OKLAHOMA TRANSPORTATION CENTER

ECONOMIC ENHANCEMENT THROUGH INFRASTRUCTURE STEWARDSHIP

THE EFFECTS OF SOIL SUCTION ON SHALLOW SLOPE STABILITY

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16. ABSTRACT

This study investigates the slope failures associated with clayey soils so engineers can better understand the problem and better predict shallow slope stability, and implement preventive measures if necessary. This research also examines the mechanics of the soil as related to matric suction changes, soil type, desiccation crack formation and expected degree of wetting. Research involves studying at least two field cases where shallow slope instability has been a problem; one case involves a cut slope section and one case involves an embankment slope. There are three primary objectives of the proposed research: 1) To provide geotechnical engineers with a method for predicting stability of cut slopes and embankment slopes composed of unsaturated soil, incorporating soil moisture condition and suction into the analysis. 2) To provide geotechnical engineers with methods for predicting changes in soil moisture conditions and suction in slopes as a function of climate changes so that a proper “design moisture condition” can be selected. This will also allow for predicting the slope stability over time based on predicted moisture content changes. 3) To provide recommendations to minimize the climate impacts on slope stability including, as necessary, reducing adverse impacts of desiccation cracking in clayey materials. Successful completion of this research will provide engineers with tools for improved analysis of shallow slope stability and recommendations for preventing landslides. The research involves field testing and monitoring of suction and moisture content, laboratory testing of unsaturated and saturated strength and flow properties, moisture diffusion modeling based on climate data, investigation of desiccation cracking and its impact on slope stability, and stability analyses. Completed research will have a positive impact on geotechnical practice related to transportation corridors. 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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The Effects of Soil Suction on Shallow Slope Stability

FINAL REPORT

July 2013

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SUMMARY

This study investigates the slope failures associated with clayey soils so engineers can better understand the problem, better predict shallow slope stability, and implement preventive measures if necessary. This research also examines the mechanics of the soil as related to matric suction changes, soil type, desiccation crack formation and expected degree of wetting. Research involves studying at least two field cases where shallow slope instability has been a problem; one case involves a cut slope section and one case involves an embankment slope. There are three primary objectives of the proposed research: 1) To provide geotechnical engineers with a method for predicting stability of cut slopes and embankment slopes composed of unsaturated soil, incorporating soil moisture condition and suction into the analysis. 2) To provide geotechnical engineers with methods for predicting changes in soil moisture conditions and suction in slopes as a function of climate changes so that a proper “design moisture condition” can be selected. This will also allow for predicting the slope stability over time based on predicted moisture content changes. 3) To provide recommendations to minimize the climate impacts on slope stability including, as necessary, reducing adverse impacts of desiccation cracking in clayey materials. Successful completion of this research will provide engineers with tools for improved analysis of shallow slope stability and recommendations for preventing landslides. The research involves field testing and monitoring of suction and moisture content, laboratory testing of unsaturated and saturated strength and flow properties, moisture diffusion modeling based on climate data, investigation of desiccation cracking and its impact on slope stability, and stability analyses. Completed research will have a positive impact on geotechnical practice related to transportation corridors. This report represents a summary of progress during the first half of the project that was partly supported by OkTC funding.

1. INTRODUCTION

1.1 Problem

Shallow slope failures in roadway cuts and on embankments are frequent problems along Oklahoma highways, and most other States for that matter; and they represent a significant burden on maintenance budgets. Often these failures are associated with clayey soils having relatively high plasticity. Generally, during construction these soils have relatively high shear strength, a stiff consistency, and produce stable slopes. However, over time the soils experience cyclic wetting and drying resulting in a net increase in soil moisture content and corresponding decrease in shear strength. Eventually, the reduction in shear strength results in a slope failure usually triggered by a rainfall event. Exacerbating the problem are desiccation cracks that develop during extreme drying periods allowing water to penetrate the soil deeper and faster. The loss of shear strength in clayey soils due to wetting is associated with two inter-related phenomena. First, as the moisture content is increased the matric suction is reduced, which reduces the intergranular or effective stress in the soil. Decreasing effective stress equates to reduced shear strength. Second, as the moisture content increases the diffuse double layers surrounding clay particles expand and take on water with a corresponding increase in soil void ratio. Reduced dry density and increased water content results in softening and substantially lower shear strength. An additional consequence of wetting is that the driving mass of the soil increases with increased moisture content. Thus, while shearing resistance (or strength) is decreasing, imposed gravitational shearing stresses are increasing, further reducing the slope stability. Research is needed so engineers can better understand the problem, better predict shallow slope stability, and implement preventive measures if necessary.

1.2 Background

In recent years there has been more effort on understanding failure mechanisms and moisture migration involved in shallow slope instability problems (e.g. Aubeny and Lytton 2004, Kim and Lee 2010, Ray et al. 2010). The work of Aubeny and Lytton (2004) is quite relevant to the proposed research as it focuses on shallow slides in compacted high plasticity clay slopes along highways in Texas. An infinite slope stability model is presented by the authors that can account for suction (negative pore water pressure) at the slope surface as well as moisture flow characteristics parallel and perpendicular to the slope. Using this model Aubeny and Lytton (2004) demonstrate the importance of seepage conditions and suction on the stability of shallow slopes. While this study provides a very useful view of the problem, and an excellent starting point for the current research, there are, however, some major assumptions in their analysis, which warrant further study. Aubeny and Lytton (2004) make a case that slope failures are mainly associated with a destabilizing hydraulic gradient in the slopes that builds up over many years of infiltration. The primary "evidence" for this assertion is based on the observation that the assumed effective stress friction angle of the soil was greater than the majority of slope angles (inclinations) in the cases they studied. If this was true, then their infinite slope stability equation would in fact suggest that the slopes should be stable unless a "destabilizing hydraulic gradient" existed that caused the failures. The effective stress friction angle used in their analysis was 25 degrees, which as mentioned, is generally larger than most highway slope angles (typical 3H:1V slope has inclination of about 18 degrees measured from horizontal). This friction angle was assumed based on available correlations with plasticity index and is a reasonable normally consolidated friction angle. Based on some convincing evidence in the literature, the authors assumed that fully wetted compacted soils would have soil properties similar to normally consolidated soils. Finally, they argue that it is unlikely that the friction angle degraded to a residual value because there is no compelling evidence that the large strains necessary to cause friction angle degradation existed for these shallow slopes. On this final point, the authors may have overlooked one important factor, which they do address in the second part of their paper that deals with moisture infiltration. That is, often these near surface high PI soils are subjected to numerous cycles of severe wetting and drying, which does produce large strains as evidenced by desiccation cracking. Desiccation cracks are tension cracks and can be interpreted within the context of tensile strength. Drying of soil is accompanied by development of tensile stresses through the soil and cracks form when the generated stresses exceed the tensile strength. Tensile strength of soil is assumed to be negligible compared to shear and compression strength; however it is considered as an important parameter for understanding the cracking behavior of soil.

There are a few laboratory techniques developed to measure tensile stress generated by shrinkage. A new device was developed by Tamrakar et.al. (2005), to measure the tensile crack of compacted clay as a function of water content, dry density, proportions of particle size and amount of fines present in the soil. The results of the study show that compressive and tensile strength increase with increasing dry density. It was also illustrated that the soils containing smaller particles (e.g. clay) have higher strength.

Several studies have been performed to investigate the mechanism of cracking considering the factors that affect the shrinkage strain and cracking of soils subjected to desiccation. Kleppe and Olson (1985) performed a series of tests on mixture of highly plastic clay and sand. They suggested that the shrinkage strain increases with increasing clay contents and with increasing compaction water content. Albert et al. (2001) presented similar results indicating that specimens compacted close to optimum water content with higher compactive effort are less prone to large volumetric shrinkage strains. Evidence of large strains due to cyclic wetting and drying is the formation of fissures and “slickensides” associated with high PI natural clays. Many of the shallow slope failures occur within the upper meter or two of soil profiles, which is a highly active zone with respect to seasonal moisture content variations. It is important to note that friction angles need not degrade to residual values to produce instability. For example the residual friction angle of a soil with PI of 50 (lower end of soil investigated by Aubeny and Lytton) would be on the order of 10 degrees (Bowles 1988). However, for a 3H:1V slope, instability would occur when the effective stress friction angle dropped below about 18 degrees, in the absence of a destabilizing hydraulic gradient and under the conditions assumed by Aubeny and Lytton (2004). This suggests only a partial degradation of effective stress friction angle is necessary to cause slope instability. Furthermore, many high PI clays have effective stress friction angles lower than 25 degrees (e.g. Duncan and Wright 2005). On another point, Aubeny and Lytton (2004) indicated that the shallow slope failures generally occurred after 12 to 31 years in the cases they studied. They attribute this to the time required for desiccation cracks to fully develop and for moisture diffusion into the slope. While the measurements of moisture diffusion support this theory, it is also possible that during this time there was in fact a softening of the slope and degradation of the friction angle as well. Furthermore, it seems unusual that none of the slopes experienced a period of significant wetting in the upper meter of the slope that produced the "destabilizing hydraulic gradient" during the first 12 to 31 years of their life. In addition, the analysis they developed assumes a fully saturated soil profile and steady-state flow conditions. It is unclear that such conditions exist leading up to slope failures. It may be possible that slopes actually fail in an unsaturated condition when suction, and corresponding shear strength, drops below some critical level. Thus, it seems likely that shallow slope instability in some situations may be caused by a single factor, while in other situations, possibly a combination of factors is responsible. Possible factors leading to shallow slope instability include destabilizing hydraulic gradients, friction angle degradation, and loss of apparent cohesion (due to suction loss). The work of Aubeny and Lytton (2004) provides an excellent starting point for analysis of shallow slope instability in high PI clays, particularly compacted clays, which was the focus of their work. However, the preceding discussion emphasizes the importance of carefully examining all of the assumptions in the stability analysis and the need for additional work on development of appropriate strength parameters for analysis. This will be especially true in natural cut slopes in residual high PI clays where significant softening and strength degradation can occur (Duncan and Wright 2005).

A primary focus of the current work is on developing appropriate unsaturated strength models for analyzing shallow slope stability as related to the expected matric suction in the slope. In this study, the shear strength will be examined from the perspective of two stress state variables (Fredlund et al. 1978). The shear strength of an unsaturated soil can be formulated in terms of the net normal stress and the matric suction. Net normal stress is the difference between the total stress and pore air pressure $(\sigma_n - u_a)$, and the matric suction is the difference between the pore air and the pore water pressure $(u_a - u_w)$. According to Fredlund and Rahardjo (1993), the shear strength of the soil can be written as:

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

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

The theory presented and described by Equation (1) assumes a planar failure envelope. However, there is considerable evidence that shear strength exhibits considerable nonlinearity with respect to matric suction (e.g. Fredlund and Rahardjo 1993, Vanapalli et al. 1996, Hamid and Miller 2009). The angle $\emptyset^b$ at low matric suction, below the air entry value, seems equal to $\emptyset'$ but at higher matric suction it decreases to a lower value. This research will examine shear strength relative to various suction ranges corresponding to regions of the Soil Water Characteristic Curve. In fact, the SWCC function can be directly incorporated into the shear strength formulation (e.g. Vanapalli et al. 1996, Hamid and Miller 2009).

Research also involves measuring and predicting moisture diffusion in and out of slopes in order to predict suction changes. Transient moisture flow in an unsaturated soil in response to suction changes is controlled by the unsaturated moisture diffusion coefficient. The moisture diffusion coefficient can be determined by measuring suction profiles over time. The laboratory testing approach involves measurement of the total suction changes with time with thermocouple psychrometers in cylindrical soil specimens with predetermined boundary conditions. The determination of the diffusion coefficient by this method is simple and relatively rapid and can be carried out on a routine basis in a geotechnical engineering laboratory (Mabirizi and Bulut 2010).

1.3 Objectives

There are three primary objectives of the proposed research:

1) To provide geotechnical engineers with a method for predicting shallow stability of cut slopes and embankment slopes composed of unsaturated soil, incorporating soil moisture condition and suction into the analysis. The focus is on moderate to high plasticity clays for which these problems are most prevalent. To meet this objective, a practical method was found to determine the unsaturated soil shear strength in the laboratory as a function of moisture content and suction. There are also some

analytical tools and a handful of computer programs available used for analyzing unsaturated slope stability. In addition to exploring available methods of analysis, this research involves extensive laboratory testing of test site soils to determine both their saturated and unsaturated soil properties. The simplified testing methods involve the use of simple suction measuring techniques and total stress methods of strength testing, combined with saturated strength testing. To complete the first goal, the methods of analysis and testing have been validated and calibrated against actual shallow slope failures. This is being accomplished by focusing the analysis and testing on two different shallow landslide sites along Oklahoma highways. One site is in an embankment section and one site is in a cut section. Thus, both compacted and naturally occurring soils are included in this first project. This will help to further refine and validate the methods developed.

2) To provide geotechnical engineers with methods for predicting changes in soil moisture conditions and suction in slopes as a function of climate changes so that a proper "design moisture condition" can be selected. This also allows for predicting the slope stability over time based on predicted moisture content changes.

   To properly assess the design moisture condition requires a number of considerations. These include climatic factors, topography, hydrogeology, vegetation, drainage structures and soil properties. Regarding the latter, the moisture diffusion and hydraulic conductivity are critically important. Additionally, the potential for desiccation cracking and its impact on moisture migration must be considered. Since the design is for a future moisture condition, one that may vary from the current condition, it is necessary to study the historical climate at a site as a means of anticipating future climate conditions. The second goal of this project is accomplished by studying methods for predicting moisture content change in soil profiles. Specifically, over the course of the study the soil moisture conditions at the test sites is being monitored and compared to predicted moisture changes based on measured soil properties and climate data. Mesonet data will be used to assess climate. 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.

Desiccation cracking is being monitored and quantified with regard to crack length, width, depth and spatial frequency across the test sites. The idea is correlate the onset and development of desiccation cracks at a site with the soil moisture conditions, and somehow incorporate the change in flux boundary surface area (i.e. ground surface where moisture is exchanged with the atmosphere) into the moisture diffusion prediction method. A simplified framework of this type is presented by Aubeny and Lytton (2004); however, this method is largely untested apart from the limited analysis presented by the authors. It does, however, provide a good starting point on which to build the current research.

3) To provide recommendations to minimize the climate impacts on shallow slope stability including, as necessary, reducing adverse impacts of desiccation cracking in clayey materials. Once the design moisture condition is established and the slope stability is analyzed, the designer must then determine what to do if the factor of safety is too low for the cut slope or embankment geometry. Embankment side slopes and cut slope geometries are standard on most roadway alignments and so the designer may have little control over this aspect due to right-of-way constraints and other considerations. There are, however, a number of options the designer can consider such as:1) doing nothing and planning for future maintenance (i.e. slope repair), 2) enhancing drainage conditions such that moisture conditions do not rise above some critical level, 3) reinforcing the slope using geosynthetics or some other soil amendments, 4) etc. As part of the proposed research, investigators have been thoroughly examining the literature for practical solutions for addressing the shallow slope failure problem, from both a new construction and remedial construction perspective. In addition, through the moisture diffusion modeling of test sites, the influence of various remedial methods on the formation of desiccation cracks and moisture diffusion is being investigated. The goal is to develop practical and cost effective recommendations for a variety of slope situations in Oklahoma including existing technical solutions and newly developed solutions based on the proposed

research. There is evidence (Aubeny and Lytton 2004) that preventing desiccation cracking can improve long-term slope stability.

2. MATERIAL AND METHODS

2.1 Physical Properties of the Soils Used In This Investigation

To determine basic physical and index properties of investigated soils, a series of laboratory tests including grain size distribution, Atterberg limits, specific gravity and modified proctor compaction tests were performed in accordance with relevant ASTM standards. The soils selected for investigation were obtained from two different research sites in Chickasha and Idabel, Oklahoma where shallow slope failures have occurred. These soils are believed to exhibit different behavior as soil 1 is considered lean clay while soil 2 is fat clay having significantly higher plasticity. The soil properties are presented in Table 1.

Table 1. Basic Properties of Test Soils

Property	Soil 1 (Chickasha)	Soil 2 (Idabel)
Liquid Limit (%)	38	72
Plastic Limit (%)	20	26
Plasticity Index (%)	18	46
Specific Gravity	2.75	2.78
Gravel (%)	0	0
Sand (%)	10.6	3.5
Silt (%)	49.4	16.9
Clay (%)	40	79.6
Maximum Dry Unit Weight, kN/m^3,(pcf)	17.3, (110)	15.2, (96.7)
Optimum Moisture Content (%)	18	24

2.2 Soil Water Characteristic Curve Testing

To study the mechanics of the soil as a function of matric suction changes, soil type, and expected degree of wetting, the soil water characteristic curve (SWCC) needs to be obtained. To determine the SWCC for representative samples from each site during primary drying and primary wetting, a number of tests were conducted using chilled mirror hygrometer (WP4) shown in Figure.1a. The WP4 measures water potential by determining the relative humidity of the air above a sample in a closed chamber. At temperature equilibrium, relative humidity is a direct measurement of water potential.

To obtain drying curve, one sample of each soil was compacted to 95% of maximum dry unit weight and wetted to the moisture content close to saturation. The sample then was allowed to dry while the moisture content and suction was measured at varying intervals. Wetting curve was produced by adding water at different intervals to the same sample and measuring the suction. The WP4 is used for high suction range while a pressure plate device (Figure 1b) was used for the low suction range and determination of air-entry values.

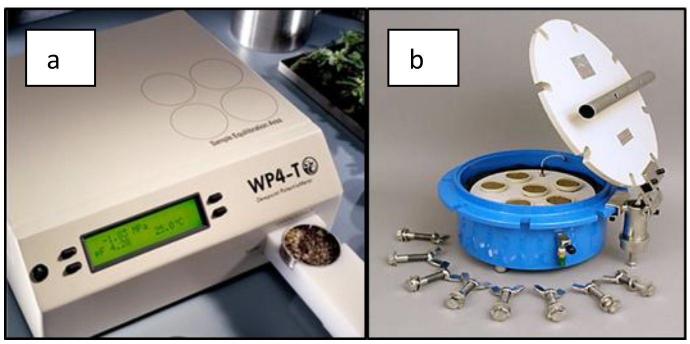

Figure 1:WP4 (a); Pressure Plate (b)

2.3 Bench Scale Desiccation Testing

Slope failures in clayey soils are often preceded by periods of drying and formation of desiccation cracks followed by significant precipitation events. Desiccation cracks have a significant impact on slope stability as they allow water to rapidly penetrate the soil, which accelerates softening and shear failure in shallow layers. To better predict the stability of shallow slopes in clayey soils it is important to fully understand the mechanics of desiccation crack formation in relationship to moisture content changes in the soil.

2.3.1 Soil Material and Sample Preparation

In this study a number of desiccation tests were performed on remolded soil beds, compacted to the target dry unit weights and with varying initial water contents. Test conditions are presented in Table 2.

Table 2. Desiccation Tests Conditions

Test No.	Material	Dry unit weight KN/m^3, (pcf)	Initial water content
1	Soil 1	17.3, (110) (γ_{dmax})	20 (+2% wet of OMC)
2	Soil 1	16.4, (104) (95% γ_{dmax})	20 (+2% wet of OMC)
3	Soil 1	16.4, (104) (95% γ_{dmax})	18 (OMC)
4	Soil 2	15.2, (96.7) (γ_{dmax})	24 (OMC)
5	Soil 2	14.4, (91.7) (95% γ_{dmax})	24 (OMC)
6	Soil 2	15.2, (96.7) (γ_{dmax})	26 (+2% wet of OMC)

All test soils were passed through a No.4 sieve and wetted to different moisture contents mentioned in Table 2. The specimens were covered and left in humidity room for 24 hours to promote uniform distribution of moisture through the soil. The prepared soils were placed into the desiccation box and compacted in one layer to the target dry density to reach a thickness of 1.3 cm (0.5 in). During compaction, the effort was made to uniformly distribute the soil and reach a uniform thickness by placing a steel plate on top of the specimen prior to applying blows from a drop hammer. The surface of specimens was smoothed using a spatula to ease the observation of crack initiation.

2.3.2 Bench Scale Desiccation Testing Device

The design and development of a bench scale desiccation apparatus initiated by conducting a series of preliminary desiccation tests using a Teflon pan. The pan was roughened at two ends on the bottom surface to produce friction and prevent the soil from away from the ends. It was believed that this restraint at the ends would cause shrinkage strains and a crack to occur at the mid-section of the soil bed. From the trial versions of desiccation tests, it was concluded that the most desirable constraining condition can be achieved by placing sufficient screws in the side walls. Figure 2 shows the preliminary stage of bench scale desiccation testing device development.

Figure 2: Development of Desiccation Box

Considering the performed experiments, a desiccation test box with dimensions of 25 cm (9.8 in) width and 30.5 cm (12 in) length was designed and fabricated. This apparatus consists of a rectangular shaped box with two separate halves. One half is fixed and there are some ball bearings under the other half to reduce the friction between the box and the surface below it. Where the two halves join, there are two load cells attached to the box to measure the tensile force generated in the specimen while it is drying. A constraining condition is applied to the specimen by placing some screws in the end walls of the box and embedded in the soil within. This prevents the soil at the boundaries from pulling away from the ends during shrinkage and causes a desiccation crack to form at the mid-section of the box where the maximum tensile stress is expected to occur (Kodikara and Choi, 2006). A Teflon sheet is used under the soil bed to minimize the friction between the box base and the specimen, such that the tensile stress developed in the soil is measured by the load cells. The apparatus sits upon a digital scale that monitors the moisture loss from the soil during drying. Figure 3 shows the desiccation box with attached load cells and readouts.

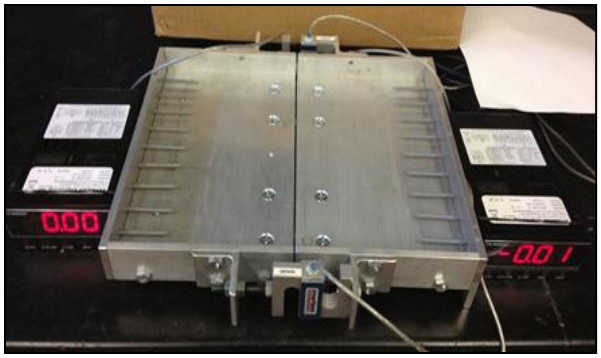

Figure 3: Desiccation Box

To run a desiccation test, the prepared specimens then were allowed to air dry at 25 ℃ (room temperature). A camera was set up to produce time lapse photos that captured both the desiccation crack development and weight of the desiccation box, by which the moisture content could be determined. A picture of the bench scale set-up including the desiccation box, overhead camera and a scale to monitor the moisture loss is shown in Figure 4.

Figure 4: Bench Scale Test Set-up

2.4 Shear Strength Testing

To model shear strength in slopes, good approximations of unsaturated strength were developed based on total stress testing of samples (no control of pore air or pore water pressure) in a triaxial device accompanied by measurements of water content and suction. In this way, strength measurements corresponding to a given moisture content and initial suction can be made that reasonably simulate those measured using the more sophisticated techniques. In addition, the saturated shear strength was determined and represents a lower bound to which approximated unsaturated shear strengths can be compared. For this purpose, back-pressure saturated consolidated drained and undrained triaxial compression testing was conducted on samples from each site. In addition, the saturated strength can be used in combination with SWCCs to predict unsaturated strength functions for comparison. Furthermore, some direct shear tests have been run to characterize the residual and fully softened shear strength of the soil as recent studies (Wright et al., 2005) have recommended using these values for designing slopes.

2.4.1 Soil Material and Sample Preparation

For this study, Shelby tubes were used to obtain undisturbed samples from both Sites 1 and 2. These samples were then used to assess the in-situ conditions of the soil at different depths. The moisture content, suction, and dry density were recorded for each sample tested using triaxial undrained compression tests.

These data were then used to prepare the remolded samples for the direct shear tests. In-situ conditions were recreated in order to assess the residual shear strength and fully softened shear strength that the soil may reach at some point.

For the remolded sample, the soil was process through a No. 40 sieve as studies have shown that the failure occurs along the smaller particles. Furthermore, the grain-size distribution analysis shows that the percentage of particles with a diameter between No. 4 and No. 40 is almost negligible. For the residual shear strength test, the soil was then mixed with water to reach the desired moisture content, covered and stored in the moisture room overnight to promote homogeneous moisture in the soil. The specimen was then prepared by compacting the soil using moist tamping in 3 equal layers in the shear box.

The preparation for the fully softened shear strength is different as the objective is to bring the soil back to its normally consolidated state. In that case, the soil is washed through a No. 40 sieve. The slurry is then air-dried until its liquid limit. This state is checked using the Casagrande device. The sample is then spread in the shear box using a spatula as shown in Figure 5.

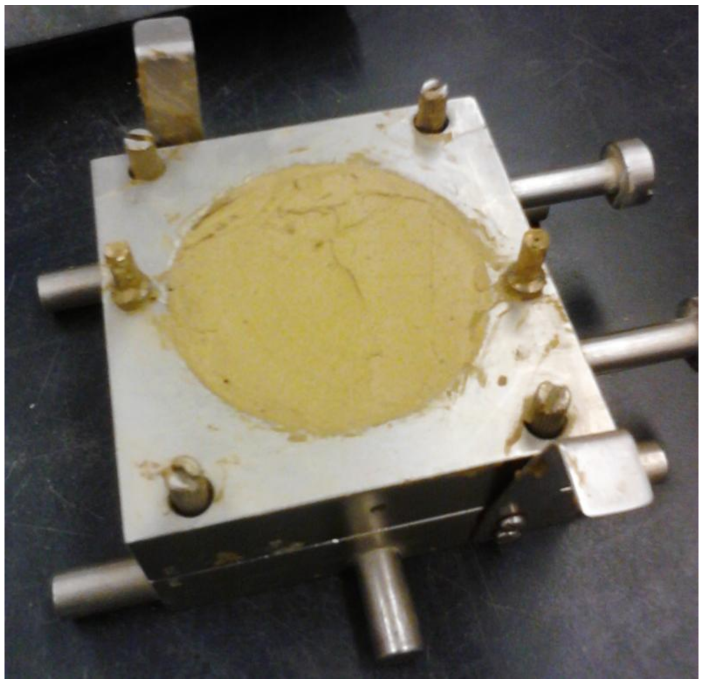

Figure 5: Preparation of the fully softened sample

2.4.2 Experimental Test Methodologies

As it is really difficult to obtain identical samples from the same depth to conduct several triaxial compression single stage tests, the same sample was used to run multistage tests for each depth. An effective pressure of 13.8 kPa (2.0 psi), roughly corresponding to the overburden pressure at a depth around 3 feet is applied for the saturation phase and for the first stage of shearing. The first shearing stage is conducted up to a strain of 2% under undrained conditions, and then the sample is unloaded and consolidated under a pressure of 34.5 kPa (5.0 psi). The same procedure is repeated for effective pressure of 69.0 kPa (10.0 psi) and 103.4 kPa (15.0 psi) when the sample is still in good condition.

For the direct shear test, once the remolded sample is ready, the box is installed in the shearing apparatus and a seating load is applied before soaking the sample. The pressure applied is 13.8 kPa (2.0 psi), the same as for the triaxial test, to be consistent. The sample is soaked to prevent the clay from drying. Time is allowed for the soil to consolidate or swell before shearing or before applying the next load. The sample is sheared at a very slow rate in order to dissipate excess water pressures. Two series of three tests were run for each test in order to get the failure envelopes for consolidation pressures of 13.8 kPa (2.0 psi), 34.5 kPa (5.0 psi) and 69.0 kPa (10 psi).

2.5 Test Site Monitoring

Test sites were visited intermittently to visually inspect landslide sites, collect soil samples for moisture content and suction determinations with depth, and monitor presence and/or growth of desiccation cracks. Samples were collected to measure moisture contents at various times of the year at various depths. In addition, climate data were collected from weather stations to calibrate and validate models for predicting moisture content variations in the soil profile. This is a critical part of being able to predict long-term stability due to climatic variations since these moisture contents can be used to estimate soil suction using SWCCs. These samples were also used to for laboratory determinations of the corresponding soil suction, which can provide validation of SWCCs determined in the laboratory. That is, the SWCC measurements from laboratory testing can be compared to SWCC information assembled through measurements of water content and suction on field samples. For subsequent project phases, additional sites with fresh slides will be sought and examined. Soil sampling and testing will cover samples obtained over the full depth of interest (i.e. extending some nominal distance below the bottom of the failure surface).

3. RESULTS AND DISCUSSION

3.1 Soil Water Characteristic Curve

Figure 6 represents the soil water characteristic curves (SWCC) of test soils obtained by the WP4 device. The moisture conditions can be linked to suction in the slopes through the soil water characteristic curve (SWCC) and the shear strength can be linked to the matric suction through strength testing. From the presented data, it can be said that at particular water content, the measured suction is considerably higher for the soil having higher Plasticity index.

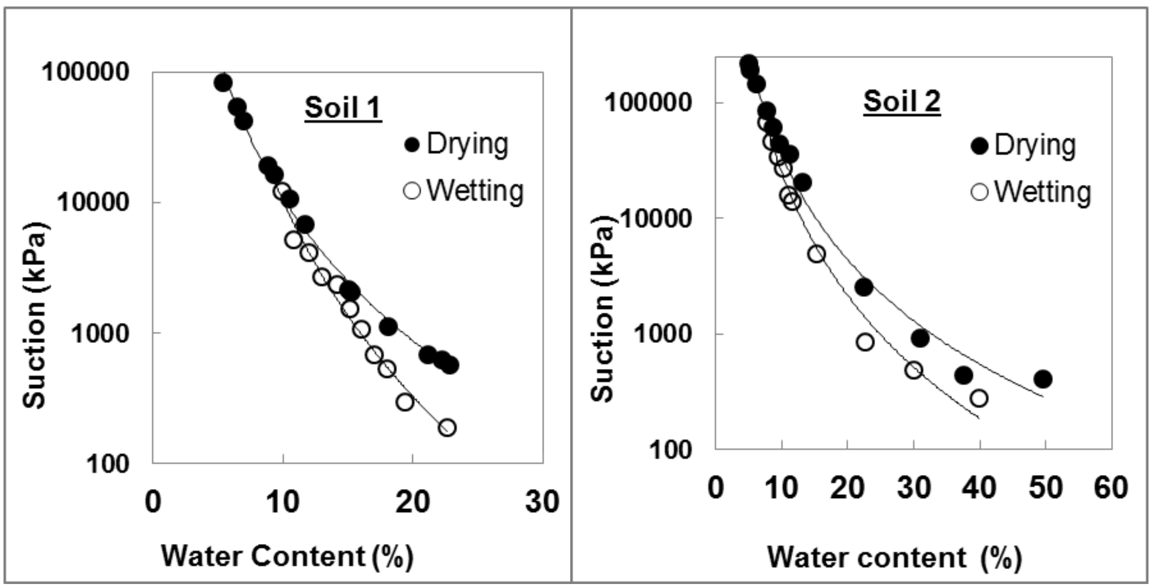

Figure 6: Measured Soil Water Characteristic Curves of Test Soils (Note: 1 psi=6.89 kPa)

3.2 Bench Scale Desiccation Testing

As soil is drying, shrinkage strains imposed on the specimen produced tensile stress. In all desiccation tests, a nearly linear crack was generated across the mid-section of the box where the tensile stress reached a peak value. The crack developed across the full width of the box and through the depth as shrinkage proceeded. Figure 7 shows the typical pattern of desiccation crack formation in a compacted bed of both soils.

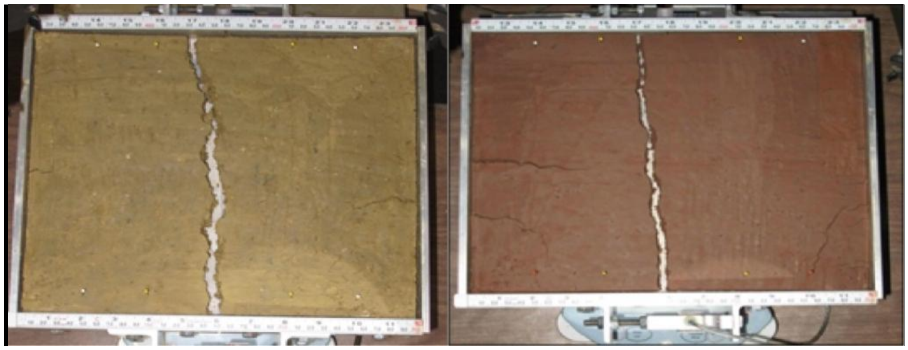

Figure 7: Typical Desiccation Crack Pattern of Soil 1(Right) and Soil 2 (left)

In all tests, it was observed that the crack occurred at the initial stage of drying when the specimens have lost less than 1% of their water content. The desiccation curves of test specimens are shown in Figure 8. All curves have a similar trend when the moisture content approaches an equilibrium state at the end of the test.

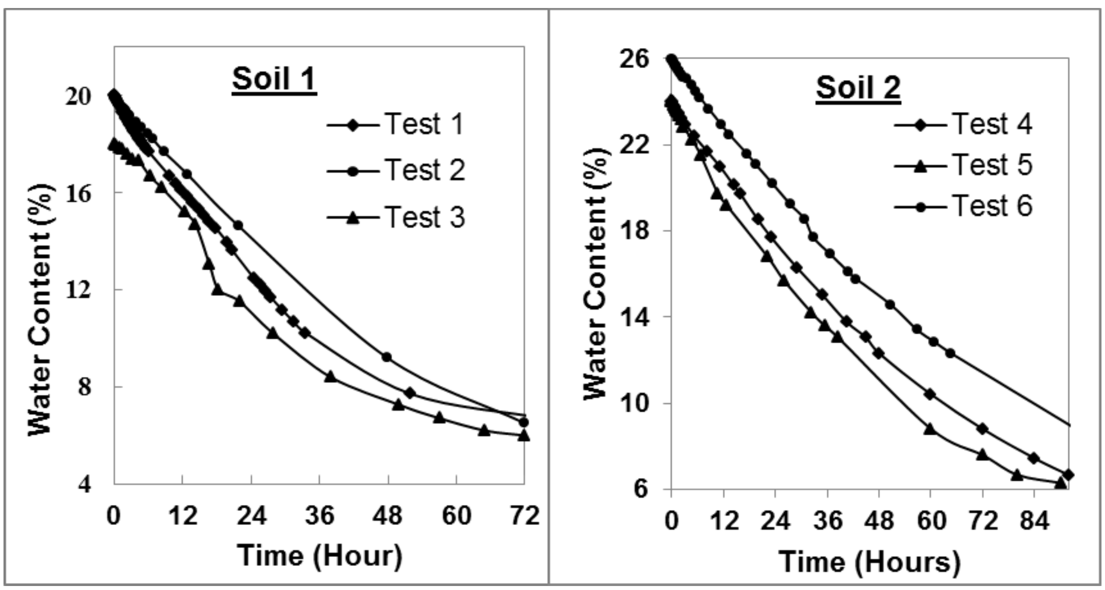

Figure 8: Desiccation Curves of Test Soils

The plots of tensile strength versus time for the desiccation tests with the same initial water content and different dry unit weights are shown in Figure 9. The peak values point to the moments when the first cracks were observed. Comparing the two curves of each plot indicates that in specimens having the same initial water content (W_i), the tensile strength is higher in soils compacted to higher dry unit weights.

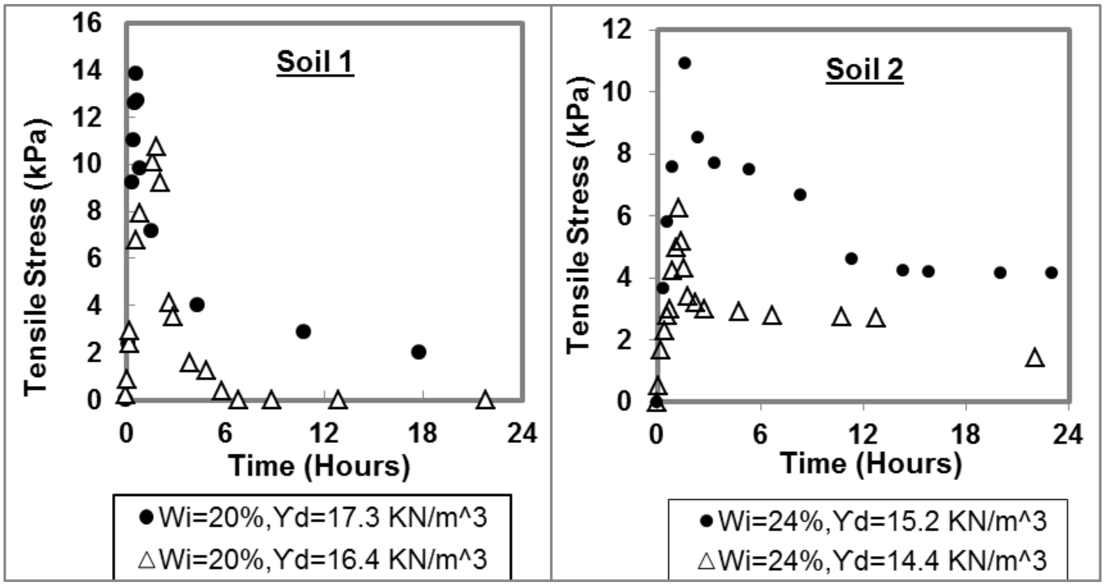

Figure 9: Effect of Dry Unit Weight on Tensile Strength

(Note: 1 psi=6.89 kPa,1 pcf=0.157 kN/m^3)

From Figure 10, it can be seen that at a constant dry unit weight, the specimens with lower water contents (OMC) tend to have lower tensile strength than those wetted to 2% wet of optimum. As illustrated in SWCCs shown in Figure 6, soil suction increases with the decrease in water content as drying progressed in soil; however the results of a study on suction-controlled tensile strength of compacted clays indicates that with increasing soil-water interactions, the tensile strength increases up to a peak value and slightly decreases afterwards (Zeh & Witt, 2005).

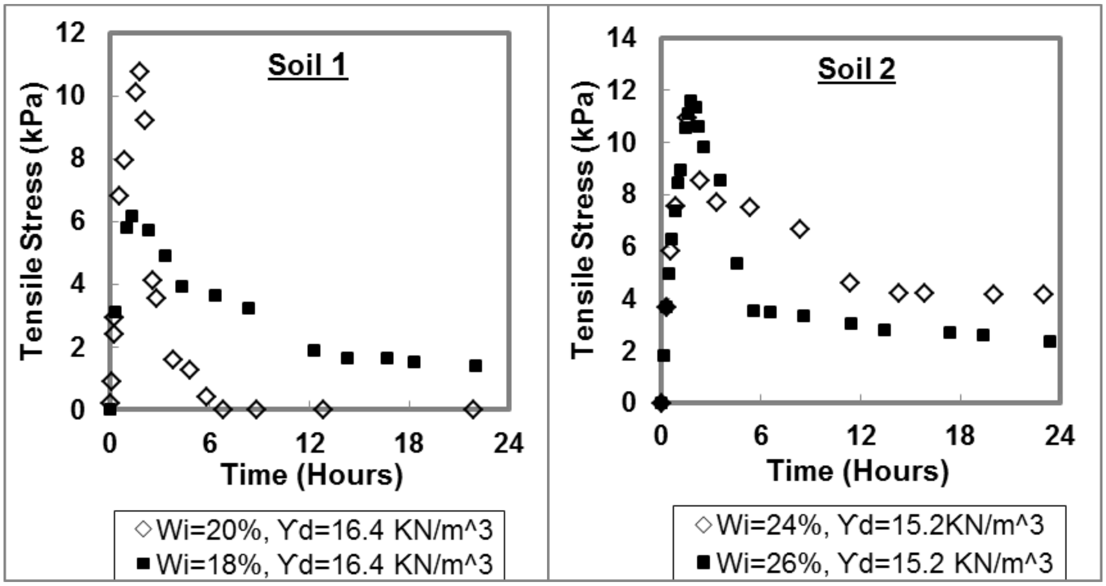

Figure 10: Effect of Water Contents on Tensile Strength

(Note: 1 psi=6.89 kPa,1 pcf=0.157 kN/m^3)

The effect of plasticity (PI) on tensile strength generated during the desiccation process is presented in Figure 11. Both tests were performed in OMC - γ_{dmax} condition. Comparing the two curves illustrate the fact that tensile strength of soil increases with an increase in plasticity index (Kim et al., 2012).

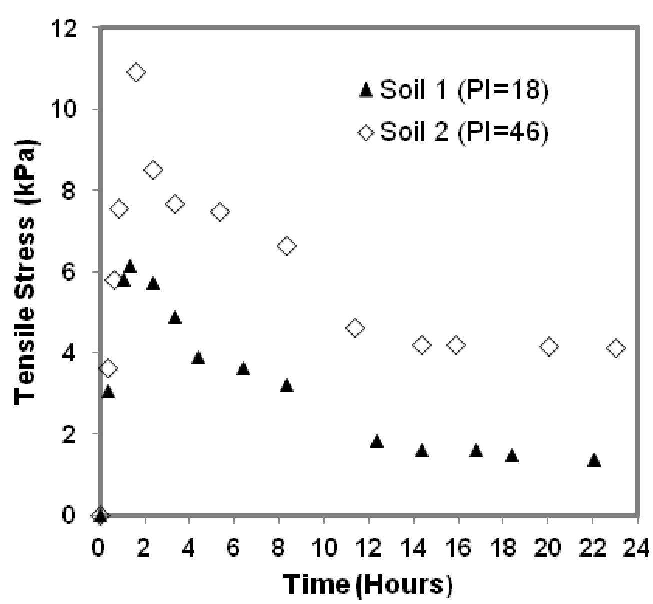

Figure 11: Effect of Plasticity Index on Tensile Strength (Note: 1 psi=6.89 kPa)

3.3 Shear Strength Testing

Triaxial tests have been conducted at different depth for both Sites 1 and 2 and give us a good sense of the peak strength of the slope under saturated conditions. Figure 12 summarizes the results of these tests, giving the friction angle as a function of depth.

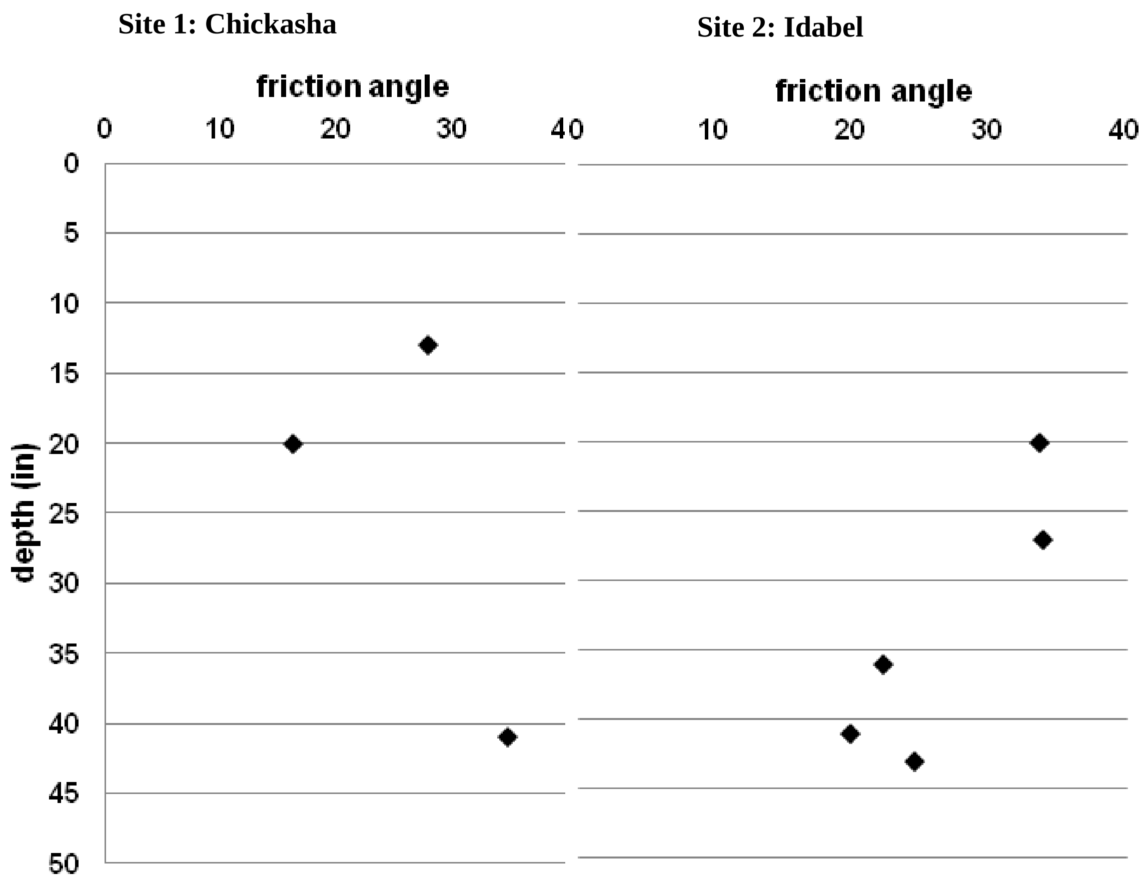

Figure 12: Friction Angle as a Function of Depth for Sites 1 and 2

From the graph, we can identify a weaker layer for site 2, around 3 feet deep. The friction angle at that location is smaller than at the surface. This is consistent with the fact that the failures are shallow and occurred around that depth.

Results of residual direct shear tests at pressure of 13.8 kPa (2.0 psi), 34.5 kPa (5.0 psi) and 69.0 kPa (10.0 psi) are presented in the Figures 13, 14 and 15 and allow us to obtain a failure envelope for the Site 2 (Figure 16).

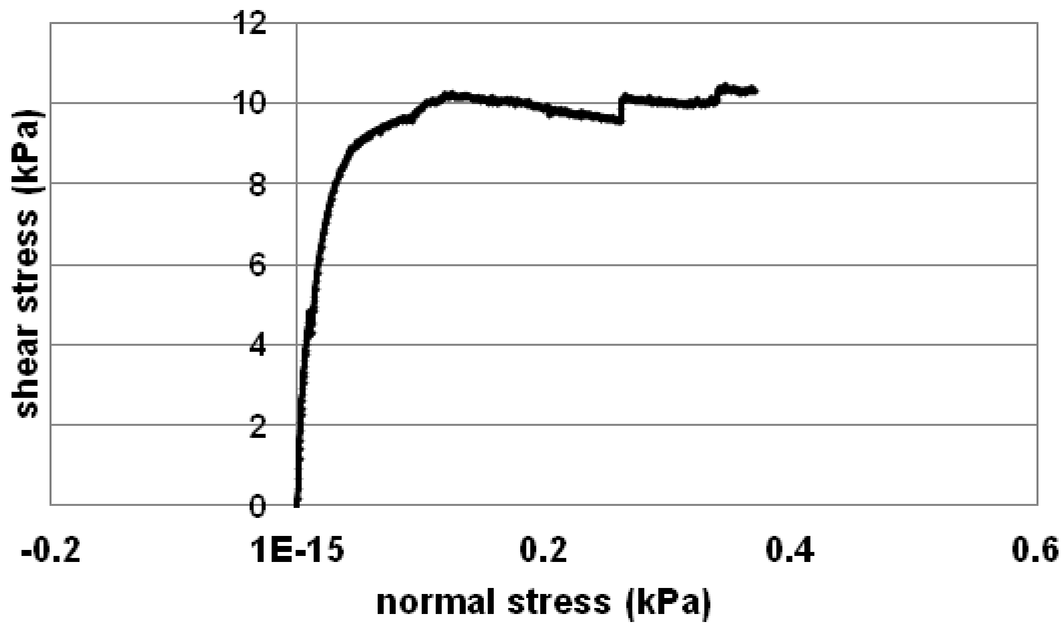

Figure 13: Direct Shear Test, 13.8 kPa (2.0 psi) Consolidation (Note: 1 psi=6.89 kPa)

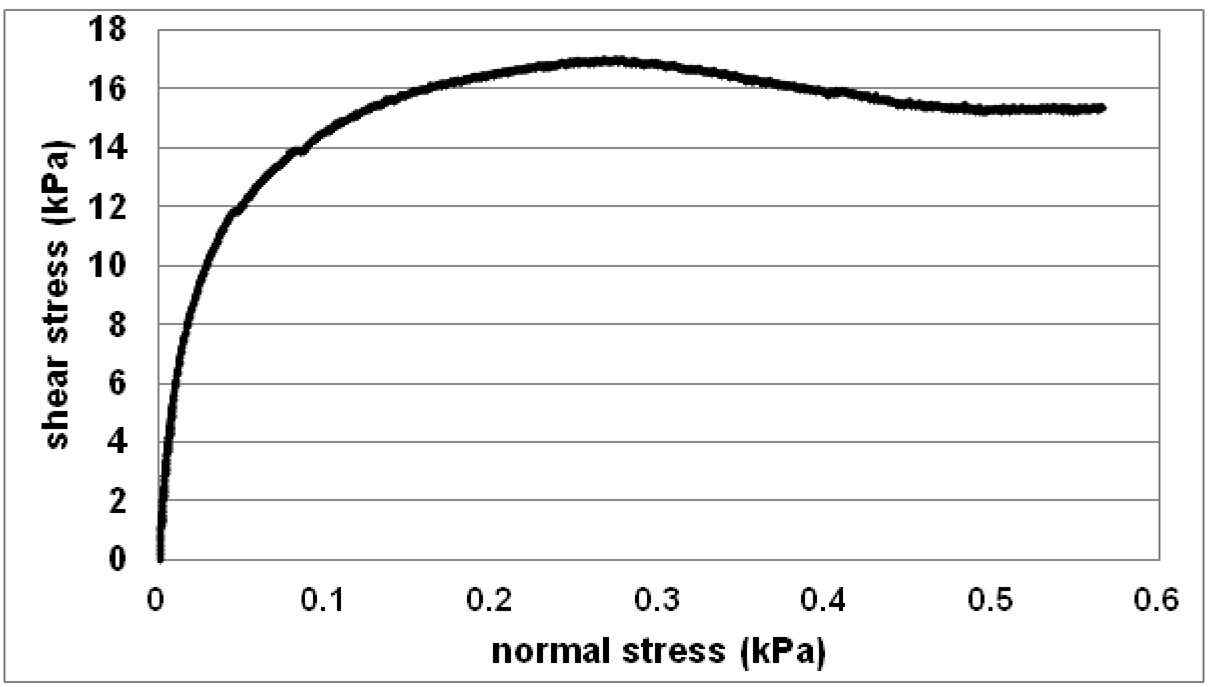

Figure 14: Direct shear test, 34.5 kPa (5 psi) consolidation (Note: 1 psi=6.89 kPa)

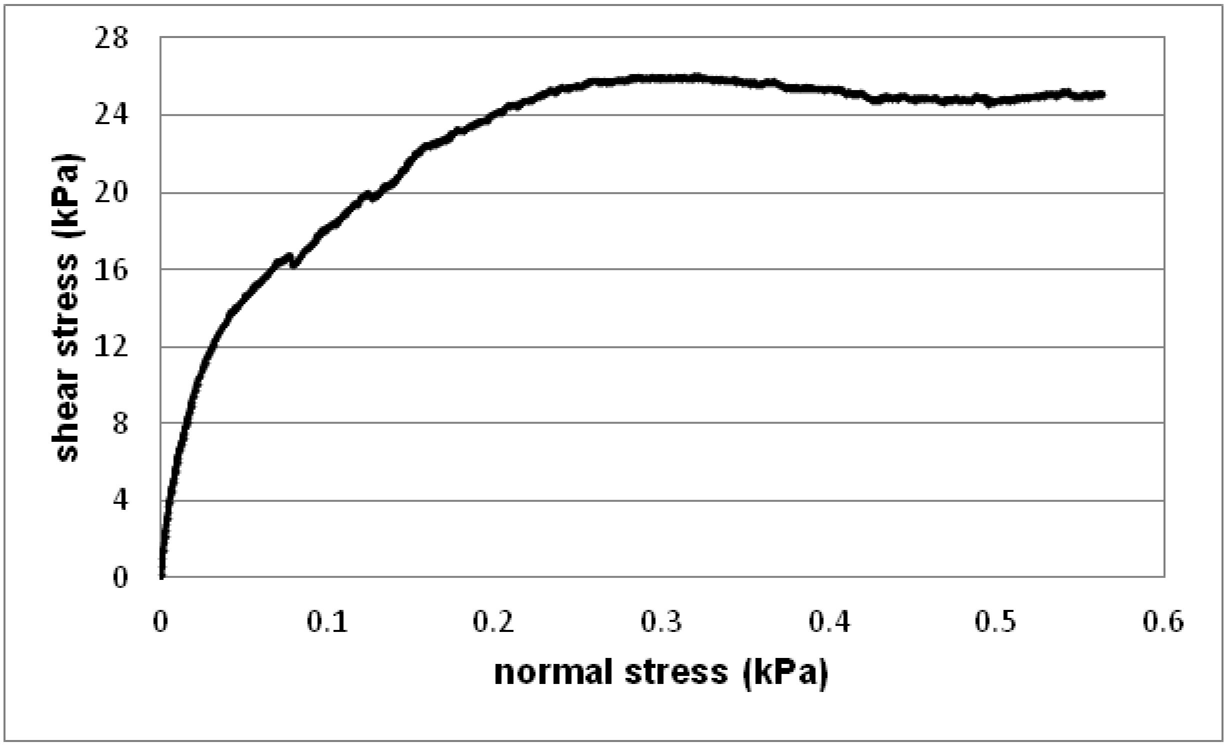

Figure 15: Direct shear test, 69.0 kPa (10 psi) consolidation (Note: 1 psi=6.89 kPa)

There is a peak and then the shear strength decreases to a constant value. It may however be necessary to compare these results with those from a ring shear device in order to verify if we actually get the residual shear strength or the post-peak shear strength.

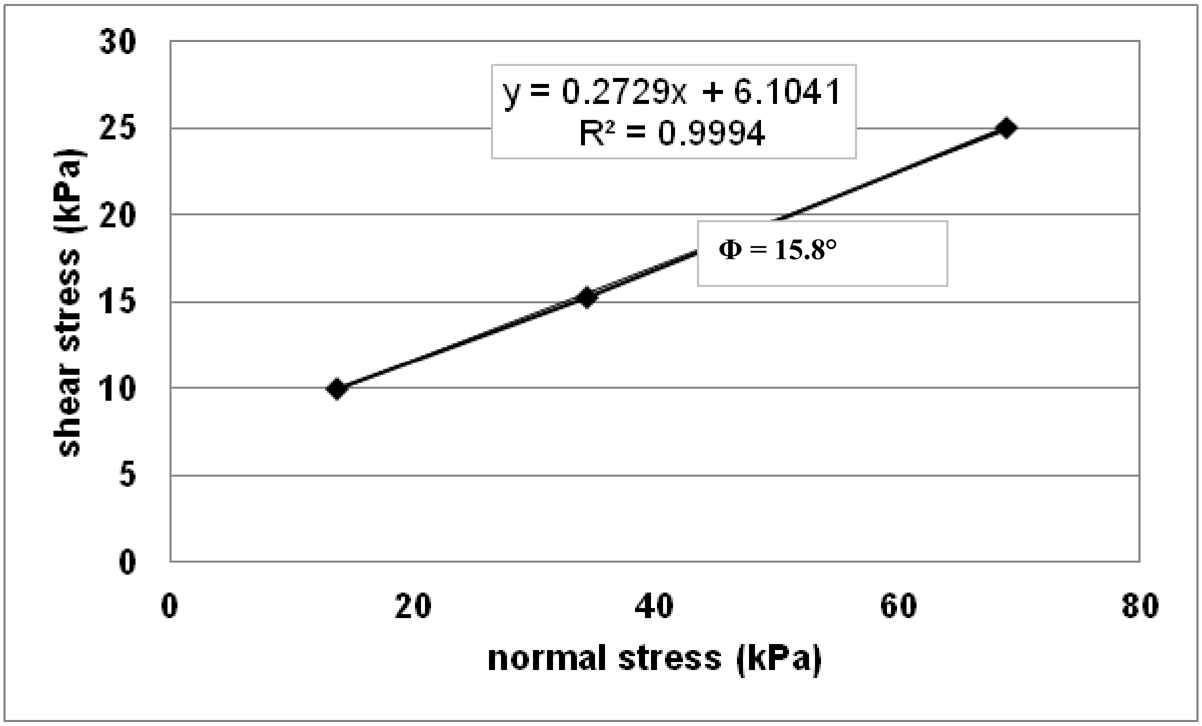

Figure 16: Residual Failure Envelope from Direct Shear Test (Note: 1 psi=6.89 kPa)

The three points obtained from the test are aligned and seem to be consistent. The coefficient of the failure envelop gives a friction angle of 15.8°.

Concerning the fully softened shear strength, the method described in the previous section is so far producing erratic results as shown in Figure 17. Another procedure is being developed to better model the process of wetting and drying that leads to softened shear strength in the field.

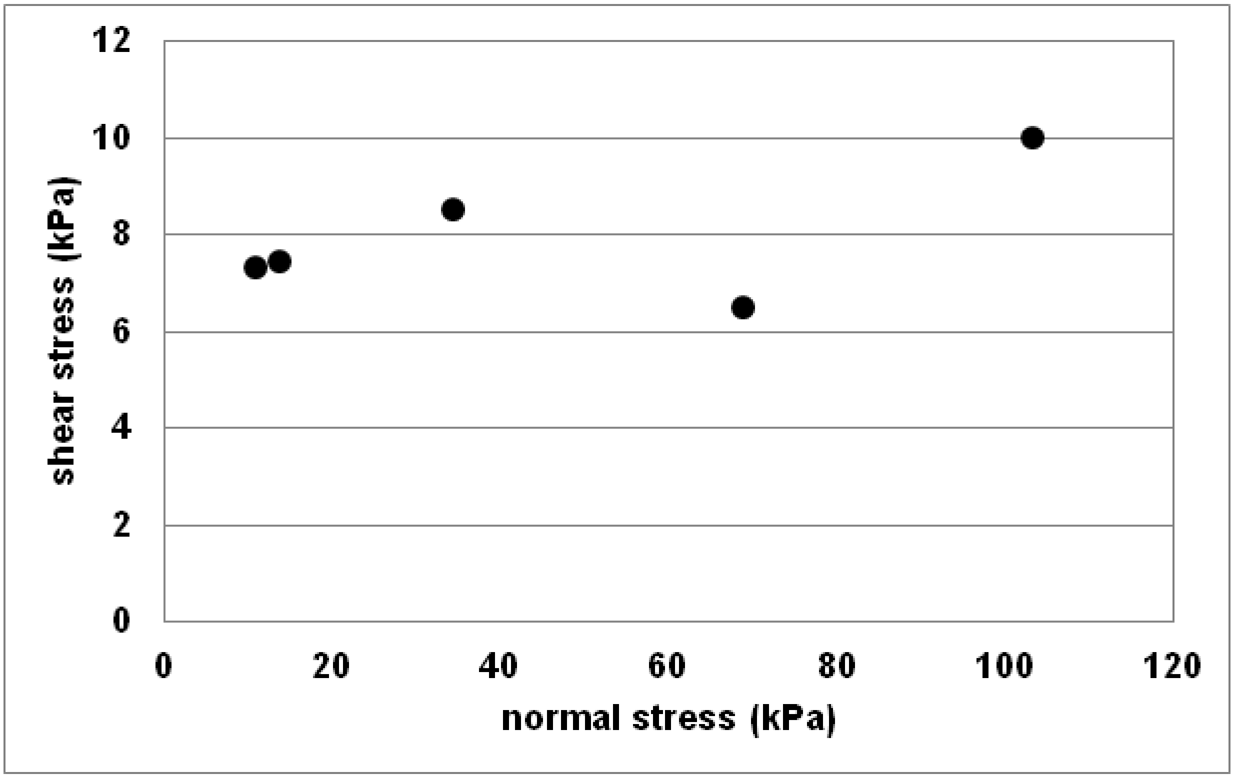

Figure 17: Fully Softened Failure Envelope from Direct Shear Test (Note: 1 psi=6.89 kPa)

3.4 Test Site Monitoring

Weather station data has been collected at Sites 1 and 2. These data include the air temperature, rainfall intensity and volumetric water content at different depths which are plotted versus time and presented in the Figures 18 and 19. The data show that these shallow moisture sensors respond rather quickly to rainfall events. However, when the soil around the sensors becomes nearly saturated, the sensors tend to go out of range, which explains the discontinuous nature of some of the volumetric water content readings. Weather data also shows that the test sites have experienced significant wetting events since monitoring began.

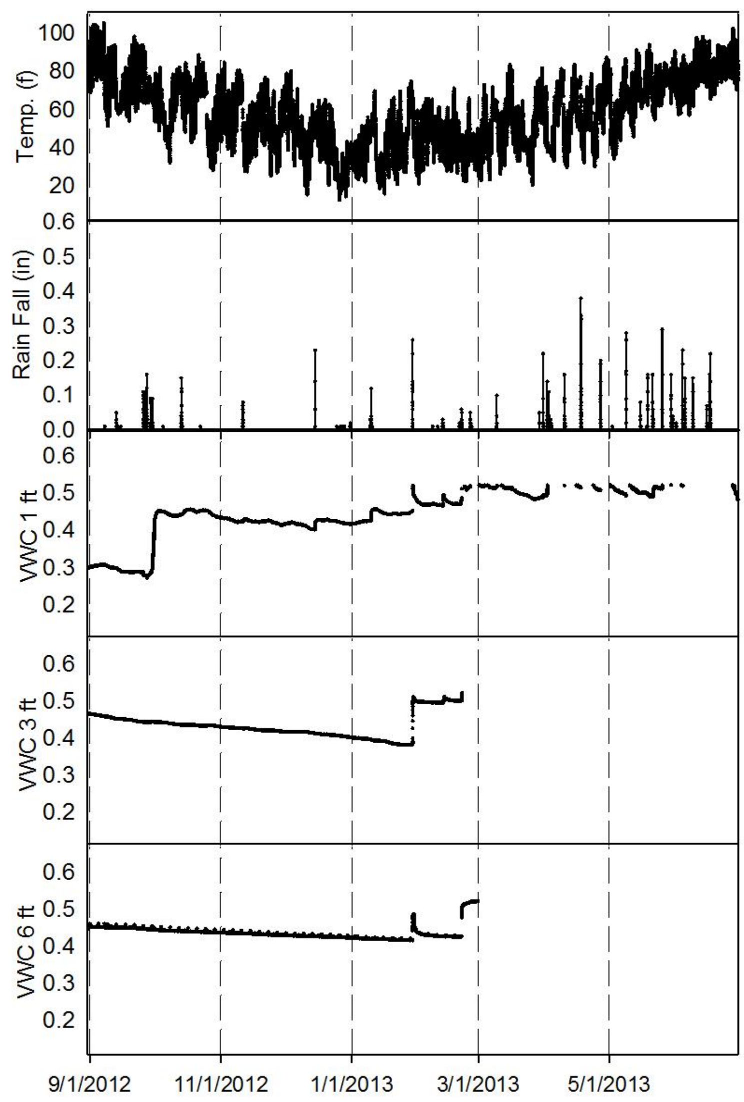

Figure18: Weather station data from Chickasha (Site 1)

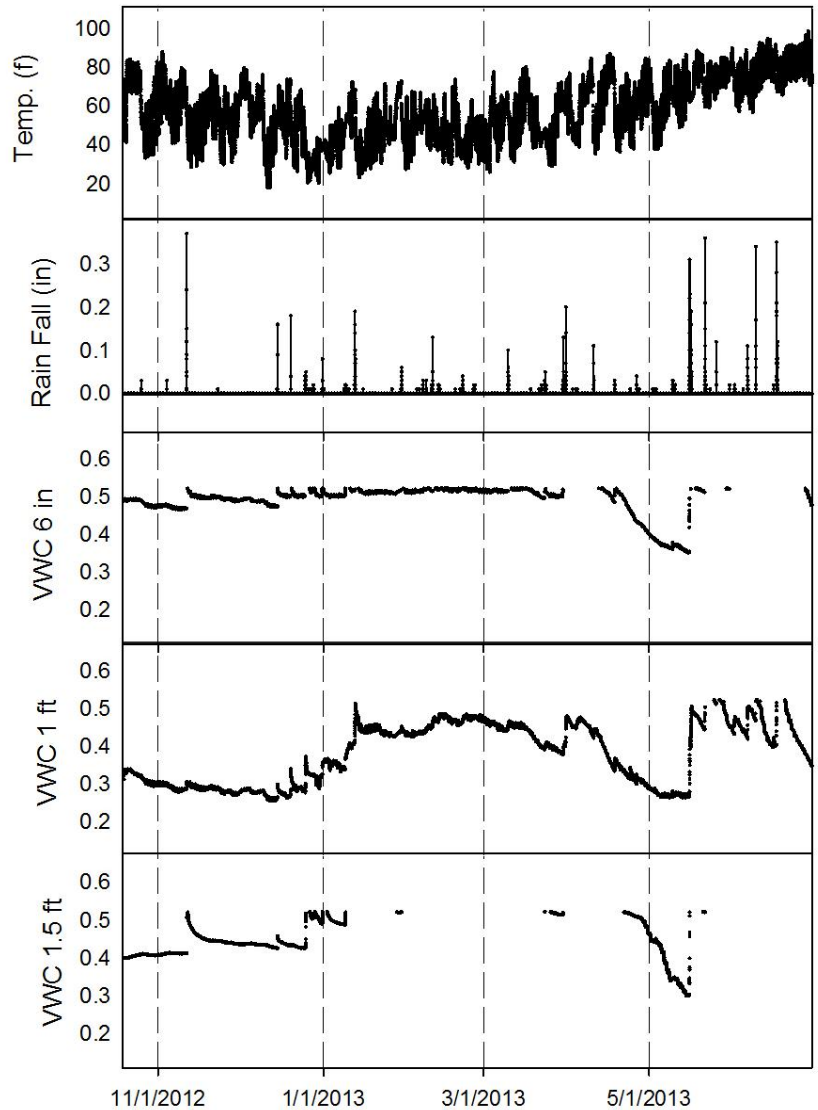

Figure19: Weather station data from Idabel (Site 2)

4. SUMMARY

This report presents results thus far obtained from a three year study examining prediction and modeling of shallow slope stability. The first year was partially supported by the OkTC and ODOT. There have so far been many accomplishments including: 1) establishing two field test sites; 2) successful installation and monitoring of weather station equipment at each site; 3) sampling and laboratory testing of basic soil properties; 4) determination of soil water characteristic curves for primary drying and wetting; 5) basic measurements of saturated shear strength; and 6) development and testing with a new laboratory device to study the mechanics of deformation crack formation. Work will continue in these areas as well as including modeling of moisture content changes and slope stability.

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