OKLAHOMA TRANSPORTATION CENTER

ECONOMIC ENHANCEMENT THROUGH INFRASTRUCTURE STEWARDSHIP

INTERPRETATION OF IN SITU TESTS AS AFFECTED BY SOIL SUCTION

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16. ABSTRACT

Soil moisture conditions are subject to change depending on the season in which they are tested. In unsaturated soils the moisture at which a soil is tested can directly affect strength and stiffness of the material. In situ testing is commonly used for geotechnical investigations; however, the analysis methods assume the soil is either completely dry or saturated. For near surface soils, these conditions are often the exception to the rule rather than the standard. Currently there are no well established methods for interpretation of in situ tests in unsaturated soils. Research is being conducted to investigate the influence of changing moisture conditions on the response of in situ tests in unsaturated soil. Two sites were instrumented with weather monitoring stations and moisture sensors were placed at depths of 1, 3 and 6 feet. At two month intervals a suite of in situ tests including; cone penetration (CPT), standard penetration (SPT), and pre-bored pressuremeter (PMT), are performed. In addition, in situ tensiometers have been installed at one site and samples are obtained for water content and suction measurements when in situ tests are conducted. Other laboratory tests are being conducted on undisturbed samples to establish baseline saturated and unsaturated soil properties as well as soil water characteristic curves. This report will present results of field tests demonstrating the importance of moisture content and matric suction on the in situ test results. The ultimate goal of the research is to better predict changes in soil moisture based on weather data and develop a framework to interpret in situ test results in unsaturated soils. This report represents a summary of progress during the first half of the project that was partly supported by OkTC funding.

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.40	millimeters	mm
ft	feet	0.3048	meters	m
yd	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm
ft^2	square feet	0.0929	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0283	cubic meters	m^3
yd^3	cubic yards	0.7645	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.4536	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.448	Newtons	N
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.0394	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yd
km	kilometers	0.6214	miles	mi
		AREA		
mm^2	square millimeters	0.00155	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.0338	fluid ounces	fl oz
L	liters	0.2642	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	degrees Celsius	9/5+32	degrees Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

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INTERPRETATION OF IN SITU TESTS AS AFFECTED BY SOIL SUCTION

FINAL REPORT

July 2013

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EXECUTIVE SUMMARY

As part of a geotechnical exploration, in situ testing is complimentary to a thorough soil investigation. For unsaturated soils, the day or season that a particular site is tested can have a strong influence on the data collected. In Oklahoma, clay type soils are widespread and drought conditions are common. Excessive periods of dry weather cause near surface clayey soils to desiccate, shrink, and stiffen. Significant changes in soil moisture content can occur to depths in excess of 10 feet; this zone of moisture content changes is referred to as the active zone. Thus, an in situ investigation during a drought in Oklahoma may predict a very strong, stiff, near surface soil profile capable of supporting shallow foundations. However, inundation with heavy rain or a prolonged wetting period can significantly change the moisture content and hence, soil properties in the active zone. Thus, it is important to design foundations for moisture conditions representing the wettest condition expected. If in situ tests are conducted during periods of low moisture content, results will not reflect the soil strength and stiffness expected during wetter periods. Unfortunately, there are currently no well established methods for interpreting results of pressuremeter tests in unsaturated soils. Research described in this paper is part of an effort to develop such methods. This report represents a summary of progress during the first half of the project that was partly supported by OkTC funding.

To establish methods for interpreting in situ test results, weather stations and soil moisture sensors were installed at two test site locations near Norman, Oklahoma to better understand the link between weather and soil moisture content changes. In addition, Pressuremeter (PMT), Cone Penetration (CPT), and Standard Penetration (SPT) tests were conducted at these locations at various times in order to study the relationships between soil moisture content, matric suction and in situ test results at the sites. The weather stations are capable of monitoring typical weather conditions as well as volumetric moisture content at depths of 1, 3, and 6 feet.

Pressuremeter tests (PMT) were performed monthly to encompass changing moisture conditions at each site. This report presents the results of PMT tests demonstrating the importance of moisture content and matric suction on in situ test

results. CPT and SPT were performed by the Oklahoma Department of Transportation (ODOT) at approximately 2 month intervals. The results of the tests were plotted and compared to the moisture conditions measured during the time of the test. PMT results showed a decrease in limit pressure (P_L) and pressuremeter modulus E_p when the soil increased in moisture. Testing started in February of 2013 when the soil is typically quite dry due to low precipitation during the winter in Oklahoma and previous drought conditions. Test were run through the spring while significant rain events occurred so the soil increased in moisture throughout the test period. There is not yet any test data that shows the soil transitioning from generally wet conditions to dry. CPT showed decreasing tip resistance between tests conducted in February and May, at both sites after significant moisture had accumulated in the soil. SPT N-value showed similar behavior, decreasing with increasing moisture. The CPT and SPT verify weather station volumetric moisture content data. These measurements collected by the weather station showed increased moisture at 1 and 3 feet and little change at 6 feet. CPT and SPT data showed noticeable softer soil conditions to a depth of roughly 5 feet at each site with little change below this. This is likely due to the permeability of the soils at the site, it is expected that with increased time the moisture will migrate further through the soil profile.

1. **INTRODUCTION**

1.1 Problem

In situ testing of soil with invasive methods such as the Cone Penetration Test (CPT), and Pre-bored Pressuremeter Test (PMT), for example, are increasingly being used in geotechnical engineering practice in the United States to estimate soil property profiles. In Oklahoma, the Materials Division of the Department of Transportation (ODOT) has led the way in the use of in situ testing, and relies heavily on the CPT and DMT in practice. However, there has been very little work to develop methods for interpreting results of these tests when performed in unsaturated soil.

During a subsurface exploration, a zone of unsaturated soil is often encountered, sometimes extending to considerable depth. This is particularly true when tests are conducted through highway embankments. It is generally understood that the behavior of unsaturated soil is different from the commonly assumed saturated, undrained or drained soil behavior; yet there are no proven methods for interpreting in situ test results that account for these differences. A great deal of research has been devoted to the interpretation of these tests in cohesive and frictional soils; however, there are currently no reliable comprehensive methods for interpreting in situ test results from unsaturated soils. It is important to develop such methods because the in situ test results in unsaturated soil will depend on the moisture conditions at the time of testing. If these conditions change, as they frequently do in near surface soils, the interpreted soil properties may not reflect the soil behavior corresponding to the moisture conditions existing during construction or over the life of supported structures.

1.2 Purpose

A primary goal of this research is to gain important knowledge about the influence of matric suction on in situ test results. In accomplishing this goal a valuable set of experimental data will be established in an area of soil mechanics where information is scarce. Analytical and numerical models will be used to enhance the development of a theoretical framework for interpreting in situ test results obtained in unsaturated soils. This will allow engineers to make reasonable predictions of soil properties at moisture conditions other than those that exist when the in situ tests are performed. This work builds upon prior work of the investigators to develop a method for interpreting in situ test results in light of expected changes in soil moisture condition and suction.

1.3 Scope and Objectives

Proposed work involves conducting selected in situ tests at two test sites at least four times per year to investigate the influence of changes in moisture conditions and soil suction on the test response. Test sites are being thoroughly characterized by a sampling and testing program with a special emphasis on defining the critical unsaturated soil properties and moisture content profiles. Additionally, test sites have been instrumented to monitor weather and soil moisture content at various depths. The analysis and modeling of results will have two major components: first to model the temporal changes in moisture content and soil suction resulting from climate changes; and second to model the influence of changes in moisture content and soil suction on in situ test results.

There are two primary objectives to the proposed research:

1. To provide geotechnical engineers with a method for interpreting the results of in situ tests in unsaturated soil. The idea is to be able to predict how the in situ test results and interpreted soil properties would change if the moisture content changed.
2. To provide geotechnical engineers with methods for predicting changes in soil moisture conditions and suction as a function of climate changes so that a proper "design moisture condition" can be selected for a given site. Thus, the expected variation of in situ test results can be predicted as a function of expected climate changes and ground water conditions.

There are three components involved in accomplishing the first objective: 1) field testing, 2) laboratory testing, and 3) model development. First, in situ tests are being conducted at two test sites at various times of the year. This provides test results for soil moisture conditions spanning wet to dry conditions. The sites were instrumented to monitor weather and soil moisture conditions. Second, to properly interpret the results and develop methods of interpretation soils were thoroughly characterized in the laboratory. This involved basic geotechnical testing as well as advanced laboratory testing to determine the unsaturated stress-strain behavior and Soil Water Characteristic Curve (SWCC). Finally, a theoretical framework for interpretation of each in situ test studied is being developed for unsaturated soils. Due to the complex behavior of unsaturated soils arising from the presence of both air and water in the pore space, this is not a simple undertaking. The plan is to focus initially on utilizing cavity expansion theory as the basic framework around which interpretation methods will be developed.

The focus was initially on the Pressuremeter Test (PMT) and Cone Penetration Test (CPT) as these have a history of interpretation using cylindrical and spherical Cavity Expansion Models (CEMs), respectively. For the most part, existing CEM models were developed for saturated soils or dry sands without consideration of unsaturated soil behavior. Fortunately, the research team had already developed preliminary CEMs for interpretation of tests in unsaturated soils as briefly discussed in the background section. During Phases 2 and 3 of the research, the work funded through Phase 1 will be extended to include constitutive modeling of test sites soils and numerical modeling of the in situ testing process. A finite element technique developed for modeling unsaturated boundary value problems will be calibrated and validated against in situ test results obtained at the field sites. This model will then be used to perform parametric analyses to investigate the importance of various soil properties on the in situ testing results. By using a calibrated numerical model it will be possible to simulate in situ tests in other soil types not actually found at the test sites. This will allow the researchers to extend to interpretation methods beyond the two soil types found at the test site.

Achieving the second objective of the research involves two primary components: 1) monitoring weather and soil moisture content at the test sites and 2) exploring methods for predicting moisture content variations in the soil profile due to weather. First, each test site was equipped with a self-contained weather station and soil moisture sensors. In addition, data is being obtained from the closest Mesonet stations for comparison to on-site measurements. The Oklahoma Mesonet is a network of over 110 automated environmental monitoring stations covering Oklahoma designed and implemented by scientists at the OU and at Oklahoma State University. There is at least one Mesonet station in each of Oklahoma's 77 counties. It is desirable to have an on-site weather station because solar radiation, evapotranspiration, and wind patterns can be significantly different even within relatively short distances. In addition to weather data, moisture content samples are being obtained with depth for each in situ testing event.

Second, two commercially available computer programs for predicting moisture content changes in soil profiles were purchased; these are Vadose/W 2007 from Geo-Slope International (http://www.geo-slope.com/products/ vadosew2007.aspx) and SVFlux 3-D + SoilVision to estimate the properties using a data base from SoilVision (http://www.soilvision.com/). Currently there is very little information on suitability of a computer model to predict moisture variations under Oklahoma conditions. The idea is to evaluate and compare these programs for predicting climate-induced moisture content variations in Oklahoma soil profiles. Based on these comparisons one computer program will be selected for future research and design applications.

1.4 Background Information

As indicated in a review of cone resistance by Yu and Mitchell (1998), "the wide use of the cone penetration test (CPT) in geotechnical engineering practice has resulted in a great demand for validated correlations between cone resistance and engineering properties of soil." Field testing with an electric friction cone penetrometer involves pushing an instrumented probe into the ground at a standard rate of 2 cm/sec, while simultaneously measuring the force exerted by the soil on the tip and on a separate friction sleeve. These forces are converted to the tip resistance and sleeve friction by dividing by the projected area of the tip and sleeve area, respectively. As indicated by Yu and Mitchell (1998), the tip resistance can be used to predict soil properties by employing theoretical correlations or by using calibration chamber based correlations. Yu and Mitchell (1998) suggest that the use of cavity expansion theory for predicting cone resistance is one of the better approaches, as it allows for elastic and plastic deformations around the probe, and to some extent can account for the buildup of stress around the cone shaft during penetration. Use of cavity expansion theory involves development of theoretical relationships between cavity limit pressures and cone resistance. Since, the limit pressures are a function of soil properties, the theoretically derived cone resistance can be compared to soil properties such as strength and stiffness. Thus, one can compare values of cone resistance from the field with theoretically derived values of cone resistance and obtain an estimate of soil properties such as undrained shear strength or friction angle, depending on soil type.

The pre-bored pressuremeter test is performed by lowering a cylindrical probe into a borehole and expanding the flexible membrane surrounding the probe under stress or strain controlled conditions. This results in an expansion curve relating applied pressure to injected volume. By accounting for membrane and system compliance, the pressure applied to the soil and the resulting volume change can be determined. Assuming the expansion of the pressuremeter represents an infinitely long expanding cylinder in an infinite soil mass, and incorporating small strain or large strain theories depending on what portion of the curve is being examined, a stress-strain relationship can be derived from the expansion curve (Briaud 1992). In addition, the at-rest earth pressure can be estimated from the initial portion of the expansion curve where the slope increases and becomes linear. It is presumed that at this point on the curve, full contact of the membrane is achieved and the initial lateral stresses are reinstated. Estimates of soil properties such as the coefficient of earth pressure at rest, elastic moduli (shear and Young's), and strength parameters can be derived by employing appropriate assumptions regarding the stress-strain behavior and drainage characteristics during the test.

For unsaturated soils, there are no proven methods of interpretation for the cone penetrometer or pressuremeter tests. Observations from cone penetration testing and pressuremeter testing in unsaturated soils by the principal investigators, show that the soil response to CPT penetration and PMT expansion is influenced significantly by the matric suction, as shown in Figure 1 (Miller and Muraleetharan 2000), Figure 2 (Tan et al. 2003), and Figure 3 (Tan and Miller 2005).

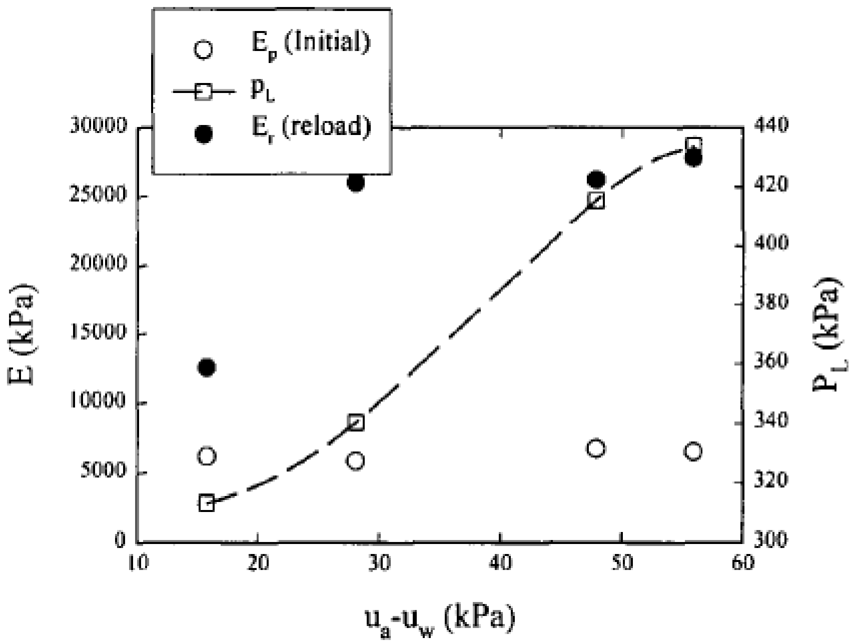

Figure 1: Pressuremeter Limit Pressure (P_L), Reload Modulus (E_r) and Pressuremeter Modulus (E_p) versus Matric Suction (u_a-u_w) from field tests in Minco Silt (After Miller and Muraleetharan, 2000)

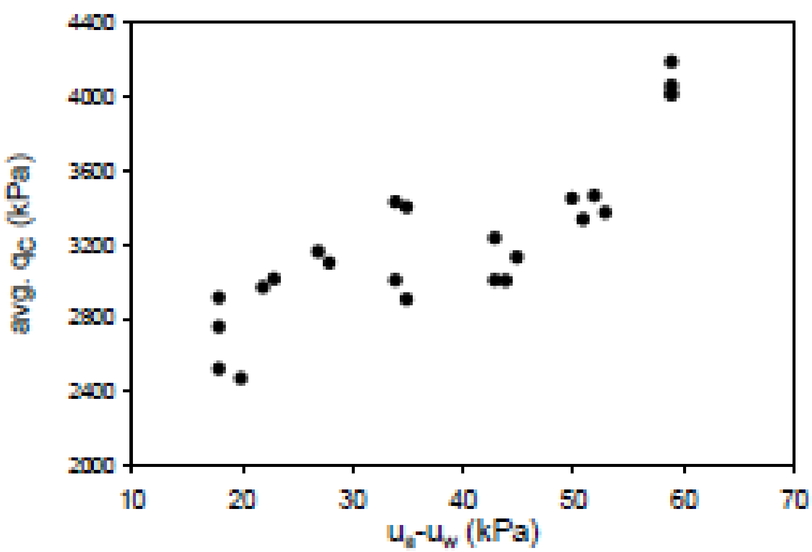

Figure 2: Tip Resistance (q_c) versus Matric Suction (u_a-u_w) from Cone Penetration Tests in Minco Silt in a Calibration Chamber (After Tan et al. 2003)

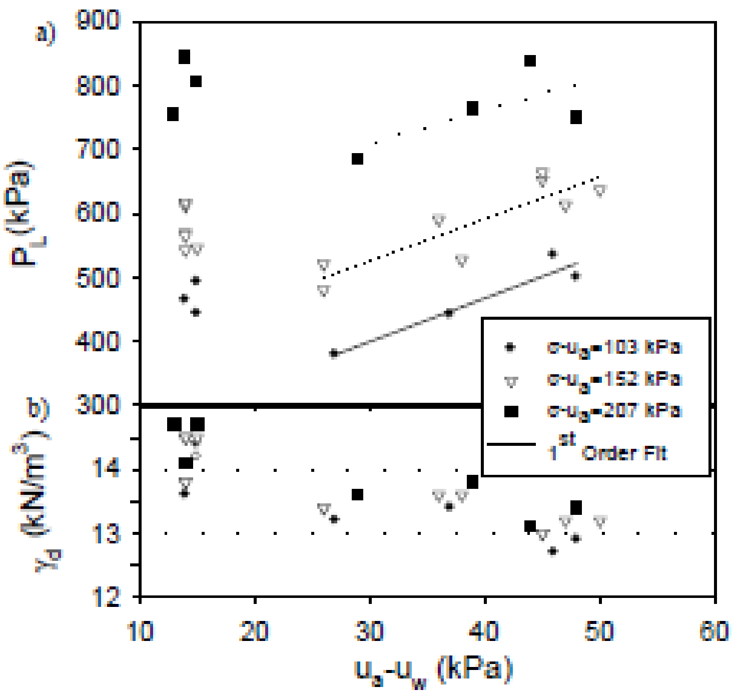

Figure 3: a) Limit Pressure (PL) versus matric suction (u_a-u_w) from PMTs in Minco Silt in a Calibration Chamber, b) Average dry unit weight (γ_d) of the soil bed versus matric suction. (After Tan and Miller 2005)

Provided the length to diameter ratio of the probe is sufficient, a pressuremeter test closely approximates the plane strain expansion of a cylindrical cavity. Therefore, cavity expansion theory provides a sound theoretical basis for interpretation of PMT results. In a subsequent section, a cylindrical cavity expansion theory is presented for unsaturated soils (Muraleetharan et al. 1998). Application of this theory to the PMT was introduced by Miller and Muraleetharan (1998 and 2000).

At the University of Oklahoma, Miller and Muraleetharan (1998, 2000) presented a framework for interpretation of pressuremeter tests in unsaturated soil. This framework is built around a cylindrical cavity expansion model developed by Muraleetharan et al. (1998). This model extends the original model developed by Vesic (1972) to include unsaturated soil behavior.

The cavity expressions developed by Vesic (1972) and methods of interpretation of pressuremeter test results hinge on the assumption of soil behavior defined by completely drained or undrained behavior. Implicit in these assumptions is that the soil behavior depends on a single independent stress-state variable, i.e., the effective stress. For unsaturated soil, it is generally accepted that the soil behavior can be described using two stress-state variables, the net normal stress, defined as the difference between the total stress and pore air pressure (σ_n-u_a) and the matric suction, defined as the difference between the pore air and pore water pressure (u_a-u_w) (Fredlund and Rahardjo 1993). To accurately describe the expansion of a cylindrical cavity in unsaturated soil, these two stress-state variables should be incorporated into the derivation of the ultimate cavity pressure.

Extending Vesic's (1972) original cavity expansion theory, Muraleetharan et al. (1998) derived the following expression for the ultimate cavity pressure (p_u) of an expanding cylindrical cavity in an unsaturated soil,

$$p_u = F_p\left[(p - u_{af}) - \frac{E}{H(1-2\nu)}\Delta(u_a - u_w) + \Delta u_a\right] + F_c c + u_{af} \quad (1)$$

where: F_p, F_c = dimensionless cylindrical cavity expansion factors given by,

$$F_p = (1+\sin\phi) I_{rr}^{\sin\phi/(1+\sin\phi)} \quad (2)$$

$$F_c = (F_p - 1)\cot\phi \quad (3)$$

p = initial (prior to the expansion) total mean normal stress, u_{af} = final pore air pressure in the plastic zone, c = cohesion, φ = internal angle of friction, I_{rr} = reduced rigidity index,

$$I_{rr} = \frac{1+\varepsilon_v}{\frac{f_2}{I_r} - \frac{2(1+\nu)\Delta(u_a - u_w)}{H(1-2\nu)}\sin\phi + \frac{2(1+\nu)\Delta u_a}{E}\sin\phi + \varepsilon_v} \quad (4)$$

Type equation here.

$$f_2 = \cos\phi \quad (5)$$

ε_v = volumetric strain in the plastic zone at the limit pressure, I_r = rigidity index

$$I_r = \frac{E}{2(1+\nu)[(p-u_a)\tan\phi + c]} \quad (6)$$

$\Delta(u_a$-$u_w)$ = change in matric suction during the cavity expansion, Δu_a = change in pore air pressure during the cavity expansion, E = Young's modulus, v = Poisson's ratio, and H = Elastic modulus with respect to the matric suction (Fredlund and Rahardjo 1993).

In deriving Eq. (1) it is assumed that at the limit pressure the radius of the cavity is R_u and this cavity is surrounded by a plastic zone of radius R_p and beyond that the soil behaves as a linear elastic material. The values of R_p and R_u are related by the following equation.

$$R_p/R_u = I_{rr}^{0.5} \tag{7}$$

Furthermore, it is assumed that the soil within the plastic zone is a compressible plastic solid defined by a Mohr-Coulomb failure criterion for unsaturated soil. The stress state variables can be used to describe the shear strength of unsaturated soil using a Mohr-Coulomb type equation with the following form:

$$\tau = c' + (\sigma_n - u_a) \tan \phi + (u_a - u_w) \tan \phi^b \tag{8}$$

where: τ = shear stress at failure on a failure plane, c' = effective cohesion, σ_n = total normal stress on the failure plane, u_a = pore air pressure at failure, ϕ = angle of internal friction associated with the net normal stress, u_w = pore water pressure at failure, and ϕ^b = angle of internal friction associated with the matric suction.

Note that for a saturated soil $u_a = u_w$ and c' and ϕ become effective-stress strength parameters. Eq. (8) describes a plane on a three dimensional plot with shear strength on the vertical axis and matric suction and net normal stress on the horizontal axes. For the situation where ϕ is constant, Eq. (8) predicts that increasing matric suction will result in failure envelopes with similar slope when projected on the plane bounded by the ($\sigma_n - u_a$) and τ axes. The slopes of the failure envelopes in this plane are given by ϕ and the cohesion intercept, c, is given by,

$$c = c' + (u_a - u_w) \tan \phi^b \tag{9}$$

and thus, Eq. (16) can be simplified to,

$$\tau = c + (\sigma_n - u_a) \tan \phi \tag{10}$$

Miller and Muraleetharan (2000) demonstrated that the cavity expansion theory for unsaturated soils can be used to interpret pressuremeter test results in unsaturated soils. They performed a series of field tests at a site in Oklahoma at different times of the year and monitored the soil suction using tensiometers (Figure 1). While the cavity expansion predictions were reasonably good, there are a number of issues with this method that will be addressed through the proposed research. Generally, the method in its current form is somewhat cumbersome because there are a large number of unknown variables in the cavity expansion equations. Some of these unknown variables can be assumed with reasonable accuracy while others can be estimated using the actual pressuremeter measurements. Current research will focus on developing a streamlined semi-empirical approach to analysis where some these variables can be combined into single parameters that depend on, for example soil type and water content. By necessity, there will be some empiricism built into the procedure; however, it will be developed around a sound theoretical foundation.

Tan et al. (2003) showed through a study at the University of Oklahoma that similarly developed equations for spherical cavity expansion in unsaturated soil could be applied to results of cone penetration tests in unsaturated soils. Again, there are unresolved issues that will be addressed through the current research with the aim of developing a sound semi-empirical approach to interpreting cone penetration test results in unsaturated soils.

2. SITE DESCRIPTION AND INSTALLATION OF WEATHER STATIONS

2.1 Site description

The sites chosen for installation of weather stations and for conducting PMT have several specific characteristics that make them desirable locations. The sites are close to campus, both are unsaturated nearly all of the time, the soil is reasonably uniform at both sites and together the sites represent low to high plasticity soils. The Northbase site, which is located at the North University Research Campus in Norman, OK primarily contains medium to high plasticity clayey soil. The Oklahoma Department of Transportation (ODOT) has significant data from previous tests near this site which help to make it an ideal location. Bedrock can be found at approximately 10 feet at this site. The Goldsby site is located at the Goldsby exit on I-35 approximately 5 miles south of Norman. The site is located on silty clay which has a reasonably uniform profile for at least 10 feet. The sites are shown on Figure 4; with Northbase indicated with a B and Goldsby indicated with an A.

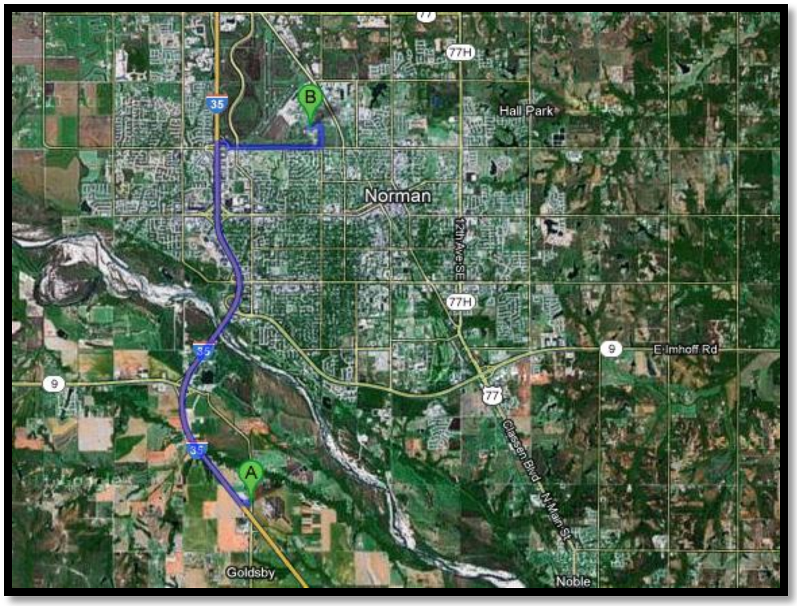

Figure 4: Test sites used for this study with Northbase indicated with B and Goldsby with A. (image from Google)

Two Campbell Scientific weather stations capable of monitoring; air temperature, wind speed/direction rainfall, solar radiation, relative humidity, and volumetric water content, were installed at Goldsby and Northbase. The volumetric moisture content monitors are located at depths of 1, 3, and 6 feet. Measurements of the weather data are collected every 10 seconds, so subtle changes in the conditions at each site are carefully monitored. Weather data from each weather station is downloaded to a computer at various increments throughout the year. This data is then plotted versus time to observe various trends in the weather data and its affect on the soil moisture. The general trend has shown that increases in rainfall result in increases in soil volumetric moisture content. This behavior indicates that the soil moisture monitors are functioning correctly. Tensiometers, which are devices that are capable of measuring in situ suction of the soil were installed at the Goldsby site. These could not be used at Northbase because the clay material at Northbase produces a suction that is out of range for commercially available Tensiometers. Tensiometer measurements were made periodically throughout the months in the year where the air temperature remained above freezing because tensiometers are filled with water and freezing could cause damage.

To properly understand the mechanical changes that occur at each site a careful examination of the soil properties is needed. The crucial soil properties examined included particle size distribution, Atterberg limits, in situ moisture content versus depth, and a soil water characteristic curve. Particle size analysis and Atterberg limits are important for determining soil classification information. In situ moisture content versus depth helps to construct the behavior of the soil throughout the monitoring period. The SWCC is typical in unsaturated soil mechanics investigations and provides a relationship between the soil moisture and suction.

The Goldsby site is underlain by uniform medium to high plasticity silt for a depth of at least 10 feet (which was the depth investigated in this research). Figure 5 provides a look at the moisture content versus depth at the site, as well as, the liquid limit and plastic limit versus depth (the difference corresponds to the plasticity index), and the percent of material passing a #200 sieve (0.003 inches (0.075 mm) in diameter particles) versus depth. The results of these tests indicate that the material found at Goldsby is medium/low plasticity silt and clay (ML to ML-CL). The SWCC curve was developed by collecting material from the site and performing a suction measurement using a WP4 potentiometer and then measuring moisture content immediately afterwards. The result is a plot of data that shows suction versus moisture content. This is useful for predicting what the suction is at a particular site based only on the moisture content and is assumed to represent the SWCC of the soil. The SWCC for Goldsby is shown in Figure 6.

Northbase has soil that is more highly plastic than what is found at Goldsby. The soil typically classifies as medium/high plasticity clay (CL to CH). Bedrock is found at around 10 feet in most areas. There is a slight variation in material between the material above and below approximately 6 feet with the deeper soil exhibiting less plasticity. Soil moisture was found to be below the plastic limit of the near the surface soil; however, it moved closer to the plastic limit and in some cases exceeded the plastic limit at greater depths. It was noticed by the researcher that the water table at the site in mid-spring was rising as water accumulated on top of the bedrock. The majority of the material found at Northbase passes a #200 sieve; however, there are rock inclusions found at depths near the bedrock. Figure 7 provides the moisture content versus depth, as well as, liquid limit and plastic limit versus depth, and percent of material passing a #200 sieve. An SWCC curve was obtained for Northbase in a similar manner to the method used to obtain it for Goldsby. The SWCC for Northbase is presented as Figure 8.

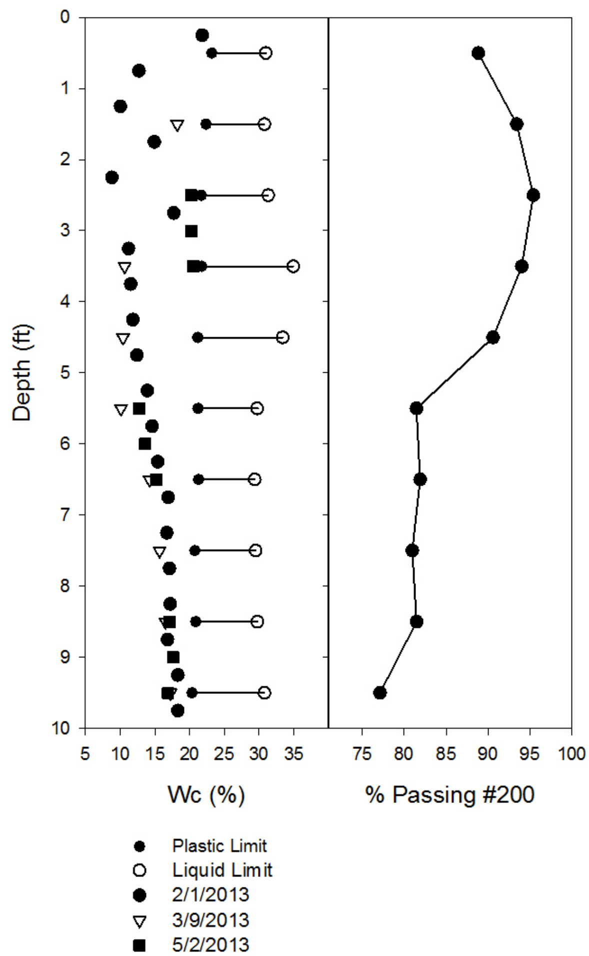

Figure 5: Soil property data from Goldsby site.

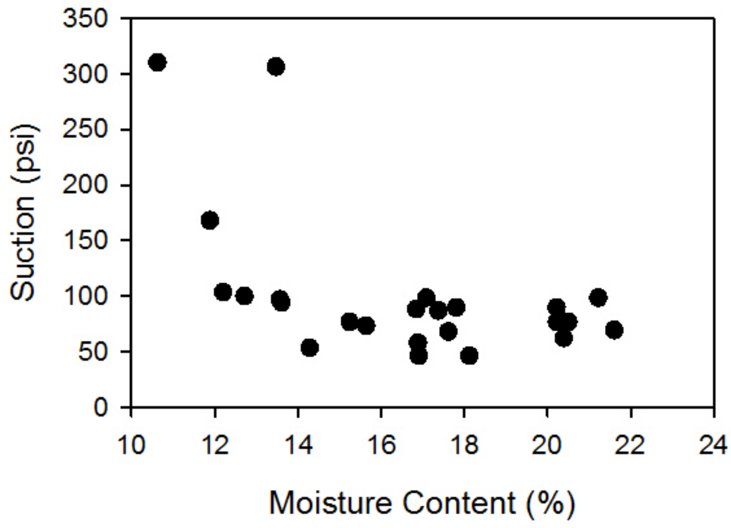

Figure 6: SWCC for Goldsby soil.

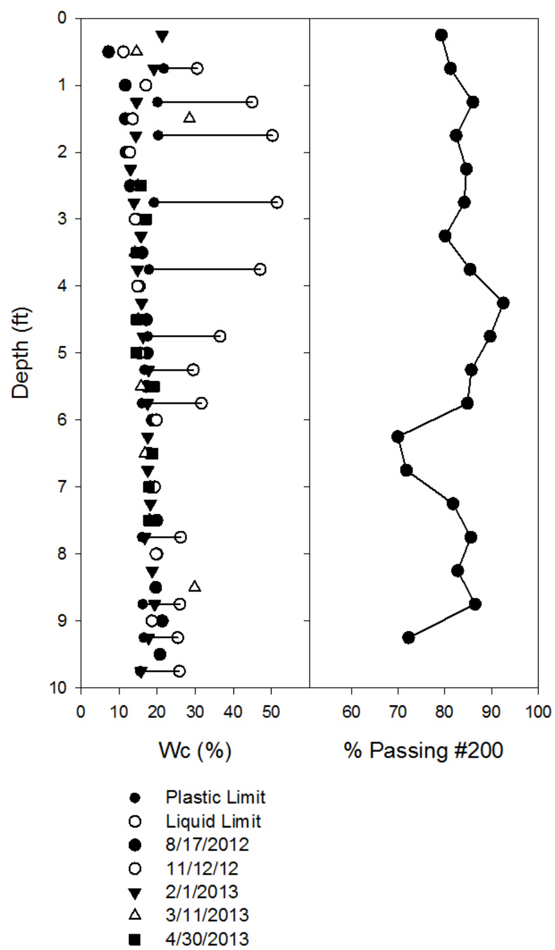

Figure 7: Soil Property data from Northbase site.

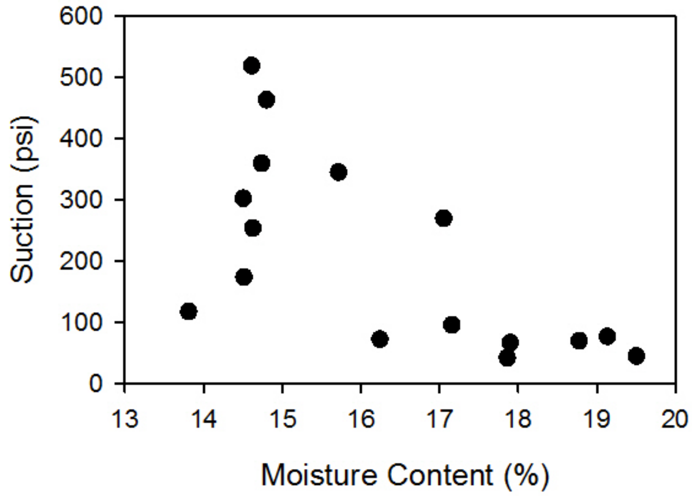

Figure 8: SWCC for Northbase soil.

2.2 Weather and Soil Moisture Data

The Goldsby weather station was set up and began recording data in May of 2012. At Northbase weather data collection started in August of 2012. The weather stations have performed as expected and have been a reliable instrument for measurement of weather data since installation. Data collected from each weather station has been plotted since the initial installation date. The moisture content monitors have shown noticeable increases in volumetric moisture content after significant rain events.

Weather data collected from the weather stations are shown in Figure 9 and Figure 10, for Goldsby and Northbase, respectively. The weather data presented for Goldsby and Northbase show the air temperature, rainfall totals and volumetric moisture contents at 1, 3, and 6 feet. Further information collected by the weather stations and used in modeling is not shown in this report

The weather data for Goldsby shows sporadic rainfall throughout the monitoring period, with increased rainfall starting in April. The increased rainfall is noticeable in the volumetric moisture content data at all depths. The largest increase is noticeable at the most shallow depth. There is also a delayed rise in moisture content corresponding with the depth of the monitor. This behavior is not unexpected because of the low permeability of the silt material.

The weather data trends at Northbase are similar to what was encountered at Goldsby. Increased amounts of rain in the spring caused a rise in volumetric moisture content. In a similar manner to the Goldsby site, the 6 foot soil monitor is slow to react to the change in moisture. This is again attributed to the low permeability of the clay material at Northbase.

3. RESULTS AND DISCUSSION – PRESSUREMETER TESTS

Prebored pressuremeter tests (PMT) were conducted with a 1-foot long rubber membrane probe. Pressure controlled tests were performed. The pressuremeter probe measures three inches in diameter and a slightly larger diameter hand auger was used to drill the hole for testing. The hand augured borehole makes a snug hole for the PMT and produces little disturbance on the walls of the borehole. Tests were performed at 3, 6, and 9 feet at Goldsby and 3, 5, and 7 feet at Northbase. Tests were initially performed at the same depths at both sites however the water table rose at Northbase and made the soil to soft for testing at 9 feet.

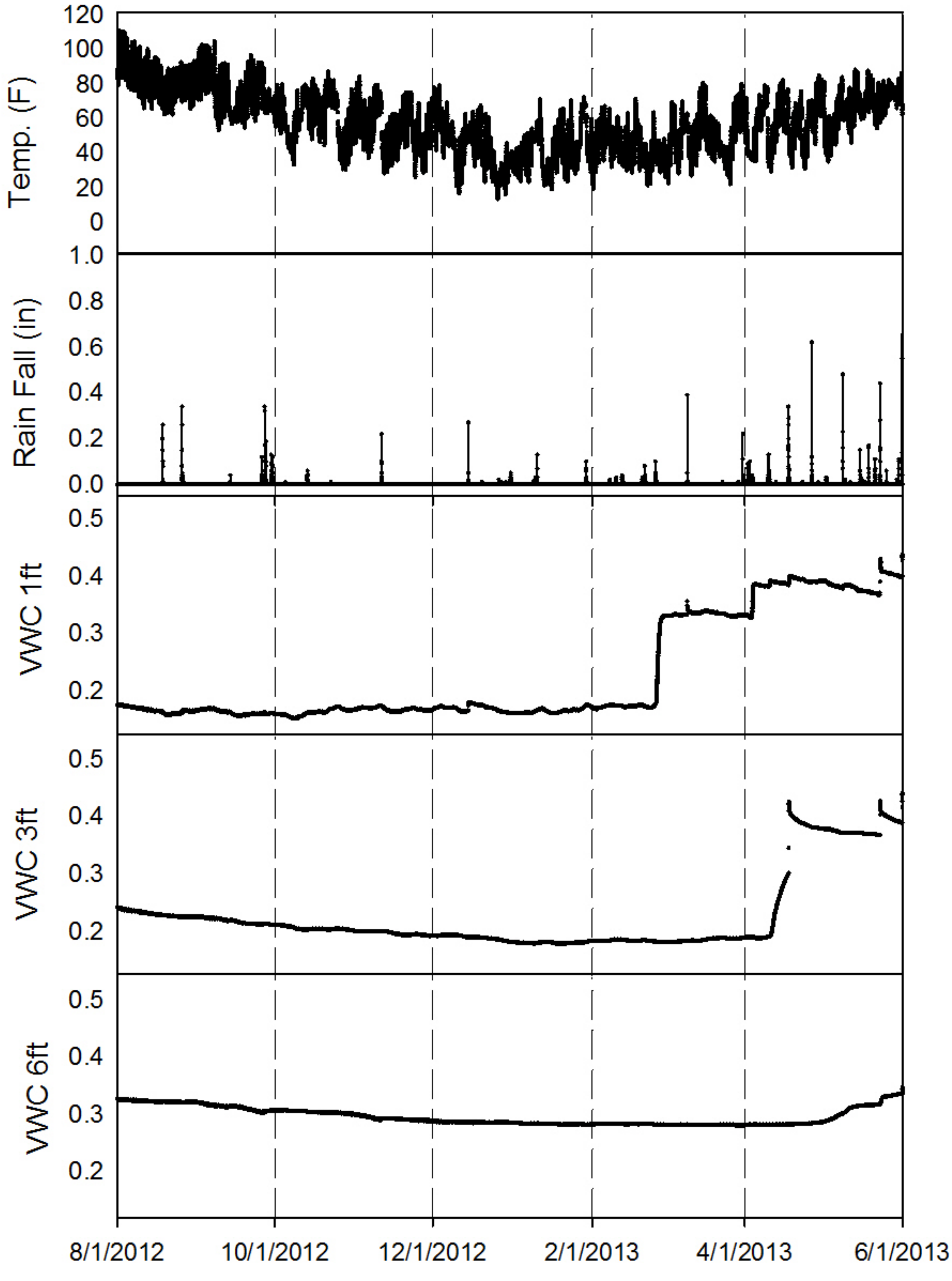

Figure 9: Weather and Soil Moisture Data from Goldsby Site.

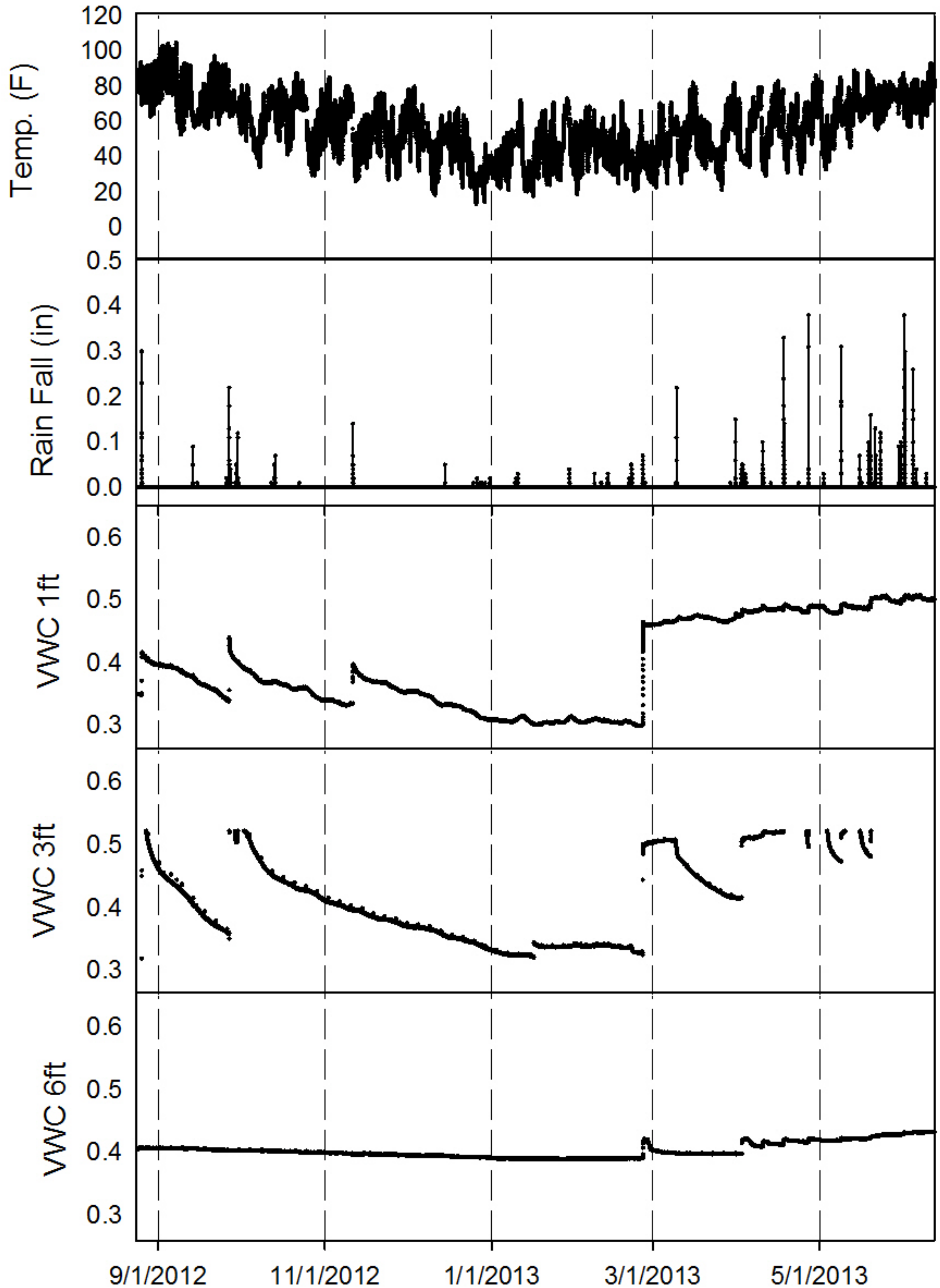

Figure 10: Weather and Soil Moisture Data from Northbase Site.

Radial stress-strain curves for Goldsby at all depths are shown in Figure 11. At 3 ft. there are noticeable differences between tests conducted in early February and March compared to the tests conducted in April, May and June. The earlier tests show a greater pressuremeter modulus and limit pressure compared to the tests conducted later. The change in behavior can be attributed to the change in moisture content and suction at the site, which is shown in the volumetric moisture data in Figure 9. The most noticeable increase in moisture content comes at approximately mid April. The relationship between moisture content, limit pressure, pressuremeter modulus, and unload-reload modulus is shown in Figure 12. In this figure it is evident that as soil moisture increases the soil shows a noticeable drop in both of these properties. The tests conducted at 6 and 9 feet show similar behavior beginning to occur after the most recent test in June. The unload-reload modulus appears not to be as sensitive to reductions in moisture content compared to the limit pressure and initial modulus.

The soil at Northbase has shown to be more noticeably affected by changes in moisture content than what was noticed at Goldsby. The initial round of tests was to be conducted at 3, 6, and 9 feet just as had been the case at Goldsby; however, the soil at 9 feet could never be tested because the soil did not provide enough resistance to conduct a full pressuremeter test. The initial test plan was modified accordingly and tests have been conducted at 3, 5 and 7 feet to collect adequate amounts of data.

Test results at Northbase show similar behavior to what was observed at Goldsby. In general as time progressed from February to April and more moisture accumulated in the soil the limit pressure and pressuremeter modulus decreased. The radial stress and strain curves for Northbase are shown in Figure 13. At 3 feet the test conducted in February shows a higher pressuremeter modulus and limit pressure than what was measured in March and April. At 5 and 7 feet the tests show similar behavior with decreasing limit pressure and pressuremeter modulus with greater increases in soil moisture. There is limited data at 7 feet, however the test conducted at the end of April shows lower limit pressure and pressuremeter modulus than the test conducted in mid April.

The relationship between moisture content and limit pressure, pressuremeter modulus and unload-reload modulus for Northbase is shown in Figure 14. The data shows that increasing moisture in the soil decreases the limit pressure and modulus. Again, there is no meaningful trend in the data at the lower depths or with the unload-reload modulus.

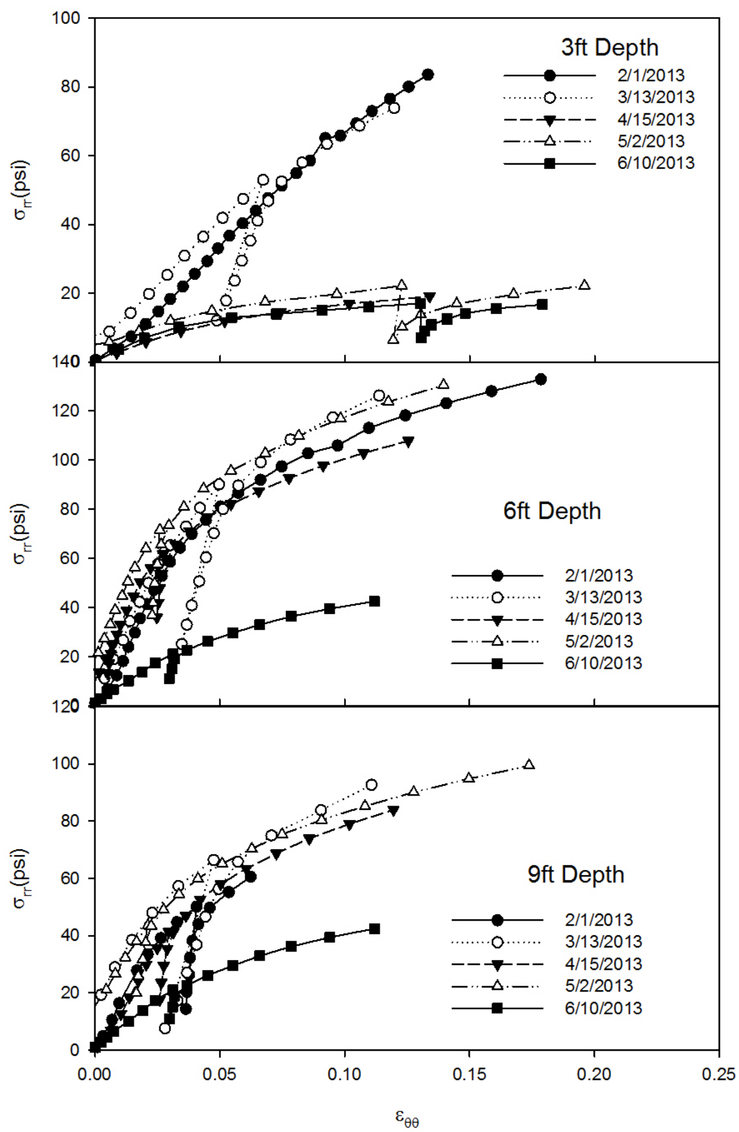

Figure 11: Goldsby PMT Stress Strain Curves

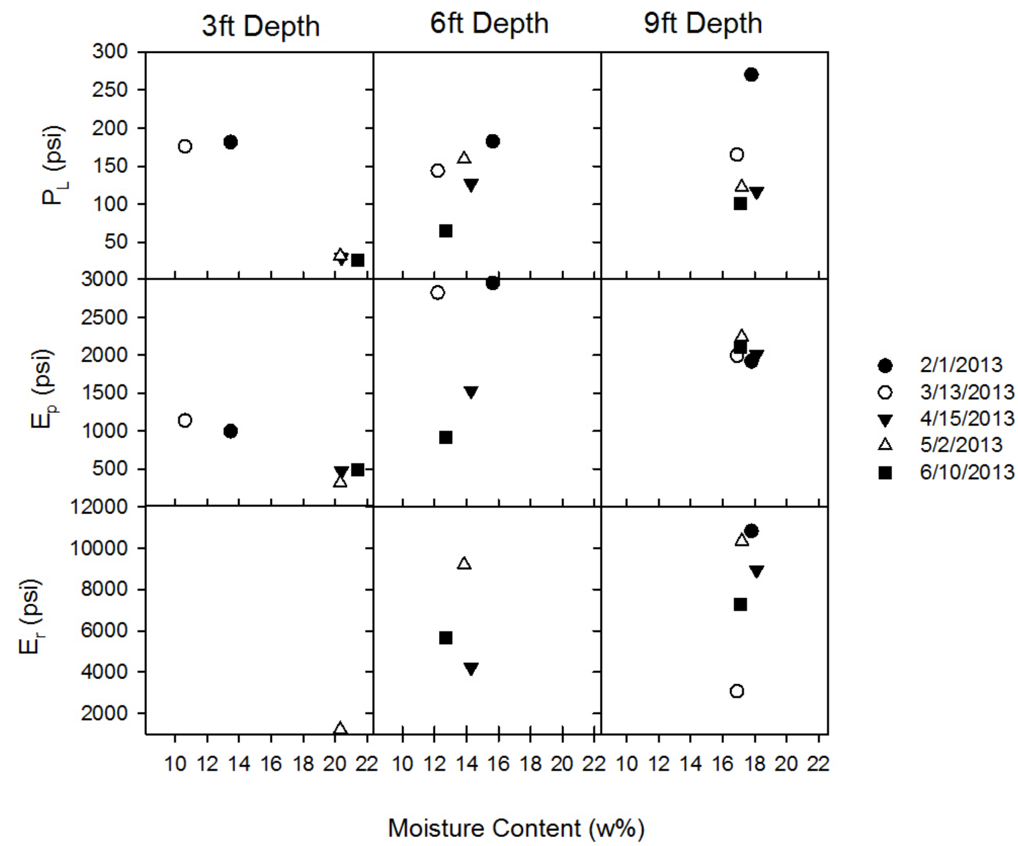

Figure 12: Relationship between moisture content and PMT results for Goldsby.

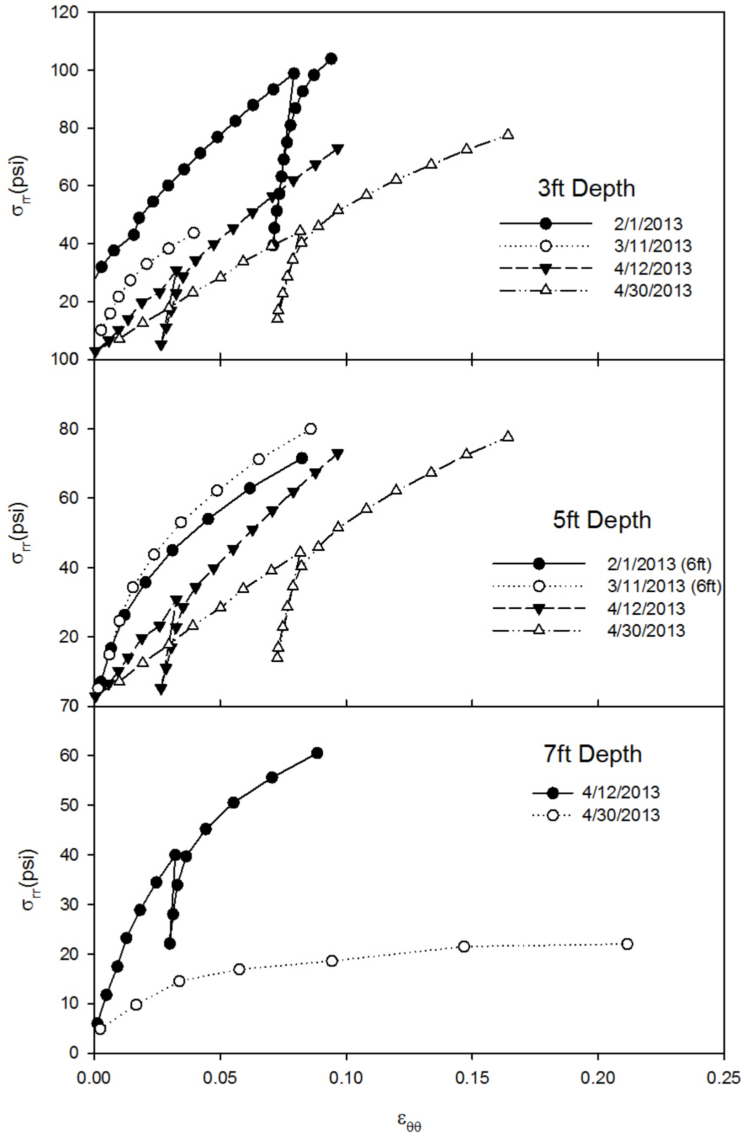

Figure 13: Northbase stress strain data.

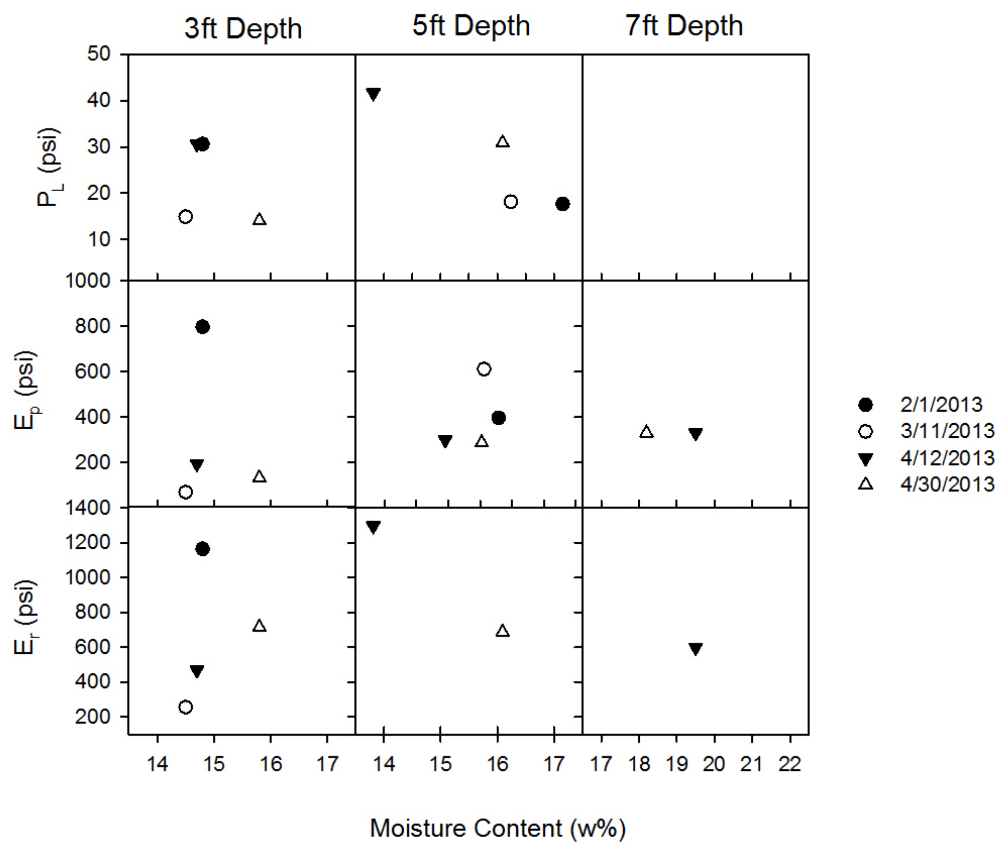

Figure 14: Relationship between moisture content and PMT results for Northbase.

4. RESULTS AND DISCUSSION – CONE AND STANDARD PENETRATION TESTS

Cone and standard penetration tests (CPT and SPT) were performed by the Oklahoma Department of Transportation at Goldsby and Northbase in February and May of 2013. Tests were conducted at varying locations around the weather stations. The soil under each test site was assumed to be uniform. An automatic hammer SPT test was performed and split barrel soil samples were collected and used for determination of moisture content with depth and Atterberg limits.

The SPT and CPT data from Goldsby is presented in Figure 15. The N value is presented with depth from SPT tests. The tip resistance (q_c) and friction ratio (FR%) from the CPT are shown to 10 feet in depth. The results from Goldsby correspond with the volumetric moisture content. At a depth of around 6 foot there is very little difference between the SPT and CPT tests conducted. This again is likely due to there being little change in moisture content at Goldsby between the testing periods at this depth.

The q_c measured at Goldsby decreases at depths where moisture has accumulated. SPT N value shows similar behavior with decreasing values after increases in moisture content. The FR% increases with increasing moisture at the same depths there is a change in behavior in the other test properties.

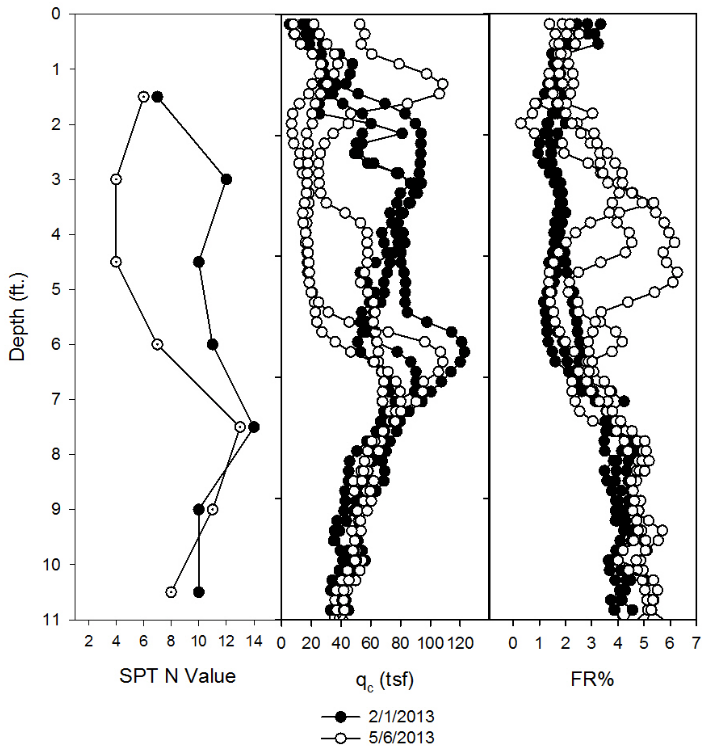

Figure 15: SPT and CPT data from Goldsby site.

Northbase SPT and CPT data is presented in Figure 16. The results of these tests are similar to the behavior encountered at Goldsby. There is a reduction in tip resistance after an increase in moisture content. There has not been enough moisture accumulation at Northbase to provide much difference in the N value and FR%.

The results of CPT and SPT show that moisture in the soil is having a profound effect on test results. The difference in test results between 3 months is substantial. Increased moisture or a prolonged drought could see results shift even more dramatically.

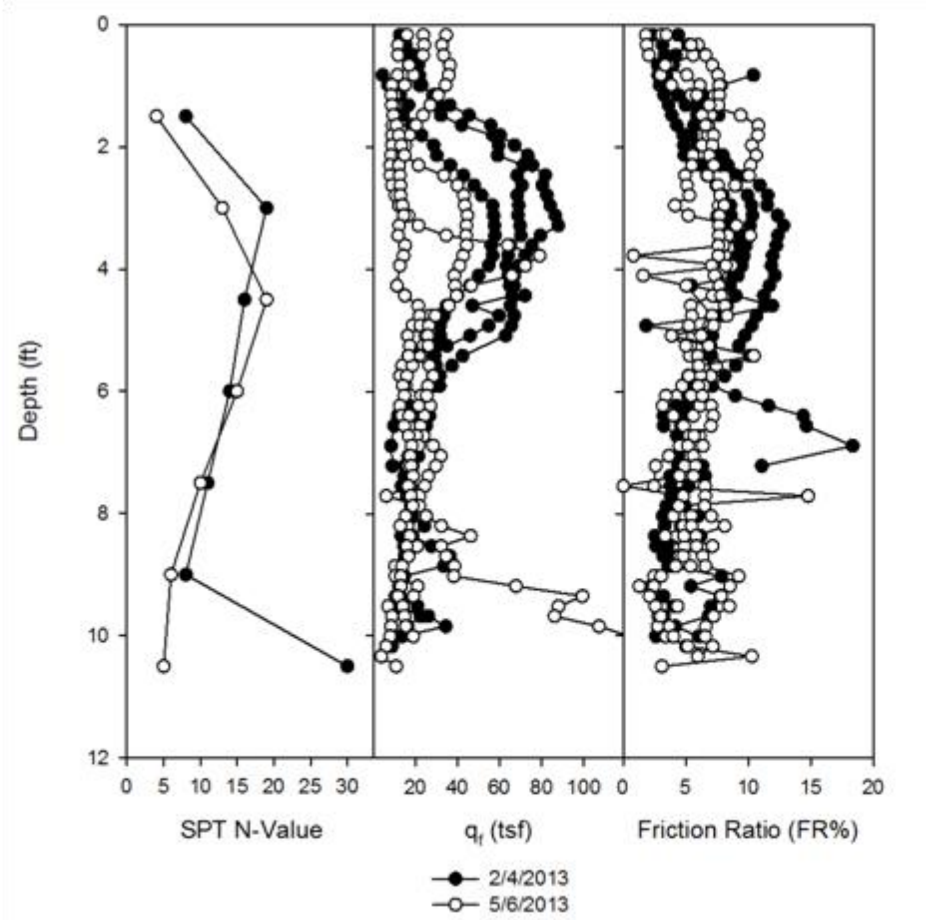

Figure 16: SPT and CPT data from Northbase site.

5. CONCLUSION AND RECOMMENDATIONS

The result of PMT, CPT and SPT results in field tests have shown that moisture has a significant influence on the results obtained. Test results obtained over a period from February to May show increasingly soft soil with increased moisture accumulation. This is behavior that had been mentioned in previous research and has been verified at the sites chosen for this research. The moisture sensors and weather station are collecting meaningful weather data which is corroborated by testing results.

Pressuremeter tests show reduced limit pressure (P_L), and pressuremeter modulus (E_p) with increasing moisture contents. This behavior is similar to what was mentioned by previous researchers (Miller and Muraleetharan, 2000), and is what was expected.

Further testing should provide an increased database of pressuremeter behavior which will be used to construct a model to predict pressuremeter behavior based on a single in situ test and some additional tests to quantify the unsaturated state of the soil.

Cone Penetration test showed reduced tip resistance (q_f) and an increased friction ratio (FR%) with increasing moisture. This was most noticeable at the Goldsby site, where there was a predominant separation between the results of tests in February and May. Further testing at Northbase after more time has elapsed should produce similar results. There was also a noticeable difference in soil properties below around six feet at both sites. This behavior can be attributed to the slow migration of water through the soil profile due to the permeability of the material. The slow migration of moisture through the soil profile was also verified by the moisture sensors at six feet which showed very little increase in moisture content. After adequate time elapses the lower depths of each test site may see increased moisture.

Further testing remains necessary to create a usable model for prediction of soil properties at various moisture content. The purpose of this research presented in this report was to provide an overview of the identification of the test sites, provide soil data and weather station data, and to provide some preliminary test results that verify the chosen sites are adequate to perform this research.

This report presents partial findings of a three year research project partially supported by both the Oklahoma Transportation Center (OkTC) and the Oklahoma Department of Transportation. Work continues with respect to weather and soil data collection, laboratory testing, modeling and development of a method of interpretation of in situ tests in unsaturated soils.

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