Laboratory Determination of Hydraulic Conductivity Functions

for Unsaturated Cracked Fine Grained Soil

by

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ABSTRACT

In geotechnical engineering, measuring the unsaturated hydraulic conductivity of fine grained soils can be time consuming and tedious. The various applications that require knowledge of the unsaturated hydraulic conductivity function are great, and in geotechnical engineering, they range from modeling seepage through landfill covers to determining infiltration of water under a building slab. The unsaturated hydraulic conductivity function can be measured using various direct and indirect techniques. The instantaneous profile method has been found to be the most promising unsteady state method for measuring the unsaturated hydraulic conductivity function for fine grained soils over a wide range of suction values. The instantaneous profile method can be modified by using different techniques to measure suction and water content and also through the way water is introduced or removed from the soil profile. In this study, the instantaneous profile method was modified by creating duplicate soil samples compacted into cylindrical tubes at two different water contents. The techniques used in the duplicate method to measure the water content and matric suction included volumetric moisture probes, manual water content measurements, and filter paper tests. The experimental testing conducted in this study provided insight into determining the unsaturated hydraulic conductivity using the instantaneous profile method for a sandy clay soil and recommendations are provided for further evaluation.

Overall, this study has demonstrated that the presence of cracks has no significant impact on the hydraulic behavior of soil in high suction ranges. The results of this study do not examine the behavior of cracked soil unsaturated hydraulic conductivity at low suction and at moisture contents near saturation.

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CHAPTER 1: INTRODUCTION

Background

In recent years, the number of professionals and researchers working in the field of unsaturated soils has vastly increased. With the increasing interest in unsaturated soil mechanics, focus on the unsaturated hydraulic conductivity, Kunsat, has become of interest to geotechnical engineers. The unsaturated hydraulic conductivity is a difficult and time consuming function to determine for a fine grained soil. Methods have been proposed by other researchers to determine the unsaturated hydraulic conductivity for an intact soil, but little information is available for this parameter for cracked soils. There may be significant differences between the hydraulic conductivities for intact and cracked soils. To observe these differences methods for determining the hydraulic conductivities for cracks soils will be presented in this study.

The hydraulic conductivity is the parameter used to assess the infiltration rate of water through soil. The hydraulic conductivity is a measure of the rate at which moisture passes through a soil as first postulated by Darcy's law. The unsaturated hydraulic conductivity is a function of the soil negative pore water pressure or suction, and changes with water content. The maximum value of hydraulic conductivity, Ksat, for a given soil occurs when the soil is completely saturated, and this maximum value is usually used in design as a conservative measure. When a soil is completely saturated, the pore pressures are positive and the hydraulic conductivity is constant, assuming steady flow, constant temperature, and no changes in the water or soil chemistry (McCartney, Villar and Zornberg, 2007). When soils are unsaturated, the hydraulic conductivity is less than the saturated hydraulic conductivity and can vary by multiple orders of magnitude. The unsaturated hydraulic conductivity of a soil is defined by its relationship between the saturated hydraulic conductivity and the soil suction or volumetric water content (Li, Zhang and Fredlund, 2009). Since the unsaturated hydraulic conductivity of soils can be a function of saturation, water content, matric suction or other parameters, measuring this parameter is done through intricate experiments such as the instantaneous profile method. Numerous environmental and physical factors affect the measurement of the unsaturated hydraulic conductivity. These measurements involve careful consideration of the procedures and techniques used in laboratory experiments. The unsaturated hydraulic conductivity is also one of the most difficult parameters to measure when dealing with fine-grained soils because of the time involved in performing the experiment and the limited suction measurement range provided by various measurement methods (McCartney, Villar and Zornberg, 2007).

Fine-grained soil exhibit different properties when compared to other coarser grained soil types. Fine-grained soils such as clays have unique properties including extremely small particle sizes resulting from different chemical weathering processes from which clay minerals were formed (Mitchell and Soga, 2005). Clays are made up of plate like shapes, which provide these soils with a greater surface area- to- mass ratio than compared to other soils. Clayey fine-grained soils, due to their physical and chemical constituents, have the potential for somewhat unique problems such as swelling, cracking, sliding, and consolidation.

Fine-grained soil typically has low saturated hydraulic conductivities ranging from 10^{-12} to 10^{-8} m/s (Coduto, 1999). The hydraulic conductivity is a significant parameter for fine-grained soil since their ability to retard movement of liquids makes them ideally suited for use as hydraulic barriers either for landfill sites, contaminant remediation, and impermeable fluid barriers. Because of the low hydraulic conductivity of fine-grained soil their infiltration rate is very slow. This low infiltration rate has implications on the measurement of the unsaturated hydraulic conductivity.

Measurement of this unsaturated parameter can be done by the instantaneous profile method, but requires special considerations for precise and accurate measurement.

Fine-grained materials, such as clays, have high plasticity and variability in shear strength due to wetting that makes them susceptible to cracking. When clay soils are exposed on the ground surface, they can encounter cycles of wet and dry periods due to rainfall patterns, irrigation in a given area and evaporation. The cracks and fissures that form due to the cyclical periods of wet and dry conditions, allow for water to slowly absorb into the clay, causing shrink-swell behavior deepening in the cracked clay zone (Rayhani, Yanful and Fakher, 2007). This type of crack formation is called desiccation cracking, which is a common phenomenon in clay materials and can change the hydraulic conductivity of the soil (Rayhani, Yanful and Fakher, 2007). The phenomenon of self-healing, which occurs in some types of clays, can also affect the hydraulic properties of the soil and is a result of this shrink-swell behavior. Current studies have shown that the presence of cracks or fissures in soils decrease the amount of surface runoff by increasing the total infiltration rate (Noval, Simunek, and van Genuchten, 2000). The cracks result in an increase the infiltration rate by allowing more water to seep into deeper portions of the soil profile, thus increasing the efficiency for which water can infiltrate the soil. The formations of cracks typically occurs when the soil is unsaturated, therefore understanding and determining the unsaturated hydraulic properties is crucial when dealing with these materials for geotechnical applications.

In geotechnical engineering, cracked fine-grained soils present implications to various design parameters for construction of infrastructure and foundations. In some situations, desiccation cracking may not be of concern, but when cracks and fissures are anticipated, understanding the effects of the cracks on the engineering properties of the soil becomes of great importance. The anisotropy effects of the crack orientation to the direction of flow may also present considerations to the effects of cracks on the hydraulic conductivity. Cracked fine-grained soils present special considerations when performing seepage analyses for saturated and unsaturated soil systems. In the analysis of these systems, the unsaturated hydraulic conductivity is of great significance since is can be used to model water flow, infiltration, volume change and the triggering of landslides (Li, Zhang and Fredlund, 2009). There has been little research conducted on the implication of cracks and fissure to the saturated and unsaturated hydraulic conductivity. This provides the opportunity to assess the effects of cracks on the hydraulic conductivity and to evaluate laboratory methods used to measure conductivity functions for cracked fine-grained soils.

There are geotechnical applications that would benefit from the analysis of cracked fine-grained soil and their hydraulic conductivity. Cracked and fissured soils are present in landfill caps, sloped structures, and foundations embankments. Fine-grained soils are sometimes used as fill materials and could experience cracking around and near foundations for structures such as bridges and buildings. Cracks present in all of the applications above could be affected by the infiltration rate of water into the subsurface. In the design of these types of structures, time and money could be saved by an accurate analysis of the cracked materials that may be encountered. For landfill applications, landfill caps are designed as barriers systems which typically incorporate compacted clay layers on the surface to prevent seepage of fluids in and out of the landfill waste mass. The compacted clay caps are exposed to the environment and could encounter desiccation cracking, in turn affecting the hydraulic conductivity of the clay layer. The design done for landfill caps requires a seepage analysis and the unsaturated hydraulic conductivity is the primary soil parameter required (Li, Zhang and Fredlund, 2009). The hydraulic conductivity of this clay soil may change due to the presence of cracks and fissures that may form over time. Thus, understanding the effects of infiltration through cracked soil systems and accurately measuring the hydraulic conductivity can aid in achieving an effective design.

It is important to model the hydraulic properties of cracked soils to investigate the effect on the infiltration rate. Cracks can be present throughout the entire saturation range of a given soil. The saturated hydraulic conductivity can be measured through a relatively simple experiment and may be quantified by comparing the hydraulic conductivity of the crack to intact conditions. The unsaturated hydraulic conductivity is a function of the matric soil suction, which gives rise to the challenge in determining the unsaturated hydraulic conductivity function for an unsaturated soil. This is typically done for an intact soil by the instantaneous profile method, which is an unsteady-state method used in the laboratory to measure the unsaturated hydraulic conductivity. There are several variations of this method which primarily differ in the measurement of the water content, soil suction, hydraulic gradient, flow rate and the way water is introduced to the system. For the cracked condition, measuring the unsaturated hydraulic conductivity can be done in a same manner but by incorporating a cracked formation into the soil profile and the effects of the cracks can be analyzed by comparing the results of the cracked and intact conditions. When measuring the unsaturated hydraulic conductivity for intact and cracked fine-grained soils, one should also consider calculating the unsaturated hydraulic conductivity and the measurement of various experimental soil parameters.

Objectives

The objectives of this study anticipate a difference in hydraulic properties for soil with cracks as compared with soil that do not have cracks. The condition that cracks create presents the anticipation of extremely different conditions for which infiltration occurs. The introduction of cracks should increase matric suction around the wall of the crack, allowing for soils to become less pervious and decrease the overall permeability of the entire soil mass (Rahman, Fredlund, Fredlund, Pham and Nguyen, 2004). The objectives of this study are to i) analyze the effects of air voids or cracks on the unsaturated hydraulic conductivity; ii) research and summarize the methods used for measuring the unsaturated hydraulic conductivity for cracked soils, and iii) propose special considerations for measuring the unsaturated hydraulic conductivity by the instantaneous profile method, including recommendations that deal with the prediction of the unsaturated hydraulic conductivity.

Scope and Limitations

The scope of this study is limited to comparison of values for unsaturated hydraulic conductivities for fine-grained soils in the cracked condition and in the intact and un-cracked condition. A review of literature is included to supplement the study with current knowledge of the unsaturated hydraulic conductivity of soils. Experiments done by other researchers on the unsaturated hydraulic conductivity for fine grained soil and infiltration tests on cracked soils will be analyzed to aid in the development of a useful laboratory testing program. Through the experiments conducted, various factors that may impact the testing and measurement of the unsaturated hydraulic conductivity for intact and cracked soil will be identified. To analyze the impact of air voids and cracks on the hydraulic conductivity, laboratory experiments using the instantaneous profile method will be performed, which will be modified to incorporate cracks in the soil profile. These methods will be used to analyze the unsaturated hydraulic conductivity. Also, the anisotropy effects of the crack orientation within the soil profile will be evaluated. Using the results from laboratory testing as part of this study and research results from current literature, the effects of the cracks to the hydraulic properties of fine-grained soils will be examined. Conclusions and observations will be discussed to answer the objectives of this study.

Organization

The organization of this report is as follows: Chapter 1 includes an introduction and identifies the importance of the work and the scope and limitations. Chapter 2 presents the literature review. Chapter 3 includes information and data on soil properties and experimental design. Chapter 4 includes description of the laboratory testing of the unsaturated hydraulic conductivity for the cracked and intact conditions. Chapter 5 includes a discussion of the results and other test methods that can be used for determining the permeability for intact and cracked clays. Chapter 6 includes conclusions and identifies the need for future research.

CHAPTER 2: LITERATURE REVIEW

Introduction

In geotechnical engineering, unsaturated soil mechanics is commonly been a specialized topic. The subject of unsaturated hydraulic conductivity for soil has only been studied on a limited basis by researchers. In order to determine suitable methods of determining the unsaturated hydraulic conductivity functions for fine grained soils, a review of studies and experiments done by previous researchers is presented. This review of literature includes functions used to model unsaturated hydraulic conductivity, measuring the unsaturated hydraulic conductivity, and the effects of cracks to the unsaturated hydraulic conductivity.

Models of Unsaturated Hydraulic Conductivity

Currently there are numerous models that describe and predict the unsaturated hydraulic conductivity for fine grained soils. Models of the unsaturated hydraulic conductivity functions generally involve two of the following properties; soil saturation, void ratio, or water content. In an unsaturated soil, the hydraulic conductivity is significantly affected by combined changes in the void ratio and the degree of saturation or water content (Fredlund and Rahardjo, 1993). However, the effect of changes in void ratio is usually small and secondary to the soil saturation or water content. As a result, the unsaturated hydraulic conductivity is often described as a singular function related to the degree of saturation or volumetric water content (Fredlund and Rahardjo, 1993). A change in matric suction can produce a more significant change in the soil saturation or water content than can be produced by a change in net normal stress (Fredlund and Rahardjo, 1993). Because of this, the hydraulic conductivity of a given soil is commonly described as a function of matric suction.

In literature there are various functions that can be used to predict the unsaturated conductivity. Most accurate models may depend on soil type. The hydraulic conductivity functions that will be presented are those that are best suited for fine grained soil. The various equations for determining the conductivity function of unsaturated soils are presented below. These equations are empirical, having been formed from statistical analysis, and are used to model the conductivity functions of soils. When the number of measurements exceeds the number of fitting parameters, a curve fitting procedure can be used to determine the fitting parameters (Fredlund, Xing and Huang 1994). This fitting procedure involves using a spreadsheet such as Excel and the Solver application. The equations presented by Broods and Corey (1964), Gardner (1958), van Genuchten et al. (1980), Arbhabhirama and Kridakorn (1968), and the Leong and Rahardjo (1997) are equations that use semi empirical fits to model the unsaturated hydraulic conductivity function. All of these functions include empirical constants that may relate to specific soil properties such as the air entry value and the slope at the deflection point. The Gardner (1958) and van Genuchten (1980) equations are the most common equation used to model the unsaturated conductivity function. Some of these equations are:

Brooks and Corey (1964) - (Fredlund and Rahardjo, 1993)

$$k_w = k_s \quad \text{for} \quad (u_a - u_w) \leq (u_s - u_w)_b \quad \text{(Eqn. 2.1)}$$

$$k_w = k_s \left[\frac{(u_a - u_w)_b}{(u_a - u_w)}\right]^n \quad \text{for} \quad (u_a - u_w) > (u_s - u_w)_b$$

(Eqn. 2.2)

k_w: Unsaturated hydraulic conductivity.
k_s: Saturated hydraulic conductivity.
$(u_s - u_w)_b$: Air entry value of the soil.
$(u_s - u_w)$: Soil matric suction.
n: Empirical constant.
$n = 2 + 3\lambda$
λ: Pore size distribution index (Refer to Figure 2.1).

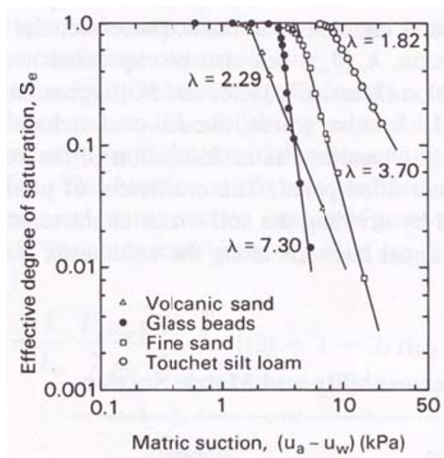

Figure 2.1: λ Values for Various Soils.

Gardner (1958) - (Fredlund and Rahardjo, 1993)

$$k_w = \frac{k_s}{1 + a\left[\frac{(u_a - u_w)}{p_w g}\right]^n} \quad \text{(Eqn. 2.3)}$$

k_w: Unsaturated hydraulic conductivity.
k_s: Saturated hydraulic conductivity.
$(u_s - u_w)$: Soil matric suction.
a: Function breaking point constant.
n: Slope function constant.
p_w: Density of water.
g: Gravity force.

Van Genuchten and Mualem (1980) – (Dye, 2008)

$$k_w = k_s \frac{\left[1-\alpha\psi^{n-1}(1+\alpha\psi^n)^{-m}\right]^2}{[1+\alpha\psi^n]^{\frac{m}{2}}} \qquad \text{(Eqn. 2.4)}$$

k_w: Unsaturated hydraulic conductivity.
k_s: Saturated hydraulic conductivity.
ψ: Soil matric suction.
m: Constant.
n: Constant.
α: Diffusion Coefficient constant.

Van Genuchten et al. (1980) - (Mitchell and Soga, 2005)

$$k_w = \left(\frac{\theta-\theta_r}{\theta_S-\theta_r}\right)^p \left\{1-\left[1-\left(\frac{\theta-\theta_r}{\theta_S-\theta_r}\right)^{\frac{1}{m}}\right]^m\right\}^2 \qquad \text{(Eqn. 2.5)}$$

k_w: Unsaturated hydraulic conductivity.
θ: Volumetric water content of soil.
θ_r: Residual volumetric water content.
θ_S: Volumetric water content at S=1.
p: Constant that describes the degree of connectivity between the water conducting pores. Mualem (1964) recommends 0.5.
m: Constant.
$m = 1 - \frac{1}{n}$ (Assumed)
n: Porosity.

Arbhabhirama and Kridakorn (1968) - (Fredlund and Rahardjo, 1993)

$$k_w = \frac{k_s}{\left[\frac{(u_a-u_w)}{(u_a-u_w)_b}\right]^{n'}+1} \qquad \text{(Eqn. 2.6)}$$

k_w: Unsaturated hydraulic conductivity.
k_s: Saturated hydraulic conductivity.
$(u_s - u_w)_b$: Air entry value of the soil.
$(u_s - u_w)$: Soil matric suction.
n': Empirical constant.

Leong and Rahardjo (1997) - (Dye, 2008)

$$k_w = k_s \left[ln \left(e + \left(\frac{\psi}{a} \right)^n \right) \right]^{-pm} \quad \text{(Eqn. 2.7)}$$

k_w: Unsaturated hydraulic conductivity.
k_s: Saturated hydraulic conductivity.
m: Air entry value of the soil.
ψ: Soil matric suction.
a: Empirical constant.
n: Empirical constant.
p: Empirical constant.

The two models presented by S. Huang, S.L. Barbour, and D.G. Fredlund (1997) and Kunze et al. (1968) are the most sophisticated efforts to predict the unsaturated hydraulic conductivity function. The S. Huang, S.L. Barbour, and D.G. Fredlund (1997) equation uses empirical constants and includes input for a given void ratio or stress state. This model also includes the air entry values which make this correlation more closely related to the soil being modeled.

The Kunze et al. (1968) equation is based on the soil water characteristic curve of the soil. This model has been proposed to be fairly accurate in predicting unsaturated conductivity values over a wide suction range (Fredlund, Xing and Huang, 1994). Both of these two models presented are stochastic models.

S. Huang, S.L. Barbour, and D.G. Fredlund (1997) - (Huang, Barbour and Fredlund, 1998)

$$k_w = k_{SO} 10^{b(e-e_o)} \qquad \text{for} \qquad \psi \leq \psi_{ave} \qquad \text{(Eqn. 2.8)}$$

$$k_w = k_{SO} 10^{b(e-e_o)} \left[\frac{\psi_{aevo} 10^{a(e-e_o)}}{\psi}\right]^{2\lambda+2} \qquad \text{for} \qquad \psi > \psi_{ave}$$

(Eqn. 2.9)

k_w: Unsaturated hydraulic conductivity.
k_{SO}: Saturated hydraulic conductivity at e_o.
e: Void ratio of soil.
e_o: Initial void ratio.
ψ: Matric suction of soil.
ψ_{ave}: Suction corresponding to the air entry value.
ψ_{aveo}: Air entry value at a void ratio at e_o.
a: Empirical constant.
b: Empirical constant.
λ: Pore size distribution index.
$n = 2\lambda + 2$
n: Porosity.

The Kunze et al equation is a statistical model that can be used to determine the unsaturated hydraulic conductivity function for an unsaturated soil using the soil water characteristic curve. This method is based on the fact that both the hydraulic conductivity function and the soil water characteristic curve are primarily determined by the pore size distribution of the soil (Fredlund, Xing and Huang, 1994). Childs and Collis-George were the first to propose this model for predicting the permeability based on the random variation of pore size (Childs and Collis-George, 1950). Marshall improved the model and it was then further modified by Kunze et al (Marshall, 1958, and Kunze, Vehara and Graham, 1968). This analysis is performed by dividing the soil water characteristic curve into equal intervals of volumetric water content. The calculation is then performed on the suction values corresponding to the midpoints of these intervals.

Kunze et al. (1968) - (Marshall, 1958)(Kunze, Vehara and Graham, 1968)

$$k(\theta_i) = \frac{k_s}{k_{sc}} \frac{T_s^2 p_w g}{2\mu_w} \frac{\theta_s^p}{N^2} \sum_{j=i}^{m} \left[(2j + 1 - 2i)\psi_j^{-2}\right] = A_d \sum_{j=i}^{m} \left[(2j + 1 - 2i)\psi_j^{-2}\right]$$

$$i = 1,2, \ldots, m$$

(Eqn. 2.10)

$$A_d = \frac{k_s}{k_{sc}} \frac{T_s^2 p_w g}{2\mu_w} \frac{\theta_s^p}{N^2}$$ (Eqn. 2.11)

$$k_{SC} = \sum_{j=1}^{m} \left[(2j - 1)\psi_j^{-2}\right]$$ (Eqn. 2.12)

$k(\theta_i)$: Predicted hydraulic conductivity for a given volumetric water content (m/s).
i: Interval number which increases as the volumetric water content decreases.
m: Total number of intervals between the saturated vol. water content and the lowest volumetric water content.
k_s: Measured saturated hydraulic conductivity (m/s).
k_{sc}: Saturated hydraulic conductivity or scaling factor (m/s).
A_d: Adjusting constant.
T_s: Surface tension of water (kN/m).
p_w: Water density (kg/m3).
g: Gravitational acceleration (m/s2).
u_w: Absolute viscosity of water (N s/m2).
θ_s: Volumetric water content at S=1.0.
p: Pore size factor = 2 (Green and Corey)
N: Total number of intervals computed between the saturated volumetric water content and the lowest water content.
ψ_j: Matric suction corresponding to the jth interval (kPa)

Measurement of the Unsaturated Hydraulic Conductivity

In geotechnical engineering there are numerous methods to measure the hydraulic conductivity of a soil, including direct or indirect techniques (Fredlund and Rahardjo, 1993). Direct measurements are referred to as permeability tests which are commonly done in the laboratory using a permeameter. Indirect methods include using the soil-water characteristic curve and volume-mass properties to predict the permeability. This study will focus on both direct and indirect methods of measurement of the hydraulic conductivity.

Most laboratory test methods used to determine the coefficient of permeability assume the validity of Darcy's Law which is stated below. Darcy's Law states that the hydraulic conductivity is the ratio of the flow rate to the hydraulic head gradient (Fredlund and Rahardjo, 1993).

$$Q = kiA \qquad \text{(Eqn. 2.13)}$$

Q: Flow rate [V/T]
k: Coefficient of hydraulic conductivity [L/T]
i: Hydraulic gradient
A: Cross-sectional area of flow [L^2]

Thus the variables measured during permeability tests are the flow rate and the hydraulic head gradient. These two variables can either be held constant with time or varied with time during the test. The independence of these variables categorizes testing procedures into groups, steady state methods where the quantity of flow is time independent and unsteady state methods where the quantity of flow is time dependent. Steady state methods are commonly not used due to their limited narrow measurement range and sometimes long equilibrium times (Fredlund and Rahardjo, 1993).

The most practical and promising method for determining the unsaturated coefficient of permeability is the instantaneous profile method. The instantaneous profile method is an unsteady state method that can use direct or indirect measurements. The method uses a cylindrical specimen of soil that is subjected to a continuous flow of water. The flow can be a wetting or drying process depending on the way water is introduced to the specimen. There are several variations in measurement procedures for determining the hydraulic gradient and water flow from the test. The first procedure involves measuring the water content and pore water pressures independently. The second procedure involves measuring only the water content and determines the pore water pressures from the soil-water characteristic curve. The third procedure involves only recording the pore water pressures and then determining the water content from the soil-water characteristic curve.

The instantaneous profile method was first described by Richards and Weeks, and has been incorporated by others over time to determine the unsaturated hydraulic conductivity (Richards and Weeks, 1953). In 1981, Hamilton et al. further describes this procedure and provided suggestions for experiment set up and the calculations of the unsaturated hydraulic conductivity from the test. Since then, numerous researchers have performed permeability tests to determine the unsaturated hydraulic conductivity. The work done in previous research will supplement this study through the conclusions and considerations made in their research. The focus of this literature review will be on studies done that relate to the instantaneous profile experiment and the measurement of the unsaturated hydraulic conductivity for fine grained soils.

In 1953, Richards and Weeks developed one of the first methods for determining the unsaturated hydraulic conductivity in the article titled "Capillary Conductivity Values from Moisture Yield and Tension Measurements on Soil Columns" (1953). Their experiment involved compacting soil into tubes 5.7cm in diameter and 35 cm long. The two soil types that were tested were Ramona loam and Yolo loam. The soil samples experienced wetting and then drying in order to gain changes in the moisture content in the soil profile over time. The suction was measured by tensiometer cups and glass manometers using mercury along the length of the sample apparatus. The research also included information regarding the calculation of the capillary conductivity and unsaturated permeability. The work done by Richards and Weeks was one of the first instantaneous profile methods, and has been used and referenced by other researchers. However, with the development of new measurement technologies numerous advancements in this method have occurred.

A study done by Hamilton, Daniel, and Olson in 1981 focused on the problem of measuring the hydraulic conductivity of partially saturated soils in the laboratory (Hamilton, Daniel, and Olson, 2006). The authors discussed the general problems involved, defined relevant terms, discussed the methods used, and provided experimental data for one soil. The instantaneous profile method was used to perform the experiment, and authors described conditions, apparatus and procedures used for the experiment. In the instantaneous profile experiment, cylindrical samples were confined in an impervious tube that is set in a horizontal position. Suctions were measured at locations along the length of the tube using tensiometers or psychrometers. The pore air pressure was maintained at a suitable value which is typically atmospheric pressure. Water flow is introduced from one end of the sample tube. The opposite end of the tube is left impervious and open to the atmosphere. Suction measurements are taken as a function of time and measurements are taken until water has advanced through the sample to the opposite end. Water contents were determined from suction measurements using a soil water characteristic curve. The authors note that the accuracy of this method depends on the accuracy of the soil water characteristic curve and the measurements of suction from the test.

From the conductivity tests performed by Hamilton et al., soil samples were compacted into plastic tubes with a 50mm diameter and 144mm in length. Psychrometers were installed along the length of the tubes. A needle was used with several disks of filter paper to uniformly distribute the flow across the soil. A flow rate of 0.7cm^3/day was typically used. The soil tested was a Goose Lake clay which had a low plasticity. The soil was prepared at 5% gravimetric water content and compacted into the sample tubes with 88% relative compaction effort from the standard proctor. A complete test for the Goose Lake clay took about 20 days. The calculated coefficients of hydraulic conductivity for the Goose Lake clay are shown below in Figure 2.2.

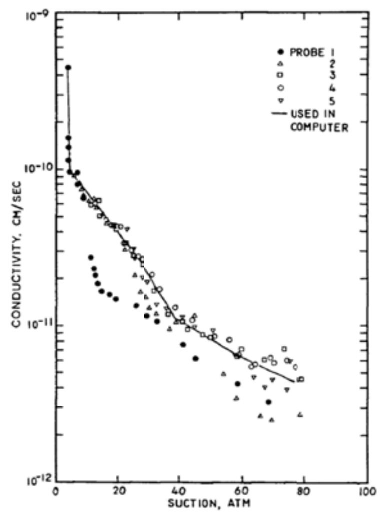

FIG. 6—Calculated coefficients of hydraulic conductivity for Goose Lake clay.

Figure 2.2: Hydraulic Conductivity Function of a Goose Lake Clay.

The method presented in the study showed that the relationship between unsaturated hydraulic conductivity and suction for the wetting of an unsaturated soil can be measured. The method is proven to be convenient and could be performed on a variety of soil types. The authors conclude that this method will work reasonably for clays with degrees of saturated between 30 and 90 percent. Comparison of the measured and predicted values was found to be good. This good agreement has influenced the use of this method to be used by other researches to determine the unsaturated hydraulic conductivity.

The estimation of the hydraulic conductivity function of unsaturated clays using an infiltration column test was performed by McCartney, Villar and Zornberg (2007). In this study the researchers defined the unsaturated hydraulic conductivity function for a lean clay (CL) using the instantaneous profile method. In their paper they present various unsaturated hydraulic conductivity functions for other soils found in other researcher which is presented below in Figure 2.3. The hydraulic conductivity values that can be measured for different soils can vary over several orders of magnitude from 1.0E-14 to 1.0E-4 m/s.

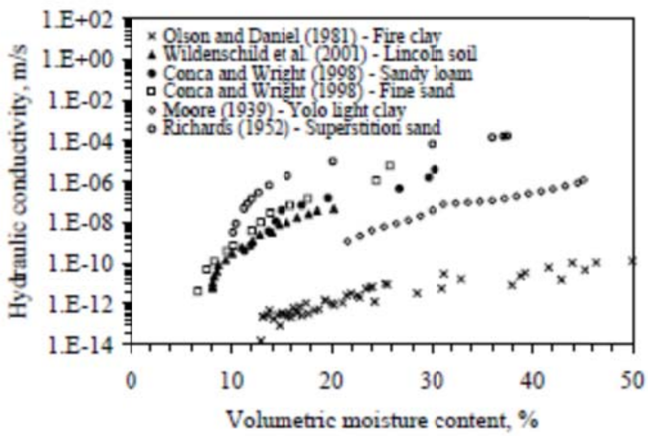

Figure 2.3: Hydraulic Conductivity Function for Various Soil.

In the study, the researchers used statistical models based on pore size distribution to predict the Kunsat function from the water retention curve. A commonly used Kunsat function model was used to predict the Kunsat function to the data by substituting the van Genuchten water retention curve model into the Mualem model which is presented below.

$$\frac{K(\theta)}{K_s} = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^b \left(\frac{\int_0^{\Theta} \frac{dx}{\psi^{2-r}(x)}}{\int_0^1 \frac{dx}{\psi^{2-r}(x)}}\right)^m$$

(Eqn. 2.14)

In the paper, the author outlines the calculations for the determination of the unsaturated hydraulic conductivity function from the results of the instantaneous profile experiment conducted. The instantaneous profile experiment performed in the study was an infiltration or wetting process. Time domain reflectometry (TDR) probes were used to gain moisture content measurements during the test. The gradient and suctions values were interpolated from the water retention curve. The experiment was set up using a 0.75m long and 203mm diameter PVC tube. The soil tested was a lean clay (CL) with a specific gravity of 2.71 and PI approximately equal to 12. The soil was compacted in the PVC tube at a 70% relative compaction. The saturated hydraulic conductivity for the clay was found to be 6.6E-6 m/s using a flexible wall permeameter. A constant water flow rate was applied to the top surface of the soil with an inflow rate of 8E-8 and 1.5E-7 m/s until steady state seepage was observed.

In the experiment, the instantaneous profile method data did not align perfectly with the steady state data because the water retention curve used to calculate the suction values only fits the infiltration data at high suctions. This plot is presented below in Figure 2.4.

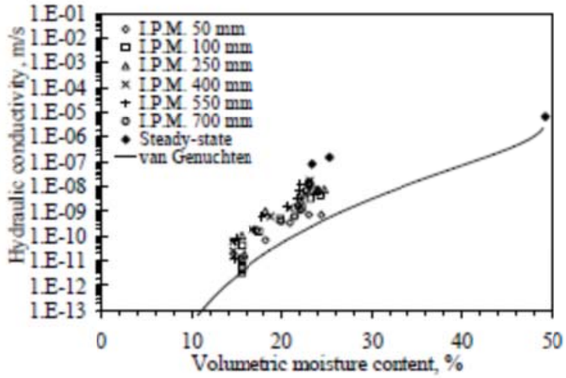

Figure 2.4: K Function Calculated by McCartney vs. Measured Data.

Some significant conclusions reported by the authors involved with the calculation of the Kunsat function from the transient and steady state infiltration data. The calculation of the Kunsat function can be affected by the use of the water retention curve to calculate suction values from measured volumetric moisture content values, the calculation of the gradient terms, and the fitting of the time series with smooth curves. The boundaries of the soil profile can have an effect on the Kunsat function. The authors noted that the only moisture measurements used excluded the lower 500mm of the soil profile for the steady state Kunsat function calculations. Also the Kunsat function is particularly sensitive to fluctuations in the suction and moisture content, which can cause some error in the gradient.

Research by Zhang and Fredlund was done to develop a direct method for the measurement of the unsaturated hydraulic conductivities (Zhang and Fredlund, 2009). In their paper titled "Wetting front advancing column test for measuring unsaturated hydraulic conductivity" they developed an experimental method using a large scale soil column test to simulate the flow of water in an unsaturated soil column. In the paper the researchers outline the main method used for measuring the unsaturated hydraulic conductivities which include the steady state method, the instantaneous profile method, and the parameter estimation method. The steady state method is performed by applying constant boundary conditions and has a limited measurement range. The parameter estimation method is performed by experimentally simulating and modeling the soil hydraulic conductivity curves or soil water characteristic curves. The experiment conducted in the study was the instantaneous profile experiment and the authors list some significant disadvantages to the test which are list below.

- The instantaneous profile test is often time consuming depending on the type of soil being testing, sample size, and suction range.
- A proper flow rate for soil wetting is difficult to choose. If the flow rate is too high, the gradually changing suction and water content profiles cannot be discerned. Recommended flow rates are from 0.2 to 5.0 cm^3/day.
- The accuracy of the test is related to the space between water content or suction measurement points. Theoretically, the closer the water content or section monitoring points are, the more accurate are the calculated unsaturated hydraulic conductivity values are.

The soil column test device was 120mm in diameter and 1000mm in height. Four theta probes where installed to measure the soil water content and four tensiometers were installed to measure the soil matric suction. The tensiometers used have a limited suction range of 0-90kPa. Various soil types were tested ranging from gravels (GW-GM), to sands (SC and SM), silts (ML) and clays (CL). Two types of tests were performed, a capillary rise test and an infiltration test. For the capillary rise test the water was ponded at the bottom of the sample and allowed to seep up into the soil profile. For the infiltration test, a constant water head was applied at the top of the soil column and allowed to seep down into the soil profile. These two experiments were performed on the soil types specified and the hydraulic conductivity curves are presented. The hydraulic conductivity curve for the lean clay (CL) is presented below in Figure 2.5. The Gardner (1958) curve fit was applied to the measured data.

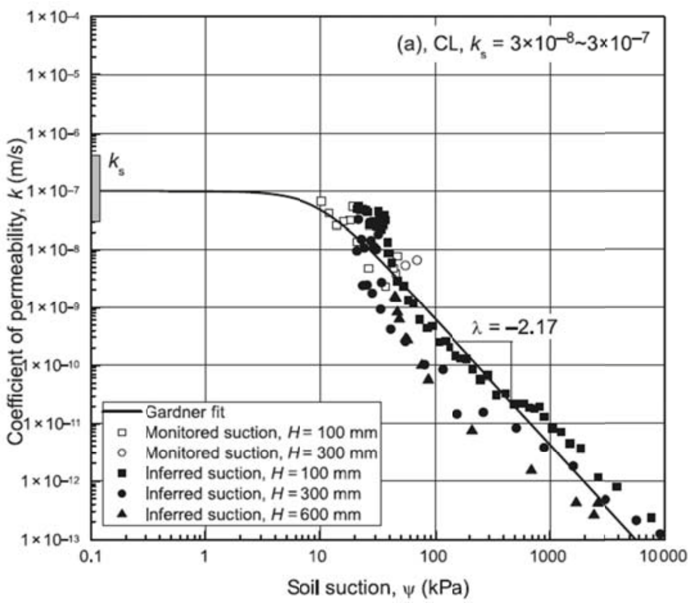

Figure 2.5: Hydraulic Conductivity Function Fit by Zhang and Fredlund.

The author also made a comparison of the unsaturated conductivity data to the process of wetting and drying of the soil. Since two experiments were conducted by the infiltration process and capillary process the data set were plotted to observe the impact of wetting and drying to the hydraulic conductivity. In Figure 2.6 below, Zhang and Fredlund show that the infiltration process produces lower hydraulic conductivity values at the same suction value.

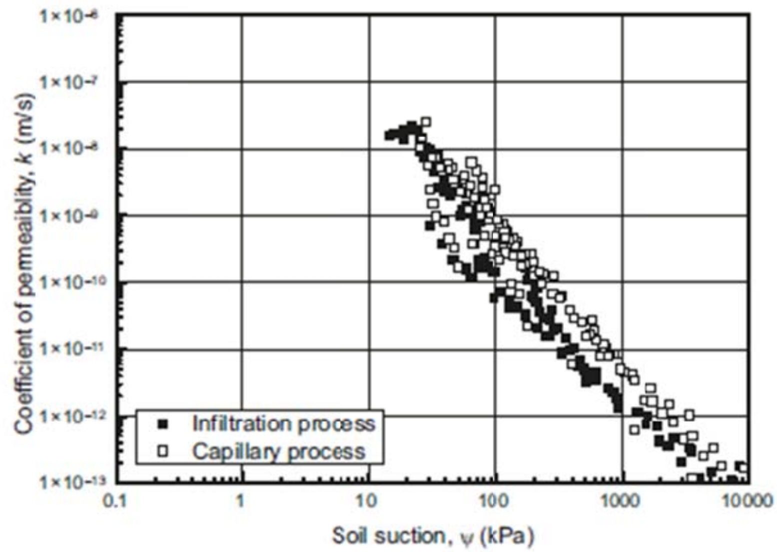

Figure 2.6: Trend of Hydraulic Conductivity Data for Wetting and Drying.

Through the experiments conducted, the researchers note the some significant features from the tests. The unsaturated hydraulic conductivities obtained are located in a log-linear hydraulic conductivity band. The upper hydraulic conductivity is about 5 to 10 times greater than the lower hydraulic conductivity at the same suction. A column length of 400 to 600m is recommended, taking into consideration factors such as sample disturbance, the wetting front advancing process, testing time, and data sufficiency. The authors note several series of unsaturated hydraulic conductivities can be obtained within 10 days using such a soil column test.

The hydraulic properties of two fine grained soils, similar to the soil types used in landfill covers were analyzed by Meerdink, Benson and Khire (1996). One objective of their study was to measure the unsaturated hydraulic conductivity functions for two fine grained soils (CL-ML and MH) under different compaction conditions. The instantaneous profile method was used to conduct the unsaturated hydraulic conductivity experiments. The soils were compacted in a apparatus device of 10.2cm in diameter and 21.3cm in length. To measure suctions and the water content at various points along the soil profile, tensiometers, thermocouples psychrometers, and time-domain reflectometry

(TRD) probes were installed. The tensiometers and thermocoupled psychrometers provided the capability to measure a suction range of approximately 0-7,600 kPa. A field experiment on the same soil tested in the laboratory was also done to analyze the correlation between the tests. Results from these experiments are shown below in Figure 2.7 for the two soil tested. Various Kunsat semi empirical curve fits were used to model the unsaturated conductivity of the data.

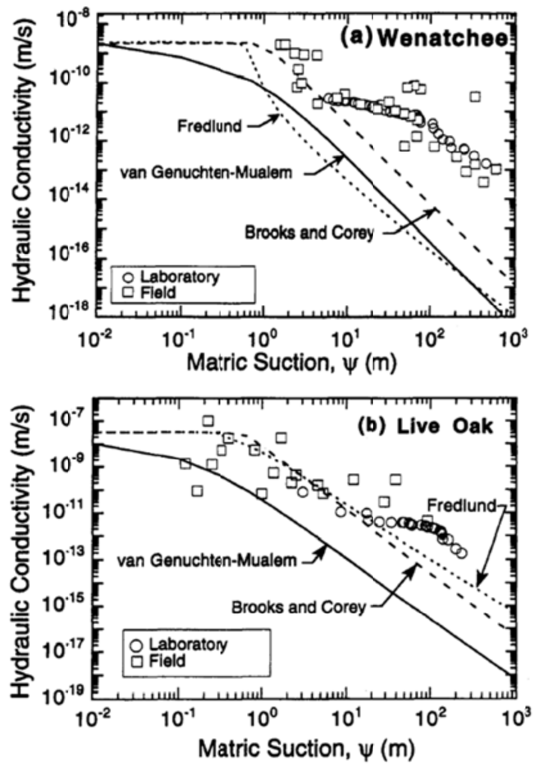

Figure 2.7: Hydraulic Conductivity Functions for a Wenatchee and Live Oak Soil.

Specimens of both soils were prepared using different compaction efforts using a standard and modified compacted techniques and prepared the soils at 3% above and below the optimum water content. The samples compacted dry and wet of optimum had the same dry density. The results of the samples being compacted wet and dry of optimum is shown below for the two soils tested in Figure 2.8. The results show a large contrast in hydraulic conductivity for water contents wet and dry of optimum and this contrast diminishes as the matric suction increases.

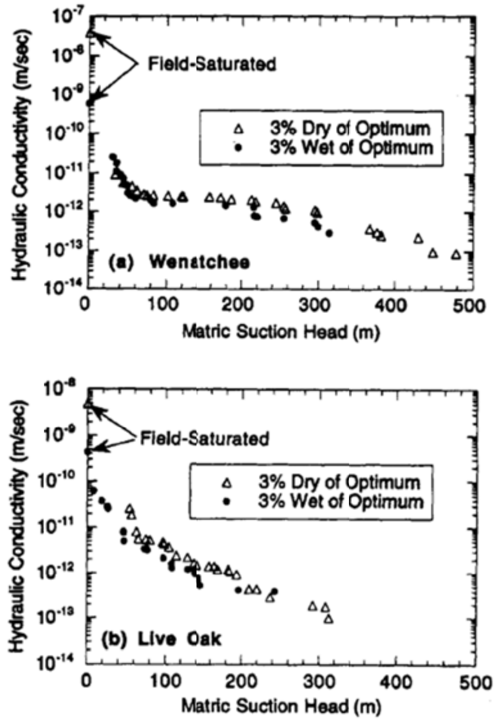

Figure 2.8: Hydraulic Conductivities at Various Compacted Water Contents.

The effect of compaction effort can be seen in the plot below in Figure 2.9. The saturated and unsaturated hydraulic conductivities for nearly all suctions for the specimens compacted with the modified proctor effort had hydraulic conductivities approximately one order of magnitude lower than the specimens compacted with the standard proctor effort. The authors believe that the specimens compacted with the modified effort had a lower hydraulic conductivities because compaction with higher effort reduces the frequency of large pores, reducing the void ratio and thus resulting in a lower hydraulic conductivity.

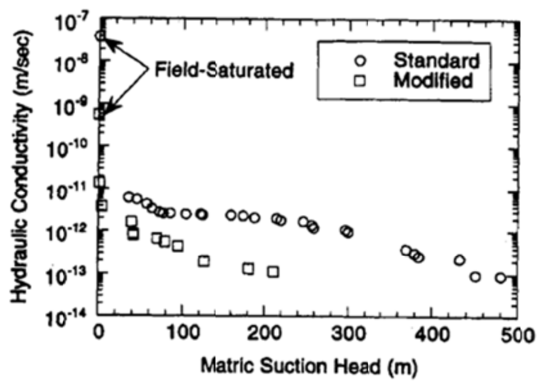

Figure 2.9: Hydraulic Conductivity at Various Compaction Conditions.

The research found a distinct difference between the desorption (drying) and sorption (wetting) curves when the unsaturated hydraulic conductivity is expressed as a function of suction. This same type of hysteresis effect can be seen in soil water characteristic curves. A soil undergoing desorption generally has a high water content than a soil undergoing sorption thus a soil undergoing desorption has a higher volumetric water content, a larger cross-sectional area for flow, less tortuous flow paths, and higher unsaturated hydraulic conductivity at the same suction. The results from the study showing the effects the hydraulic conductivity to the wetting and drying process is presented below titled Figure 2.10.

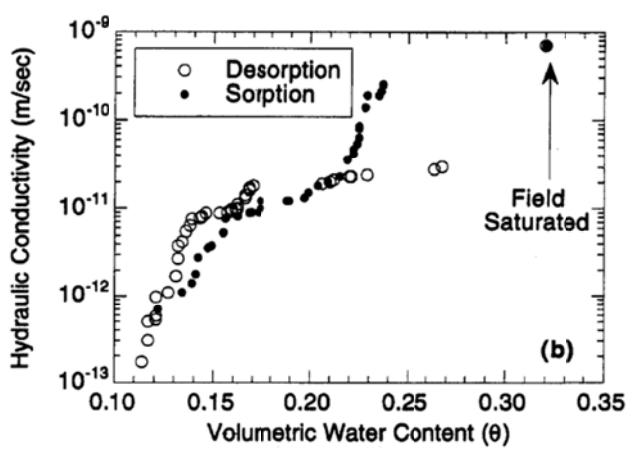

Figure 2.10: Hydraulic Conductivities by Meerdink et al. for Wetting and Drying.

An experiment using the instantaneous profile method was done by Vanapalli, Garga and Brisson (2007). There experiment showed the limitations of certain measurement devices which they used in their experiment. In their research, they developed a modified permeameter that was design and developed to determine the hydraulic conductivity for unsaturated nickel tailings using large size samples. In the study they were able to determine values for the unsaturated hydraulic conductivity with little scatter over a low suction range using the instantaneous profile method. This is largely due to the soil chemistry and the devices used to measure the water flow and hydraulic gradient. The flow was determined using Time Deflection Reflectometry (TDR) probes and manual water contents. The pore water pressures were measured by tensiometers. One reason why the unsaturated hydraulic conductivities are only limited to a low suction range may be due to the limitations of the measurement sensors. The tensiometers used could only measure with in a suction range of 0 to 85 kPa.

A study done by Krisdani, Rahrdjo, and Leong, compared direct measurement through the instantaneous profile method to current statistical models (2009). The objective of the study was to illustrate the applications of both direct and indirect methods in the determination of the unsaturated hydraulic conductivity. The soil types tested in the experiment were a sandy silt (ML) and a silty sand (SM). The instantaneous profile experiment conducted was a drying process that was performed on a sloped model. Tensiometers were used to measure the soil suction and the soil water characteristic curve was used to determine the soil water content. Conclusions of the study were that the instantaneous profile method and statistical methods could be used to obtain Kunsat function for the soils tested. They stated that these methods could be adopted if there is no direct measurement of the saturated coefficient of permeability. In the statically model used in the study the saturated hydraulic conductivity was off by an order of magnitude.

In Poland a study was done by Salwinski, Walczak and Skiefucha on the instantaneous profile method titled "Error analysis of water conductivity coefficient measurement by instantaneous profiles method" (2006). The study included the testing of four different soil types including a clay. The analysis included the average values of unsaturated hydraulic conductivity for a range of suction values of 9.81 to 981 kPa. The article also includes equations for the determination of the unsaturated hydraulic conductivity. In their analysis, they found that there was greater error from water content measurements at low water contents which can be reflected by the measurements taken from the TDR probes used to measure water content. The study recommended individual calibration of these sensors to increase the accuracy. Also, the average relative maximum error on the hydraulic conductivity for clays was higher than the other soil types tested, which were sand and silts. This plot is presented below in Figure 2.11.

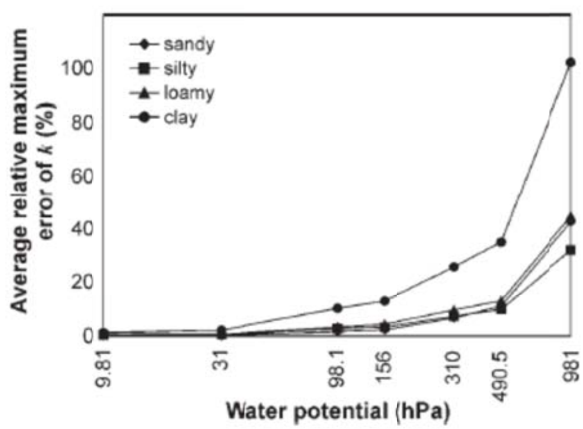

Figure 2.11: Average Error of Water Content Measurements made by TDR probes.

The instantaneous profile method is the most preferred method for determining the unsaturated hydraulic conductivity for fine grained soils. Based on the published work reviewed the instantaneous profile method is mostly used. This method works reasonably well for clays with degrees of saturation between 30 and 90 percent and has good agreement with predicted values (Hamilton, Daniel and Olson, 1979). The experiments done by other researchers have used various methods for measuring either the soil water content or matric suction or both over time. In some of the experiments reviewed TDR probes were used along with manual water contents. Suction was measured using tensiometers or thermocouples psychrometers. The use of measuring the water content and matric suction using TDR probes, tensiometers, or thermocouples is prone to limitations on their range of measurement and accuracy.

Many of the instantaneous profile experiments previously conducted used the soil water characteristic curve to interpolate water content and suction measurements. This method is performed frequently in unsaturated soil testing and is an acceptable means of interpretation. When the water content or suction was indirectly measured from direct measurements these measurements are made from empirical correlations. In some experiments such as the one performed by McCartney, Vilar, and Zornberg, their instantaneous profile method data did not align perfectly with the predicted results due to the use of the water retention curve. The authors noted that the Kunsat function can be affected by the use of the water retention curve to calculate suction and the calculation of gradient terms. This suggests that the indirect measurement made should be made from a well-established and accurate soil water characteristic curve.

The research done by Meerdink, Benson and Khireshowed showed that the unsaturated hydraulic conductivity can be affected significantly by its compaction conditions (1996). In the review of their research it can be concluded that when performing conductivity experiments for comparison that the entire sample be created and compacted at the same dry density and water content and using the same amount and type of compaction energy. The apparatus used for most instantaneous profile experiment is a rigid form and is typically cylindrical. PVC and clear Plexiglas tubing was the most common apparatus material probably due to the impermeability and rigidity. Data was compiled of the length and size of the apparatus used in each instantaneous profile experiment reviewed. This is presented in Table 2.1 below which also presents the length to width ratios. The average length to width ratio ranges from 2.5 to 5.

Table 2.1: Apparatus Length to Width Ratios of Published Instantaneous Profile Experiments.

Researcher	Length(cm)	Width or Diameter (cm)	L/W Ratio
Richards and Weeks (1953)	35	5.7	6.14
Hamilton, Daniel, and Olson (1979)	14.4	5	2.88
McCartney, Vllar, and Zornberg	75	20.3	3.69
Li, Zhang, and Fredlund (2009)	100	12	8.33
Li, Zhang, and Fredlund (2009) Recommended	50	12	4.17
Meerdink, Benson, and Khire (1996)	21.3	10.2	2.09
Vanapalli, Garga, and Brisson (2007)	40	20	2.00
Krisdani, Rahardjo, and Leong (2009)	200	40	5.00
Slawinski, Walczak, and Skierucha (2006)	5	5.5	0.91

Effects of Cracks to the Unsaturated Hydraulic Conductivity

The effects of cracks on the unsaturated hydraulic conductivity are still not fully understood. There is very limited research available on the behavior of soils with cracks. Cracks are also called tensile cracks (or soil fracturing) and desiccation cracking. Tensile cracks develop when there are external loads that result in tensile stresses in the exposed soil surface, such as those that can occur on the crest of a landslide or a vertical cut. When these cracks filled with water, it can lead to further instability (Mitchell and Soga, 2005).

Crack formations in fine grained soils caused by the evaporation process are called desiccation cracks. Evaporation causes a reduction in the pore water pressure and an increase in effective stress (Mitchell and Soga, 2005). Throughout the evaporation process the soil grains get pulled closer together and from this process the crack is formed. The size of the crack depends of the tensile strength of the soil, the type and amount of fine grained material, water content, soil density, and elastic properties. The physics and mechanics behind the process of crack formation will not be discussed in this study.

Understanding hydraulic conductivity behavior for cracked fine grained soils could be beneficial when evaluating soil used for contaminant barrier systems in landfills, and for sloped structures. In these type of engineered systems, advanced analysis typically incorporates parameters or functions of the soil unsaturated hydraulic conductivity. To develop a good understanding of the hydraulic conductivity for cracked soils, a review of current literature on the hydraulic conductivity and the effect of cracks is conducted. This review will also aid in the experimental design for cracked instantaneous profile test that are conducted in this study.

An article titled "Desiccation Induced Cracking and its Effect on the Hydraulic Conductivity of Clayey Soil from Iran" by Rayhani, Ynaful and Fakher pertains heavily to this study (2007). The article describes the effect of desiccation induced cracking on the hydraulic conductivity of clay soils involving the testing of four different clay soils. Each soil was compacted into sample tubes using a standard proctor mold at 95% of the maximum compaction, at a moisture content of 2% above optimum. The samples were initially tested for the saturated hydraulic conductivity and cycled through periods of wet and dry conditions. The conditions for the wet and dry periods were taken from typical atmospheric conditions in Iran. The researchers provide an analysis of the effects of the cracking to the hydraulic conductivity, volume change, and self-healing.

The results of the tests indicated that the effects of the cracks in fine grained soils affected the hydraulic conductivity of the soil. The authors found that the hydraulic conductivity increased with an increase in number of wet and dry conditions and the presents of cracks. This variation in hydraulic conductivity was on the order of two orders of magnitude. A plot from the article is presented below in Figure 2.12. The researchers concluded that this phenomenon is generally referred to as self-healing and is believed that the different changes in hydraulic conductivities are associated with the self-healing processes that affect the various soil types by different degrees.

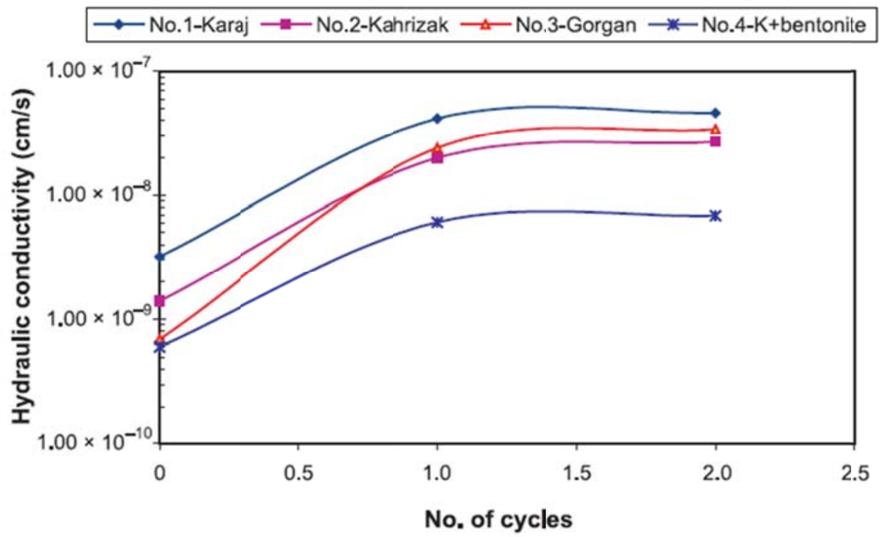

Figure 2.12: Hydraulic Conductivity records for Different Cycles of Drying and Wetting.

Another study titled "Infiltration Tests on Fractured Compacted Clay" by McBrayer, Mauldon, Drumm, and Wilson investigated the transient hydraulic response of clay fractures during infiltration tests and the extent of preferential flow paths in compacted clay (1997). In this study, infiltration tests were performed on a kaolinite clay soil. Samples were compacted into molds 10.2 and 15.2cm in diameter and 5.1 cm in thickness. Three sample sets were created, one uncracked, and two cracked sets. The cracked surfaces for each set of soil samples were formed either by desiccation cracks from cycles of wetting and drying, and or were formed by cycles of freezing and thawing. The infiltration tests performed used a Mariotte device to maintain a constant head of 5cm of red dye solutions on the sample. The rate of infiltration was recorded with time until steady state flow conditions were obtained. After infiltration, the samples were allowed to dry and then cut into slices. The slices were then recorded with a camera and evaluated using the dye to qualitatively evaluate the degree of infiltration.

Some significant findings from this study are as follows. Desiccation and freeze/thaw induced cracks appear to heal upon rehydration, but re-open on subsequent cycles of desiccation or freeze/thaw. The infiltration of a cracked clay has an initial transient stage during which the preferential flow paths play a dominant role. Although cracks appear to be healed, they still contribute to flow. The authors note that these considerations could have an effect on judging the quality and integrity of compacted clay barriers. Due to clay swelling and closing of fractures, flow calculations based on hydraulic conductivity determined for steady-state conditions may underestimate flow during the dynamic stages of infiltration.

A study done by Yesiller, Miller, Inci, and Yaldo on desiccation cracking behavior explained the effects of cracking to characteristics of fine grained soils (2000). This article indicates that desiccations cracks are formed as a result of water loss to the atmosphere. The drying causes suction to develop in the soil, increasing the effective stress. The volume of soil begins to decrease and cracks develop in the soil mass. One significant finding from their study was that the size of the cracks created from cycles of wetting and drying was greater when the soil was compacted at moisture contents above the optimum moisture content as compared with soil compacted at moisture contents less than the optimum moisture content. The extent of cracking is a function of both the amount of water in the soil at the onset of drying and the suction attained during drying.

Field studies have also been conducted demonstrating the effects of cracking on the hydraulic conductivity. In Taiwan, Lui et al. performed infiltration tests on cracked paddy field soils. These soils became cracked from drainage and exposure to sunlight after two days of rain fall (2003). Intact laboratory infiltration tests were conducted on paddy soil samples to compare with field observations. The results showed an increase in crack size when soils are saturated which temporarily increases the infiltration rate. When the cracks initially fill, the soils swell and this also affects the infiltration rate. This swelling of the soil closes or heals the cracks. During this healing process the researchers observed that the clay particles disperse and redeposit themselves on the surface of cracks. This effect significantly reduces the infiltration rate.

Review of these studies offers many considerations pertinent to the experimental design for this paper. Experiments performed by Rayhani et al., involving measurements of the hydraulic conductivity after cycles of wetting and drying showed that an increased in the number of cycles caused in increase in crack volume and an increase in the hydraulic conductivity (2007). McBrayer et al. showed evidence that there is an initial stage of infiltration for cracked soils. During this initial stage, the crack tends to heal, while it still contributes to flow (1997). The experiments done by Yesiller et al. showed that the size of the crack created from cycles of wetting and drying was greater when the soil is compacted wet of optimum (2000).

CHAPTER 3: SOIL CHARACTERIZATION AND EXPERIMENTAL DESIGN

Soil Characterization

The soil used for the National Science Foundation (NSF) cracked clay research project and this study is an Otay clay from San Diego, California. A clayey soil was chosen for this study because these soils are susceptible to cracking which is the focus of the NSF study. The soil sample was characterized by determining the classical index properties and the soil type using the tests listed in Table 3.1 below. Other tests were performed to determine the swell potential, water retention, hydraulic conductivity, and consolidation characteristics. The soil tests shown in Table 3.1 were performed in accordance to the ASTM standard specified.

Table 3.1: ASTM Standards for Soil Tests Performed.

Soil Test	ASTM Specification
Sieve Analysis and Hydrometer	ASTM D 422-63: Standard Test Method for Particle Size Analysis of Soils
Atterberg Limits	ASTM D 4318-00: Standard Test Methods for Liquid Limits, Plastic Limit, and Plasticity Index of Soils
USCS Classification	ASTM D 2487-00: Standard Practice for Classification of Soils for Engineering Purposes (USCS)
Specific Gravity	ASTM D 854-02: Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer
Standard Proctor Compaction Test	ASTM D 698-00: Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort
Consolidation	ASTM D 2435-04: Standard Test Methods for One Dimensional Consolidation Properties of Soils Using Incremental Loading
Saturated Coefficient of Hydraulic Conductivity	ASTM D 5084-03: Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter
Expansion Index	ASTM D 4829-03: Standard Test Method for Expansion Index of Soils
Swell Potential	ASTM D 4546-03: Standard Test Methods for One Dimensional Swell or Settlement Potential of Cohesive Soils

Index Properties:

The gradation plot for the San Diego soil is presented below in Figure 3.1. The particle gradation was determined by performing a sieve analysis and hydrometer analysis on the soil. The percentages of Sand, Gravel and Clay are summarized below:

% Gravel = 2%
% Sand = 63%
% Clay = 35%

D10 = 0.0045mm
D30 = 0.06mm
D60 = 0.18mm

$$Cu = \frac{D60}{D10} = 40 \quad \text{(Eqn. 3.1)}$$

$$Cc = \frac{D30^2}{D10 * D60} = 4.44 \quad \text{(Eqn. 3.2)}$$

The Atterberg limits were determined for the soil and are presented in Table 3.2 below.

Table 3.2: San Diego Soil Atterberg Limits.

LL	40.85%
PL	17.73%
PI	23.12%

Based on the result of the gradation test and Atterberg limits, the soil is classified as a Clayey Sand (SC). The soil was described as fine grained and brown in color.

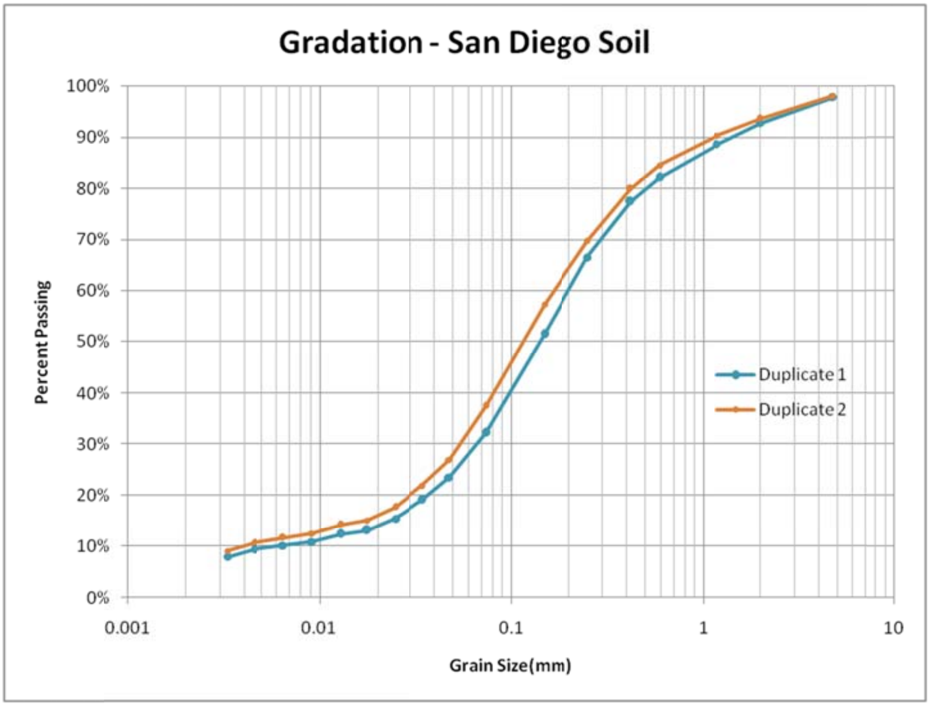

Figure 3.1: Gradation Plot for the San Diego Soil.

The specific gravity of the soil solids for the Sand Diego clay is 2.72.

Gs = 2.72

A standard proctor test to determine the maximum density and optimum moisture content was also performed. The compaction curve is presented in Figure 3.2. The maximum dry density and optimum water content are as follows:

Maximum Dry Unit Weight = 108.7 pcf
Optimum Water Content = 17.4%

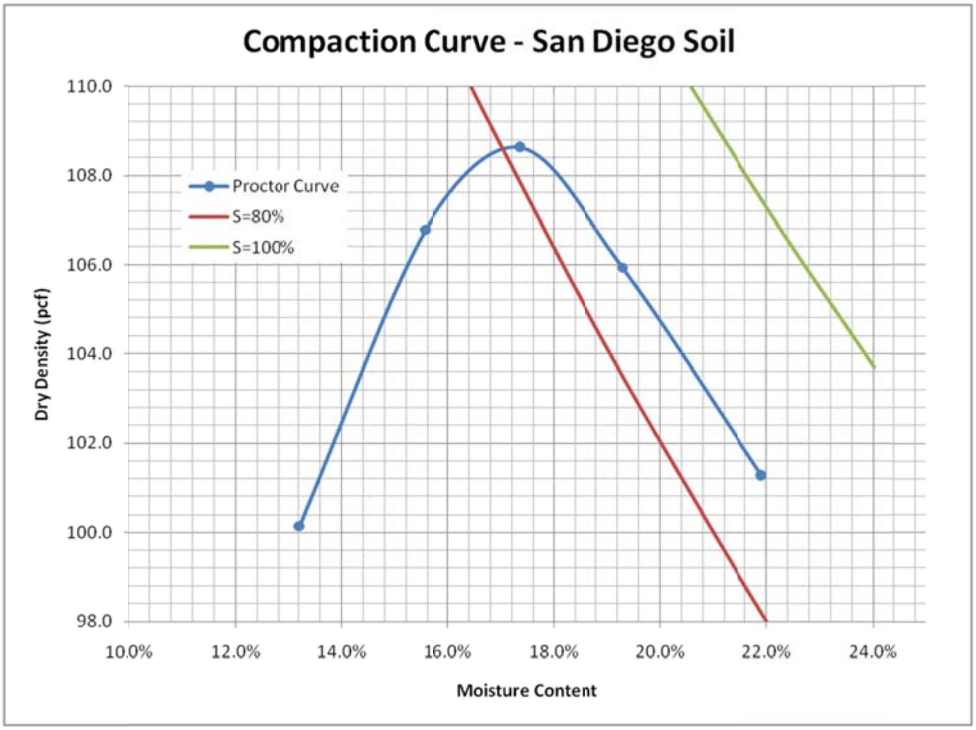

Figure 3.2: Compaction Curve for the Sand Diego Soil.

Consolidation Tests:

A series of consolidation tests were performed on the Sand Diego clay. The consolidation tests were performed at pressures of 12, 25, 50, 200, 400, and 800 kPa. With the consolidation results the stress strain curve was determined for the sample. The stress strain curve for the Sand Diego clay is presented in Figure 3.3 below. The preconsolidation pressure was calculated using the Casagrande correction method to be approximately 220 kPa.

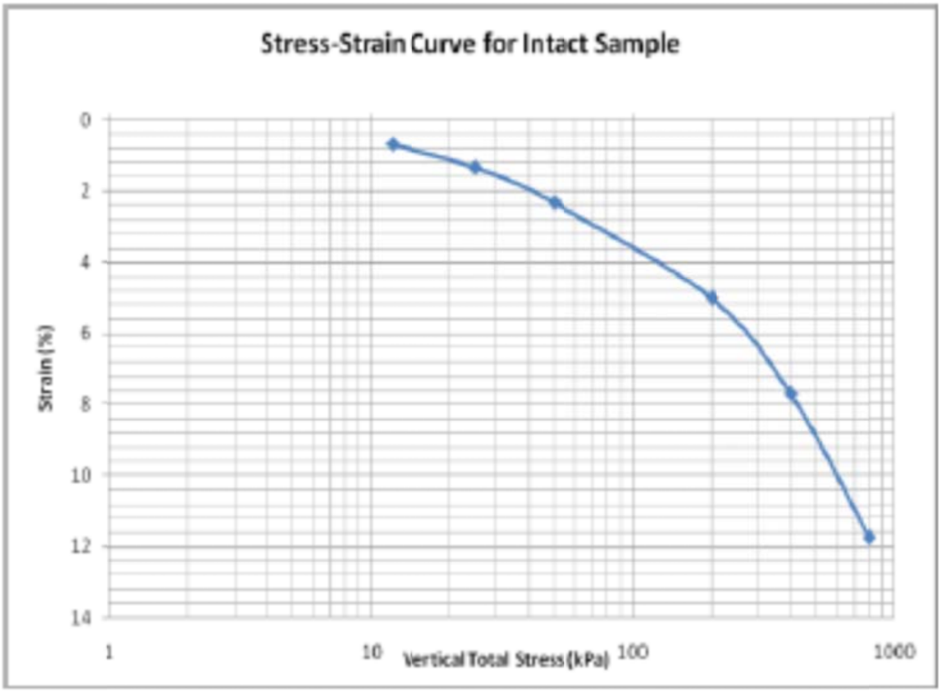

Figure 3.3: Stress Strain Curve for the San Diego Clay.

Swell Index:

To determine the expansion potential for the Sand Diego soil, an expansion index test and various swell tests were performed. The results from the expansion index are presented in Table 3.3 below. Note that the Expansion Index (EI) test was performed at a saturation of 40%. The AZ expansion index was correlated from Figure 3.4 in the following.

Table 3.3: Expansion Index Results for San Diego Soil.

EI meas	106.8
ASTM EI%	68.0
EI(AZ) %	7.75

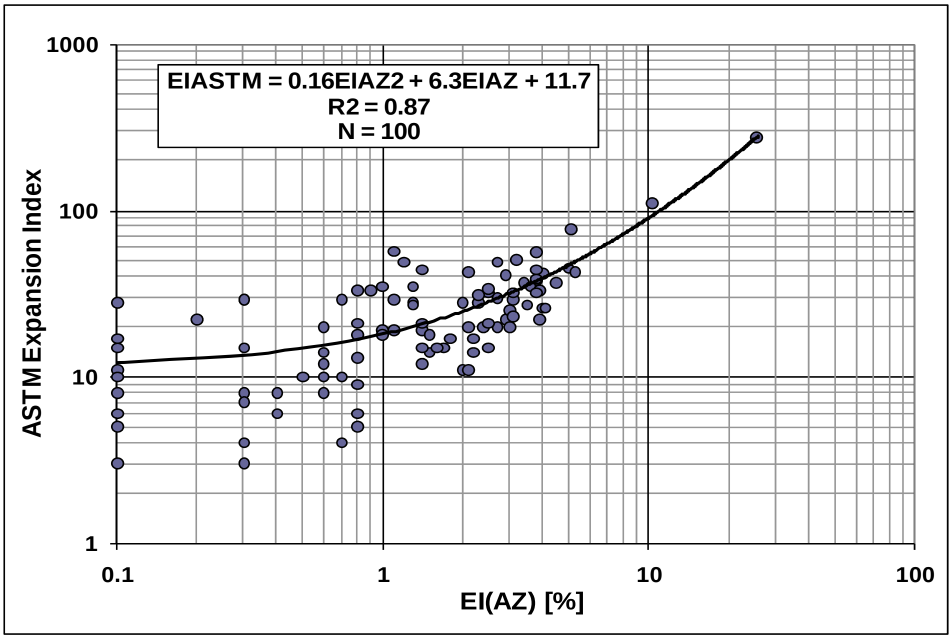

Figure 3.4: Correlation Between ASTM EI and AZ EI.

Free Swell Tests:

The percent swell presented in Table 3.4 below was found using the free swell method (Method A ASTM D 4546-03). For some of the sample the swell pressure was also determined. These swell tests were performed using a consolidometer. Swell determined using the consolidometer indicated an average swell of 4 to 5 % for relative compactions greater than 95%.

Table 3.4: Free Swell Results for San Diego Soil.

Swell Test No.	Compaction Specification (%)	Moisture Content	Saturation (%)	Initial Loading Pressure kPa	% Swell	Swell Pressure kPa
3	89.10	0.18	64.99	3.19	5.078%	64.95
4	89.55	0.174	63.57	3.22	2.391%	56.46
5	89.54	0.174	63.54	5.07	2.616%	NA
6	94.18	0.179	73.90	3.23	6.441%	117.66
7	94.16	0.179	73.87	3.26	4.062%	NA
8	94.56	0.177	73.83	3.19	5.281%	108.43
9	96.88	0.177	78.59	3.29	3.785%	141.95
10	95.85	0.156	67.37	3.19	4.672%	NA
11	99.24	0.185	87.63	3.23	3.422%	NA
12	100.37	0.172	84.08	3.23	6.239%	NA
13	99.02	0.188	88.52	3.23	5.535%	NA

The swell pressure was also determined using a direct shear apparatus configured for a free swell test using the procedures outlined in ASTM D4546-03. The swell pressures from the free swell method are presented in Table 3.5. The samples for the swell results in the following were performed at a relative compaction of 98% and at -2% from the optimum water content.

Table 3.5: Swell Pressure from Free Swell Method.

Test No.	Setting Load (N)	Swell Pressure (kPa)
14	5	45
15	25	40
16	145	0
17	125	0

Average Swell Pressure	42.5

Constant Volume Swell Tests:

The swell pressure was also determined using the direct shear apparatus configured for a constant volume swell test using procedures outlined in ASTM D4546-03. The swell pressures from the constant volume method are presented in Table 3.6. The samples for the swell results in the following were performed at a relative compaction of 98% and at -2% from the optimum water content.

Table 3.6: Swell Pressures from Constant Volume Method.

Test No.	Swell Pressure, kPa
18	14
19	15
20	18

Saturated Hydraulic Conductivity Tests:

The saturated hydraulic conductivity of the San Diego soil was determined by using a triaxial apparatus to run a saturated hydraulic conductivity test. The soil was compacted at 98% relative compaction and at optimum water content. The average saturated hydraulic conductivity was calculated to be 1.33 10^8 m/s. Table 3.7 below presents the saturated hydraulic conductivity for the three tests performed.

Table 3.7: Saturated Hydraulic Conductivity Values.

Test No.	Ksat (m/s)	Avg. Ksat (m/s)
1	1.07E-08	1.33E-08
2	8.68E-09	
3	2.07E-08	

Water Retention Tests (SWCC):

The soil water characteristic curve (SWCC) was determined from the San Diego soil. The SWCC plot for the soil is presented in Figure 3.5 below. The points on this plot were taken from instantaneous profile experiments where both water content and matric suction was measured. SWCC curves were fit to the data points using the van Genuchten (1980) equation (Zapata, 1999). The Fredlund and Xing (1994) and van Genuchten (1980) SWCC equations along with the description of the fitting parameters is presented below in Table 3.8. The Fredlund and Xing SWCC model was not used and not fit to the data.

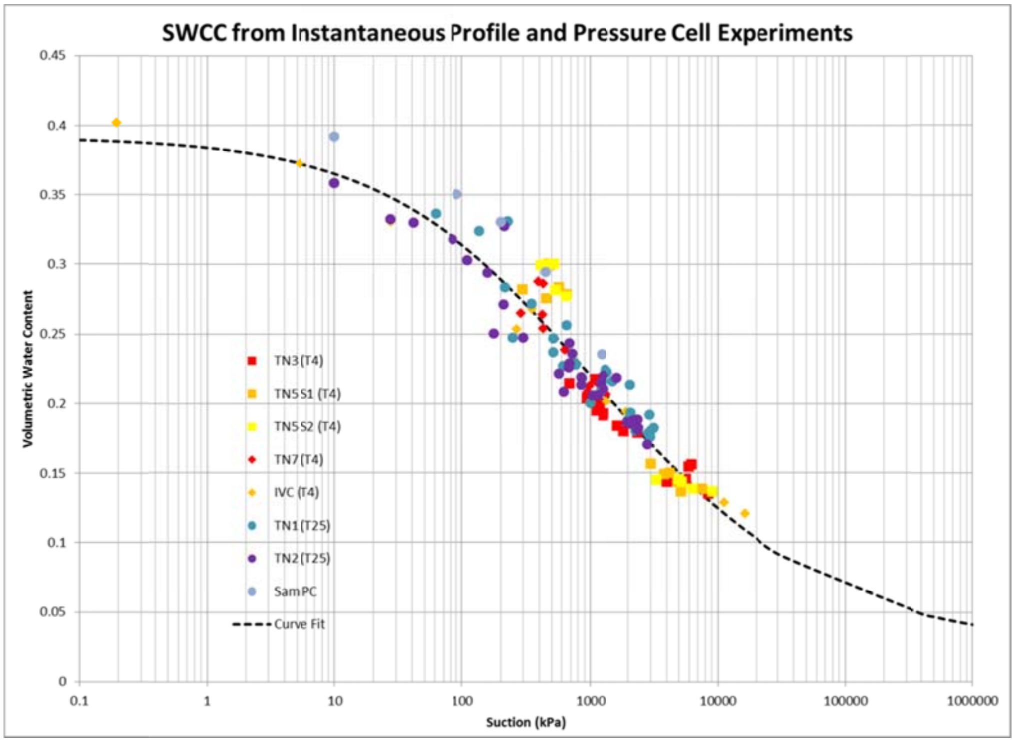

Figure 3.5: SWCC for the San Diego Soil.

Table 3.8: SWCC van Genuchten Fitting Parameters.

Fitting Parameters	
a	602.191
b	0.547
c	0.747
θr	0.023
θsat	0.392

Fredlund and Xing (1994) SWCC Equation:

$$\theta w = C(h) * \left[\frac{\theta s}{\left[\ln\left(exp(1) + \left(\frac{h}{a}\right)^{b} \right) \right]^{c}} \right] \quad \text{(Eqn. 3.3)}$$

$$C(h) = 1 - \frac{\ln\left(1 + \frac{h}{hr}\right)}{\ln\left(1 + \frac{10^6}{hr}\right)} \quad \text{(Eqn. 3.4)}$$

Van Genuchten (1980) SWCC Equation:

$$\theta w = \theta r + \frac{\theta s - \theta r}{\left[1+\left(\frac{h}{a}\right)^{b}\right]^{c}} \qquad \text{(Eqn. 3.5)}$$

Variables and parameters:

θw: Volumetric water content.
θs: Saturated volumetric water content.
a: Soil parameter related to the air entry value.
b: Soil parameter related to the rate of water extraction.
c: Soil parameter related to the residual water content.
hr: Soil parameter related to the residual water content (kPa).
θr: Residual volumetric water content.
h: Height of water in cm.

Using the SWCC for the soil sample, the air entry value and residual suction values were determined. The parameters are provided below.

Air Entry Value = 20 kPa
Residual Suction = 20,000 kPa

Experimental Design

The objective of this experiment is to analyze the effects of air voids and cracks on the unsaturated hydraulic conductivity. To analyze the hydraulic behavior of the soil, separate experiments were used to test the intact and cracked conditions using the instantaneous profile method. This analysis was done by comparing the hydraulic conductivities of the intact and cracked conditions using similar experiments. Numerous methods for determining the unsaturated hydraulic conductivity have been presented for the intact condition. The challenge is determining suitable methods for measuring the unsaturated coefficients of permeability for the cracked conditions.

The same soil was used for all instantaneous profile experiments and other experiments performed in this study. The soil used was obtained from San Diego and its properties were described in the previous section. The soil density was maintained to be the same for each experiment by using the same compaction of 98% of a standard proctor test. All instantaneous profile experiment samples were compacted in layers in the sample tubes to maintain a uniform dry unit weight. The height of each compaction layer lift was kept at 1.5 inches. The interface between each compaction layer lift was scarified to allow for good contact between layers in general agreement with procedures used for standard proctor test sample preparation. Effort was taken to keep the properties of the soil consistent in order for the results from each experiment to be comparable.

Details for the seven experiments conducted for this study are summarized in Table 3.9 below. Each individual instantaneous profile experiment was designed to analyze a different suction range for the intact conductivity function or a different aspect of the way water infiltrates through a cracked section. Seven experiments titled Test Numbers 1 through 7 are titled accordingly. Each experiment includes separate samples which vary in each experiment. In Table 3.9, the test number along with a description of the experiment is presented.

Table 3.9: Summary of Instantaneous Profile Experiments.

Test Number	Intact or Cracked	Method	Appratus Length	Number of Soil Sections	Experiment Description
Test No. 1	Intact	Trial	36"	4	Volumetric moisture probes installed.
Test No. 2	Intact	Trial	36"	4	Duplicate of Test No. 1
Test No. 3	Intact	Duplicate	9"	2	
Test No. 4	Cracked	Method B	9"	2	Two sets with different number of horizontal cracks.
Test No. 5	Cracked	Method C	9"	2	Two set of different crack widths.
Test No. 6	Cracked and Intact	Method A	9"	1	
Test No. 7	Intact	Duplicate	9"	2	Lower suction range than TN3

Intact Instantaneous Profile Experiments

To determine the intact unsaturated hydraulic conductivity the instantaneous profile experiment was used. The results of the intact experiments were used for comparison purposes with results for cracked soils. Two different types of experiments were performed to determine the intact unsaturated hydraulic conductivity for the soil. The first instantaneous profile experiments are titled Test Number 1 (TN1) and Test Number 2 (TN2), which were trial experiments used to provide information on the accuracy and quality of the methods used for measurement and the overall experiment performance. Test Number 3 (TN3) and Test Number 7 (TN7) were also intact instantaneous profile experiments. These experiments were designed from observations and problematic issues encountered in TN1 and TN2 that could be improved. Some improvements included changes to the sampling methods, testing procedures, and the general method used. The changes and improvements made for TN3 and TN7 from TN1 and TN2 are discussed in Chapter 5. The changes made were significant. For TN3 and

TN7, the experiment included duplicate samples that could be sampled at different time periods. The following sections present the experimental design of the instantaneous profile experiments for the intact condition.

Test Number 1:

Test Number 1 (TN1) was an instantaneous profile experiment using a long soil column with four different sections of different water content. The test tube was split into equal sections for which soil was to be compacted at different water contents. Each water content was chosen for each section based on the overall suction range to be analyzed and the desired hydraulic gradient. The water contents chosen gave suction values that varied over a broad range which was desired for this experiment. The test sample is placed in the horizontal position and the soil is allowed to equilibrate. The water content was recorded over time by taking manual water content samples from the soil inside the test tube and from the volumetric moisture probes. The matric suction was measured at the same locations for which manual water contents are taken and the suction was measured using filter paper tests. Typically sampling events occur every 28 days and the results were recorded.

Test Number 2:

Test Number 2 (TN2) was a duplicate of TN1. Test conditions for TN2 were the same as TN1, including the sectional water contents, sampling methods and time periods, and test set up. The only difference in the TN2 experiment was volumetric moisture probes were not used. The primary purpose of TN2 was for manipulation/reconfiguration of the experiments. At the beginning of this experiment it was thought that if the flow in the samples was too slow, TN2 would be used to accelerate the infiltration process by introducing water into the sample. TN2 was also used to check the reproducibility of the results from the experiment.

Test Number 3:

The instantaneous profile experiments TN1 and TN2 were initiated prior to the experimental design of Test Number 3 (TN3). Observations from TN1 and TN2 were based on the results obtained and the method and procedures used. From these results, some scatter was observed and the movement of water or change in water content at each measurement points was very slow. To improve the accuracy and reliability of the results, a new test methodology was used for TN3. The disadvantages of TN1 and TN2 and the improvements of TN3 are presented in Chapter 5.

Test Number 3 was an instantaneous profile experiment that used only two soil sections of different water content. This allowed for improved control over the suction gradients. The apparatus for TN3 was shorter than that used for TN1 and TN2 since only two soil sections were used. The methodology for TN3 involved creating 6 duplicate samples with the same soil conditions at the same time and then completely destroying the sample specimens for sampling at different time periods. This duplicate method allowed for the sample specimens to be completely destroyed so the measurement of water content was more accurate and representative. Also the matric suction was measured using filter paper tests. Filter paper was placed in between soil compaction layers and were removed and measured during the sampling events. The sampling events were performed at various time periods with increasing time between sampling events. Typical sampling time intervals used were 25, 50, 75, 100, 150 and 300 days.

Test Number 7:

Test Number 7(TN7) used the same test methodology as TN3. Test Number 7 was an instantaneous profile experiment with a lower target suction range for which unsaturated hydraulic conductivity was determined. This was done to gain a wider range of suction values for the hydraulic conductivity function for the intact condition. To gain conductivity values in a lower suction range lower initial water contents were used for TN7 than used in TN3.

Cracked Instantaneous Profile Experiments

The objective of the cracked instantaneous profile experiments was to measure the unsaturated coefficients of permeability for the cracked condition. These experiments differed from the intact experiments in that the samples were prepared with cracks or air voids. Different methods were proposed to simulate and measure the infiltration of water through a cracked matrix. The determination of the cracked unsaturated hydraulic conductivity function may comprise of a combination of the cracked methods presented. Experiments include different test method that varied the orientation and direction of the cracks with respect to the soil profile. These experiments allowed for the anisotropy and crack orientation effects to be considered. To analyze the aspects of how water flows through a soil sample with that experienced in the field, three methods were used to simulate direction of the water flow with respect to the crack orientation or direction. Figure 3.6 below presents the three methods and their relation to the moisture flow.

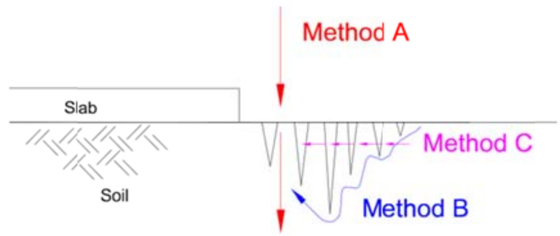

Figure 3.6: Method Flow Directions.

Method A simulated the condition when water enters the cracked surface from the vertical direction and then infiltrates into the soil. This would simulate the field condition where the soil was continually being irrigated and rained on. Method B simulated the condition when the water seeps through the soil either around the cracks or transfers through the crack by evapotransfer. This would simulate horizontal migration or seepage of water through a soil profile. Method C simulated the water infiltration through the crack itself. This method considered the effects of air space within a crack and water movement from one side of a crack to the other side. Each method measured a different way water flows through a cracked matrix with respect to the direction of the water flow and the crack orientation. The three methods that were included in this study are listed below.

Cracked Instantaneous Profile Methods and Test Number:

Method A: Vertical Infiltration (Test Number 6)
Method B: Horizontal Infiltration (Test Number 4)
Method C: Single Crack Infiltration (Test Number 5)

Test Number 4:

Test Number 4 (TN4) uses Method B where the crack orientation was perpendicular to the soil profile and the direction of the flow of water through the sample. This experiment was designed to observe the possible tortousity effects of having cracks that divert or render the water movement through the soil. To consider this effect and measure the hydraulic conductivity for this type of simulation two experiments were conducted with a different number of perpendicular cracks which may create different lengths in flow paths. With this experiment, the impact of the number of cracks from one sample set to another and for comparison to results for intact samples.

This method was conducted using procedures similar to those used for TN3 using the duplicate method so samples could be completely sampled and destroyed at desired time periods. The sample was compacted into cylindrical tubes with two soil sections of different water content. The water contents were chosen to provide the desired suction range and hydraulic gradient. The matric suction was measured using filter paper tests. Filter paper sandwiches were placed between compacted soil layers and were removed and measured during each sampling event. The sampling events were performed at various time periods with increasing time between sampling events. The cracks were cut into the soil profile using a circular saw after the soil was compacted in the apparatus tubes. Each sample was prepared so cracks extend from the side of the sample tube. The crack volume for each sample set was determined. Both sample sets had a crack volume ratio similar to Method A, but one sample had significantly more cracks cut into the tube. Figure 3.7 below presents the two crack configurations for Method B.

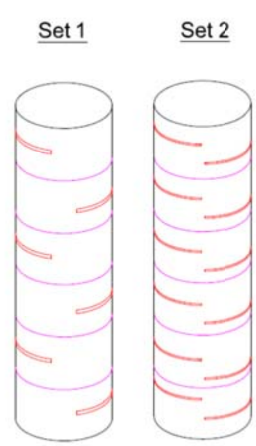

Figure 3.7: Method B Crack Configuration.

Test Number 5:

Test Number 5 (TN5) used Method C for a condition in which a single crack existed horizontally in the middle of the soil profile. This method was used to analyze the interface of a single crack and the air-water-vapor transfer that occurs at this interface. The conductivity that is calculated over the air gap represents a lower limit of the hydraulic conductivity and may represent the conductivity of evapotransfer. A special procedure was used to create the crack in the middle of the tube. This procedure involves compacting a soil section into half of a sample tube. Soil plugs from two half tubes were then extruded into a sample tube from opposite ends. The soil plug sections were carefully pushed together so that a small air gap remained in the middle of the tube at the desired width. Two sample sets, Set 3 and Set 4, with air gaps of 1/8' and 1/4" respectively were prepared.

This method was conducted using procedures similar to those used for TN3 using the duplicate method so samples could be completely sampled and destroyed at desired time periods. The samples were compacted into cylindrical tubes in layers at two different water contents. The water contents were chosen to provide the desired suction range and hydraulic gradient. The matric suction was measured using filter paper tests. Filter papers were placed between soil compaction layers and were removed and measured during each sampling event. These sample tubes were stored in an environmental chamber to maintain moisture contents. Figure 3.8 below presents the configuration for Method C.

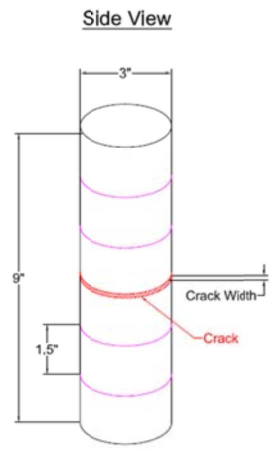

Figure 3.8: Method C Configuration.

Test Number 6:

Test Number 6 (TN6) incorporated Method A where the cracks were located at the top of the sample. Water was added to the top of the tube where the cracks extended into the sample and provided a path for water to infiltrate into the sample. This method used a duplicate intact sample in order to compare results and observe the impact of the cracks on the hydraulic conductivity. The intact duplicate sample was needed because no permeability measurements had been taken using a method where water infiltrated vertically downward into the sample. All samples for TN7 were created in the same manner using the same procedure. For the cracked samples, the cracks were formed using cracked configuration used in previous testing related to this study by driving a wedge into the soil. The sample specimen were prepared and compacted in layers at a single water content which was chosen to provide results within the desired suction range. The water content was the only parameter measured, and it was measured at two locations using volumetric moisture probes. The matrix suction was determined using the relationship from the SWCC for the soil. Each cracked and intact test was measured continuously until equilibrium was achieved.

CHAPTER 4: LABORATORY TESTING OF UNSATURATED HYDRAULIC CONDUCTIVITY

Introduction

The seven planned instantaneous profile experiments titled Test Nos. 1 through 7 were conducted at Arizona State University. Except for two of the samples, samples from each experiment were stored in a controlled environment using an isolation or environmental chamber located in the basement of ISTB2 at ASU. The temperature of the environmental chamber was maintained at 4 ^{o} C plus or minus 2 ^{o} C. For the first 175 days of run time, experiments TN1 and TN2 were stored in a lab area which has an approximate temperature of 25 ^{o} C. Effort was taken to ensure the samples encountered minimal disturbance by not moving the samples and keeping the surrounding environment at a constant temperature.

The soil conditions for each instantaneous profile experiment was keep the same. All samples were compacted at a density of 98% of the maximum density using Method A of a standard proctor test. This was done to eliminate any effects to hydraulic conductivity related to mass volume changes. The properties of the soil used in this study are presented in Chapter 3.

This chapter presents the results of each instantaneous profile experiment. For each experiment the set- up conditions and procedures, apparatus type, sampling procedures, observations and results are discussed. Each experiment was conducted according to the methods described for each experiment in Chapter 3. The computations for determining the unsaturated hydraulic conductivity are presented in this chapter along with the method for measuring the soil matric suction. Water content samples were taken according the ASTM D2216-98 the "Standard Test Method for Laboratory Determination of Water Content of Soil and Rock by Mass".

Computations for the Instantaneous Profile Experiment

The apparatus of the instantaneous profile method is a cylindrical tube with a standard length and diameter. Soil is compacted into the apparatus in sections of different water contents. Each section with different water contents creates differences in the pore water pressure or suctions which drive the water flow.

For this experiment, to calculate the unsaturated hydraulic conductivity, the water content and matric suction at points along the profile of the test tube must be measured. The parameters needed to calculate the unsaturated hydraulic conductivity are the volumetric water content and matric suction between two points at two times, the distance between the two points, and the time interval in which two water content and suction measurements were obtained. The matric suction could be calculated from the water content measurements by interpolation from a SWCC curve, but it is more accurate to use indirect measurements such as from a filter paper tests. In order to increase the accuracy of the results it is best to take numerous measurements of the water content and suction over various time periods and at various locations along the tube. This increases the number of data points and allows for more conductivity points to be calculated.

In this report, the positions or locations for which sampling occurs are denoted as positions, P#. A sampling event is when water content and matric suction samples were taken and measured. One sampling event occurred at each location at a given time period. Each position, such as the example P6 shown in Figure 4.1, is the approximate distance in inches from the dry end of the tube apparatus.

Figure 4.1: Example of Position Location, P6.

Data from the instantaneous profile test was plotted for different time intervals on a plot of the volumetric water content versus the distance from the dry end of the tube. This plot is the Volumetric Water Content Profile and is presented in Figure 4.2. This plot was used to calculate the flow of water between sampling locations at different time intervals. The plot shown below is typical for an instantaneous profile test. After a sufficient time period, the water contents of each section should equilibrate to the same water content. The time period for which this occurs is a function of the soil unsaturated hydraulic conductivity.

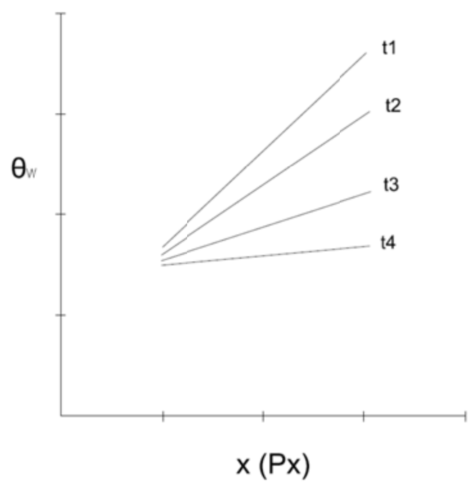

Figure 4.2: Volumetric Water Content Profile.

The unsaturated coefficient of permeability varies with water content and suction. Because of this, the unsaturated hydraulic conductivity, Kunsat must be calculated at different sections of water content and time periods to allow for an adequate change in suction. Also, to gain points at different suction values, the water content of each section of the tube is carefully considered beforehand to get a good range of suction values from the experiment. Typical results from a laboratory instantaneous profile experiment are present in a plot of Kunsat versus suction as shown in Figure 4.3 (Fredlund and Rahardjo, 1993). The unsaturated hydraulic conductivities shown in this figure are for a clay. As shown, the data indicate a trend for unsaturated hydraulic conductivity to decrease with increases in suction.

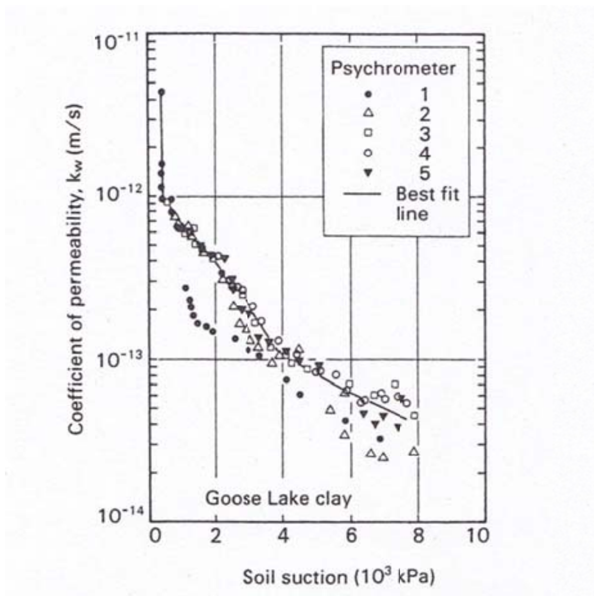

Figure 4.3: Typical Instantaneous Profile Results for Clay.
(Hamilton et al. 1981)

In the following, an example calculation shows the steps for determining Kunsat for a simple one dimensional example between two points over one time interval. This example presents the equations used to calculate multiple values of Kunsat at different time intervals and suction values by repeating the process over various points along the soil profile. Figure 4.4 below presents the set-up of this two point example using two sampling events. The sampling event includes an initial and final water content and suction measured for each point location.

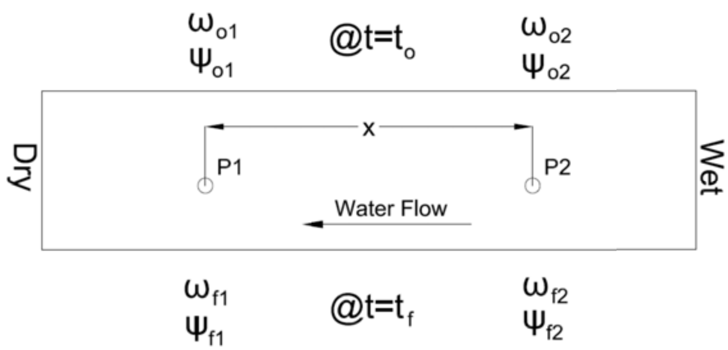

Figure 4.4: Two Point Sampling Event.

ω_{o1}: Initial water content at P1 at time=t_o
ω_{o2}: Initial water content at P2 at time=t_o
ω_{f1}: Final water content at P1 at time=t_f
ω_{f2}: Final water content at P2 at time=t_f
ψ_{o1}: Initial matric suction at P1 at time=t_o
ψ_{o2}: Initial matric suction at P2 at time=t_o
ψ_{f1}: Final matric suction at P1 at time=t_f
ψ_{f2}: Final matric suction at P2 at time=t_f
t_o: Initial time
t_f: Final time
P1: Position at some distance from dry end of the tube
P2: Position at some distance form dry end of the tube

The parameters shown in Figure 4.4 above are used in calculating Kunsat. If the water contents are gravimetric, they must be converted to volumetric water contents using Eqn 4.1 below.

$$\theta_w = \omega \times \left(\frac{RC \times (\gamma_d)_{max}}{\gamma_w}\right) \qquad \text{(Eqn. 4.1)}$$

θ_w: Volumetric water content
ω: Gravimetric water content
RC: Relative Compaction
$(\gamma_d)_{max}$: Maximum dry density from proctor compaction test
γ_w: Unit weight of water

The average hydraulic gradient, i, between two points is calculated using Eqn. 4.2.

$$i = \frac{dh_w}{dx} = \frac{\frac{(\psi_1 - \psi_2)}{\gamma_w}}{dx} \qquad \text{(Eqn. 4.2)}$$

dh_w: Difference in height of water between two points
dx: Distance between the two points
$$dx = P2 - P1\ [m]$$
ψ_1: Matric suction at P1 [kPa]
ψ_2: Matric suction at P2 [kPa]
γ_w: Unit weight of water (9.81kN/m2)

When calculating the hydraulic gradient for the instantaneous profile test, the average hydraulic gradient should be calculated using the average of the two suction values for each point. The plot presented in Figure 4.5 shows an example of the suction values between two points and how the suction values used in the gradient calculation are determined. The calculation using the average suction values is shown in Eqn. 4.3.

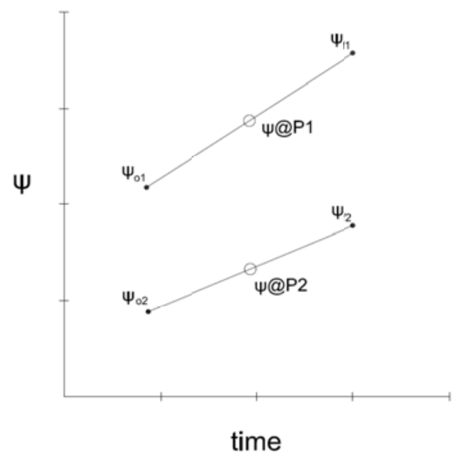

Figure 4.5: Suction Profile.

$$i_{ave} = \frac{\frac{\left(\frac{1}{2}(\psi_{o1}+\psi_{f1}) - \frac{1}{2}(\psi_{o2}+\psi_{f2})\right)}{\gamma_w}}{P2 - P1} \qquad \text{(Eqn. 4.3)}$$

The unsaturated hydraulic conductivity is calculated using Eqn. 4.4.

$$Kunsat = \frac{v_w}{i_{ave}} = \frac{dv_w}{Adt} \times \frac{1}{i_{ave}} \qquad \text{(Eqn. 4.4)}$$

dv_w: Change in the volume of water between the two points
v_w: Volume of water that flowed between the two points
A: Cross-sectional are of tube
dt: Change in time
i_{ave}: Average hydraulic gradient

The volume of water that flows between the two points during the time interval is known as dv_w. This is calculated by determining the area between the two curves from the volumetric water content profile. This area represents the volume of water that flows over the time period. This area is presented in Figure 4.6 below.

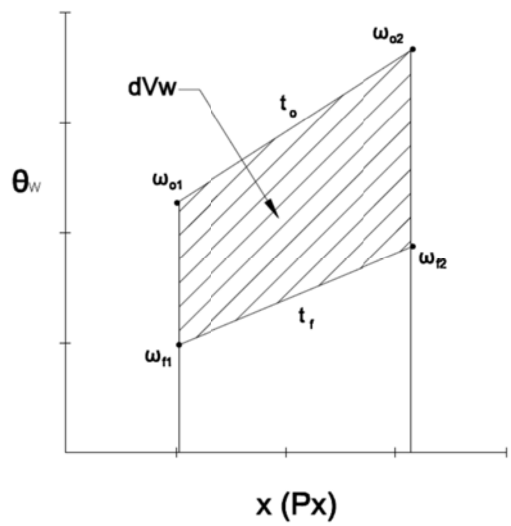

Figure 4.6: Volumetric Water Content Profile and dv_w.

The area between the two curves for determining the volume of water that flowed between the two points is calculated using a triangulation method. Figure 4.7, presented below shows how the areas under the curves are calculated during both time periods. The equations Eqns. 4.5, 4.6, 4.7, 4.8 and 4.9 shows the steps used to calculate the area under the curves and the change in volume of water between the two points. The water contents used for determining the flow must first be converted to volumetric water contents.

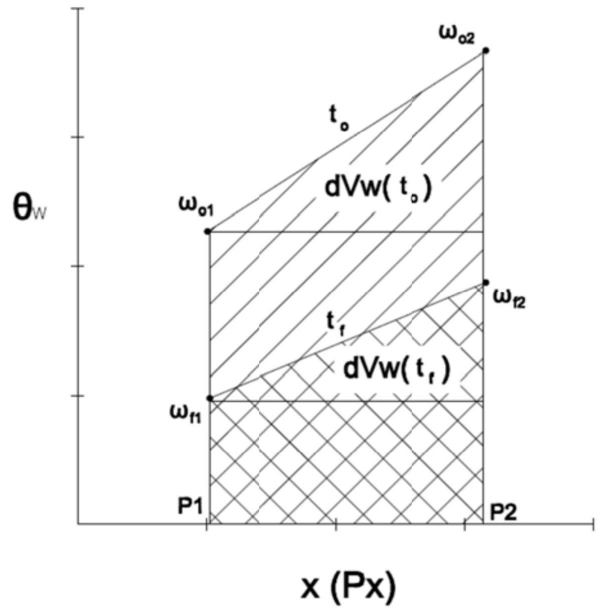

Figure 4.7: Volume of Water Calculation Plot.

$$dv_w = A\int_{P1}^{P2}\theta(x)dx \quad [\text{m3}] \qquad \text{(Eqn. 4.5)}$$

$$dv_w(t_o) = (P2 - P1)(\omega_{o1}) + \frac{1}{2}(P2 - P1)(\omega_{o2} - \omega_{o1}) \qquad \text{(Eqn. 4.6)}$$

$$dv_w(t_f) = (P2 - P1)(\omega_{f1}) + \frac{1}{2}(P2 - P1)(\omega_{f2} - \omega_{f1}) \qquad \text{(Eqn. 4.7)}$$

$$dv_w = dv_w(t_o) - dv_w(t_f) \qquad \text{(Eqn. 4.8)}$$

$$dv_w = (P2 - P1)\left(\omega_{o1} + \frac{1}{2}\omega_{o2} - \frac{1}{2}\omega_{o1} - \omega_{f1} - \frac{1}{2}\omega_{f2} + \frac{1}{2}\omega_{f1}\right)$$

$$= \frac{1}{2}(P2 - P1)(\omega_{o1} + \omega_{o2} - \omega_{f1} - \omega_{f2}) \qquad \text{(Eqn. 4.9)}$$

Note: Water contents represented by ω are volumetric water contents.

Once the change in volume of water and hydraulic gradient are calculated, the unsaturated hydraulic conductivity can be calculated using Eqn. 4.10.

$$Kunsat = \frac{v_w}{i_{ave}} = \frac{dv_w}{Adt} \times \frac{1}{i_{ave}} \qquad \text{(Eqn. 4.10)}$$

This computation is used to determine the unsaturated hydraulic conductivity for each instantaneous profile experiments. The data for each test is tabulated in a spreadsheet and this simple 1-D approach is used for different locations within each sample to gain numerous conductivity values from one sampling event.

Matric Suction Measurements

The matric suction was measured with filter paper tests for the instantaneous profile experiments performed, except for Test No. 6. Filter paper tests are used to measure the matric suction because filter paper measurements have been found to be fairly reliable and cover the full suction range of interest expected for this soil (Houston, Houston and Wagner, 1994). In this study, Whatman's No. 42 filter paper was used. The filter paper tests were conducted in accordance to ASTM D5298-03, "Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper" and the journal article titled "Laboratory Filter Paper Suction Measurements" by S.L. Houston, W.N. Houston, and AM. Wagner (1994).

Filter paper tests for measuring soil suction must be conducted carefully to obtain accurate results. The method for determining the matric suction using filter paper consists of placing a small piece of filter paper in direct contact with the soil. It is important that the specimens with filter paper tests be placed in a temperature controlled environment. The filter paper is allowed time to equilibrate to the soil water content and the filter paper water content is then related to the soil matric suction. The relationship between the filter paper water content and the soil matric suction is specific to the type of filter paper used. Since Whatman's No. 42 filter paper was used, the following relationship was used as presented below. This calibration curve for the filter paper water content and the soil matric suction was taken from the article by R.J Chandler and C.I. Gutierrez titled "The Filter-Paper Method of Suction Measurement".

$$\psi(pF) = 5.850 - 0.0622 w_{filter\ paper} \quad \text{(Eqn. 4.11)}$$

$$\psi(kPa) = \gamma_w \times 10^{\psi(pF)} \quad \text{(Eqn. 4.12)}$$

$\psi(pF)$: Soil matric suction in pF.
$\psi(kPa)$: Soil matric suction in kPa.
$w_{filter\ paper}$: Filter paper water content.
γ_w: Unit weight of water.

The procedure for the filter paper tests followed the guidelines outlined in the previously stated article titled "Laboratory Filter Paper Suction Measurements". In this article, specific steps in the contact methods are outlined to gain quality results. The procedure for performing filter paper tests were all conducted in the same manner following this procedure.

Prior to placing the filter paper in the soil, the filter paper pieces were dried for 24 hours at 110 ^{o} C in an oven. Whenever handling the filter paper, latex gloves were worn to ensure that the filter paper remained clean. After drying, the filter paper was cut into pieces. The total amount of filter paper introduced into the soil should be small to minimize system compliance (Houston, Houston and Wagner, 1994). The area of soil where the filter paper was placed was scarified to gain good contact between the soil and the filter paper. To ensure intimate contact between the filter paper and the soil, the filter paper piece was sandwiched between two other pieces of filter paper so that no soil will come in contact with the dried filter paper piece. The filter paper sandwich is then buried and the soil above is then compacted to specifications. The filter paper is allowed to equilibrate with the surrounding soil for a minimum of 7 days.

When the filter paper was to be removed and measured, the soil around the filter paper sandwich was removed. Again, latex gloves were worn to prevent any unwanted particles from contaminating the clean filter paper piece. The filter paper sandwich is carefully removed from the soil and then the sandwich is unwrapped and the clean piece of filter paper is immediately placed in a pre-weighted plastic bag. The bag with the filter paper is weighted and the piece of filter paper is placed in an oven maintained at a temperature of 110 ^{o} C to completely dry. After 24 hours and once the piece of filter paper are dry, the dry weight of the filter paper piece is recorded. With the wet and dry mass of the filter paper the correlation above can be used to determine the matric suction of the soil at the time the filter paper was removed.

Ec-5 Volumetric Moisture Probes

Decagon Volumetric moisture probes were used to track and record the water content over time for various experiments. This sensor is shown if Figure 4.8 below. The volumetric probes used are the Decagon Model Ec-5. The probes are not a time domain reflectometry (TDR) sensors but are based on measuring the dielectric constant variation of the soil (Decagon). The Ec-5 probes measure at a very high frequency to allow accurate measurement of all types of soil and are much less sensitive to variation in texture and electrical conductivity (Decagon). The probes are connected to a data acquisition unit that records the volumetric water content over time. The probes have a 5cm radius of influence.

Figure 4.8: Volumetric Moisture Probe (Decagon).

These sensors included a general calibration to relate the voltage output of the sensor to the volumetric water content of the soil. This calibration is automatically implemented in the data that is downloaded from the acquisition unit. The sensors were first calibrated using the soil used in the study to gain a more accurate calibration and relationship between the senor output and the actual gravimetric water content of the soil. This was done by compacting soil in standard proctor molds at different water contents ranging from 7.5% to 23.5%. Four sensors were placed in soil samples prepared at different water contents. The soil was compacted to a density of 98% of the maximum density based on a Method A standard proctor test. The samples were allowed to equilibrate for 24 hours and within this time period the volumetric sensor reading stabilized. A photo of the volumetric probes placed in the proctor mold for calibration is shown in Figure 4.9 below.

Figure 4.9: Volumetric Probe Calibration.

With the data acquired from the calibration of the volumetric probes, the output voltage of the sensor was plotted against the gravimetric water content for each respective soil sample. The data was plotted with a reasonable correlation and the trend line of the data was used to relate all volumetric probes measurements for water content. This data is shown in Figure 4.10. The calibration equation is presented below.

$$w\%(\text{gravimetric}) = 0.00017299(\text{sensor voltage output}) - 0.0070865$$

(Eqn. 4.13)

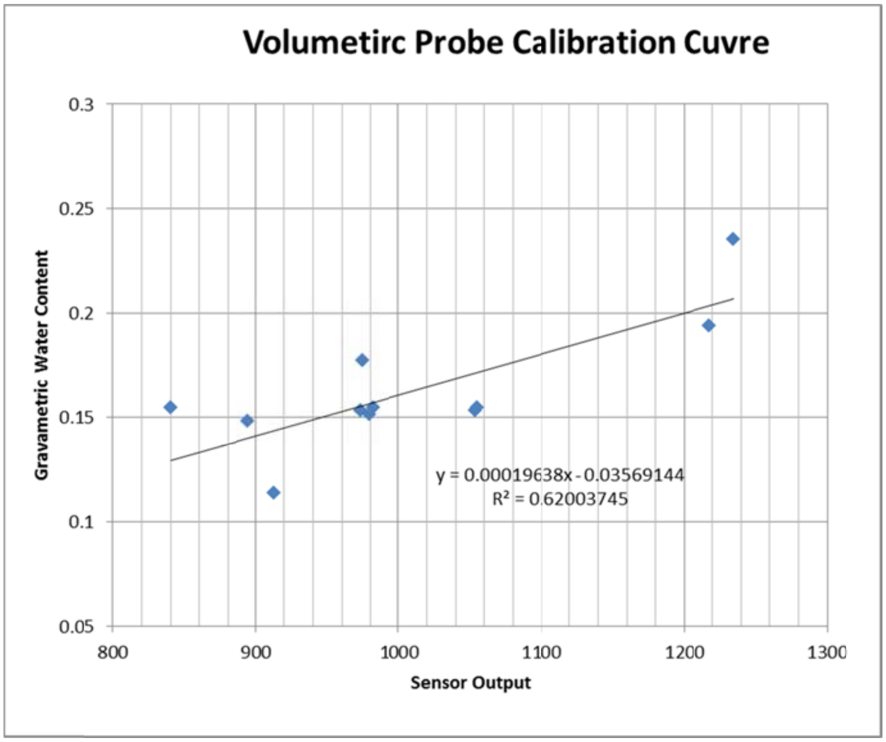

Figure 4.10: Volumetric Probe Calibration Plot.

Intact Instantaneous Profile Results

The results of the five intact instantaneous profile experiments are presented in the following section. The initial soil conditions, set up procedures, measurement locations, testing conditions, sampling procedures and observations during the experiments are discussed. The results for each experiment are also presented through the water content and suction trends over time, the water content and suction profiles and the unsaturated hydraulic conductivity or Kunsat plots.

Test Number 1:

The instantaneous profile experiment Test Number 1 (TN1) was started on October 20, 2009. This experiment consisted of four different soil sections, each at different water contents. Each section was of equal volume and consisted of soil compacted to the same dry unit weight. The water content and matric suction were measured periodically as the moisture flows from the wet to dry sections of soil. With measurements of the soil water content and matric suction, the unsaturated hydraulic conductivity was calculated.

The apparatus used for TN1 was a 36 inch long, 3 inch inside diameter clear cylindrical Plexiglas tube. The tube was prepared with two rows of access holes evenly spaced along the longitudinal axis of the tube. These holes provided access to the soil and were where the filter paper samples were replaced and where water content samples were obtained. The access holes were spaced approximately 3 inches apart. Soil was prepared at approximately 11%, 12.5%, 14.5%, and 21% water contents and was placed and compacted in the tubes. The soil was allowed to equilibrate for 24 hours prior to being compacted into the apparatus and checked to ensure that the water content was as close to the desired water content as possible. The water content used for the soil sections was chosen in order to cover a wide range of suction and to drive moisture flow. The initial soil conditions and the apparatus dimensions are shown in Figure 4.11 below, which presents the actual locations of the sampling locations for this apparatus. The sampling locations where chosen to be as close to the middle of each soil section as possible.

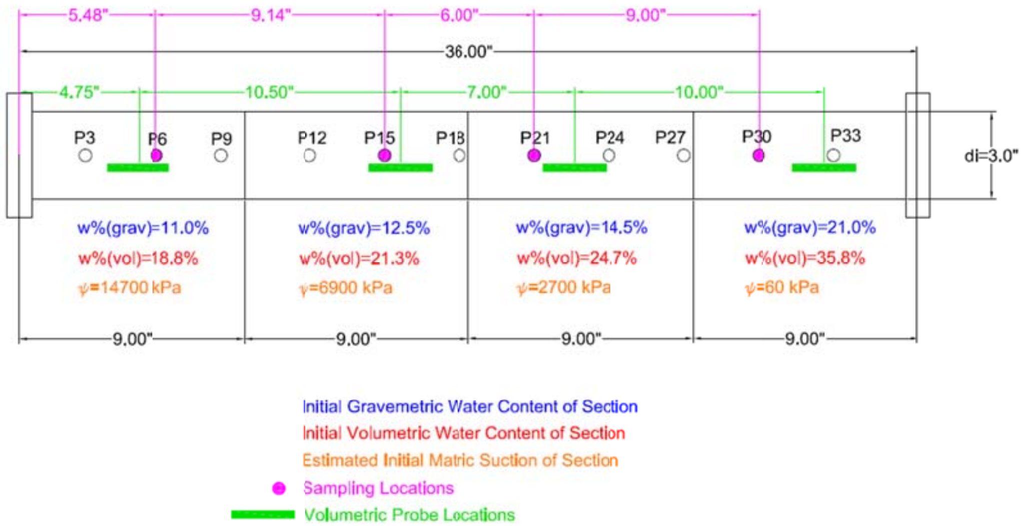

Figure 4.11: Test No. 1 Initial Soil Conditions and Sampling Locations.

Table 4.1 below presents the initial testing conditions of the soil for TN1, including relevant soil properties. . The initial conditions reported in Table 4.1 were taken from water content measurements during the sample creation. Section 1 is the driest section and section 4 is the wettest section. The suction values reported are interpolated from the SWCC curve for the soil. The actual matric suction measurements where determined from filter paper tests 7 days after sample creation and are used as the initial suction values.

Table 4.1: Test Nos. 1 and 2 Initial Soil Conditions.
* Calculated from SWCC.

Section	1	2	3	4
Desired w% (grav)	0.11	0.125	0.145	0.21
Relative Compaction %	0.98	0.98	0.98	0.98
Dry Density (pcf)	106.5	106.5	106.5	106.5
Actual w% (grav)	11.00%	12.50%	14.50%	21.00%
Actual w% (vol)	18.77%	21.33%	24.75%	35.84%
Saturation %	50.40%	57.27%	66.43%	96.21%
Matric Suction (kPa)*	14700	6900	2640	60
Actual Matric Suction (kPa)	1940	754	214	3.5
Void Ratio	0.594	0.594	0.594	0.594

The soil was compacted in the apparatus tubes in 1.5 inch lifts. This was done to keep the dry unit weight of the soil consistent through the profile. To ensure uniform density, for each 1.5 inch lift the amount of soil required to occupy the volume at the required dry unit weight was weighted out beforehand, and then compacted to the volume of each lift. The dry soil section was compacted in the tubes first since the last lift was difficult to make at the top of the tubes, so the wet sections was placed last since it is easier to manipulate.

Volumetric moisture probes where installed in TN1 to track moisture flow. The volumetric moisture probes where placed during compaction in each section of different water content. Care was taken during compaction not to break the probes. The probes were located in the center of the cross-section of the tube, pointing in the length direction of the tube. The probes where placed in this manner to gain the most influence by the surrounding soil. The probes have a 5cm radius of influence. The location of the volumetric moisture probes is shown if Figure 4.11.

The soil was compacted in the sample tubes using a standard proctor hammer which weighs 5.5 pounds and is dropped a distance of 12 inches. The amount of hammer blows with a standard proctor hammer required to compact the soil into a 1.5 inch lift decreased as the number of lifts increased. The plugs in the two rows of holes in the apparatus tube where sealed and capped prior to compaction. Once the soil was completely compacted in the apparatus, the end caps where sealed and fastened with bolts. Figure 4.12 below shows the sample tubes with the dry section compacted in the tubes.

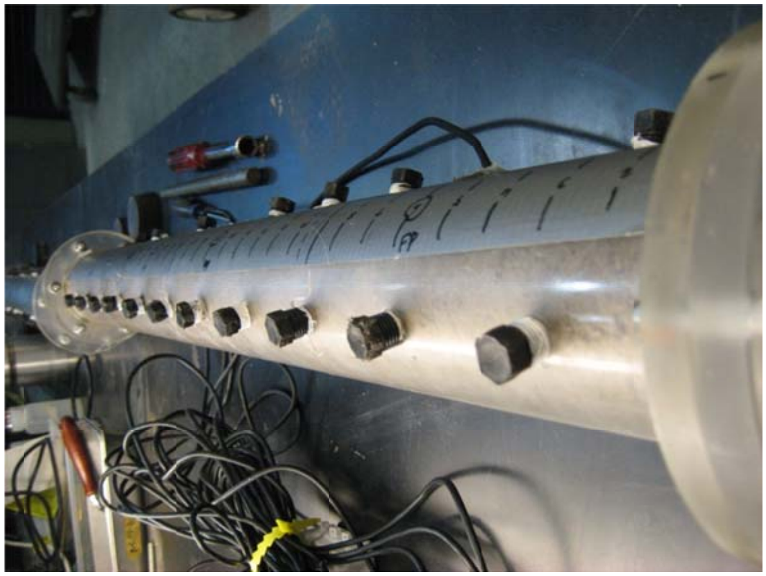

Figure 4.12: Test No. 1 Compacted Sample.

After sample compaction, filter paper sandwiches were placed at the locations shown in Figure 4.11. Small holes where first created by ramming hollow tube in the soil and then a filter paper sandwich was pushed into each hole. The hole was backfilled with soil prepared to the same water content of that of each section at the time of the sampling event. The backfilled soil was then carefully compacted to the density of the surrounding soil. Tape was also placed along the length of the tube to denote each sampling location and placement of volumetric moisture probes. Figure 4.13 below shows the sample tube from TN1 at the wettest section or section 4. The completed samples were stored in the ISTB2 Geotechnical laboratory area.

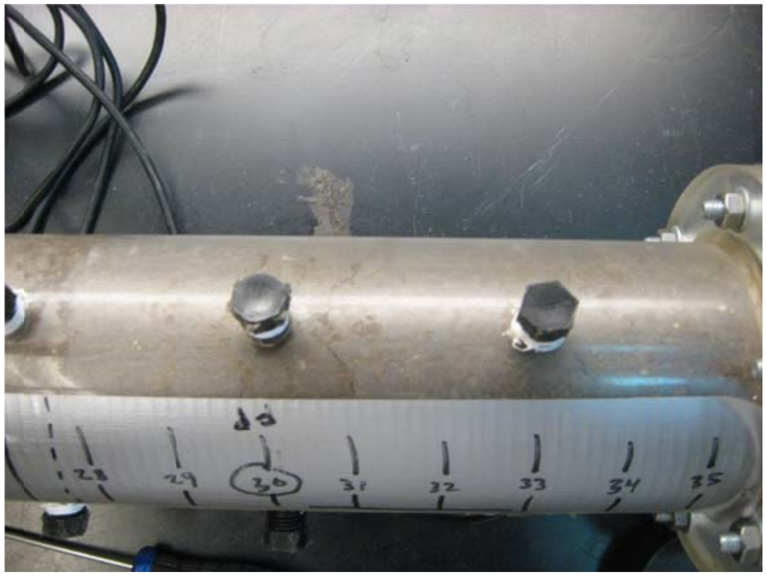

Figure 4.13: Test No. 1 Sample Tube.

The sample procedure for TN1 was performed as follows. First, four sample containers and bags were pre-weighted for the water content and filter paper measurements. One sample of water content and suction was taken for each soil section. Each soil section has one hole that is used to gain water content samples and retrieve and replace the filter paper samples. At each sampling location the cap is removed to provide access to the soil. A hollow rod is driven into the soil to the depth of the filter paper sandwich. The hollow rod is extracted and the soil that is pulled out of the sample from the inside of the hollow rod is used as a water content sample for that location. The filter paper sandwiches are removed from the soil carefully using needle nose pliers. The filter paper piece inside the filter paper sandwich is removed carefully using latex gloves and tweezers, and put in a sealed bag. The wet weight of the filter paper piece is then recorded. This is done at each of the four locations along the length of the tube for a given sampling event. Both the water content and filter paper samples are put in an oven for 24 hours and the dry weights are recorded.

The total run time for TN1 was 255 days. Thirteen sampling events occurred at increasing timer intervals between sampling events. The experiment was ended to retrieve the volumetric moisture probes for use in another experiment. This experiment used volumetric moisture probes to record water content and they were not used since there was bad correlation between volumetric probe measurements and the measured manual water contents. The date and run times of the sampling events for TN1 are presented in Table 4.2 below.

Table 4.2: Test No. 1 Sampling Times and Dates.

Sample Number	Run Time (days)	Sample Date
	0	10/20/2009
1	7	10/27/2009
2	14	11/3/2009
3	28	11/17/2009
4	42	12/1/2009
5	56	12/15/2009
6	70	12/29/2009
7	84	1/12/2009
8	112	2/9/2010
9	140	3/9/2010
10	168	4/6/2010
11	196	5/4/2010
12	225	6/1/2010
13	255	7/1/2010

The results of the water content and suction measurements from TN1 are presented in the following. The data acquired during the sampling of TN1 was tabulated into a spreadsheet and plots were made to analyze the trends of the water content and suction. Figures 4.14 and 4.15 present the water content and suctions of the different soil sections during the test. The test was ended on the 255th day of run time. The soil sections within the profile did not reach equilibrium. This experiment was ended due to inaccuracies in the testing procedures that influenced the measured water contents and suction. During the test period enough change in water content occurred to calculate hydraulic conductivity values.

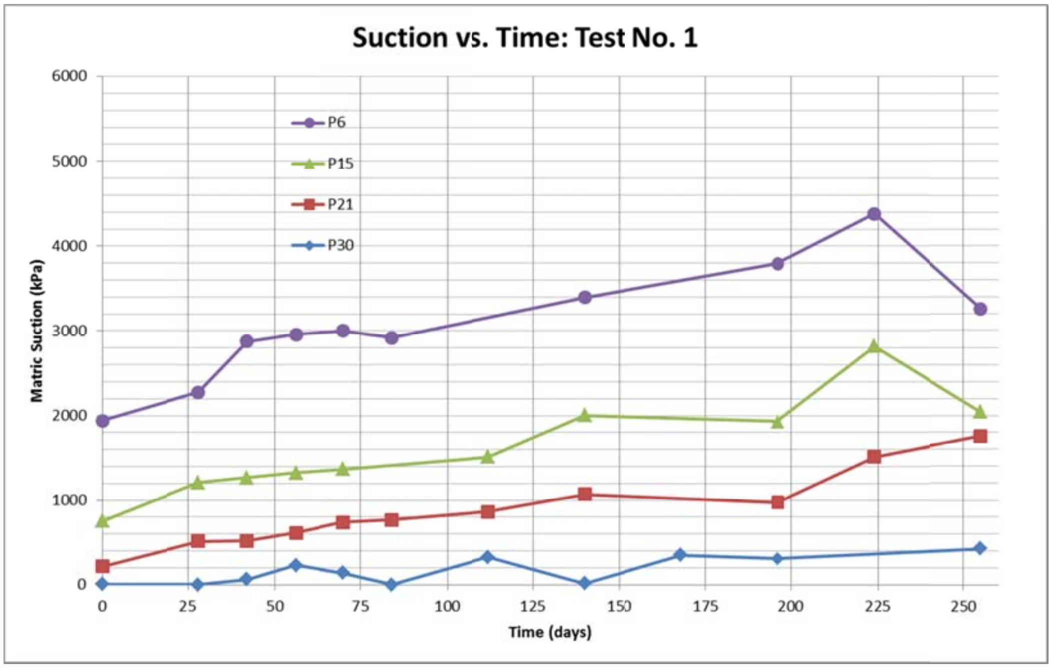

Figure 4.14: Test No. 1 Matric Suction versus Time.

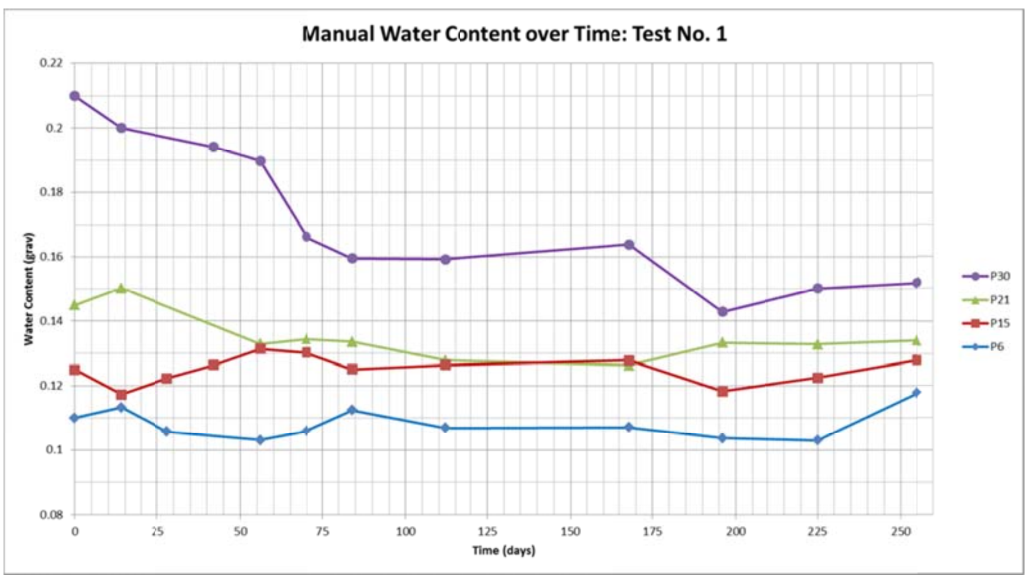

Figure 4.15: Test No. 1 Soil Gravimetric Water Content versus Time.

The measured data was averaged over the test period to gain smother functions of the water content and suction trends to reduce the scatter in the calculation of the hydraulic conductivity. This was done for both the water content and suction data for TN1. These corrected results of the water content and suction trends are presented in Figures 4.16 and 4.17 below. This corrected data follows the same trends as the measured results. This data was used to determine unsaturated hydraulic conductivity values over 20 day time periods. The water content profile is presented in a plot in Figure 4.18.

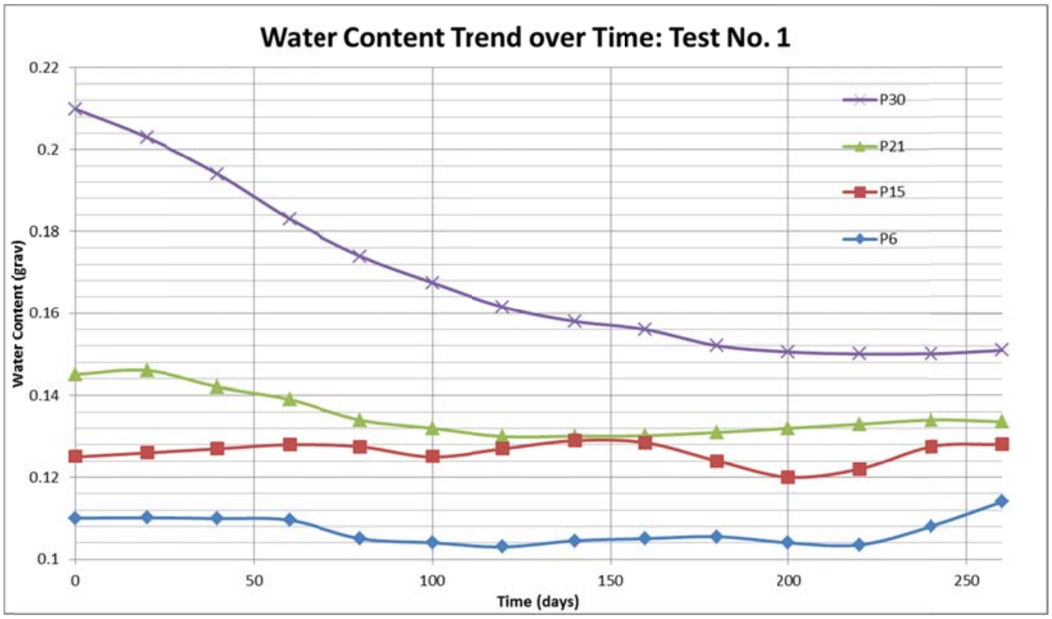

Figure 4.16: Test No. 1 Corrected Water Content versus Time.

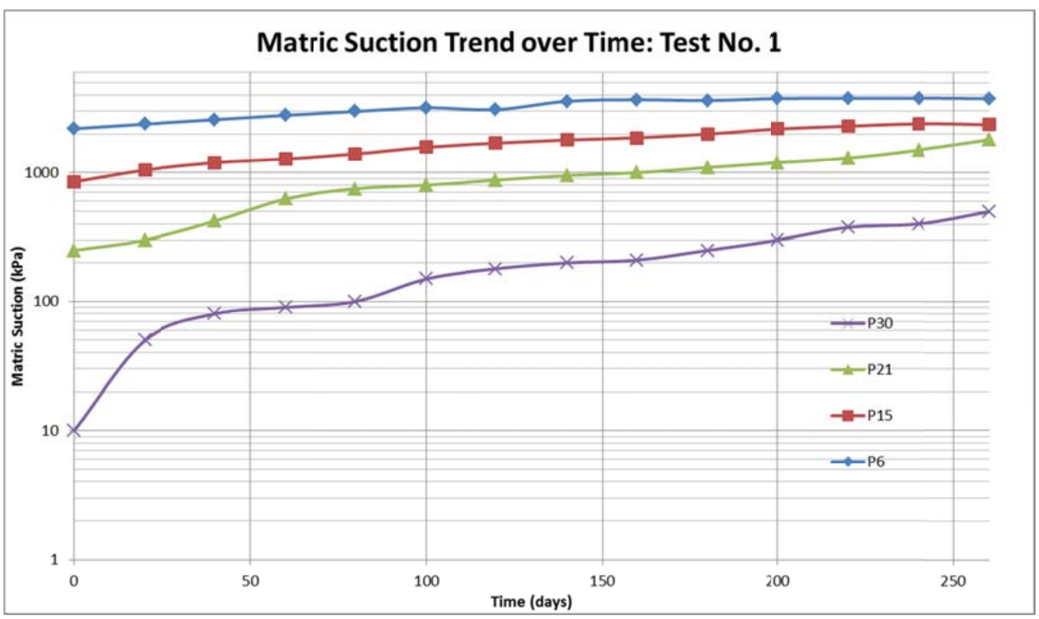

Figure 4.17: Test No. 1 Corrected Suction versus Time.

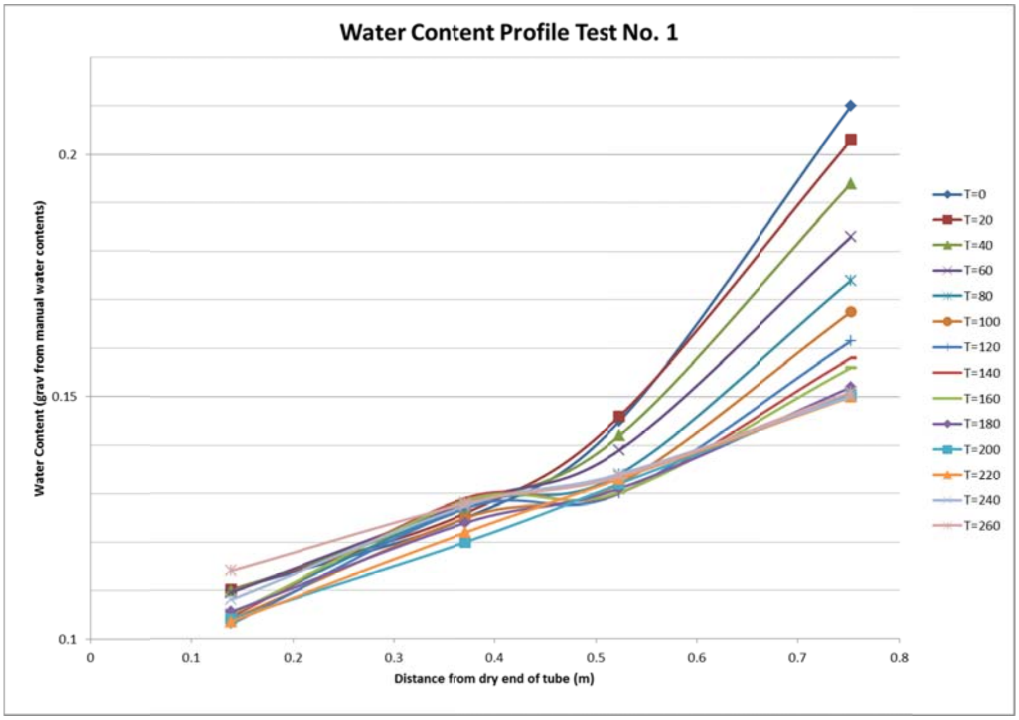

Figure 4.18: Test No. 1 Water Content Profile.

The calculated unsaturated hydraulic conductivity values for TN1 are presented below. The conductivity values were calculated using the approach previously stated in this chapter over various intervals within the soil profile of TN1. Various intervals are chosen to gain multiple points at different suction values which can be done along various points of the soil profile. Figure 4.19 below, presents the unsaturated hydraulic conductivity values calculated over various positions and time intervals. The locations of the intervals is presented in Figure 4.19 are also shown in Figure 4.11. The unsaturated hydraulic conductivity values obtained from TN1 range over 2.5 orders of magnitude and over a range of suction from 400 to 2600 kPa. The wide range of data and variability shows that the unsaturated conductivity for a soil can vary greatly for a given suction. The data presented in Figure 4.20 below presents the best and most accurate representation of the unsaturated hydraulic conductivity from TN1. This plot presents the computations of the hydraulic conductivity over the long time periods from 40 to 60 days and presents best average trend of the results. This can be seen in Figure 4.20 as the unsaturated hydraulic conductivity follows a good average trend of the data.

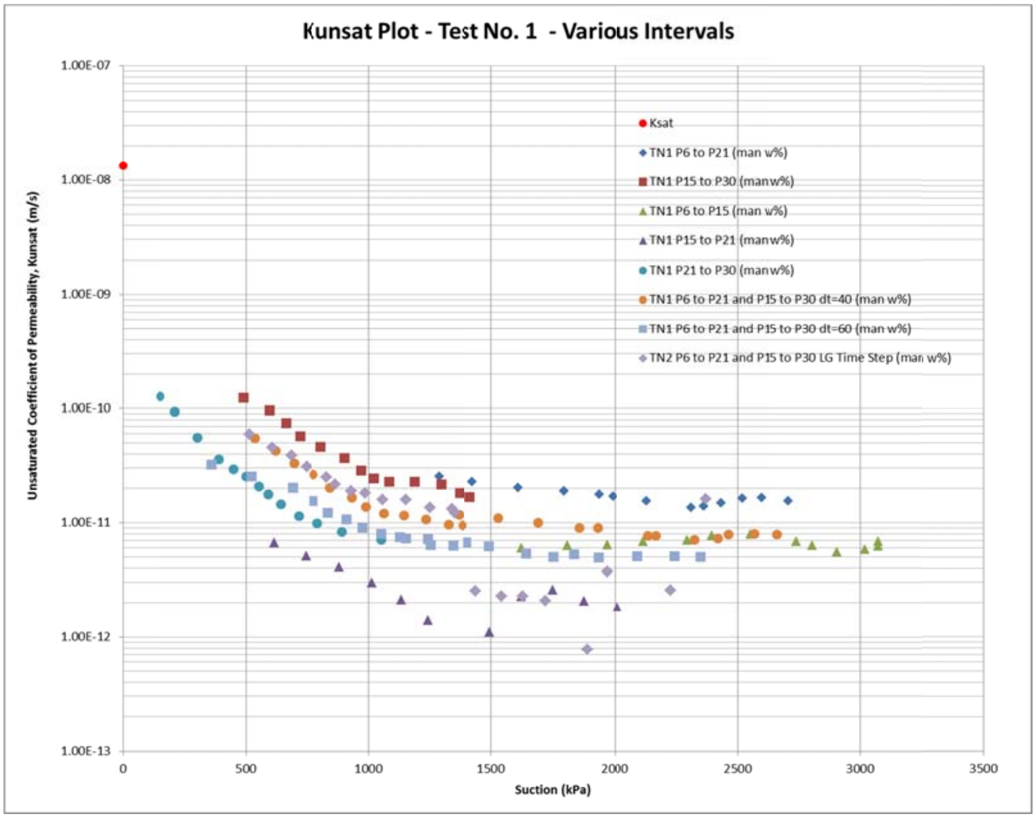

Figure 4.19: Test No. 1 Unsaturated Hydraulic Conductivity Plot over Various Intervals.

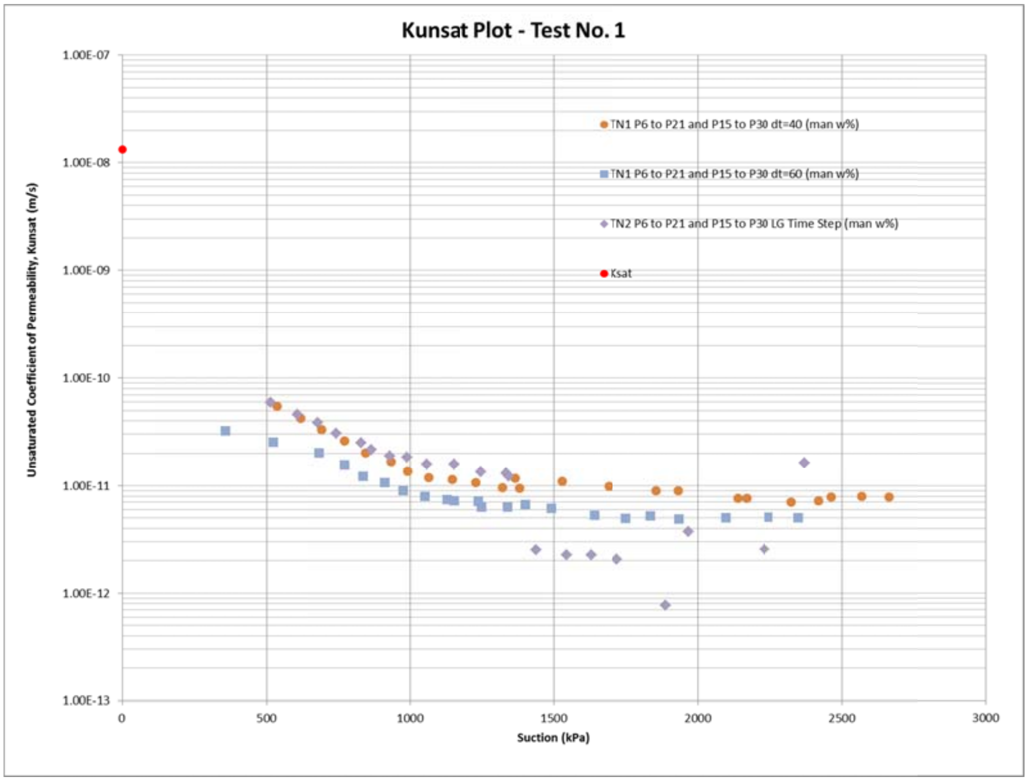

Figure 4.20: Test No. 1 Unsaturated Hydraulic Conductivity Plot.

Test Number 2:

The instantaneous profile experiment Test Number 2 (TN2) was started on October 20, 2009. This experiment was considered a duplicate of Test Number 1 in case any modifications to the experiment were desired. This experiment consists of four different soil sections of different water contents. Each section is of equal volume and has the same dry unit weight. The water content and matric suction were measured periodically as the moisture flows from the wet to dry sections of soil. With the measurements the unsaturated hydraulic conductivity was calculated.

The apparatus used for TN2 was a 36 inch long, 3 inch inner diameter clear cylindrical Plexiglas tube. The tube also has two row of access holes even spaced along the sample tube. These holes provide access to the soil for water content measurements and access to replace filter paper samples. Soil was prepared at approximately 11%, 12.5%, 14.5%, and 21% water content to be compacted into the sample tubes. The soil was allowed to equilibrate for 24 hours prior to being compacted into the tubes and checked to ensure that the water content was at the desired water content. The water content used for the soil sections was chosen in order to cover a wide range of suction and to drive moisture flow. The initial soil conditions and the apparatus dimension are presented in Figure 4.21 below. Figure 4.21 presents the sampling locations for the apparatus. The sampling locations are chosen to be as close to the middle of each soil section as possible.

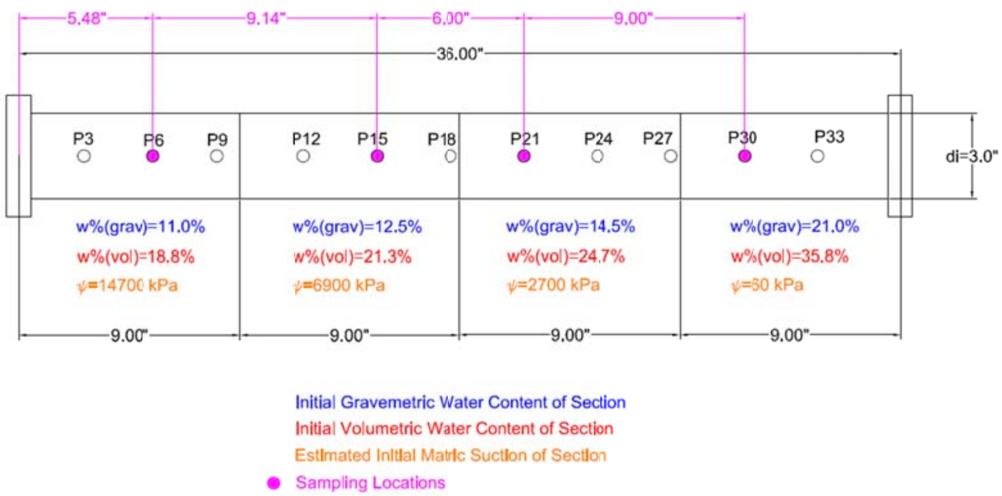

Figure 4.21: Test No. 2 Initial Soil Conditions and Sampling Locations.

The initial soil conditions for TN2 are the same as TN1, and are presented in Table 4.1. The initial conditions reported in Table 4.1 are taken from water content measurements during sample creation. Section 1 is the driest section and section 4 is the wettest section. The suction values reported were interpolated from the SWCC for the soil. The actual matric suction measurements where determine from filter paper test 7 days after sample creation and are used as the initial suction values.

The set up procedure and method of sampling for TN2 was the same as TN1. Since TN2 is a duplicate of TN1 care was taken to create both samples to the same specifications. The only difference between TN2 and TN1 is that TN2 does not have volumetric moisture probes imbedded in the soil profile. The sample made for TN2 was also stored and sampled the same as TN1. This experiment ran longer than TN1. The sampling event dates and run times for TN2 are presented in Table 4.3 below.

Table 4.3: Test No. 2 Sampling Times and Dates.

Sample Number	Run Time (days)	Sample Date
	0	10/20/2009
1	7	10/27/2009
2	14	11/3/2009
3	28	11/17/2009
4	42	12/1/2009
5	56	12/15/2009
6	70	12/29/2009
7	84	1/12/2009
8	112	2/9/2010
9	140	3/9/2010
10	168	4/6/2010
11	196	5/4/2010
12	225	6/1/2010
13	255	7/1/2010
14	294	8/10/2010
15	322	9/7/2010
16	350	10/5/2010
17	426	12/20/2010
18	471	2/3/2011

The results of the water content and suction measurements for TN2 are presented in the following. The data acquired during the testing of TN2 were tabulated into a spreadsheet and plots were made to analyze the trends of the water content and suction. Figures 4.22 and 4.23 present the water content and matric suction measurements over time for the different sections during the test. The TN2 experiment ended on the 471st day of runt time. The soil profile did not reach equilibrium. The experiment was ended due to time constraints on testing. During the testing period, enough change in water content occurred to calculate hydraulic conductivity values.

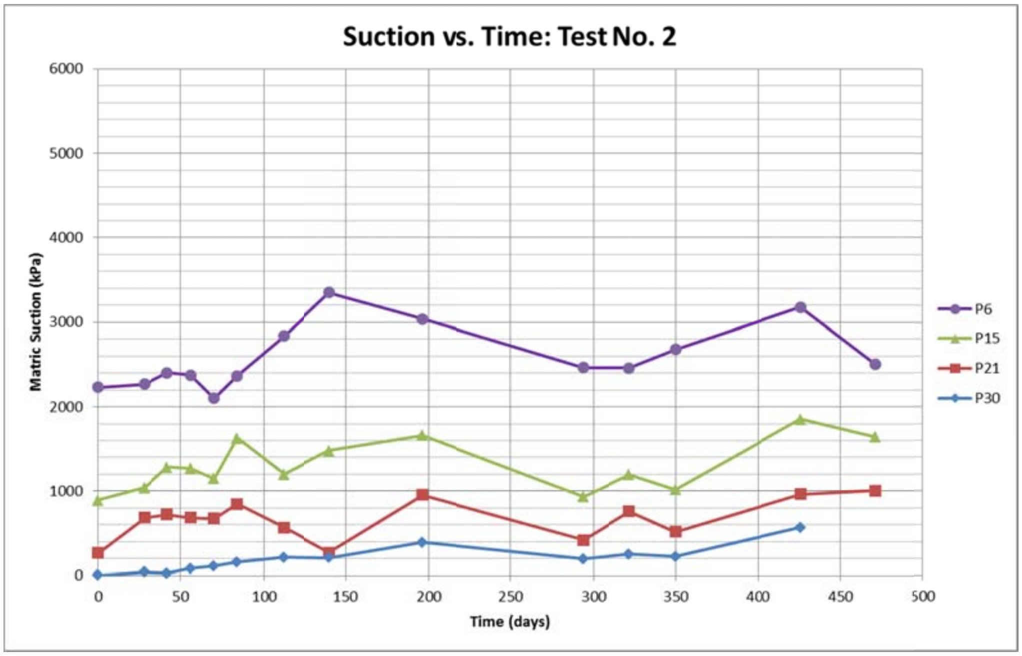

Figure 4.22: Test No. 2 Matric Suction versus Time.

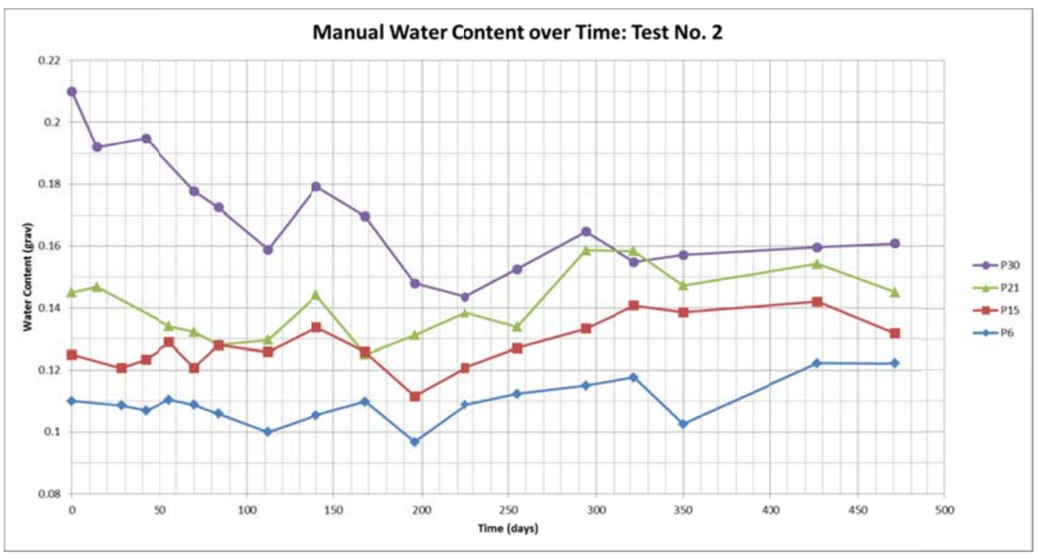

Figure 4.23: Test No. 2 Soil Gravimetric Water Content versus Time.

The measured data was averaged over the test period to gain smother functions with less scatter in calculating the unsaturated hydraulic conductivity. This was done for both the water content and suction data for TN2. The corrected results are presented in Figures 4.24 and 4.25 below. The corrected data follows the same trend as the measured results. The data was used to determine unsaturated hydraulic conductivity values over 20 day time periods. The water content profile is presented in Figure 4.26.

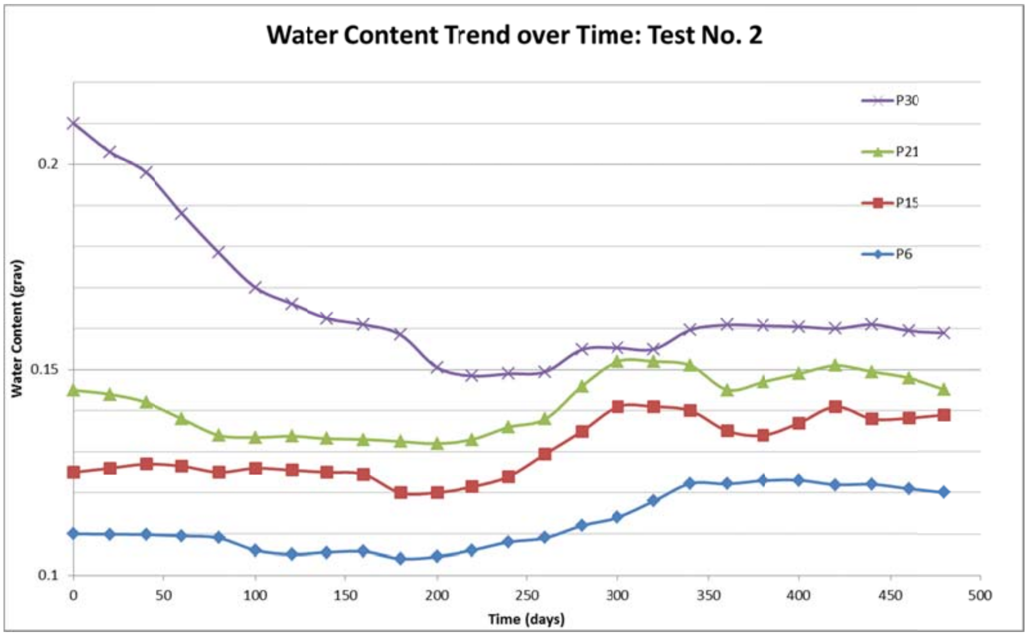

Figure 4.24: Test No. 2 Corrected Water Content versus Time.

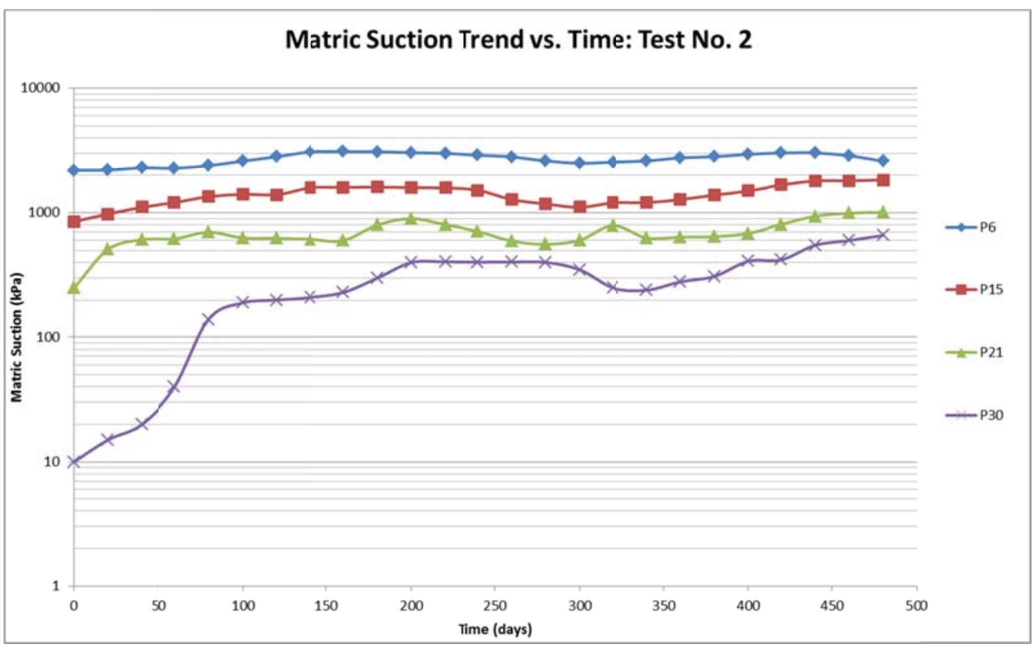

Figure 4.25: Test No. 2 Corrected Matric Suction versus Time.

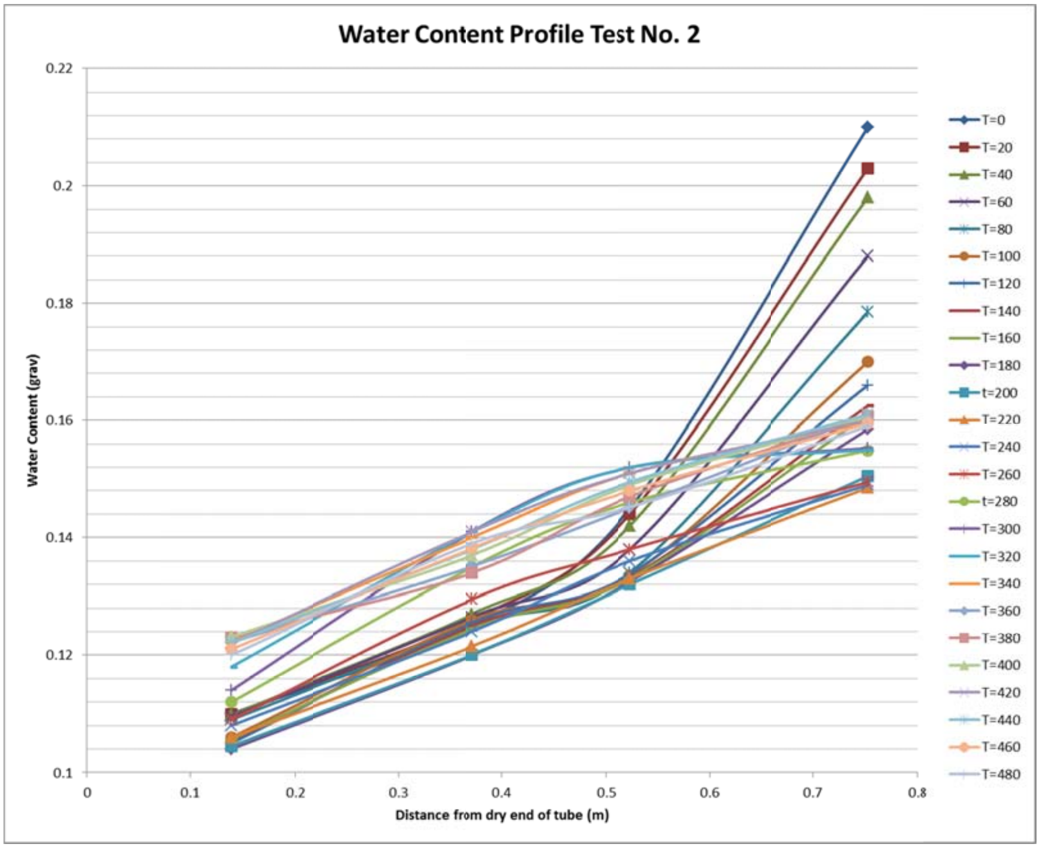

Figure 4.26: Test No. 2 Water Content Profile.

The calculated unsaturated hydraulic conductivity values for TN2 are presented below. The conductivity values were calculated using the approach previously stated in this chapter over various intervals within the soil profile for TN2. Various intervals used to gain multiple conductivity values at different suctions. Figure 4.27 below, presents the unsaturated hydraulic conductivity values calculated over various distances and time intervals. The location of the sampling intervals for the Kunsat Plots is presented in Figure 4.21. The range of conductivity values obtained from TN2 range over 2.3 orders of magnitude over a range of suction values from 200 to 2400 kPa. The wide range of conductivity values and large variability show that the unsaturated conductivity can vary greatly for a given suction. The data presented in Figure 4.28 below presents the best representation of the unsaturated hydraulic conductivity for TN2. This plot presents the unsaturated hydraulic conductivities over the long time periods and present. This can be seen in Figure 4.28 showing that the unsaturated hydraulic conductivity values follow a good average trend of the data.

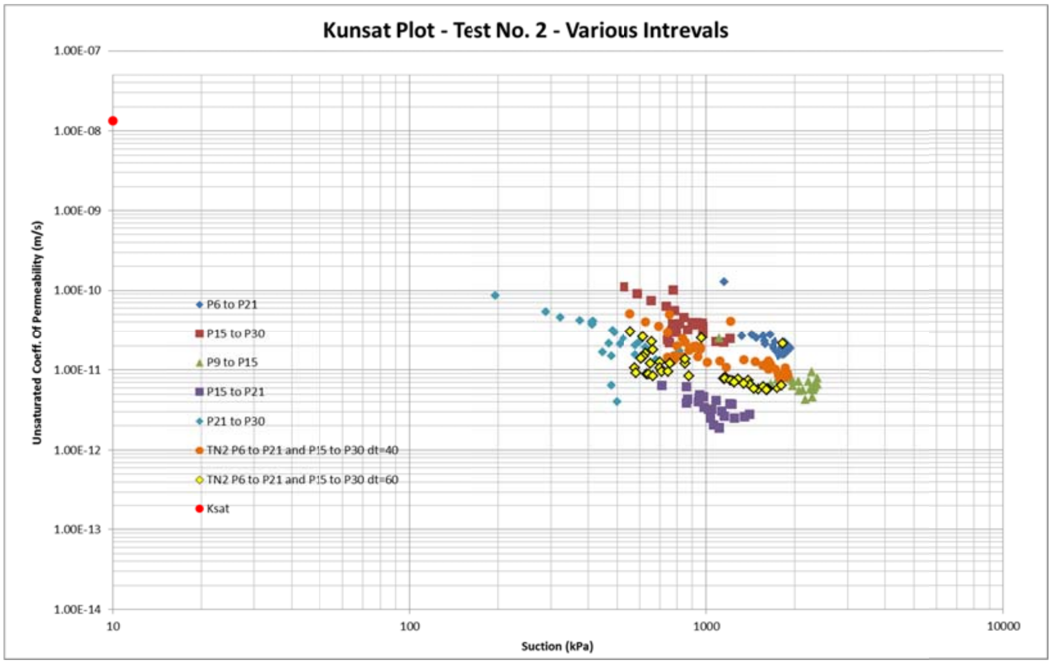

Figure 4.27: Test No. 2 Unsaturated Hydraulic Conductivity Plot over Various Intervals.

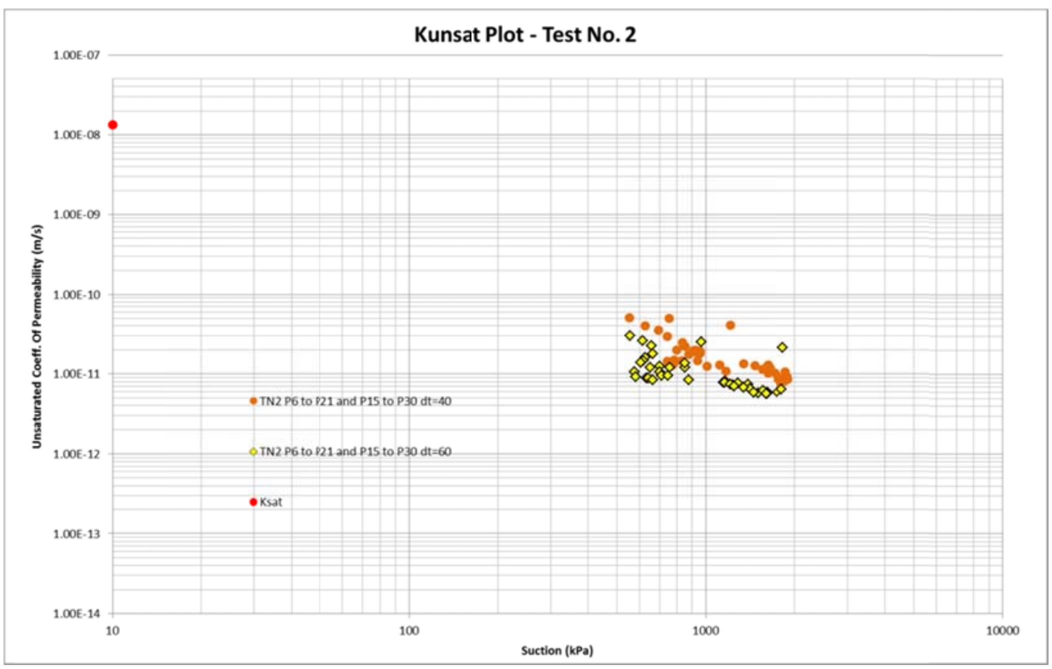

Figure 4.28: Test No. 2 Unsaturated Hydraulic Conductivity Plot.

Test Number 3:

The instantaneous profile experiment identified as Test Number 3 (TN3) was started on March 6, 2010. As stated in the experimental design section in Chapter 3, this experiment is configured and designed around observations and issues with Test No. 1 and 2. The ratiocination behind the changes in methodology of TN3 to TN1 and TN2 is discussed in Chapter 5.

The apparatus used for TN3 is a 9 inch long, 2.75 inch inner diameter clear cylindrical Plexiglas tube. Soil was prepared at approximately 9% and 14.5% water content to be compacted into the sample tube. The soil was allowed to equilibrate for 24 hours prior to being compacted into the tubes and checked to ensure that the water content was as close to the desired water content. The water content used for the two soil section was chosen in order to provide a good range of suction during the test which was 5,090kPa to 750kPa for each section. This provided a hydraulic gradient of approximately 5000. A high hydraulic gradient was desired to drive moisture flow and create significant changes in water content over the testing period. Figure 4.29 below, shows the testing apparatus dimensions along with the initial water content and soil suction.

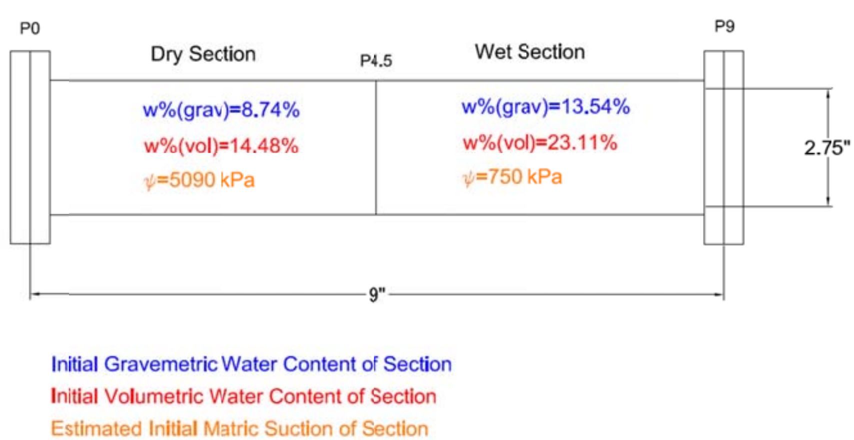

Figure 4.29: Test No. 3 Initial Soil Conditions.

The table below titled Table 4.4, presents the initial soil conditions and other relevant soil properties for TN3. The initial conditions reported in Table 4.4 were taken from water content measurements during the sample creation. Section 1 is the dry section and section 2 is the wet section. The suction values reported was interpolated from the SWCC curve for the soil.

Table 4.4: Test No. 3 Initial Soil Conditions.

Section	1	2
Desired w% (grav)	0.09	0.145
Relative Compaction %	0.98	0.98
Dry Density (pcf)	106.5	106.5
Actual w% (grav)	8.74%	13.54%
Actual w% (vol)	14.92%	23.11%
Saturation %	40.04%	62.03%
Matric Suction (kPa)	5090	750
Void Ratio	0.594	0.594

The soil is compacted in the apparatus tubes in 1.5 inch lifts. This is done to keep the density of the soil consistent through the profile. To ensure uniform density, for each 1.5 inch lift the amount of soil required to occupy the volume at the required dry density was weighted out beforehand. In between each lift the soil was scarified to ensure good contact and continuity between lifts. The dry soil section was compacted first since the last lift is difficult to make at the top of the tubes. The wet sections is placed last since it is easier to manipulate. The soil was compacted in the sample tubes using a standard proctor hammer. The amount of hammer blows with a standard proctor hammer required to compact the soil into the 1.5 inch lift decreased as the number of lifts increased. To help with the compaction process marks were put on the sample tubes and 1.5 inch spacing to help with the compaction process. Figure 4.30 below shows the sample tubes with the dry soil section compacted in the tubes.

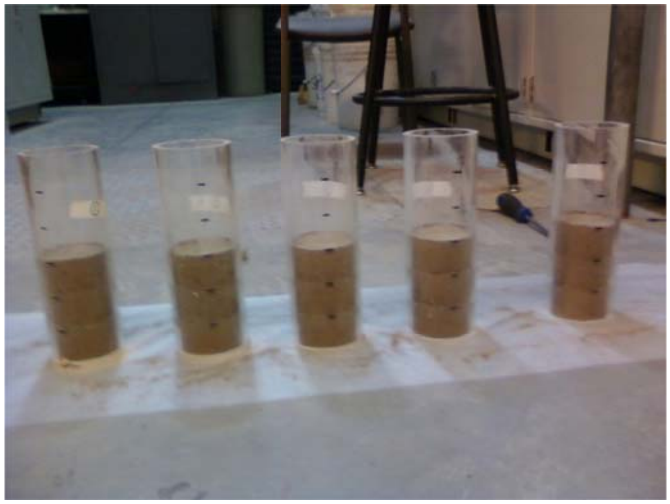

Figure 4.30: Sample Set-up and Compaction of Dry Section.

For this experiment, the matric suction is measured at three locations. One filter paper sandwich is located in the middle of the soil profile and one filter paper sandwich is located at 1.5 inches from the end of the samples. These locations provide suction measurements through the profile of the tube. Figure 4.31 below, shows the locations of the filter paper sandwiches in the sample tube.

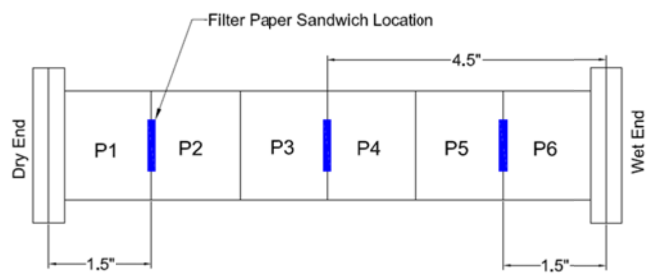

Figure 4.31: Test No. 3 Filter Paper Sandwich Locations.

The soil samples were completely compacted and then sealed at each end using first a layer of wax paper and then covered with plastic Saran warp. The plastic warp was sealed to the tubes with duct tape. A photo of a completed sample for TN3 is shown in Figure 4.32 below. All the sample specimens created for TN3 were completed as desired from visual observation.


Figure 4.32: Test No. 3 Finished Compacted Samples.

The sampling procedure for TN3 is performed as described in the following. First, sample containers and bags for water content and filter paper samples are weighted and recorded. Ten water content samples are taken. A sample specimen from the experiment is retrieved from the environmental chamber and the plastic and wax paper on the ends is removed. The sample is then extruded using the extruder shown in Figure 4.33 below. The sample is extruded by pushing from the dry section to prevent excessive compression of the wet soil section. The soil is extruded from the sample tube and the sample is carefully broken at the interface between lifts.

The sampling process starts from the dry end. The lifts are broken apart at the locations where filter paper sandwiches are located. The filter paper piece inside the filter paper sandwich is removed carefully using latex gloves and tweezers, and put in a sealed bag. The wet weight of the filter paper piece is recorded. A photo of the filter paper piece being removed from the soil is presented in Figure 4.34 for a sample from TN3. The filter paper pieces are all removed the soil and the soil profile is divided up and water content samples are taken. To measure the water content, the soil plug is separated at each lift interface as depicted in Figure 4.31. Each P# represents a location along the soil profile starting from the dry end. One water content sample is taken at each end piece (P1 and P6), and two water content samples are taken for each piece within the soil profile (P2 through P5). Both the water content and filter paper samples are put in an oven for 24 hours and the dry weights are recorded.

Figure 4.33: Test No. 3 Extruding Process.

Figure 4.34: Obtaining Filter Paper Sandwich from Soil Sample.

The total run time for TN3 is 305 days. Five sampling events occurred at increasing time intervals between sampling events. The sample number, sample date and run time for each sample specimen for TN3 is presented in Table 4.5 below. In the following a photo of the sample on the 305th day of run time is shown. The sample specimen on the 305th day of run time is presented in Figure 4.35. From visual observation the soil sections appeared to have significantly different color, suggesting that the sample has not yet reached equilibrium.

Table 4.5: Test No. 3 Sample Run Time and Sampling Event Dates.

Sample Number	Sample Date	Run Time
1	3/31/2010	25
2	4/26/2010	51
3	5/20/2010	75
5	8/3/2010	150
4	1/4/2011	305

Figure 4.35: Test No. 3 Extruded Sample on Day 305 of Run Time.

The results of the water content and suction measurements from TN3 are presented in the following. The data acquired during the sampling of TN3 was tabulated into a spreadsheet and plots were made to analyze the trends of the water content and suction. Figure 4.36 and 4.37 show that the water content and suction of the two soil sections did not reached complete equilibrium in 305 days. During this period enough change in water content occurred to calculate hydraulic conductivity.

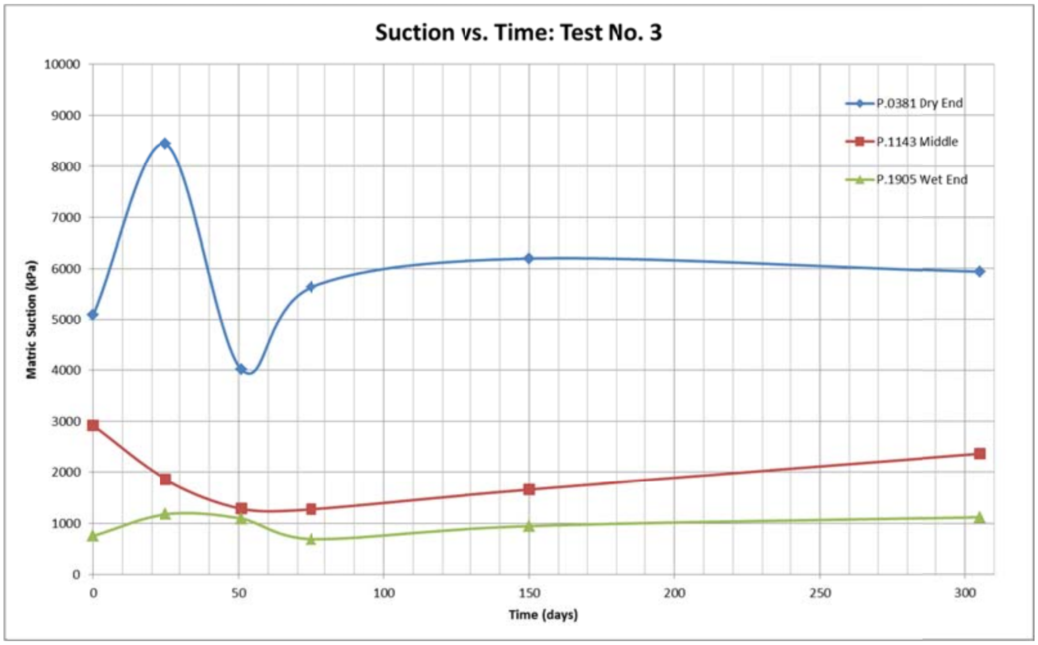

Figure 4.36: Test No. 3 Matric Suction vs. Time.

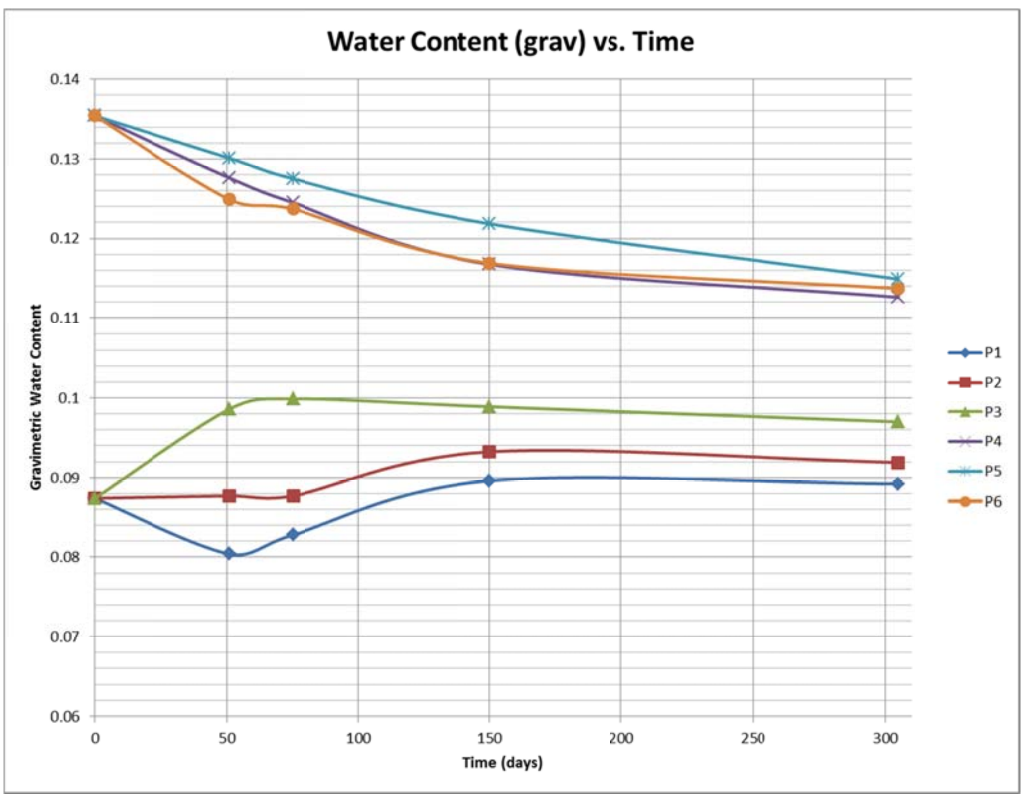

Figure 4.37: Test No. 3 Water Content over Time.

From the water content profile presented in Figure 4.38 below it was noted that the results from the sampling event on the 25th day could not be used. The amount of run time for this sample did not allow for the sample to equilibrate to is moisture conditions and the surrounding environmental conditions. This sampling event is omitted from the calculation of hydraulic conductivity values for this experiment. The plot shows that changes in water content have occurred during the testing period which means that water has flowed from the wet section to the dry section. This can also be observed in the suction profile as well in Figure 4.39.

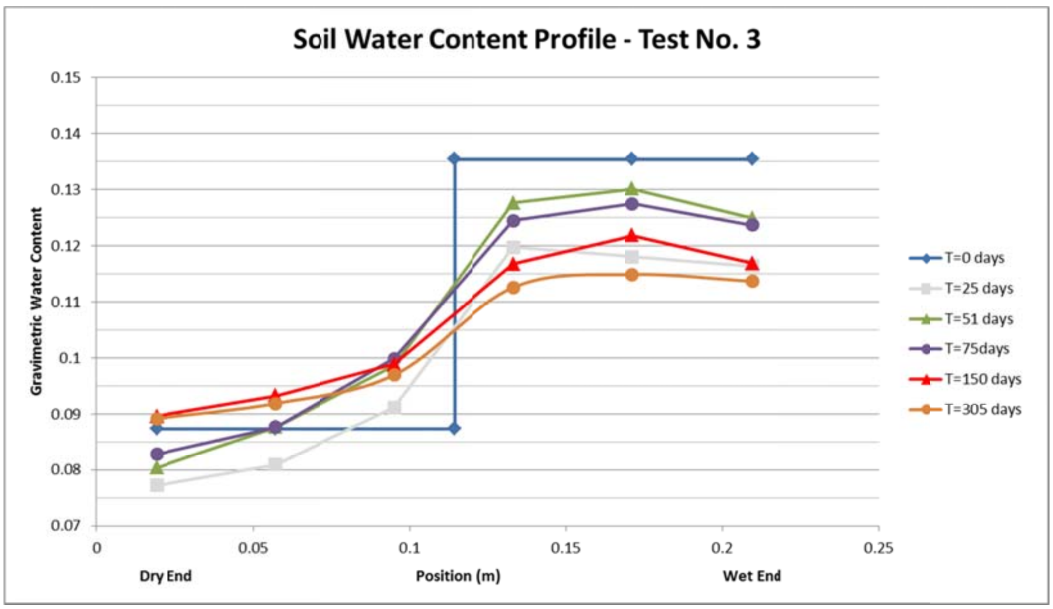

Figure 4.38: Test No. 3 Soil Water Content Profile.

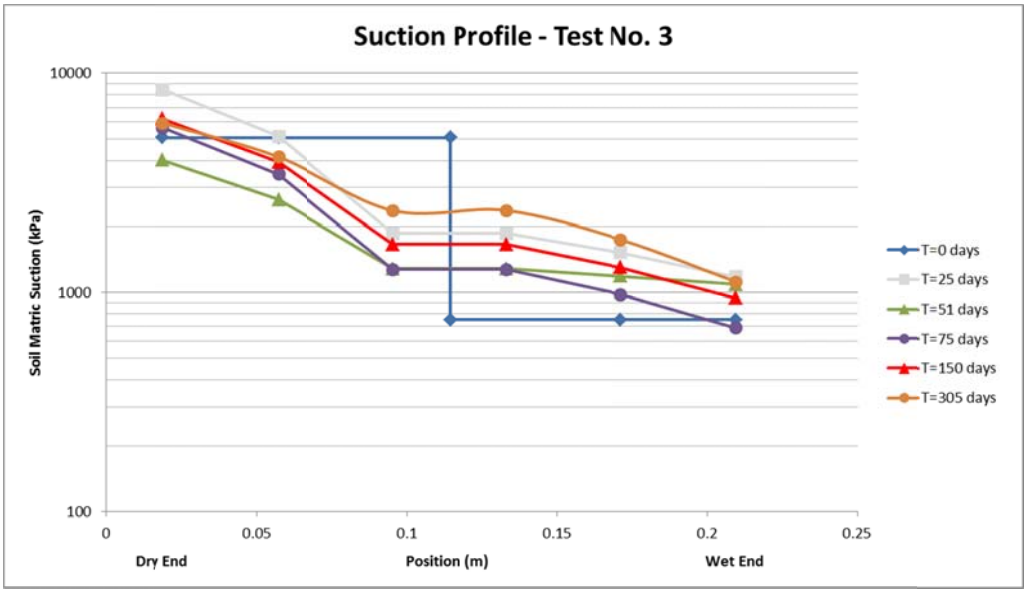

Figure 4.39: Test No. 3 Soil Suction Profile.

The calculated unsaturated hydraulic conductivity values for TN3 are presented below. The conductivity values were calculated using the approach previously stated in this chapter over various intervals with the soil profile of TN3. Various intervals are chosen to gain multiple values of unsaturated hydraulic conductivity at different suction values which can be done along various points of the soil profile. In Figure 4.40 below the unsaturated hydraulic conductivity values were calculated over the various intervals presented. The locations of the intervals presenting in Figure 4.29 and are also shown in Figure 4.41. The range of conductivity values obtained from TN3 range over 3.5 orders of magnitude and over a range of suction values from 1,000 to 6,000 kPa. The wide range of data and large variability shows that the unsaturated conductivity can vary greatly for a given suction.

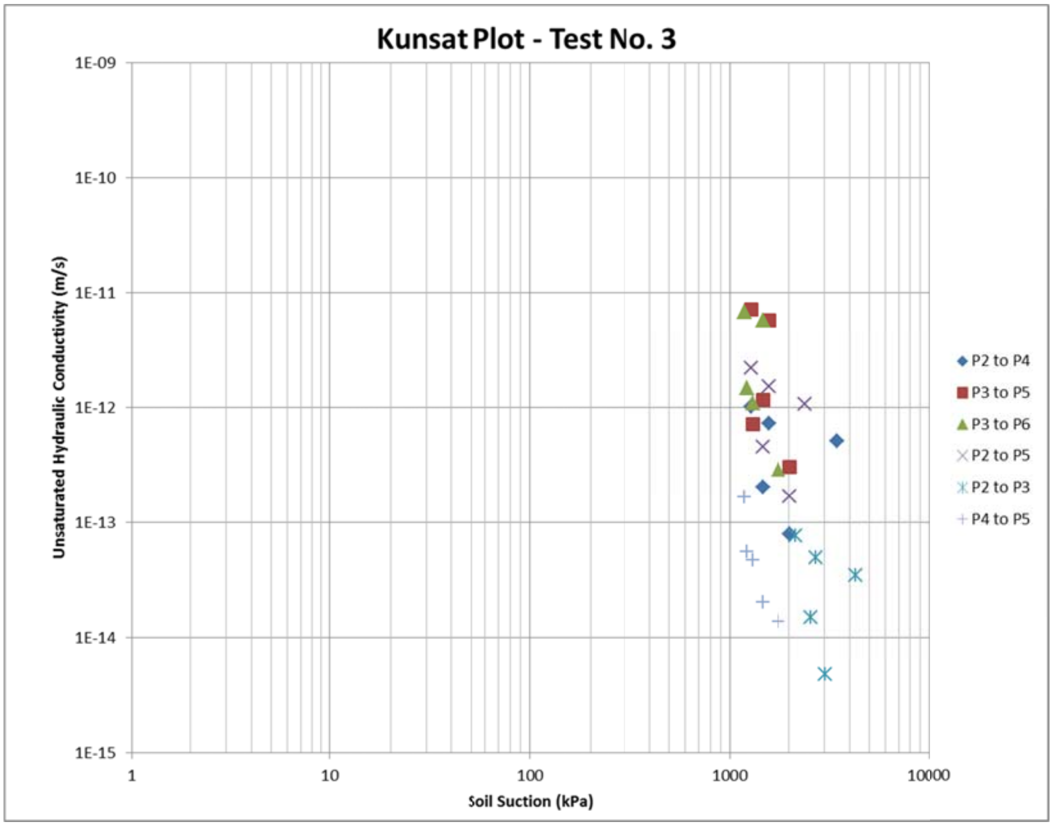

Figure 4.40: Test No. 3 Kunsat Plot.
Refer to Figure 4.41 for Location Description.

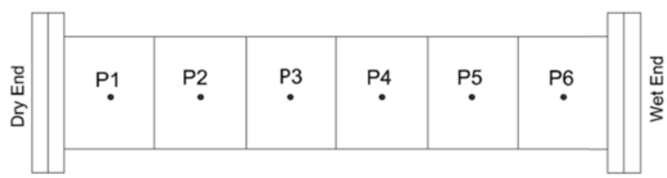

Figure 4.41: Locations of Kunsat Computation Intervals.

Test Number 6 (Intact):

The instantaneous profile experiment Test No. 6 (TN6) is a vertical infiltration test that is conducted in both the intact and cracked conditions. The sample for TN6 for the intact condition is identified as TN6I. The experiment for TN6I was started on August 12, 2010. This experiment was designed according to the configuration and methods explained in the experimental design section in Chapter 3. The experiment is designed in order to simulate vertical infiltration.

The apparatus used for TN6I is a 9 inch long, 3 inch inner diameter clear cylindrical Plexiglas tube. Soil was prepared at approximately 15.5% water content prior to being compacted in the sample tube. The soil was allowed to equilibrate for 24 hours prior to being compacted into the sample tube and checked to ensure that the water content was at the desired water content. The initial soil properties for TN6I are shown in Table 4.6 below.

Table 4.6: Test No. 6 I Initial Soil Conditions.

Section	1
Desired w% (grav)	0.15
Relative Compaction %	0.98
Dry Density (pcf)	106.5
Actual w% (grav)	15.50%
Actual w% (vol)	26.45%
Saturation %	71.01%
Matric Suction (kPa)	350
Void Ratio	0.594

The soil is compacted in the test apparatus tubes in 1.5 inch lifts. This is done to ensure uniform density. To ensure uniform density, each 1.5 inch lift had the amount of soil required to occupy the volume at the required dry density was weighted out beforehand. In between each lift the soil was scarified to ensure good contact and continuity between soil lifts.

The Decagon Ec-5 volumetric moisture probes that were used in TN1 were also used in TN6I to record and measure the volumetric water content over time. The volumetric moisture probes were used to interpolate matric suction values from the soil water characteristic curve for the soil. The volumetric moisture probes were installed during the compaction of each layer where they are located. The volumetric moisture probes are installed from the side to have better influence from the soil. When the moisture probes are positioned in the orientation shown in Figure 4.42, there is more soil in the 5cm radius of influence of the probes. The positioning of the probes was chosen to increase the accuracy of the measurements obtain by the sensors.

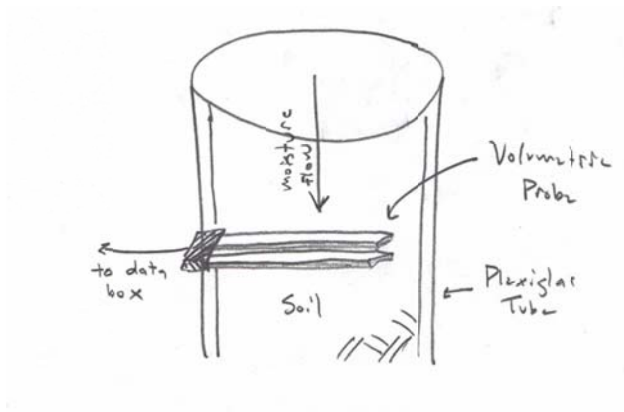

Figure 4.42: Orientation of Vol. Moisture Probe for Test No. 6.

The volumetric moisture probes were installed through slits cut in the sides of the sample tubes. At each slit where the sensors enter the sample tube, tape is placed to seal moisture inside the sample and prevent leakage. The locations of the volumetric moisture probes are shown in Figure 4.43.

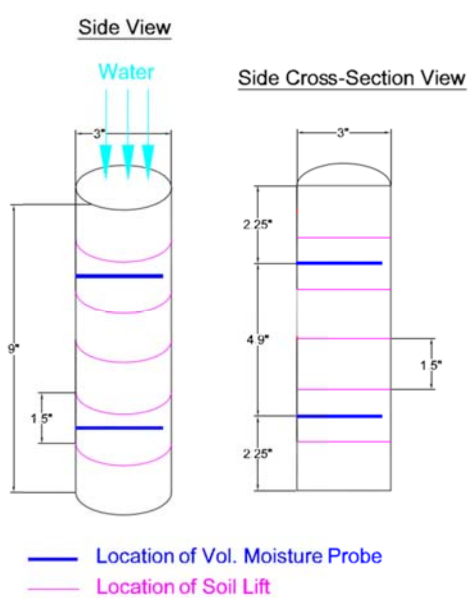

Figure 4.43: Location of Vol. Moisture Probes for Test No. 6.

The sample was completely compacted and the top of surface of the samples was made smooth. The top surface of the sample tube was cleaned for gluing. The completed sample prior to inundation is presented in Figure 4.44 below.

Figure 4.44: Test No. 6 I Compacted Sample with Vol. Probes Installed.

For this experiment water is ponded on the top surface of the soil profile and allowed to infiltrate into the soil. Another clear Plexiglas tube was glued to the top of the sample tube to allow water to be ponded. A plastic bag was sealed at the top to prevent any evaporation. The sample was sealed and stored in the environmental chamber for 24 hours to allow the soil and volumetric probes equilibrate to the soil and surrounding environment. Since volumetric moisture probes were used to record the volumetric water content over time the sample was monitored to determine when the sample equilibrated. This is also useful in determining when the soil in the sample equilibrates and the experiment is completed. The assembled sample for TN6I stored in the environmental chamber is presented in Figure 4.45 below.

Figure 4.45: Test No. 6 I Completed Sample in Environmental Chamber.

The amount of water that was applied to the sample is based on achieving a small change in water content that would still allow the sample to be unsaturated throughout the experiment. The amount of water added to the sample is 120 grams which would allow for a 2-4% change in gravimetric water content. The small amount of water was also chosen so that the sample would change in water content and over time be able to equilibrate to the same water content. The sample was inundated 24 hours after the sample was placed in the environmental chamber and allowed to equilibrate. The sample was inundated on August 12, 2010 and was allowed to run until the sample equilibrated.

The experiment for TN6I ran for 2330 hours. During this period the volumetric moisture probes recorded the water content every 20 minutes. The test was monitored throughout its run time. The water content data stored on the data acquisition unit was downloaded and then imported into an Excel spreadsheet for analysis. The calibration described previously for the Ec-5 probes was used to determine the gravimetric water content of the sample over time. The plot of the water content over time is presented below in Figure 4.46.

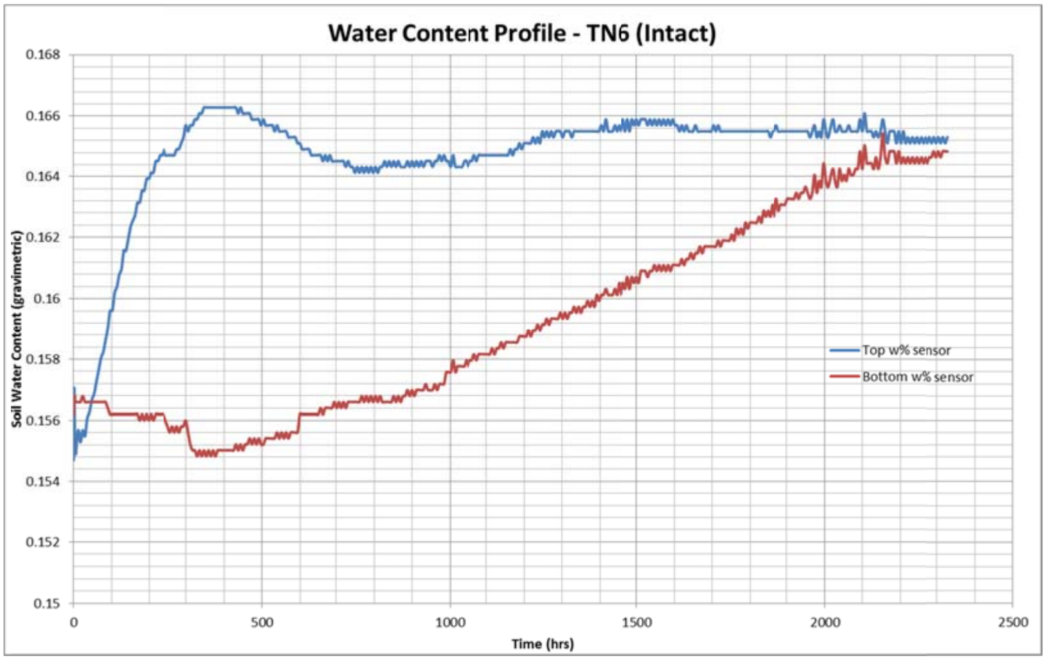

Figure 4.46: Test No .6 I Water Content Profile.

The matric suction is determined using the soil water characteristic curve for the soil. The gravimetric water content data was converted to the volumetric water content and the matric suction is interpolated using the SWCC. The soil suction profile for TN6I is presented in Figure 4.47.

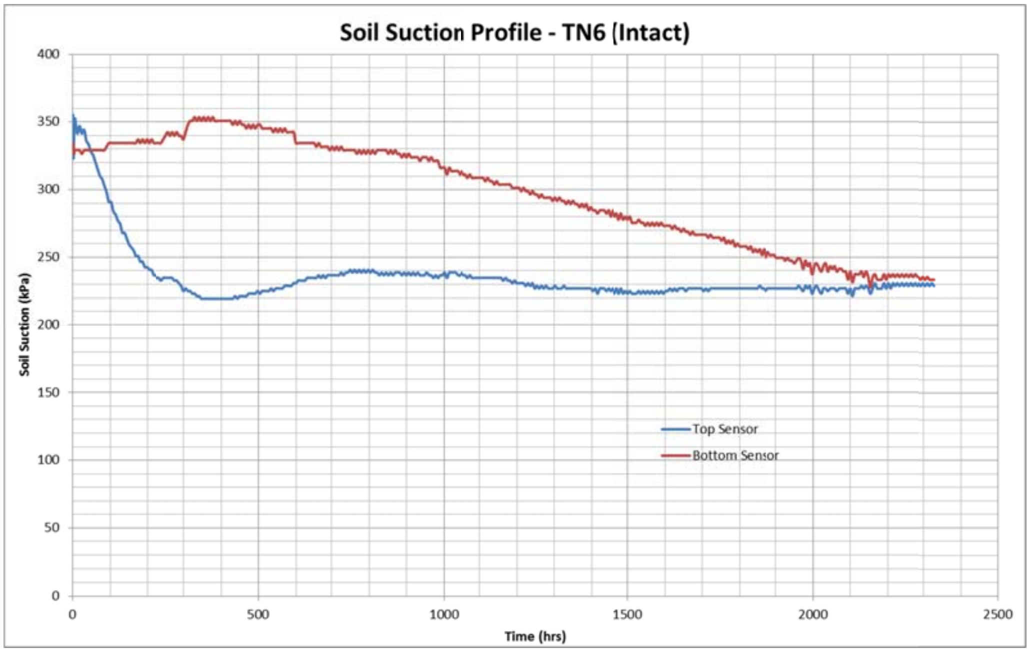

Figure 4.47: Test No. 6 I Soil Suction Profile.

The amount of water ponded on top of the sample was also recorded over time. This is shown in Figure 4.48 below. In the beginning of the experiment the water level drop significantly and then declines at a steady rate.

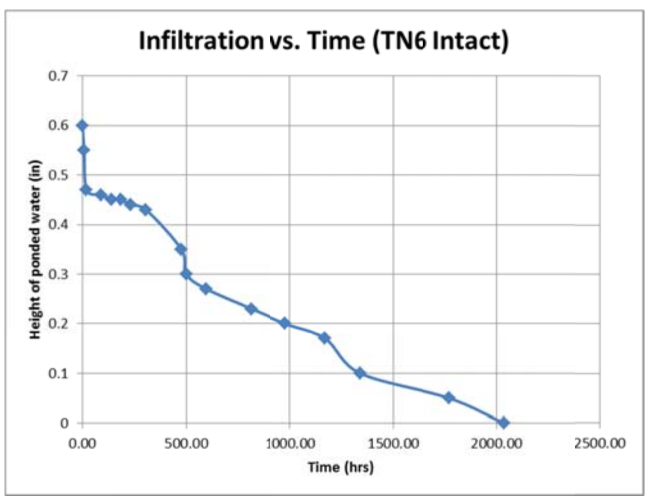

Figure 4.48: Test No. 6 I Infiltration Data.

The calculated unsaturated hydraulic conductivity values for TN6I are presented below. The conductivity values were calculated using the approach previously described in this chapter. The conductivity values were calculated between the two volumetric moisture probes and over 100 hour time periods. The range of conductivity values obtained from TN6I range from 4.2*10^-12 to 5.0*10^-12 m/s over a suction from of 230 to 330 kPa. This data is presented in Figure 4.49 below.

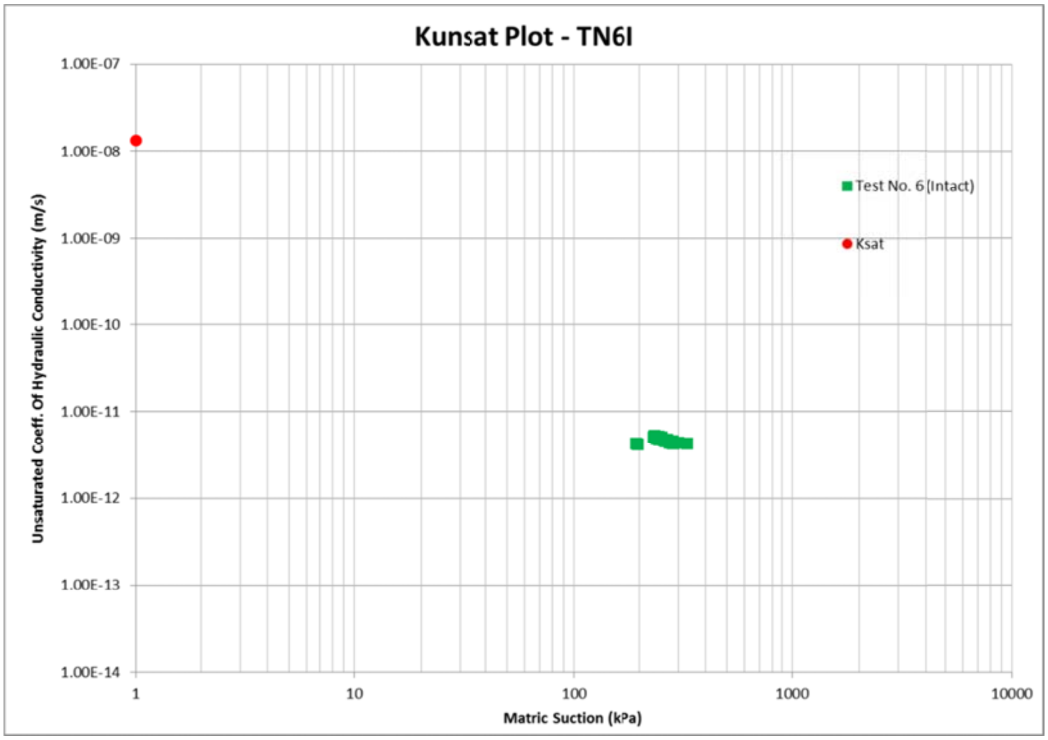

Figure 4.49: Test No. 6 I Coefficients of Unsaturated Hydraulic Conductivity.

Test Number 7:

The instantaneous profile experiment identified as Test Number 7 (TN7) was started on August 13, 2010. This experiment was designed to supplement the intact unsaturated hydraulic conductivity data with points in a lower suction range. TN7 is conducted using the same methods and procedures as described for TN3.

The apparatus used for TN7 is a 9 inch long, 2.5 inch inner diameter clear cylindrical Plexiglas tube. Soil was prepared at approximately 12% and 18% water content for compaction into the sample tubes. The soil was allowed to equilibrate for 24 hours prior to being compacted into the tubes and checked to ensure that the water content was at the desired water content. The water content used for the two soil section was chosen in order to have a good range of suction for the experiment which was 1405kPa to 87kPa for each soil section. This provided a hydraulic gradient of approximately 900. Figure 4.50 below shows the testing apparatus dimensions and the initial water content and suction of the soil.

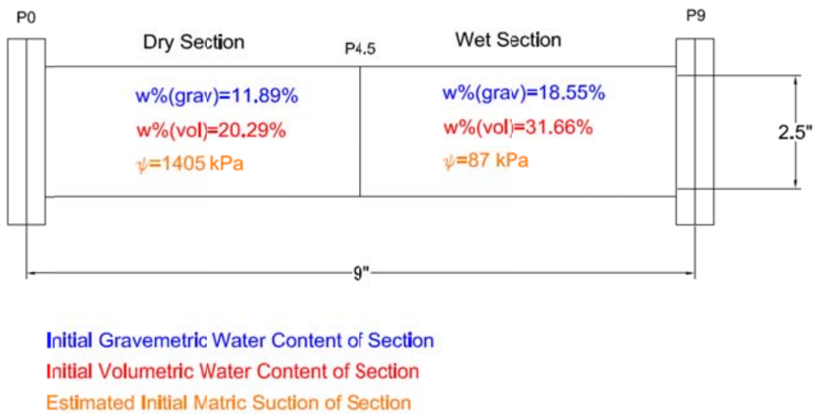

Figure 4.50: Test No. 7 Initial Soil Conditions and Apparatus.

The table below titled Table 4.7 presents the initial testing conditions of the soil and other relevant soil parameters. The initial conditions reported in Table 4.7 were taken from water content measurements during the sample creation. Section 1 is the dry section and section 2 is the wet section. The suction values reported were taken from filter paper samples taken 7 days after sample creation.

Table 4.7: Test No. 7 Initial Soil Conditions.

Section	1	2
Desired w% (grav)	0.12	0.18
Relative Compaction %	0.98	0.98
Dry Density (pcf)	106.5	106.5
Actual w% (grav)	11.89%	18.55%
Actual w% (vol)	20.29%	31.66%
Saturation %	54.47%	84.99%
Matric Suction (kPa)	1405	87
Void Ratio	0.594	0.594

The soil is compacted in the apparatus tubes in 1.5 inch lifts. This is done to help keep the dry density of the soil consistent through the soil profile. To ensure uniform density, each 1.5 inch lift had the amount of soil required to occupy the volume at the required dry unit weight weighted out beforehand. In between each lift the soil is scarified to ensure good contact and continuity between soil lifts. The dry soil section was compacted in the tubes first since the last lift is difficult to make at the top of the tubes. The wet section is placed last since it is easier to manipulate. The soil was compacted in the sample tubes using a standard proctor hammer. The amount of hammer blows required to compact the soil into a 1.5 inch lift decreased as the number of lifts increased. To help with the compaction process marks were put on the sample tubes at 1.5 inch spacing to help with the compaction process. Figure 4.51 below shows the sample tubes with the dry section compacted in the sample tubes and the placement of a filter paper sandwich.

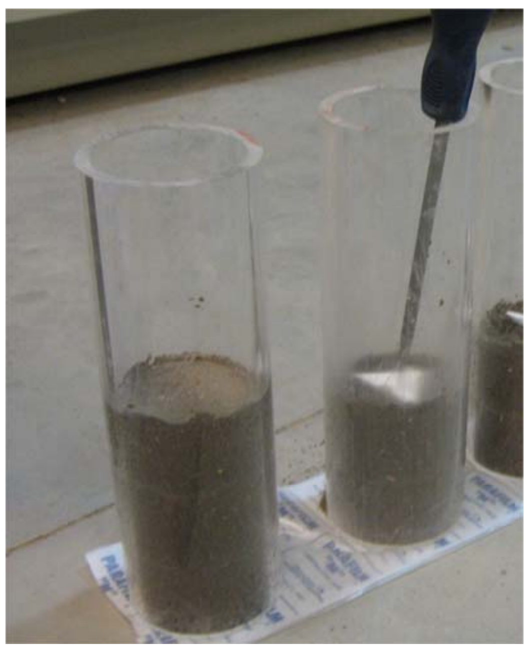

Figure 4.51: Test No. 7 Sample creation and Placement of Filter Paper Sandwich.

For this experiment, the matric suction is measured at five locations. One filter paper sandwich is located in between each soil lift. These locations provide suction measurements throughout the soil profile. Figure 4.52 below, shows the locations of the filter paper sandwiches in the sample tube.

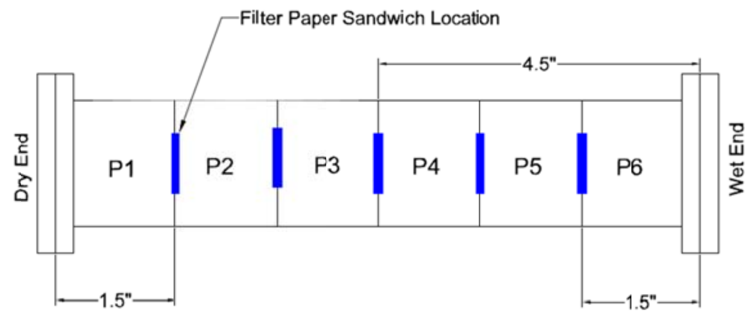

Figure 4.52: Test No. 7 Filter Paper Sandwich Locations.

The soil samples were completely compacted and then sealed at each end using a layer of wax paper and then covered with plastic Saran warp. The plastic warp was then sealed to the tubes with tape. A photo of a completed sample for TN7 is shown in Figure 4.53 below. All the specimens created for TN7 were completed as desired from visual observation.

Figure 4.53: Test No. 7 Finished Compacted Sample.

The sampling procedure for TN7 was performed the same as TN3. The samples for TN7 are extruded, the filter paper is retrieved and water content samples were taken from each soil section. This procedure remains consistent for all instantaneous profile experiments that in cooperates the duplicate method. The process and method for sampling for TN7 was performed as described in the section for TN3.

The total run time for TN7 is 200 days. Four sampling events occurred at the times presented in Table 4.8 below. The sample number, sample date and run time for each specimen in TN7is presented in Table 4.8. In the following Figure 4.54, a photo of the sample on the 200th day of run time is shown to present the color of the soil at the end of the test. From visual observation the soil sections have significantly different color, suggesting that the sample has not reach equilibrium.

Table 4.8: Test No. 7 Sample Run Times and Sampling Event Dates.

Sample Number	Sample Date	Run Time (days)
1	10/2/2010	50
2	12/21/2010	130
3	2/4/2011	175
4	3/1/2011	200

Figure 4.54: TN7 Extruded Sample on Day 200 of Run Time.

The results of the water content and suction measurements from TN7 are presented in the following. The data acquired during the sampling of TN7 was tabulated into a spreadsheet and plots were made to analyze the trends of the water content and suction data. Figures 4.55 and 4.56 show the water content and suction data over time for points in the soil profile. Figures 4.55 and 4.56 show the two soil sections did not reach complete equilibrium in 200 days. During this time period, enough change in water content occurred to calculate hydraulic conductivity values from.

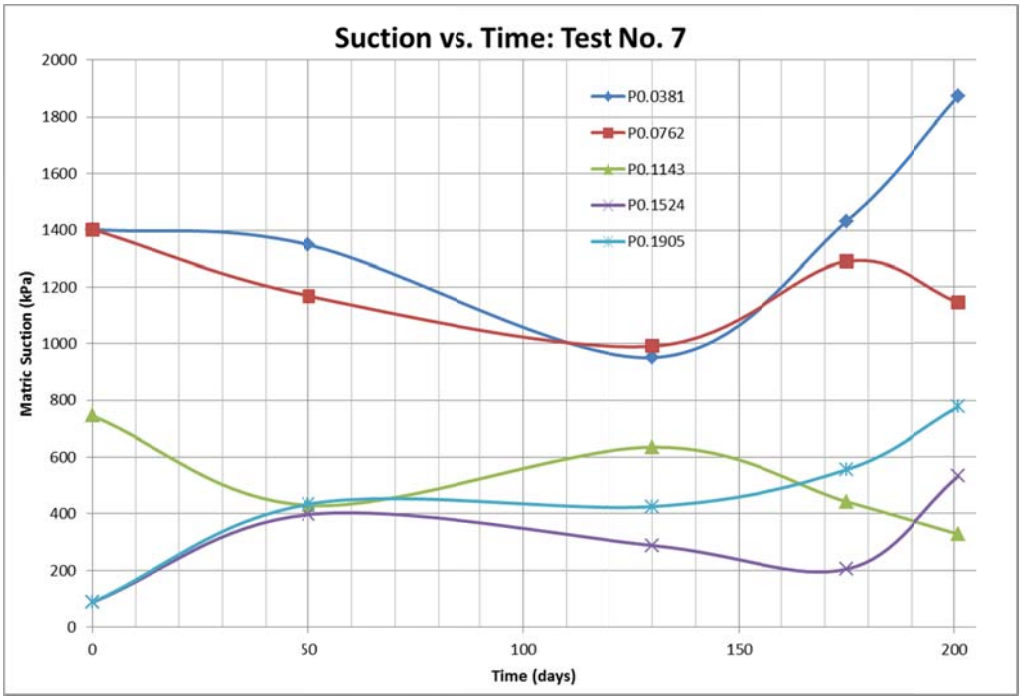

Figure 4.55: Test No. 7 Matric Suction over Time.

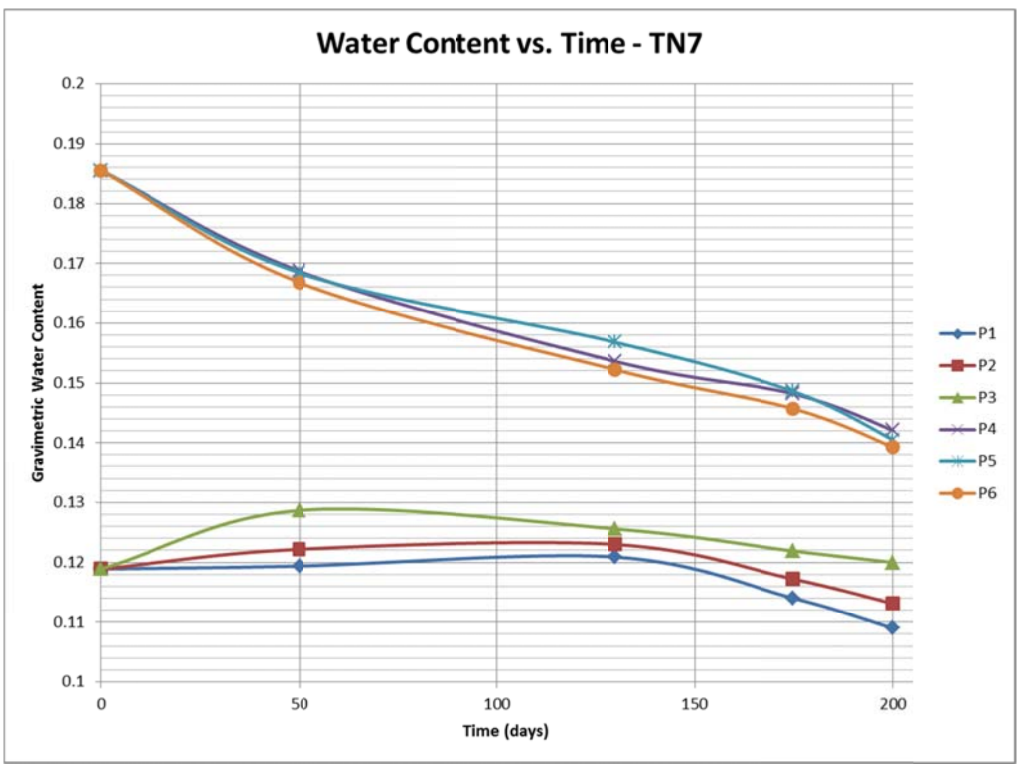

Figure 4.56: Test No. 7 Water Content over Time.

The water content profile for TN7 is presented in Figure 4.57 below. Presented this plot of the water content over time and the soil water content profile, the water content trends from TN7 are good and preformed as desired. It can be observed that change in water content occurred during the test period which infers that water flowed from the wet to dry soil sections. The soil suction profile for TN7 is presented in Figure 4.58.

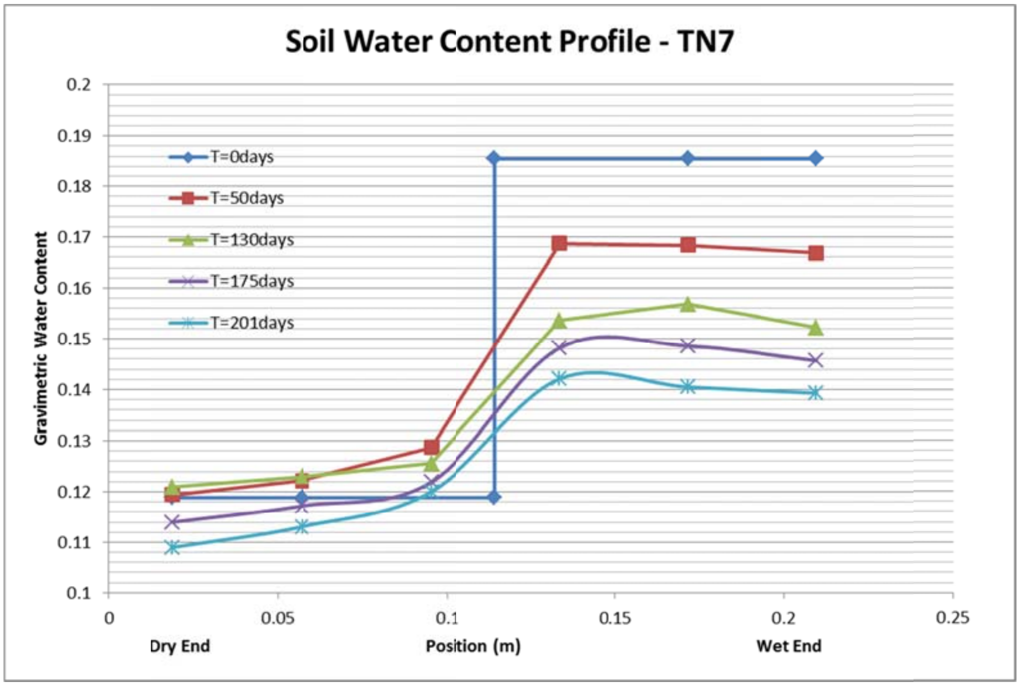

Figure 4.57: Test No. 7 Soil Water Content Profile.

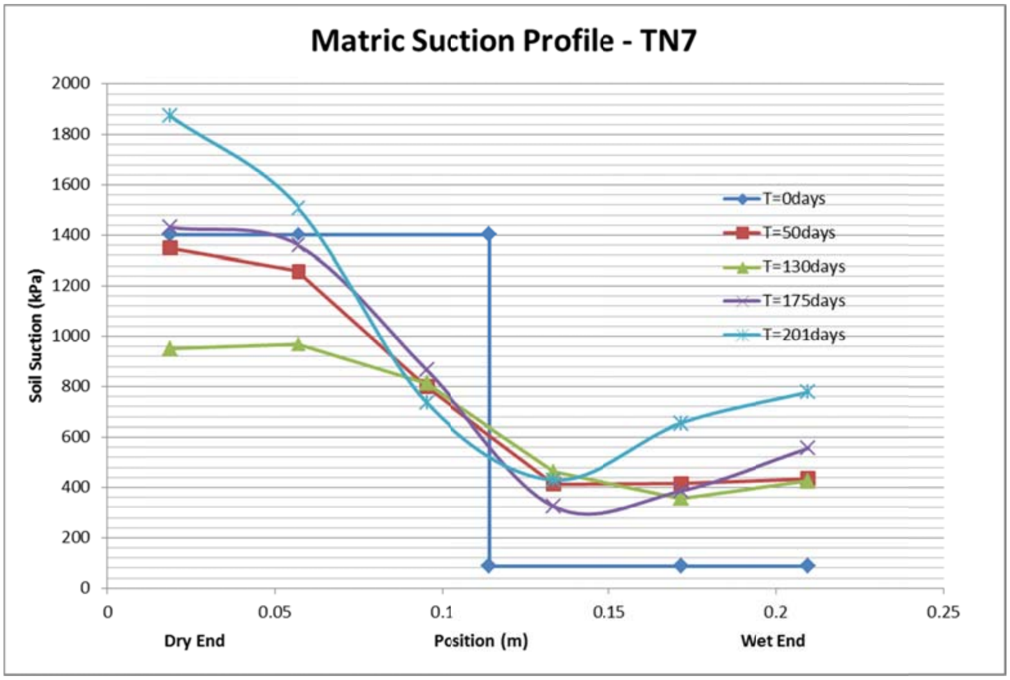

Figure 4.58: Test No. 7 Soil Suction Profile.

The calculated unsaturated hydraulic conductivity values for TN7 are presented below in Figure 4.59. The conductivity values were calculated using the approach previously stated in this chapter over various intervals in the soil profile. The various intervals chosen allow for multiple unsaturated hydraulic conductivity values at different suction values to be obtained. The locations of the various intervals and position locations are shown in Figure 4.50 and are the same as TN3. The unsaturated hydraulic conductivity values obtained from TN7 range over 2.5 orders of magnitude over a range of suction values from 250 to 1,200 kPa.

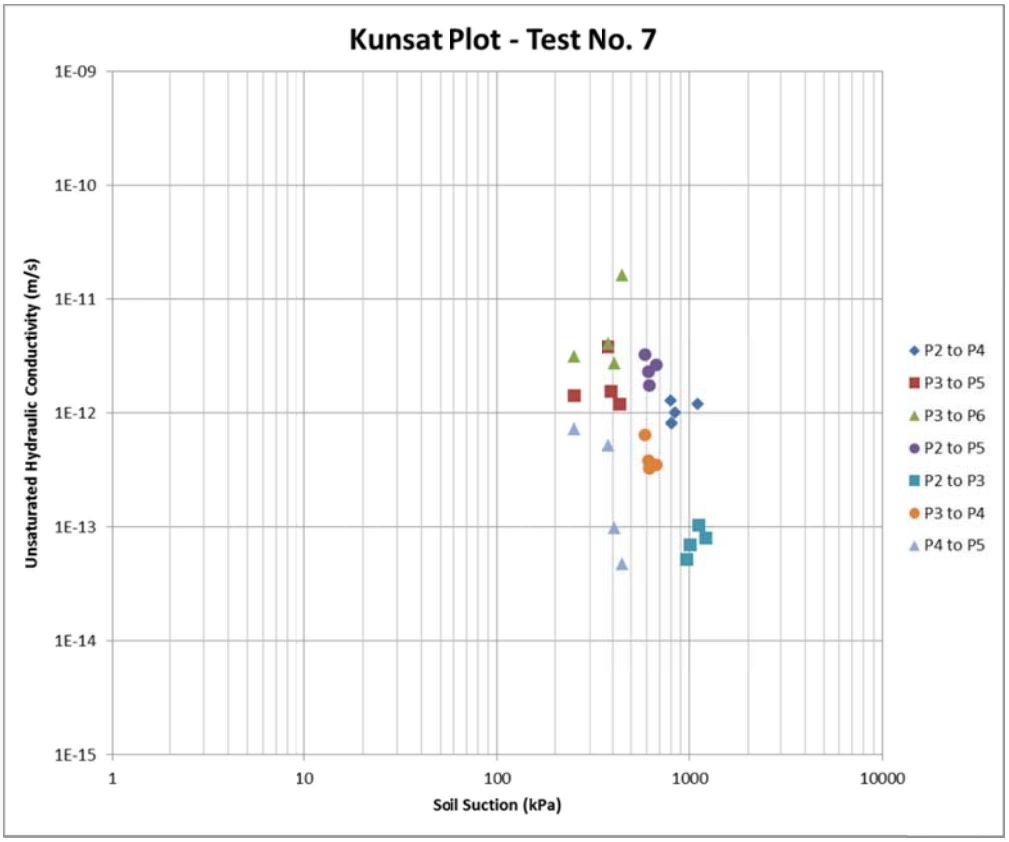

Figure 4.59: Test No. 7 Kunsat Plot.

Cracked Instantaneous Profile Results

The results of the three cracked instantaneous profile experiments are presented in the following section. The initial soil conditions, set up procedures, measurement locations, testing conditions, sampling procedures and observations during the experiments are discussed. The results for each cracked experiment will be presented through the water content and suction trends, the water content and suction profiles, and the unsaturated conductivity, Kunsat plots.

Test Number 4:

The instantaneous profile experiment identified as Test Number 4 (TN4) was started on June 7, 2010. This experiment follows the experimental design discussed for the cracked Method B from chapter 3. The experiment is conducted the same as the intact instantaneous profile experiment TN3 using the duplicate method. The primary difference for TN4 is that the soil profile contains cracks or voids oriented horizontally. For this experiment two sample sets are created. The two sample sets are identified as Set 1 and Set 2. Sample Set 2 has double the crack volume from Set 1.

The apparatus used for TN4 is a 9 inch long, 3 inch inner diameter black PVC cylindrical tube. Soil was prepared at approximately 8% and 14% water content to be compacted into the sample tubes. The soil was allowed to equilibrate for 24 hours prior to being compacted into the tubes and checked to ensure that the water content was at the desired water content. The water content used for the two soil sections was chosen to have a good range of suction during the test which was 6,130kPa to 450kPa for each section. This provided a hydraulic gradient of approximately 9,000. Figure 4.60 below presents the testing apparatus dimensions along with the initial water content and suction values for the soil.

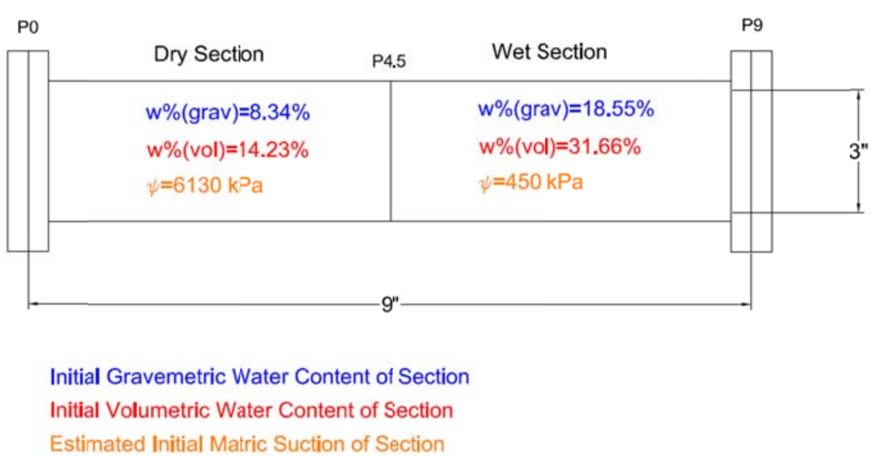

Figure 4.60: Test No. 4 Initial Soil Conditions and Test Apparatus.

The table below titled Table 4.9 presents the initial soil conditions and other relevant parameters. The initial conditions reported in Table 4.9 were taken from water content measurements during sample creation. Section 1 is the dry section and section 2 is the wet section. The suction values reported were taken from filter paper samples taken 7 days after sample creation.

Table 4.9: Test No. 4 Initial Soil Conditions.

Section	1	2
Desired w% (grav)	0.08	0.14
Relative Compaction %	0.98	0.98
Dry Density (pcf)	106.5	106.5
Actual w% (grav)	8.34%	14.85%
Actual w% (vol)	14.23%	25.34%
Saturation %	38.21%	68.04%
Matric Suction (kPa)	6130	450
Void Ratio	0.594	0.594

The soil is compacted in the apparatus tubes in 1.5 inch lifts. This is done the keep the dry density of the soil consistent through the soil profile. To ensure uniform density, for each 1.5 inch lift the amount of soil required to occupy the volume at the required dry density was weighted out beforehand. In between each compaction lift the soil was scarified to ensure good contact and continuity between lifts. The dry soil section was compacted in the tubes first. The last lift is difficult to make at the top of the sample tubes so the wet sections was placed last since it is easier to manipulate. The soil was compacted in the sample tubes using a standard proctor hammer. Figures 4.62 and 4.63 below show the soil being placed and compacted in the tubes, the placement of a filter paper sandwiches and the scarification between soil lifts.

Figure 4.61: Test No. 4 Sample Creation.

Figure 4.62: Test No. 4 Sample Compaction.

Figure 4.63: Test No. 4 Filter Paper Sandwich Placement and Soil Scarification.

Twelve samples were created for TN4 to have six duplicate samples for each set. The samples were compacted using the sampling procedure to the compaction of the soil, scarification between soil layers, the placement of filter paper sandwiches, soil water contents and dry unit weight. For this experiment, the matric suction is measured at five locations in the soil profile. One filter paper sandwich is located in between each soil lift and in between areas in the soil profile has a crack. Figure 4.64 below, shows the locations of the filter paper sandwiches in the sample tube.

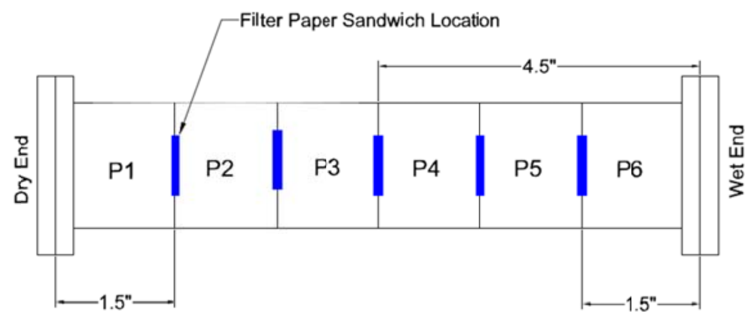

Figure 4.64: Test No. 4 Filter Paper Sandwich Locations.

The horizontal cracks were to be created in the sample tubes using a Silk circular saw. The thickness of the crack was limited by the thickness of the saw blade. A trial experiment was conducted prior to cutting the cracks in the samples for TN4 to measure the actual thickness of the void from the cut. The crack thickness was determined to be 0.13 inches. With this parameter identified the crack depth was then determine in order to achieve a crack to soil volume ratio in the range of 2-5%. This crack ratio was based on other experiments being conducted in relation with this study. The crack ratio is used in order to compare data from other experiments. For Set 1, one crack is located in each soil lift having a total of 6 cracks for each sample. Set 2 has two cracks located in each soil lift having a total of 12 cracks for each sample. To determine the depth of the cut require to achieve a desired crack ratio the following calculation is performed.

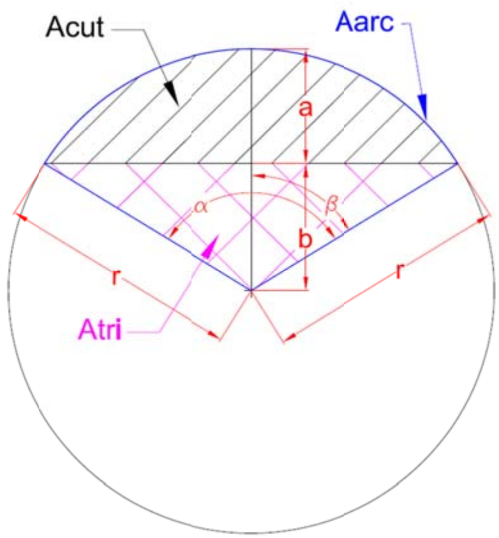

Figure 4.65: Dimension of Crack Cut.

$$A_{ARC} = \frac{\alpha \pi r^2}{360} \quad \text{(Eqn. 4.14)}$$

$$b = r - a \quad \text{(Eqn. 4.15)}$$

$$A_{Tri} = b \times r \quad \text{(Eqn. 4.16)}$$

$$A_{CUT} = A_{ARC} - A_{Tri} \quad \text{(Eqn. 4.17)}$$

$$V_{Crack} = N_{cracks} \times A_{Cut} \times t_{Cut} \quad \text{(Eqn. 4.18)}$$

$$CSVR = \frac{V_{Crack}}{V_{Soil}} \quad \text{(Eqn. 4.19)}$$

A_{ARC}: Area of the circle within the arc.
A_{Tri}: Area of the triangle within the arc.
A_{Cut}: Area of the cut for a given cut depth a.
a: Cut depth of the saw and maximum depth of the crack.
r: Radius of the sample tube = 1.5".
b: Length of base of triangle within the arc.
α: Angle of arc.

$$\alpha = 2\cos^{-1}\left(\frac{b}{r}\right) \quad \text{(Eqn. 4.20)}$$

V_{Crack}: Volume of crack space.
N_{Cracks}: Number of cracks in a sample.
t_{Cut}: Thickness of void made by saw cut = .13"
$CSVR$: Crack to soil volume ratio.
V_{Soil}: Volume of soil.

A cut depth, a, is 1.2 inches and is used for both sample sets. This provides crack ratios of 3.23% for Set 1 and 6.45% for Set 2. To create the cuts into the soil sample the cracks were located 1.5 inches apart for Set 1 and 0.5-0.8 inches apart for Set 2. The cracks were positioned in locations where the distance between a crack and filter paper sandwich was maximized. Figure 4.66 presents the layout of the crack locations. The crack locations were marked on the sample tubes prior to cutting. Figure 4.67 presented a competed samples specimens prior to cutting.

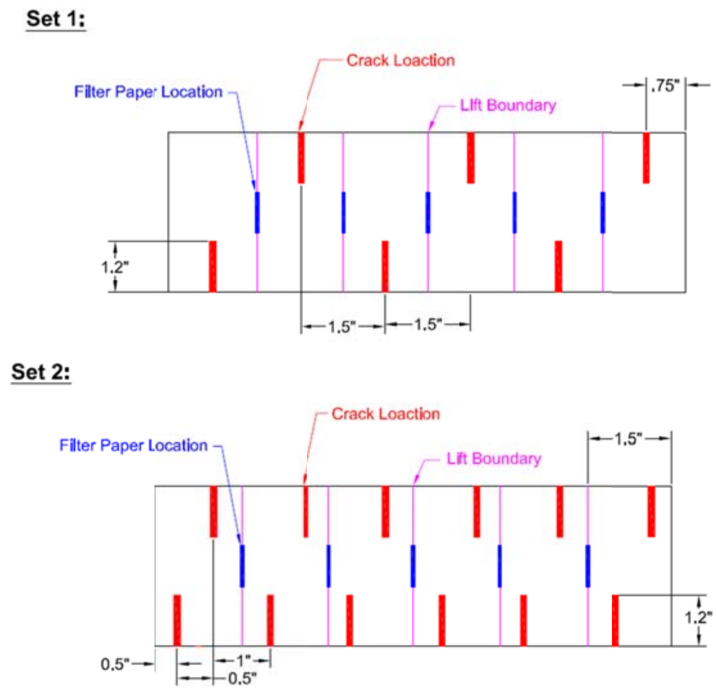

Figure 4.66: Test No. 4 Cracks Locations for Sets 1 and 2.

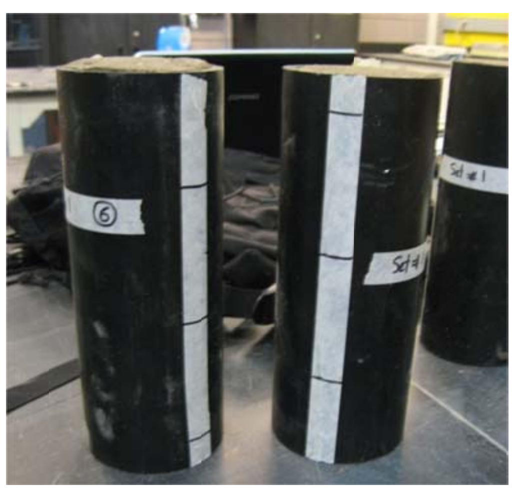

Figure 4.67: Test No. 4 Completed Samples.

The sample sets were cut using the silk saw at the desired locations. The soil created significant resistance when cutting especially in the dry soil sections. The blade sharpness dulled rapidly from cutting through the soil. Once the crack were cut into the samples the void created by the cuts were cleaned of any unwanted particles created from cutting. Plastic shavings from cutting through the plastic was loosely scattered in the cracks and was easily removed. Great care had to be taken in cutting cracks for sample Set 2. Due to the short distance between crack locations the cracks were cut slowly in order not to create any unwanted disturbance such as creating internal cracks and pushing the soil and closing adjacent crack spaces. Figures 4.68 and 4.69 below present photos of the samples from Set 1 and 2 with the cracks cut and cleaned.

Figure 4.68: Test No. 4 Set 1 Cut Sample.

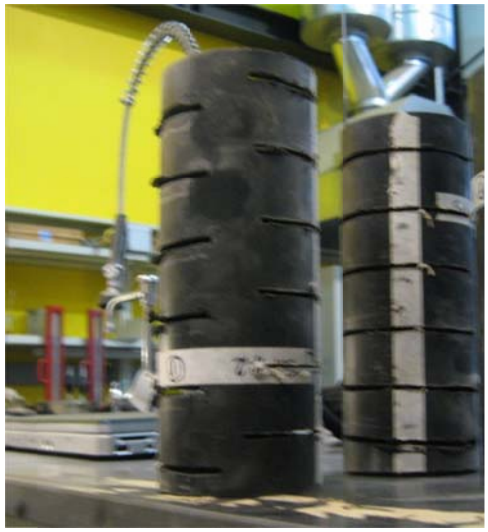

Figure 4.69: Test No. 4 Set 2 Cut Sample.

All the samples created except one sample were completed as desired from visual observation. Figure 4.70 shows the damage the sample in Set 2. The sample damage should be insignificant since the end portions of the samples are not considered or significant when calculating hydraulic conductivity values. The soil samples were completely compacted and sealed at each end using a layer of wax paper and then covered with plastic Saran warp. The plastic warp was then sealed to the tubes with tape. Figure 4.71 presents the samples prior to storage in the environmental chamber.

Figure 4.70: Test No. 4 Sample Damage.


Figure 4.71: Test No. 4 Sealed Samples.

The sampling procedure for TN4 was performed the same as TN3 and TN7. Samples were extruded, the filter paper was retrieved and water content samples were taken from each soil section. The procedure remains consistent for all instantaneous profile experiments that use the duplicate method. The process and methods for sampling for TN4 that are performed are described in the section for TN3.

The soil samples were successfully extruded from the sample tubes. From visual inspection during sampling the sample specimens cracks remained open throughout the run time of the experiment. From the extrusion process, some of the crack spaces in the dry soil sections tended to close up due to the friction between the sample tube and the soil. Figure 4.72 below shows this issue though it did not seem to impact the results.


Figure 4.72: Test No. 4 Extruded sample.

The total run time for TN4 was 300 days. Five sampling events occurred at increasing time intervals between sampling events. The sample number, sample date and run time for each specimen for TN7 is presented in Table 4.10 below. Presented below is a photo of the samples from each sample set on the 300th day of run time in Figure 4.73. From visual observation the soil sections appear to have significantly different color suggesting that the sample did not reach equilibrium.

Table 4.10: Test No. 4 Sample Run Times and Sampling Dates.

Sample Number	Sample Date	Run Time (days)
1	7/27/2010	50
2	9/15/2010	100
3	12/27/2010	203
4	2/14/2011	252
5	3/3/2011	300

Figure 4.73: Test No. 4 Extruded Samples on Day 300.
(Set 1 Left, Set 2 Right Photo)

The results of the water content and suction measurements from TN4 are presented in Figures 4.76 and 4.79. Individual plots for each sample set of the water content and suction measurements are presented in Figure 4.74, 4.75, 4.77, and 4.78. The data acquired from testing is tabulated into a spreadsheet and plots were made to analyze trends in the water content and suction data. In Figures 4.75 and 4.78, is can be observed that the samples did not reach complete equilibrium in 300 days of run time. During the testing period enough change in water content occurred to calculated hydraulic conductivity values. From Figure 4.76 of the suction data shows that the suction trends for each set is very different.

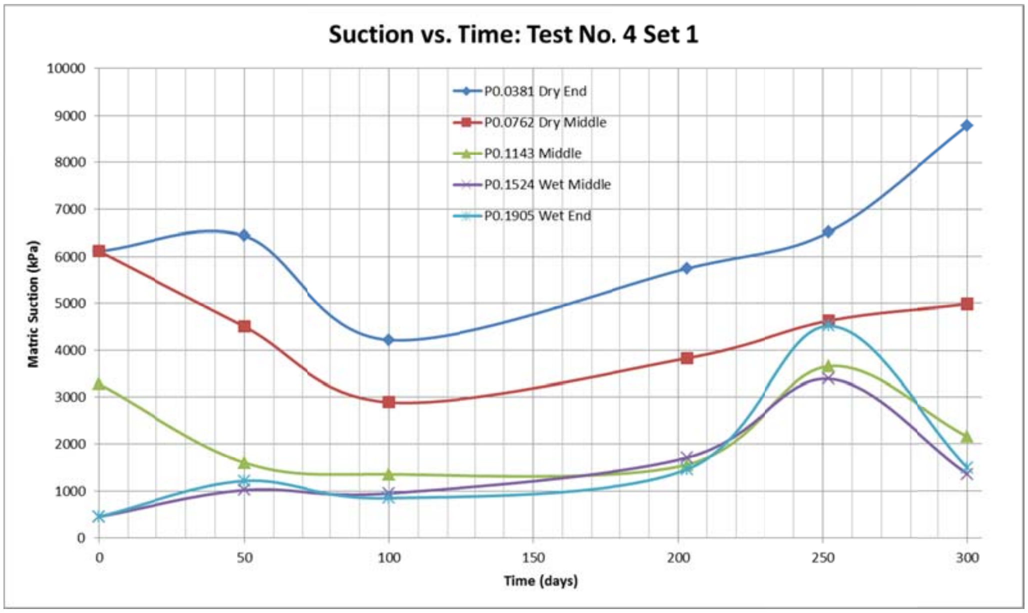

Figure 4.74: Test No. 4, Set 1, Matric Suction over Time.

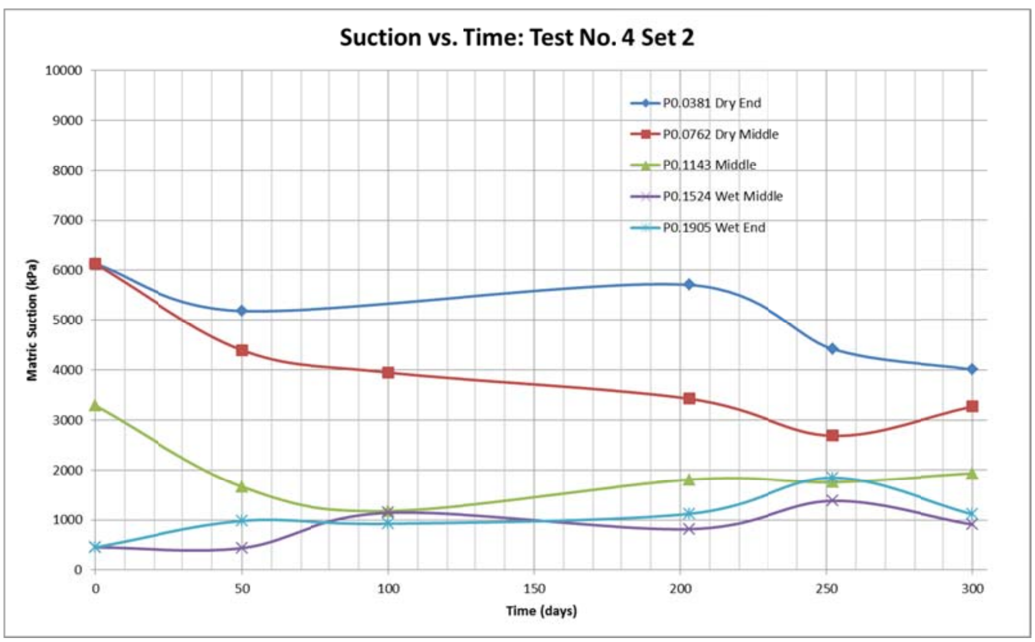

Figure 4.75: Test No. 4, Set 2, Matric Suction over Time.

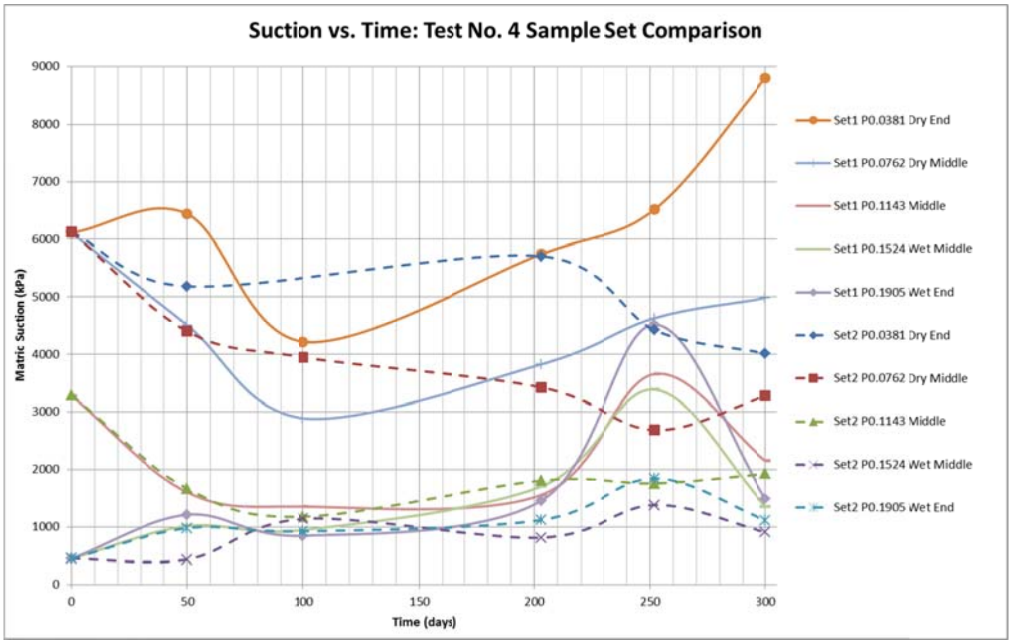

Figure 4.76: Test No. 4 Matric Suction over Time Sample Set Comparison.

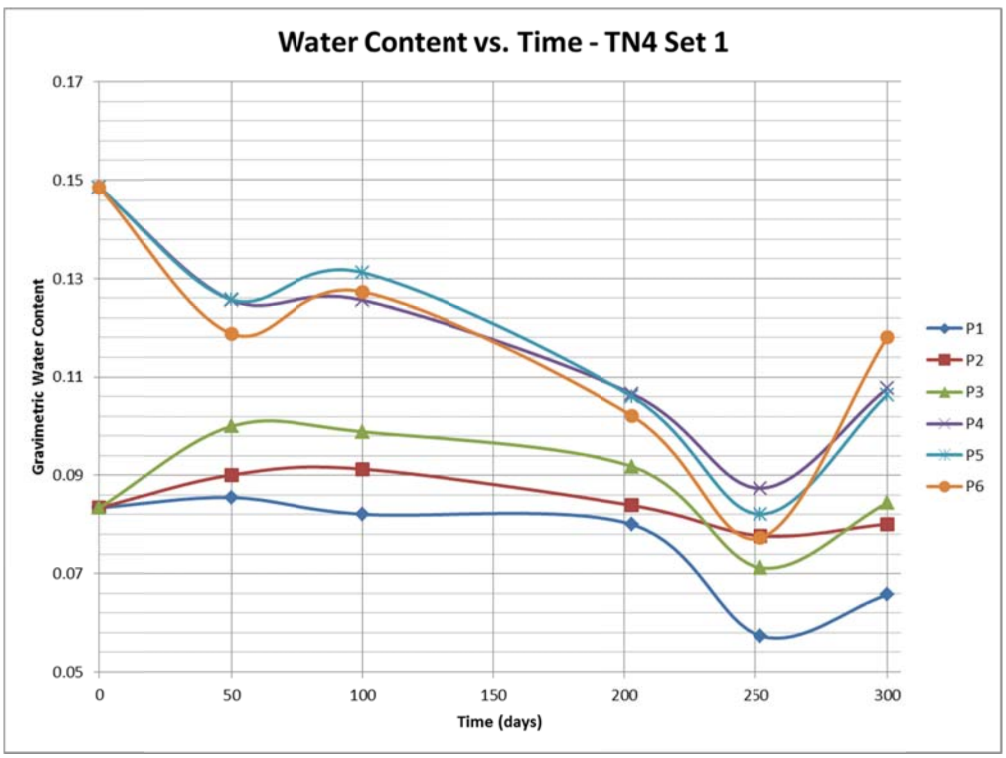

Figure 4.77: Test No. 4, Set 1, Water Content over Time.

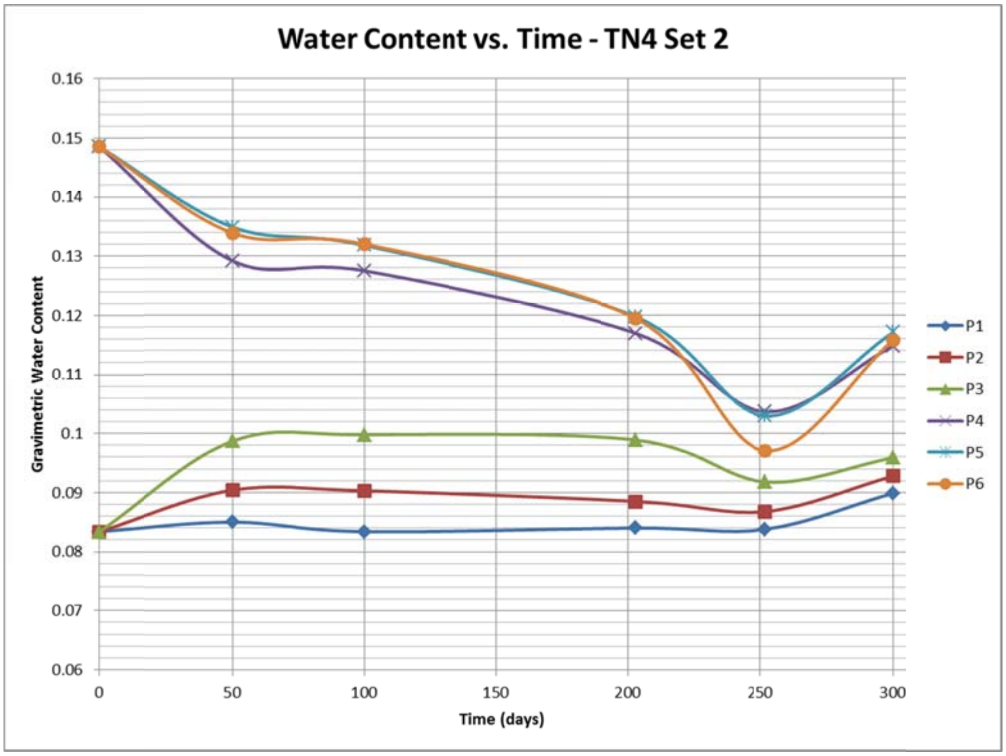

Figure 4.78: Test No. 4, Set 2, Water Content over Time.

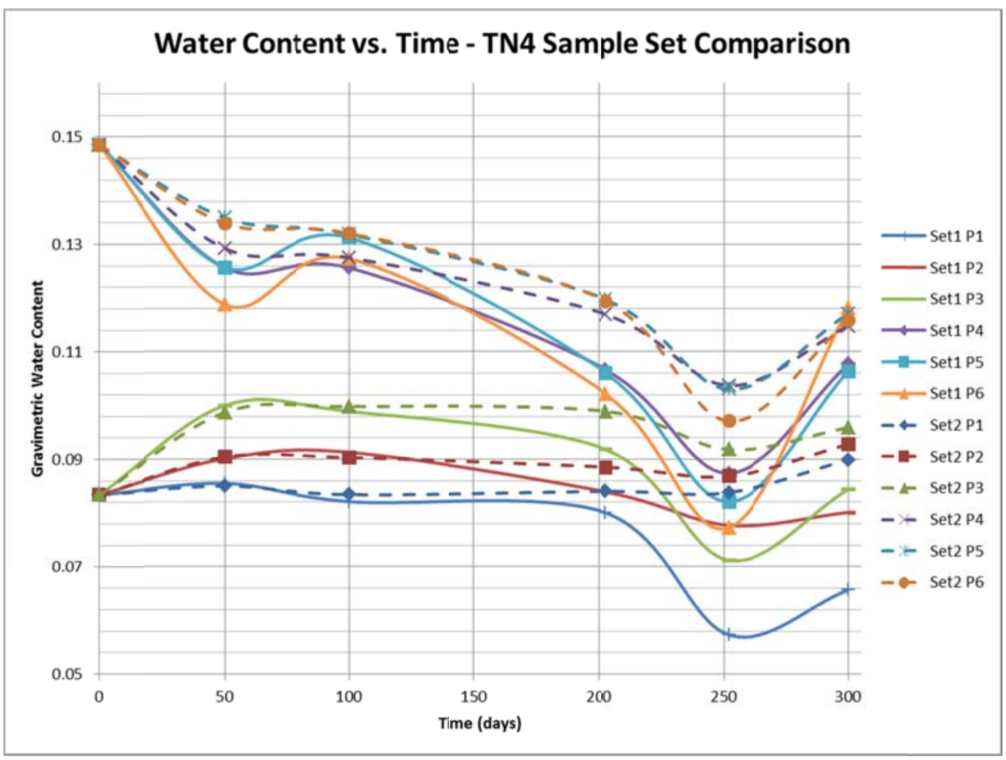

Figure 4.79: Test No. 4 Water Content over Time Sample Set Comparison.

The water content trends as shown in Figure 4.76 show that the trends in water content for each set are slightly similar. Both sample sets show deviation from the expected trends on the 252nd day of run time. The sampling events of the 252nd day of run time had observations that the specimens sampled from both sets were very loose in the sample tubes. From observation the soil seem to shrink inside the sample tubes for both sample sets. Due to this issue the water content and suction data from this sampling event is not used in the calculation of the unsaturated hydraulic conductivity for this sample interval. If this data is removed from the water content and suction plot over time the plots show better trends. The water content and suction measurements over time for both sample sets with the data on the 252nd day are removed and presented in Figures 4.80 and 4.81 and is used in the calculation of Kunsat for TN4.

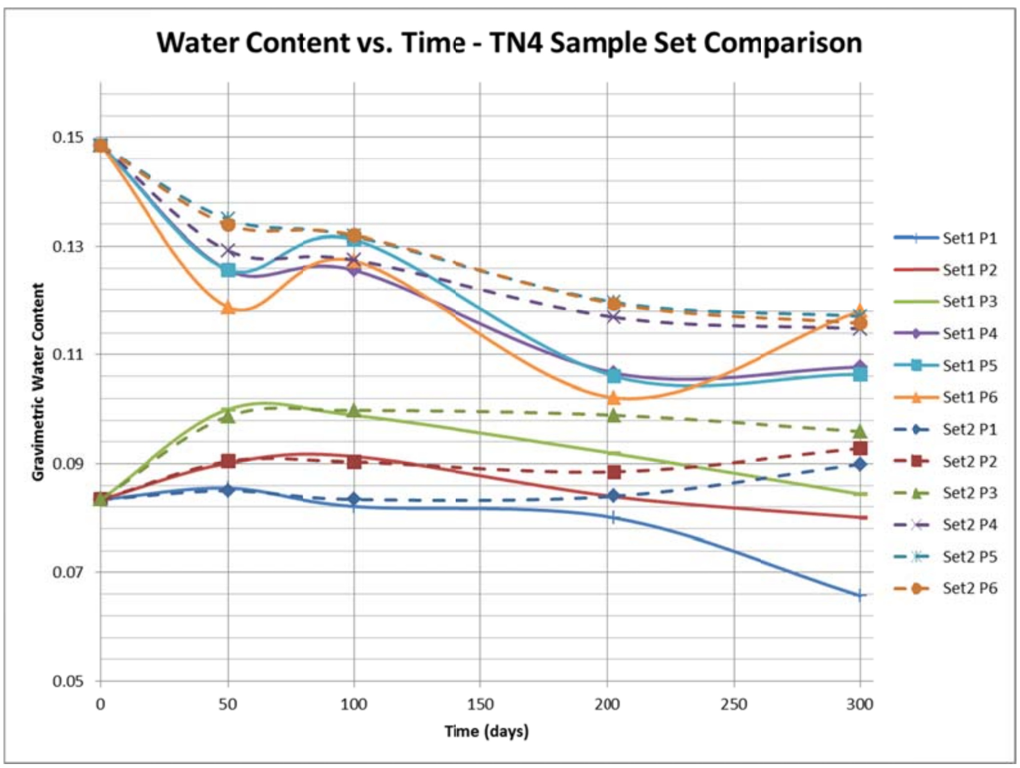

Figure 4.80: Test No. 4 Corrected Water Contents over Time for Both Sample Sets.

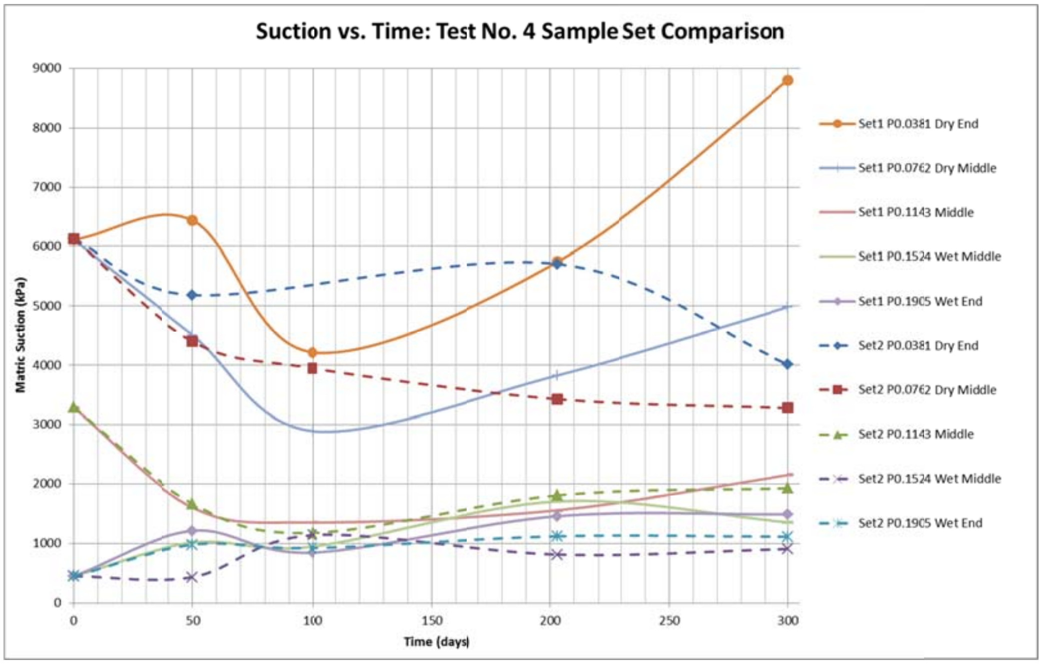

Figure 4.81: Test No. 4 Corrected Suction over Time for Both Sample Sets.

The water content and suction profiles for each sample set from TN4 is presented below in Figure 4.82, 4.83, 4.85 and 4.86. Note that the water content and suction data for Set 1 on the 252th day is not used. The comparison of water content and suction profiles for both sample set is presented in Figures 4.84 and 4.87.

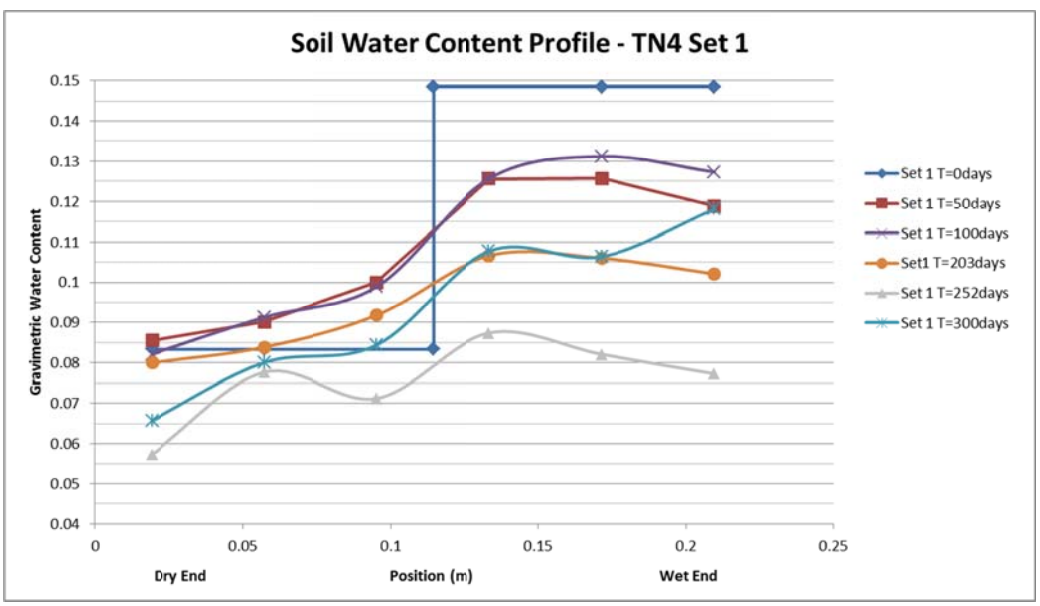

Figure 4.82: Test No. 4, Set 1, Water Content Profile.

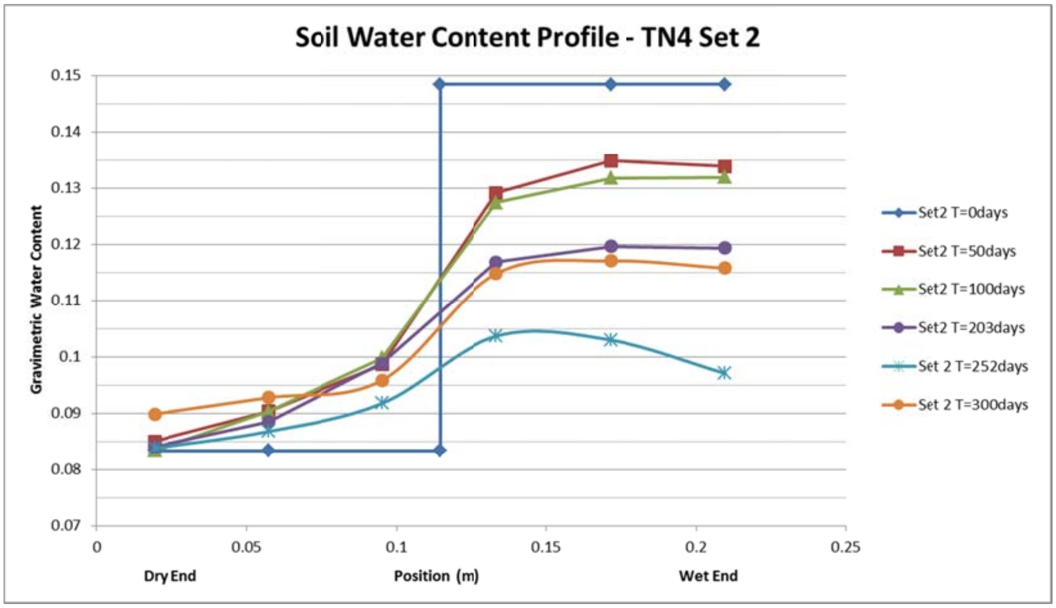

Figure 4.83: Test No. 4 Set 2, Water Content Profile.

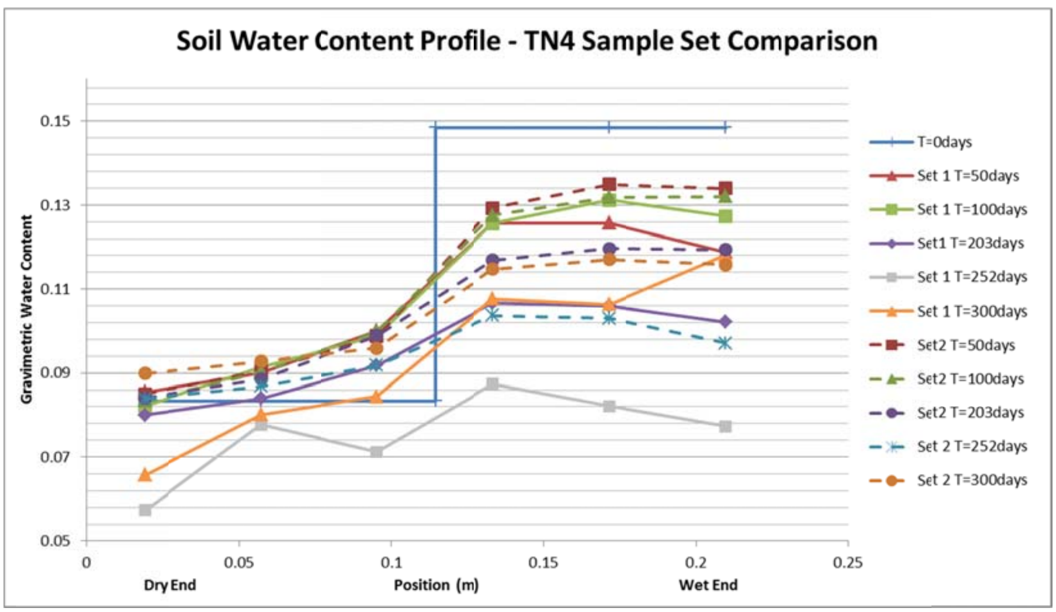

Figure 4.84: Test No. 4 Water Content Profile Set Comparison.

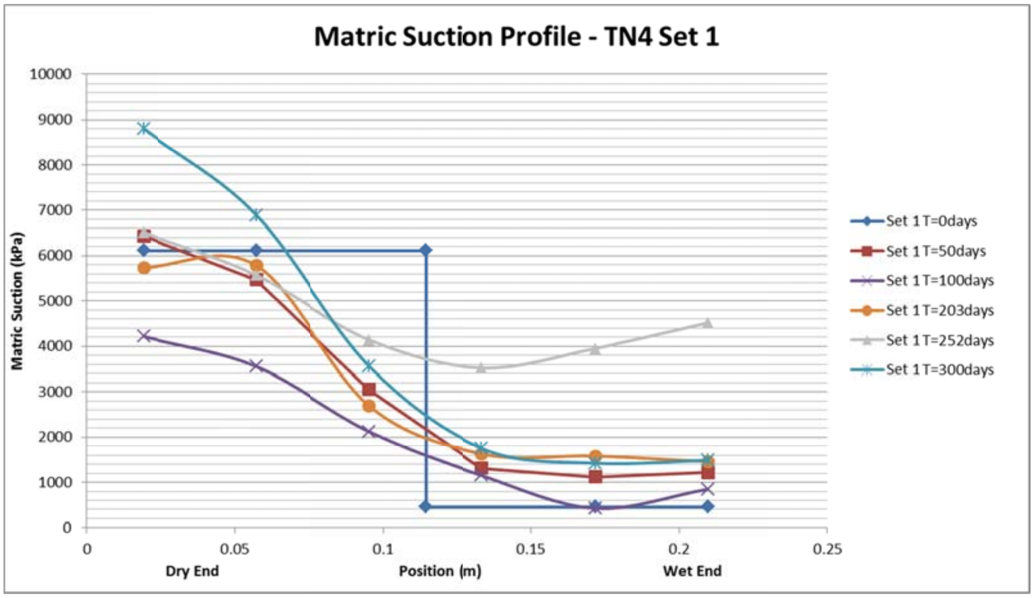

Figure 4.85: Test No. 4, Set 1, Matric Suction Profile.

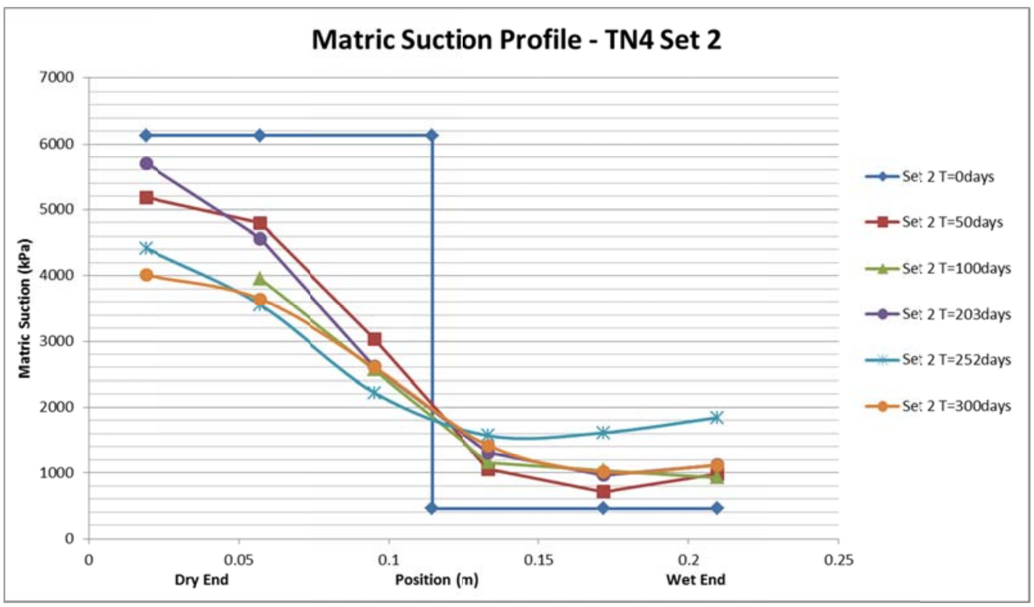

Figure 4.86: Test No. 4, Set 2, Matric Suction Profile.

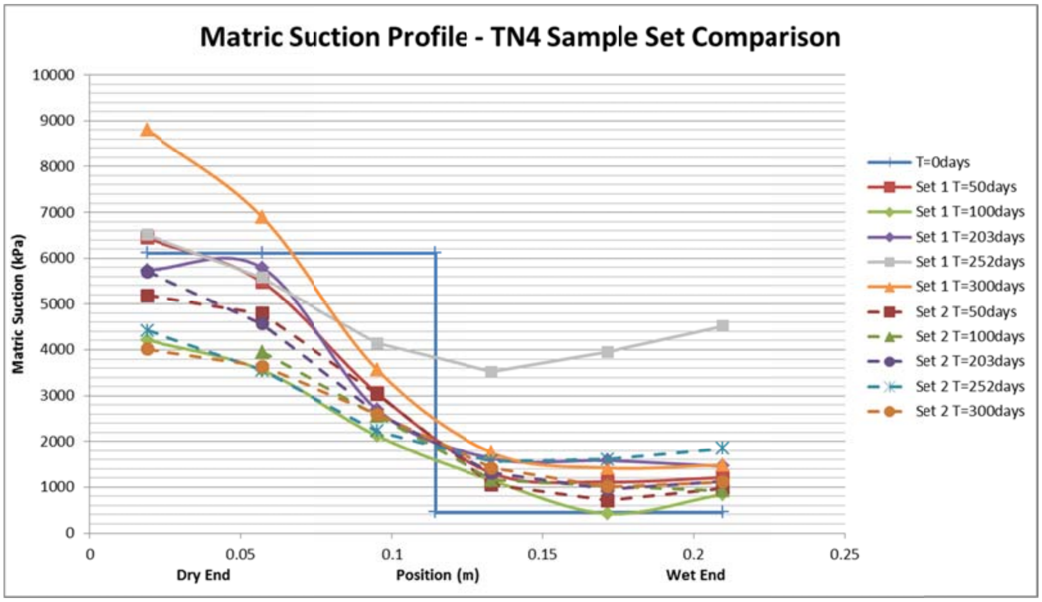

Figure 4.87: Test No. 4 Matric Suction Profile Set Comparison.

The calculated unsaturated hydraulic conductivity values for TN4 for each sample set are presented in Figures 4.88 and 4.89. The conductivity values were calculated using the approach previous stated in this chapter over various intervals with in the soil profile. The various intervals chosen are used to gain multiple hydraulic conductivity values in different suction ranges. The locations of the intervals presented in the figures below are shown in Figure 4.63 and are the same as TN3. The Kunsat plot presented in Figure 4.90 shows the results from both sample sets together. The data shows no significant difference between sample sets.

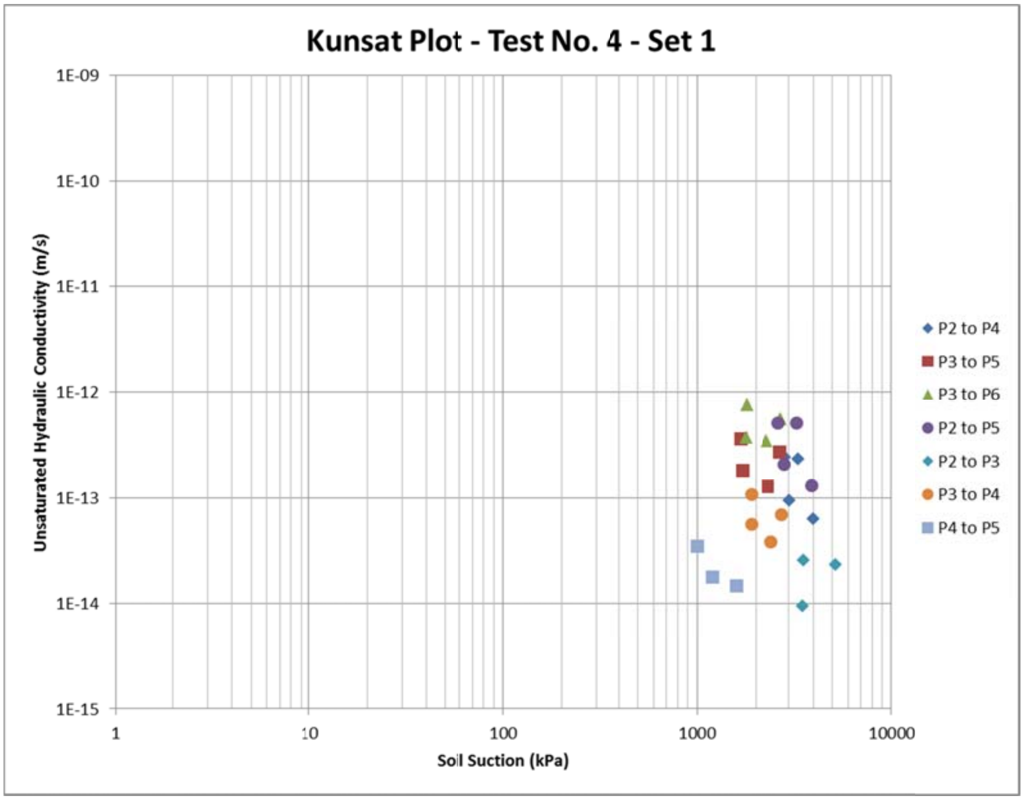

Figure 4.88: Test No. 4, Set 1, Kunsat Plot.

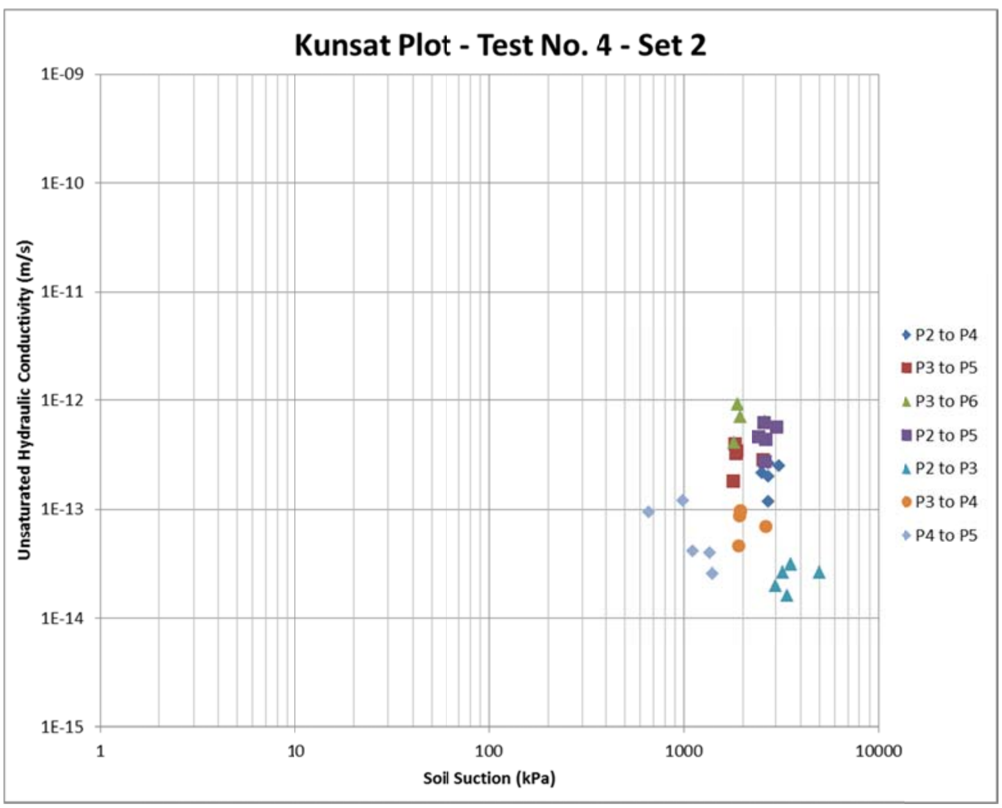

Figure 4.89: Test No. 4, Set 2, Kunsat Plot.

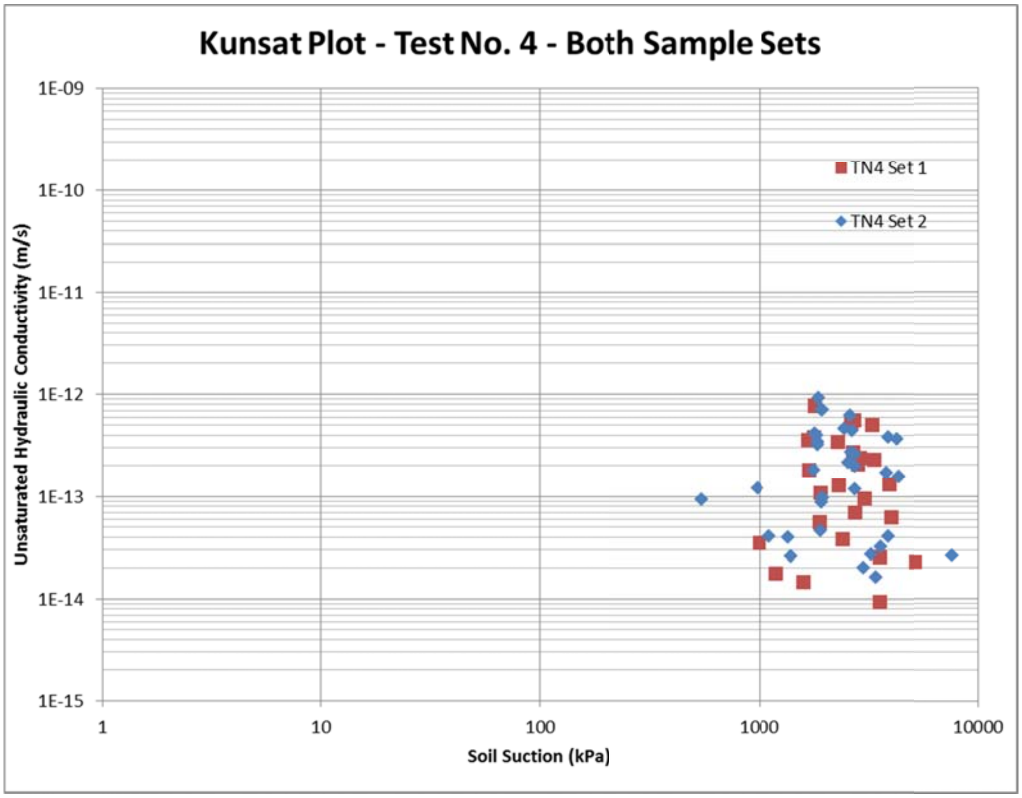

Figure 4.90: Test No. 4, Kunsat Plot of Both Sample Sets.

Test Number 5:

The instantaneous profile experiment identified as Test Number 5 (TN5) was started on July 14, 2010. The experiment follows the experimental design discussed for the cracked Method C. This experiment is conducted the same manner as the intact instantaneous profile experiment TN3 using the duplicate method. The primary difference for TN5 is that the soil profile contains an air gap between two soil sections of different water content. For this experiment two sample sets are created. The two sample sets are identified as sample Set 3 and Set 4. Sample Set 3 has a smaller gap width than sample Set 3.

The apparatus used for TN5 is a 9 inch long, 2.5 inch inner diameter clear Plexiglas cylindrical tube. Soil was prepared at approximately 8% and 19.5% water content to be compacted into the sample tubes. The soil was allowed to equilibrate for 24 hours before being compacted into the sample tubes and checked to ensure that the water content was at desired water content. The water content used for the two soil section was chosen in order to have a good range of suction values during the test which was 14,000kPa to 15kPa for each section. This provides a hydraulic gradient of approximately 12,500. A large hydraulic gradient was chosen to drive moisture flow and allow for significant evapotranspiration over the air gap between the soil sections. Figure 4.91 below presents the testing apparatus dimensions and the initial water content and soil suction.

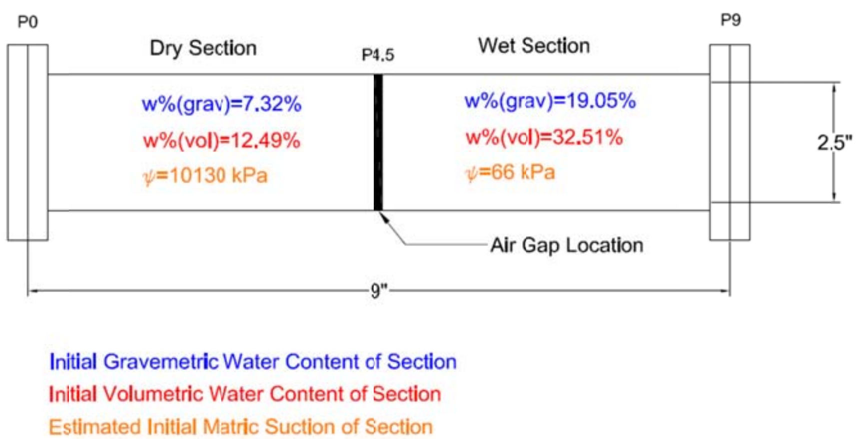

Figure 4.91: Test No. 5 Initial Soil Conditions and Test Apparatus.

The table below titled Table 4.11 presents the initial soil conditions and other relevant parameters. The initial conditions reported in Table 4.11 were taken from water content measurements during the sample creation. Section 1 is the dry section and section 2 is the wet section. The suction values reported were taken from filter paper tests taken 7 days after sample creation.

Table 4.11: Test No. 5 Initial Soil Conditions.

Section	1	2
Desired w% (grav)	0.08	0.195
Relative Compaction %	0.98	0.98
Dry Density (pcf)	106.5	106.5
Actual w% (grav)	7.32%	19.05%
Actual w% (vol)	12.49%	32.51%
Saturation %	33.54%	87.28%
Matric Suction (kPa)	10130	66
Void Ratio	0.594	0.594

A sample creation was used to create and compact the sample so that an air gap exists in between the two soil sections. Both soil sections 1 and 2 where first compacted into the sample tube with the same sample height. This is presented in Figure 4.92 below. The soil is compacted in the apparatus tubes in 1.5 inch lifts. To ensure uniform density for each 1.5 inch lift the amount of soil required to occupy the volume at the required dry density is weighted out beforehand. In between each lift the soil is scarified to ensure good contact and continuity between lifts.

Figure 4.92: Test No. 5 Soil Sections Compacted in Sample Tubes.

Twelve samples are created for TN5. Six duplicate samples are created for each sample set. The samples are created using the same procedure as to the compaction of the soil, scarification between soil layers, placement of filter paper, the soil water content and dry unit weight. For this experiment, the matric suction is measured at four locations in each sample. One filter paper sandwich is located in between each soil lift. No filter paper was placed at the air gap interface. These locations provide suction measurements throughout the soil profile. Figure 4.93 below shows the locations of the filter paper sandwiches in the sample tube.

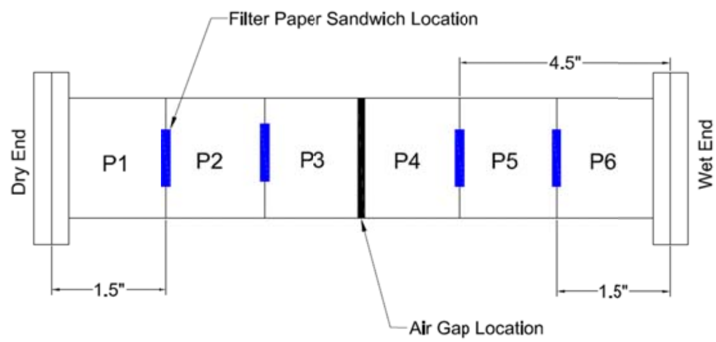

Figure 4.93: Test No. 5 Filter Paper Sandwich Locations.

Both soil sections are compacted in the sample tubes and the dry soil section is push into the sample tube of the wet soil section. This is done using an extruder as shown in Figure 4.94 below. This method worked well in producing the desired air gap width. Using the clear tubes is required to visible see the width of the air gap. A photo of the extruded sample for Set 3 is shown in Figure 4.95. After the dry soil section was pushed into the sample tube the samples were sealed and stored in the environmental chamber.

Figure 4.94: Test No. 5 Sample Creation Extruding Process.

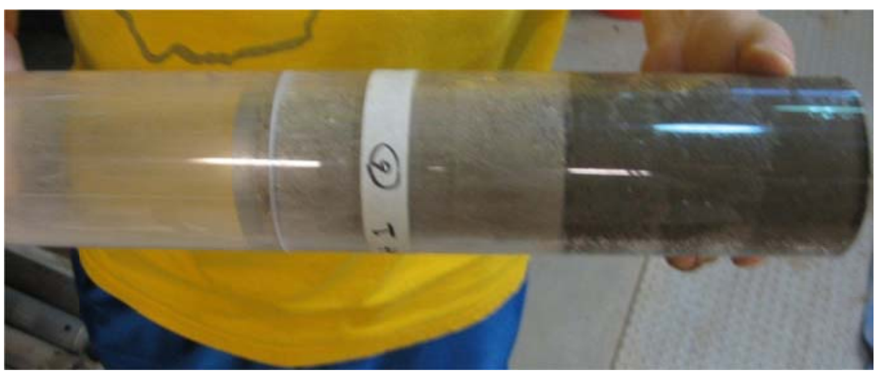

Figure 4.95: Test No. 5 Sample after Sample Extrusion.

The two sample sets air gap widths are different for comparison to the conductivity as a function of the width of the air gap. Set 3 has an air gap width of 0.125 inches and Set 4 has an air gap width of 0.375 inches. Presented in Figure 4.96 and 4.97 are the two sample sets showing the air gaps created from the extrusion process. The width of the air gap varies slightly due to the roughness of the soil surfaces but the width reported are based on average measurements taken after the sample were created.

Figure 4.96: Test No. 5 Set 3 Air Gap.

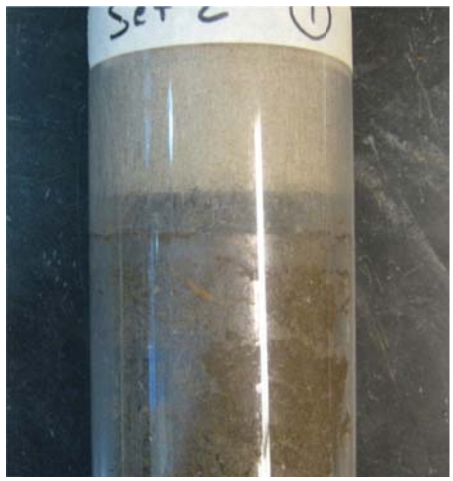

Figure 4.97: Test No. 5 Set 4 Air Gap.

The sampling procedure for TN5 is performed the same as TN3, TN4, and TN7. Samples were extruded, the filter paper was retrieved and water content samples were taken from each soil section. This procedure remains consistent for all instantaneous profile experiments that in cooperates the duplicate method. The process and methodology for sampling in TN5 is performed as described for TN3.

The soil samples for TN5 were able to be successfully extruded from the sample tubes. From visual inspection during sampling the air gaps remained at the specified width with some slight insignificant swelling that occurred during the experiment. The air gap width for all the samples remained very close to the gap width created at the time of sample creation. Figure 4.98 presents a picture of samples from Sets 3 and 4 showing the air gaps before a sampling event. During extrusion of the samples it was observed that water flowed from the wet to dry soil section. This can be seen in Figure 4.99.

Figure 4.98: Test No. 5 Specimen Conditions at Day 250 of Run Time.

The total run time for TN5 was 250 days. Five sampling events occurred at increasing time intervals between sampling events. The sample number, sample date and run time for each sample specimens for TN5 is presented in Table 4.12. From visual observation the soil sections appear to have significantly different color suggesting that the sample did not reach equilibrium.

Table 4.12: Test No. 5 Sample Run Times and Sampling Dates.

Sample Number	Sample Date	Run Time (days)
1	9/2/2010	50
2	10/22/2010	100
3	12/21/2010	160
4	1/30/2011	200
5	3/21/2011	250


Figure 4.99: Test No. 5 Extruded Sample on Day 250 of Run Time.

The results of the water content and suction measurements from TN5 for both sample sets are presented in Figures 4.102 and 4.105. Individual plots for each sample set of the water content and suction measurements are presented in Figure 4.100, 4.101, 4.103, and 4.104. The data obtained from the experiment was tabulated into a spreadsheet and plots were made to analyze the trends in the water content and suction data. In Figures 4.102 and 4.105, show that the samples did not reach complete equilibrium after 250 days of run time. During the testing period enough change in water content occurred to calculated hydraulic conductivity values.

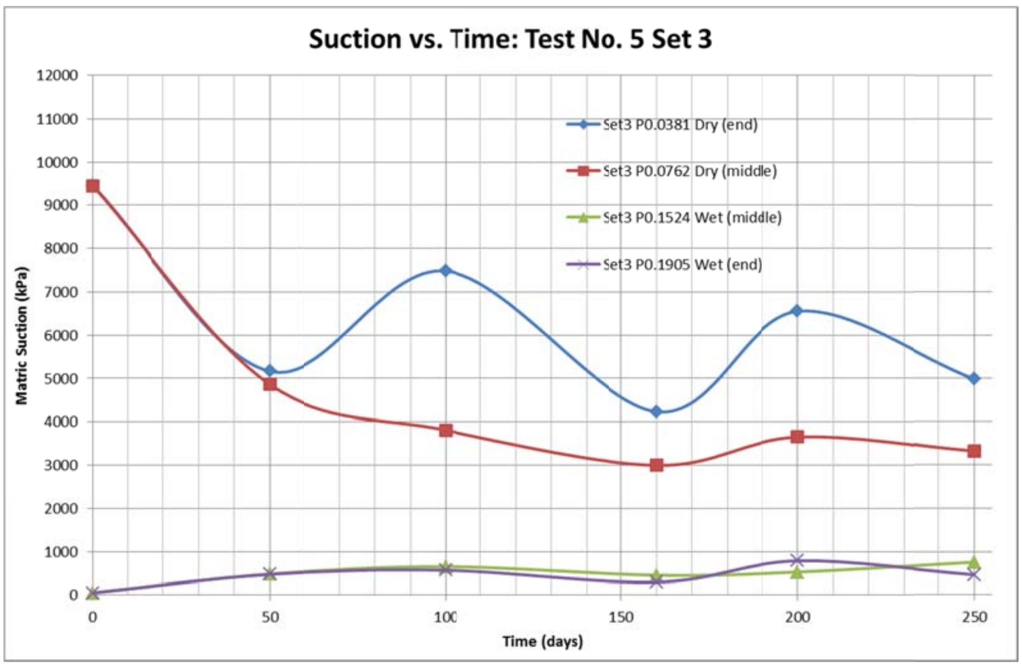

Figure 4.100: Test No. 5, Set 3, Matric Suction over Time.

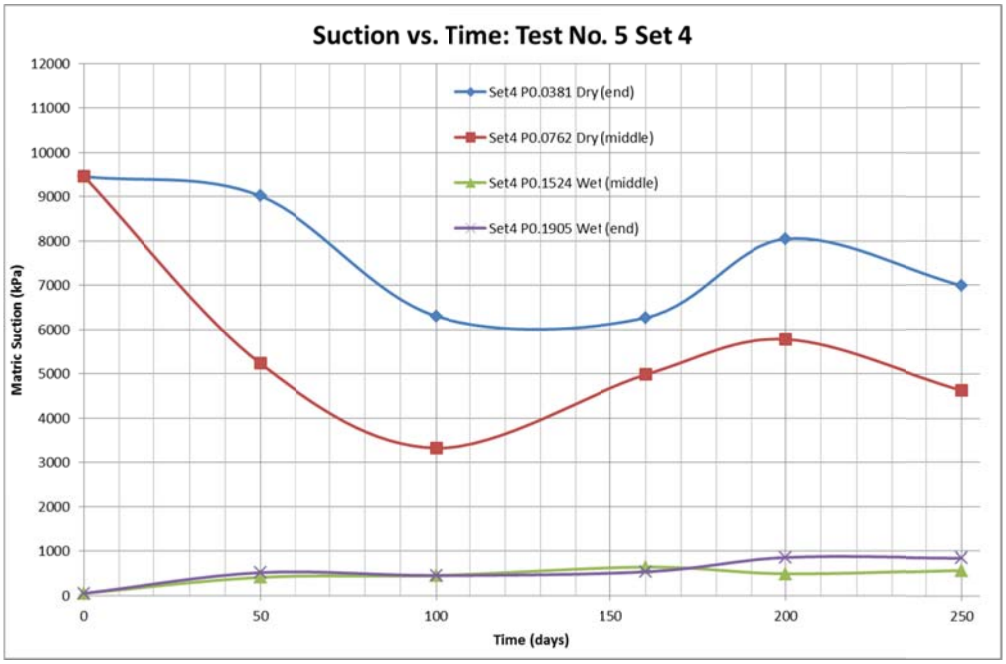

Figure 4.101: Test No. 5, Set 4, Matric Suction over Time.

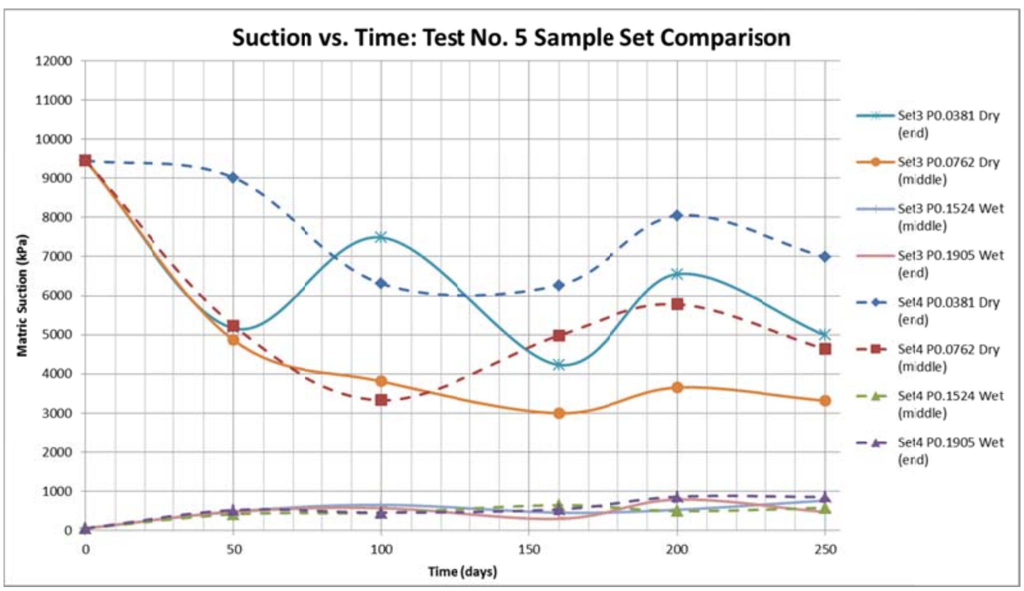

Figure 4.102: Test No. 5 Matric Suction over Time Sample Set Comparison.

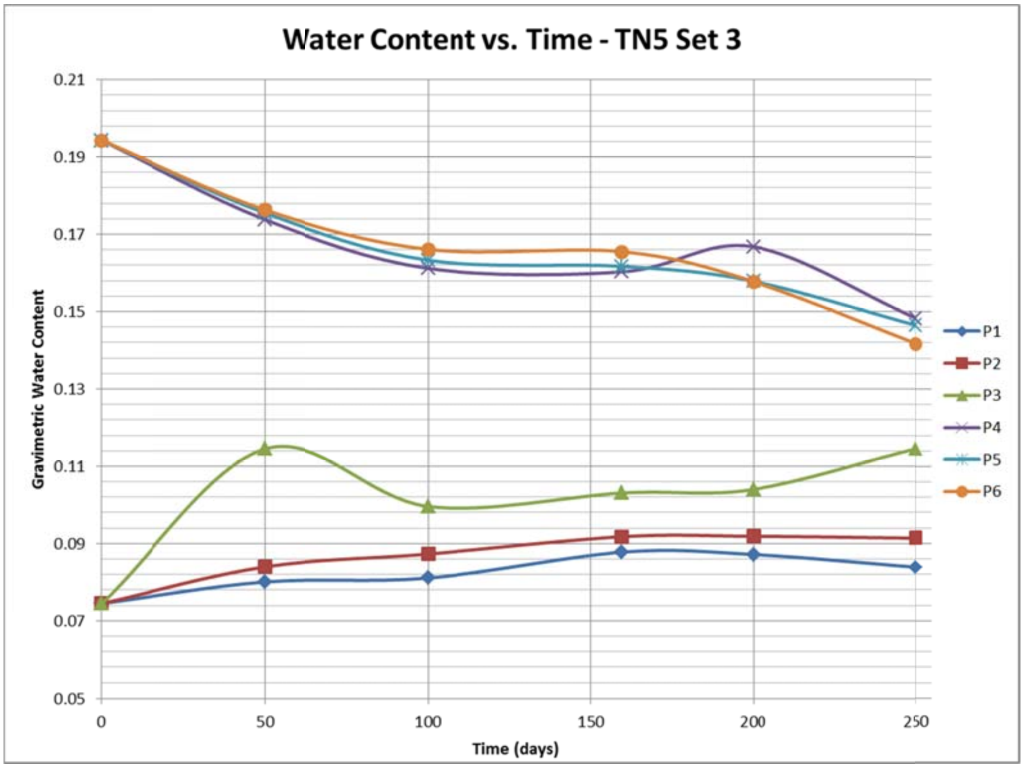

Figure 4.103: Test No. 5, Set 3, Water Content over Time.

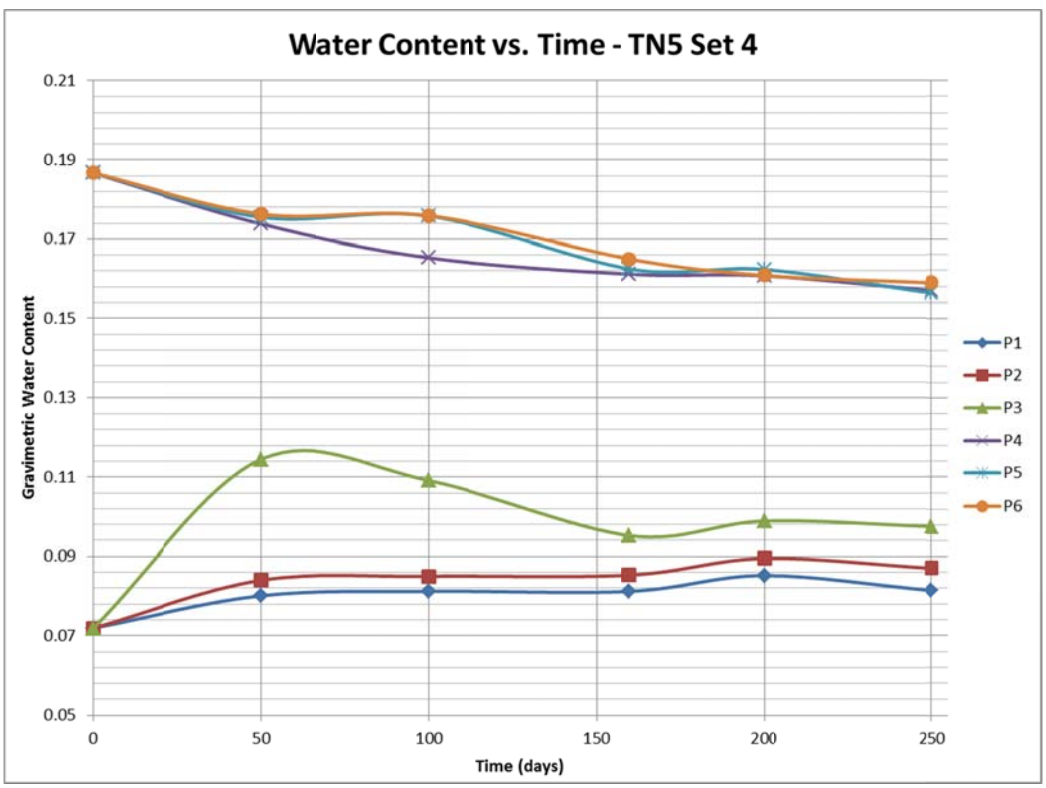

Figure 4.104: Test No. 5, Set 4, Water Content over Time.

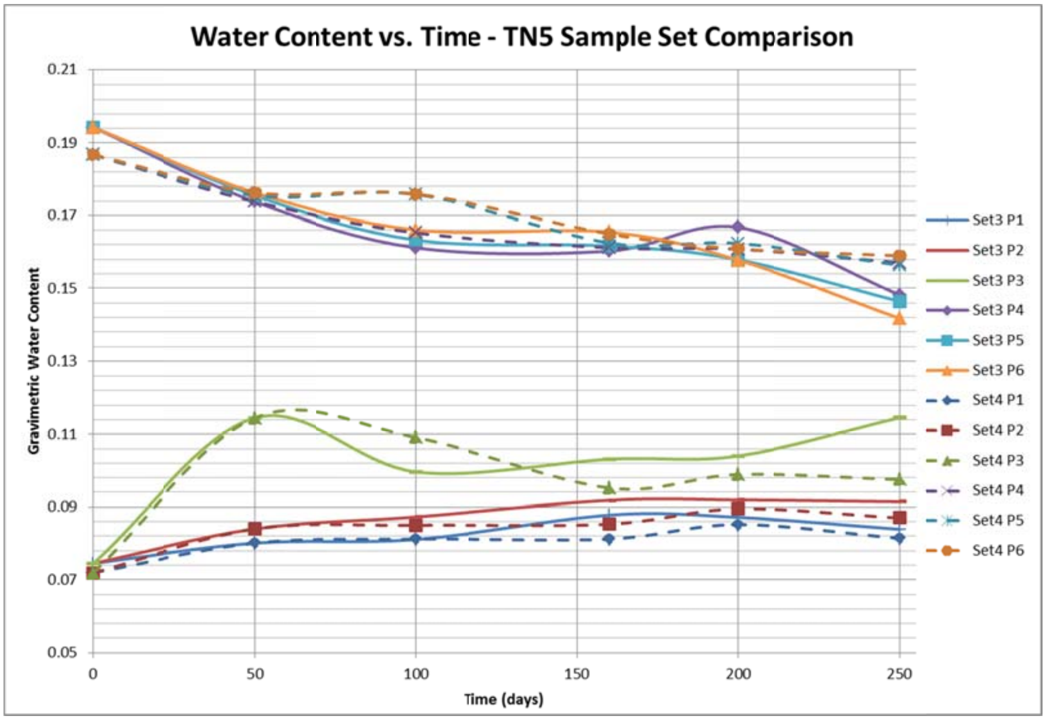

Figure 4.105: Test No. 5 Water Content over Time Sample Set Comparison.

From the figures above of the sample set comparison for TN5 the water content and suction trends are very similar for both sample sets 3 and 4. The suction trends in the drier soil section are slightly different from comparison from set 3 to set 4. The water content and suction profiles for each sample set from TN5 and are presented below in Figures 4.106, 4.107, 4.109 and 4.110. Comparison plots of the water content and suction profiles are presented in Figures 4.108 and 4.111.

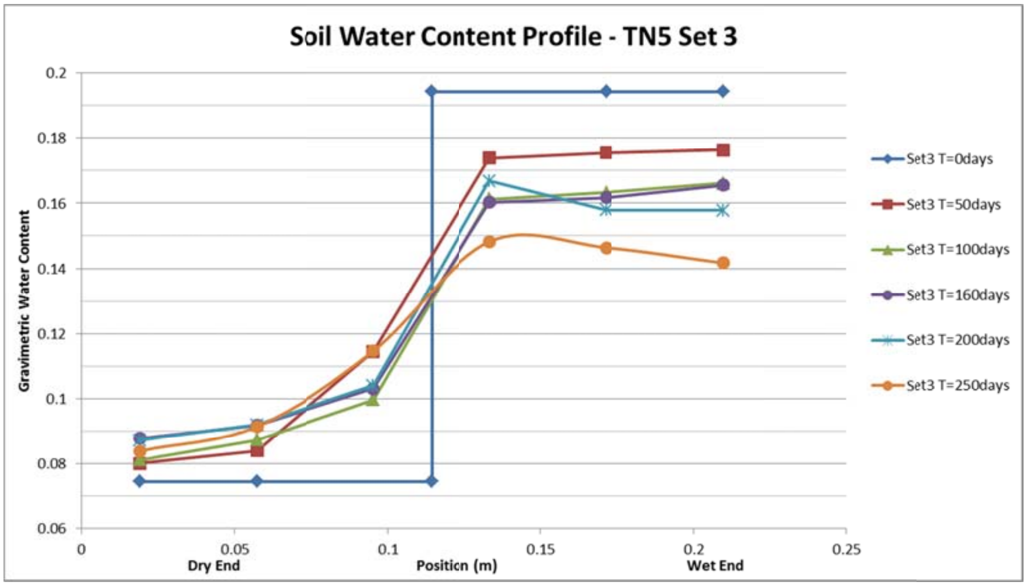

Figure 4.106: Test No. 5, Set 3, Water Content Profile.

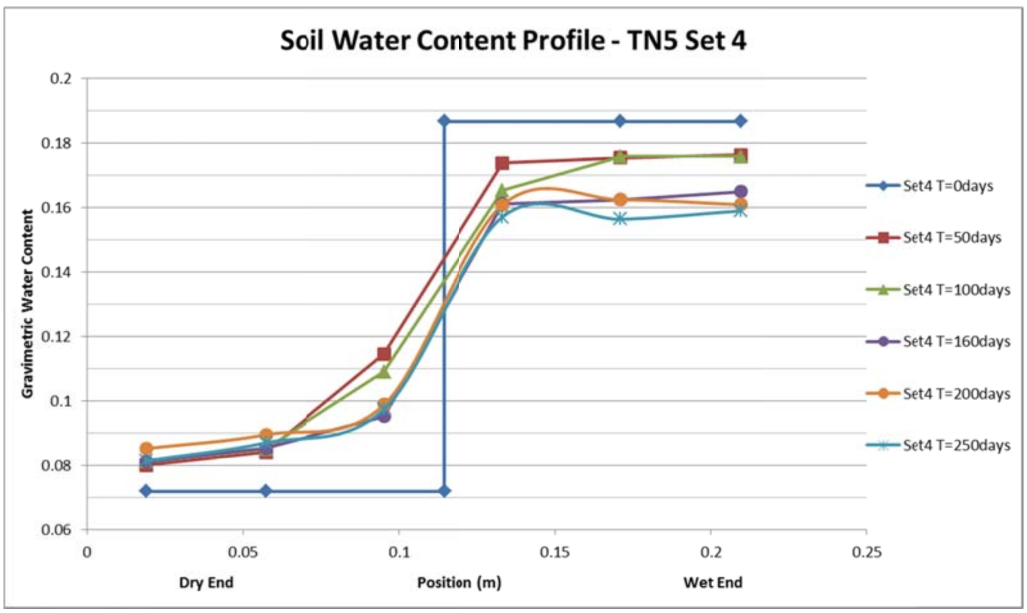

Figure 4.107: Test No. 5, Set 4, Water Content Profile.

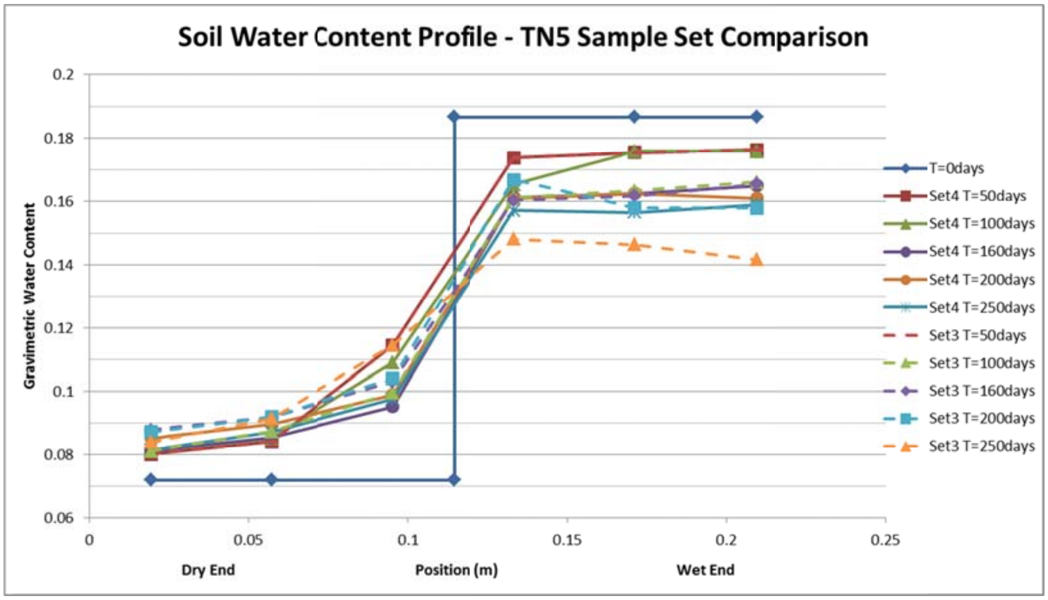

Figure 4.108: Test No. 5 Water Content Profile Set Comparison.

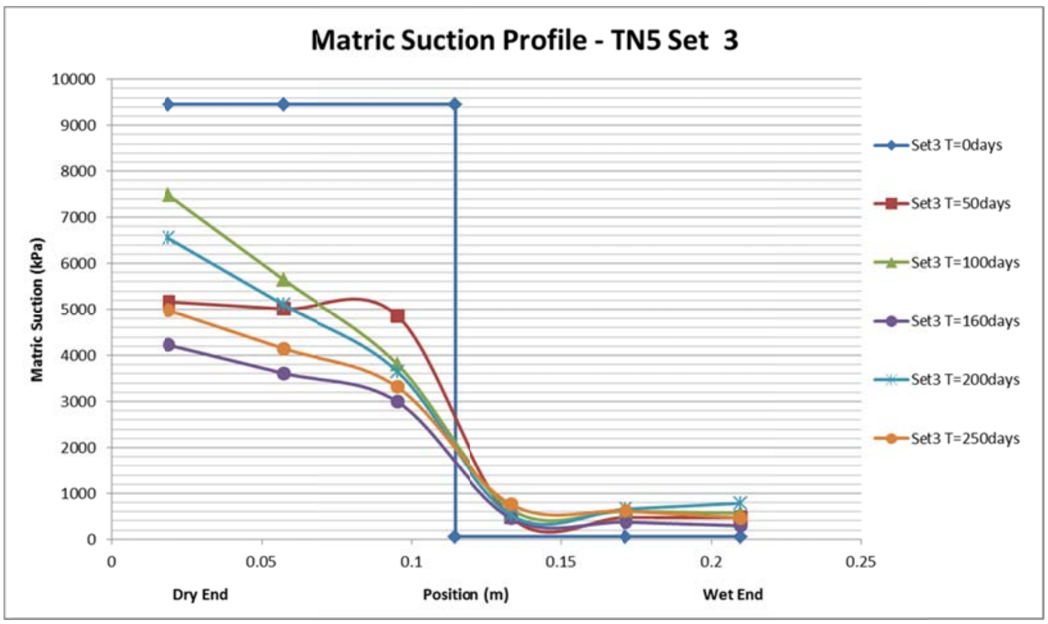

Figure 4.109: Test No. 5, Set 3, Matric Suction Profile.

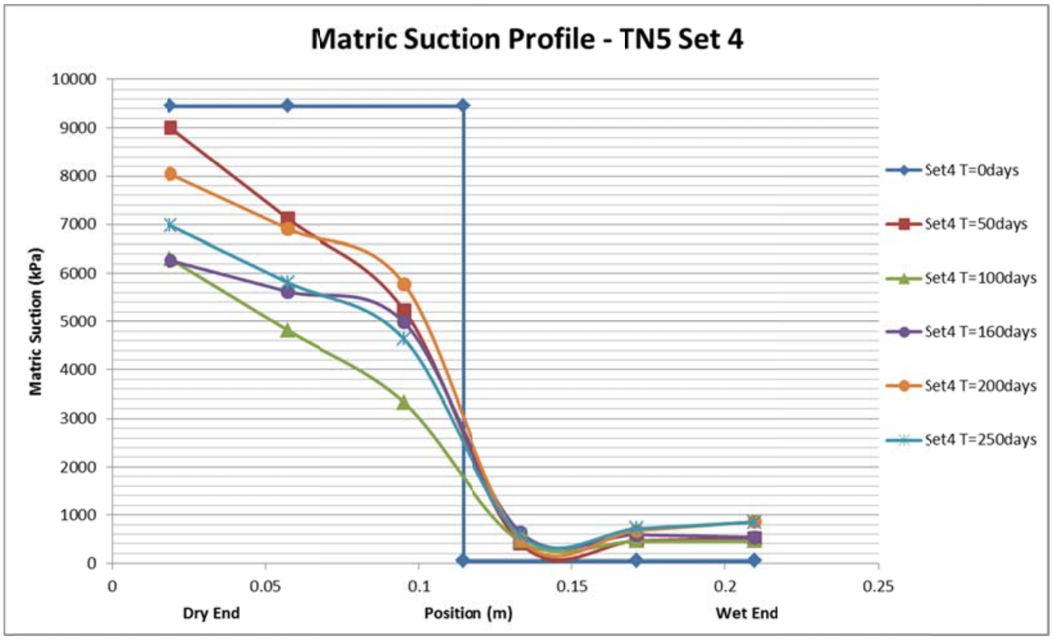

Figure 4.110: Test No. 5, Set 4, Matric Suction Profile.

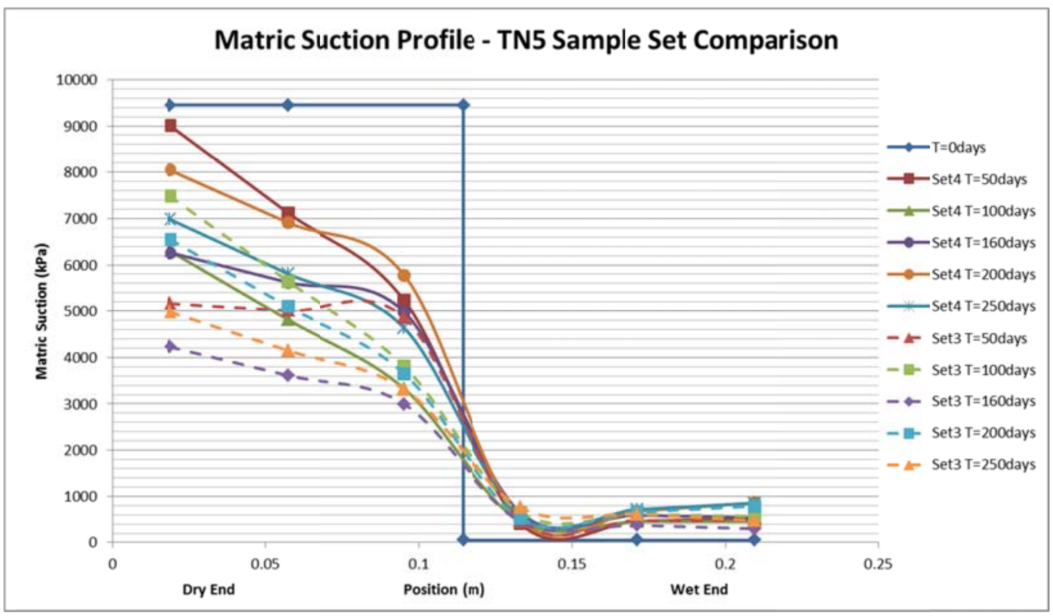

Figure 4.111: Test No. 5 Matric Suction Profile Set Comparison.

The calculated unsaturated hydraulic conductivity values for TN5 for each sample set are presented in Figures 4.112 and 4.113. The conductivity values were calculated using the approach previous stated in this chapter over various intervals with in the soil profile. The various intervals were chosen to gain multiple hydraulic conductivities at different suction values. The location of the intervals presented in the figures below is shown in Figure 4.93 and are the same as TN3, TN4, and TN7. The conductivity calculated over the air gap are calculated for two different situations. The long air gap conductivities are calculated as normal with the distance between the analyzed points being equal to 1.5 inches. The short air gap conductivities are calculated using the distance to the length of the air gap. For this situation it is assumed that the soil conditions are the same at the interface as in the adjacent soil lift. The Kunsat plot presented in Figure 4.114 presents the results for both sample sets together.

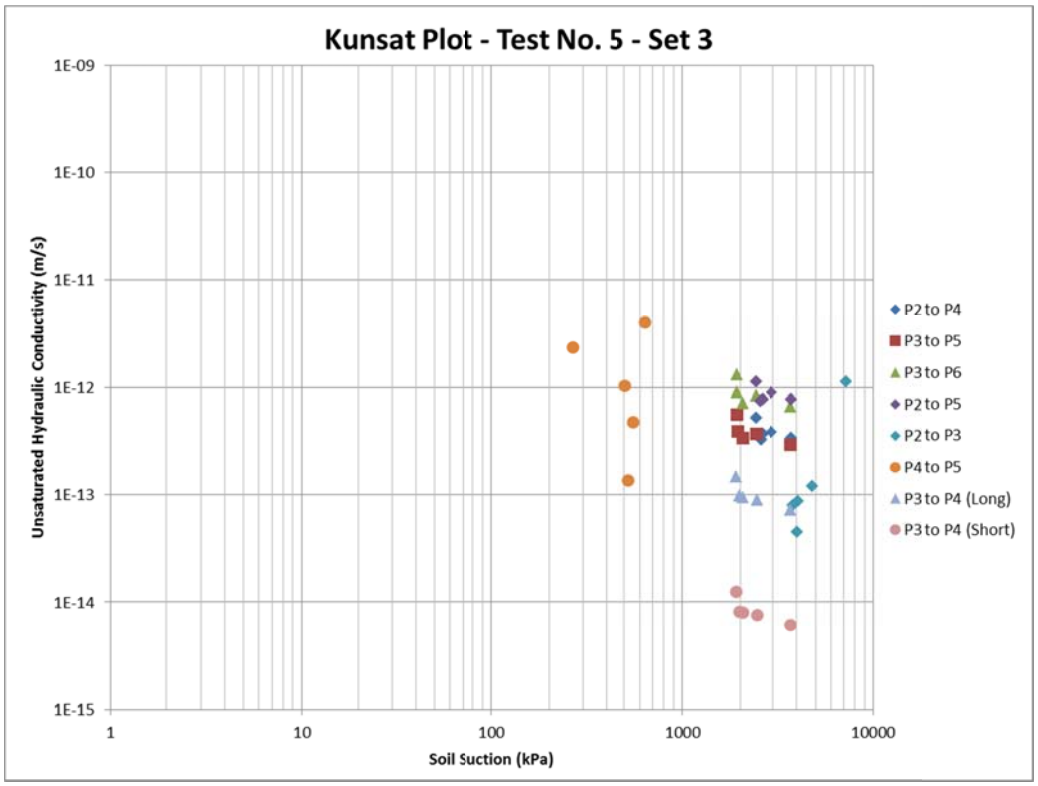

Figure 4.112: Test No. 5, Set 3, Kunsat Plot.

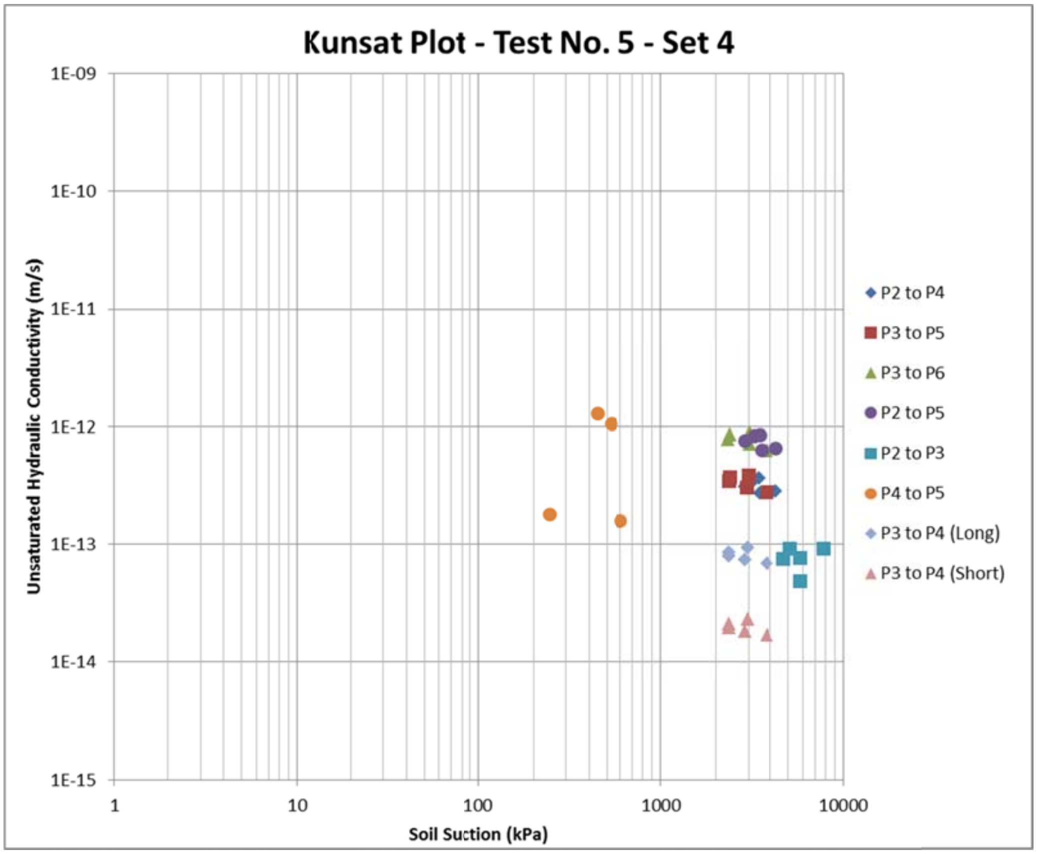

Figure 4.113: Test No. 5, Set 4, Kunsat Plot.

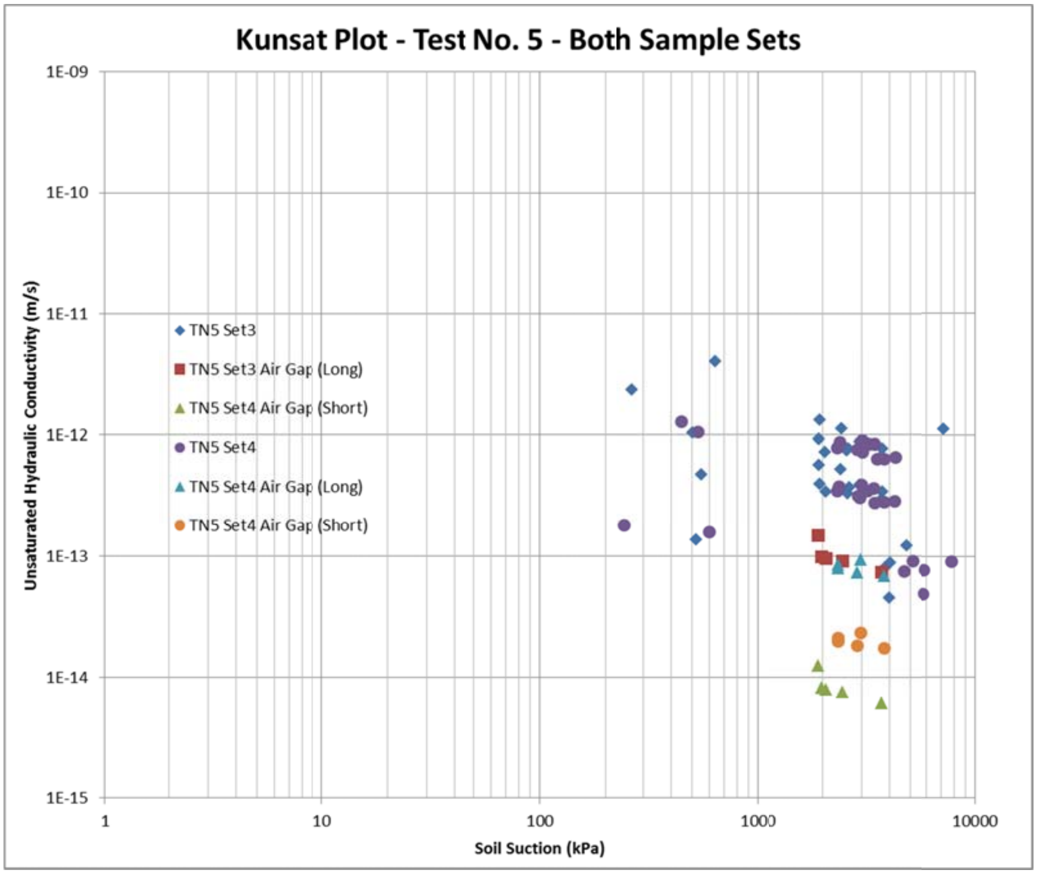

Figure 4.114: Test No. 5, Kunsat Plot of Both Sample Sets.

From the unsaturated hydraulic conductivity plots presented above is can be observed that the conductivity points in intact section of the soil profile agree well with each other. The conductivity values calculated over the air gaps are significantly lower than the conductivity values calculated over the intact sections of the soil profile. This was expected since the air gap should significantly restrict the flow of moisture over the air gap. The conductivity values over the shot air gap are used as the hydraulic conductivity of the water vapor transmissivity and are used as a minimum value for the soil unsaturated hydraulic conductivity.

Test Number 6 (Cracked):

The cracked instantaneous profile experiment Test Number 6 is a vertical infiltration test that is analyzed in tandem with TN6I. The samples for Test Number 6 in the cracked condition are identified as TN6C. The experiment for TN6C was started on December 15, 2010. This experiment was designed according to the configuration and methods explained in the experiment design section in Chapter 3. This experiment was design to simulate a vertical infiltration condition.

The apparatus used for TN6C is a 9 inch long, 3 inch inner diameter clear cylindrical Plexiglas tube. Soil was prepared at approximately 15.5% water content prior to being compacted into the sample tubes. The soil was allowed to equilibrate for 24 hours before being compacted into the sample tubes. The initial soil properties for TN6C and other relative soil properties are shown in Table 4.13 below.

Table 4.13: Test No. 6 C Initial Soil Conditions.

Section	1
Desired w% (grav)	0.15
Relative Compaction %	0.98
Dry Density (pcf)	106.5
Actual w% (grav)	15.30%
Actual w% (vol)	26.11%
Saturation %	70.10%
Matric Suction (kPa)	400
Void Ratio	0.594

The samples for TN6C were compacted in the same manner and using the same procedure and specifications as TN6I. The soil was compacted in the test apparatus tubes in 1.5 inch lifts. This is done to ensure uniform density. The Ec-5 volumetric moisture probes were to measure the water content over time. These results were also used to interpolate matric suction values using soil water characteristic curve for the soil. The moisture probes are positioned in the same orientation and locations as TN6I as shown in Figure 4.42. The volumetric moisture probes were installed through slits cut in the sides of the sample tubes. The locations of the volumetric moisture probes are shown in Figure 4.43.

The sample for TN6C is the cracked companion of TN6I, the intact sample. The crack pattern used is developed by Sam Abbaszadeh who was working on a study in parallel with this study. Sam's crack pattern is based on research in literature focusing on the natural development of cracks, size of cracks, and crack patterns. The crack pattern that is used for TN6C is presented in Figure 4.115 below.

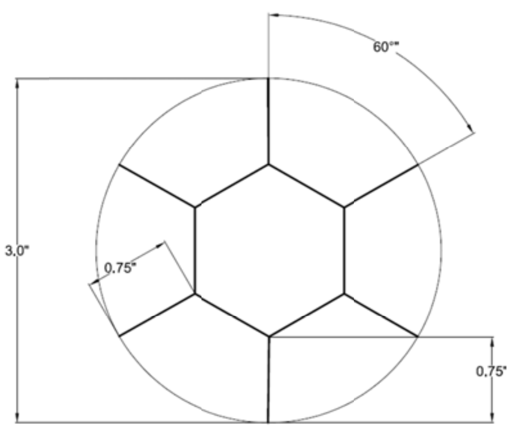

Figure 4.115: Test No. 6 C Crack Pattern.

The cracks were formed using a piece of steel that is 0.75 inches in length and 1.25 inches thick. The piece of metal was driven into the top of the soil profile using a rubber mallet. The steel piece was driven 1.3 inches into the soil profile to gain a crack ratio of 3.13%. The perimeter cracks were formed first and then the cracks in the middle were created. Great care was taken in forming the cracks because the soil pieces surrounding the cracks are very fragile and would easily break off is overly disturbed. The cracks were formed immediately after the sample was compacted. The process of forming the crack pattern for TN6C is shown in Figures 4.116, 4.117, 4.118 and 4.119 below.


Figure 4.116: Creating Crack Formation for Test No. 6 C (1).


Figure 4.117: Creating Crack Formation for Test No. 6 C (2).

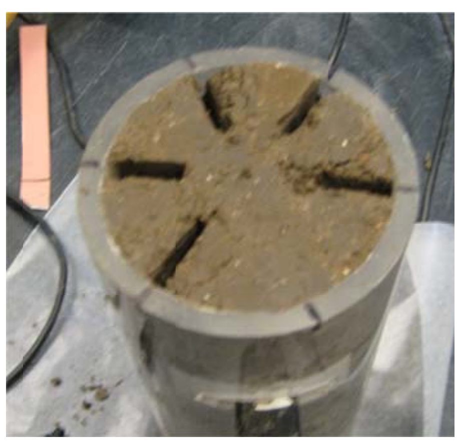
Figure 4.118: Creating Crack Formation for Test No. 6 C (3).

Figure 4.119: Creating Crack Formation for Test No. 6 C (4).

During the creation of the crack pattern the top lift of the soil profile had slightly more compaction due to the creation of the cracks. When the steel pieces are driven into the soil profile, the soil below the steel piece drives the surrounds soil laterally and down to the bottom of the crack. This may lead to higher soil densities then desired from the creation of the cracks. Also when a crack is created on one side of the sample the soil is pushed to the other side, decreasing the width of some cracks. To prevent this and to ensure that each crack had approximately the same width the cracks are re-formed many times with the steel form. After the cracks were formed and the sample was put in the environmental chamber and allowed to equilibrate for 24 hours until the sample was inundated.

Prior to inundation the crack width, length and depth was measured. Before this was done each crack was cleaned of any soil particles that may have remained in the cracks. Figure 4.120 below shows the crack prior to measurement and before inundation.

Figure 4.120: Completed Sample for Test No. 6 C.

The measurements of each cracks and the measured crack volume of the sample is presented in Table 4.14 below. The actual crack ratio is different form the calculated crack ratio by about 1%. The actual measured crack ratio is still within the desired range of crack ratios desired for study which is 2% to 5%.

Table 4.14: Test No. 6 C Crack Measurements and Crack Volume. Refer to Figure 4.121 for Crack No. Locations

Crack No.	Crack Width (in)	Crack Depth (in)	Crack Length (in)	Crack Volume (in^3)
1	0.1715	1.2275	0.9465	0.1993
2	0.1680	1.1560	0.9255	0.1797
3	0.1385	1.1720	0.9555	0.1551
4	0.1495	1.2050	0.9325	0.1680
5	0.1630	1.1850	0.9730	0.1879
6	0.1880	1.2100	0.9700	0.2207
7	0.1170	1.2258	0.5020	0.0720
8	0.1265	0.9875	0.4415	0.0552
9	0.1265	1.0715	0.5400	0.0732
10	0.1595	0.9350	0.4310	0.0643
11	0.1655	0.1025	0.4965	0.0084
12	0.1115	0.1285	0.3710	0.0053
			Total Vol (in^3)	1.389
			Crack Ratio	2.18%

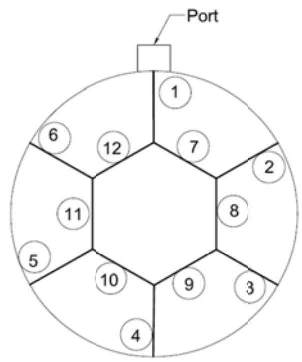

Figure 4.121: Test No. 6 C Crack Number Locations.

Water is ponded on the top surface of the soil profile and allowed to infiltrate the soil the same as TN6I. Another clear Plexiglas tube was glued to the top of the sample tube to allow water to be ponded. Also a bag is sealed at the top to prevent any unwanted evaporation. The sample was sealed and stored in the environmental chamber for 24 hours to allow the soil and volumetric probes equilibrate to the surrounding environment. The assembled sample with water ponded stored in the environmental chamber is presented in Figure 4.122 below. The amount of water that is applied to the sample was based on achieving a small change in water content that would allow the sample to be unsaturated throughout the experiment. The amount of water added was 120 grams which should cause a 2-4% change in gravimetric water content. The sample was inundated on December 15, 2010 and ran until the sample equilibrated or the test was completed.


Figure 4.122: Test No. 6 C Sample Stored in Environmental Chamber.

The experiment for TN6C ran for 1400 hours. During this period the volumetric moisture probes recorded the water content every 60 minutes. The test was monitored throughout its run time. The water content data stored on the data acquisition unit and was downloaded and imported into an Excel spreadsheet for analysis. The calibration described previously was used to determine the gravimetric water content of the sample over time. The plot of the gravimetric water content over time is presented below in Figure 4.123. The sample did not completely equilibrate in the time allocated for this experiment.

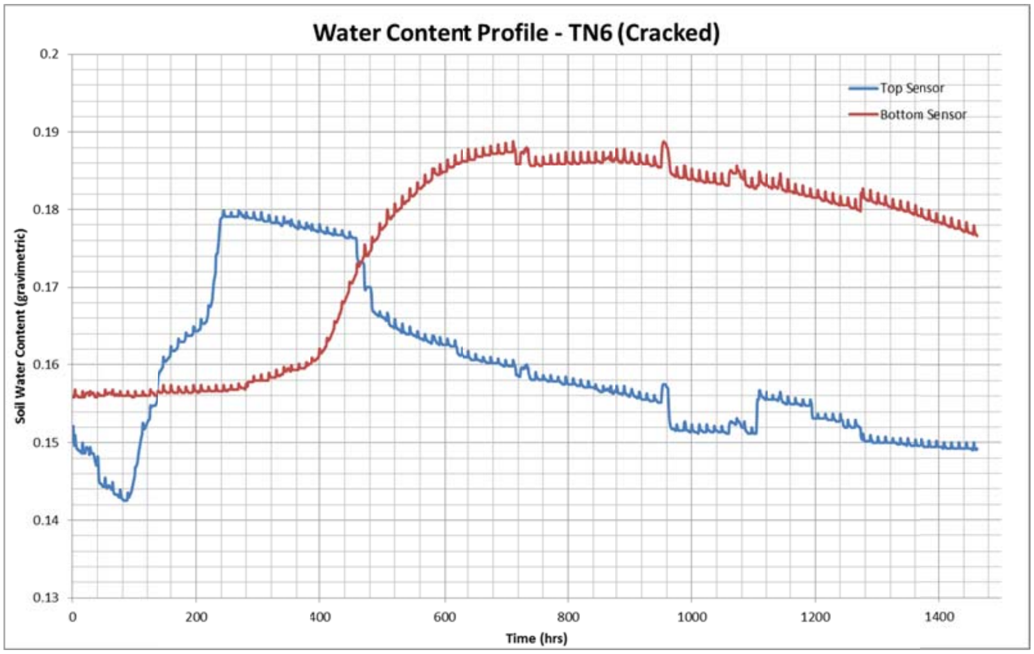

Figure 4.123: Test No. 6 C Water Content Profile.

The matric suction was determined using the soil after characteristic curve for the soil. The gravimetric water content was converted to the volumetric water content and the matric suction was interpolated from the SWCC for the soil. The soil suction Profile for TN6C is presented in Figure 4.124.

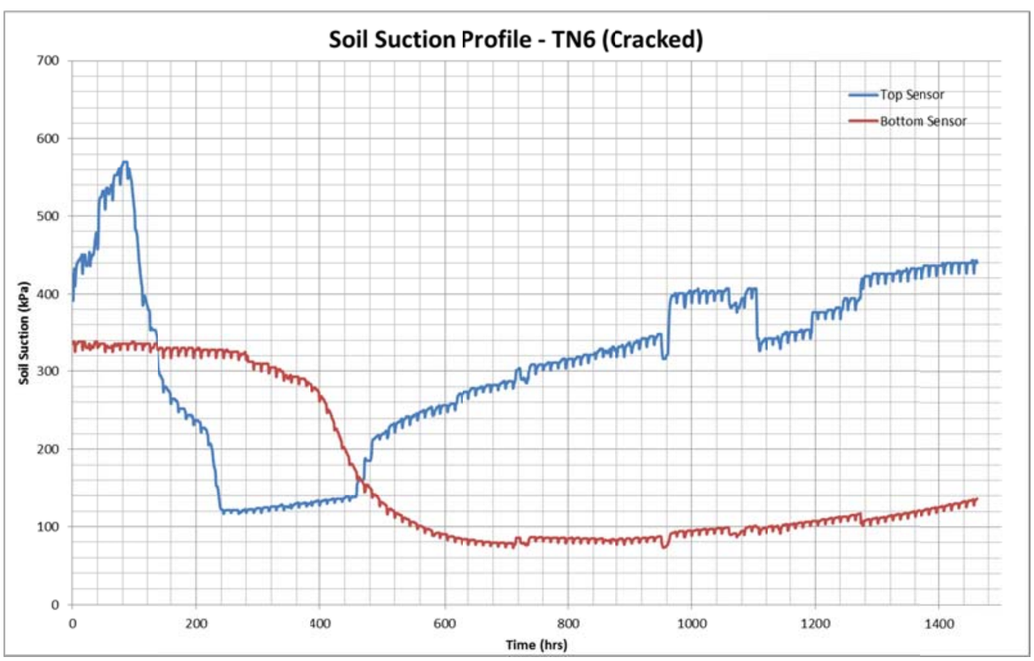

Figure 4.124: Test No. 6 C Soil Suction Profile.

The amount of water ponded on top of the sample was recorded over time. This is shown in Figure 4.125 below. As shown in the plot below the level of the ponded water completely infiltrates the sample with the first450 hours of the experiment.

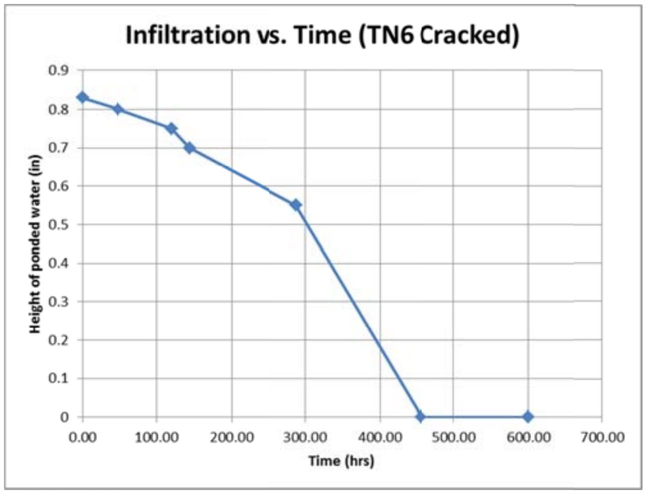

Figure 4.125: Test No. 6 C Infiltration Data.

The calculated unsaturated hydraulic conductivity values for TN6C are presented below. The conductivity values are calculated using the approach previously described in this chapter. The conductivity values were calculated for the interval between the two volumetric moisture probes and over 50 day time periods. The range of conductivity values obtained from TN6C range from 1.0*10^-11 to 6.3*10^-12 m/s over a suction from of 150 to 410 kPa. This plot is presented in Figure 4.126 below.

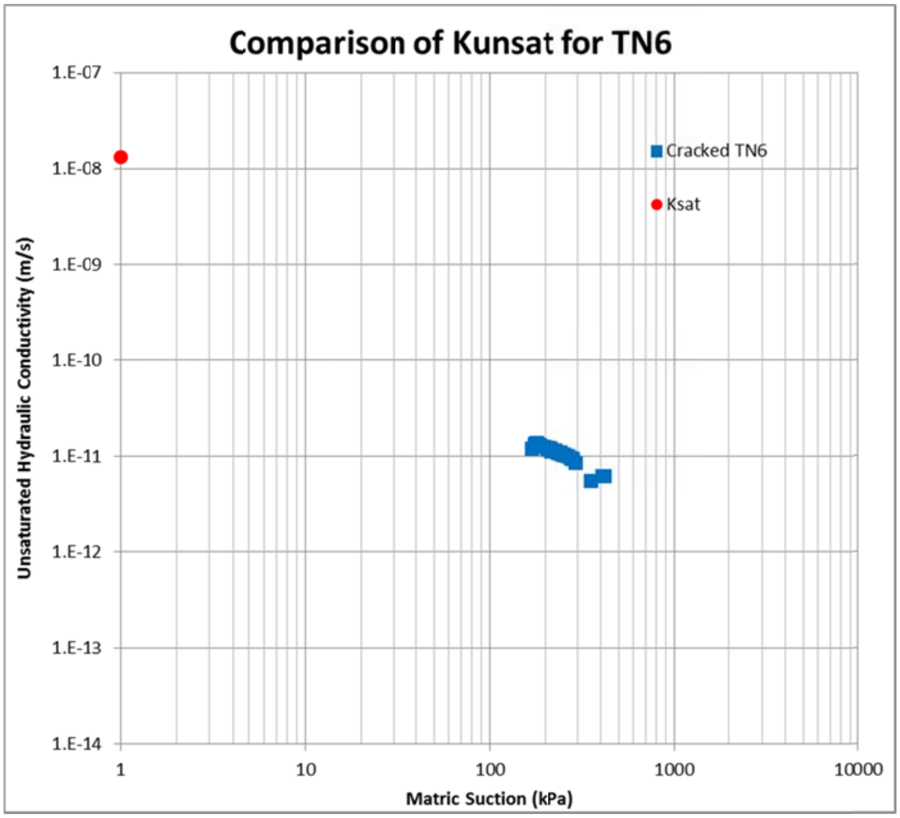

Figure 4.126: Test No. 6 C Coefficients of Unsaturated Hydraulic Conductivity.

CHAPTER 5: CONSIDERATIONS AND METHODS FOR DETERMINING THE UNSATURATED HYDRAULIC CONDUCTIVITY FOR INTACT AND CRACKED CLAYS

Introduction

The instantaneous profile experiments conducted in this study provided results for the sandy clay soil tested over a wide suction range. The unsaturated hydraulic conductivity values determined for the intact condition in the suction ranges chosen have not been seen in current literature. The results from the seven instantaneous profile experiments are presented in this chapter for the intact and cracked conditions. Various models of the unsaturated hydraulic conductivity functions are used for analysis. With these statistical and semi empirical functions fitted to the results, comments are made to the fit and actual representation of the data obtained. Finally, a new model for the unsaturated hydraulic conductivity function is proposed based on the results determined from the experiments performed.

This chapter discusses considerations to the method used for determining the unsaturated hydraulic conductivity values by the instantaneous profile method. Through experimentation using the instantaneous profile method various considerations are concluded to the general method, procedures and sampling method used. The analysis of the data will be presented including combining all intact and cracked results from each experiment for analysis. The considerations discussed in this chapter may provide insight to the amount of scatter and trends in the data obtained from the experiments. Finally, the intact and cracked unsaturated hydraulic conductivity results are compared and analyzed.

Considerations of Method for Determining the Unsaturated Hydraulic Conductivity by the Instantaneous Profile Method

The first instantaneous profile experiments conducted in this study are Test Numbers 1 and 2 (TN1 and TN2). These experiments are designed based on recommendations from current literature. These two experiments are considered trial experiments and were used to test the general method used and sampling procedures. TN1 and TN2 use a long soil profile containing four different sections of different water content compacted at the same dry densities. The results from these two experiment produced results that were considered to have a high amount of scatter and not representative of the actual hydraulic conductivity of the soil. Also because of the manner in which the experiments were sampled, the results were considered prone to inaccuracies.

The primary source of error encountered in TN1 and TN2 was due to the way the experiment was sampled. The sampling procedure for TN1 and TN2 was performed by driving a hollow into the soil profile to the center of the cross-section of the sample tube. The hollow tube is then pulled out and the soil from the inside of the tube is used for a water content measurement. From the hole created from driving the hollow tube, the filter paper sandwich is then retrieved. After sampling is completed, another filter paper sandwich is placed inside the hole. The hole is then re-compacted with the same soil water content as measured from the sample recovered from the hollow tube. This method of sampling allows for unwanted influence and disturbance to the soil profile and the water content in each section.

The first disturbance issue for TN1 and TN2 is that the soil used to fill the hole created from sampling is not exactly the same water content as the surrounding soil in the soil profile. The required amount of time for a water content measurement is 24 hours, so the soil is not replaced back into the soil profile for a total time of one day. The second disturbance issue is that this continuous method of sampling and replacing the soil, creates some unwanted influence to the soil water content. Because the soil is continually replaced during sampling events, it may not actually be the water content of the surrounding soil in a specific soil section. The high suction range that the experiments were conducted at requires that the soil to take a great deal of time to equilibrate. Typical sampling intervals were performed every 28 days and the time require for the soil to equilibrate may take longer than this allowed time interval.

Another weakness in this method is the change in the soil fabric with respect to the direction of compaction. During creating the samples for TN1 and TN2 the soil was compaction in the direction of the length of the tube so that the clay particles are oriented perpendicular to the length of the sample tube. During the replacement of the soil from sampling, the soil was compacted in the radial direction from the sample tube. A figure of this compaction situation is presented in Figure 5.1 below. This disturbance in soil fabric may have a significant effect on the conductivity behavior of the soil. The hydraulic conductivity has significant consideration to the orientation of the soil particles and direction of compaction (Mitchell and Soga, 2005). The hydraulic conductivity is different in the horizontal direction from the vertical direction due to soil fabric effects which may have affected the results.

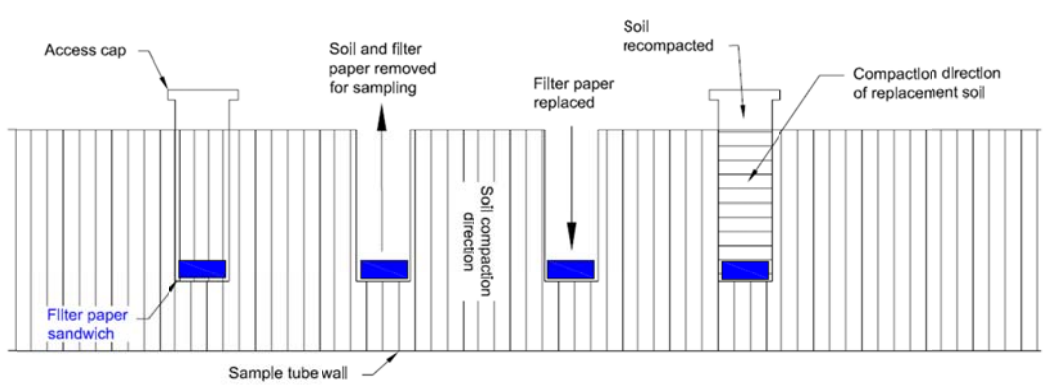

Figure 5.1: Test No. 1 and Test No. 2 Soil Fabric Sample Disturbance.

The test method used for TN1 and TN2 uses four soil sections. The soil sections are considered independent of each other. Controlling the suction and gradients between these sections has proved to not be easy and involves a lot of considerations, assumptions to the direction of flow, and if the sample section are wetting or dry. If different water contents were chosen to gain a greater hydraulic gradient, the change in the water content in the soil profile may be greater or less than time required to gain hydraulic conductivity values. The rate of moisture flow is controlled and dependent of the soil hydraulic conductivity. The experiments for TN1 and TN2 were not stored in a temperature controlled environment but in the general lab area were the ambient temperature varied significantly but not recorded. This temperature variation brings into consideration the temperature effects onto the hydraulic conductivity which are not included in the scope of this study.

With the deficiencies associated with this method of the instantaneous profile method, improvements can be made to improve the method and gain more accurate measurements with less influence from the test method and sampling procedures. Most problems in these two experiments, TN1 and TN2 are associated with the sampling method, number of soil sections, disturbance issues, apparatus size, initial soil conditions, and environmental conditions. When these issues are considered, a new modification to the instantaneous profile test was created. This modification is called the duplicate method and is considered to produce more accurate measurements that resemble the actually change in water content and suction in a soil.

The duplicate method is used in Test Numbers 3, 4, 5, and 7 which include both intact and cracked experiments. The duplicate method consists of creating a number of identical samples at the same time with the same soil conditions. The duplicate method uses two soil section of different water content and use short sample tubes, 9 inches in length. The number of duplicate samples created ranges from 4 to 6 samples, allowing for a various range of sampling times. During the sample creation process, filter paper sandwiches are placed in between soil compaction lifts in the soil profile to measure the matric suction. The primary advantage of the duplicate method is that the samples can be completely destroyed from sampling. Because of this, the water content measurements along the soil profile can be very accurately measured using large water content samples and multiple water content samples with a soil section. This cause the water content samples to be more representative of the actual water content of the soil sampled. Also the filter paper sandwiches can be easily retrieved from the specimens.

Other advantages of the duplicate method are that sample creation can be done very easily and with little cost. The materials needed to perform the duplicate method instantaneous profile experiment using manual water contents and filter paper tests can be done only using plastic tubes, filter paper, plastic wrap and tape. Other equipment includes common geotechnical equipment found in soil laboratories are used to create and compact the samples. The duplicate method also allows for the user to choose the suction range for which they desire to measure unsaturated hydraulic conductivity values for. Since only two soil sections are used, the range of anticipated water contents and suction is easily controlled. Also the gradient can be easily determined. The user can also choose were to measure suction and water content and can be done at various locations within the soil profile.

The duplicate method does have some disadvantages. The duplicate method creates a large amount of variability and scatter of the unsaturated hydraulic conductivity values calculated from various locations within the soil profile. This is due to the non-homogeneous sample set, the fact that not all the soil sample encounter the same change in water content and that not all the samples are compacted at exactly the same conditions. The boundary effects of the sample apparatus also create some disadvantages. The soils near the ends of the sample typically experience lower water contents and suctions than anticipated. This may be due to possible evaporation and desorption of water into the end cap seals. The scatter observed from the duplicate experiments may also be a result of the soil fabric effects due to compaction of the soils at different water contents. It has been discussed in literature that the soil fabric being flocculated or dispersed has an effect on the hydraulic conductivity of a soil (Mitchell and Soga 2005).

The vertical infiltration experiment Test No. 6 (TN6) performed well and as expected. This experiment allowed for unsaturated conductivity values to be acquired in the least amount of time. For the intact run for this experiment, the soil sample equilibrated within 2500 hours. This experiment required significantly less time than the duplicate method which during the testing period did not equilibrate within 300 days. The results from the experiment also produce a nice trend in the unsaturated hydraulic conductivity which is due to continuous measurement of the water content at the same location in the soil profile over time. Note that no direct suction measurements were made and the water content was measured using volumetric moisture probes. Limitations of this method include that the water content of the soil must not reach complete saturation in order to gain values in the unsaturated range. The amount of water added to the sample must be carefully predetermined in order to not reach complete saturation at any time during the experiment. Also this experiment was conducted at a lower suction than other instantaneous profile experiments conducted in this study. It is unknown from this study if this method could be used to gain hydraulic conductivity values at higher suction greater than 1000kPa, but from vertical infiltration experiments conducted by Li, Zhang and Fredlund, conductivity values were able to be measure at higher suctions (2009).

The experiments conducted in this study have led to various considerations to improvements that could be made to the instantaneous profile method. The improvements discussed in the following are made from observations in this study and considerations found in literature. The use of the duplicate method is a good modification to the instantaneous profile experiment for determining unsaturated hydraulic conductivity values over a wide range of suction and in high suction ranges. One improvement to this method would be to incorporate various techniques to increase the rate in the flow of water

The best way to decrease the amount of scatter in the unsaturated hydraulic conductivity could be done by continual measurements the water content, matric suction or both at location within the soil profile over time like in TN6. The use of various water content and suction measurement devices could be implemented to record the soil water content and matric suction over time at a single location within the soil profile. The volumetric moisture probes used in this study proved to be accurate and reliable at measuring the water content in the soil samples using the appropriate configuration of the probes to increase the range of influence of the sensors. From experiments in this study using these sensors some sensitivity to boundary and compaction conditions have led to some inaccuracies but with careful considerations to installation and sample preparation these inaccuracies could be minimized. Different types of sensors also seem promising for measuring water contents and suctions at low water contents for this study as seen in Table 5.1.

There are various method and techniques that could be used to measure the soil matric suction. In this study, filter paper test were only used to measure suction but there are other methods available. The table below titled "Common laboratory techniques for measuring soil suction" presents various techniques that could be used to measure soil suction (Masrouri, Katia and Kawai, 2008). The most promising method that could be used to measure soil suction over a wide suction range would be the electrical/thermal conductivity sensors. These sensors are also known as gypsum block sensors and have the ability to measure suctions up to 4000kPa.

Table5.1: Common Laboratory Techniques for Measuring Soil Suction (Masrouri 2008).

Technique		Suction component	Measure suction from/control suction with	Suction range (MPa)
To measure suction	Tensiometer	Matric	Negative pore-water pressure	0–0.1 (1.5)
	Electrical/thermal conductivity sensor	Matric	Thermal conductivity	0.01–4
	Filter paper	Matric/ total	Water content of paper	0.1–3
	Psycrometer chilled-mirror hygrometers, polymeter resist./capacit. sensors	Total	Humidity of vapour	0.1–100

The use of large sample sizes could also increase the accuracy of measurements in the instantaneous profile experiment. Many of the measurement techniques used rely on sensors that have a specific radius of influence. Large sample sizes could decrease the boundary effect of the sample apparatus and have less influence on the measurements devices such as the volumetric moisture probes. Also the accuracy of the test is also related to the space between the water content and suction monitoring points (Li, Zhang and Fredlund, 2009). Theoretically, the closer the monitoring points are to each other the more accurate the calculated unsaturated hydraulic conductivity values become.

Another recommendation to improve the duplicate method would be use a more gradual change in water content in the different soil section used in a sample specimen. To decrease the effects of the sharp contrast in water contents between the two water content sections used in the duplicate method, the soil sections could be prepared to gradually represent a gradual change in the water content from one section to the other. This could be done by using three or four different sections of water content within a soil sample. This modification could allow for the water to more easily transfer or move from the wet to dry soil sections and increase the rate at which unsaturated hydraulic conductivity values could be obtained decreasing the amount of time required to obtain hydraulic conductivities.

Analysis of Results

For analysis of the unsaturated hydraulic conductivity values or Kunsat values for both the intact and cracked conditions, the results from each type of experiment are combined. The intact experiments include Test Numbers 3, 6, and 7. The instantaneous profile experiments Test Number 1 and 2 are not included in the intact Kunsat plots since these points are not considered to be accurate, reliable or representative. The Kunsat values calculated from TN1 and TN2 did not fit the expected trends and were conducted at different conditions such as the testing environment so they are not included in the intact Kunsat plot. The cracked experiments include Test Numbers 4, 5 and 6. In the following the Kunsat plots for each condition, intact and cracked, will be presented along with observation and conclusions of the results.

In another experiment conducted at San Diego State University performed in parallel to the research project that this study was used for, unsaturated hydraulic conductivity values were obtained in a lower suction range. The experiment at SDSU was a tilt table experiment that studies the behavior of water infiltration for intact and cracked conditions and with different sloped conditions. From the zero slope, intact condition the volumetric water content data was provided to compute hydraulic conductivity values from and are labeled at tilt table values or TT. The SWCC for the soil was used to interpolate suction values from the volumetric water content data. The volumetric water contents over time were provided for points at depth with in the soil profile from the experiment. From this data the TT points are computed.

The Kunsat Plot for the intact condition from the various experiments conducted is presented below in Figure 5.2. As presented in this plot the conductivity values follow a trend with increasing variability of the unsaturated hydraulic conductivity as suction increases. The data from each experiment does agree well with each other. For the instantaneous profile experiments TN3 and TN7, the unsaturated conductivity points were obtained in the desired suction ranges. Both the intact and cracked, saturated hydraulic conductivities or Ksat measurements were made by Sam Abbaszadeh during an experiment in parallel with this study.

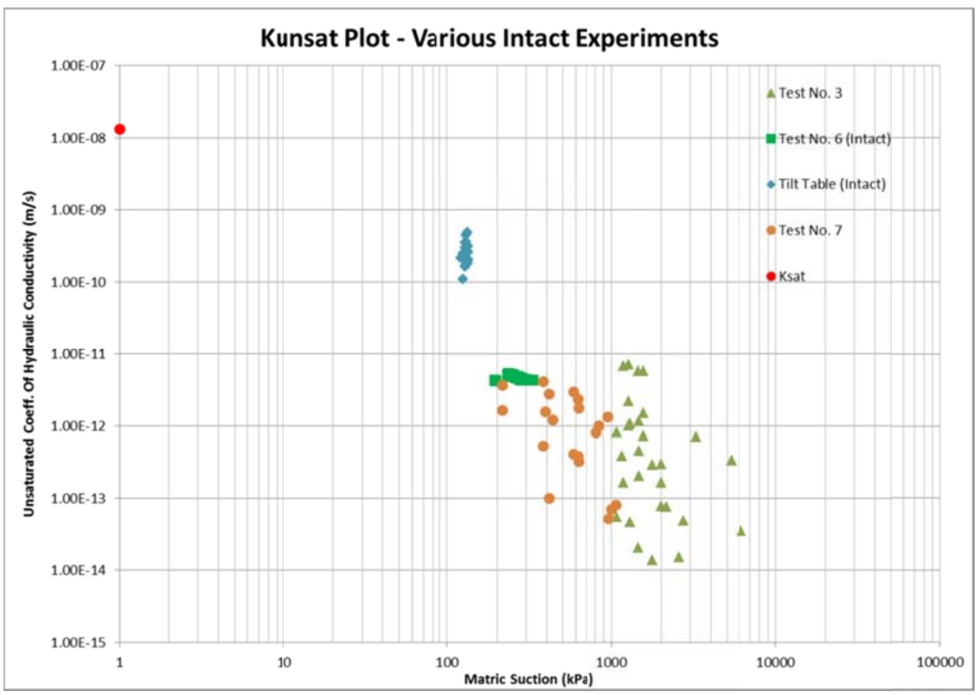

Figure 5.2: Kunsat Plot from Various Intact Experiments.

The unsaturated hydraulic conductivity points from TN1 and TN2 are not considered in the intact Kunsat plot for the soil. Unsaturated hydraulic conductivity values were calculated from this experiment and are shown in the figure below. Figure

5.3 below presents the Kunsat plot including the points taken from TN1 and TN2. As seen in this plot the data points from TN1 and TN2 do not fit the overall trend of the other data points from the other instantaneous profile experiments. These points are also not considered because of the various inaccuracies in the experiment described in the previous section in this chapter.

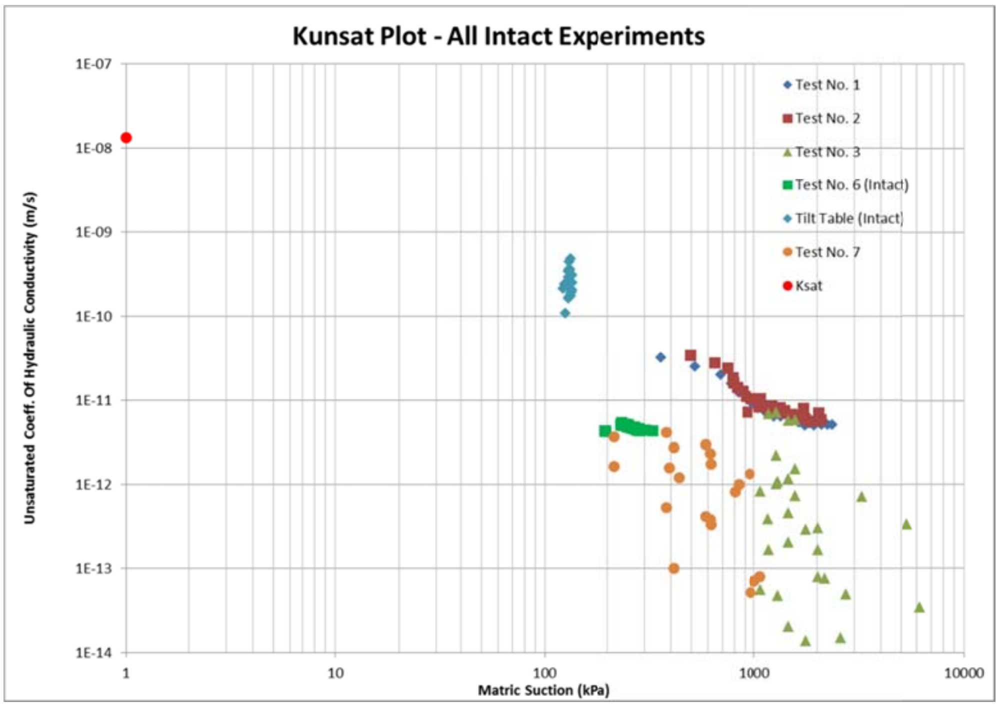

Figure 5.3: Kunsat Plot for All Intact Instantaneous Profile Experiments.

The Kunsat Plot for the various cracked conditions from instantaneous profile experiments conducted is presented below in Figure 5.4. The saturated hydraulic conductivity used in this plot is for the cracked condition using the same crack pattern as in TN6C with a crack volume ratio around 2-4% (Abbaszadeh, 2011). The results on this plot show that the cracked unsaturated hydraulic conductivity follows a similar trend to the intact data with increasing scatter as suction increases. The values of the unsaturated hydraulic conductivity from the cracked experiments using Methods B and C (TN4 and TN5) from the different sample sets with different cracked specification do not presented any significant differences. The points from set 1, 2, 3 and 4 are very similar with only slight differences in hydraulic conductivity for a given suction.

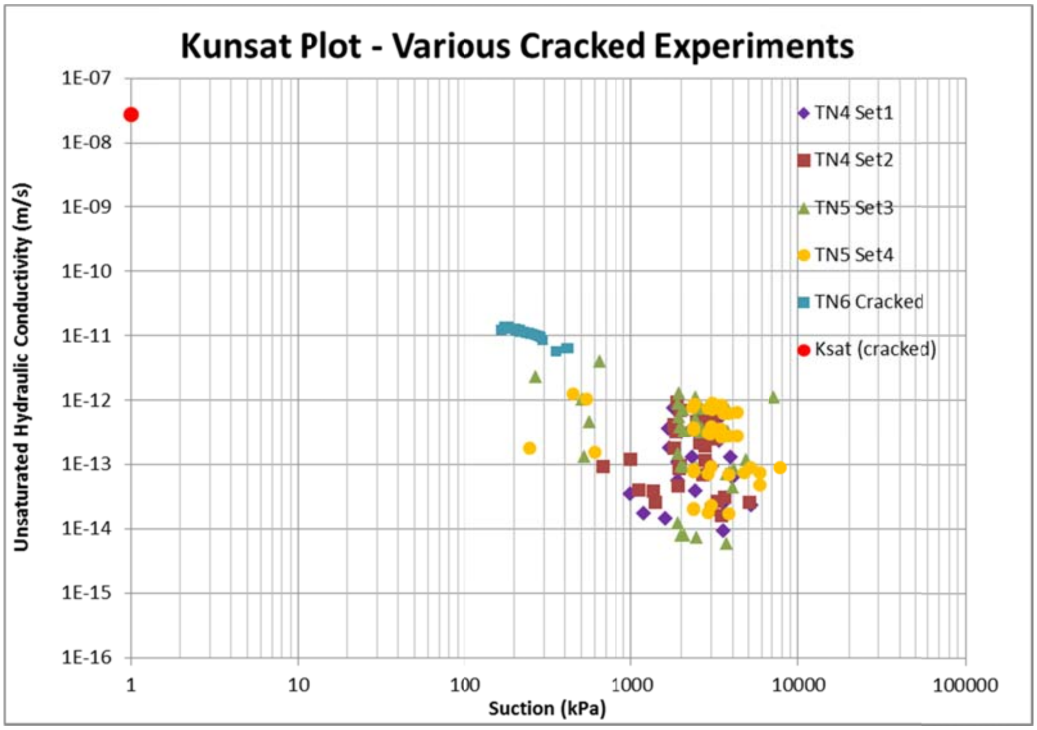

Figure 5.4: Kunsat Plot from Various Cracked Experiments.

There are various aspects to consider in relation the scatter of the data for both the intact and cracked unsaturated hydraulic conductivity data sets. Anisotropic soil conditions add a variation to the permeability function of the soil. As shown in Figure 5.5 below from Fredlund (2006) the primary change in the permeability function is associated with the difference between the maximum and minimum coefficient of hydraulic conductivity to the principal direction of anisotropy. This is also similar to the behavior of the wetting and drying hydraulic conductivity functions for a soil. In the instantaneous profile experiments performed some soil section experienced wetting and drying throughout the testing period which may also account for some of the scatter.

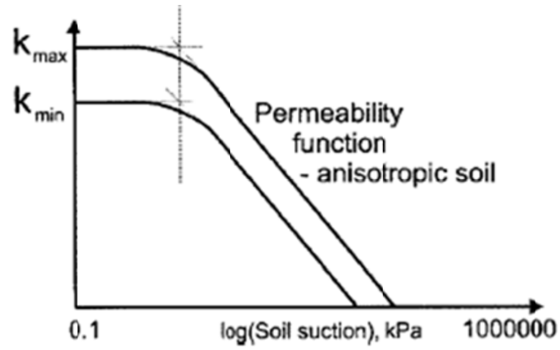

Figure 5.5: Example of Permeability Function for an Anisotropic Soil.

In the experimental design of this study it was considered that the effects of compacting the different soil sections at different water contents would have an effect on the unsaturated hydraulic conductivity. Some experimentation was performed in this regard on the saturated hydraulic conductivities of soil compacted a different water content and the impacts of this were found to be minimal and insignificant. Table 5.2 below presents the results of this experimentation. As presented in Table 5.2 there is no significant difference in the saturated hydraulic conductivities due to initial compacting the samples at different water contents. This observation concludes that the effects of soil fabric with respect to water content on the unsaturated hydraulic conductivity are minimal.

Table 5.2: Ksat Measurement at Different Compacted Water Contents.

Test	intact 1 8% wc	intact 2 8% wc	intact 3 20% wc	Intact Average from Previous tests with 18% wc
K (m/s)	**2.52×10^{-8}**	**3.92×10^{-8}**	**2.1×10^{-8}**	**1.33×10^{-8}**

The unsaturated hydraulic conductivity plots for each cracked method is presented and used to analyze the difference in crack specifications used such as the difference in number of cracks in TN4 and the difference in the cap widths in TN5. The comparison between sets 1 and 2, used for Method B that has different numbers of horizontal cracks, is presented in Figure 5.6. From this plot no significant difference can be seen in the results. The effects of the horizontal cracks can be slightly seen in the water content profile sample set comparison in Figure 4.83. There is a slight difference in the contour lines from Set 1 to Set 2 show that less change in water content occurred for Set 2 with more horizontal cracks. This difference is still considered to be insignificant.

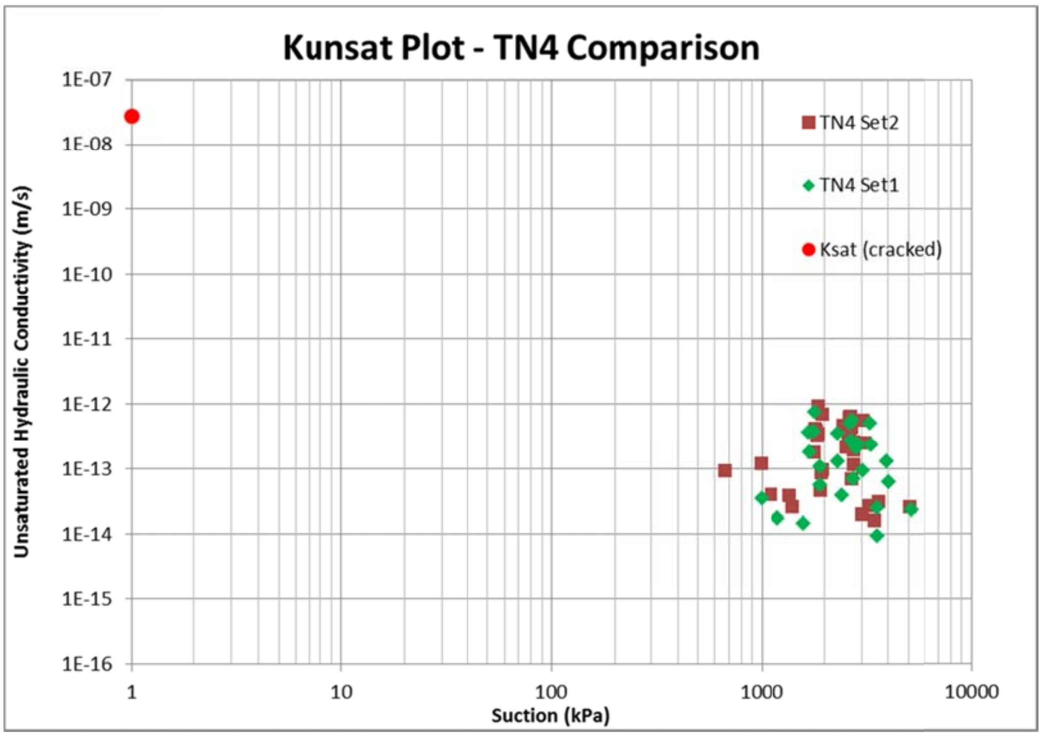

Figure 5.6: Comparison of Kunsat Values for Test No. 4.

The comparison of the sample sets 3 and 4 used for Method C for TN5 that have different air gap widths is presented in Figure 5.7. From this plot only a slight significant difference can be seen in the results. The slight difference can be seen in the groups of data points for a given unsaturated conductivity. For Set 3, with the smaller air gap, the conductivities seem to occur at a lower suction. This result may be a consequence of the water being able to transfer more quickly from one soil section to the other.

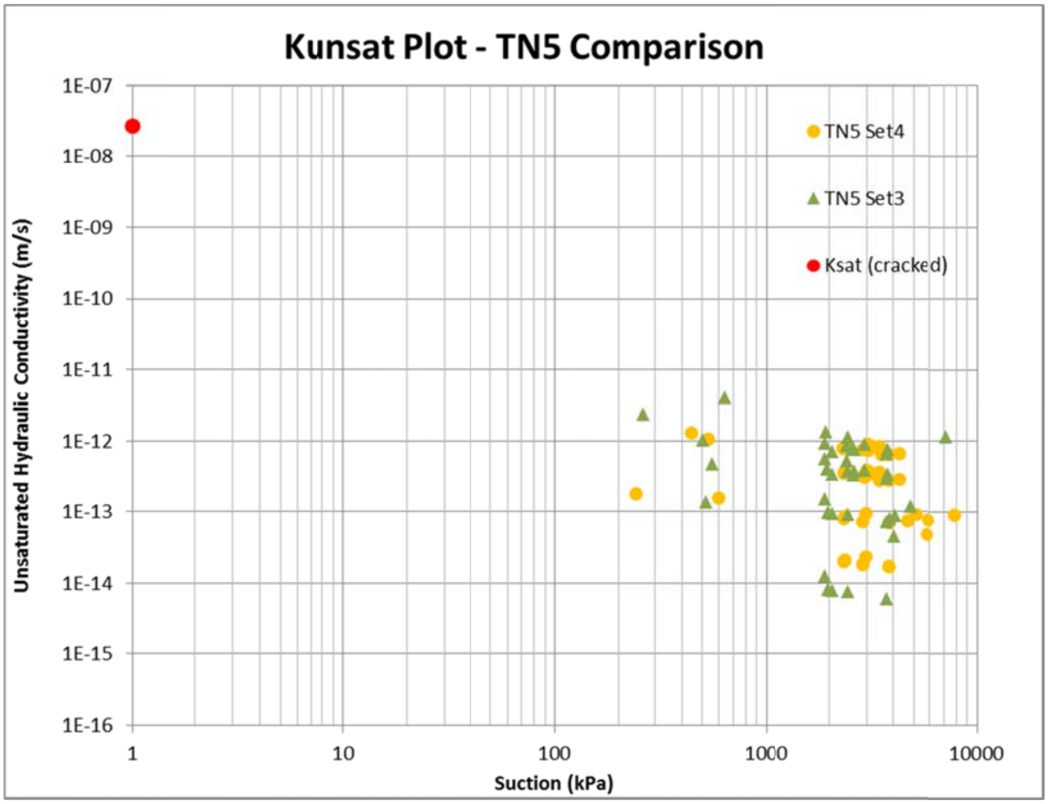

Figure 5.7: Comparison of Kunsat Values for Test No. 5.

The primary objective of TN5 was to determine the conductivity over the air gap as to simulate the conductivity of an unsaturated crack. This experiment was successful in determining this water vapor conductivity value for this situation for the two gap widths used for both sample sets. As shown in Figure 5.15 are the results for TN5 over the air gap. The average conductivity values over the air gap for Set 3 are 8.4*10^-15 m/s and 2.0*10^-14 for Set 4. The conductivity values calculated over the air gap for Set 3 are considered to be a minimum value of the hydraulic conductivity for the soil since it is calculated over the smallest air gap and is the conductivity of the water vapor flow over the gap.

Unsaturated Hydraulic Conductivity Models

The intact unsaturated hydraulic conductivity results are used to fit various statistical and semi empirical fitting curves to the data. There are numerous relationships between soil suction and hydraulic conductivity, so the most commonly used relationships were used including the Gardner (1958), van Genuchten-Mualem (1980), Leong and Rahardjo (1997), and the Kunze et al (1968) models. The plot in Figure 5.8 presents the intact unsaturated hydraulic conductivities along with the models used to fit the data. Table 5.2 in the following presents the fitting parameters used in the models. Refer to Chapter 2 for the equations of the models used. The fitting parameters were fit to the data using the solver function in Excel.

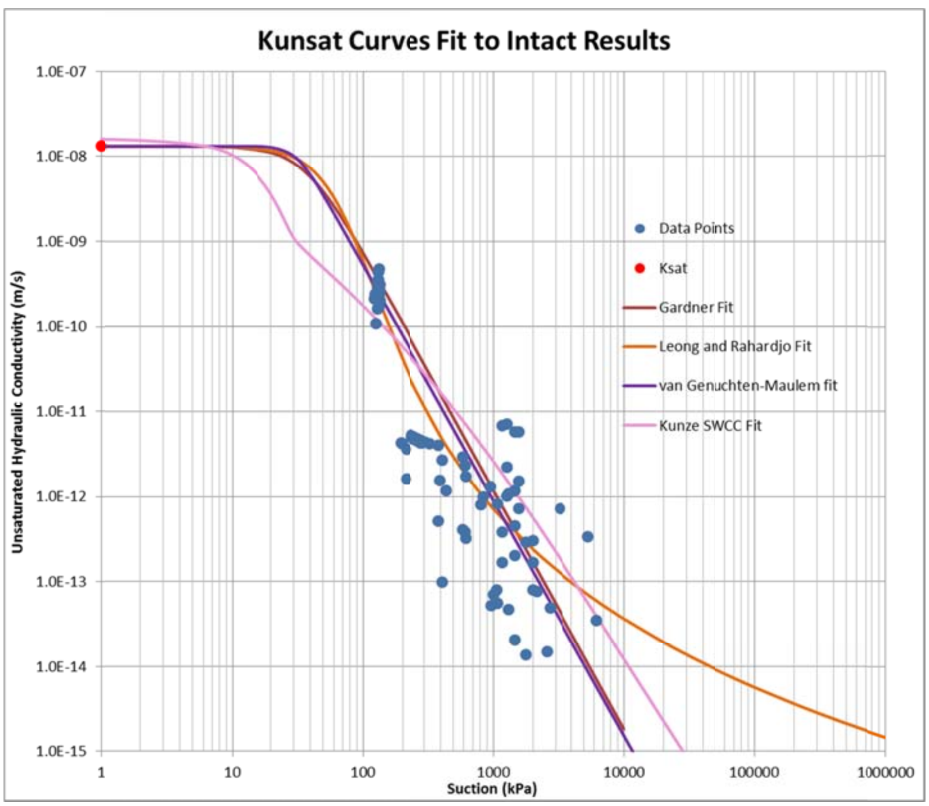

Figure 5.8: Kunsat Curves Fit to Intact Unsaturated Conductivity Data.

Table 5.3: Fitting Parameters for Various Kunsat Functions Used.

Equation	Fitting Parameters			
	a	m	n	R^2
Gardner (1958)	0.025		2.815	89.38%
Leong and Rahardjo (1997)	59.590	2.505163	2.517	89.69%
Van Genuchten and Maulem (1980)	1.000E-09	0.92	6.020	89.35%

The Kunze (1968) model used is based off the SWCC of the soil. This model determined the unsaturated hydraulic conductivity from the pore size distribution and also uses matching factor. To gain a good fit using this model the drying curve from the SWCC must be used (Kunze 1968). According the Michel and Soga (2005), this computation procedure is most successful for sand soils having a relatively narrow pore size distribution which may be the reason that this relationship does not fit to the data well.

The semi empirical relationships used to model the unsaturated hydraulic conductivity fit the data well using the fitting parameters shown in Table 5.2. The Gardner and van Genuchten-Mualem models fit the data well but to not accurately predict the conductivity behavior at high suctions. Figure 5.8 also shows that the hydraulic conductivity functions continuously decrease after the air entry value of the soil. Research done by Ebrahimi-B, Gitirana Jr., D. Fredlund, M. Fredlund and Samarasekera (2006) suggest that there is a lower limit for the water permeability coefficient equal to 1*10^-14 m/s. This lower limit agrees well with the minimum values of hydraulic conductivity calculated from the instantaneous profile experiments performed in this study. With this consideration of a lower limit to the hydraulic conductivity, the use of these type of semi empirical functions that continuously plummet after the air entry value may not be suitable or accurate to the actual unsaturated conductivity function for the soil and may have impactions in use for modeling the unsaturated hydraulic conductivity of soils at high suction values.

The Leong and Rahardjo (1997) model best fit the experimental data from a visual standpoint and also has a good correlation or R-squared value. This function begins to level off near the residual suction which may be more realistic to the actual hydraulic conductivity behavior of the soil.

Proposed Unsaturated Hydraulic Conductivity Function

To better model the unsaturated hydraulic conductivity of the soil, the soil-water-air-vapor phases and transitions between these phases are considered. As illustrated in the Figure 5.9 below, the transition zones in the SWCC cure are dictated by the air entry value and the residual conditions. Models of the unsaturated hydraulic conductivity already considers the unsaturated conductivity to be equal to the saturated hydraulic conductivity for suctions up to the air entry value such as the Brooks and Corey (1964) model. In the transition zone as depicted in Figure 5.9, the unsaturated conductivity becomes a function of the desaturation of the pores as suction increases.

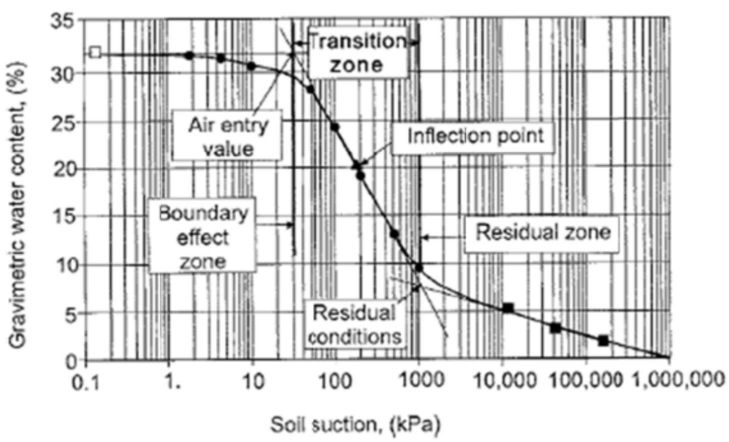

Figure 5.9: Desaturation Zones Defined by a SWCC.

In the work done by Ebrahimi-B, Gitirana Jr., D. Fredlund, M. Fredlund and Samarasekera (2006) suggest that there is a lower limit to the coefficient of water permeability for all soils equal to 1*10^-14 m/s. In their analysis they examined the unsaturated hydraulic conductivities and vapor conductivity functions to analyze the behavior of the unsaturated hydraulic conductivity function of a soil over a wide suction range up to 1*10^6 kPa. In Figure 5.10 below, the author's state that the conductivity of the soil is at the highest value when the soil is saturated and starts to decline as air starts entering the pores of the soil. When the conductivity reaches the residual condition the vapor conductivity dominates the overall conductivity of the soil. This suggests that the entire permeability function of a soil is a combination of both the soil-water and vapor conductivities.

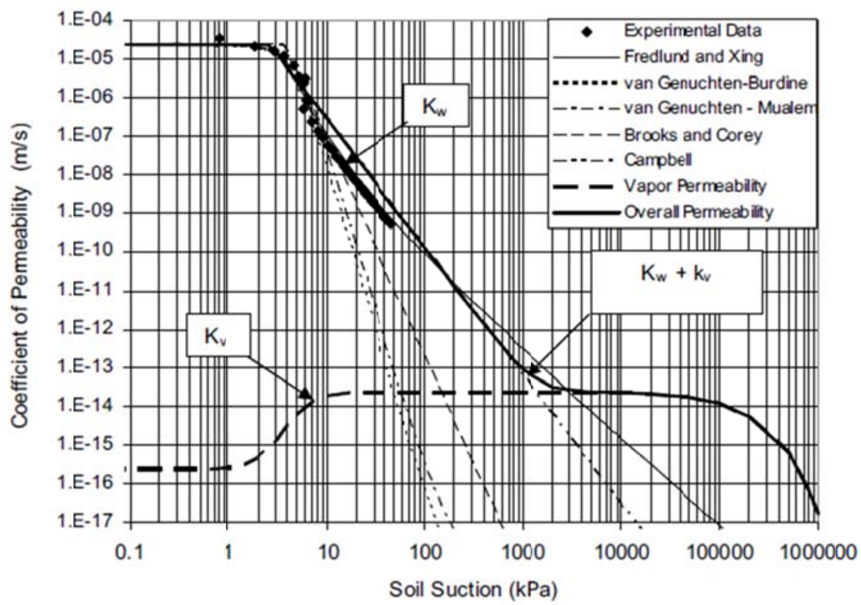

Figure 5.10: Variation of Liquid Water, Vapor, and Overall Permeability Coefficient with Soil Suction.

With the considerations provided by Ebrahimi-B et al. (2006) and results from this study are used, a new proposed unsaturated hydraulic conductivity function was proposed. The primary factors in the proposed function incorporate both the saturated and residual behaviors of soil hydraulic conductivity. For the proposed function, the conductivity is considered to be constant from zero suction to the air entry value and equal to the saturated hydraulic conductivity of the soil. The soil conductivity declines as suction increases at a rate determined by the maximum and minimum hydraulic conductivity and a fitting parameter. The hydraulic conductivity function levels off at the minimum unsaturated hydraulic conductivity or Kmin which should be equal to the minimum conductivity calculated from TN5 as the conductivity over the air gap.

The best empirical function that could be used to model this behavior is a hyperbolic profile equation which is a solution to a logistical equation which is shown below.

$$y' = \alpha x - y^2 \quad \text{(Eqn. 5.1)}$$

This equation states a y increases over x, that y will become saturated and function will steadily levels off to a constant value. This equation suits unsaturated hydraulic behavior because is represents the competition between the water and vapor phases at high suctions were the vapor phase overcomes the water phase which should dominate the unsaturated hydraulic conductivity near the residual condition. The general solution to the equation is present below as a hyperbolic function. The standard graphical representation and parameters of this hyperbolic profile equation are shown in Figure 5.11. The hyperbolic profile is used to model the unsaturated hydraulic conductivity with some modifications.

$$y = -\beta \tanh(\alpha x) \quad \text{(Eqn. 5.2)}$$

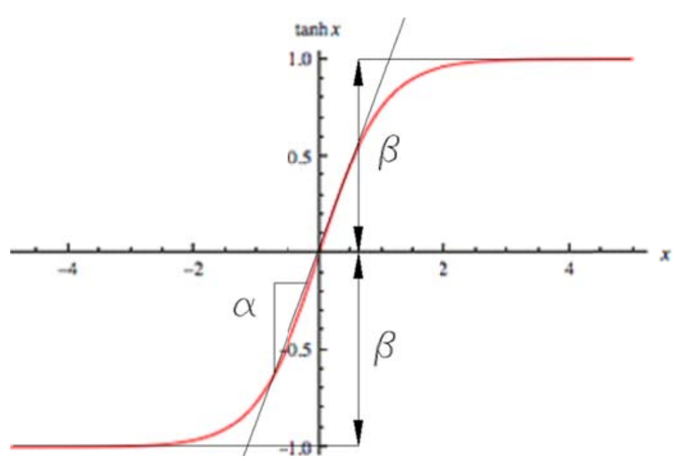

Figure 5.11: Example of Hyperbolic Profile and Parameters.

Using the hyperbolic profile and the modifications below, parameters in the equation are fit to the unsaturated hydraulic conductivity values for the used soil in this study. The averaging of the saturated (maximum) and minimum hydraulic conductivities and air entry value and residual suctions allows for the translation of the function for an appropriate fit to the data.

$$\beta = \frac{K_{sat} - K_{min}}{2} \qquad \text{(Eqn. 5.3)}$$

$$\alpha = \frac{2}{\psi_{residual} - \psi_{AEV}} \qquad \text{(Eqn. 5.4)}$$

$$K_{Avg} = \sqrt{K_{sat} K_{min}} \qquad \text{(Eqn. 5.5)}$$

$$\psi_{Avg} = \sqrt{\psi_{AEV} \psi_{residual}} \qquad \text{(Eqn. 5.6)}$$

$$\log(K_w) = \log(K_{Avg}) - \beta \times \tanh\left(\alpha \times log\left(\frac{\psi}{\psi_{Avg}}\right)\right) \qquad \text{(Eqn. 5.7)}$$

Parameters:

ψ: Soil suction.
ψ_{AEV}: Soil air entry value.
$\psi_{residual}$: Residual suction value.
K_{sat}: Saturated Hydraulic Conductivity.
K_{min}: Minimum unsaturated hydraulic conductivity.

The simplified form of the proposed unsaturated hydraulic conductivity function using relevant soil parameter, K_{sat}, K_{min}, ψ_{AEV}, and $\psi_{residual}$ and two fitting parameters a and b is presented below. The fitting parameter a, is related to the slope in the transition zone. The fitting parameter b reduces the residual suction value to increase the fit to the data. The residual suction value is related to the residual water content from the SWCC and is sometimes hard to accurately determine a representative value for.

$$K_w = \sqrt{K_{sat}K_{min}} \times 10^{\left[\frac{1}{2}\log\left(\frac{K_{sat}}{K_{min}}\right)\times\tanh\left(\frac{log\left(\frac{\psi}{\sqrt{b\times\psi_{AEV}\psi_{residual}}}\right)}{2\times log\left(\frac{b\times\psi_{residual}}{\psi_{AEV}}\right)}\right)^{a}\right]}$$

(Eqn. 5.9)

Parameters:

K_w: Unsaturated hydraulic conductivity.
a: Fitting parameters related to the slope in the transition zone.
b: Fitting parameters related to the residual suction value.

This proposed model is formulated to better represent the results from the instantaneous profile experiments performed in this study. Values were determine in high suction ranges and this model better represent the data by taking into account the saturated hydraulic conductivity and the minimum conductivity. This model was fit to the instantaneous profile results and is presented in Figure 5.12 below.

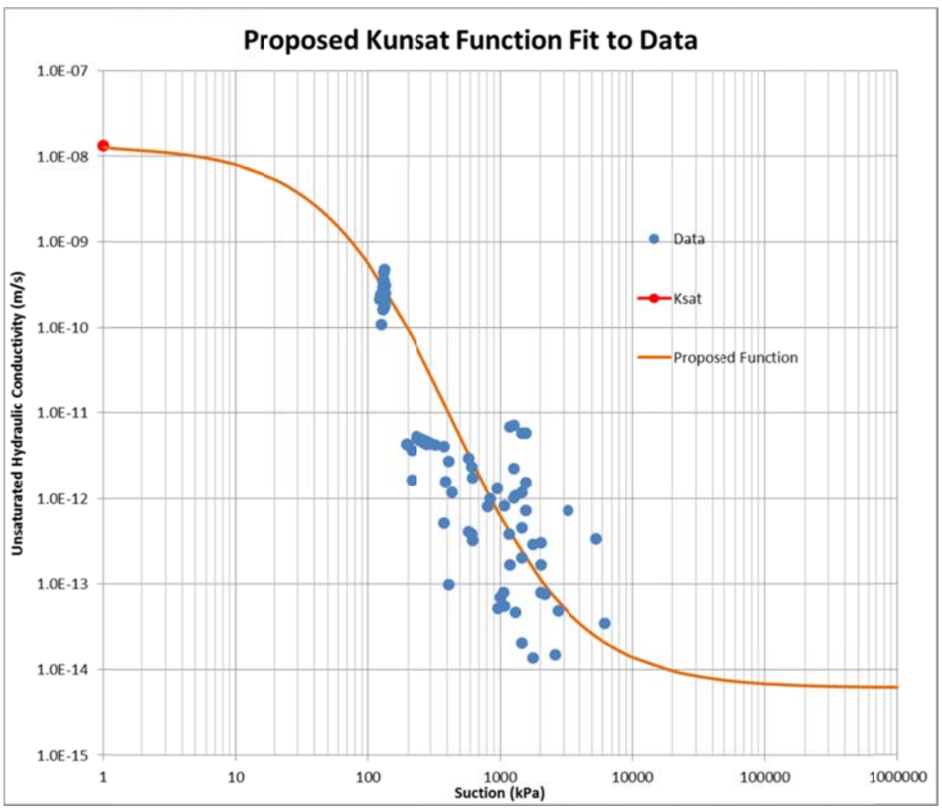

Figure 5.12: Proposed Kunsat Function Fit the Data.

The values used for the inputs into the proposed unsaturated hydraulic conductivity function, for the saturated and minimum conductivities and the air entry value and residual suction are presented below.

Table 5.4: Input Parameters to Proposed Kunsat Function.

Ksat (m/s)	1.33E-08
Kmin (m/s)	6.10E-15
Residual Suction (kPa)	20000
Air Entry Value (kPa)	20
a	0.61
b	0.45

The proposed unsaturated hydraulic conductivity function fit the results from the instantaneous profile experiment well and better resembles the actual behavior of the permeability of a soil taking into account a minimum conductivity. When this model is compared to other soil hydraulic conductivity models found in literature, the results indicate a better fit according to the R-squared values and shown in Table 5.4 below.

Table 5.5: Fitting parameters Used for Proposed Kunsat Function and Comparison to Other Kunsat Models.

Equation	Fitting Parameters				
	a	b	m	n	R^2
Gardner (1958)	0.025			2.815	89.38%
Leong and Rahardjo (1997)	59.590		2.505163	2.517	89.69%
Van Genuchten and Maulem (1980)	1.000E-09		0.92	6.020	89.35%
Proposed Function	0.61	0.45			89.49%

Comparison and Analysis of Intact and Cracked Unsaturated Hydraulic Conductivity Results

To analyze the effect of air voids and cracks to the unsaturated hydraulic conductivity, the intact and cracked results are compared. The scope of this analysis is limited to the suction range for which the instantaneous profile experiments were conducted at. The cracked instantaneous profile experiments TN4 and TN5 can be compared to the intact data sets from TN3, TN6I and TN7. The results for both intact and cracked vertical infiltration experiments from TN6 are compared to each other since they were conducted in the same manner in using the same soil conditions. In this section conclusions are presented from the results of this study and the differences in the intact and cracked conditions are examined.

The cracked unsaturated hydraulic conductivity results from TN4 are compared to the intact results in Figure 5.13. As presented in this plot, the results from TN4 fall within the scatter of the intact data. Most of the unsaturated hydraulic conductivity values from TN4 fall within the band of data for TN3. The data shows no significant difference between the intact and cracked conditions for this experiment.

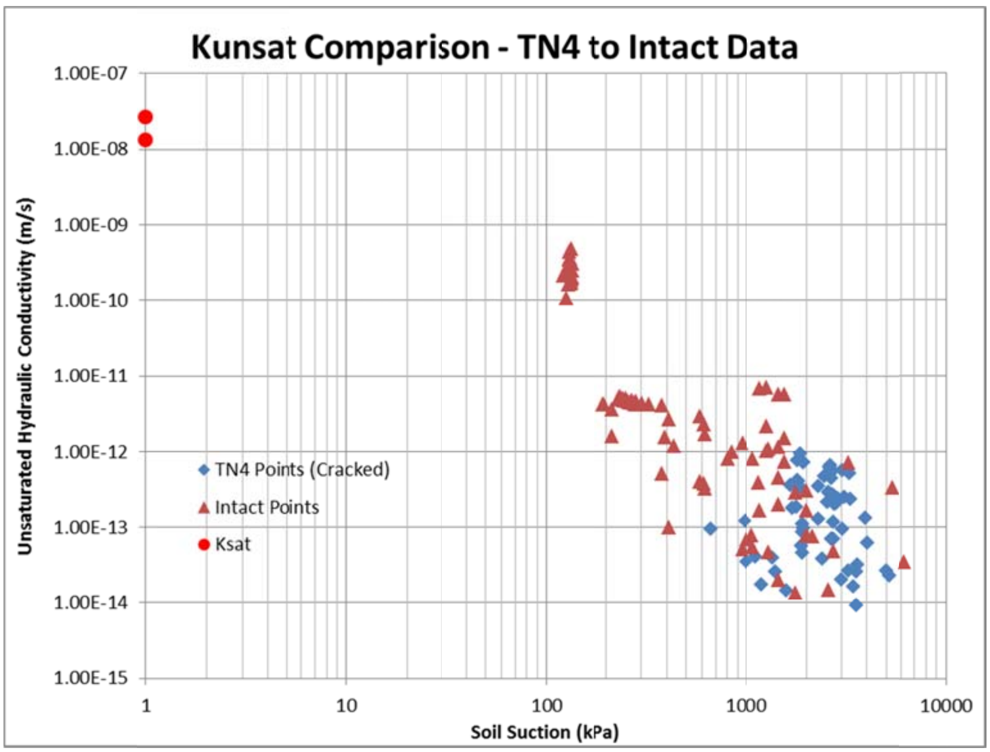

Figure 5.13: Kunsat Comparison of Test No. 4 to Intact Data.

The cracked unsaturated hydraulic conductivity results from the air gap cracked instantaneous profile experiment TN5 are compared to the intact results in Figure 5.14. The conductivities calculated over the air gap are included in the TN5 results and are represented as the lower conductivity conductivities for TN5. The results presented in this plot show that the results from TN5 fall within the scatter of the intact data. Most of the unsaturated hydraulic conductivity values from TN5 fall within the band of data from TN3 with a few points falling into the range of data from TN7 in a lower suction range. The results from TN5 show not significant difference from the intact results besides the points calculated over the air gap.

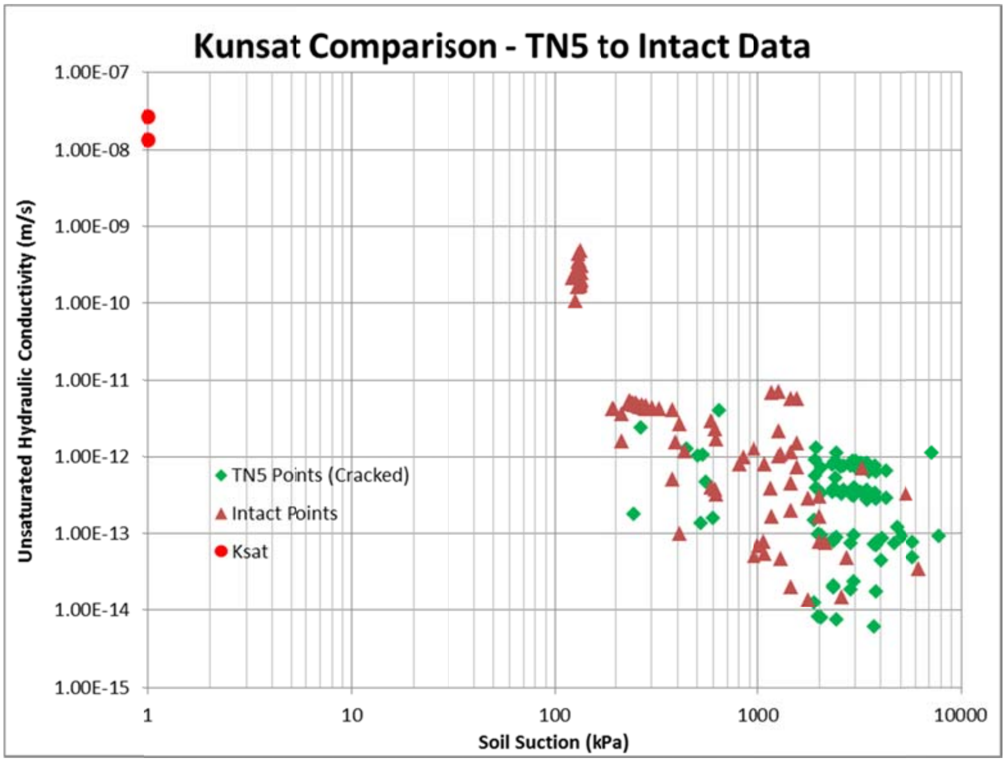

Figure 5.14: Kunsat Comparison of Test No. 5 to Intact Data.

The conductivities calculated over the air gap from TN5 are compared to the entire intact data set in Figure 5.15. In this figure it can be observed that the conductivities over the air gap are less than the majority intact unsaturated hydraulic conductivity values. This was expected since the conductivity over the air gap should be the conductivity of the water-vapor transfer potential of the soil. Also some of the conductivities calculated over the air gap are less than the minimum value of hydraulic conductivity suggested by Ebrahimi-B et al. (2006) which is 1*10^-14 m/s.

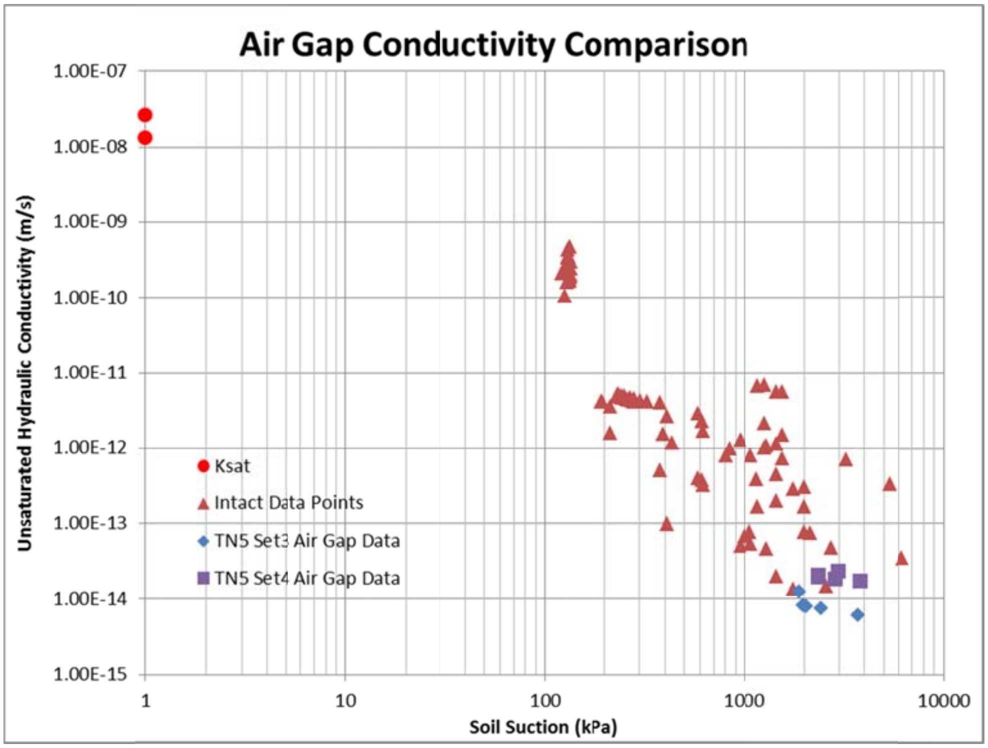

Figure 5.15: Air Gap Conductivities Compared to Intact Data.

The cracked unsaturated hydraulic conductivity results from the vertical infiltration test of TN6C are compared the intact results from TN6I in Figure 5.16. The conductivities calculated from both the intact and cracked experiments from TN6 are within the same suction range which allows for a good comparison between results from each experiment. The unsaturated hydraulic conductivities from TN6C are greater than the unsaturated hydraulic conductivities from TN6I. From visual observation the difference between the conductivities between the cracked and intact results appears to be different but the actual difference in hydraulic conductivity is insignificant and on the order of 6.3*10^-12 m/s on average. This suggests that there is no significant difference between the unsaturated hydraulic conductivities for this experiment at the suction range used in the experiment.

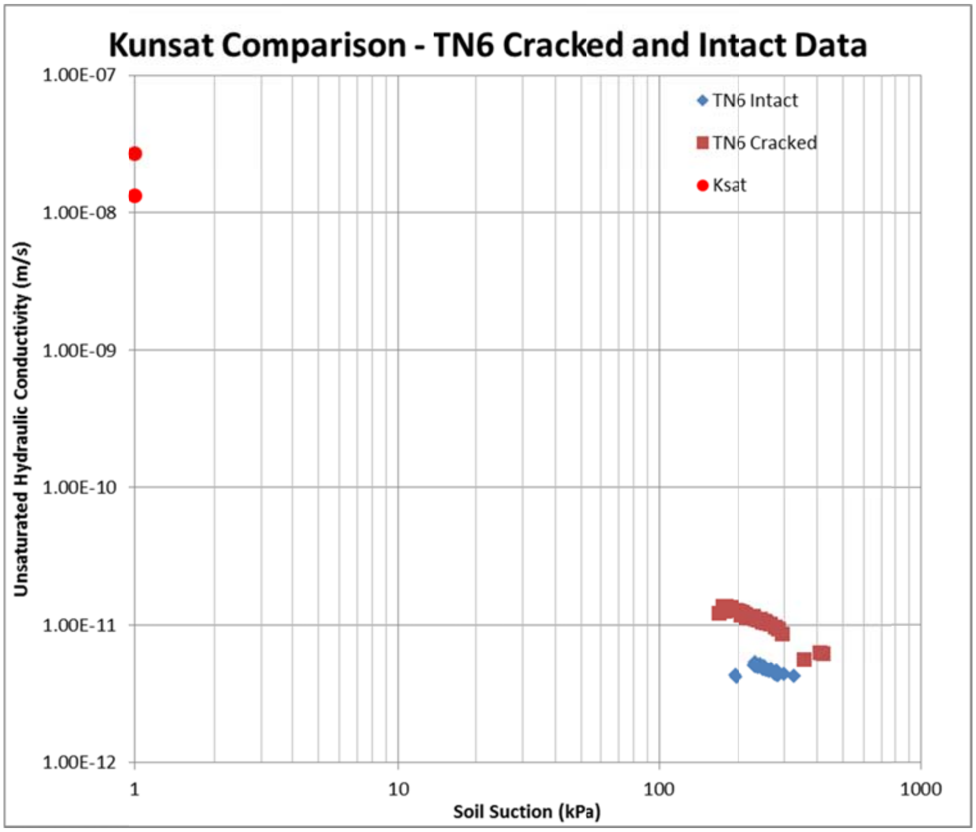

Figure 5.16: Kunsat Comparison of Cracked and Intact Data from Test No. 6.

The results from the instantaneous profile experiments conducted in this study for cracked and intact conditions suggest that there is no difference in the unsaturated hydraulic conductivity in the suction range tested. The suctions of the unsaturated hydraulic conductivities for the cracked and intact conditions range from 200 to 8,000 kPa. In this range of suction there is not an evident difference in the results of the hydraulic conductivities within the band of scatter of the data.

In the paper presented by Zhang, Li and Fredlund (2011) on the "Hydraulic Conductivity Function for an Unsaturated Cracked Soil" concludes that the permeability may only be dominated by the crack network at low suctions. As shown in Figure 5.17 below from their study, it shows that at high suctions there is no apparent difference in the hydraulic conductivity between the cracked and intact conditions.

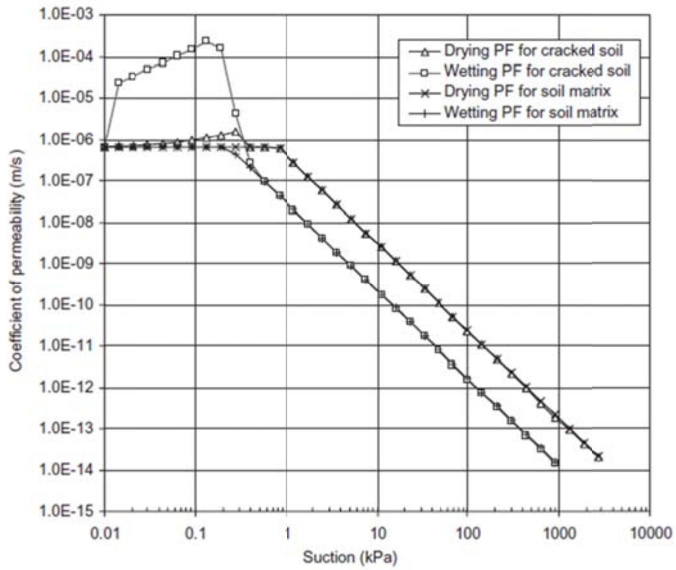

Figure 5.17: Permeability of Cracked and Intact Soil (Zhang et al. 2011).

The results from Zhang et al. (2011) agree well with the outcome of this study that shows no significant or observable difference in the unsaturated hydraulic conductivities from the intact and cracked conditions at high suctions. When all the cracked and intact results are combined as presented in Figure 5.18, there conductivities values all fall within the same band of scatter within all the experimental results.

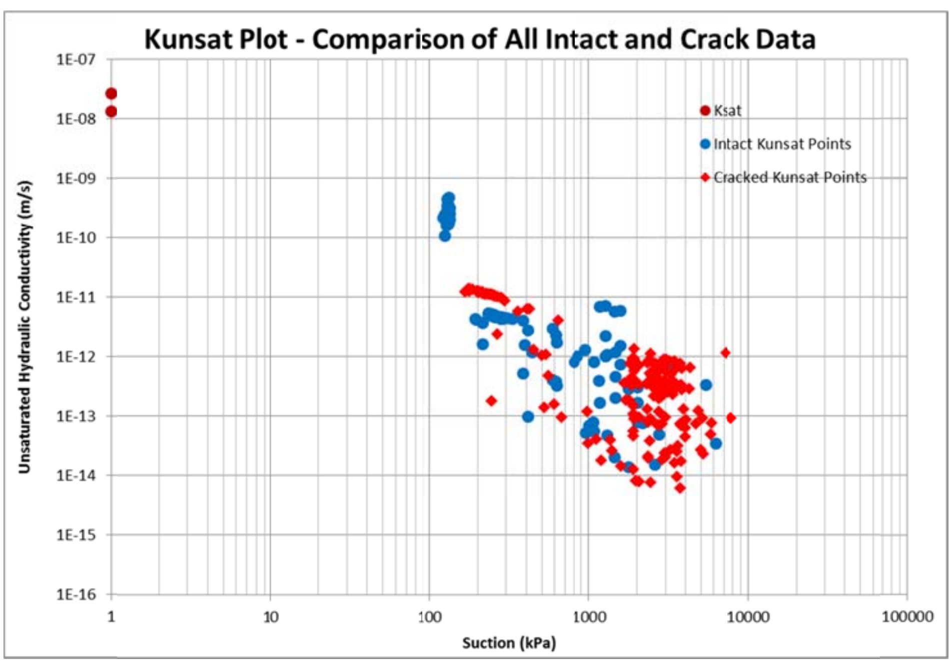

Figure 5.18: Kunsat Plot Comparison of All Cracked and Intact Data Points.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Determining the unsaturated hydraulic conductivity of a fine grained soil is a tedious and time consuming process. Implications and considerations increase in complexity, when measuring the unsaturated hydraulic conductivity for a cracked soil. In this study, seven instantaneous profile experiments were designed and conducted to measure the unsaturated hydraulic conductivity for intact and cracked fine grained soil. The experiments performed in this study provide insight to various aspects to the measurement, experimental design, calculation, and procedures used for measuring the unsaturated hydraulic conductivity of a soil. A summary of the research conducted is presented below along with the conclusions to the research objectives and recommendations for future research related to the measurement of the unsaturated hydraulic conductivity for fine grained soils.

Summary

In chapter 1, the scope of the research performed in this study was outlined along with the objectives and importance of this research. Cracked fine grained soils present various implications to the design of infrastructure and foundation construction. Desiccation cracking can occur in numerous situations and understanding the behavior of the water flow is of great importance. In the analysis of some soil systems, the unsaturated hydraulic conductivity is a significant parameter since is used to model water flow, infiltration, volume change and the triggering of landslides (Li, Zhang and Fredlund, 2009). There has been little research done on the implications of cracks and fissures to the unsaturated hydraulic conductivity which provided the opportunity to assess these effects.

It is important to model the hydraulic properties of cracked soils to investigate the effect on the infiltration rate. The measurement of the saturated hydraulic conductivity can be done through a relatively simple experiment and comparing the hydraulic conductivity of the cracked and intact condition can be done. The instantaneous profile method is an unsteady-state method that is used to measure the unsaturated hydraulic conductivity. There are several variations of this method which primarily differ in the general method used, sampling procedures and the way water is removed or introduced into the system. For the cracked condition, measuring the unsaturated hydraulic conductivity can be done similarly to the intact condition by incorporating cracks into the soil profile so that their effects can be analyzed by comparing the results from each condition.

The objectives of this study were to i) analyze the effects of air voids or cracks on the unsaturated hydraulic conductivity; ii) research and summarize the methods used for measuring the unsaturated hydraulic conductivity for cracked soils, and iii) propose special considerations for measuring the unsaturated hydraulic conductivity by the instantaneous profile method, including recommendations that deal with the prediction of the unsaturated hydraulic conductivity.

In chapter 2, a literature review was conducted in order to provide insight into current methods and techniques used for measuring the unsaturated hydraulic conductivity for intact and cracked fine grained soil. In general, it was found that the subject of unsaturated hydraulic conductivity has been studied by researchers, but the publications are limited.

It was found in the literature that there are various functions that can be used to predict the unsaturated conductivity. The equations presented and used are semi empirical in nature and have been developed from statistical equations which are used to model the conductivity behavior of soil. The equations presented by Broods and Corey (1964), Gardner (1958), van Genuchten et al. (1980), Arbhabhirama and Kridakorn (1968), and Leong and Rahardjo (1997) are equations that use statistical fits to model the unsaturated coefficient of permeability function. All of these functions include empirical constants that may relate to specific soil properties such as the air entry value and the slope of the SWCC at the deflection point. Gardner (1958) and van Genuchten (1980) equations are the most common equation used to model the unsaturated conductivity function.

In geotechnical engineering there are numerous methods to measure the unsaturated hydraulic conductivity of a soil. The unsaturated hydraulic conductivity can be measured using direct or indirect techniques (Fredlund and Rahardjo, 1993). The most practical and promising method for determining the unsaturated hydraulic conductivity is the instantaneous profile method. The instantaneous profile method is an unsteady state method that can use direct or indirect measurements. The method uses a cylindrical specimen of soil that may be subjected to a continuous flow of water. Many researchers have used instantaneous profile experiments to determine the unsaturated hydraulic conductivity. This method is performed frequently in unsaturated soil testing and is an acceptable direct technique of testing. On the other hand, researchers have noted that the Kunsat function can be affected by the use of the soil water characteristic curve to calculate suction and to calculate gradient terms. This suggests that the indirect measurement used should be made from a well-established and accurate soil water characteristic curve.

The apparatus used for most instantaneous profile experiment is a rigid form cylindrical tube. Data was compiled of the length and size of the apparatus used in each instantaneous profile experiment reviewed.

Regarding the effect of the presence of cracks on the unsaturated hydraulic conductivity, it was found that this is a topic in unsaturated soil mechanics that is still not fully understood. There is very limited research available to the behavior of soils when there are cracks. The considerations from the review of the studies performed by various researchers on the hydraulic behavior of cracks in fine grained soils offers some considerations to the experimental design that were used in this study.

One of the objectives of this research work was to analyze the effects of air void and cracks on the unsaturated hydraulic conductivity. The soil used for the study was fully characterized as a Clayey Sand (SC) through an extensive testing program to index the soil. The complete geotechnical analysis and testing is shown in chapter 3. Also the experimental designed is outlined and explained. To analyze the hydraulic behavior of the soil, separate experiments were conducted to test the intact and cracked conditions using the instantaneous profile method.

To determine the coefficient of permeability for intact soil, the instantaneous profile experiment was used. Two different types of experiments were performed: The first instantaneous profile experiments titled Test Number 1 (TN1) and Test Number 2 (TN2) were trial experiments which were used to provide information on the accuracy and quality of the methods used for measurement and the overall experiment performance. Test Number 3 (TN3) and Test Number 7 (TN7) are also intact instantaneous profile experiments. These experiments were designed from observations and problematic issues encountered in TN1 and TN2 that were improved. Some improvements include the sampling methods, testing procedures and the general method used. The changes made were significant for TN3 and TN7 and the experiment use the duplicate method.

The objective of the cracked instantaneous profile experiments was to measure the unsaturated hydraulic conductivity for the cracked condition. The cracked experiments differed from the intact experiments in that they have cracks or voids formed into the soil profile. Different methods were proposed in order to simulate and measure the infiltration process of water through a cracked surface. Differences between experiments included the orientation and direction of the cracks with respect to the soil profile and the path of water flow. These experiments also allowed for the anisotropy and crack orientation effects to be considered. To analyze the aspects of water flow through the soil three methods were proposed to each simulate a different direction of the water flow with respect to the crack orientation.

In chapter 4, the computation and calculation procedures used to determine the unsaturated hydraulic conductivity were discussed. Also, the methods used to measure suction and water content were outlined, and the results of the intact and cracked experiments were presented. Seven planned instantaneous profile experiments titled Test Numbers 1 through 7 were conducted at Arizona State University. The samples from each experiment were stored in a controlled environment by using an environmental chamber located in the basement of ISTB2 at ASU except for TN1 and TN2 which were stored in the Geotechnical laboratory area.

The results of the five intact instantaneous profile experiments were presented, as well as the results of the three cracked instantaneous profile experiments. The initial soil conditions, set up procedures, measurement locations, testing conditions, sampling procedures, observations during the experiments, and results were discussed and presented.

In chapter 5, the analysis of the results was presented for the cracked and intact conditions along with consideration of the method used for determining the unsaturated hydraulic conductivity by the instantaneous profile method. Also, the use of unsaturated hydraulic conductivity models was presented and a new unsaturated hydraulic conductivity model is proposed. Various considerations to the general methods, sampling methods, sampling procedures and storage conditions used were also discussed. The instantaneous profile experiments conducted in this study provide results for the sandy clay soil tested over a wide suction range. The unsaturated hydraulic conductivity values determined for the intact condition in the suction range tested have not been seen in current literature reviewed. In the analysis of the unsaturated hydraulic conductivity values for both the intact and cracked conditions, the results from each type of experiment are combined. The intact experiments include Test Nos. 3, 6, and 7. The cracked experiments include Test Nos. 4, 5 and 6.

The unsaturated hydraulic conductivity plots or Kunsat plots for the intact condition from the various experiments conducted are presented. The Kunsat plots show that the conductivity values follow a trend with increasing variability of the unsaturated hydraulic conductivity as suction increases. The data from each experiment type does agree well with each other. The results from instantaneous profile experiments TN3 and TN7 show that unsaturated conductivity values could be obtained in the desired suction ranges. The results from these experiments show that the cracked unsaturated hydraulic conductivity follows a similar trend as to the intact results with increasing scatter as suction increases. The points from the cracked experiments using Methods B and C (TN4 and TN5), from the different sample sets, with different cracked specification do not presented any significant differences.

There are various aspects to consider in relation the scatter to the data for both the intact and cracked unsaturated conductivity data sets. Anisotropic soil conditions add a variation to the permeability function of the soil. The primary change in the permeability function is associated with the difference between the maximum and minimum coefficient of hydraulic conductivity to the principal direction of anisotropy. This is also similar to the behavior of the wetting and drying functions of a permeability function. In the instantaneous profile experiments performed show that some soil sections experienced wetting and drying through the testing which may also account for the amount of scatter in the hydraulic conductivities.

Using the intact unsaturated hydraulic conductivity data and results, various statistical and semi empirical models were fit to the data. There are numerous relationships between soil suction and hydraulic conductivity, so the most commonly used models were used including the Gardner (1958), van Genuchten-Mualem (1980), Leong and Rahardjo (1997), and the Kunze et al (1968) relationships. The semi empirical relationships used to model the unsaturated hydraulic conductivity fit the data well. The Gardner and van Genuchten-Mualem models fit the data well but do not accurately predict the conductivity behavior at high suctions. Research done by Ebrahimi-B, Gitirana Jr., D. Fredlund, M. Fredlund and Samarasekera (2006) suggests that there is a lower limit for the water permeability coefficient equal to 1*10^-14 m/s. This lower limit agrees well with the minimum values of hydraulic conductivity calculated from the instantaneous profile experiments performed. With this consideration, using these types of semi empirical functions that continuously plummet after the air entry value may not be accurate to the actual unsaturated conductivity behavior for the soil and may have impactions in the use of modeling soils at high suctions. The Leong and Rahardjo (1997) model best fit the experimental data from a visual standpoint and also has a good correlation value. Also this function begins to level off near the residual suction which may be more realistic to the actual hydraulic conductivity behavior of the soil.

To better model the unsaturated hydraulic conductivity of a soil, the soil-water-air-vapor phases and transition between these phases should be considered. With the consideration provided by Ebrahimi-B et al. (2006) and the results from this study a new proposed unsaturated hydraulic conductivity function was proposed. The primary factors in the proposed function incorporate both the saturated and residual behaviors for soil permeability. This proposed model is formulated to better represent the data from the instantaneous profile experiments performed in this study. Since values were determine in high suction ranges, the model better represents the data by taking into account the saturated hydraulic conductivity and the minimum conductivity from TN5 over the air gap. The proposed unsaturated hydraulic conductivity function fits the results from the instantaneous profile experiment well due to its correlation values are compared to other relationship used to model the results of this study.

To analyze the effect of air voids and cracks on the unsaturated hydraulic conductivity, the intact and cracked results were compared. The scope of this analysis was limited to the suction range for which the instantaneous profile experiments were conducted at and to the results of these experiments. The cracked instantaneous profile experiments TN4 and TN5 can be compared to the intact data sets from TN3, TN6I and TN7. The results for both intact and cracked vertical infiltration experiments from TN6 are compared to each other since they were conducted in the same manner at the same suction range. The results from TN4 fall within the scatter of the intact data and therefore, the results showed no significant difference between the intact and cracked conditions. Furthermore, the results from TN5 fall within the scatter of the intact data. Hence, data from TN5 showed no significant difference from the intact data besides the points calculated over the air gap.

The results and conclusion from Zhang et al. (2011) agree well with the outcome of this study that shows no significant or observable difference in the unsaturated hydraulic conductivities from the intact and cracked conditions at high suction values.

Conclusions

The outcome of this research study on the unsaturated hydraulic conductivity measurements on an intact and cracked fine grained soil has given insight into various aspects of the hydraulic behavior of water through soil. Due to the conditions of testing, the results of the hydraulic conductivity from experimentation are within the high suction range for soils. From the comparison of the results from the intact and cracked unsaturated hydraulic conductivity data obtained, it was found that there was no significant difference between the intact and cracked conductivity functions for the suction range tested. This result confirms finding provided by Zhang et al. (2011). The methods used to analyze the presence of cracks in a soil profile to their unsaturated hydraulic conductivity values performed as desired.

Overall from this study it has been found that the presence of cracks has no significant bearing on the hydraulic behavior of soil when subjected to high suction ranges. The results of this study do not apply to the behavior of cracked soil at low suction or near saturation.

The experimental testing conducted in this study provided insight into methods and considerations for determining the unsaturated hydraulic conductivity using the instantaneous profile method. From performing the instantaneous profile experiments, various conclusions were made to the general method and sampling procedures, as outlined below.

- The results from experiments TN1 and TN2, which were performed by following the standard instantaneous profile procedure produced results that were considered to have a high amount of scatter. It was concluded that the sampling technique makes the standard test prone to inaccuracies due to disturbance issues.
- An important consideration of the standard method is the change in the soil fabric with respect to the direction of compaction. This is a clear weakness given the fact that the hydraulic conductivity is very much affected by the orientation of the soil particles and direction of compaction (Mitchell and Soga, 2005). The hydraulic conductivity is different in the horizontal direction from the vertical direction in a soil profile due to soil fabric effects.
- Another issue with the test method used for TN1 and TN2 is the amount of soil sections. The procedure use to perform these experiments used four different soil sections which are all considered independent of each other. Controlling the suction and gradients between these sections proved to not be easy and involved a lot of considerations including the assumptions regarding the direction of flow, and to the wetting or drying cycles the samples were subjected to at the time of testing.
- The duplicate method provides some advantages over the method used for TN1 and TN2. The primary advantage of the duplicate method is that the samples can be completely destroyed for water content sampling. Because of this, the water content measurements along the soil profile can be very accurately measured from using large water content samples and sample taken are more representative. Also the filter paper sandwiches can be easily retrieved.
- Other advantages of the duplicate method are the simplified procedure for specimen production and the small cost associated with it.

- The duplicate method also allows for the user to choose the suction range for which they would like to measure hydraulic conductivity values. Since only two soil sections are used, the range of anticipated water contents and suction is easier to control. Also the hydraulic and suction gradients can be easily determined.
- The duplicate method does have some disadvantages. The duplicate method creates a large amount of variability and scatter from the computation of hydraulic conductivity points calculated through various locations within the soil profile. This is due to the non-homogeneous sample set and the fact that not all the soil sample encounters the same change in water content and is not compacted at exactly the same conditions.
- The scatter observed from the duplicate experiments may also be a result of the soil fabric effects of compacting the soils above and below the optimum water content. It has been discussed in literature that the soil fabric being either flocculated or dispersed has an effect on the hydraulic conductivity of a soil (Mitchell and Soga 2005).
- The vertical infiltration experiment Test No. 6 (TN6) performed well and as expected. This experiment allowed for unsaturated conductivity values to be acquired in the smallest amount of time.
- The use of large sample sizes could also increase the accuracy of measurements obtained by the instantaneous profile experiment. Many of the measurement techniques used rely of sensors that have a specific radius of influence. Large sample sizes could decrease the boundary effect of the sample apparatus and have less influence on the measurements of devices such as the volumetric moisture probes.

Recommendations for Future Research

This study provided contribution to the unsaturated hydraulic conductivity behavior for high soil suctions and considerations to methods using the instantaneous profile method. However more research could be conducted in the areas listed below:

- Further testing over the entire suction range of soil using the duplicate method could provide a complete unsaturated hydraulic conductivity function. Also more testing of the hydraulic conductivity at high suction ranges could be performed to further understand the unsaturated hydraulic behavior at high suction ranges.
- Testing different soil types would determine the impact of use, accuracy and applicability of the duplicate method.
- The new proposed unsaturated hydraulic conductivity function presented in this study could be fit to unsaturated hydraulic conductivity functions for different soil types. The input parameters of the equation could be further explored and related to know soil properties.
- Longer testing periods of the unsaturated hydraulic conductivity could be performed using the duplicate method to determine if the soil sample would eventually come to moisture equilibrium.
- Further research could be done to analyze the wetting and drying patterns of the unsaturated hydraulic conductivity data. Determining the trends in the unsaturated hydraulic conductivity data could be determined for the wetting and drying and related to the wetting and drying trends used in the SWCC.
- More unsaturated hydraulic conductivity testing could be performed at high suctions using various measurement techniques such as electrical/thermal conductivity sensors to measure suction. The use of this type of sensors may

increase the accuracy of the measured values and decrease the amount of scatter in the results.

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APPENDIX A

INTACT UNSATURATED HYDRAULIC CONDUCTIVITY DATA SET

Test No.	Test Temp (C)	Soil γd (pcf)	Test Section	Suction (kPa)	Kunsat (m/s)
1	25	106.5	P6 to P21	1125	7.47016E-12
1	25	106.5	P6 to P21	1240	7.14413E-12
1	25	106.5	P6 to P21	1340	6.28279E-12
1	25	106.5	P6 to P21	1490	6.13465E-12
1	25	106.5	P6 to P21	1640	5.32342E-12
1	25	106.5	P6 to P21	1750	4.98351E-12
1	25	106.5	P6 to P21	1835	5.25267E-12
1	25	106.5	P6 to P21	1935	4.89618E-12
1	25	106.5	P6 to P21	2095	5.02549E-12
1	25	106.5	P6 to P21	2245	5.08342E-12
1	25	106.5	P6 to P21	2350	5.00945E-12
1	25	106.5	P15 to P30	360	3.23413E-11
1	25	106.5	P15 to P30	522.5	2.51805E-11
1	25	106.5	P15 to P30	687.5	2.01372E-11
1	25	106.5	P15 to P30	775	1.54874E-11
1	25	106.5	P15 to P30	837.5	1.22088E-11
1	25	106.5	P15 to P30	912.5	1.06234E-11
1	25	106.5	P15 to P30	975	8.96308E-12
1	25	106.5	P15 to P30	1050	7.99496E-12
1	25	106.5	P15 to P30	1150	7.25987E-12
1	25	106.5	P15 to P30	1250	6.32768E-12
1	25	106.5	P15 to P30	1400	6.70822E-12

Test No.	Test Temp (C)	Soil γd (pcf)	Test Section	Suction (kPa)	Kunsat (m/s)
2	25	106.5	P6 to P21	1055	8.31142E-12
2	25	106.5	P6 to P21	1195	7.90885E-12
2	25	106.5	P6 to P21	1335	8.05685E-12
2	25	106.5	P6 to P21	1405	7.39856E-12
2	25	106.5	P6 to P21	1505	6.67826E-12
2	25	106.5	P6 to P21	1615	6.57797E-12
2	25	106.5	P6 to P21	1670	6.39595E-12
2	25	106.5	P6 to P21	1750	5.92616E-12
2	25	106.5	P6 to P21	1845	5.5788E-12
2	25	106.5	P6 to P21	1920	5.62343E-12
2	25	106.5	P6 to P21	2000	5.57696E-12
2	25	106.5	P6 to P21	2075	5.82846E-12
2	25	106.5	P6 to P21	2025	7.05392E-12
2	25	106.5	P6 to P21	1725	7.96238E-12
2	25	106.5	P15 to P30	495	3.39264E-11
2	25	106.5	P15 to P30	645	2.78172E-11
2	25	106.5	P15 to P30	740	2.39685E-11
2	25	106.5	P15 to P30	785	1.85758E-11
2	25	106.5	P15 to P30	795	1.59232E-11
2	25	106.5	P15 to P30	825	1.39816E-11
2	25	106.5	P15 to P30	875	1.2819E-11
2	25	106.5	P15 to P30	910	1.09047E-11
2	25	106.5	P15 to P30	960	1.03757E-11
2	25	106.5	P15 to P30	1075	1.02684E-11
2	25	106.5	P15 to P30	1215	8.41103E-12
2	25	106.5	P15 to P30	1330	7.00865E-12
2	25	106.5	P15 to P30	1190	6.95459E-12
2	25	106.5	P15 to P30	925	7.16097E-12

Test No.	Test Temp (C)	Soil γd (pcf)	Test Section	Suction (kPa)	Kunsat (m/s)
3	4	106.5	P2 to P4	5360.985	3.34375E-13
3	4	106.5	P2 to P4	1568.635	7.3111E-13
3	4	106.5	P2 to P4	1275.71	1.01443E-12
3	4	106.5	P2 to P4	1464.365	2.03327E-13
3	4	106.5	P3 to P5	1165.015	3.8598E-13
3	4	106.5	P3 to P5	1568.635	5.79617E-12
3	4	106.5	P3 to P5	1275.71	7.16952E-12
3	4	106.5	P3 to P5	1464.365	1.16933E-12
3	4	106.5	P3 to P6	1079.8725	8.17101E-13
3	4	106.5	P3 to P6	1459.65375	5.7521E-12
3	4	106.5	P3 to P6	1179.06875	6.83743E-12
3	4	106.5	P3 to P6	1302.18375	1.08779E-12
3	4	106.5	P2 to P5	3263	7.1689E-13
3	4	106.5	P2 to P5	1568.635	1.51994E-12
3	4	106.5	P2 to P5	1275.71	2.20566E-12
3	4	106.5	P2 to P5	1464.365	4.52918E-13
3	4	106.5	P2 to P3	6184.61125	3.50163E-14
3	4	106.5	P2 to P3	2733.55125	4.912E-14
3	4	106.5	P2 to P3	2162.12875	7.63797E-14
3	4	106.5	P2 to P3	2576.96	1.50472E-14
3	4	106.5	P4 to P5	1079.8725	5.55187E-14
3	4	106.5	P4 to P5	1459.65375	2.03566E-14
3	4	106.5	P4 to P5	1179.06875	1.66804E-13
3	4	106.5	P4 to P5	1302.18375	4.68424E-14
3	4	106.5	P2 to P4	2010.44	7.91638E-14
3	4	106.5	P3 to P5	2010.44	3.0254E-13
3	4	106.5	P3 to P6	1765.33375	2.89116E-13
3	4	106.5	P2 to P5	2010.44	1.67446E-13

Test No.	Test Temp (C)	Soil γd (pcf)	Test Section	Suction (kPa)	Kunsat (m/s)
6	4	106.5	2 Pt.	328.8158124	4.24E-12
6	4	106.5	3 Pt.	301.3160356	4.39E-12
6	4	106.5	4 Pt.	196.8331579	4.18E-12
6	4	106.5	5 Pt.	194.4051999	4.28E-12
6	4	106.5	6 Pt.	285.3252296	4.30E-12
6	4	106.5	7 Pt.	284.5927299	4.30E-12
6	4	106.5	8 Pt.	283.9351616	4.57E-12
6	4	106.5	9 Pt.	283.443041	4.30E-12
6	4	106.5	10 Pt.	281.47959	4.59E-12
6	4	106.5	11 Pt.	278.9065378	4.35E-12
6	4	106.5	12 Pt.	274.6048793	4.41E-12
6	4	106.5	13 Pt.	268.9032699	4.76E-12
6	4	106.5	14 Pt.	263.7868587	4.56E-12
6	4	106.5	15 Pt.	258.1837707	4.64E-12
6	4	106.5	16 Pt.	252.676069	5.01E-12
6	4	106.5	17 Pt.	249.8264272	4.76E-12
6	4	106.5	18 Pt.	247.510115	4.79E-12
6	4	106.5	19 Pt.	244.1607373	5.15E-12
6	4	106.5	20 Pt.	240.3691109	4.90E-12
6	4	106.5	21 Pt.	236.7226159	4.96E-12
6	4	106.5	22 Pt.	234.1716459	5.32304E-12
6	4	106.5	23 Pt.	233.6284072	5.02395E-12
6	4	106.5	24 Pt.	232.6211495	5.03428E-12

Test No.	Test Temp (C)	Soil γd (pcf)	Test Section	Suction (kPa)	Kunsat (m/s)
7	4	106.5		953.499519	1.31465E-12
7	4	106.5		215.0475195	1.62266E-12
7	4	106.5		215.6250195	3.64144E-12
7	4	106.5		584.2735193	2.95364E-12
7	4	106.5		1068.399519	7.95865E-14
7	4	106.5		584.2735193	4.06173E-13
7	4	106.5		806.245	8.00955E-13
7	4	106.5		437.615	1.18729E-12
7	4	106.5		411.9025	2.72002E-12
7	4	106.5		621.93	1.73794E-12
7	4	106.5		960.4875	5.18757E-14
7	4	106.5		621.93	3.24395E-13
7	4	106.5		411.9025	9.91699E-14
7	4	106.5		839.745	9.96566E-13
7	4	106.5		392.73	1.54495E-12
7	4	106.5		381.9075	4.06548E-12
7	4	106.5		616.2375	2.30867E-12
7	4	106.5		1002.7275	7.00141E-14
7	4	106.5		616.2375	3.79762E-13
7	4	106.5		381.9075	5.1997E-13

Test No.	Test Temp (C)	Soil γd (pcf)	Test Section	Suction (kPa)	Kunsat (m/s)
TT	20	106.5	AB	129.4923509	2.92082E-10
TT	20	106.5	AB	130.1135922	4.3855E-10
TT	20	106.5	AB	130.7405457	1.68673E-10
TT	20	106.5	AB	129.6598872	3.44534E-10
TT	20	106.5	AB	128.8584298	1.61733E-10
TT	20	106.5	AB	130.9088698	3.55776E-10
TT	20	106.5	AB	132.8954851	1.88532E-10
TT	20	106.5	AB	132.8595893	4.77192E-10
TT	20	106.5	AB	125.407498	1.08307E-10
TT	20	106.5	AB	133.0534137	1.92575E-10
TT	20	106.5	AB	134.2305026	3.08751E-10
TT	20	106.5	AB	134.5105522	2.02662E-10
TT	20	106.5	AB	135.0293793	2.51879E-10
TT	20	106.5	AB	132.9461043	1.74617E-10
TT	20	106.5	AB	130.5802781	3.54564E-10
TT	20	106.5	AB	128.4730755	2.37493E-10
TT	20	106.5	AB	124.4827362	2.40991E-10
TT	20	106.5	AB	121.5481205	2.11596E-10
TT	20	106.5	BC	144.5951219	3.64891E-10
TT	20	106.5	BC	147.8081066	7.67911E-10
TT	20	106.5	BC	147.9486697	2.98486E-10
TT	20	106.5	BC	145.3395587	6.0577E-10
TT	20	106.5	BC	146.9936726	3.00491E-10
TT	20	106.5	BC	148.2075061	6.71333E-10
TT	20	106.5	BC	149.6082515	3.56137E-10
TT	20	106.5	BC	153.4813519	8.7203E-10
TT	20	106.5	BC	150.3085408	1.96783E-10
TT	20	106.5	BC	153.1887249	3.49899E-10
TT	20	106.5	BC	155.0937479	5.77977E-10
TT	20	106.5	BC	157.0636295	3.96041E-10
TT	20	106.5	BC	158.1554206	4.6635E-10
TT	20	106.5	BC	157.5561391	3.21279E-10
TT	20	106.5	BC	155.8594156	6.49087E-10
TT	20	106.5	BC	152.9459733	4.38492E-10
TT	20	106.5	BC	149.5971176	4.47095E-10
TT	20	106.5	BC	147.6991661	3.86524E-10
TT	20	106.5	CD	150.3857735	3.92998E-10
TT	20	106.5	CD	153.4882516	8.29697E-10
TT	20	106.5	CD	153.8347163	3.21939E-10
TT	20	106.5	CD	151.9074765	6.49901E-10
TT	20	106.5	CD	154.0360772	3.21336E-10
TT	20	106.5	CD	155.3111444	7.187E-10
TT	20	106.5	CD	156.4707853	3.81138E-10
TT	20	106.5	CD	160.9070465	9.32802E-10
TT	20	106.5	CD	161.2396594	2.07115E-10
TT	20	106.5	CD	163.2623064	3.6951E-10
TT	20	106.5	CD	165.9927836	6.07882E-10
TT	20	106.5	CD	169.122077	4.14629E-10
TT	20	106.5	CD	171.9514777	4.83984E-10
TT	20	106.5	CD	173.2301333	3.30787E-10
TT	20	106.5	CD	172.7857055	6.62539E-10
TT	20	106.5	CD	170.7240822	4.46076E-10
TT	20	106.5	CD	168.8329565	4.49382E-10
TT	20	106.5	CD	167.8100825	3.87208E-10

APPENDIX B

CRACKED UNSATURATED HYDRAULIC CONDUCTIVITY DATA SET

Test No.	Set No.	Test Temp (C)	Soil γd (pcf)	Test Section	Suction (kPa)	Kunsat (m/s)
4	1	4	106.5	P2 to P4	3337.27	2.30549E-13
4	1	4	106.5	P2 to P4	2872.25	2.39324E-13
4	1	4	106.5	P2 to P4	3030.45	9.49973E-14
4	1	4	106.5	P2 to P4	4015.38	6.28169E-14
4	1	4	106.5	P3 to P5	2684.02	2.68964E-13
4	1	4	106.5	P3 to P5	1679.5	3.58865E-13
4	1	4	106.5	P3 to P5	1705.4825	1.8088E-13
4	1	4	106.5	P3 to P5	2315.945	1.29065E-13
4	1	4	106.5	P3 to P6	2708.52	5.66488E-13
4	1	4	106.5	P3 to P6	1809.75	7.66927E-13
4	1	4	106.5	P3 to P6	1780.41	3.79166E-13
4	1	4	106.5	P3 to P6	2301.685	3.46889E-13
4	1	4	106.5	P2 to P5	3288.52	5.09143E-13
4	1	4	106.5	P2 to P5	2641.75	5.10726E-13
4	1	4	106.5	P2 to P5	2836.3775	2.0788E-13
4	1	4	106.5	P2 to P5	3920.2275	1.30647E-13
4	1	4	106.5	P2 to P3	5188.275	2.30401E-14
4	1	4	106.5	P2 to P3	3551.25	2.55856E-14
4	1	4	106.5	P2 to P3	3538.645	9.36027E-15
4	1	4	106.5	P3 to P4	2732.77	6.8936E-14
4	1	4	106.5	P3 to P4	1910	1.08362E-13
4	1	4	106.5	P3 to P4	1899.555	5.57695E-14
4	1	4	106.5	P3 to P4	2411.0975	3.84577E-14
4	1	4	106.5	P4 to P5	1000.5	3.47897E-14
4	1	4	106.5	P4 to P5	1197.2875	1.75948E-14
4	1	4	106.5	P4 to P5	1597.5125	1.44803E-14

Test No.	Set No.	Test Temp (C)	Soil γd (pcf)	Test Section	Suction (kPa)	Kunsat (m/s)
4	2	4	106.5	P2 to P4	3106.4575	2.48359E-13
4	2	4	106.5	P2 to P4	2738.0025	2.61979E-13
4	2	4	106.5	P2 to P4	2746.445	1.18566E-13
4	2	4	106.5	P2 to P4	2750.2125	1.98553E-13
4	2	4	106.5	P2 to P4	2546.1625	2.16685E-13
4	2	4	106.5	P3 to P5	2580.9575	2.84999E-13
4	2	4	106.5	P3 to P5	1834.75	3.98223E-13
4	2	4	106.5	P3 to P5	1794.22	1.81195E-13
4	2	4	106.5	P3 to P5	1853.675	3.24947E-13
4	2	4	106.5	P3 to P5	1862.0525	3.45497E-13
4	2	4	106.5	P3 to P6	2648.9575	6.57263E-13
4	2	4	106.5	P3 to P6	1875.5	9.24585E-13
4	2	4	106.5	P3 to P6	1806.5775	4.13333E-13
4	2	4	106.5	P3 to P6	1951.14	7.12234E-13
4	2	4	106.5	P3 to P6	1945.695	7.13127E-13
4	2	4	106.5	P2 to P5	3020.7075	5.68748E-13
4	2	4	106.5	P2 to P5	2620.7525	6.22315E-13
4	2	4	106.5	P2 to P5	2628.0275	2.74166E-13
4	2	4	106.5	P2 to P5	2674.25	4.41835E-13
4	2	4	106.5	P2 to P5	2455.42	4.673E-13
4	2	4	106.5	P2 to P3	5020.9	2.65533E-14
4	2	4	106.5	P2 to P3	3584.5025	3.18597E-14
4	2	4	106.5	P2 to P3	3424.0525	1.62992E-14
4	2	4	106.5	P2 to P3	3239.73	2.69416E-14
4	2	4	106.5	P2 to P3	3005.1325	2.00049E-14
4	2	4	106.5	P3 to P4	2666.7075	7.02525E-14
4	2	4	106.5	P3 to P4	1952	9.67258E-14
4	2	4	106.5	P3 to P4	1912.6375	4.60593E-14
4	2	4	106.5	P3 to P4	1929.6375	8.76846E-14
4	2	4	106.5	P3 to P4	1952.795	9.83425E-14
4	2	4	106.5	P4 to P5	666.515	9.35162E-14
4	2	4	106.5	P4 to P5	988.25	1.19987E-13
4	2	4	106.5	P4 to P5	1116.6125	4.09469E-14
4	2	4	106.5	P4 to P5	1364.1575	3.96863E-14
4	2	4	106.5	P4 to P5	1403.0825	2.58395E-14

Test No.	Set No.	Test Temp (C)	Soil γd (pcf)	Test Section	Suction (kPa)	Kunsat (m/s)
5	3	4	106.5	P2 to P4	3749.64625	3.38653E-13
5	3	4	106.5	P2 to P4	2948.13375	3.86736E-13
5	3	4	106.5	P2 to P4	2591.4775	3.27558E-13
5	3	4	106.5	P2 to P4	2423.84	5.21771E-13
5	3	4	106.5	P2 to P4	2634.6225	3.7219E-13
5	3	4	106.5	P3 to P5	3710.68625	2.95251E-13
5	3	4	106.5	P3 to P5	2438.67375	3.70297E-13
5	3	4	106.5	P3 to P5	1947.1725	3.94286E-13
5	3	4	106.5	P3 to P5	1919.9775	5.63643E-13
5	3	4	106.5	P3 to P5	2059.585	3.38742E-13
5	3	4	106.5	P3 to P6	3709.6275	6.6705E-13
5	3	4	106.5	P3 to P6	2427.365	8.52137E-13
5	3	4	106.5	P3 to P6	1917.06	9.16055E-13
5	3	4	106.5	P3 to P6	1932.6675	1.32185E-12
5	3	4	106.5	P3 to P6	2055.8425	7.17594E-13
5	3	4	106.5	P2 to P5	3748.635	7.67926E-13
5	3	4	106.5	P2 to P5	2936.8725	8.86165E-13
5	3	4	106.5	P2 to P5	2561.365	7.44129E-13
5	3	4	106.5	P2 to P5	2436.5325	1.11994E-12
5	3	4	106.5	P2 to P5	2630.8825	7.67948E-13
5	3	4	106.5	P2 to P3 (Intact)	7194.61375	1.1307E-12
5	3	4	106.5	P2 to P3 (Intact)	4831.92875	1.20861E-13
5	3	4	106.5	P2 to P3 (Intact)	4015.9525	4.50477E-14
5	3	4	106.5	P2 to P3 (Intact)	3840.525	7.96628E-14
5	3	4	106.5	P2 to P3 (Intact)	4054.5825	8.69278E-14
5	3	4	106.5	P3 to P4 (Long)	3711.6975	7.31403E-14
5	3	4	106.5	P3 to P4 (Long)	2449.935	9.02898E-14
5	3	4	106.5	P3 to P4 (Long)	1977.285	9.77747E-14
5	3	4	106.5	P3 to P4 (Long)	1907.285	1.48958E-13
5	3	4	106.5	P3 to P4 (Long)	2063.325	9.55096E-14
5	3	4	106.5	P3 to P4 (Short)	3711.6975	6.09502E-15
5	3	4	106.5	P3 to P4 (Short)	2449.935	7.52415E-15
5	3	4	106.5	P3 to P4 (Short)	1977.285	8.14789E-15
5	3	4	106.5	P3 to P4 (Short)	1907.285	1.24132E-14
5	3	4	106.5	P3 to P4 (Short)	2063.325	7.95914E-15
5	3	4	106.5	P4 to P5 (Inact)	265.71875	2.36503E-12
5	3	4	106.5	P4 to P5 (Inact)	554.87875	4.74726E-13
5	3	4	106.5	P4 to P5 (Inact)	522.6975	1.36266E-13
5	3	4	106.5	P4 to P5 (Inact)	503.2925	1.03913E-12
5	3	4	106.5	P4 to P5 (Inact)	639.625	4.02493E-12

Test No.	Set No.	Test Temp (C)	Soil γd (pcf)	Test Section	Suction (kPa)	Kunsat (m/s)
5	4	4	106.5	P2 to P4	4260.12125	2.85852E-13
5	4	4	106.5	P2 to P4	3201.10875	3.45764E-13
5	4	4	106.5	P2 to P4	2883.7975	3.13544E-13
5	4	4	106.5	P2 to P4	3417.72	3.6329E-13
5	4	4	106.5	P2 to P4	3447.545	2.73148E-13
5	4	4	106.5	P3 to P5	3800.8175	2.79302E-13
5	4	4	106.5	P3 to P5	2369.43	3.76244E-13
5	4	4	106.5	P3 to P5	2337.3925	3.46056E-13
5	4	4	106.5	P3 to P5	3005.7575	3.87692E-13
5	4	4	106.5	P3 to P5	2950.175	3.05442E-13
5	4	4	106.5	P3 to P6	3814.07	6.3366E-13
5	4	4	106.5	P3 to P6	2382.8075	8.58528E-13
5	4	4	106.5	P3 to P6	2324.3275	7.88064E-13
5	4	4	106.5	P3 to P6	3038.245	8.91175E-13
5	4	4	106.5	P3 to P6	3030.5325	7.19043E-13
5	4	4	106.5	P2 to P5	4273.37375	6.50651E-13
5	4	4	106.5	P2 to P5	3214.48625	8.37816E-13
5	4	4	106.5	P2 to P5	2870.7575	7.54556E-13
5	4	4	106.5	P2 to P5	3450.215	8.43118E-13
5	4	4	106.5	P2 to P5	3527.885	6.36036E-13
5	4	4	106.5	P2 to P3 (Intact)	7815.39625	9.08014E-14
5	4	4	106.5	P2 to P3 (Intact)	5124.46125	9.08978E-14
5	4	4	106.5	P2 to P3 (Intact)	4686.62	7.47342E-14
5	4	4	106.5	P2 to P3 (Intact)	5823.4325	7.63631E-14
5	4	4	106.5	P2 to P3 (Intact)	5782.95	4.84607E-14
5	4	4	106.5	P3 to P4 (Long)	3787.565	6.88925E-14
5	4	4	106.5	P3 to P4 (Long)	2356.0525	8.4483E-14
5	4	4	106.5	P3 to P4 (Long)	2350.4325	7.94663E-14
5	4	4	106.5	P3 to P4 (Long)	2973.2625	9.34939E-14
5	4	4	106.5	P3 to P4 (Long)	2869.835	7.31914E-14
5	4	4	106.5	P3 to P4 (Short)	3787.565	1.72231E-14
5	4	4	106.5	P3 to P4 (Short)	2356.0525	2.11208E-14
5	4	4	106.5	P3 to P4 (Short)	2350.4325	1.98666E-14
5	4	4	106.5	P3 to P4 (Short)	2973.2625	2.33735E-14
5	4	4	106.5	P3 to P4 (Short)	2869.835	1.82979E-14
5	4	4	106.5	P4 to P5 (Inact)	245.5425	1.80467E-13
5	4	4	106.5	P4 to P5 (Inact)	446.0775	1.28301E-12
5	4	4	106.5	P4 to P5 (Inact)	534.57	1.06089E-12
5	4	4	106.5	P4 to P5 (Inact)	600.045	1.56941E-13

Test No.	Set No.	Test Temp (C)	Soil γd (pcf)	Test Section	Suction (kPa)	Kunsat (m/s)
6	Cracked	4	106.5	NA	408.6655802	6.27367E-12
6	Cracked	4	106.5	NA	421.5389483	6.21611E-12
6	Cracked	4	106.5	NA	356.1206861	5.631E-12
6	Cracked	4	106.5	NA	294.5982583	8.56118E-12
6	Cracked	4	106.5	NA	254.6969226	1.03929E-11
6	Cracked	4	106.5	NA	221.6237275	1.12216E-11
6	Cracked	4	106.5	NA	214.9588919	1.14226E-11
6	Cracked	4	106.5	NA	203.6348717	1.18086E-11
6	Cracked	4	106.5	NA	177.4775822	1.26178E-11
6	Cracked	4	106.5	NA	168.2240281	1.21228E-11
6	Cracked	4	106.5	NA	176.0767099	1.32235E-11
6	Cracked	4	106.5	NA	174.6734407	1.35543E-11
6	Cracked	4	106.5	NA	177.4334611	1.36057E-11
6	Cracked	4	106.5	NA	178.7412817	1.37438E-11
6	Cracked	4	106.5	NA	185.9352456	1.33675E-11
6	Cracked	4	106.5	NA	198.3890215	1.26925E-11
6	Cracked	4	106.5	NA	203.6479143	1.25004E-11
6	Cracked	4	106.5	NA	208.8862919	1.22978E-11
6	Cracked	4	106.5	NA	215.1861884	1.20274E-11
6	Cracked	4	106.5	NA	229.0121188	1.15046E-11
6	Cracked	4	106.5	NA	244.6897654	1.09468E-11
6	Cracked	4	106.5	NA	252.5543794	1.0611E-11
6	Cracked	4	106.5	NA	240.5598573	1.08889E-11
6	Cracked	4	106.5	NA	234.4581516	1.10459E-11
6	Cracked	4	106.5	NA	248.8607113	1.05445E-11
6	Cracked	4	106.5	NA	257.345179	1.03371E-11
6	Cracked	4	106.5	NA	266.487512	1.0074E-11
6	Cracked	4	106.5	NA	277.63792	9.65936E-12
6	Cracked	4	106.5	NA	285.2350003	9.38879E-12