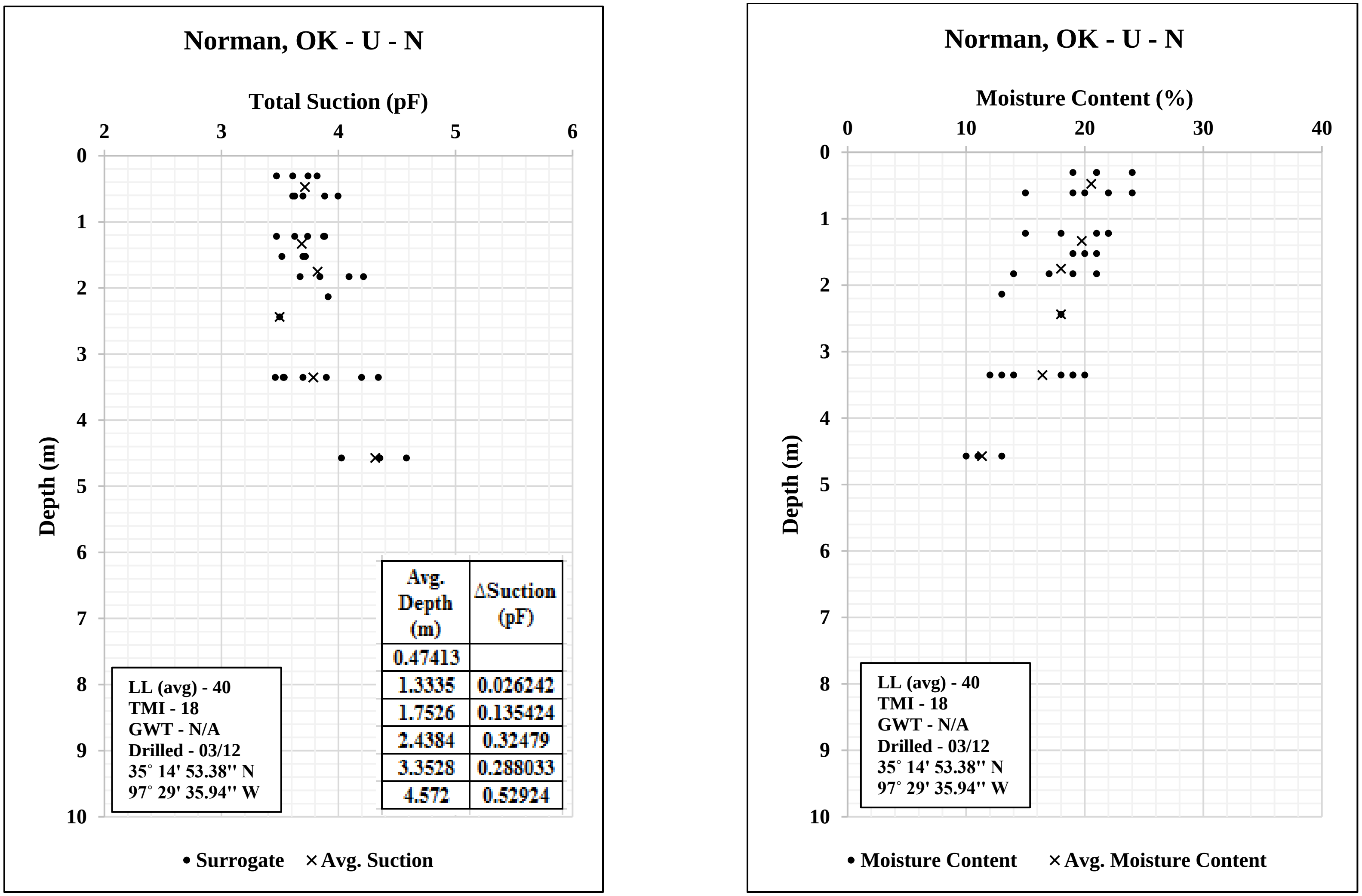
Avg. Depth (m)	ΔSuction (pF)
1.524	
1.7272	0.346313
2.4384	0.036067
3.9624	0.07132
4.8768	0.091395
5.7912	0.150555
6.096	0.080164
7.0104	0.079611

Figure 76: Field Suction Profile (left) and Moisture Content Profile (right) for Aurora, CO



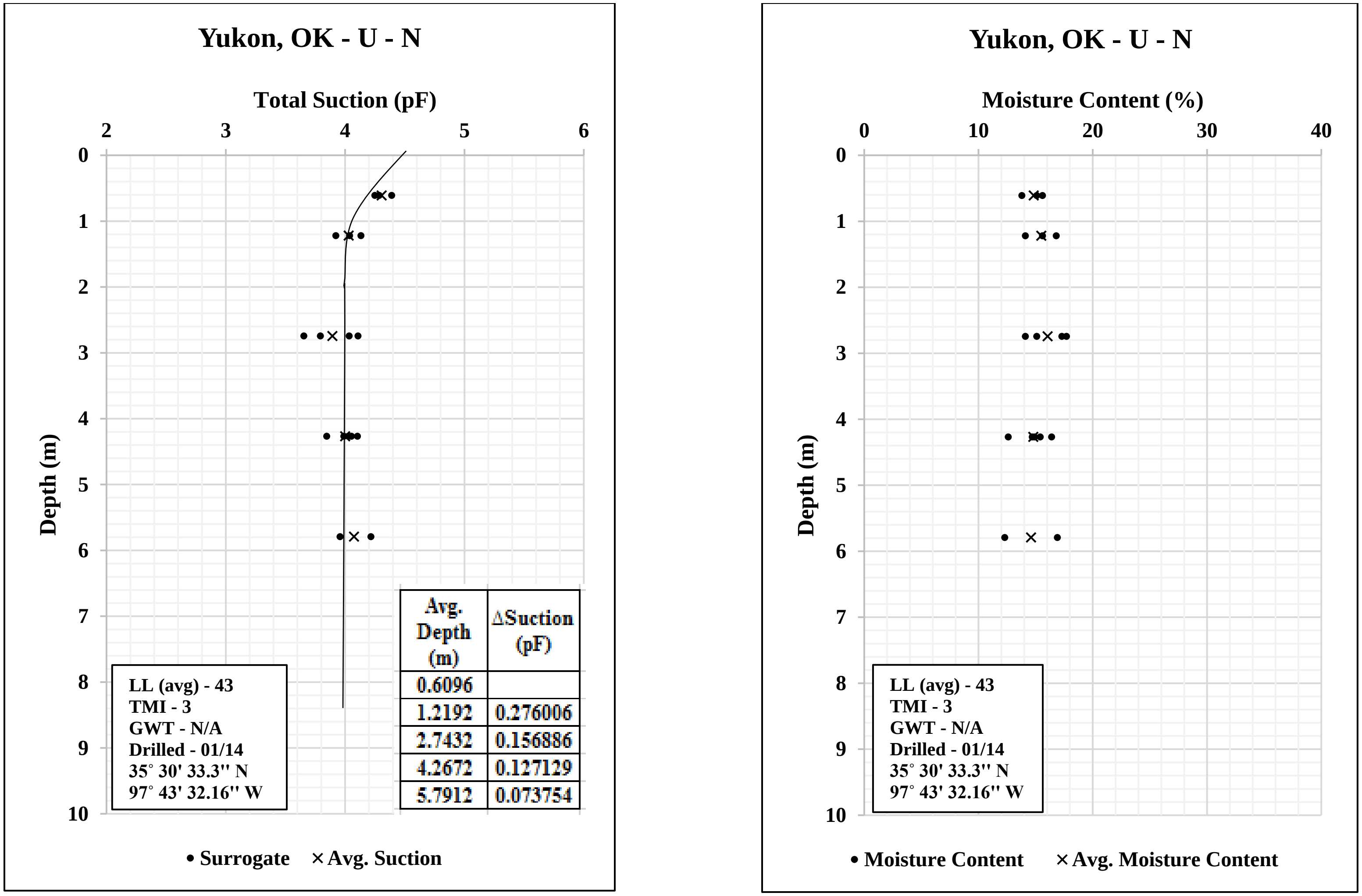
Avg. Depth (m)	ΔSuction (pF)
0.6096	
1.524	0.540454
1.78526	0.084925
2.8448	0.110748
3.048	0.357741
4.2672	0.044219
5.7912	0.306909

Figure 77: Field Suction Profile (left) and Moisture Content Profile (right) for Fountain, CO



Avg. Depth (m)	ΔSuction (pF)
0.47413	
1.3335	0.026242
1.7526	0.135424
2.4384	0.32479
3.3528	0.288033
4.572	0.52924

Figure 78: Field Suction Profile (left) and Moisture Content Profile for Norman, OK



Avg. Depth (m)	ΔSuction (pF)
0.6096	
1.2192	0.276006
2.7432	0.156886
4.2672	0.127129
5.7912	0.073754

Figure 79: Field Suction Profile (left) and Moisture Content Profile (right) for Yukon, OK

APPENDIX C

UNCOVERED/ IRRIGATED FIELD SUCTION AND MOISTURE PROFILE

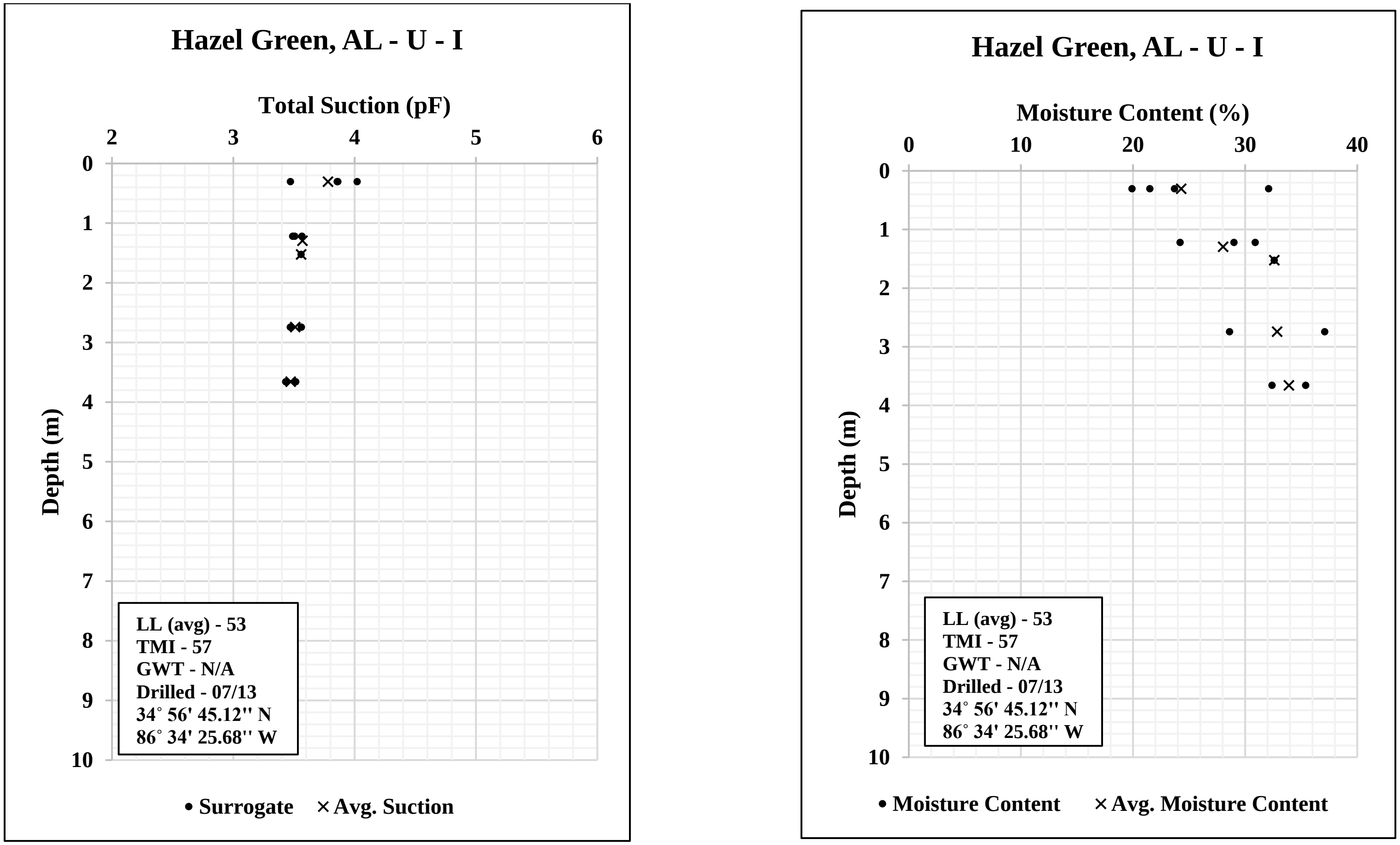
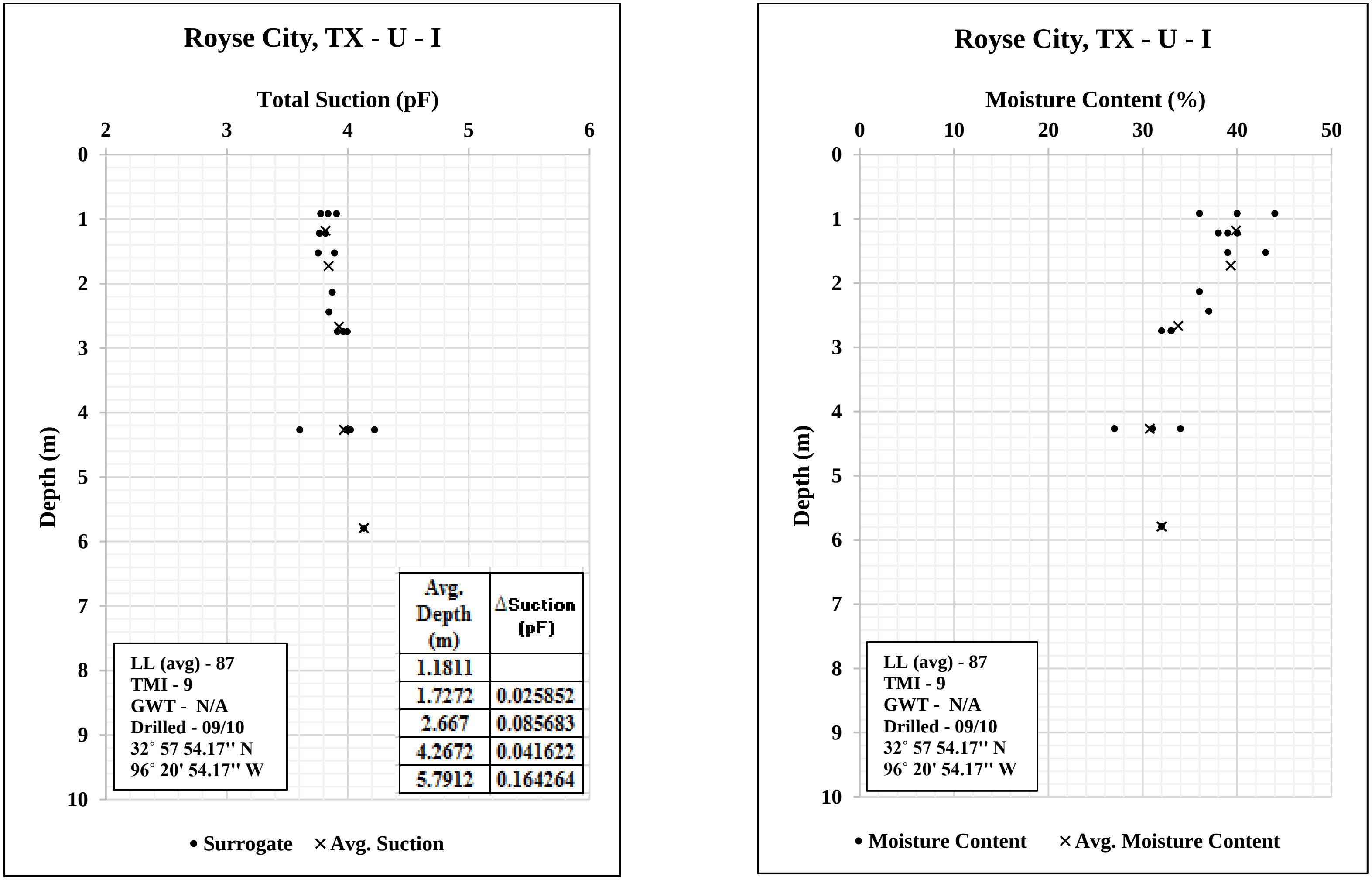
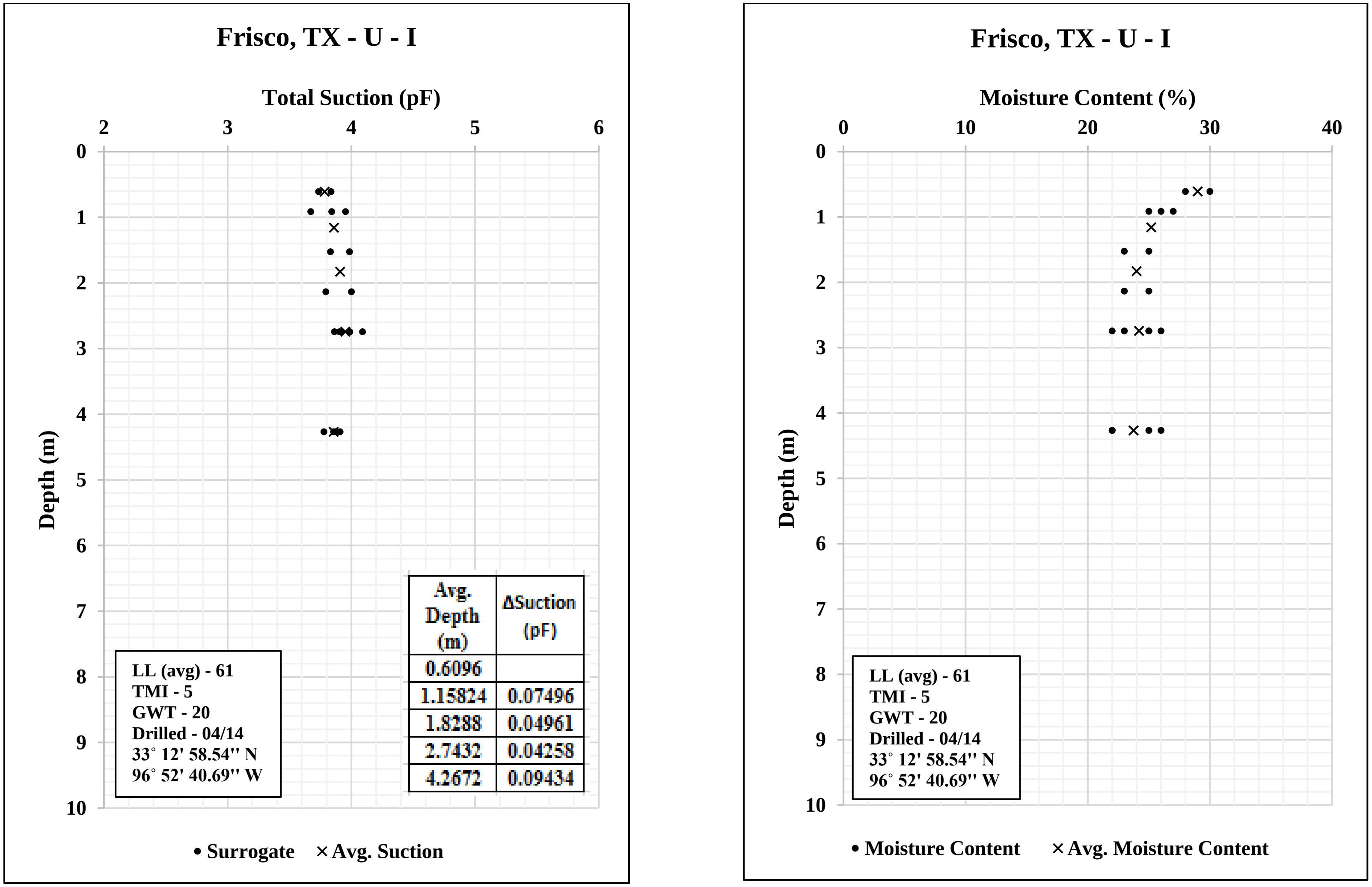


Figure 80: Field Suction Profile (left) and Moisture Content Profile (right) for Hazel Green, AL



Avg. Depth (m)	ΔSuction (pF)
1.1811	
1.7272	0.025852
2.667	0.085683
4.2672	0.041622
5.7912	0.164264

Figure 81: Field Suction Profile (left) and Moisture Content Profile (right) for Royse City, TX



Avg. Depth (m)	ΔSuction (pF)
0.6096	
1.15824	0.07496
1.8288	0.04961
2.7432	0.04258
4.2672	0.09434

Figure 82: Field Suction Profile (left) and Moisture Content Profile (right) for Frisco, TX

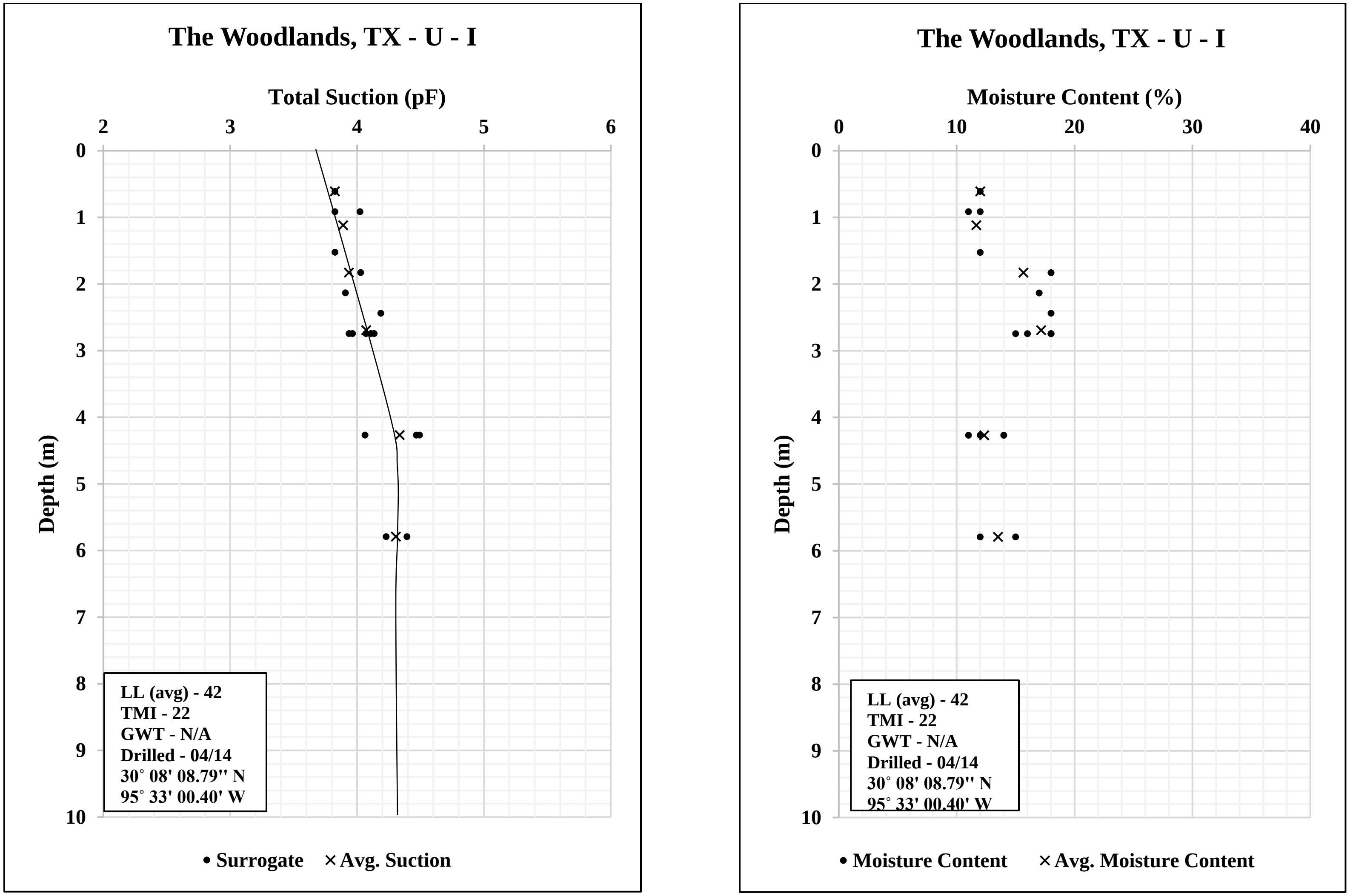


Figure 83: Field Suction Profile (left) and Moisture Content Profile (right) for The Woodlands, TX

APPENDIX D

COVERED/ NON-IRRIGATED FIELD SUCTION AND MOISTURE PROFILE

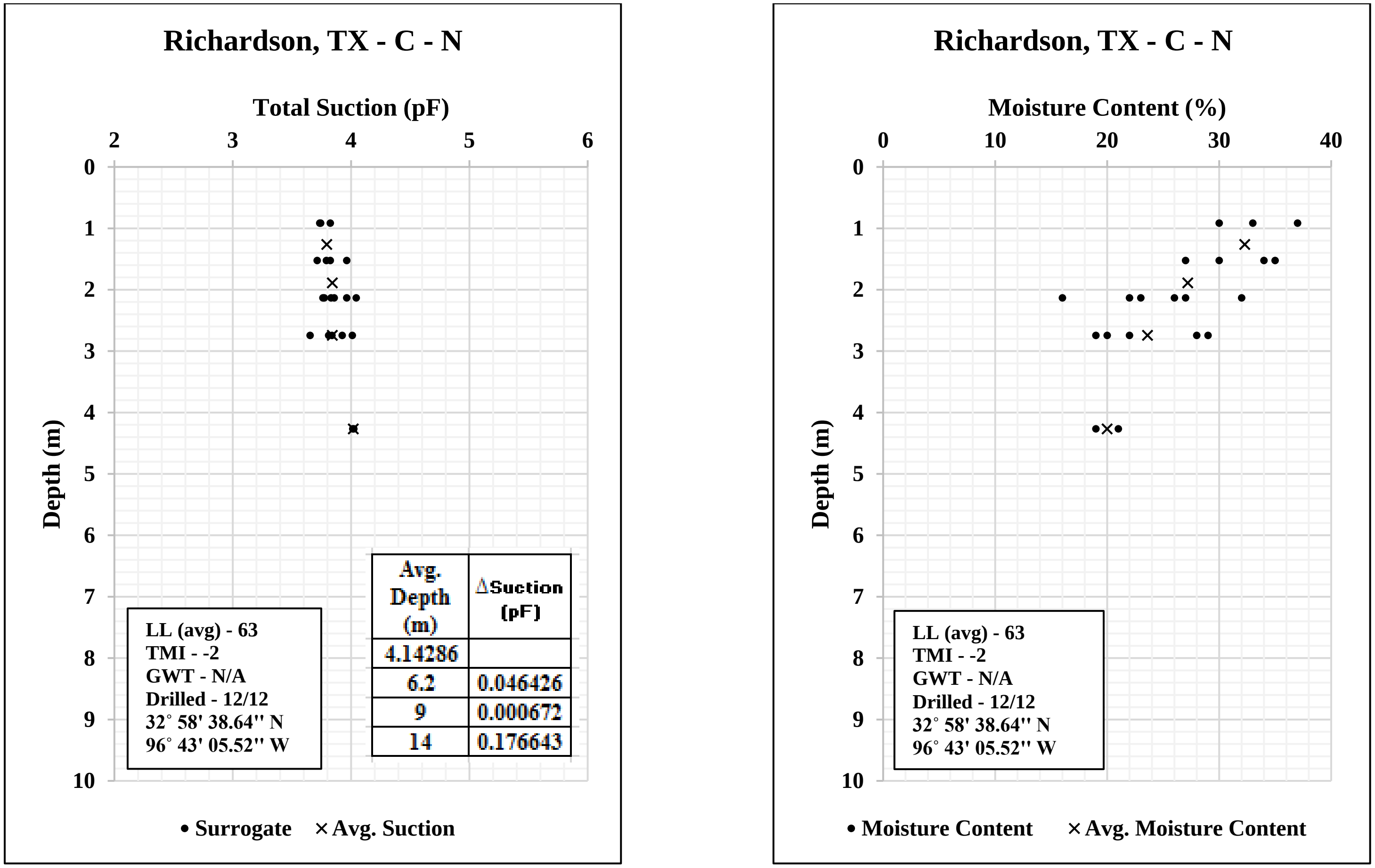
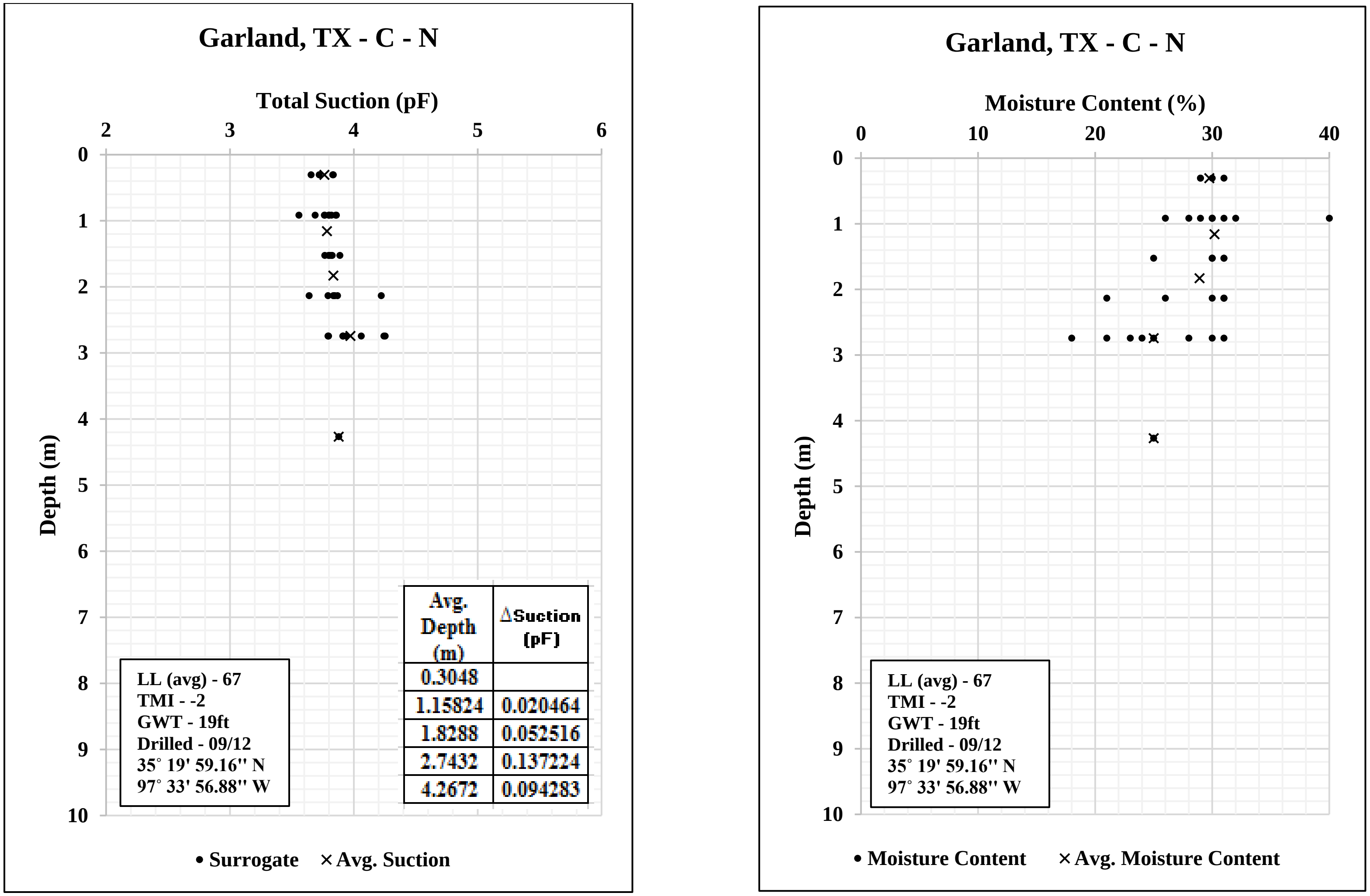
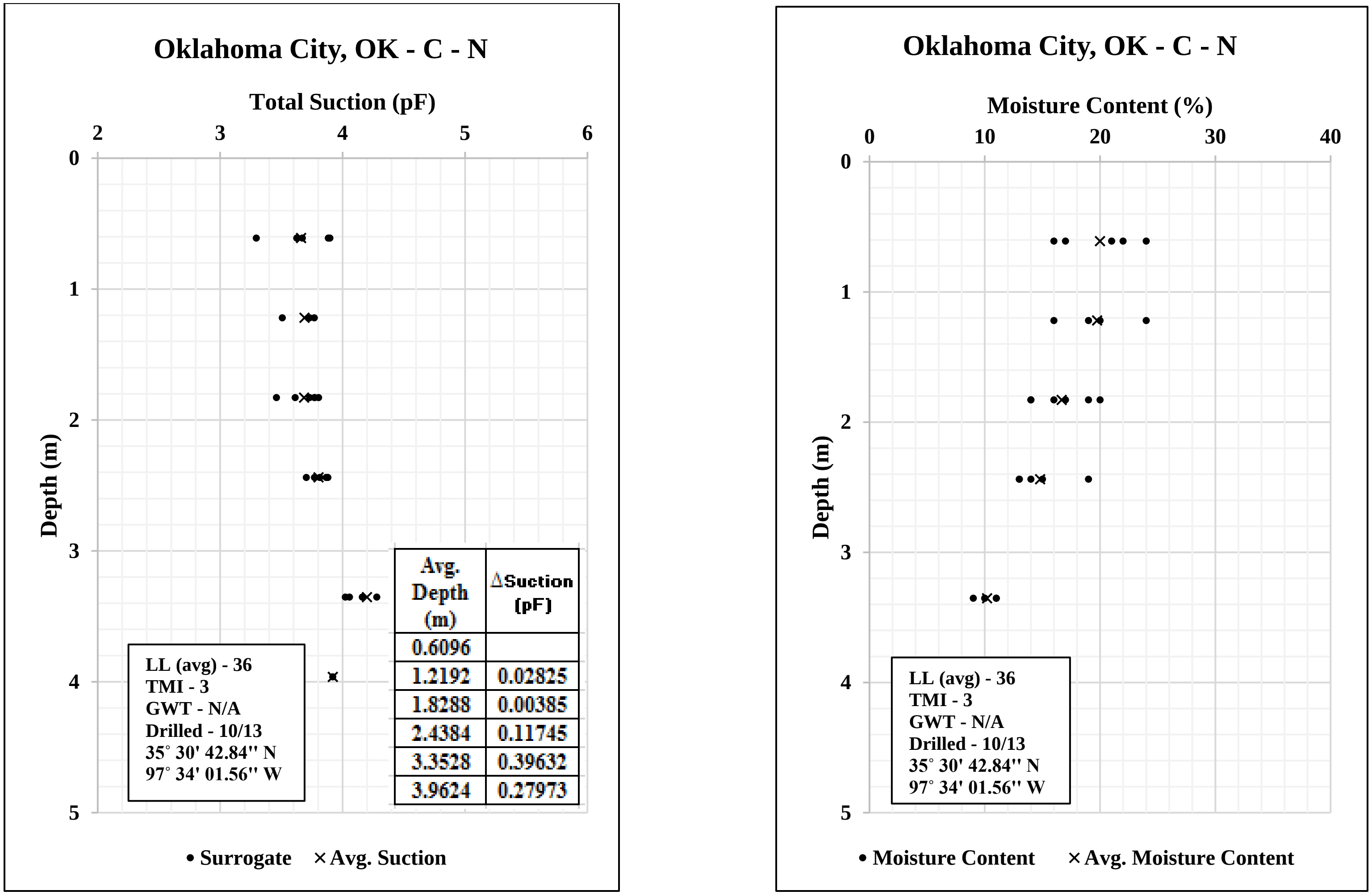


Figure 84: Field Suction Profile (left) and Moisture Content Profile (right) for Richardson, TX



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

Figure 85: Field Suction Profile (left) and Moisture Content Profile (right) for Garland, TX

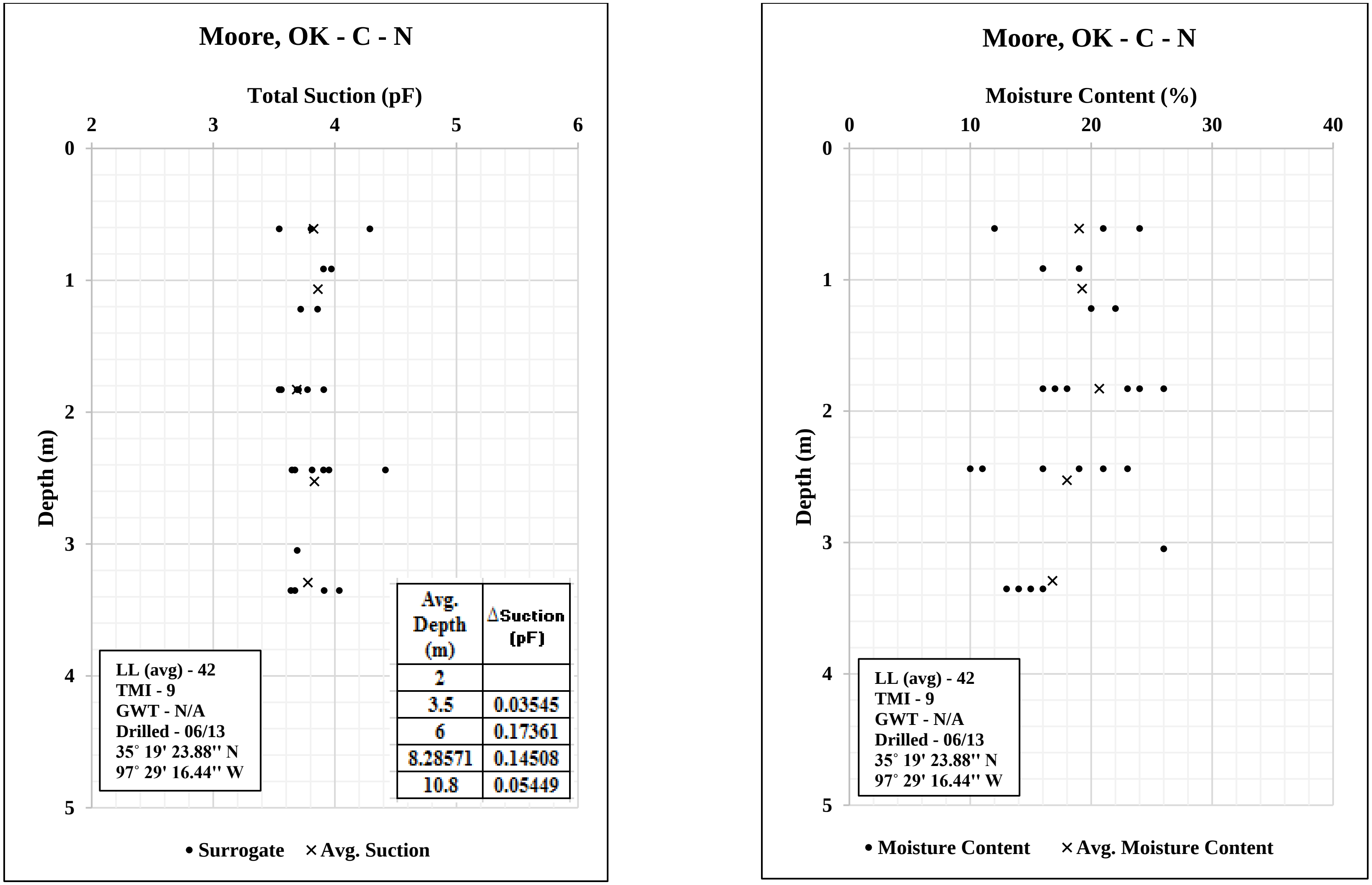


Avg. Depth (m)	ΔSuction (pF)
0.6096	
1.2192	0.02825
1.8288	0.00385
2.4384	0.11745
3.3528	0.39632
3.9624	0.27973

LL (avg) - 36
TMI - 3
GWT - N/A
Drilled - 10/13
35° 30' 42.84'' N
97° 34' 01.56'' W

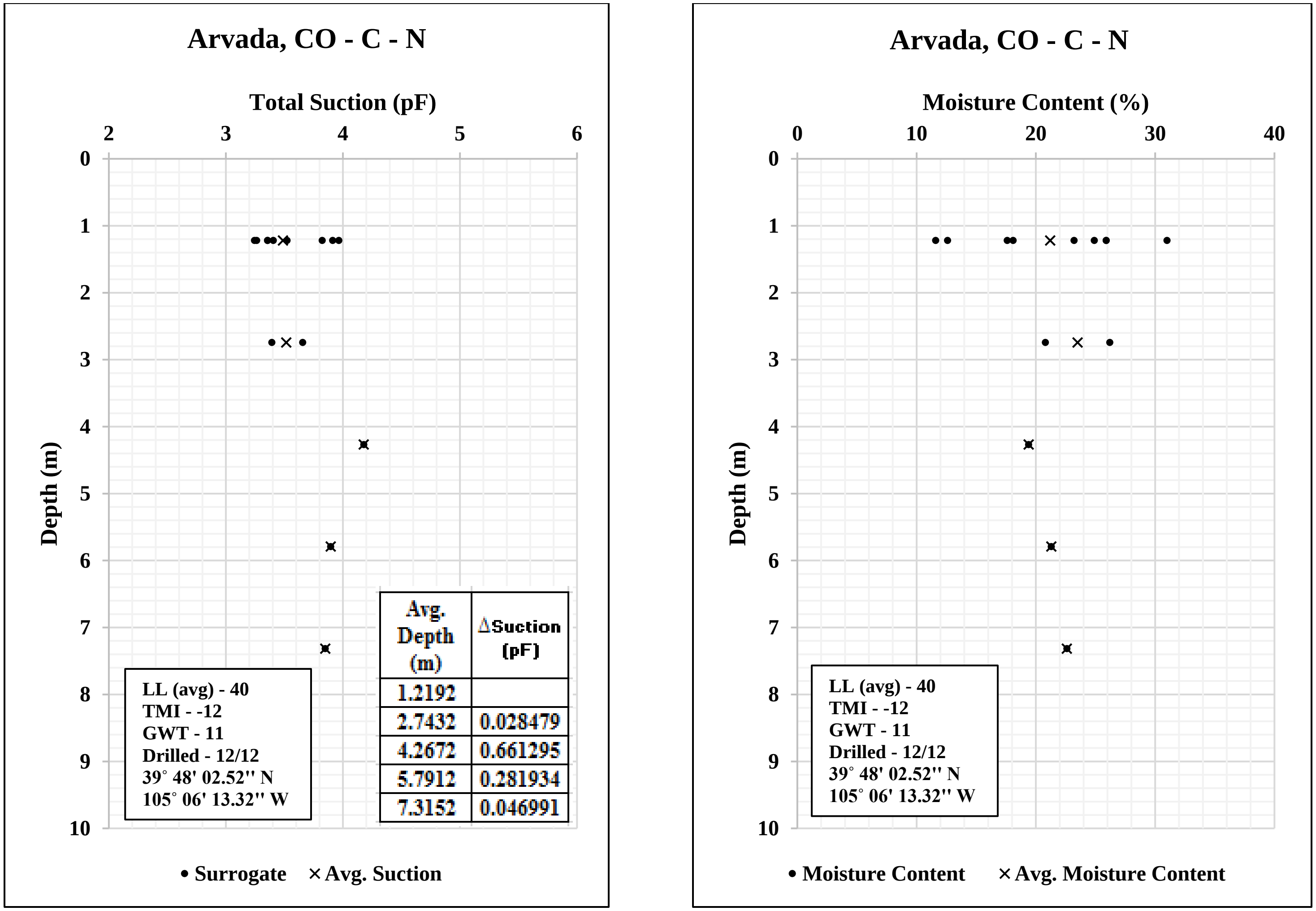
LL (avg) - 36
TMI - 3
GWT - N/A
Drilled - 10/13
35° 30' 42.84'' N
97° 34' 01.56'' W

Figure 86: Field Suction Profile (left) and Moisture Content Profile (right) for Oklahoma City, OK



Avg. Depth (m)	ΔSuction (pF)
2	
3.5	0.03545
6	0.17361
8.28571	0.14508
10.8	0.05449

Figure 87: Field Suction Profile (left) and Moisture Content Profile (right) for Moore, OK

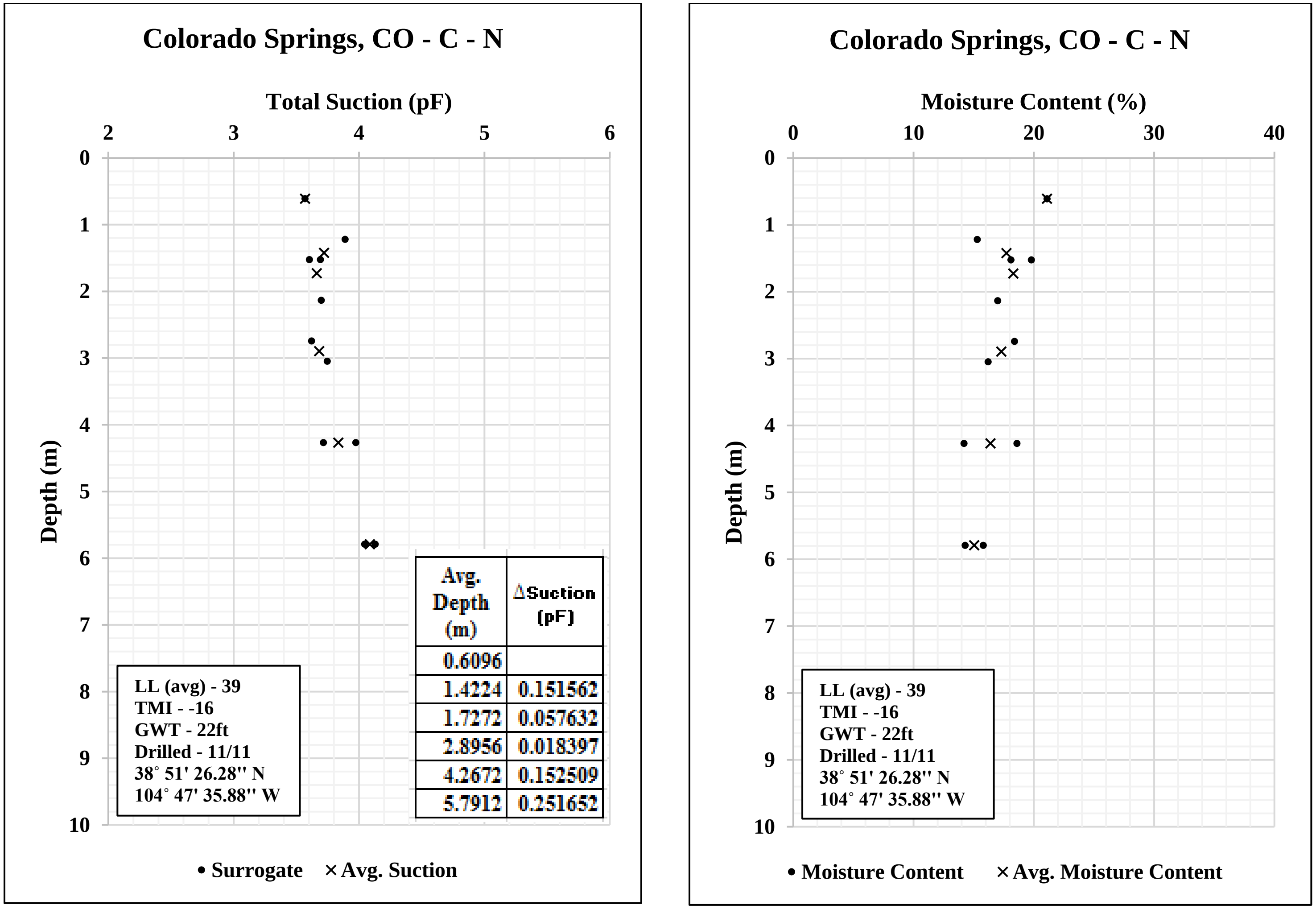


LL (avg) - 40
TMI - -12
GWT - 11
Drilled - 12/12
39° 48' 02.52'' N
105° 06' 13.32'' W

Avg. Depth (m)	ΔSuction (pF)
1.2192	
2.7432	0.028479
4.2672	0.661295
5.7912	0.281934
7.3152	0.046991

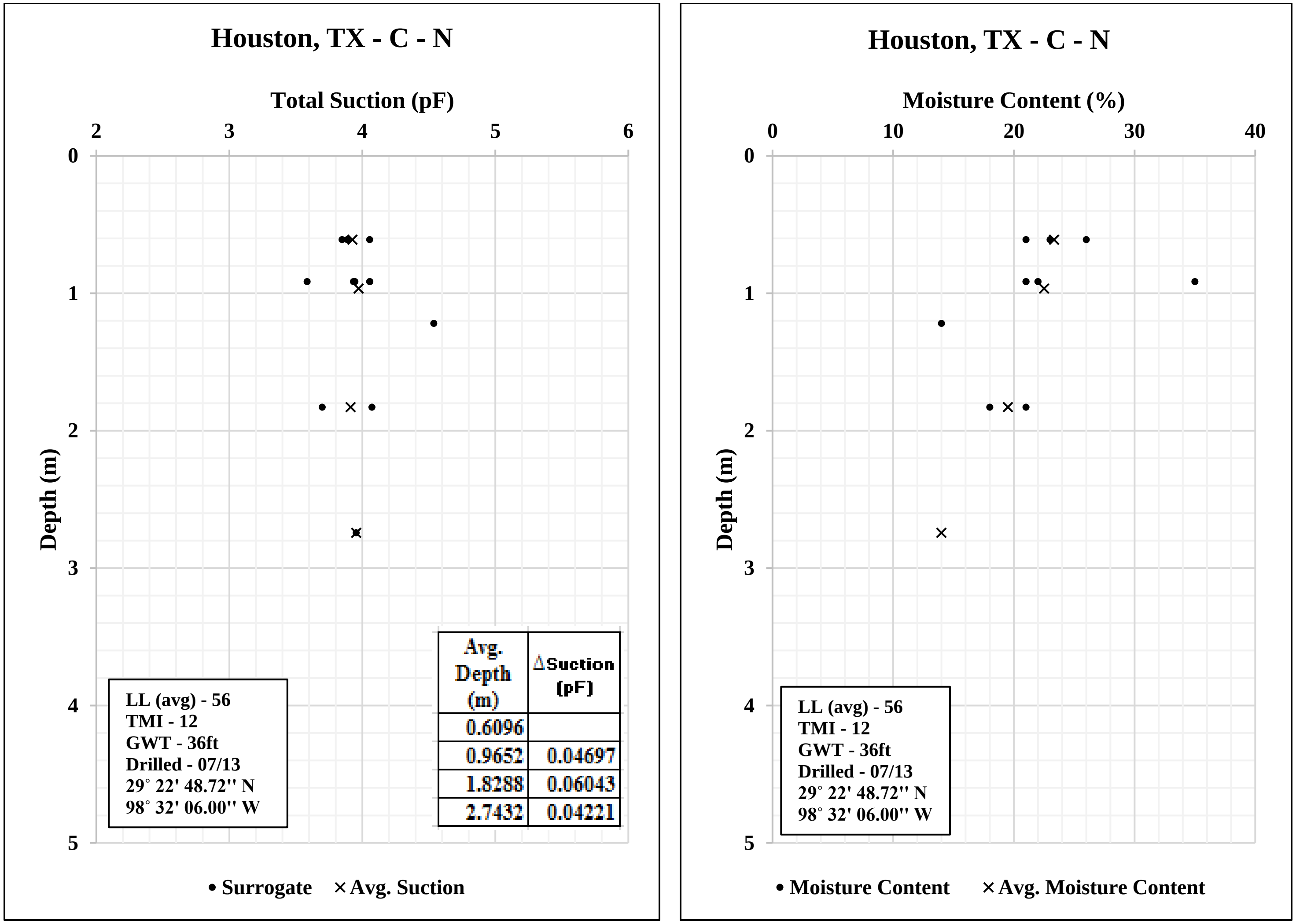
LL (avg) - 40
TMI - -12
GWT - 11
Drilled - 12/12
39° 48' 02.52'' N
105° 06' 13.32'' W

Figure 88: Field Suction Profile (left) and Moisture Content Profile (right) for Arvada, CO



Avg. Depth (m)	ΔSuction (pF)
0.6096	
1.4224	0.151562
1.7272	0.057632
2.8956	0.018397
4.2672	0.152509
5.7912	0.251652

Figure 89: Field Suction Profile (left) and Moisture Content Profile (right) for Colorado Springs, CO



Avg. Depth (m)	ΔSuction (pF)
0.6096	
0.9652	0.04697
1.8288	0.06043
2.7432	0.04221

Figure 90: Field Suction Profile (left) and Moisture Content Profile (right) for Houston, TX

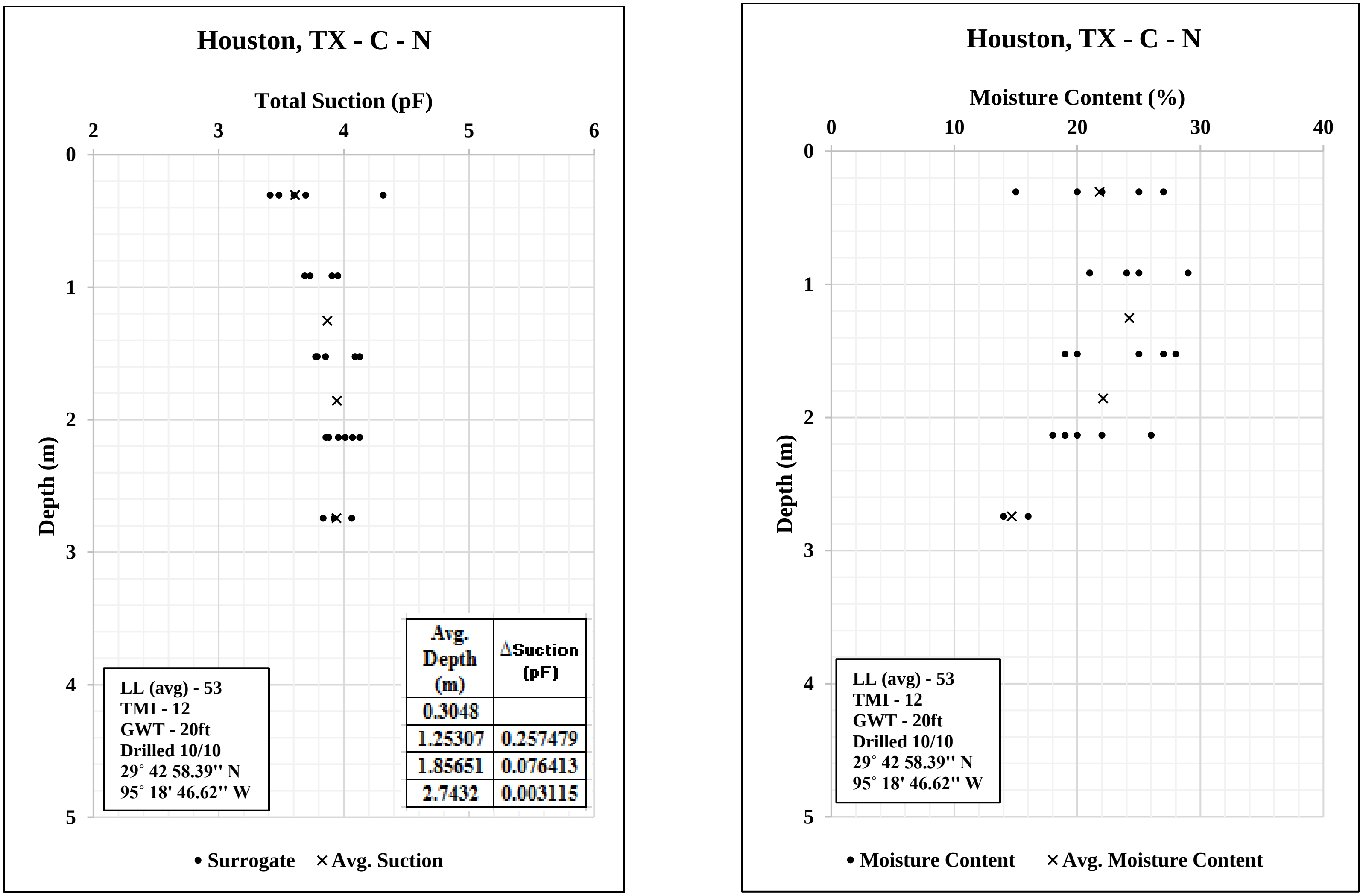
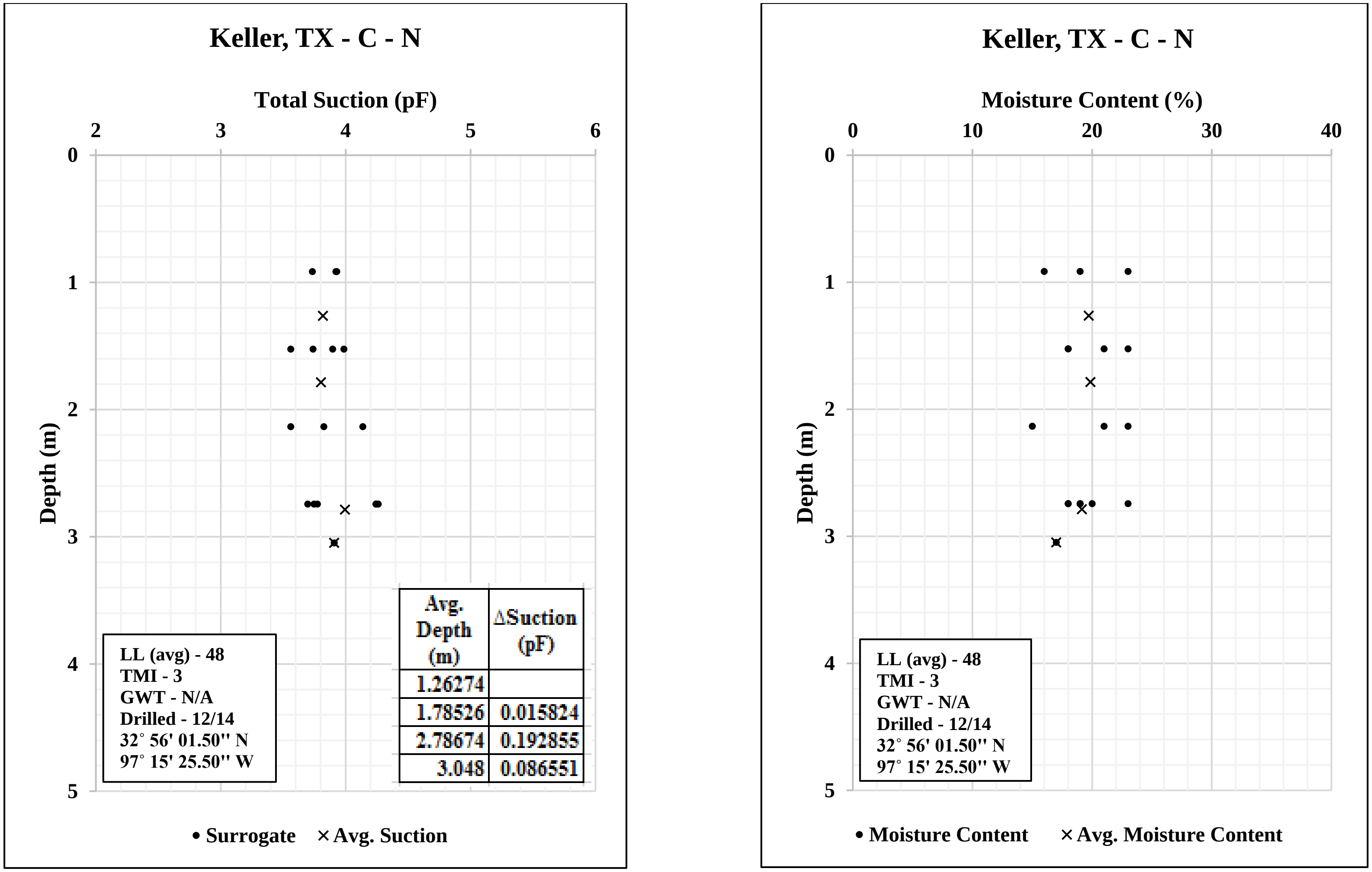
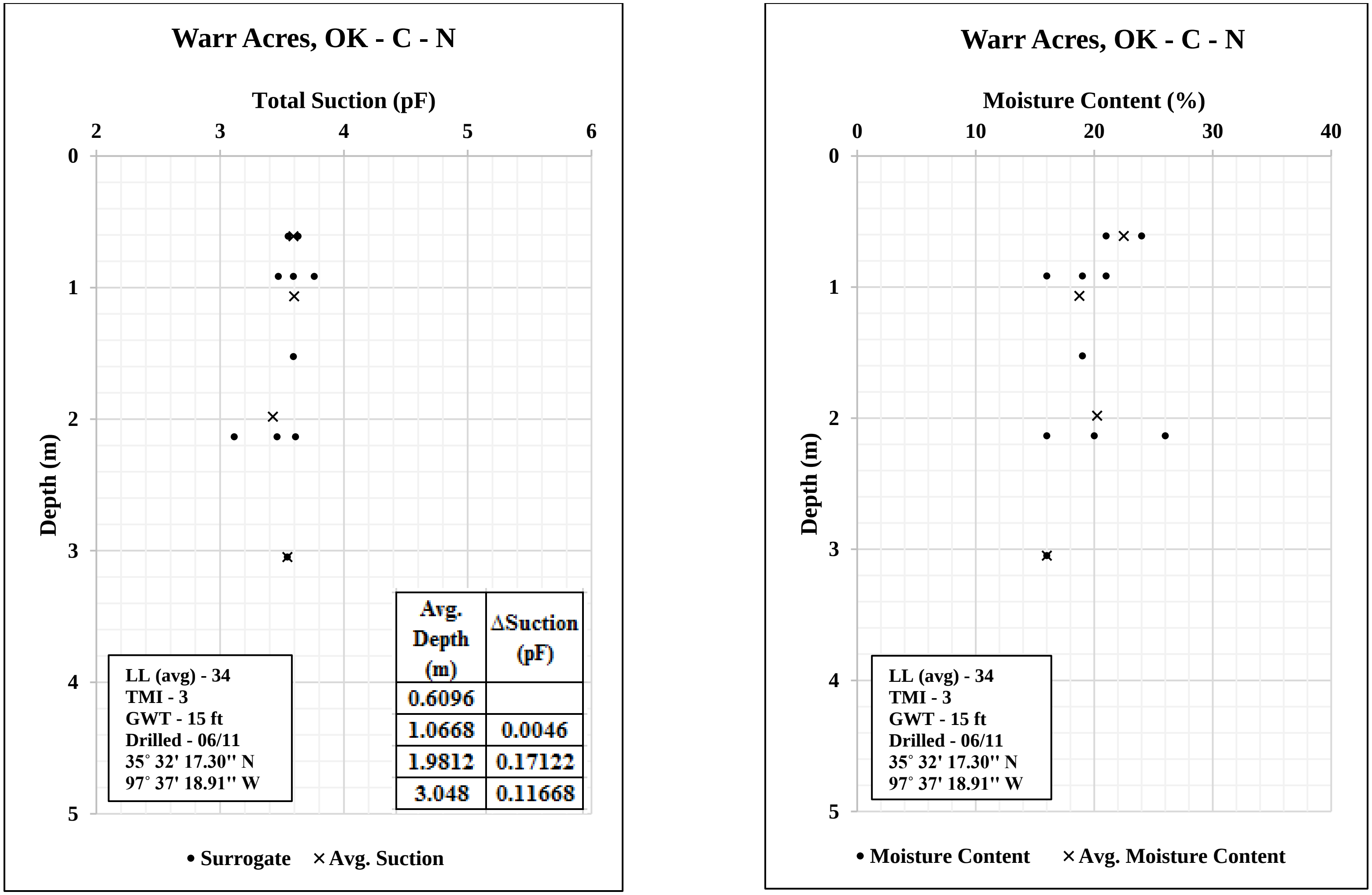


Figure 91: Field Suction Profile (left) and Moisture Content Profile (right) for Houston, TX



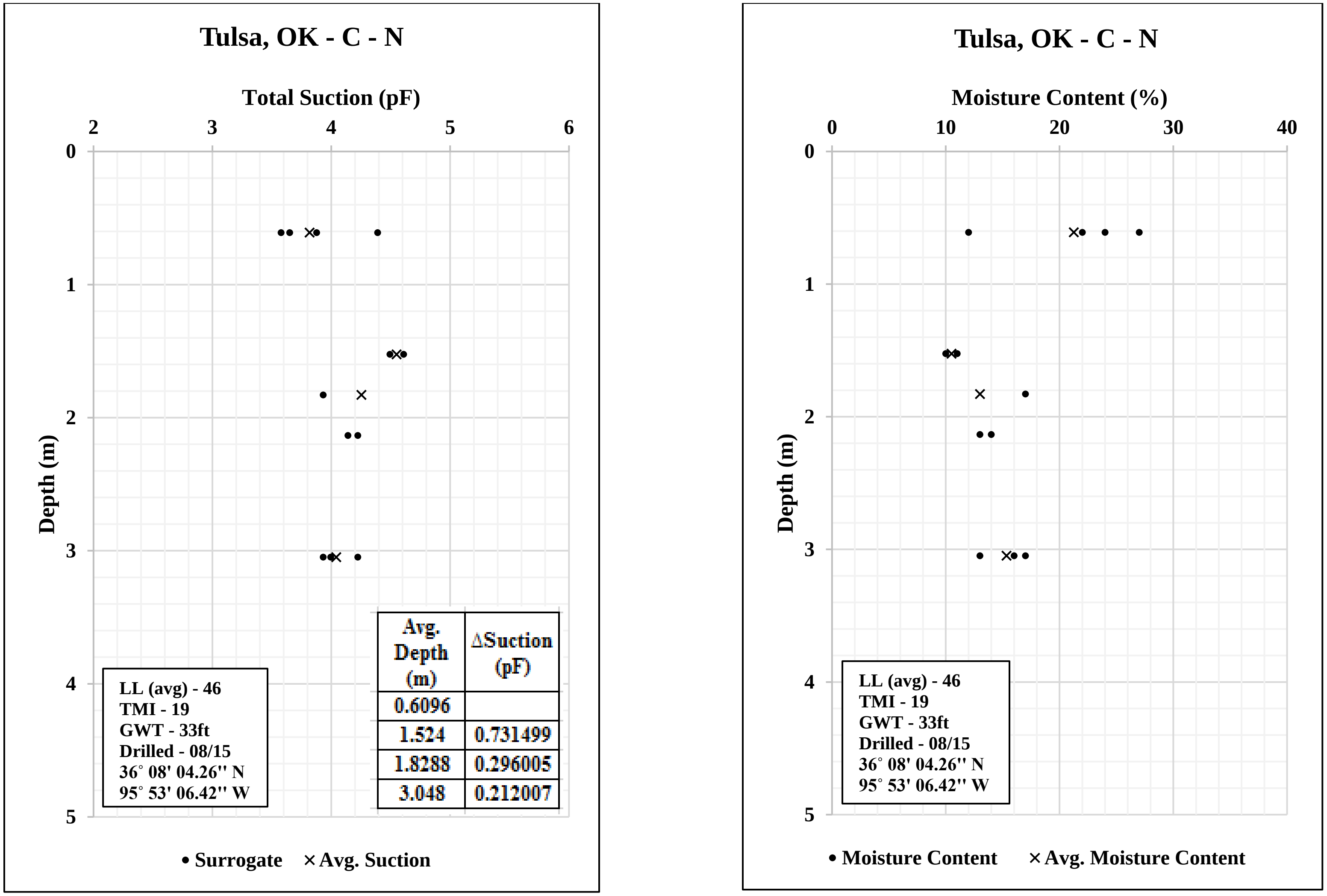
Avg. Depth (m)	ΔSuction (pF)
1.26274	
1.78526	0.015824
2.78674	0.192855
3.048	0.086551

Figure 92: Field Suction Profile (left) and Moisture Content Profile (right) for Keller, TX



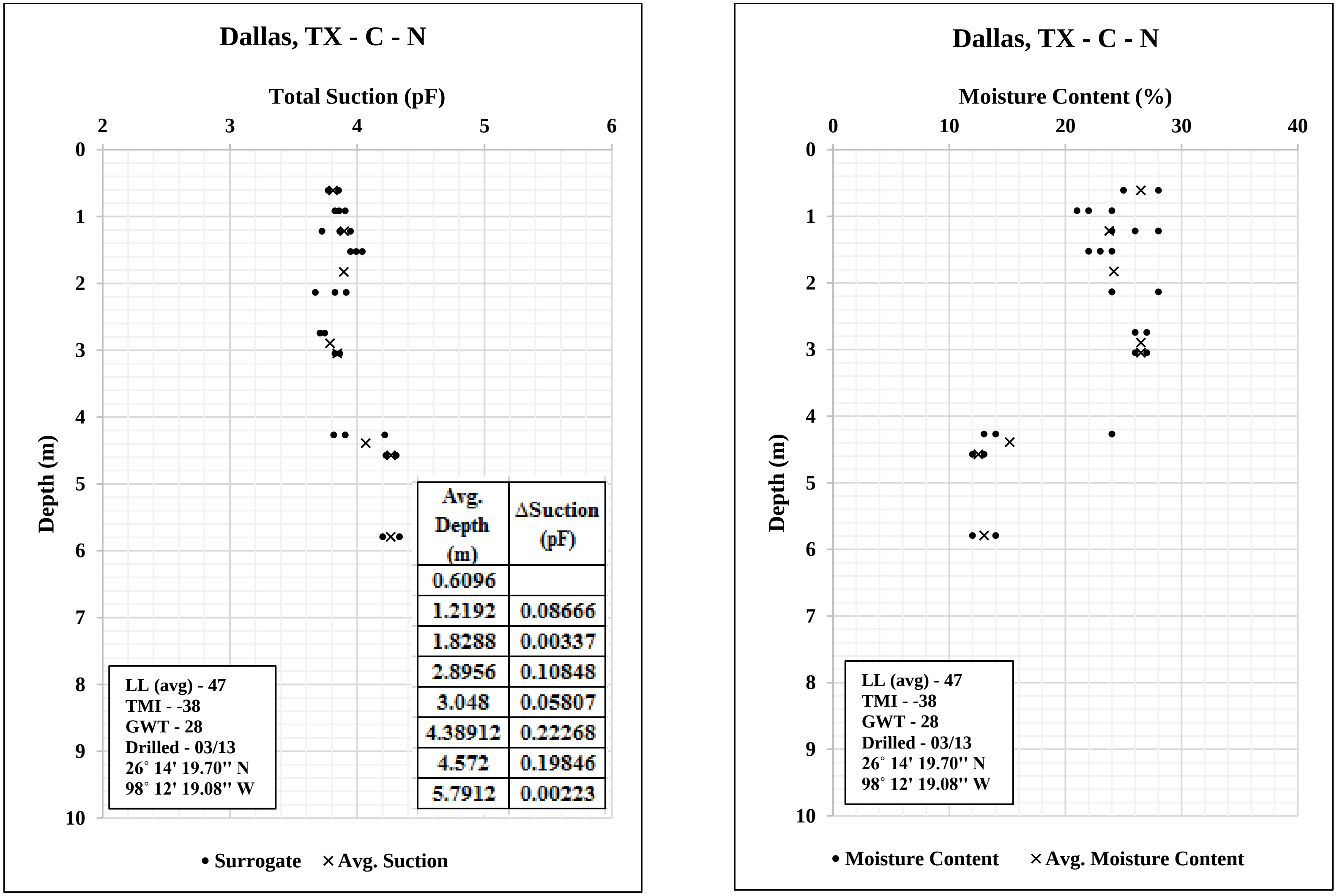
Avg. Depth (m)	ΔSuction (pF)
0.6096	
1.0668	0.0046
1.9812	0.17122
3.048	0.11668

Figure 93: Field Suction Profile (left) and Moisture Content Profile (right) for Warr Acres, OK



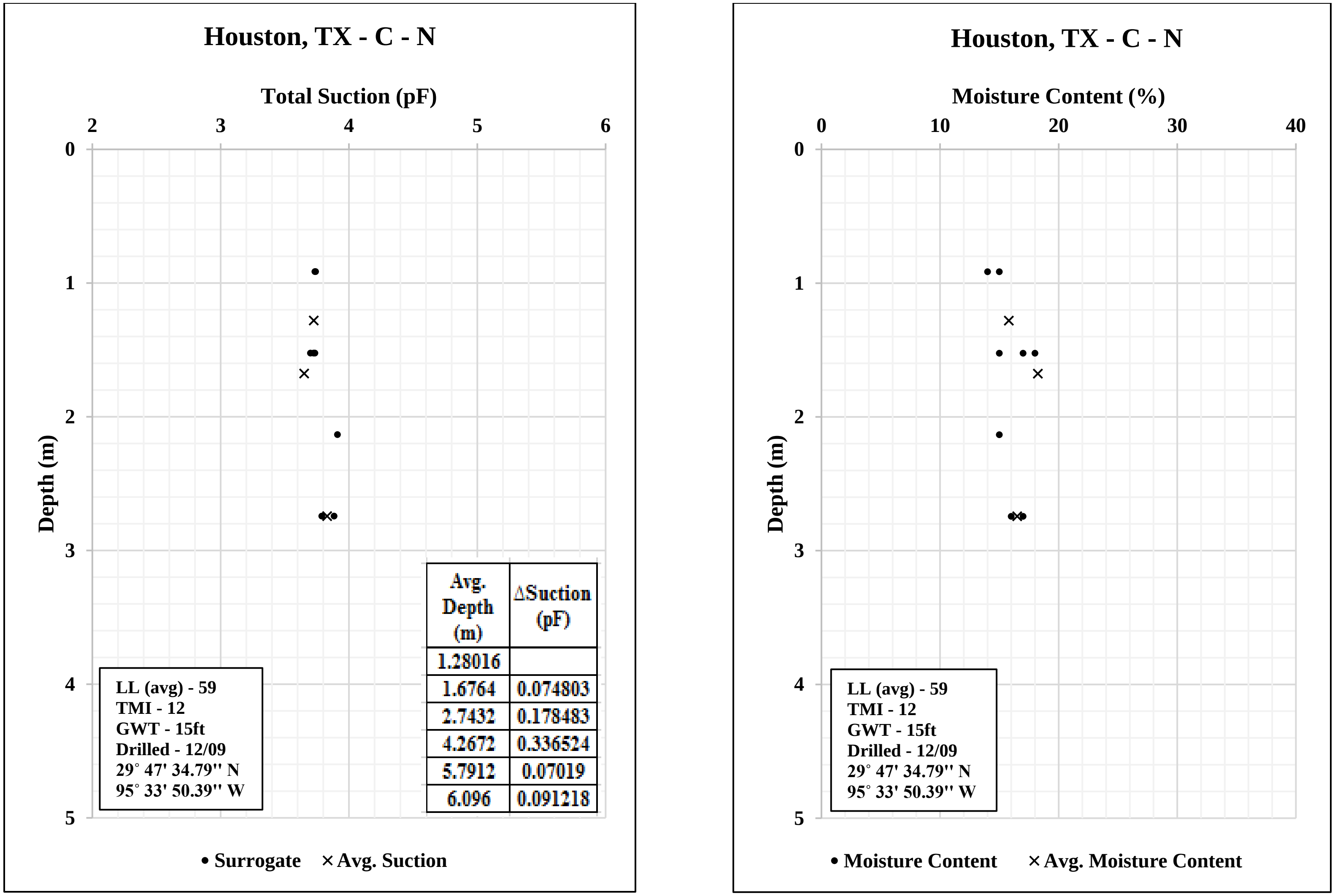
Avg. Depth (m)	ΔSuction (pF)
0.6096	
1.524	0.731499
1.8288	0.296005
3.048	0.212007

Figure 94: Field Suction Profile (left) and Moisture Content Profile (right) for Tulsa, OK



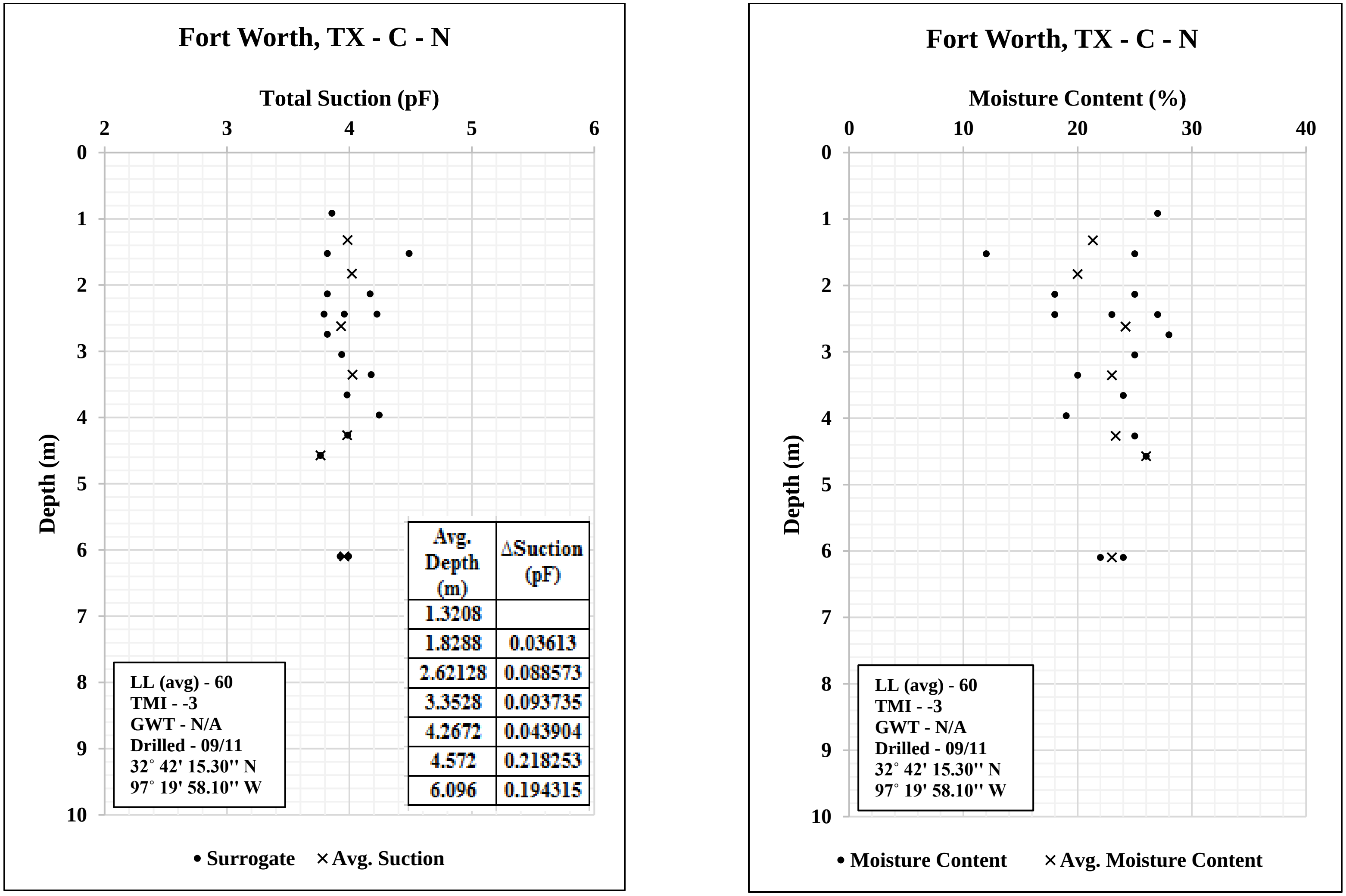
Avg. Depth (m)	ΔSuction (pF)
0.6096	
1.2192	0.08666
1.8288	0.00337
2.8956	0.10848
3.048	0.05807
4.38912	0.22268
4.572	0.19846
5.7912	0.00223

Figure 95: Field Suction Profile (left) and Moisture Content Profile (right) for Dallas, TX



Avg. Depth (m)	ΔSuction (pF)
1.28016	
1.6764	0.074803
2.7432	0.178483
4.2672	0.336524
5.7912	0.07019
6.096	0.091218

Figure 96: Field Suction Profile (left) and Moisture Content Profile (right) for Houston, TX



Avg. Depth (m)	ΔSuction (pF)
1.3208	
1.8288	0.03613
2.62128	0.088573
3.3528	0.093735
4.2672	0.043904
4.572	0.218253
6.096	0.194315

Figure 97: Field Suction Profile (left) and Moisture Content Profile (right) for Fort Worth, TX