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Characterization of Soil Unsaturated Flow Properties Using Steady State Centrifuge Methods

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Characterization of Soil Unsaturated Flow Properties Using Steady State Centrifuge Methods

by

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Characterization of Soil Unsaturated Flow Properties Using Steady State Centrifuge Methods

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Three testing procedures were developed in this research to allow expeditious characterization of soil unsaturated flow properties using steady state centrifuge methods. The first testing procedure, referred to as the "instrumented" procedure, focuses on using in-flight measurement of the suction and volumetric water content of soil samples under centrifugation. The measurements are used to calculate the soil water retention curve and hydraulic conductivity function (K-function) of soil samples. A good agreement was found between results determined using the "instrumented" procedure and standard testing methods.

Several possible sources of inaccuracy were determined with the "instrumented" procedure. The void ratio, the changes of which were not measured, was found to decrease during centrifugation and the lower boundary condition, which was not accounted for in the evaluation, was found to affect a large portion of the sample. In order to improve the accuracy of results, two additional testing procedures were developed that accounted for these issues and incorporated the void ratio of the soil as an additional variable. The first additional procedure was used to measure the soil water retention surface (SWRS) of soil samples while the second was used to measure the unsaturated hydraulic conductivity surface (K-surface) of soil samples.

Both new procedures, referred to as the "hydrostatic" and "imposed flow" procedures, were used to characterize the unsaturated flow properties of a low plasticity clay ("RMA" soil). The unsaturated flow characteristics of the RMA soil were evaluated for a wide range of void ratio and three compaction moisture conditions. As a result, the effects of void ratio and compaction moisture content on the unsaturated flow characteristics could be determined for the RMA soil.

The compaction water content was shown to have significant effects on both the retention behavior and the unsaturated hydraulic conductivity of the RMA soil. In general, increases in compaction water content resulted in a decrease of large pore sizes in the soil, resulting in higher water retention and lower unsaturated hydraulic conductivity. The void ratio was found to have comparatively lesser, but still significant, effects on both retention and conductivity characteristics. Specifically, decreases in void ratio were shown to reduce the unsaturated hydraulic conductivity. In addition, decreases in void ratio were shown to result in either increases or decreases on the soil water retention, depending on the level of suction in the soil.

A good agreement was found between results obtained using standard methods and those from the hydrostatic and imposed flow procedures. Accordingly, steady state centrifuge methods were ultimately found to provide a both expeditious and accurate method for characterizing the unsaturated flow properties of soil.

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1 INTRODUCTION

The measurement of unsaturated hydraulic properties of soil is relevant in many areas of geotechnical engineering. Some traditional applications include evaluation of foundations and pavements over expansive clays, the design of drainage systems, as well as the evaluation of the stability of levees, embankments, and earth dam under fluctuating water levels. Other critical but less conventional applications include evapotranspirative cover systems, geothermal piles, and bentonite barriers used to seal underground repositories.

The unsaturated hydraulic analysis of these systems is necessary in order to accurately evaluate variations in moisture content, pore pressures, and seepage rates. The primary hydraulic characteristics required for analysis are the soil water retention curve (SWRC) and the hydraulic conductivity function (K-function). The SWRC relates the amount of moisture retained in a soil with the level of matric suction. The K-function relates the hydraulic conductivity of a soil with the amount of water it contains (or the corresponding matric suction).

Unsaturated soil characteristics are most often used in predicting flow processes but can also be of interest in other areas such as determining the stability and deformability of geotechnical systems. For example, improper drainage systems and formation of capillary barriers are issues that can result in reduction of soil strength and failures of slopes or retaining structures. The proper analysis of these stability issues requires unsaturated soil characterization in order to predict the distribution of moisture in the soils and therefore the strength.

The SWRC and K-function of soils are challenging to determine, partly because of lengthy testing times. As a result, the direct unsaturated hydraulic characterization of soils has often been neglected and, instead, empirical correlations or theoretical models have been relied on to predict the unsaturated hydraulic behavior. This is especially true for the K-function, which is rarely measured directly in engineering practice. This is of concern as the predictions for the K-function have been shown to be questionable (e.g. Poulson et al. 1999) and the K-function is critical for the accurate prediction of unsaturated flow.

Even for projects where the prediction of unsaturated flow is critical, such as evapotranspirative landfill covers, SWRCs have been measured (in some of these projects) but the K-function has been generally predicted using correlations based on SWRC parameters. This is particularly worrisome as the K-function is often significantly more relevant in the accurate prediction of unsaturated flow. This is because the hydraulic conductivity varies orders of magnitude depending on the soil type and moisture condition while the hydraulic gradient (which the SWRC is used to predict) generally does not.

This research project focuses on using centrifuge technology to directly measure the unsaturated flow properties of a low plasticity clay. In particular the SWRC and K-function will be examined. Centrifuges have the ability to increase the hydraulic gradient of soil samples by scaling the gravitational gradient independently of pressure gradient. The independent scaling of gravitational gradient allows centrifuge methods to accelerate unsaturated flow processes without affecting the matric suction and therefore saturation of soil samples. This is a unique benefit of centrifuge testing, as traditional testing methods can only increase the hydraulic gradient by changing the pressure gradient and therefore saturation of samples.

The ability to quickly characterize unsaturated soil properties will be used to explore the effects of soil properties, particularly the compaction water content and void ratio, on the SWRC and K-function. The effects of compaction water content and void ratio on saturated hydraulic conductivity have been investigated extensively but the same evaluation has not been completed on unsaturated soils. Such evaluation has largely been undefined due to the difficulty and time required for traditional testing methods. The time saving benefits of centrifuge technology will be leveraged in over to conduct such testing in order to provide insight into the effects compaction water content and void ratio on unsaturated soils. The improved understanding of the effects of these properties on unsaturated soil behavior will help improve the accuracy of predictions of unsaturated soil flow characteristics. In addition, it is anticipated that the successful, quick, and direct testing of unsaturated flow properties will facilitate the incorporation of rigorous unsaturated flow analysis in geotechnical practice.

1.1 Research Objectives

The overall objective of this research includes the development a centrifuge testing setup and procedure that allows unsaturated hydraulic characteristics of soils to be expeditiously characterized. In turn, this will facilitate the evaluation of the parameters that affect their trends. The research utilized the capabilities of the Centrifuge Permeameter for Unsaturated Soil (CPUS) at the University of Texas and built upon research performed by McCartney (2007) and Kuhn (2010). Several experimental methods were developed in this study. Advantages of these procedures include:

- *Characterization of a low plasticity clay:* A significant portion of previous research has been conducted on unsaturated sands or silts. This project focused on a low plasticity clay, which expand the scope of experience in centrifuge testing.
- *Ability to imposed flow rates during centrifugation*: The CPUS includes a low flow rotary union that allows flow pumps outside the centrifuge environment to apply a constant flow rate to each sample.
- *Steady state testing*: By using a constant imposed flow rate on the surface of samples and measuring the same outflow rate from the base samples, steady state conditions can be verified. This validation is fundamental to the procedures used in the interpretation of measurements of unsaturated hydraulic conductivity.

- *In-flight data acquisition*: The CPUS used in this study incorporates a robust data acquisition setup that allows properties of the soil to be measured during centrifugation.
- *Measurements of soil properties along the sample height:* The distribution of volumetric water content and void ratio were determined along the entire height of samples. Previous research often relied on average measurements of soil properties for the entire sample leading to inaccuracies.
- *Measurement of void ratio:* The void ratio of samples was directly measured after centrifugation by using a split tube sampler. Previous research has often neglected to measure changes in void ratio that may occur during centrifugation.

An additional objective of this study was to verify the centrifuge testing setup and procedures produced valid results. Some specific questions that were answered in order to validate the procedures include:

- Are the principles for flow through soil valid under increase centrifugal acceleration?
- Does the centrifuge procedure produce SWRC data that is in agreement with that obtained using standard testing methods?
- Is the k-function determined using the centrifuge method in agreement with that obtained under 1g conditions?

Finally, specific objectives of this research project pertaining to the behavior of the unsaturated soil (RMA soil) investigated in this study include:

- Determine the relationships among soil volumetric water content, matric suction, and void ratio (referred to as the soil water retention surface);
- Determine the relationships among volumetric water content, void ratio, and hydraulic conductivity (referred to as the hydraulic conductivity surface);

- Determine the effects of compaction moisture content on the soil water retention surface;
- Determine the effects of compaction moisture content on the unsaturated hydraulic surface;
- Evaluate hysteresis in the soil using centrifuge techniques.

These topics, particularly the changes in unsaturated hydraulic conductivity with compaction water content and void ratio, have not previously been investigated in depth. As a result, this research will provide new insight into the behavior of unsaturated soils.

1.2 Organization of Dissertation

Background information regarding information pertinent to the performed research is discussed in Chapter 2. General information regarding the theory of unsaturated flow in soils will be presented. Previous research conducted on parameters affecting the SWRC and K-function will also be discussed. Finally, previous centrifuge research conducted on unsaturated soils will be reviewed.

The equipment used in this research study will be described in Chapter 3. This includes the centrifuge equipment that is the focus of this research as well as pressure plate devices in order to determine the SWRC, and fixed and flexible wall permeameters to determine the saturated hydraulic conductivity.

The soil used in this investigation (Rocky Mountain Arsenal soil) is described in Chapter 4. Standard geotechnical testing results are presented of the soil along with unsaturated properties pertinent to the centrifuge investigation.

Three series of testing were conducted using different testing procedures. The first series of tests (Series "I") is discussed in Chapter 5 and is referred to as the "instrumented" testing series. Issues with the instrumented setup were identified during testing that were found to affect the accuracy of results. The results are discussed along with lessons learned from the instrumented procedure.

Changes that were implemented to the centrifuge equipment due to findings from the instrumented testing procedure are discussed in Chapter 6. The main improvement involved the addition of a split tube sampler that allowed the distribution of void ratio to be accurately measured in samples after testing.

The second testing series (Series "H") is discussed in Chapter 7. Tests conducted in this series are referred to as the "hydrostatic" tests. Testing was conducted for three compaction moisture conditions and the retention behavior was characterized for a wide range in void ratio. The relationship between void ratio, suction, and volumetric water content was defined for each compaction moisture condition and three dimensional surfaces were fit to each data set.

The third testing series (Series "IF") is presented in Chapter 8 and is referred to as the "imposed flow" testing. The imposed flow procedure was used for determination of the unsaturated hydraulic conductivity of centrifuge samples. Testing was conducted for at three compaction moisture conditions. The results were used to define the relationships among hydraulic conductivity, void ratio, and volumetric water content for each compaction moisture condition.

Detailed analysis of results is included in Chapter 9. The analysis focuses on results from the hydrostatic and imposed flow testing series as these included improvements over the instrumented testing series, which resulted in more accurate data. Analysis includes the effects of compaction water content and void ratio, the validity of centrifuge scaling of gravitational gradient, and comparison of results with standard testing results for verification of the centrifuge procedures.

Finally, the conclusions of the research study are stated in Chapter 10 along with recommendations for improvements to the procedure and areas for future research.

2 BACKGROUND INFORMATION

Background information that pertains to centrifuge research on unsaturated flow is included in this chapter. The topics to be discussed are:

- Soil suction (Section 2.1)
- Flow through soil under centrifugation (Section 2.2)
- Water retention characteristics of soils (Section 2.3)
- K-function of soils (Section 2.4)
- Entrapped air and quasi-saturation of soil (Section 2.5)
- Previous research on soil unsaturated flow in centrifuges (Section 2.6)

2.1 SOIL SUCTION

Total suction in soil is divided into two components, the matric suction and the osmotic suction. Therefore, the total suction is defined as:

$$\psi_t = \psi_m + \psi_o \tag{1}$$

where ψ_t, ψ_m, and ψ_o are the total, matric, and osmotic suctions respectively. The matric suction is made up of a combination of the adsorptive properties of soil particles and capillary forces due to surface tension (Olson and Langfelder 1965). The osmotic suction is a result of concentrations of dissolved ions in the pore fluid. It has been shown (Krahn and Fredlund 1972) that when matric and osmotic suctions are independently measured, their sum is equal to the independently measured total suction.

In the majority of geotechnical testing osmotic suction does create any suction gradients in soil samples. This is a result of the pore fluid having the same composition of surrounding fluids (at least after equilibrium). Therefore, when “suction” is measured in geotechnical testing it generally refers to the matric suction of the soil. The matric suction of the soil is defined as:

$$\psi_m = P_a - P_w \tag{2}$$

where P_a and P_w are the air pressure and water pressure of the soil respectively. Based on this principle, geotechnical tests such as the hanging column method and pressure plate techniques (ASTM D6836) apply matric suctions to soils samples by either increasing the air pressure while holding the water pressure constant (pressure plate) or decreasing the water pressure while holding the air pressure constant (hanging column). Select geotechnical testing methods measure the total suction of soils. These methods are generally based on changing the relative humidity around the soil in order to change the vapor pressure, resulting in measurements of total suction.

Following standard geotechnical practice, when "suction" is reported or discussed in this dissertation it refers to the matric component of suction. In select cases where osmotic suctions are applicable, they are specifically noted.

2.2 Flow Through Soils Under Centrifugation

One of the fundamental advantages of centrifuge testing is the ability to apply a field of increased acceleration to soil samples. The centrifuge accelerates the sample inwards by centripetal forces. When viewed from the frame of the rotating sample there is an apparent acceleration field outward (with respects to the center of rotation), which increases the potential energy of objects within the field.

The increase in potential energy in the centrifuge can be directly incorporated into equations governing the flow of water through soils as these equations already take into account the potential energy of the fluids due to an acceleration field (gravity). Based on Bernoulli's equation, the fluid potential is defined as:

$$\phi = gz - \frac{P}{\rho_w} + \frac{v^2}{2} \tag{3}$$

where g is the gravitational acceleration, z is the height above the datum, P is the fluid pressure, ρ_w is the density of the fluid (water), and v is the fluid velocity. The velocity of flow in soils is low resulting in negligible energy and therefore last term is neglected in most formulations. Using this formulation the gravitational acceleration, g, can be replaced directly with the acceleration field of the centrifuge. It is common to normalize the acceleration in centrifuges by gravity such that the acceleration in the centrifuge is defined as:

$$N = \frac{a_c}{g} \tag{4}$$

where N is the "g-level" of the centrifuge, g is the gravitational acceleration, and a_c is the acceleration field of the centrifuge. In this case the fluid potential can be defined as:

$$\phi = Ngz - \frac{P}{\rho_w} \tag{5}$$

This formulation is an over-simplification for most applications as the acceleration field in the centrifuge scales with radius and thus is not constant as the above formulation implies. The acceleration field in the centrifuge is calculated as:

$$a_c = \omega^2 r \tag{6}$$

where ω is the rotational velocity and r is the centrifuge radius (distance from center of rotation). When the variable acceleration is integrated across radius in order to determine the potential energy, the fluid potential in the centrifuge is defined as:

$$\phi_c = -\frac{1}{2}\omega^2({r_0}^2 - (r_0 - z)^2) - \frac{P}{\rho_w} \tag{7}$$

where r_0 is the radius of the datum. The equation most commonly used for flow through soils was proposed by Henry Darcy in a report published in 1856 (Darcy 1856). Darcy conducted experiments involving the flow of water through sands and empirically came up with a formula governing flow though porous medium as:

$$Q = K\frac{s}{e}(h + e \pm h_0) \tag{8}$$

where Q is the volume of outflow per unit time, s is the surface area of the sample, e is the thickness (length) of sample, h is the height of water on top of specimen, h0 is the height of water at bottom of layer, and K is the permeability coefficient (now referred to as hydraulic conductivity). The formulation has since been refined to the well-known form of:

$$Q = -KiA \tag{9}$$

where A is a cross-sectional area of the sample and i is the hydraulic gradient.

The hydraulic gradient is defined as:

$$i = \frac{\Delta\bar{h}}{\Delta L} \tag{10}$$

Where:

$$\Delta\bar{h} = \left[\frac{\Delta P}{\rho g}\right] + \left[\frac{\Delta(v^2)}{2g}\right] + \Delta z \tag{11}$$

and L is the length of the sample.

It is important to note that the hydraulic gradient by definition is the energy gradient normalized by the unit weight of the fluid. Specifically, the hydraulic gradient is the energy gradient per unit volume per unit weight of fluid per unit length. In order to calculate hydraulic gradient from fluid potential the fluid potential must also be normalized such that:

$$i = -\frac{1}{g_1}\frac{d\phi_c}{dr} \tag{12}$$

where g_1 is the gravitational acceleration. The gravitational constant is referred to with a subscript “1” in order to avoid confusion of the possible scaling of g with the centrifuge G-level. It is possible to separate the hydraulic gradient due to potential energy and pressure. If this is completed, the total gradient is be defined as:

$$i = i_g + i_p \tag{13}$$

where:

$$i_g = -\frac{\omega^2 r}{g_1} \tag{14}$$

and:

$$i_p = \frac{1}{g_1 \rho_w} \frac{dP}{dr} \tag{15}$$

In centrifuge testing the acceleration always promotes flow away from the center of rotation. The pressure gradient can promote flow in either direction but at steady state conditions the pressure gradient promotes flow towards the center of rotation (assuming an unsaturated soil and zero pressure lower boundary).

2.3 Water Retention Characteristics of Soil

The soil water retention curve (SWRC) is the relationship between the amount of water retained in a soil at a given the suction applied to the soil. The SWRC is typically defined in reference to the matric suction of the soil. Occasionally, the SWRC is reported based on total suction when measurements are not able to isolate the matric portion of the total suction. The SWRC is sometimes referred to as the soil water characteristic curve (SWCC). The amount of water retained is represented by either the volumetric water content (VWC or θ) or the degree of saturation (S_r). The suction is often plotted on the x-axis, usually in logarithmic scale, and the VWC or degree of saturation on the y-axis. The shape of the SWRC depends on the soil properties but generally has an "S" type shape depicted in Figure 2.1. When a soil is started in a saturated state and suction incrementally applied, the soil remains saturated up until reaching a suction value that is referred to as the air entry suction. As the applied suction is increased, the retained water is decreased up until a point where increases in suction have little effect on the retained water. The constant level of moisture at high suctions is referred to as the residual water content.

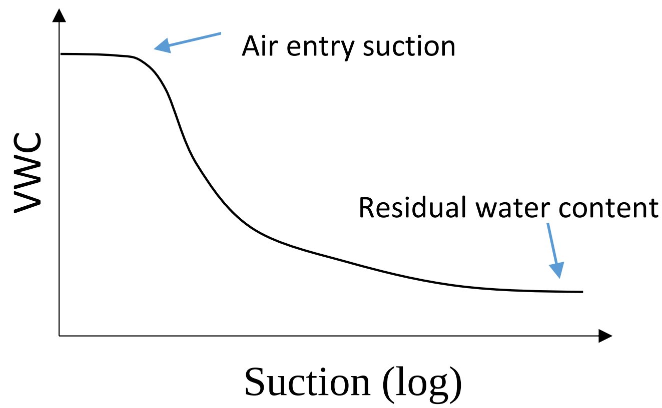

Figure 2.1 – Typical shape of soil water retention curve

One of the most relevant factors affecting the shape of the SWRC is the size of pores in the soil. The pore sizes in the soil affect the retention of water in the soil due to capillarity. If the pore shapes in soils are simplified to circular tubes, the Young-Laplace equation can be used to predict the suction required to remove water from a pore with a known radius:

$$\psi = \frac{2\sigma_{aw} cos\gamma}{R} \tag{16}$$

where R is radius of the pore, σ_{aw} is the surface tension of water in air, and γ is the wetting contact angle.

The effects of this are seen clearly in different soil types. Specifically, soils with large particles and resulting pore sizes such as gravels and sands lose a majority of their water at low suctions. On the other hand, soils with small pore sizes can retain a significant portion of their water even up to extremely high suctions. Results from a variety of soils are included in Figure 2.2 with fine grained soils retaining a larger portion of their pore water at high suctions.

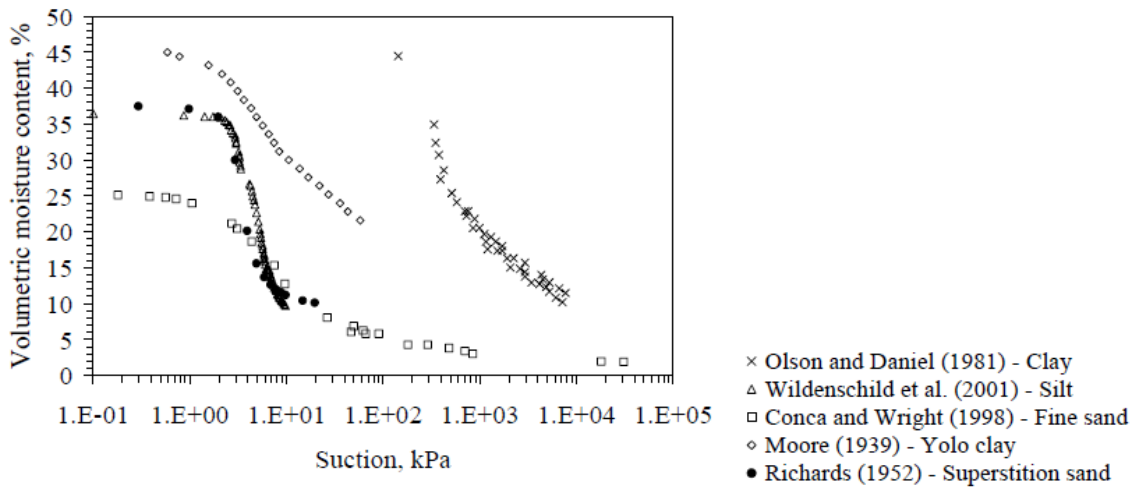

Figure 2.2 - SWRCs for various soils (from McCartney 2007)

Factors affecting the SWRC beyond the pore size distribution include soil mineralogy, density, structure, macro-features, chemical composition and pH of the fluid, as well as temperature (Olson and Langfelder 1965, Kleppe and Olson 1985, Henry and Smith 2003, Hopmans and Dane 1986).

A variety of mathematical functions have been developed to model a continuous SWRC. Two of the commonly used functions are the Brooks and Corey (1964) and the van Genuchten (1980) models. The Brooks and Corey model is defined as:

$$\theta = \theta_r + (\theta_s - \theta_r)\left(\frac{\psi}{\psi_{aep}}\right)^{-\lambda_{BC}} \tag{17}$$

where $\theta_r$is the residual moisture content, θ_s is the saturated moisture content (porosity), ψ_{aep} is the air entry suction, and λ_{BC} is a fitting parameter.

The van Genuchten model is defined as:

$$\theta = \theta_r + (\theta_s - \theta_r)[1 + (\alpha_{vG}\psi)^{N_{vG}}]^{-\left(1-\frac{1}{N_{vG}}\right)} \tag{18}$$

where α_{vG} and N_{vG} are fitting parameters. For the purposes of this dissertation the van Genuchten model will be used to model SWRC data.

The soil water retention curve is often considered a characteristic curve of soil. However, substantially different curves can result from the same sample if it is tested starting from different moisture conditions in a phenomenon referred to as SWRC hysteresis. If a soil sample is tested beginning at a saturated state with progressively increasing suction the sample will often have higher water contents for a given suction than a soil started dry and then subject to progressively reduced suctions. This effect is illustrated in Figure 2.3. Various causes have been reported (Hillel 1980, Stephens 1995, Zhou 2013) for hysteresis in soils. These include the "ink bottle effect" where a large pore is surrounded by small pores and will remain saturated at a given suction during drying but will not fill with water at the same suction when wetted, different liquid-solid contact angles for advancing and receding water menisci, and entrapped air in wetted soils.

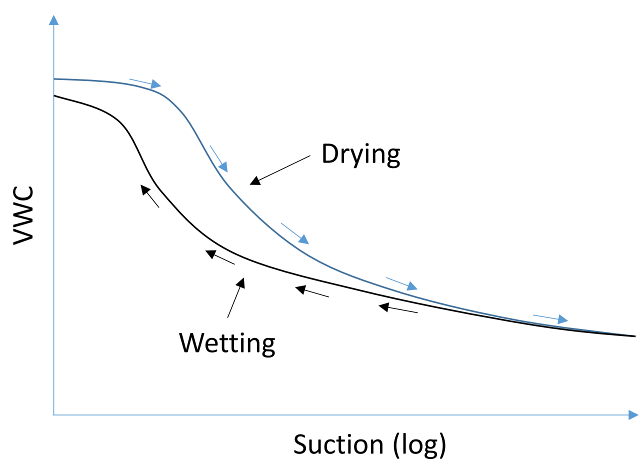

Figure 2.3 - Soil water retention curve hysteresis

Void ratio has been shown to have significant effects on the retention behavior of soils (Tinjum et al 1997, Salager et al 2007, McCartney 2007). Traditionally the retention behavior of soils is defined at a constant density or void ratio in the form of the SWRC. Research performed by Salager et al (2007) showed that a 3-dimensional surface can be used to represent the relationship between the volumetric water content, suction, and void ratio. This was called the soil-water retention surface (SWRS) and is illustrated in Figure 2.4.

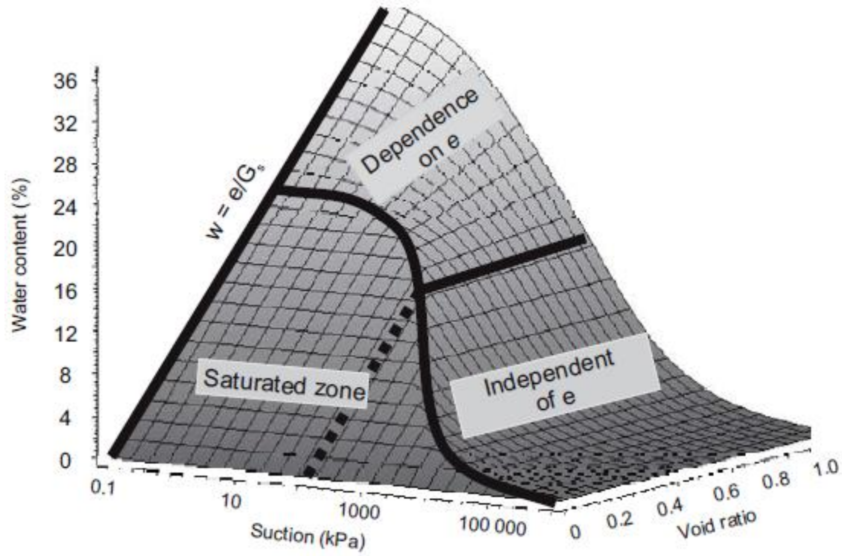

Figure 2.4 – Illustrated Soil Water Retention Surface (from Salager et al 2007).

The acceleration field of the centrifuge results in significantly increased stresses in soil samples. The stress in samples increases from the surface to the base resulting in a non-uniform void ratio distribution throughout samples. As a result, retention results determined using centrifuge procedures often relate to the retention characteristics of the soil at a range of void ratios. For this reason the use of the SWRS, which relates soil retention behavior with void ratio, is particularly useful for displaying centrifuge retention results.

2.4 K-function of Soils

The K-function refers to the relationship between the hydraulic conductivity and the volumetric water content (or suction) of a soil. As the VWC of a soil decreases the hydraulic conductivity also is reduced. This is a result of a reduction in water filled flow paths, which allow water to be transmitted through the pore space of the soil.

It is often preferable to represent the K-function as a function of VWC rather than suction. This is because hysteresis in the SWRC results in multiple VWCs for a given suction. If suction is used to define the K-function the hysteresis of the SWRC is also seen in the K-function. No hysteresis has been reported to occur when the K-function is defined by VWC or degree of saturation (Topp and Miller 1966).

The K-function is typically not measured in practice. If a project requires the K-function it is often estimated using the saturated hydraulic conductivity and measured SWRC. Early estimations of the K-function were based on the concept that the saturated hydraulic conductivity (K) is scaled by the volumetric water content (θ) such that:

$$K(\theta) = K_s \left(\frac{\theta - \theta_s}{\theta_s - \theta_r}\right)^{\beta} \tag{19}$$

where K_s is the saturated hydraulic conductivity, θ_s and θ_r are the saturated and residual volumetric water contents respectively, and β is a fitting factor (values 3.0 and 3.5 were often used).

Later predictions built upon Equation (19) and were based on methods to predict the K-function based on modeling the soil as a series of interconnected pores with the pore size distribution determined from the SWRC. In geotechnical engineering the most common of these models is the Mualem (1976) model with adjustments made by van Genuchten (1980) such that:

$$K(\theta) = K_s \sqrt{\frac{\theta - \theta_s}{\theta_s - \theta_r}} \left[1 - \left(1 - \left(\frac{\theta - \theta_s}{\theta_s - \theta_r}\right)^{1/m}\right)^{m}\right]^2 \tag{20}$$

where m is the fitting parameter from the van Genuchten SWRC model.

When used to predict the K-function based only on the SWRC and saturated hydraulic conductivity mixed results have been found. Khaleel et al. (1995) measured unsaturated hydraulic conductivity of twenty two sands and compared the measured values with predicted values from the Mualem-van Genuchten model. Errors up to four orders of magnitude were reported with the majority of predictions falling within two orders of magnitude of the measured value. The comparison of measured and predicted unsaturated hydraulic conductivity is shown in Figure 2.5.

Poulsen et al. (1999) compared predicted and measured values for unsaturated soils from a large database and found that the best models predictions still deviated by up to two orders of magnitude from measured values. The comparison of measured and predicted unsaturated hydraulic conductivity from four different models (including 95% confidence lines) is shown in Figure 2.6.

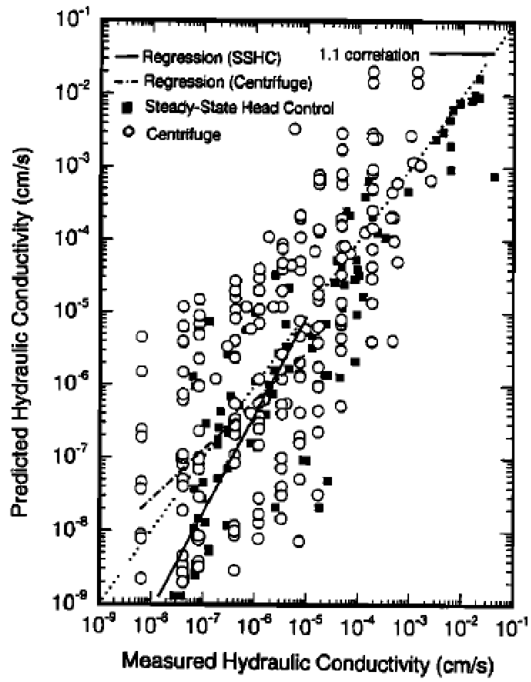

Figure 2.5 - Measured vs. predicted unsaturated hydraulic conductivity (from Khaleel et al. 1995)

Overall the prediction models have been shown to follow the general trend of the K-function but have limited accuracy. Khaleel et al. (1995) found the use of a single measured unsaturated hydraulic conductivity value in order to fit the K-function predictive models resulted in higher accuracy with errors reduced from approximately two orders of magnitude to a single order of magnitude. Even with the improvements (due to the inclusion of a single point of measured data) the models have relatively low accuracy and may lead to large errors when used predicted unsaturated hydraulic conductivity is used for calculating flow.

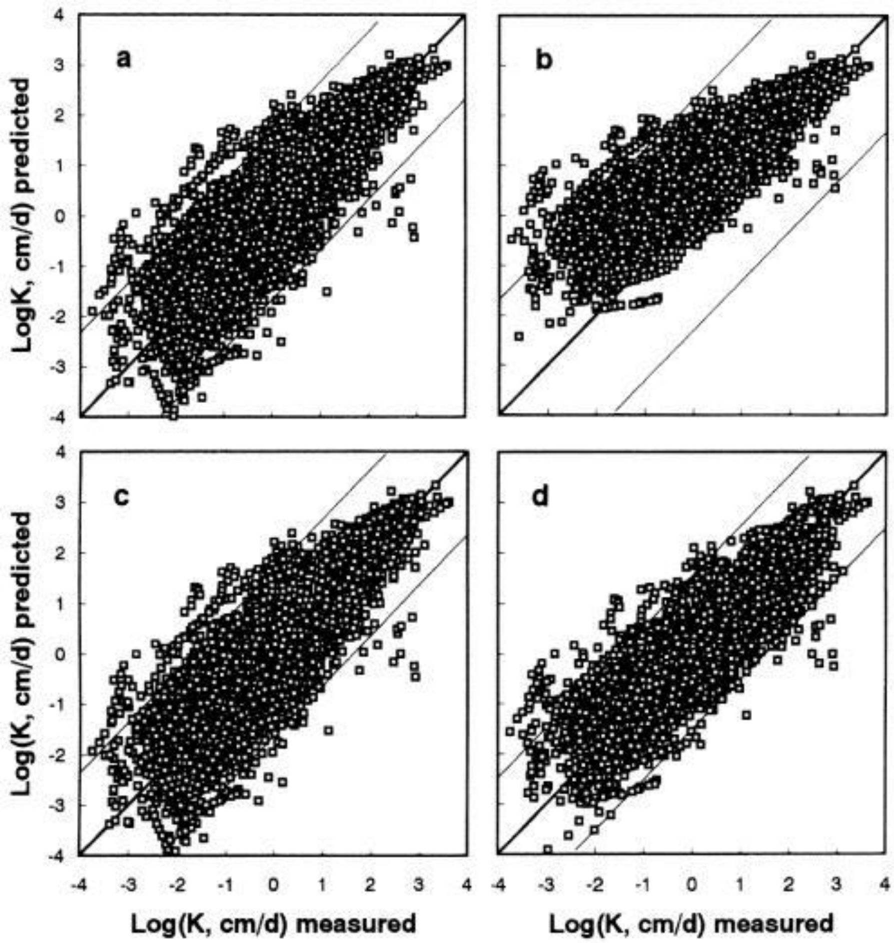

Figure 2.6 - Measured vs. predicted unsaturated hydraulic conductivity: a) Campbell b) Alexander and Skaggs c) DLC d) SLC (from Poulson et al 1999)

2.5 ENTRAPPED AIR AND QUASI-SATURATION OF SOILS

Entrapped air is common in soils that undergo repeated wetting and drying cycles. Entrapped air is defined as air inside a soil sample which is not connected to the atmosphere (Youngs and Peck, 1964). Full saturation of a soil with entrapped air often requires using back pressure saturation methods, which increase the pore pressure in samples reducing the volume of air. It is not uncommon for large back pressures to be required to saturate specimens during laboratory testing. Research performed by Mitchell et al (1965) showed that the back pressure required to saturate specimens depended on the volume of entrapped air. Large pressures (>50 psi or 350 kPa) were required to saturate typical soil samples.

Soils with entrapped air that are not saturated by back pressure will remain at degrees of saturation under 100% even when given access to water. The term “quasi-saturated” has been used (Sakaguchi et al., 2007) to refer to such soils, which contain entrapped air but have zero or positive pore pressure.

Research has been conducted that shows large changes in hydraulic conductivity due to entrapped air. Sakagushi et al. (2007) reported approximately an order of magnitude decrease in hydraulic conductivity due to a 10% volume of entrapped air. Mitchell et al. (1965) reported decreases between approximately 30% and 75% for similar volumes of entrapped air.

In most applications of unsaturated flow, soil is unlikely to ever become fully saturated. This is a result of unsaturated flow generally occurring above the water table where large pore pressures required for saturation are uncommon. Therefore, it is important to be aware of differences between full saturation and quasi-saturation. Standard laboratory measurements (such as hydraulic conductivity) are usually completed by first fully saturating specimens using back pressure. As a result the characteristics measured in the laboratory test may be unrepresentative of the natural soil, which will likely never be fully saturated.

2.6 Previous Centrifuge Research on Unsaturated Flow

Research into flow through soils under centrifugation has primarily focused on saturated flow. Cargill and Ko (1983) performed research on the transient flow through an earth embankment model in the centrifuge. Headwater and tailwater were imposed on the model embankment and pressures were monitored over time within the embankment. The research focused on the saturated area of the embankment for measurement of flow and did not consider the unsaturated zone.

Nimmo et al. (1987) were the first to perform research that focused on steady state unsaturated flow in the centrifuge. Centrifuge tests were performed on an unsaturated sand at g-levels ranging from 200 to 1650. Flow rates were imposed on top of the samples using ceramic discs and the flow rate adjusted either by changing the ceramic disc (for a different permeability) and adjustment of the headwater. The centrifuge was stopped during the test in order to refill the reservoir to maintain a closer to constant flow rate. At the end of the test, samples were sliced and the water content was measured across the sample height and moisture distributions were found to be nearly constant in the entire soil sample. The resulting k-function with a comparison to 1g testing is shown in Figure 2.7. The results matched well with tests performed outside the centrifuge and the repeatability of tests was found to be very good. Testing for hydraulic conductivities as low as 8×10^{-13} m/s were performed in under 24 hours, which was very encouraging. The method developed by Nimmo (1987) is expected to result errors due to the need to stop the centrifuge to maintain a constant flow rate and to take measurements, resulting in a changing state of stress and hydraulic gradients at periods of the test. The results were for a sand, which has distinctly different unsaturated characteristics than silts and clays.

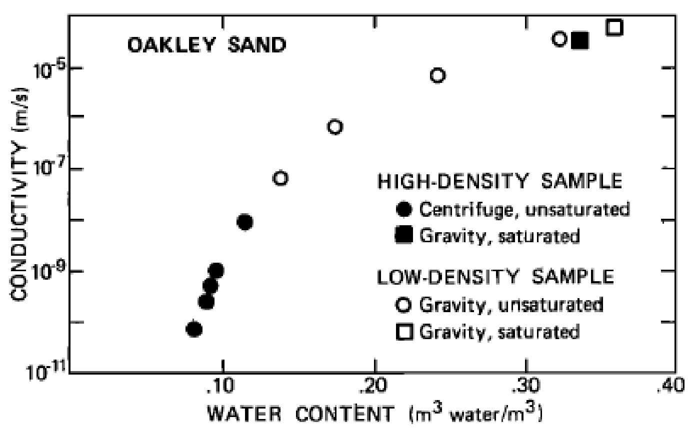

Figure 2.7 - Results from Nimmo (1987) K-function

Nimmo (1990) later tested transient unsaturated flow in the centrifuge by starting with a sample of saturated sand and subjecting the sample to high g-levels. The lower boundary was a constant pressure boundary imposed by using a saturated ceramic disc and water reservoir. Electrodes monitored the water content in the sample throughout the test while the sample was subjected to progressively increasing g-levels. The sensor's results were analyzed using Richard's equation and showed a generally good agreement between measurements and theory although in select tests large different were found between the predicted and measured distributions of water content. Simunek and Nimmo (2005) later used numerical simulation to model the results and developed a modified Hydrus (unsaturated flow finite difference program) package for analysis of unsaturated flow in the centrifuge.

Conca and Wright (1992) developed a centrifuge setup similar to that of Nimmo et al. (1987) but improved on the imposed flow condition by using flow pumps rather than ceramic discs. ASTM D6527 was developed from their procedure. Outflow volume and the mass of the specimen were measured by stopping the centrifuge periodically during the test. After steady state conditions had been met, the gravimetric water content of the sample was measured. The suction gradient was assumed to be zero allowing the unsaturated hydraulic conductivity to be calculated. However, the research project was performed for commercial purposes and the results are not readily available. The corresponding ASTM standard relates unsaturated flow properties to the average values for the entire sample, which is only valid if the distribution of moisture and density in the sample is constant. The distribution is not measured in this procedure.

Khaleel et al. (1995) developed a centrifuge permeameter based on the methods of Conca and Wright (1992) and Nimmo et al. (1987). The centrifuge was used to evaluate the unsaturated hydraulic conductivity of twenty two soils in order to evaluate the accuracy of predictive methods for the K-function. The soils were coarse to fine sands. A reasonable agreement was found between unsaturated hydraulic conductivity results determined using steady-state methods performed outside the centrifuge and the centrifuge results.

Poulose et al. (2000) conducted testing by ponding water on top of a silt sample and centrifuging the sample at different g-levels and lengths of time. At the end of testing the sample was sliced and water content measured across the sample height. The results were compared against each other to determine effects of testing time and g-level but results were not compared to standard testing methods nor were soil properties calculated.

Khanzode et al. (2002) determined the SWRC of three fine grained soils by centrifuge testing. Suction was imposed on samples by using the increased g-level and the water content of samples was determined at the end of testing. Testing of all three soils resulted in greatly reduced testing times compared with standard procedures. The centrifuge results were found to consistently produce SWRCs with a higher water content than those measured by traditional methods.

Dell'Avanzi et al. (2004) developed a theoretical framework for determining steady state moisture profiles of centrifuge samples with an imposed flow rate on the surface and a constant suction at the base. The SWRC was simplified to an exponential form in order to obtain a closed form solution. The resulting moisture profiles showed that g-level reduced the area of influence for the lower boundary condition resulting in a large zone of constant moisture content from the top of sample to close to the base. The moisture content of this upper portion was independent of the lower boundary condition.

McCartney (2007) performed unsaturated flow testing in the large, instrumented centrifuge permeameter that will be used in this research study. The testing setup included an in-flight data acquisition system that allowed the soil and outflow to be monitored during centrifugation. Flow rates were imposed on the surface of specimens by using flow pumps and the lower boundary was "open flow" and assumed to be a zero suction boundary. Testing was performed on initially saturated specimens and flow was imposed on the samples until steady state conditions. The SWRC and k-function were determined by instrumentation measured in-flight. Volumetric water content was measured by a single Time Domain Reflectometer (TDR) in the upper thirds of the sample. Suction was measured across the sample height in three locations by tensionmeter. The tensionmeters were unable to measure low suctions and would result in cavitation if exposed to higher suctions that limited the measureable range to relatively high flow rates and hydraulic conductivities. While a limited number of samples were tested, the results showed a reasonably good agreement with data measured using traditional methods. Differences in soil densities made the comparison between centrifuge and traditional data difficult.

3 Equipment

The equipment used in this research project will be discussed in the following sections. The focus of this section is on two pieces of geotechnical equipment unique to the laboratories at the University of Texas at Austin, namely the “Centrifuge Permeameter for Unsaturated Soils” and the “Modified Pressure Plate Device”. The discussion of this non-traditional equipment will be followed by a brief review of other standard equipment used in this study.

3.1 Centrifuge Permeameter for Unsaturated Soils (CPUS)

The centrifuge testing program conducted in this research study was performed using the Centrifuge Permeameter for Unsaturated Soils (CPUS) located at the University of Texas at Austin. The CPUS is a unique geotechnical centrifuge in that the design of the centrifuge focuses on hydraulic flow. Typical geotechnical centrifuges operate at relatively low g-levels and hold large specimens that are used to model full scale projects. The increased g-level is used to scale the stresses in the model so that the stress profile of the model matches that of the full scale prototypes. The CPUS was not designed for this purpose and instead focused on using the acceleration of the centrifuge to increase the gravitational gradient in soil samples promoting expedited flow through unsaturated soil specimens. The CPUS is fully described by McCartney (2007). Therefore, only an overview of the centrifuge is included in this report highlighting updates that were completed after the description by McCartney (2007). The centrifuge setup is illustrated in Figure 3.1. The main rotating centrifuge testing environment is located in the top portion of the centrifuge. The rotating testing environment includes space for two samples. A large fixed permeameter, which was not used in this research study, is shown in the illustration on one side of the centrifuge. The smaller hanging permeameter is shown on the opposite side and was used exclusively during this research study. An electrical slip ring stack and a fiber-optic rotary joint are included at the base of the central shaft for communication with the rotating testing environment.

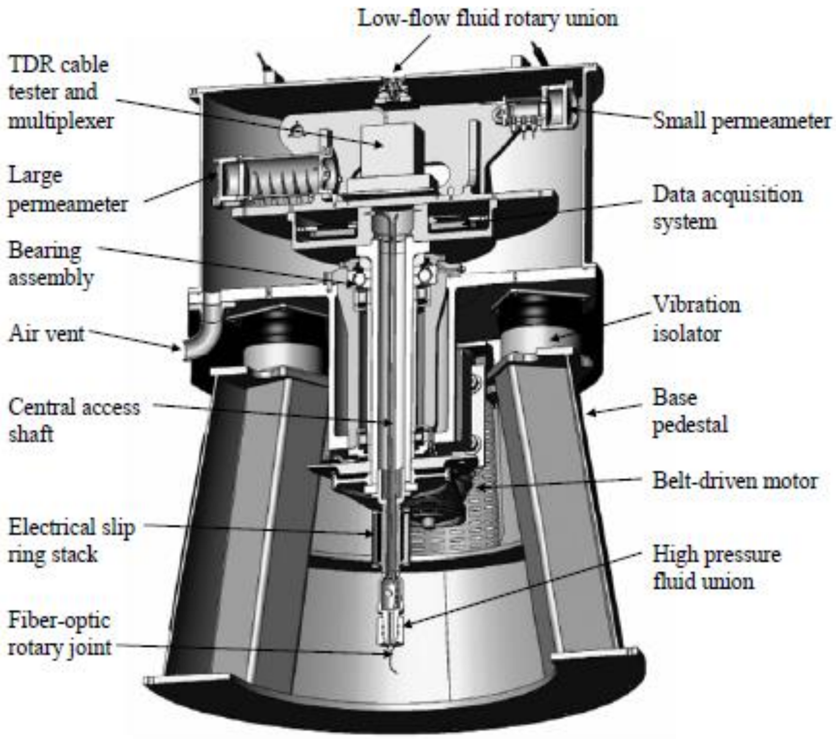

Figure 3.1 - Centrifuge Permeameter for Unsaturated Soils (CPUS)

An enlarged illustration of the rotating testing environment is shown as Figure 3.2. The testing environment is illustrated as it was used in this project, with small hanging permeameters on both sides of the testing environment. The small permeameters are fixed to the centrifuge by rotating joints. The joints allow the specimens to rotate freely during centrifugation resulting in the specimens maintaining an orientation parallel to the direction of maximum acceleration. The joints are located approximately 0.46 meters from the center of rotation. With the current sample setup, this results in a radius of 0.486 meters at the top and 0.613 meters at the base of specimens. Based on the rotational capabilities of the centrifuge this allows g-levels of up to 400 to be imposed on the samples during centrifugation. A plot of the relationship between g-level (N) at different locations in the centrifuge and the angular velocity of the centrifuge is included as Figure 3.3. Alternative testing environments are available for the CPUS that use fixed specimens rather than hanging specimens. These setups, which allow for larger specimens, were not used in this research study.

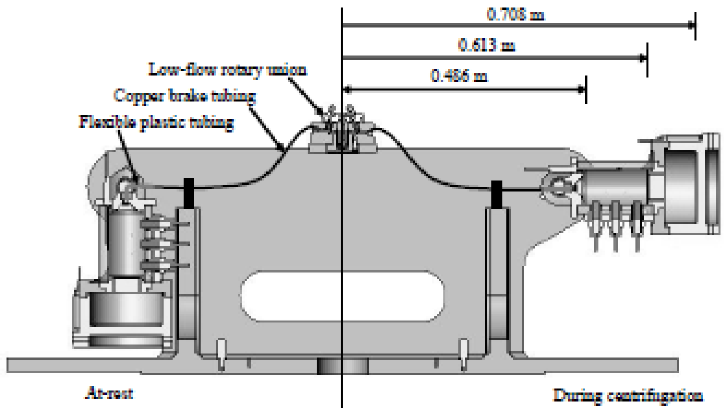

Figure 3.2 – Centrifuge testing environment (from McCartney 2007)

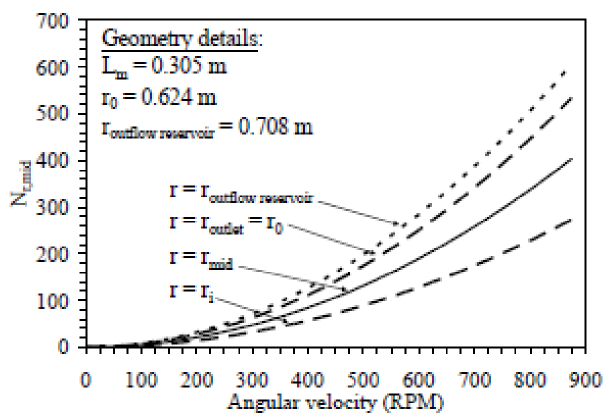

Figure 3.3 - G-level capabilities of CPUS (from McCartney 2007)

One of the main features of the CPUS is the ability to control and monitor the testing environment while under centrifugation. This includes the capability to impose flow rates on the surface of samples using a low-flow fluid rotary union (shown in Figure 3.4). The union allows external flow pumps to introduce flow into the rotating testing environment.

A high pressure fluid union (which was not used in this study) is also included that allows pressure to be controlled inside the testing environment.

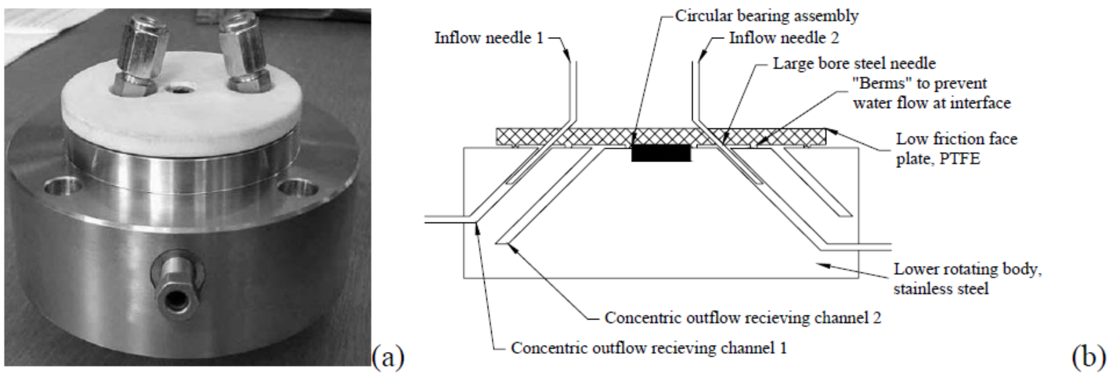

Figure 3.4 - Low-flow rotary unions - a) Photo b) Diagram (from McCartney 2007)

In order to monitor the testing environment, the CPUS includes a full featured data acquisition system located inside the rotating testing environment. The system is based around the “DaqOEM/2001” board by Measurement Computing. Included in the system are two multiplexer expansion boards (DBK80 from Measurement Computing) resulting in a total of 32 analog channels and 32 digital I/O channels available for the measurement and control of instrumentation. The system is capable of signal amplifications of up to 1000x. Communication with the DaqOEM/2001 system is completed using standard Ethernet (CAT-5) networking cables attached to a Windows computer. Initially, the centrifuge was capable of transmitting the Ethernet signal to a computer outside the centrifuge using two methods. The first method was to convert the signal to an optic one and then send it across the fiber optic rotary union. The second method was to splice the Ethernet cable across the slip ring stack. A third option was later added by Kuhn (2010) during testing of expansive clays. This method transmitted the Ethernet signal wirelessly by using a Wifi access point inside the centrifuge.

None of these methods were found reliable during the initial testing conducted in this research project. The slip ring stack introduced noise into the signal resulting in errors in communication. The fiber optic rotary union malfunctioned and was unable to be used during this research. The Wifi signal was found unreliable for long testing periods as interference would cause the signal to be lost long enough to cause the acquisition to stop.

In order to solve these issues, a solid state Windows based computer was installed near the center of rotation in the centrifuge. The computer was connected directly to the data acquisition system via CAT-5 cable, removing any communication issues between the data acquisition computer and the data acquisition board. The computer inside the centrifuge was accessed via Remote Desktop Protocol (RDP) over a Wifi connection. Using this setup, any issues with the Wifi signal did not affect the acquisition of data as the Wifi connection was only used to view the data, not to record it. A photo of the computer installed inside the rotating testing environment is included as Figure 3.5.

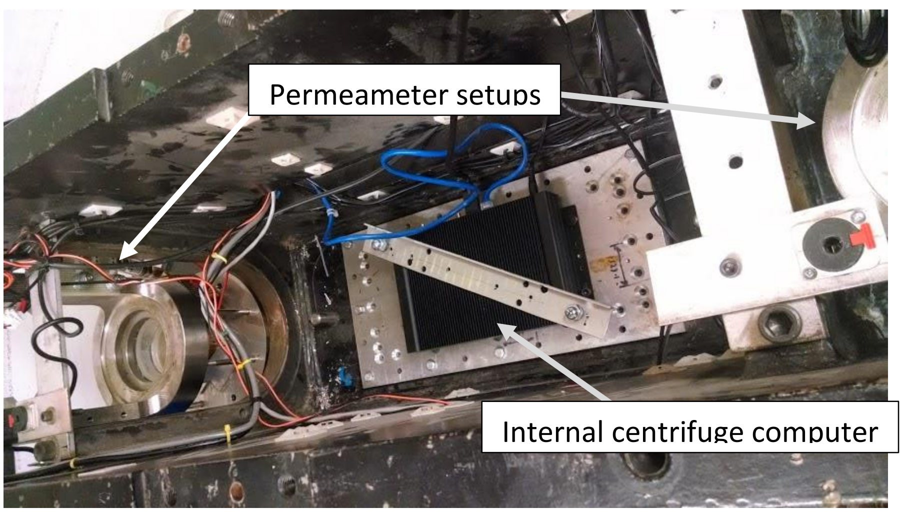

Figure 3.5 - Internal data acquisition computer

A diagram of the data acquisition system communication is shown as Figure 3.6. Instrumentation in the centrifuge is connected to the centrifuge data acquisition board. Sensor outputs can be read as an analog voltage signal or a digital signal (via serial interface or similar methods). The readings from the data acquisition board are then packaged and sent across a CAT5 cable to the internal centrifuge computer. The internal centrifuge computer is used to record the readings from the instrumentation and control the data acquisition system (triggering readings or digital output changes). The internal centrifuge computer can be accessed during centrifugation using RDP over a Wifi connection.

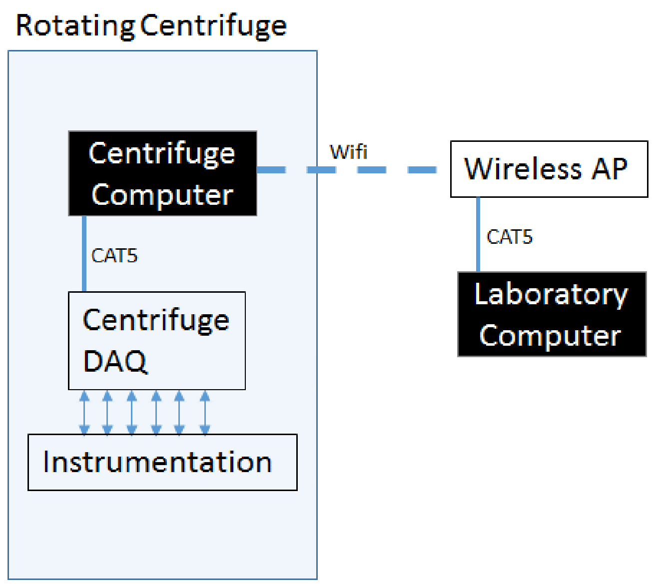

Figure 3.6 - Communication diagram for centrifuge data acquisition system (DAQ)

The original data acquisition board was controlled by proprietary software from the original designer. This software was found to be restrictive and was unable to control equipment inside the centrifuge using digital output from the data acquisition board. The software was replaced with a custom Labview software based control system, which was adapted to accommodate the requirements of each testing procedure completed in the CPUS.

The data acquisition system allows a wide range of instrumentation to be used in the centrifuge testing environment. If necessary, there is space available to install additional data acquisition equipment to measure instrumentation not supported by the current system. In previous research (McCartney 2007), a cable tester for time domain reflectometers (TDR) was installed in order to measure volumetric moisture content of samples.

3.2 Modified Pressure Plate Device

A modified pressure plate (MPP) system was developed in order to accurately measure the retention characteristics of soil while tracking the total volume of the sample. The pressure plate device was designed in order to improve on two main problems encountered with the previous devices used for the measurement of the soil water retention curve.

The first problem with previous devices was that the previous devices were unable to accurately monitor the moisture content of samples during multi-stage testing. Multi-stage testing refers to performing multiple stages of pressure on a single sample. The water content of each stage is determined by either measuring the flow of moisture into and out of the pressure plate device or removing the sample between test stages in order to measure the mass. Both of these methods have serious downsides.

If the moisture is monitored by measuring the outflow and inflow from pressure plate devices, leakage and evaporation greatly affect results. Also, air that may leak around the ceramic disk in the pressure plate device will be measured as outflow volume as the air displaces the water resulting in increased outflow. Methods have been used (such as circulating water under the ceramic disk and using air traps) in order to negate the effect of air leakage however these methods often lead to more evaporation from the system due to the pumping systems required.

On the other hand, if the sample is removed from the pressure plate chamber to measure the mass other errors are introduced. These errors are generally the result of the sample absorbing additional water when the air pressure is removed in order to open the chamber and remove the sample. Other problems include loss of soil mass or disturbing specimens resulting in volume changes.

The second issue that was addressed with the MPP device is the monitoring of volume change in specimens. Traditional pressure plate devices do not include the ability to monitor the volume of specimens during testing. If multi-stage testing is completed without volume measurement, only the initial and final volume is known. If volume changes occur, the testing stages that the volume change occurred at is unknown.

The MPP device solved two issues discussed. The volume of water in the sample is determined throughout testing by monitoring the total mass of the testing setup. An increase in mass of the testing setup is due to the inflow of water into the sample. The mass of the setup is monitored in real time and does not require the pressure to be removed from the sample. In addition, the device includes a piston that is in contact with the soil specimen with a small seating load. Any change in volume of the sample is measured by deflections of the piston.

The MPP is comprised of three main parts, the top cap, the base, and the specimen ring. The top cap is shown in Figure 3.7. The top cap includes a central threaded port for the piston to be connected. On the side, a second port is included for the application of air pressure. The top cap includes two O-rings, one that seals the port for the piston, and the other that seals the top cap to the specimen ring.

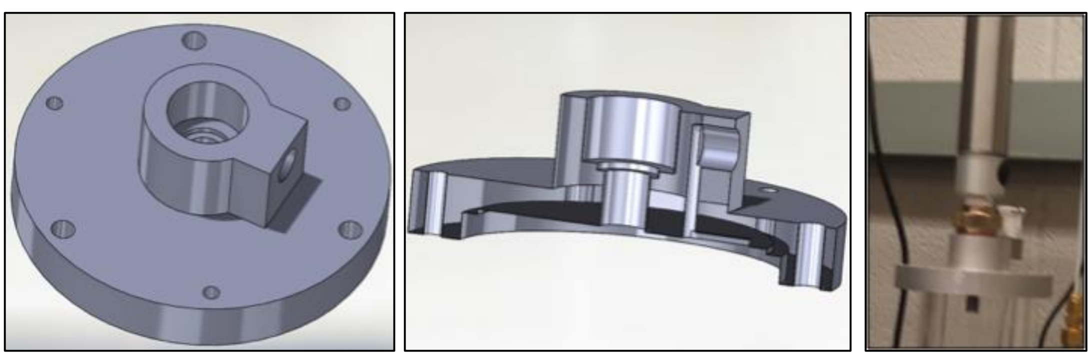

Figure 3.7 - Top cap of the MPP device

The base of the device is shown in Figure 3.8. A ceramic disc (not pictured) sits in the base of the device and is sealed from the lower portion of the base by an O-ring. Below the ceramic disc are flow channels that circulate water in order to remove any air that may leak below the ceramic disc. Two ports are included on the base that are used to circulate water through the flow channels beneath the ceramic disc. The specimen ring is placed on top of the ceramic disc and it sealed to outside pressure by a second O-ring. The assembled device is shown on the right in Figure 3.8.

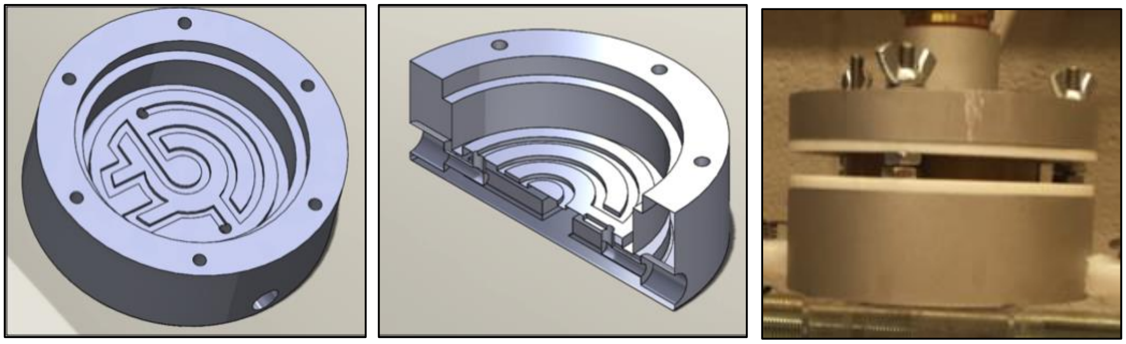

Figure 3.8 - Base of the MPP device

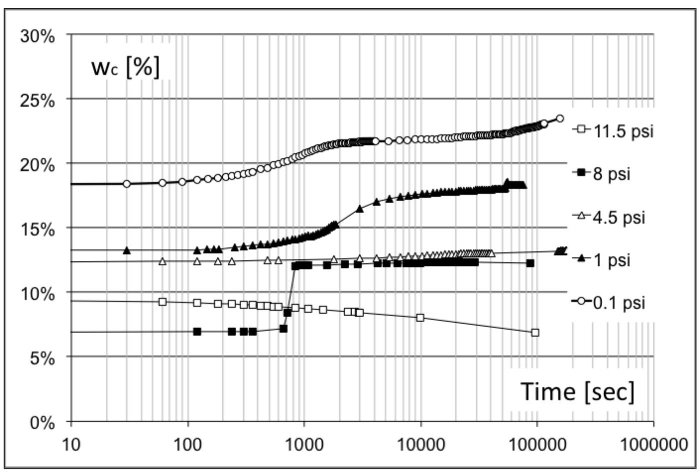

Figure 3.9 - Typical results from MPP device, multi-stage test

Typical results from a multi-stage retention test are shown in Figure 3.9. The test started at an initial (as-compacted) gravimetric water content of approximately 10%. The first testing stage was completed at 11.5 psi (~80 kPa) and resulted in a decrease in water content to approximately 7%. Subsequent testing stages (8, 4.5, 1, 0.1 psi) resulted in increases in water content of the sample. The gravimetric water content of the final stage was approximately 24% corresponding to a suction of 0.1 psi (~7 kPa). Measurement of the mass of the entire MPP device was found to be reliable and accurate method for monitoring moisture changes in the soil between each testing stage. In this particular test, the volume change in the sample was negligible and is not shown.

3.3 STANDARD GEOTECHNICAL EQUIPMENT

Additional laboratory devices were used in the characterization of the soil studied in this research project. The laboratory devices were standard commercial devices and will not be described in this dissertation. These devices were as follows:

- Hanging column: Used for measurement of retention characteristics. Standard Buchner setup was used.
- Tempe cell: Used for measurement of retention characteristics. Manufactured by Soil Moisture Corp.
- Flexible wall permeameter: Used for the measurement of saturated hydraulic conductivity. Manufactured by Trautwein Soil Testing Equipment Co.
- Fixed wall permeameter: Used for the measurement of quasi-saturated hydraulic conductivity. Manufactured by Trautwein Soil Testing Equipment Co.

4 ROCKY MOUNTAIN ARSENAL (RMA) TYPE 2 SOIL

The soil used in this research study is a low plasticity clay obtained from the Rocky Mountain Arsenal near Denver, Colorado. The soil is similar to soil previously characterized in the CPUS (McCartney 2007) but was obtained from a slightly different location at the RMA site. Standard soil characterization was performed on the soil and the results are presented and briefly discussed in the following sections. For the purposes of this dissertation the soil will be referred to as the "RMA" soil.

4.1 GEOTECHNICAL CLASSIFICATION

The grain size distribution was determined by sieve and hydrometer for the RMA soil and is included as Figure 4.1. D10, D50, and D90 were found to be approximately 0.0007, 0.08, 0.3 mm respectively. Atterberg limits were performed according to ASTM D4318 and resulted in a liquid limit of 32.2%, plastic limit of 11.6%, and a plasticity index of 20.6%. Specific gravity was determined to be 2.77 according to ASTM D854. These results are summarized in Table 3.

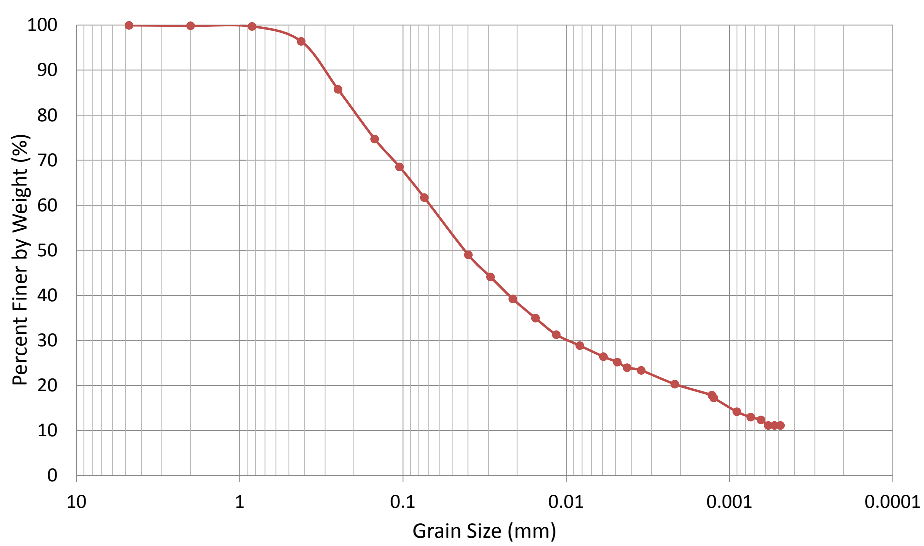

Figure 4.1 - Grain size distribution of RMA soil

Table 4-1- Geotechnical classification results of RMA soil

Property	Result
D_{10}	0.0005 mm
D_{50}	0.04 mm
D_{90}	0.3 mm
LL	32.2
PL	11.6
PI	20.6
G_s	2.77

4.2 Standard Proctor

Standard proctor compaction tests were run on seven RMA soil samples. Standard proctor compactive effort was applied to the samples, which ranged in water content from 11% to 19%. The resulting dry density of the samples were between 1.74 and 1.84 g/cc (17 to 18 kN/m^3). Optimum water content was determined to be 14.5% with a corresponding maximum dry density of 1.84 g/cc (18.1 kN/m^3). The standard proctor compaction curve is plotted in Figure 4.2.

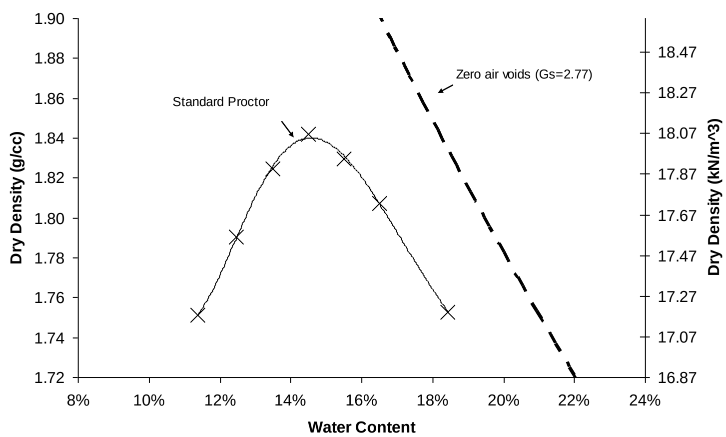

Figure 4.2 - Standard proctor compaction results (RMA soil)

4.3 Hydraulic Conductivity

Hydraulic conductivity of the RMA soil was determined using both flexible and fixed wall permeameter devices. The flexible wall tests were completed in accordance with ASTM

D5084 and specimens were back-pressure saturated in order to determine the saturated hydraulic conductivity of the RMA soil. The fixed wall permeameter tests were conducted without back-pressure saturation in order to determine the quasi-saturated hydraulic conductivity of the RMA soil. The results from each method are discussed individually in Sections 4.3.1-4.3.2.

4.3.1 Flexible Wall Permeameter Tests

Hydraulic conductivity tests were performed on six samples of RMA soil in flexible wall permeameters according to ASTM D5084. Samples were compacted between 75% and 85% of standard proctor at optimum water content. Samples were trimmed to a height of 2.5 cm with the exception of one sample that was tested at 5.1 cm. The shorter samples were tested at a gradient of 10 while the taller sample was tested at a gradient of 27.

Samples were back-pressure saturated until a B-value of at least 0.95 was determined. Once the satisfactory B-value was obtained the samples were consolidated to an effective stress of 5 psi and the hydraulic conductivity was measured. These samples were then further consolidated to 10, 20, 30 and 40 psi, measuring the hydraulic conductivity at each stage. Unfortunately after completion of the saturated hydraulic conductivity testing it was determined that the volume measurements taken during consolidation stages were inaccurate due to leakage. Therefore, the void ratio of the samples were unable to be calculated for each effect stress.

Compaction density did not have a discernable effect of the resulting saturated hydraulic conductivity. The variability in measured hydraulic conductivity was approximately an order of magnitude at each effective stress, disguising any differences in hydraulic conductivity that may have occurred due to compaction density.

Effective stress had a large effect on the hydraulic conductivity. The hydraulic conductivity dropped approximately an order of magnitude for an increase in effective stress of 20 psi.

This effect was seen in all of the samples. The resulting hydraulic conductivities have been graphed versus effective stress in Figure 4.3.

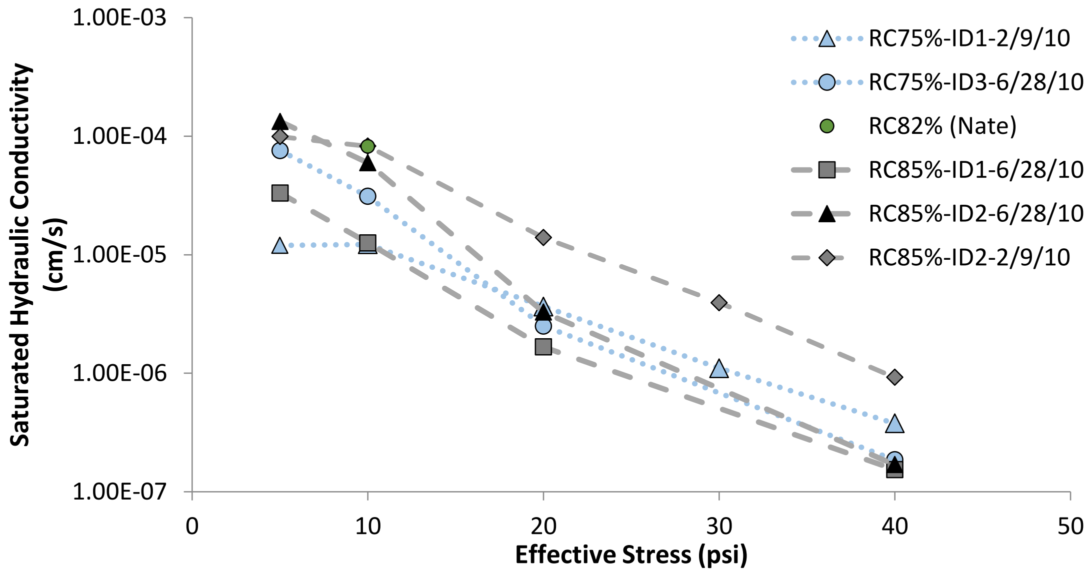

Figure 4.3: Hydraulic Conductivity of RMA cover soil at various effective stresses.

4.3.2 Fixed Wall Permeameter Tests

Fixed wall permeameter tests were conducted on seven samples of the RMA soil. The samples were compacted to six different initial (as-compacted) conditions in order to determine the effects of relative compaction and compaction water content on the quasi-saturated hydraulic conductivity. The compaction conditions of the six samples are included in Table 4-2 along with the measured hydraulic conductivity for each sample.

Table 4-2 - Fixed wall permeameter results

Sample ID	RC[1]	CWC[2]	K (cm/s)	Log10(K)	VWC	e	n
RMA-80-7.5	80	Dry	2.63E-05	-4.58	0.395	0.896	0.472
RMA-90-7.5-5	90	Dry	3.74E-06	-5.43	0.352	0.678	0.404
RMA-80-14.5-7	80	Opt	1.65E-05	-4.78	0.371	0.873	0.466
RMA-90-14.5-3	90	Opt	1.62E-06	-5.79	0.354	0.673	0.402
RMA-90-14.5-6	90	Opt	2.03E-06	-5.69	0.348	0.664	0.399
RMA-80-21.5-6	80	Wet	6.67E-05	-4.18	0.443	0.85	0.46
RMA-90-21.5-4	90	Wet	1.64E-08	-7.79	0.382	0.7	0.412

1 – Relative compaction (%)
2 – Compaction water condition

Compaction conditions of 80% and 90% relative compaction (to standard proctor) produced void ratios between approximately 0.65 and 0.9. The compaction moisture content varied from 7.5% (“dry” condition) to 21.5% (“wet” condition). The optimum compaction moisture condition was 14.5%.

The void ratio had a significant effect on the quasi-saturated hydraulic conductivity of the RMA soil. The quasi-saturated hydraulic conductivity results are shown compared with void ratio in Figure 4.4. Similar trends were seen in the samples compacted at the dry and optimum moisture conditions. A increase of approximately an order of magnitude was seen in quasi-saturated hydraulic conductivity between void ratios of 0.65 and 0.9 for the dry and optimum compaction moisture conditions. The samples compacted as the wet moisture showed a much larger change in quasi-saturated (nearly four orders of magnitude increase) for a similar range in void ratios.

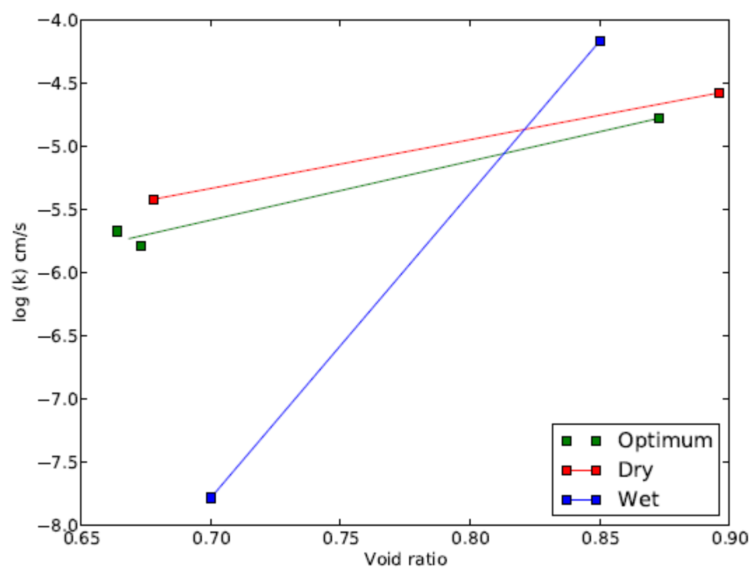

Figure 4.4 - Measured quasi-saturated hydraulic conductivity

The measured volumetric water content of the RMA samples at the end of each fixed wall permeameter test are shown in Figure 4.5. A line representing the saturated volumetric water content is included for reference. The difference in measured volumetric water content and the line for saturation represents the volume of entrapped air in the soil samples. A large volume of entrapped air (5-10% of the total volume) was seen for the samples compacted at the dry and optimum moisture conditions. The samples compacted at the wet moisture condition resulted in much lower volumes (2-3% of total volume) of entrapped air.

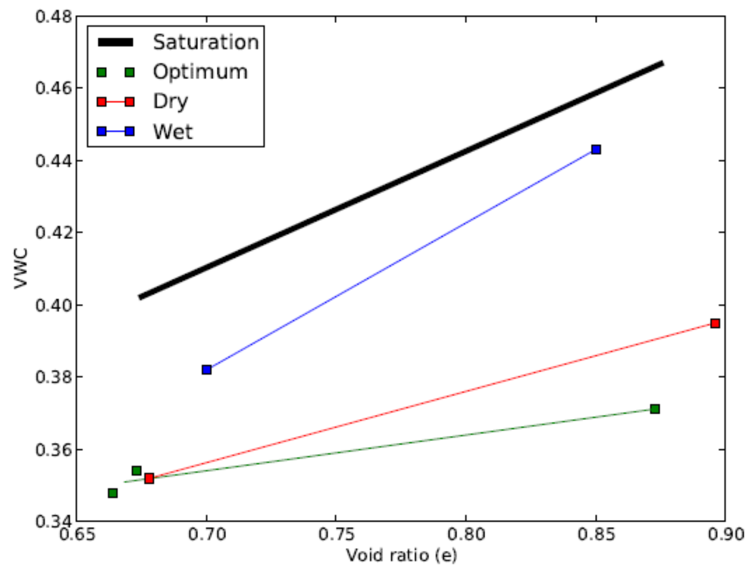

Figure 4.5 - Measured volumetric water content of fixed wall permeameter tests

4.4 Soil Water Retention Curve Testing

Two stages of retention tests were completed on the RMA soil. The first stage of testing determined the soil water retention curve of the RMA soil using a combination of hanging column, pressure plate, and thermodynamic testing methods. The retention tests were conducted on RMA samples compacted to 100% standard proctor with optimum water content using the "drying" method. The drying method determined the soil water retention curve starting at a near saturated state and then increased suction to remove water. This is opposite of the "wetting" method where samples begin the retention tests at a dry state and are progressively wetted by reducing the applied suction to the samples.

Hanging column tests were performed on the RMA soil for suctions up to 1 psi, pressure plate tests were performed for suctions between 0.5 and 8 psi, and thermodynamic testing was completed at a select points between 60 and 40k psi. Thermodynamic testing was performed by using relative humidity to impose suction on samples. It was therefore a measurement of total suction rather than matric suction and likely has an osmotic component of suction that is unknown. The resulting data and best fit curves using the van Genuchten and bi-modal van Genuchten model are included in Figure 4.6.

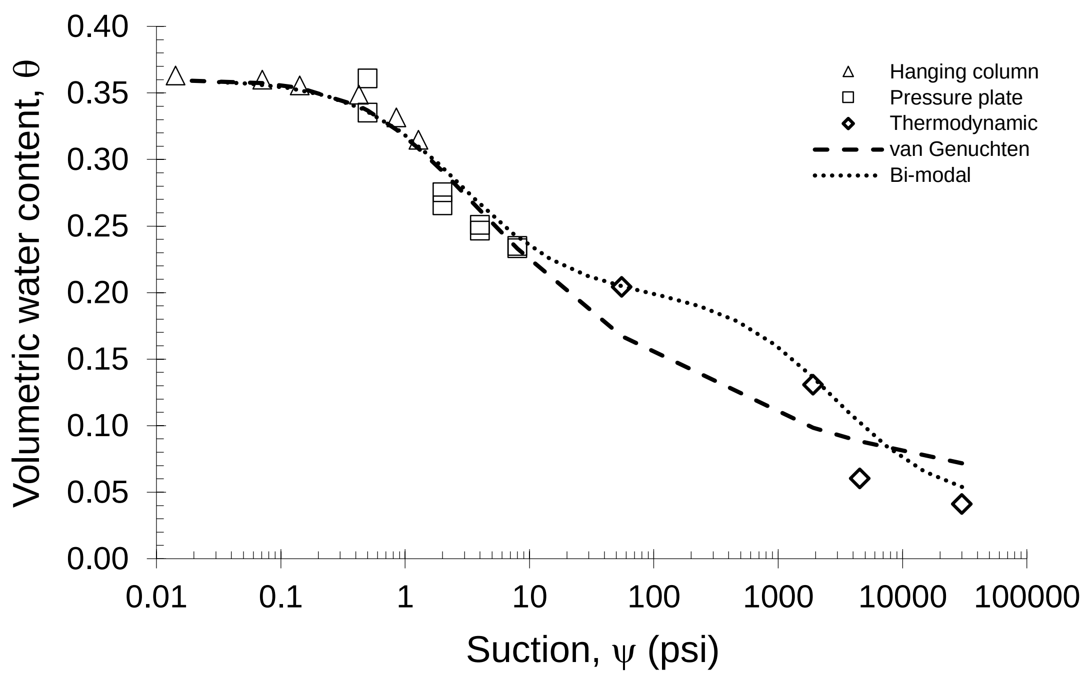

Figure 4.6 - Soil water retention curve of RMA soil

The second set of tests conducted in order to characterize the retention behavior of the RMA soil were completed using the modified pressure plate device described in Section 3.2. The second set of tests was conducted in order to determine the effects of relative compaction on the retention behavior of the RMA soil. Testing was conducted on samples at relative compaction levels of 80%, 90%, and 100% using both the "wetting" and "drying" methods. The results for samples from all three compaction conditions are shown in Figure 4.7. Limited retention results were collected for the "80% wetting" and "90% drying" conditions. The modified pressure plate device was designed and completed late in this research study and a full characterization of hysteresis was not completed for every relative compaction condition for the RMA soil.

Samples of the RMA soil compacted to 100% relative compaction showed the least hysteresis with only a few percentage difference in volumetric water content between tests conducted using the wetting and drying methods. Samples compacted to 90% relative compaction resulted in the largest hysteresis with samples conducted using the drying method resulting in approximately 10% higher VWC for the ranges of suction tested. Samples compacted at 80% relative compaction resulted in moderate hysteresis with approximately 5% VWC difference between wetting and drying methods.

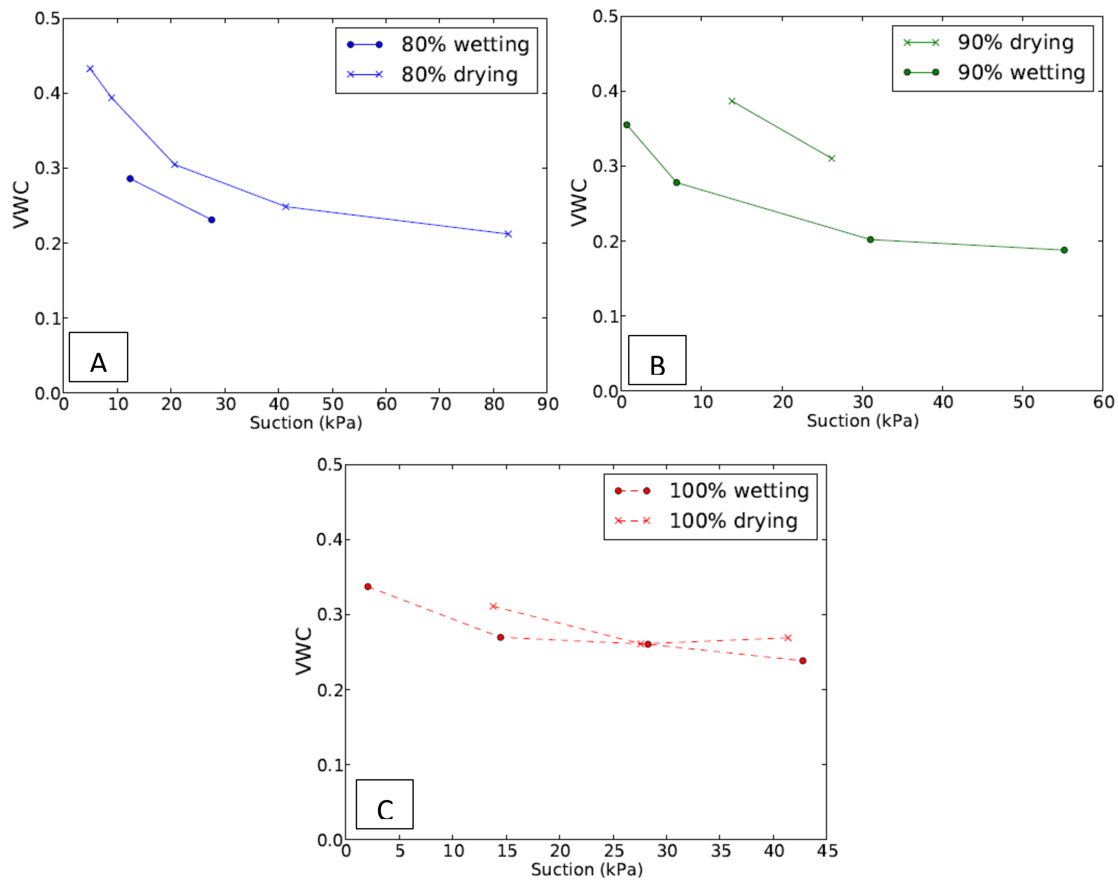

Figure 4.7 - Retention results from modified pressure plate device: a) 80% RC, b) 90% RC c) 100% RC

5 Testing Series "I": Instrumented Procedure

The first series of centrifuge testing conducted in this research project was completed using a procedure referred to as the *instrumented procedure*. The instrumented procedure was the first centrifuge experimental setup used in this research project. During analysis of results from the instrumented procedure it was determined that several of the assumptions made led to inaccuracies in the results. These finding were valuable and used to improve the testing setup and experimental procedures. The improvements were implemented into the testing series "B" and "C" which are discussed in Sections 7 and 8.

Series "I" testing was performed by imposing a constant flow rate on the surface of samples and using an "open flow" boundary at the base. It had been previously shown (e.g. McCartney 2007, Dell'Avanzi et al. 2004) that when centrifuge tests with these boundary conditions come to equilibrium the area affected by the lower boundary is minimal. The lower portion of the sample that is closest to the open flow boundary has significant boundary effects and transitions from a near saturated condition at the base of the sample to a lower moisture content that is a function of the imposed flow rate. The upper portion of the sample is not affected by the boundary and comes to equilibrium at a relatively constant moisture content with depth. These two zones will be referred to as the "transition zone" that develops towards the base of the sample and the "zero suction gradient zone" that occurs in the upper portion of the sample. The zero suction gradient zone is characterized by having a constant moisture content and therefore suction in this area resulting in negligible suction gradient. The two zones are illustrated in Figure 5.1.

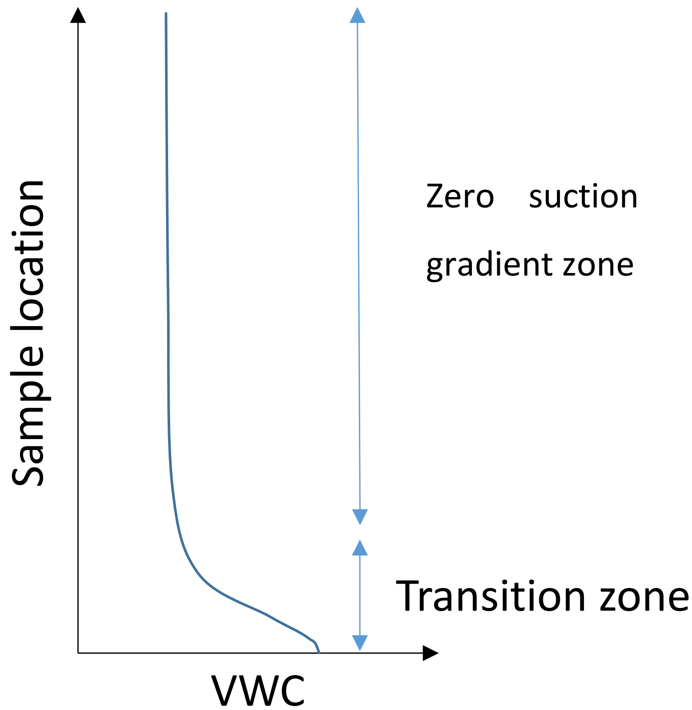

Figure 5.1 – Moisture distribution in centrifuge samples

The size of the transition zone should decrease with increasing g-level and increasing flow rates (Dell'Avanzi 2004). The increased g-level increases the gravitational gradient in the transition zone reducing the length required to transition from the saturated base to the water content of the zero suction gradient zone. Higher flow rates increase the water content of the zero suction gradient zone reducing the change in water content between the base and the zero suction gradient zone. As a result, higher flow rights reduce the size of the transition zone.

One goal of Series "I" testing was to rapidly characterize the K-function of unsaturated soils. In order to determine the K-function, various flow conditions were imposed on centrifuge samples. The volumetric water content (VWC) and suction were measured by instrumentation. The hydraulic conductivity was calculated in the zero suction gradient zone as the gradient was equal to the gravitation gradient. The hydraulic conductivity and measured VWC were then used to define a point on the K-function. This process was repeated for a variety of imposed flow rates and g-levels in order to target a wide range of hydraulic conductivity in the sample. As both the suction and volumetric water content were measured in the zone of zero suction gradient, data for the soil water retention curve was also obtained at each testing stage.

The target hydraulic conductivity for each testing stage was defined as:

$$K_t = \frac{Q}{A i_g} \qquad (21)$$

where Q is the imposed flow rate, generally in mL per hour, A is the area of the sample, generally in cm^2, and i_g is the gravitational gradient, dimensionless and equal to the g-level. The target hydraulic conductivity is a useful parameter as it will be the hydraulic conductivity that is imposed on the sample in the zero suction gradient zone and is controlled in testing as the flow rate and gravitational gradient are controlled during testing.

The testing procedure and setup in testing Series "I" of this project was designed to follow the general setup used by McCartney (2007) in order to verify similar results were able to be produced. The main differences between the two setups was the instrumentation used in the soil samples.

5.1 Description of Testing Setup

Centrifuge testing performed by McCartney (2007) in the CPUS included a single Time Domain Reflectometer (TDR) sensor for measurement of VWC and three tensionmeters along the height of the sample for measurement of suction. The arrangement in sensors is shown in Figure 5.2. Some issues found with the instrumentation used by McCartney (2007) were:

- The range of suctions measurable by the tensiometers was narrow. Only suctions below 100 kPa could be measured and when the sensors were exposed to higher suctions cavitation occurred resulting in loss of readings until the test was stopped and the tensiometer could be flushed with water.

- The TDR sensor was large with prongs approximately 80 mm in length. This allowed only one sensor to be placed in the sample. Consequently the measurements were an average of approximately the top half of the specimen.

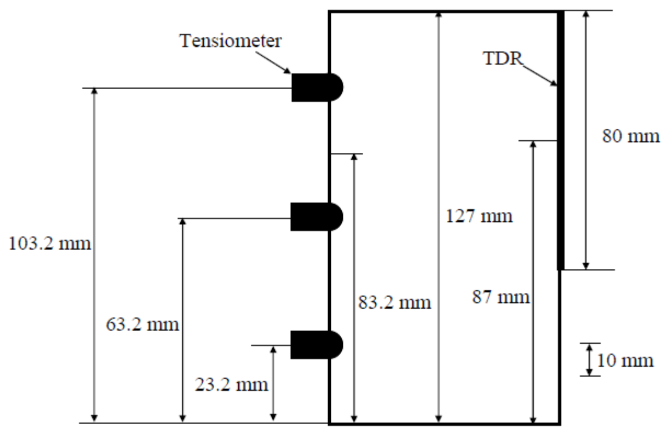

Figure 5.2 - Previous instrumentation by McCartney (2007)

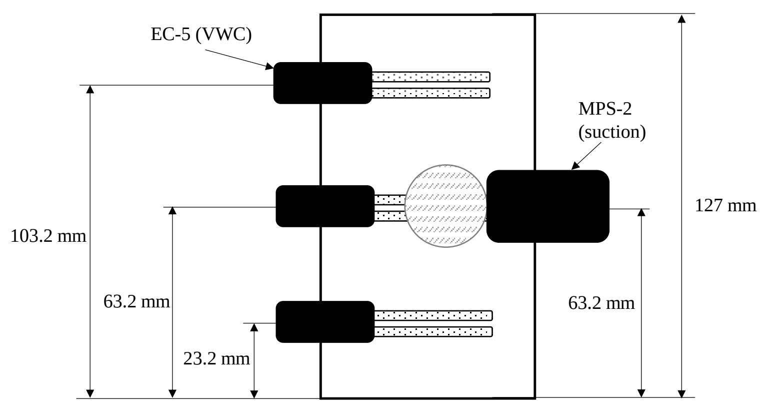

Figure 5.3 - Instrumentation for testing (sensor size not to scale)

In order to improve the previous instrumentation, new sensors by Decagon Devices were used in Series “I” of this research. Three EC-5 sensors were used instead of the TDR sensor to monitor moisture content. The size and area of influence of the EC-5 sensors was much smaller than the TDR and allowed the sensors to be placed along the profile of the sample. A single MPS-2 sensor was used instead of the tensiometers and was placed at mid-height of the sample to measure suction. The MPS-2 sensor is able to read a much wider range of suctions and if the sensor is exposed to suctions outside its range, no negative effects such as cavitation occur. The new sensor setup is shown in Figure 5.3. Details on the EC-5 and MPS-2 sensors are discussed in Sections 5.1.1 and 5.1.2.

5.1.1 EC-5 Volumetric Water Content Sensor

The EC-5 is a volumetric moisture content sensor manufactured by Decagon Devices. The sensor determines the volumetric water content by measuring the dielectric constant of the soil-water mass. As the dielectric constant of water is much higher than those of soil and air, increases in moisture content result in a significant increase in dielectric constant. The sensor measures the dielectric constant in a capacitive manner. The two probes in essence form a capacitor with the soil-water mixture as dielectric. When the volume of water increases in between the probes the dielectric increases resulting in a higher effective capacitance of the two probes. The sensor includes a high frequency oscillator that is affected by changes in capacitance of the probe and these changes are measured by an integrated circuit. The integrated circuit outputs these changes as a voltage, which is calibrated to volumetric water content. The sensor specifications provided by the sensor manufacturer are listed in Table 5-1.

Table 5-1 – EC-5 manufacturer provided sensor specification

ACCURACY	**Mineral Soil:** **±3% VWC, most mineral soils, up to 8 dS/m** **±1-2% VWC with soil-specific calibration** **Rockwool: ±3% VWC, 0.5 to 8 dS/m** **Potting Soil: ±3% VWC, 3 to 14 dS/m**
RESOLUTION	0.1% VWC (mineral soil) 0.25% VWC (rockwool)
RANGE	calibration dependent; up to 0-100% VWC with polynomial equation
DIMENSIONS	8.9 x 1.8 x 0.7 cm

The stated accuracy of the sensors is +/- 1-2% for a soil-specific calibration. A soil-specific calibration is shown in Figure 5.4 (Azevedo 2012). In practice, it was found that the sensor readings were greatly affected by placement conditions and void ratio, meaning that the soil-specific calibration was not sufficiently accurate. For example, raw sensor data resulting from a centrifuge test is shown in Figure 5.5. This test started at the compaction condition and then a flow rate was applied to the top of the sample, increasing the moisture content of the sample. For this test, the calibration would show that the initial water content (compaction in this case) varied between approximately 22% and 29% volumetric water content (among the three sensors) even though the known condition was 15% VWC.

Even though the soil-specific calibration produced inaccurate results, the sensors were found to reliably measure trends in water content and were useful for tracking a progressing moisture front. Using sample-specific calibration showed much better results than the soil-specific calibration. The sample-specific calibrations and accuracy of the EC-5 sensors will be further discussed in Section 5.5.1.

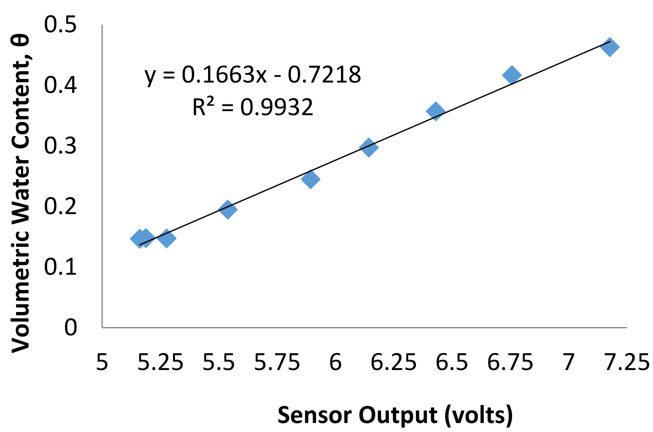

Figure 5.4 - EC-5 Calibration

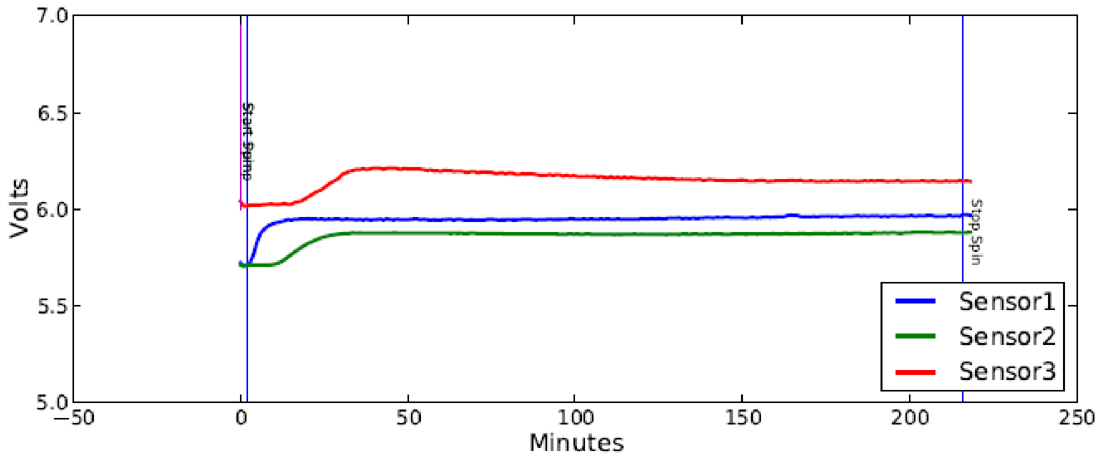

Figure 5.5 – EC-5 sensor output from centrifuge flow test

5.1.2 MPS-2 Dielectric Water Potential Sensor

The MPS-2 Dielectric Water Potential Sensor is a sensor developed by Decagon Devices that operates based on the same fundamental principles as the EC-5 sensor. Similar probes are used. However, the probes are encased by two ceramic discs that have a well-defined water retention profile. The water retention profile allows a suction to be calculated if the volumetric water content of the ceramic is known. The MPS-2 essentially measures the volumetric water content of the two ceramic discs by measuring their dielectric constant. Suction can then be predicted based on the known relation between volumetric water content and suction of the ceramic discs. Since the ceramic disc is embedded and in contact with the soil the suction of the ceramic disc will be the same as the soil once equilibrium occurs.

The main advantages of the MPS-2 sensor includes a wide range of measurement (-10 to -500 kPa) and no problems with cavitation such as those of tensiometers. The main disadvantages are low accuracy, large size, and potentially long equilibrium time. The manufacturer-provided specifications are provided in Table 5-2. Typical sensor output from a centrifuge flow test is shown in Figure 5.6.

Table 5-2 – MPS-2 manufacturer provided sensor specification

ACCURACY	**Soil Water Potential: ± 25% of reading from -10 kPa to -100 kPa,** **Soil Temperature: ± 1°C**
RESOLUTION	Soil Water Potential: 0.1 kPa Soil Temperature: 0.1°C
RANGE	Soil Water Potential: -10 to -500 kPa (pF 2.01 to pF 3.71) Soil Temperature: -40° to 50°C
MEASUREMENT SPEED	150 ms (milliseconds)
EQUILIBRATION TIME	10 min to 1 hr depending on soil water potential

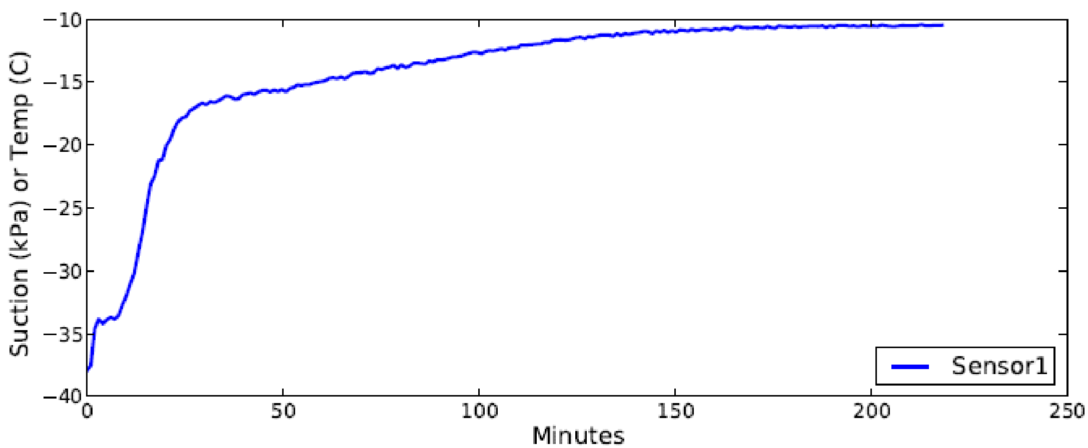

Figure 5.6 – MPS-2 sensor output from centrifuge flow test

5.2 Testing Procedure

The testing procedure used during Series "I" testing is summarized in the following sections. Testing was conducted using reconstituted soil samples, compacted using kneading compaction methods. These samples were subsequently tested at elevated g-levels in the CPUS.

5.2.1 Sample Preparation

__Soil processing__ – Soil was spread loosely and air dried at room temperature. After several days the soil was processed using a soil crusher and sieved using a #10 sieve. Water content was measured of the sieved soil and water was added as necessary to bring the soil to the target water content. The majority of tests were performed at gravimetric water contents ranging from 7% to 11%. These dry (relative to optimum) water contents provided a greater contrast between initial (as compacted) conditions and the conditions after the wetting front. Once the additional water was mixed into the soil it was allowed to rest in a sealed container for at least 48 hours in order to allow the moisture to equalize.

Compaction – Samples were compacted using two centimeter lifts using kneading compaction. Select samples were compacted using one centimeter lifts in order to evaluate if a smaller lift would result in a more uniform distribution in density. It was found that two centimeter lifts were adequate as long as a small enough kneading compaction head was used. This was in order for the kneading force to reach the base of the layer. The process for a compaction lift was as follows:

1. Calculate the mass of wet soil required for the lift volume based on a previously measured gravimetric water content and target dry density.
2. Measure the mass of the testing cup and initial height prior to addition of soil for the compaction lift. The initial height should be measured using a mounted caliper and seating dish. The seating dish provides a larger area of measurement so that the measurement is an average of peaks of an area.
3. Loosely place the target mass of soil in the testing cup. Using the small kneading compaction head, begin compaction the soil using a pattern that evenly distributes kneading blows to the sample. The larger head may be used afterwards in order to provide a more even compaction surface for the lift.
4. Measure the new height. Iterate between additional kneading compaction (using either the large or small kneading head) and measurement of height until the target height has been reached. The height was deemed acceptable if it was within 0.25 mm of the target (although in some cases larger errors were allowed).

5. Repeat 2-4 until the total sample height has been achieved. Sample heights between 4 and 12 centimeters were evaluated in this testing phase with the majority of the samples being prepared at 12 centimeters.

Sensors were placed during compaction. If sensors were required to be inserted into a layer, the volume of the sensors were measured and the mass of soil required for the layer was reduced accordingly. Sensors were placed and then soil was compacted around the sensors. Care was taken to ensure good contact between sensor and soil and that the density of the soil was evenly distributed around and under sensors.

5.2.2 Centrifugation

Samples were placed into the centrifuge and spun at g-levels of either 25, 50, or 100. These g-levels were selected as a range to evaluate the effects of g-level while still remaining within the working range of the centrifuge. Samples were spun for approximately 15 minutes before starting the flow pumps. Tests were performed by progressively wetting the samples by increasing the flow rate in stages. Samples were removed after each stage and the mass measured in order to calculate an average volumetric water content of the sample. The testing procedure is summarized as follows:

1. Place samples in centrifuge and start centrifuge at a g-level or 25, 50, or 100.
2. Start flow pumps at a low flow rate. Initial flow rates ranged from 1-10 mL per hour for each sample, which corresponds to target hydraulic conductivities of approximately $2x10^{-7}$ cm/s to $2x10^{-6}$ cm/s.
3. Observe the response of the sensors and continue testing until the moisture front has advanced through the entire specimen and the sensors readings have stabilized.
4. Stop the flow pumps and centrifuge and measure the mass of the samples in order to determine an average water content of the sample.

5. Repeat steps 1-4 at progressively higher flow rates. The flow rate was generally doubled for each testing cycle up to a maximum target hydraulic conductivity of approximately $4x10^{-5}$ cm/s.

Typical un-calibrated EC-5 (Figure 5.7) and MPS-2 (Figure 5.8) data are shown for the first wetting phase of a centrifuge test. As shown in Figure 5.7, the wetting front reaches Sensor1 (near top of sample) almost immediately after flow has been initiated. Approximately 10 minutes later an increase is seen in EC-5 Sensor2 and a decrease in suction in the MPS-1 sensor (both located at mid-height of the sample). Finally the wetting front reaches EC-5 Sensor3 located at the base of the sample approximately 20 minutes after flow was initiated at the top of the sample. The test was continued for approximately three hours until the sensors had stabilized.

The initial wetting phase shown in the Figure 5.7 and Figure 5.8 results in the largest change in water content in the sample during testing. The volumetric water content increased from an initial (as compacted) water content of 12-15% up to 25-28% after the first stage of infiltration. Subsequent wetting phases, where the flow rate was typically doubled from the previous flow rate, resulted in smaller changes on the order of 1-2% VWC per stage.

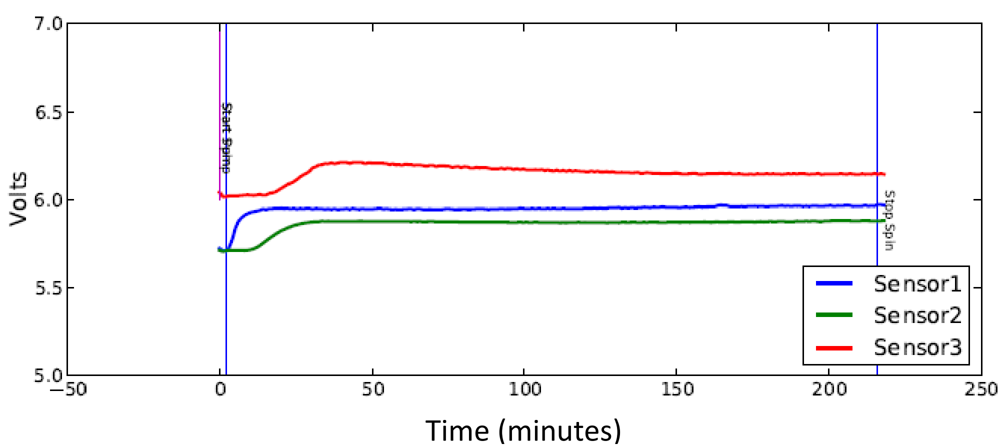

Figure 5.7 – Typical first wetting phase of EC-5 sensors

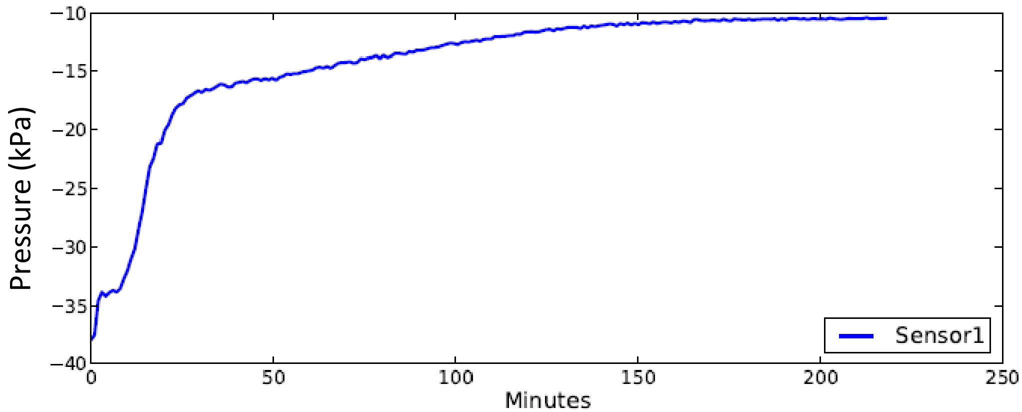

Figure 5.8 – Typical first wetting phase of MPS-2 sensor

5.3 Testing Program

A total of 90 tests were performed on 16 samples during testing Series "I". Flow rates ranged from 2 mL/h up to 320 mL/h corresponding to unsaturated hydraulic conductivities of $2x10^{-7}$ cm/s to $4x10^{-5}$ cm/s. Table 5-3 lists all tests performed in Series "I" of the research project. In addition to the tests listed in Table 5-3, several instrumented tests with modified pı Time (minutes) rformed to evaluate directly the moisture distribution in samples. These tests are discussed separately in Section 5.4.5.

Table 5-3 – Summary of Series "I" testing program

Test	Sample ID	G-level	Flow (mL/h)	Test	Sample ID	G-level	Flow (mL/h)
1	s2_15_2013_6	50	75	46	s4_10_2013_4	100	80
2	s2_15_2013_6	25	150	47	s4_10_2013_4	100	160
3	s2_15_2013_4	50	75	48	s4_10_2013_4	100	160
4	s2_15_2013_4	25	150	49	s4_10_2013_4	100	160
5	s5_31_2012_6	50	10	50	s4_10_2013_4	100	320
6	s5_31_2012_6	50	20	51	s4_10_2013_4	50	160
7	s5_31_2012_6	50	40	52	s4_10_2013_4	25	80
8	s5_31_2012_6	50	80	53	s4_10_2013_4	50	80
9	s5_31_2012_6	50	160	54	s4_10_2013_4	25	40
10	s5_31_2012_6	50	160	55	s7_10_2013_6	50	40
11	s5_31_2012_4	50	10	56	s7_10_2013_6	50	80
12	s5_31_2012_4	50	20	57	s7_10_2013_6	50	160
13	s5_31_2012_4	50	40	58	s7_10_2013_6	50	160
14	s5_31_2012_4	50	160	59	s7_10_2013_6	50	250
15	s5_31_2012_4	50	160	60	s7_10_2013_4	50	40
16	s3_20_2013_6	100	2	61	s7_10_2013_4	50	80
17	s3_20_2013_6	100	10	62	s7_10_2013_4	50	160
18	s3_20_2013_6	100	20	63	s7_10_2013_4	50	160
19	s3_20_2013_6	100	40	64	s7_10_2013_4	50	250
20	s3_20_2013_6	100	80	65	RMA1	100	5
21	s3_20_2013_6	100	160	66	RMA1	100	10
22	s3_20_2013_6	100	320	67	RMA1	100	20
23	s3_20_2013_4	100	2	68	RMA1	100	40
24	s3_20_2013_4	100	10	69	RMA1	100	80
25	s3_20_2013_4	100	20	70	RMA1	100	160
26	s3_20_2013_4	100	40	71	RMA2	100	5
27	s3_20_2013_4	100	80	72	RMA2	100	10
28	s3_20_2013_4	100	160	73	RMA2	100	20
29	s3_20_2013_4	100	320	74	RMA2	100	40
30	s4_10_2013_6	100	10	75	RMA2	100	80
31	s4_10_2013_6	100	20	76	RMA2	100	160
32	s4_10_2013_6	100	40	77	RMA5	100	5
33	s4_10_2013_6	100	80	78	RMA5	100	10
34	s4_10_2013_6	100	160	79	RMA5	100	20
35	s4_10_2013_6	100	160	80	RMA5	100	40
36	s4_10_2013_6	100	160	81	RMA5	100	80
37	s4_10_2013_6	100	320	82	RMA5	100	160
38	s4_10_2013_6	50	160	83	RMA6	100	5
39	s4_10_2013_6	25	80	84	RMA6	100	10
40	s4_10_2013_6	50	80	85	RMA6	100	20
41	s4_10_2013_6	25	40	86	RMA6	100	40
42	s4_10_2013_4	100	10	87	RMA6	100	80
43	s4_10_2013_4	100	20	88	RMA6	100	160
44	s4_10_2013_4	100	40	89	RMA7	50	5
45	s4_10_2013_4	100	80	90	RMA8	50	5

5.4 Results & Analysis

A significant amount of data was collected for each centrifuge flow test conducted as part of Series "I". The data includes the average volumetric water content of samples at the end of each stage determined using mass balance, transient and steady state sensor data, and the imposed g-level and flow rate during each testing stage. The data is presented and discussed in the following sections.

The average volumetric water content (determined by mass balance), EC-5 volumetric water content data, and MPS-2 suction sensor are discussed individually in Sections 5.4.1-0. A number of tests, which were conducted during Series "I" testing in order to evaluate the effects of g-level on the instrumented testing procedure, are discussed in Section 5.4.4. A second group of tests that were conducted with a modified procedure in order to directly measure the distribution of gravimetric water content in samples are discussed in Section 5.4.5. Finally, the K-function and soil water retention data obtained during Series "I" testing are discussed in Section 5.4.6.

5.4.1 Determination of Average VWC by Mass Balance

The mass of each centrifuge soil sample was measured prior to testing and at the end of each testing stage. Any increase in mass of the specimen was due to an increase in moisture stored in the soil sample. Mass measurements were taken without the permeameter cup base and porous metal grid in order to minimize any errors due to moisture storage that may occur outside the soil sample. The average water content of the sample at the end of stage *i* was calculated as:

$$VWC_i = VWC_c + \frac{M_i - M_c}{V} \qquad (22)$$

where VWC_c and M_c are the volumetric water content and sample mass at compaction, VWC_i and M_i are the volumetric water content and sample mass at the end of stage i, and V is the volume of the sample. Interpretation of the results of Series "I" testing assumes that the transition zone of centrifuge samples is small enough that an average water content of the entire sample provides a representative value of the water content in the zone of zero suction gradient. As discussed in Section 5.5.2, it was found that for the majority of flow rates tested during Series "I" testing the transition zone was larger than predicted, so using an average water content of the entire specimen led to an over prediction of the moisture content in the zero suction gradient zone. As discussed in Sections 7 and 8, the testing setup was modified and the testing procedure was changed in order to quantify moisture changes along the soil sample, accounting for the large transition zone. This is a major advantage of the later testing procedures (Series "H" and "IF").

5.4.2 Evaluation of Volumetric Water Content Data from EC-5 Sensors

Data was recorded from the EC-5 volumetric water content sensors throughout centrifugation. As discussed in Section 5.1.1 the EC-5 sensors were sensitive to placement at compaction and a generic calibration for the sensors could not be determined that produced quantitatively reliable results for the RMA soil. Accordingly, the measured voltage from each sensor at the end of each stage of testing is plotted versus the average volumetric water content determined using mass balance (Figure 5.9). If the distribution of water contents in the sample was uniform, there should be a linear calibration relationship between the sensor voltage and average water content. In areas of lower average water content (denoted as area (1) in Figure 5.9) a large range in voltage is seen from the sensors for a given average water content. The range is significantly reduced in area (2) that corresponds to higher average water contents. This trend is consistent with an increase in the uniformity of moisture distributions at higher flow rates (and corresponding water contents). This trend could be explained as follows:

- Low flow rates result in a lower volumetric water content to be transmitted through the sample. Higher flow rates result in higher water contents.

- The lower boundary of the sample is free draining. Accordingly, the moisture content at the lower boundary should increase to near saturation before drainage occurs.
- The moisture content in the sample varies from the nearly saturated condition at the base to the moisture content required to transmit the imposed flow rate under negligible suction gradient in the upper portion of the sample.
- The size of the transition zone (Figure 5.1) is dependent on the g-level and the change in water content from the lower boundary (saturation) to the water content of the zone of zero suction gradient. Lower flow rates result in lower water contents in the zero suction gradient zone requiring a larger change in water content across the transition zone resulting in a larger transition zone.
- The data included in Figure 5.9 is in agreement with the trend of increasing uniformity of water content with increases in average water content. Zone (1), which have lower average water contents, has a wide range in voltages reported from the EC-5 sensors. This is expected given a non-uniform moisture distribution. At a given average moisture content value, a sensor located at the top of the sample in an area dry relative to the average would output a lower voltage than a sensor at the base (in an area wet relative to the average).
- At high flow rates (Zone (2) in Figure 5.9) the range in sensor values is significantly reduced as the distribution of moisture content in samples is more uniform.

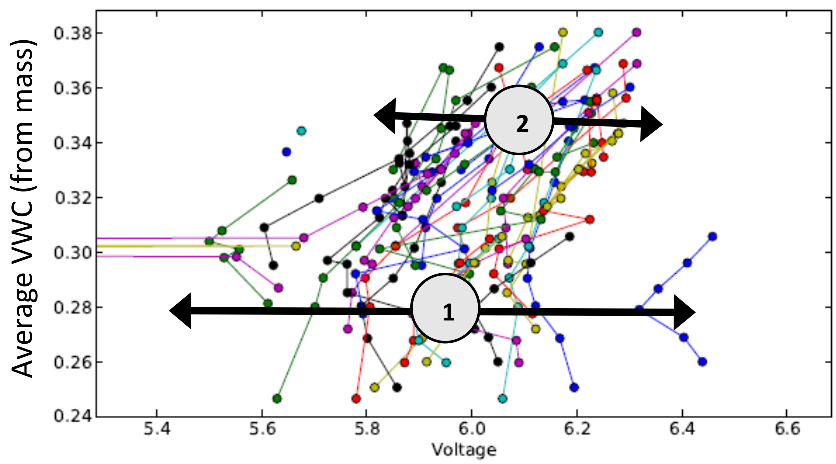

Figure 5.9 – EC-5 output voltage vs. average VWC from mass balance

A calibration was calculated based on the previous assessment for each test and EC-5 sensor. The initial condition (as compaction) was used as one point of reference and the final stage conducted at the highest imposed flow rate as the second reference. These two reference points were chosen as they represent the two times when the moisture distribution in the samples was most uniform and would correlate best with measured average water content for the entire sample. The calibration for one of the samples is shown as Figure 5.10. The compaction and final volumetric water contents were approximately 15% and 37%.

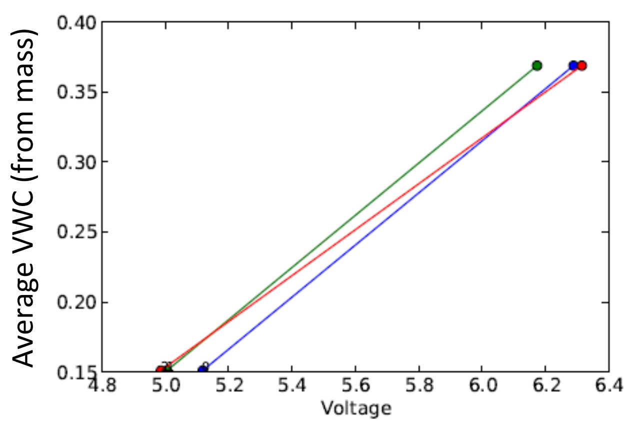

Figure 5.10 – Sample specific EC-5 calibration

All three sensors from this sample show similar calibration curves. The calibration was used to define moisture profile distributions at the end of each testing stage, which is when the samples had reached equilibrium. The resulting profiles are shown in Figure 5.11 and show mixed results. These results are consistent with some of the expected trends, specifically:

- The profiles show a trend of increasing water content with increasing flow rate.
- At lower flow rates the top sensor readings are lower those of the base sensor.

However, some behavior from the sensors contradicted the expected trends. Specifically:

- The middle sensor shows a higher water content than the base. This sensor is located near the MPS-2 suction sensor. It is possible that the EC-5 reading was affected by its proximity to the other sensor.
- The base remains at a relatively constant water content for the first three flow stages and then shows a large increase for the last two.

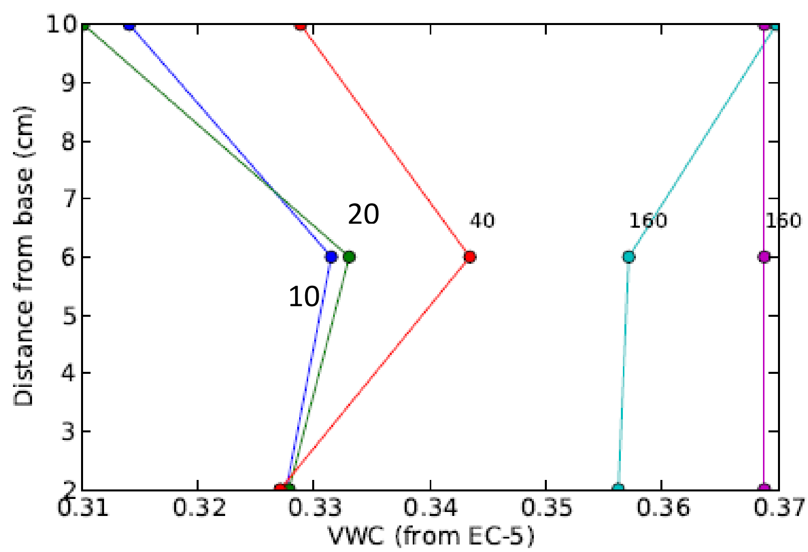

Figure 5.11 – Moisture profiles resulting from sample specific calibration, imposed flow rate shown in mL/h

This behavior is likely a combination of the relatively narrow range in water contents tested and the low accuracy of the sensors. The total range in equilibrium water contents seen in testing performed between 10 and 160 mL/h was approximately 6%. The published accuracy of the EC-5 sensor is +/- 1-2% if a soil-specific calibration is used.

Unfortunately this means that the EC-5 sensors do not produce data that is accurate enough to distinguish between the different stages of flow for soil characterization (which vary 1-2% VWC between stages). However, the sensors were found to be useful in monitoring the movement of the moisture front and in assessing the general trends in volumetric water content.

5.4.3 Evaluation of Suction Data from MPS-2 Sensors

The MPS-2 suction data was recorded at the same intervals as the EC-5 data. The MPS-2 sensor is pre-calibrated and does not require soil-specific calibration. The accuracy of the sensors is fairly low (on the order of +/- 25%) but the sensors are suitable for a wide range of suction values and do not show the cavitation problems that are typical of tensiometers.

The data collected at the end of each flow stage once the samples had come to equilibrium is shown in Figure 5.12. Other than in three samples, the results show very good repeatability. Two of the bad results can be explained by damaged sensors that were repaired for later tests. The third abnormal result is consistent with a sensor that was wet in the beginning of the tests and had not been given enough time to equilibrate. These test results were not considered in the subsequent analysis.

The minimum suction that can be measured by the MPS-2 sensors is 10 kPa. For the RMA soil tested in this program, suction values as low as 10 kPa were reached at a hydraulic conductivity values ranging from 10^{-6} and 10^{-5} cm/s. Testing conducted at flow rates that corresponded to higher hydraulic conductivities and lower suctions resulted in the MPS-2 sensors giving unreliable results, remaining fairly constant at a reading near 10 kPa for further flow stages.

Overall the MPS-2 sensors provided reliable data when tested within their stated suction range. However, as discussed fully in Section 5.5.2, the transition zone of the sample was much larger than expected for low flow rates. This resulted in the MPS-2 sensor (located at mid-height of the soil sample) not being located in the zone of zero suction gradient for low flow rates. Therefore, the measured suction cannot be directly correlated to the target hydraulic conductivity.

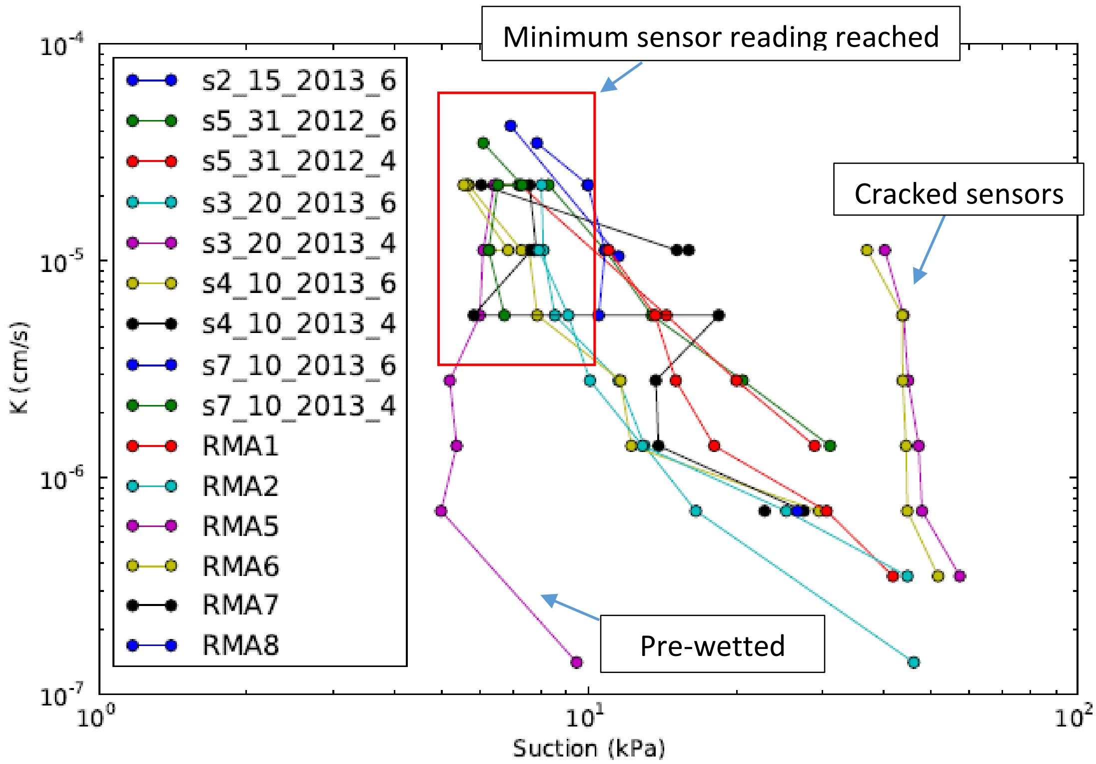

Figure 5.12 – Equilibrium MPS-2 suction data at end of flow test

5.4.4 Evaluation of the Effect of G-level

During the testing program outlined in Section 5.3 the g-level imposed on the centrifuge samples was set at either 25, 50, or 100. These g-levels refer to the calculated value at the base of samples. The g-level decreases approximately 20% towards the top of the sample due to a reduction in radius from the center of rotation. The change in g-level across the sample is accounted for in the analysis of results. However, for simplicity, tests are denoted by the g-level calculated at the sample.

In order to verify that the methods for accounting for increased g-level during unsaturated flow are valid, a series of tests were completed at different g-levels targeting the same hydraulic conductivities. This verification was conducted before it had been determined that the moisture profiles of centrifuge sample varied greatly across the sample for a majority of flow rates used in the testing plan. While not completely accurate, the performed tests still provide a reasonable source to verify the methods used to account for an increased gravitational acceleration during flow testing.

The general validation approach is as follows:

- If two samples are tested at the same target unsaturated hydraulic conductivity they should result in the same volumetric water content.
- Given the Darcy flow equation, Q=-KiA, the same unsaturated hydraulic conductivity can be target at different combinations of flow rate and gradient.
- A sample should come to equilibrium at the same water content given twice the flow rate and twice the gradient. If the increased gravitational acceleration of the centrifuge can be accounted for by simply scaling the elevation gradient, a test with twice the flow rate should come to equilibrium at the same water content as one at half the flow rate if the gradient has been doubled by increasing the g-level.

A sample was tested initially at a g-level of 100 and at progressively increasing flow rates. A series of three repeat tests were performed at the same g-level and flow rate in order to assess the repeatability of results. Subsequently the flow rate was doubled and then two additional tests were performed at this same target hydraulic conductivity but different g-levels by adjusting the flow rate accordingly. The g-level and flow rate for each testing stage is outline in Table 5-4. The resulting volumetric water content of the sample measured by mass balance procedures outlined in Section 5.4.1 for each stage are plotted in Figure 5.13. The same process and testing stages were repeated on a second sample with results displayed in Figure 5.14.

Table 5-4 – Centrifuge testing program for evaluation of g-level

Stage	G-level	Flow Rate (mL/h)	K_{target} (cm/s)
1	100	10	7.02E-07
2	100	20	1.40E-06
3	100	40	2.81E-06
4	100	80	5.61E-06
5	100	80	5.61E-06
6	100	160	1.12E-05
7	100	160	1.12E-05
8	100	160	1.12E-05
9	100	320	2.25E-05
10	50	160	2.25E-05
11	25	80	2.25E-05
12	50	80	1.12E-05
13	25	40	1.12E-05

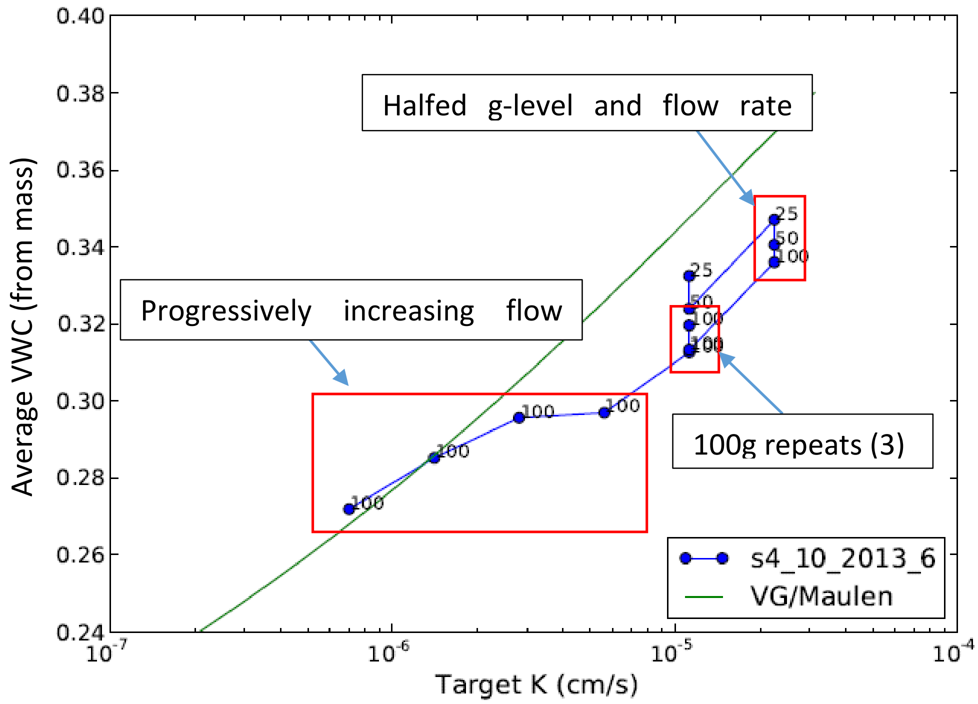

Figure 5.13 – Mass balance VWC results for 's4_10_2013_6"

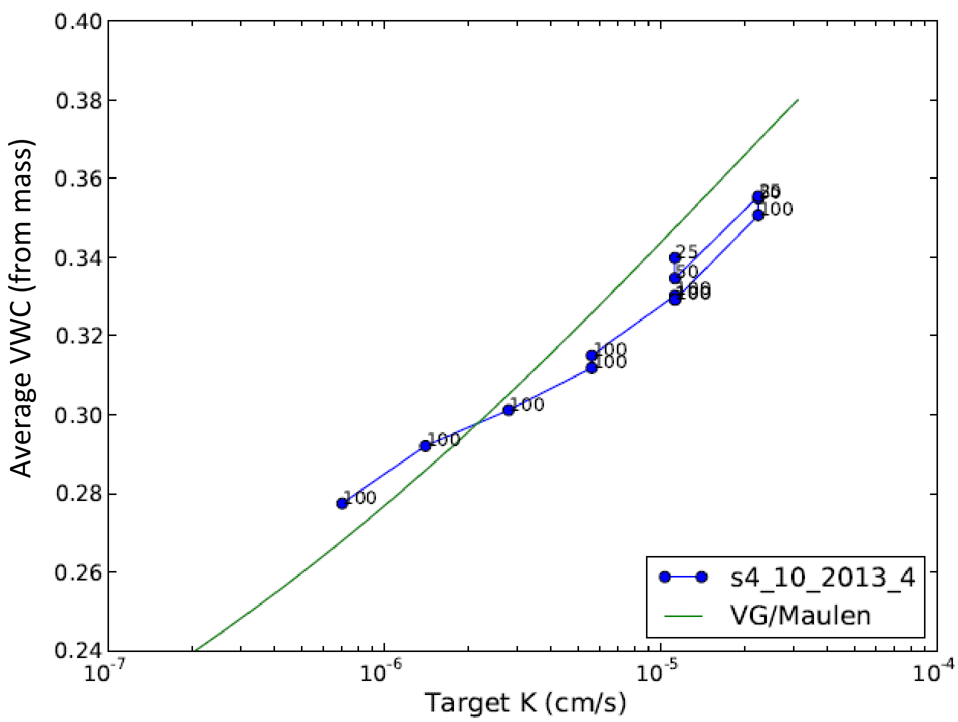

Figure 5.14 - Mass balance VWC results for 's4_10_2013_4"

The following observations can be drawn from the test results:

- The measured VWC was very close in the repeat tests performed at the same g-level and flow rate in both samples.
- The measured VWC in the tests performed at the same target hydraulic conductivity but different g-levels was similar for all tests performed in both samples.
- In both samples, tests run at the same target hydraulic conductivity but at lower g-levels results in slightly higher measured VWC. The effect was more pronounced in ‘s4_10_2013_6’ (Figure 5.13) than in ‘s4_10_2013_4” (Figure 5.14).
- The increases in VWC at lower g-levels were much smaller in magnitude than the changes in VWC seen between flow stages tested at different target hydraulic conductivities.

The repeatability obtained in both samples was considered very good. However, tests ran at the same target hydraulic conductivity but different g-levels showed a small but consistent trend of an increasing average volumetric moisture content with decreasing g-level. This trend can be explained due to the non-uniform distribution of water contents in centrifuge samples. Figure 5.15 illustrates a typical distribution of moisture contents for two tests performed at the same target hydraulic conductivity but different g-levels. Both profiles reach the same volumetric moisture content in locations that are sufficiently far from the lower boundary of the samples (i.e. in the zone of zero suction zone). However the length of the transition zone from the boundary condition until reaching a constant moisture content is different. Specifically, tests run at higher g-level result in a reduced transition zone. This results in tests run at higher g-levels having a slightly lower average volumetric water content for the sample, which was supported by the results of the conducted tests.

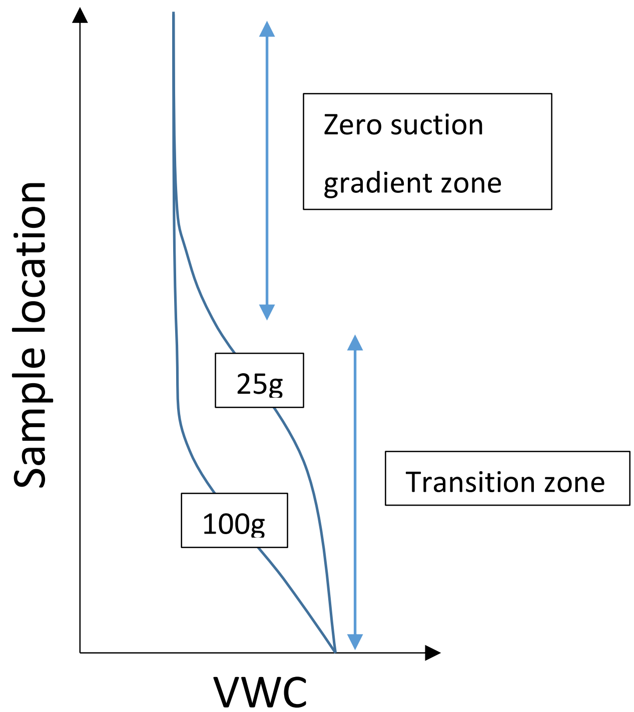

Figure 5.15 – Illustrated moisture profiles at different g-levels

5.4.5 Evaluation of Results from Tests with Direct Measurements of GWC

Interpretation of centrifuge test results is facilitated if the distribution of volumetric moisture content in centrifuge flow tests is assumed to be uniform for the majority of the sample (with a small transition period at the base of the sample near the outflow boundary). This assumption was based on research conducted by Nimmo et al. (1987), Dell'Avanzi (2004), and McCartney (2007) who all found the moisture distribution to be uniform in centrifuge samples other than at the very base. However, while completing testing Series "I", several observations were made that suggested that this assumption was not valid for the majority of the tested flow rates. These observations are summarized as follows:

- Data from the EC-5 sensors showed lower water content readings at the top of the sample than at the middle and base. This trend was less significant as the flow rate reached higher levels.

- Shorter specimens resulted in higher average water contents than tallersamples.
- Test performed at the same target hydraulic conductivity but at lower g-levels resulted in higher measured water contents.

In order to directly evaluate the distribution of moisture content tests were performed on six samples by slicing the specimen along a vertical profile at the end of the test and measuring the gravimetric water content of each slice individually. For samples “RMA11” and “RMA12” an attempt was made to also measure the density of the sample. The testing conditions for the six samples are listed in Table 5-5.

Table 5-5 – Testing program for evaluating moisture distribution by slicing of specimens

Sample	Height (cm)	G-level	Flow Rate (mL/h)	Overburden*
RMA9	4	50	5	N/A
RMA10	4	50	5	N/A
RMA11	12	50	5	N/A
RMA12	12	50	5	N/A
RMA13	4	50	5	8
RMA14	4	50	5	8

*Overburden is represented by the soil height in centimeters required to obtain the same overburden pressure

The resulting gravimetric water contents for the tests are plotted in Figure 5.16. The repeat tests showed very good consistency in measured gravimetric water. All samples showed a decreasing gravimetric water content with increasing distance from the lower boundary. This showed that the transition zone for these testing conditions was actually larger than the sample, and that no zone of zero suction gradient had occurred in the samples. On the taller tested specimens it appears that the moisture contents had reached a uniform value at the top of the specimens, although the transition zone still covered the entire specimen. The measured gravimetric water content for the short specimens was noticeably higher than for the tall specimens. This is likely due to a difference in overall stress, and therefore density of the samples.

Samples “RMA13” and “RMA14” were tested with steel bearings on top of the samples with a mass equal to approximately eight centimeters of soil. This resulted in the four centimeter samples having a similar stress distribution as the bottom four centimeters of a 12 centimeter sample. The measured gravimetric water content of the four centimeter samples with overburden was found to be very close to that of the 12 centimeter samples with the exception of the lowest measured point. This confirms that stress and density has a significant effect on the results.

Dry density was obtained by dividing the oven dried soil mass by the volume of each slice. The slice volume was difficult to measure accurately and likely contributed to the scatter seen in results. The density results for “RMA11” and “RMA12” are plotted in Figure 5.17. The target dry density for these samples was 1.48 g/cc. One of the samples showed fairly consistent density measurements with density increasing from top to bottom. The second sample showed much more scatter in the density results. Both samples showed an overall increase in density from the as-compacted target density due to the stresses applied during centrifugation.

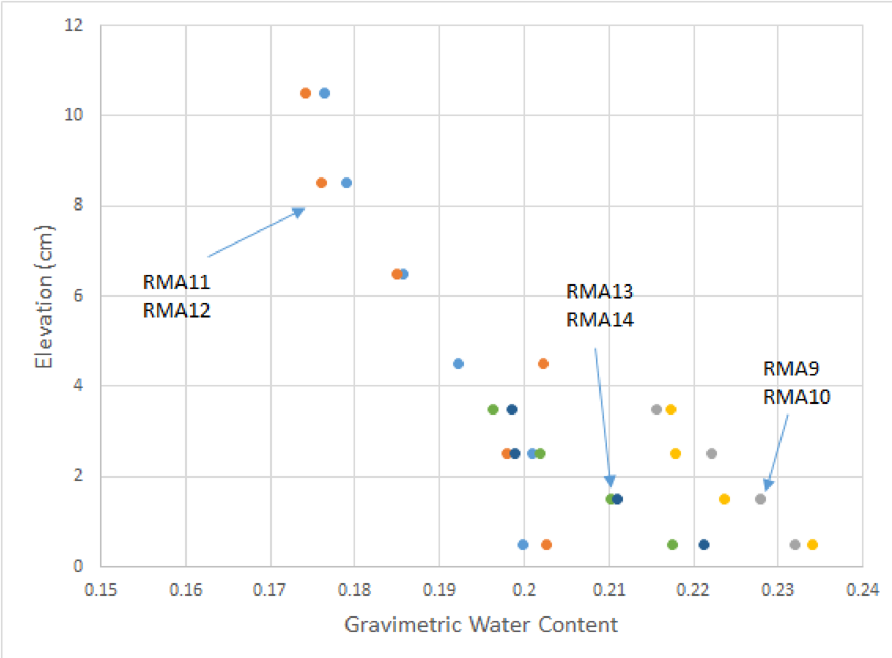

Figure 5.16 – Moisture content distribution from sliced specimens

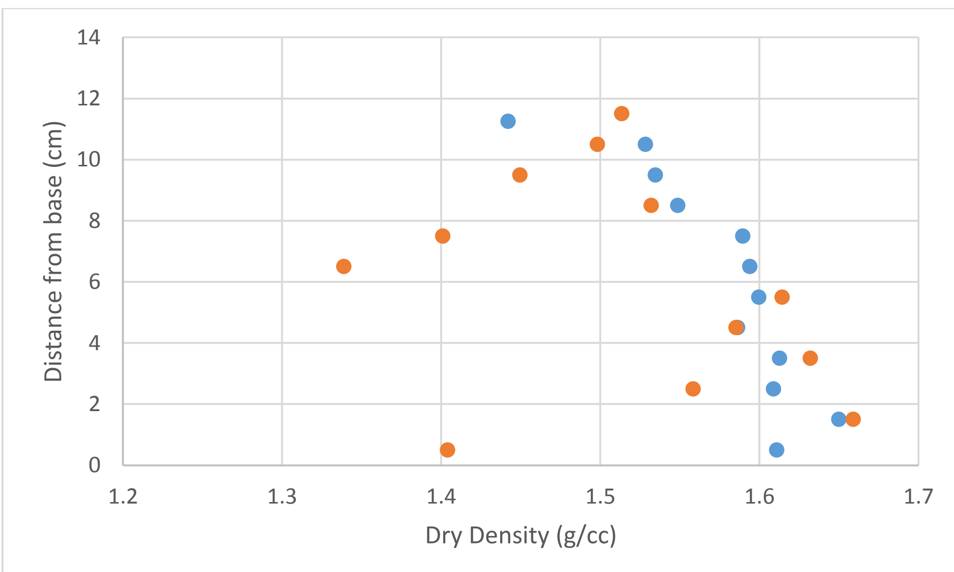

Figure 5.17 – Dry density distribtuion from two sliced specimens

5.4.6 Soil Water Retention Curve and K-function Determined from Series "I" Results

Series "I" involved a significant testing program conducted in order to evaluate the effectiveness of the CPUS centrifuge permeameter for the characterization of unsaturated soils. The primary goal was to characterize the water retention curve and K-function of the soil. This was accomplished by imposing a flow rate on the specimens and measuring the resulting volumetric water content and suction of the sample.

Using data generated in the Series "I" testing program, the K-function was populated using the target unsaturated hydraulic conductivity and the average volumetric water content of the sample determined using mass balance. Using the average volumetric water content was found to lead to inaccuracies because the transition zone between the lower boundary of the sample and the zero suction gradient zone affects the measurements. The transition zone is at a higher water content than the zero suction gradient zone leading to an over estimation of the water content in the zero suction gradient zone (which the target hydraulic conductivity is valid for). This effect is most pronounced for low g-levels and flow rates. The resulting K-function populated using data from thirteen samples tested in Series "I" at a combined 90 flow rates is shown as Figure 5.18.

The Mualem-van Genuchten (van Genuchten 1980) prediction of the K-function based on the soil water retention curve and saturated hydraulic conductivity is included in the plot for reference. Overall the measured data from the centrifuge matches well with the curve predicted by Mualem-van Genuchten. At high hydraulic conductivities the measured data is at a lower volumetric water content than the predicted curve. As the flow rates are reduced the measured data crosses over the predicted relationship and ends up with higher volumetric water contents. These higher values are also in the area (low flow rate) where the average water content by mass balance would over predict the volumetric water content of the zero suction gradient zone, so it is probable that the measured centrifuge data would fall below the Mualem-van Genuchten prediction for the entire curve if an accurate water content in the zero suction gradient zone was used.

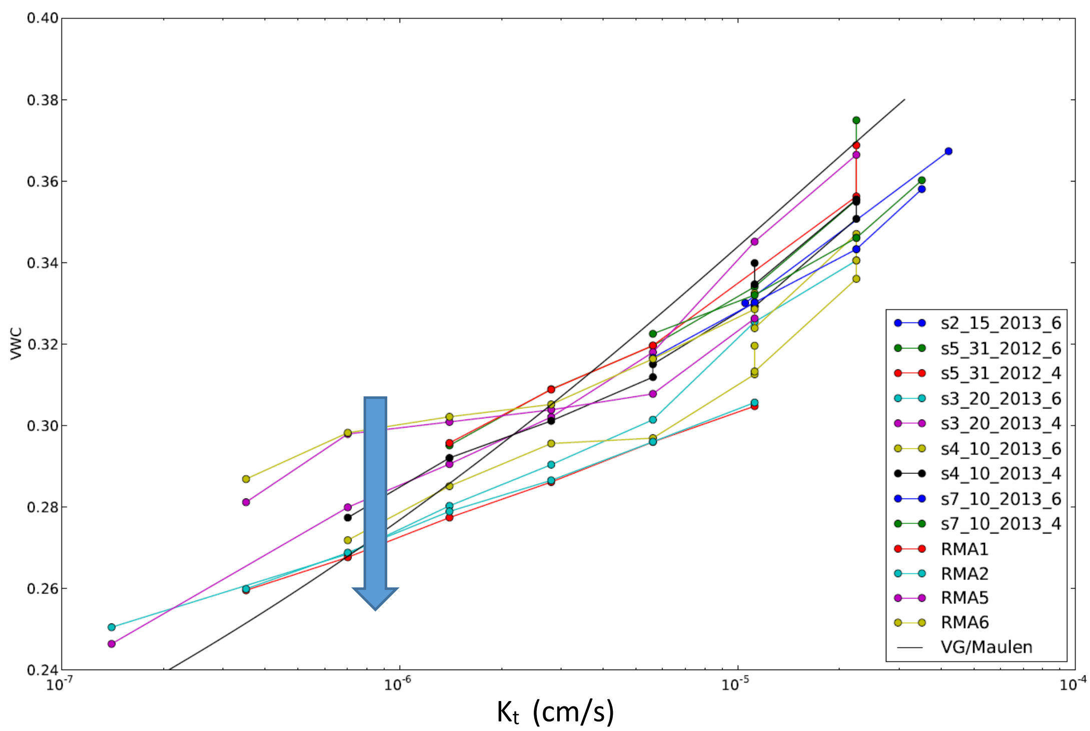

Figure 5.18 – K-function results from centrifuge testing

The soil water retention curve was populated by using the average volumetric water content measured by mass balance and the MPS-2 suction data and is shown in Figure 5.19. Soil water retention curve data from conventional testing method is included for reference. The majority of conventional SWRC results were conducted using hanging column and pressure plate devices. A few points were determined by relative humidity methods and are included (note: relative humidity methods may include an osmotic component of suction whereas the other results are based only on matric suction). The SWRC results were conducted at relative compactions ranging from 75% to 100%. Several observations can be made regarding the SWRC determined from Series “I” results:

- The majority of Series “I” results fall in between the conventional curves measured at 75% and 100% relative compaction. The centrifuge samples were prepared at

80% relative compaction but additional densification likely occurred during centrifugation.

- The MPS-2 suction sensors have a minimum reading of 10 kPa. Data collected at or below 10 kPa is likely not accurate and would shift the wetter portion of the centrifuge data left.
- The volumetric water content is for the average of the whole sample. The suction sensor was located mid height. Depending on the distribution of moisture content this could result in the average being above or below the actual water content at mid height.

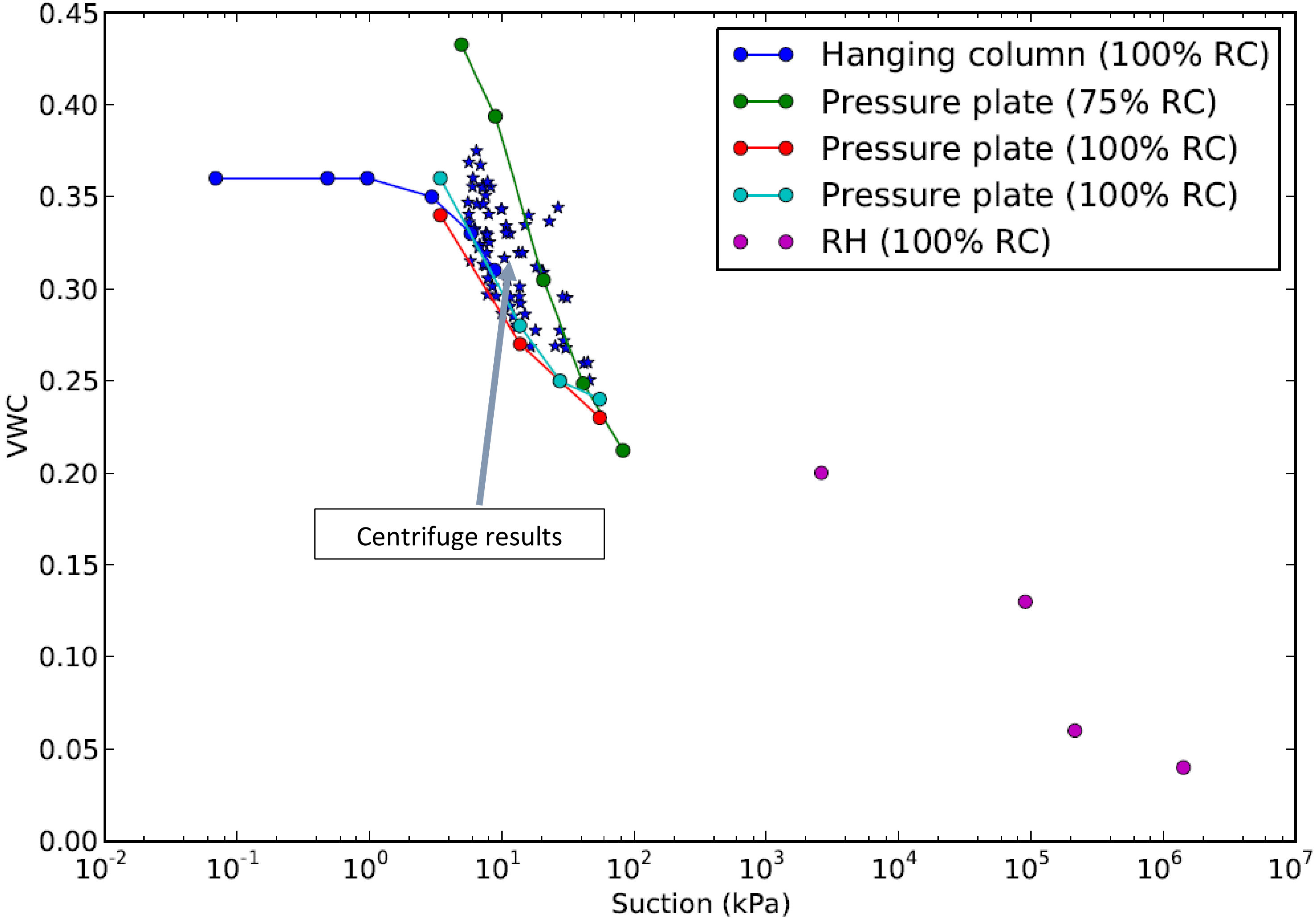

Figure 5.19 – SWRC data from entrifuge testing and standard methods

5.5 SOURCES OF ERROR

The unsaturated centrifuge flow tests conducted during Series "I" produced results that matched well with results from conventional methods. However, there were several aspects of the centrifuge testing procedure that led to inaccuracies. These fall into the three main categories of sensor accuracy, variable water content profiles, and variable density of samples. These sources are individually discussed in Sections 5.5.1-5.5.3.

5.5.1 Sensor Accuracy

In the Series "I" testing procedure, the EC-5 and MPS-2 sensor data was originally envisioned to provide the volumetric water content and suction values that were representative of the "zero suction gradient" zone. These results were expected to be combined with the imposed target hydraulic conductivity in order to define the soil water retention curve and k-function for soils tested in the centrifuge. Unfortunately, after performing the Series "I" testing program, it was determined that the various sensors were less accurate than desired for soil characterization.

Specifically, the EC-5 sensors used to measure volumetric water content were very sensitive to placement conditions and a general calibration relationship could not be defined with sufficient accuracy. Sample-specific calibrations were also attempted but it was ultimately determined that the accuracy accomplished was still not acceptable for a characterization test. Consequently, volumetric water contents were determined using mass balance methods rather than sensor data for analysis of the Series "I" testing program.

The MPS-2 sensors produced mixed suction results. The accuracy of the sensors was low and the minimum suction that could be measured was 10 kPa. This meant that a significant portion of the tests resulted in suctions that were outside the measureable range of the MPS-2 sensors. The MPS-2 data was still used in the instrumented testing as no other source of suction data was available.

In addition, both sensor types made uniform soil sample compaction difficult due to their large footprints. The sensors may also have affected flow results by blocking a portion of the cross-section of the soil samples. Finally, the inclusions of sensors made it extremely difficult to extrude and slice specimens in order to get accurate measurements of gravimetric water content and density along the profile of soil samples after testing.

Due to the problems associated with both types of sensors, it was determined that the testing procedure should be revised to not include sensors in the sample, but to rely on the more accurate, yet non-continuous direct measurement of gravimetric water content and density along the profile of the sample. These tests have been described in Section 5.4.5. Specifically, direct measurement was found to provide accurate information on the distribution of water content along the sample profile. This approach, however, does not capitalize on one of the main benefits of the centrifuge permeameter being used in this research project namely an in-flight data acquisition system. Accordingly, further research will be required into instrumentation setups that can accurately measure volumetric water content and suction in the centrifuge.

5.5.2 Size of Transition Zone

The experimental setup and testing procedures were designed with the assumption that there would be a large portion of the sample at a constant moisture content (i.e. the “zero suction gradient” zone). This assumption was based on previous research on unsaturated flow in centrifuges (Nimmo et al. 1987, Dell’Avanzi 2004, McCartney 2007). Moisture distributions in centrifuge samples from these research studies are included as Figure 5.20. All of the studies found that at increased g-level, the effect of the lower boundary was negligible and was only seen at the base of samples.

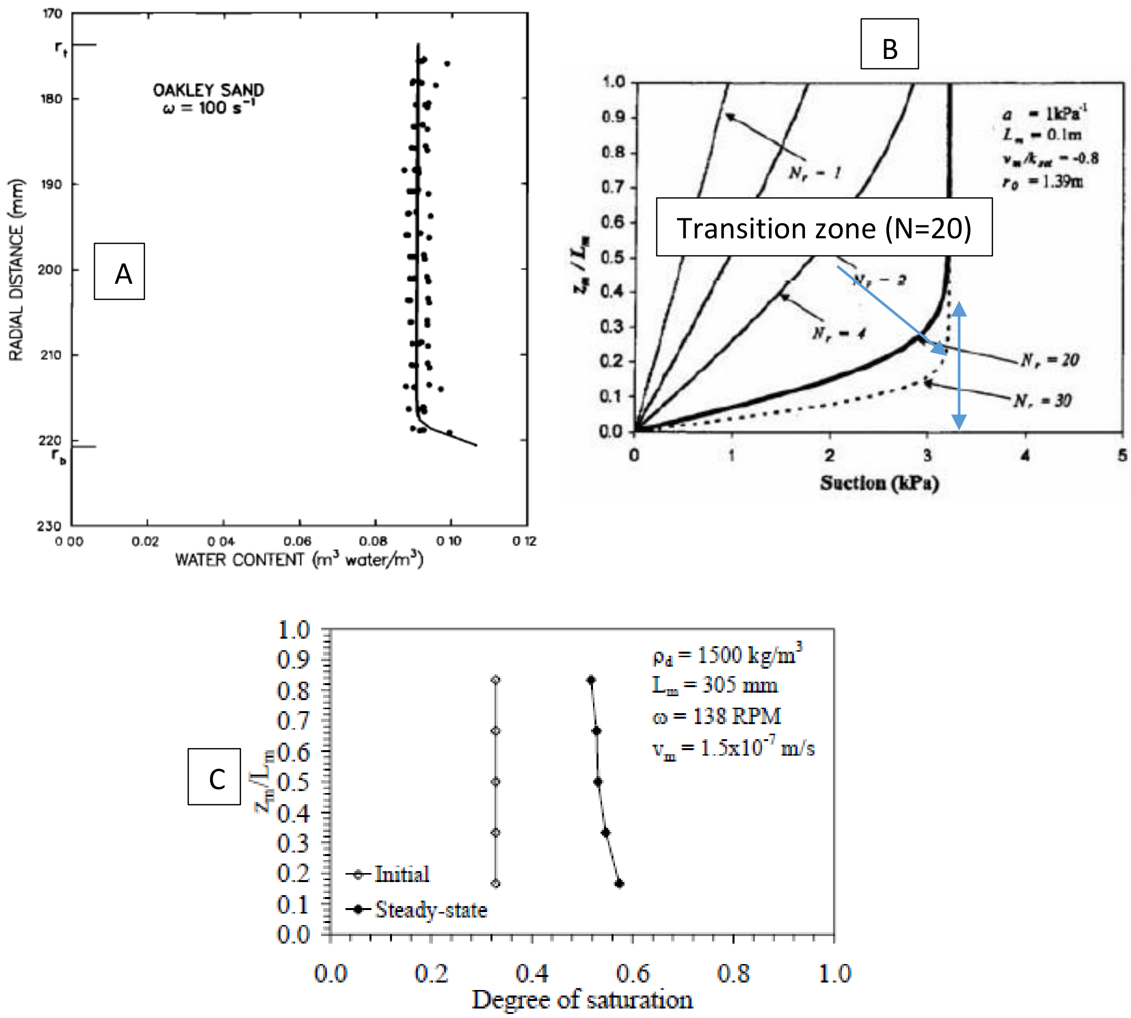

Figure 5.20 - Moisture distributions from previous research: a) Nimmo et al. (1987) b) Dell'Avanzi (2004) c) McCartney (2007)

Results from Series “I” testing showed that the transition zone in centrifuge soil samples was much larger than reported in previous studies. As a result, the experimental setup and testing procedure were adjusted in subsequent testing (Series “H” and “IF”) in order to account for the effects of the lower boundary. The reason for the difference in distributions of moisture content between those observed in this and previous testing studies could be explained as follows:

- Previous testing (McCartney 2007) and modeling (Dell'Avanzi et al. 2004) was conducted at relatively high flow rates. At these high flow rates the size of the transition zone is small because the equilibrium water content of the zero suction gradient zone is similar to that of the boundary condition.
- Testing conducted by Nimmo et al. (1987) was performed on a sand. Sands reach their residual water content at relatively low suctions resulting in much smaller transition zone. For soils (such as the low plasticity clay in this research study) that retain a significant amount of moisture at large suctions, the transition zone was found to be more significant.

5.5.3 Variability of Void Ratio

Previous testing by McCartney (2007) on a similar soil had shown that changes in sample height during centrifugation were small (generally less than 1mm on a 12 cm sample) and the resulting void ratio was effectively unchanged between compaction and the end of testing. The small changes in height were also observed in Series "I" testing of this research project, although it was initially assumed that the void ratio remained constant across the height of the centrifuge samples. Results were observed in testing Series "I" that suggested the void ratio was not uniform. Consequently, testing was performed in order to directly evaluate the void ratio distributions in samples by slicing samples at the end of testing.

It was found that the void ratio of samples decreased from the as-compacted state due to the high stresses experienced under centrifugation. The effect was highest at the base of specimens, which experienced the highest stress. The changes in void ratio that occurred in the samples were not captured through measurement of the total sample height because the density of the upper portion of the sample was found to decrease due to a slight expansion or relaxation. Dry density results from a pair of soil samples are shown in Figure 5.21. The top two specimens were found to have a significantly lower density (higher void ratio) than the as-compacted state.

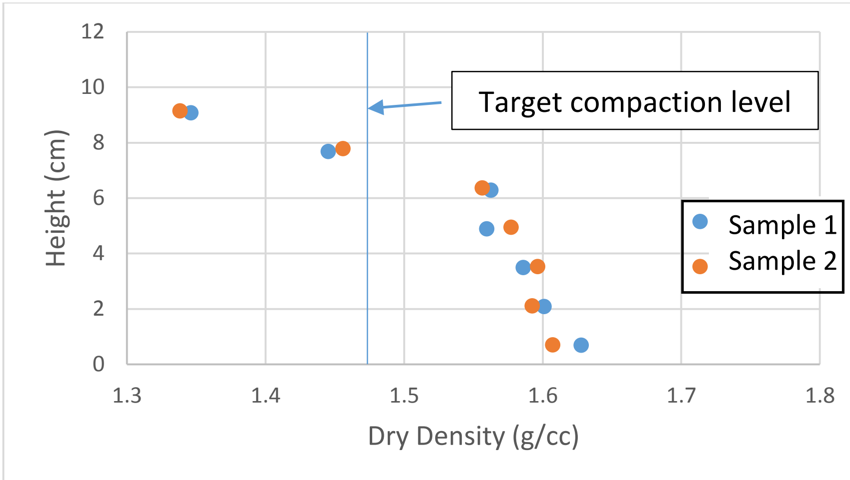

Figure 5.21 - Density distribution of centrifuge sample

The changes in void ratio of samples during centrifugation must be captured in order to accurately characterize unsaturated soil properties which should be defined under in-flight conditions. Accordingly, the testing procedure was modified for the subsequent tests in this investigation (Series “H” and “IF”) in order to directly measure the distribution of void ratio within samples.

5.6 Summary and Findings

A testing procedure, referred to as the instrumented procedure, was developed in order to measure the soil water retention curve and K-function of soils. The procedure relied on instrumentation for the in-flight measurement of volumetric water content and suction. Flow rates were imposed on the surface of centrifuge samples and the distribution of suction and moisture were determined after reaching steady state flow conditions.

During Series “I” testing (which was conducted using the instrumented procedure), some difficulties were encountered with the instrumentation. The suction sensors (MPS-2) were found not to provide reliable measurements below approximately 10 kPa. Yet, suctions below this limit were reached in flow tests conducted at target hydraulic conductivities above approximately $3x10^{-5}$ cm/s (corresponded to volumetric water contents above 30%). As a result, the effective range of the testing setup was limited to hydraulic conductivities and volumetric water contents below these values.

The observed accuracy of the EC-5 sensors was found to be approximately +/- 4%. This range in error was larger than the manufacturer rated accuracy of +/- 2% for soil-specific calibration. Accordingly, the accuracy of the EC-5 sensors was found to be insufficient for measuring changes in volumetric water content in this study. The change in volumetric water content of the soil between subsequent flow rates imposed in the testing procedure was on the order of 1-2%. This change is smaller than the accuracy of the sensors. As a result, the inherent variability of the moisture sensor dominated the readings rather than the actual changes in VWC of the soil due to changes in imposed flow rates.

In addition to issues with instrumentation, several assumptions of the testing procedure were found to lead to inaccuracies in results. The first assumption was that the effects of the lower boundary condition were negligible. However, it was found that the portion of soil samples affected by the lower boundary was significant. In extreme cases, the entire sample was found to be affected by the lower boundary. The procedure for predicting the hydraulic conductivity of soil samples in Series “I” testing assumed the lower boundary did not affect the moisture and suction in the upper portion of the sample. As a result, a change in procedure was implemented in Series “H” and “IF” testing in order to account for the effects of the lower boundary in the sample.

The density of soil samples was also found to vary significantly across the sample profile (from 1.3 to 1.6 g/cc). The highest density was measured at the base of samples where the greatest stresses occurred. The density was not measured in the majority of samples tested during the Series “I” (instrumented) testing program. Therefore, the unsaturated soil properties from this series can only be associated to a range in density.

Even with the sources of inaccuracy summarized above, the soil water retention curve measured during the instrumented testing series was found to match well with the results obtained from conventional testing procedures (conducted for similar ranges of density as those found to have occurred in centrifuge tests). Also, the K-function determined during instrumented testing was found to match trends expected for unsaturated hydraulic conductivity and showed a high degree of repeatability.

6 IMPROVEMENTS TO CENTRIFUGE EQUIPMENT

Several significant improvements were made to the centrifuge testing setup in order to address the sources of inaccuracy that were identified during Series "I" testing. The most significant change was to be able to accurately measure the void ratio distribution with height in samples after testing. In order to facilitate the accurate measurement of void ratio, the embedded sensors were removed from the sample. In addition, an improved chamber to measure outflow was implemented. Finally, the lower boundary condition of the sample was imposed, by fixing it at zero suction by using a ceramic disc. These changes are discussed thoroughly in the following sections.

6.1 SPLIT TUBE SAMPLER

The centrifuge testing environment was modified to incorporate a "split tube" sampler. This setup allowed the sample to be accurately cut into slices of a known volume, resulting in the added ability to accurately measure density and void ratio of samples with height. In order to incorporate the split tube sampler in the centrifuge without machining entirely new cups, the sample size was decreased slightly to allow rings to be placed inside the centrifuge cups. The inside diameter of the centrifuge cups was 2.75" and the addition of the rings inside reduced the sample diameter to 2.5".

In order to hold the rings in place while samples were compacted, a top cap was designed with an inside diameter of 2.5". The top cap was screwed down onto the rings holding them in place. Overall, eight rings (approximately 0.55" each in height) were used in each cup. The setup is illustrated in Figure 6.1 along with a photo of the plastic rings.

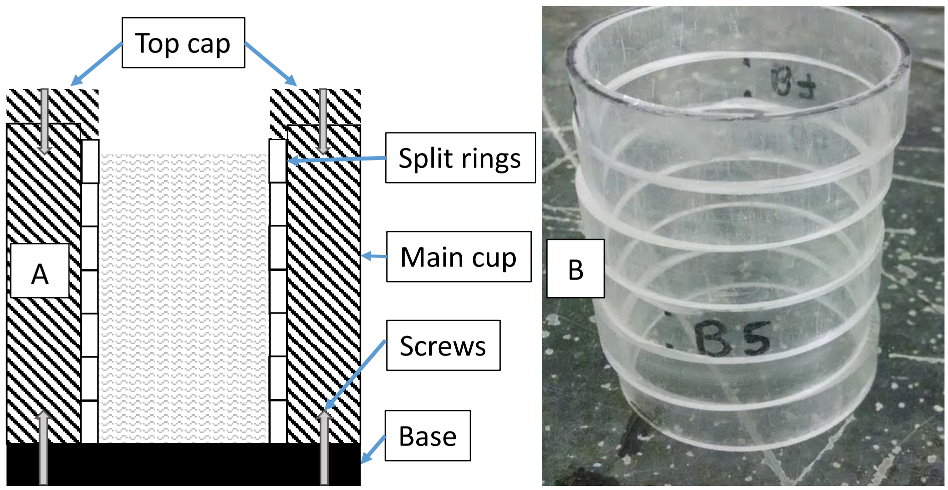

Figure 6.1 - Split ring setup a) Setup b) Rings

In future studies, it may be advantageous to machine the rings out of aluminum rather than acrylic plastic. This would allow the samples to be sliced and then oven dried in the rings rather than extruding the slice from each ring. The extrusion of soil from the rings is currently necessary as the acrylic rings cannot be oven dried without damaging the rings.

The procedure for slicing specimens is discussed in detail in Section 7.1.3. It involves using a wire saw to cut the soil in between each ring and has been found to produce highly consistent measurements of density and void ratio. Typical measured density from two samples using the split tube sampler are included as Figure 6.2. The variation in measured density between the samples was low (<0.1 g/cc).

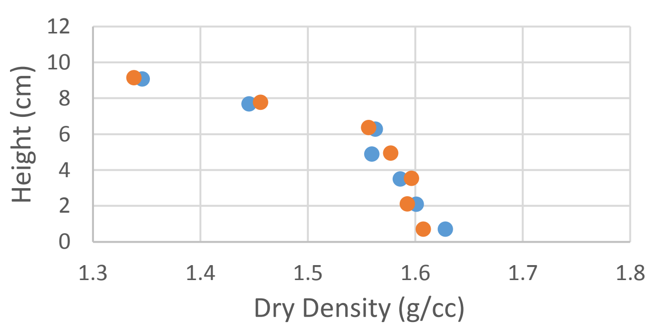

Figure 6.2 - Measured density for two samples using split tube setup

6.2 Lower Boundary Condition

The centrifuge permeameter cup base was redesigned in order to change the outflow boundary condition from a freely draining (open flow) to a constant suction condition. During Series “H” and “IF” testing, the suction at the base of the sample was held at zero suction. The design allows for higher suctions to be applied at the base if a vacuum pump is installed in the outflow chamber.

The zero suction boundary was imposed at the base of the sample by using a ceramic disc and a spillover port located at the same elevation as the center of the ceramic disc. The characteristics of the spillover port design can be seen in Figure 6.3. The sample is in direct contact with the saturated ceramic disc. Any outflow from the sample travels through the ceramic disc and enters a port in the permeameter base labeled “Inflow port from ceramic disc base” in Figure 6.3. The flow is routed out and around the ceramic disc to the spillover port. The volume between the ceramic disc and the spillover port remains filled with water regardless of the flow rate or lack of flow. This keeps zero hydraulic head in the ceramic disc when the center of the disc is taken as the datum. The spillover valve is located at mid-height of the ceramic disc and the air around the spillover port is at atmospheric pressure. Once water exits the spillover port, it is routed to the outflow chamber for outflow rate to be measured using a pressure transducer. Two O-rings are used to route water from the sample through the ceramic disc and capture it in the outflow chamber.

The zero suction base was added to impose a precise boundary condition. The boundary condition used in Series “I” testing and in previous research was “free draining”. Free draining boundaries generally result in a zero suction boundary condition but depending on the material used directly below to support the sample some suction may develop. The new design also has the advantage that in future research projects it will be possible to apply suctions to the base of the sample by decreasing the air pressure at the spillover port. This can be accomplished by reducing the air pressure in the outflow chamber by vacuum pump or similar method.

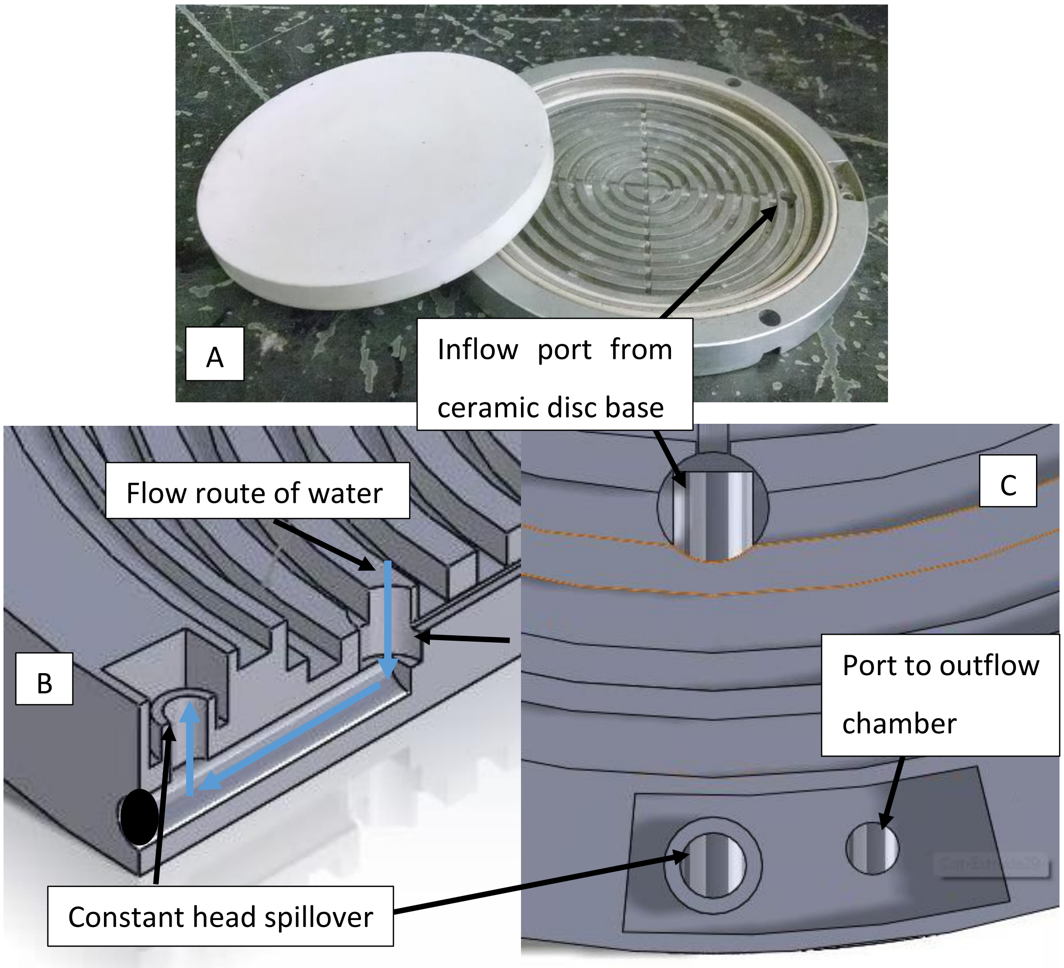

Figure 6.3 - New base for permeameter cup: a) Photo b) Cross-section view c) Top down view

6.3 OUTFLOW CHAMBER

The previous outflow chamber used in the CPUS centrifuge prior to this research project was found to be unreliable for measuring the low flow rates of interest in this study. As all sensors within the sample were removed in Series "H" and "IF" tests in order to accurately measure void ratio, the outflow chamber became very important as it became the only way to determine when the samples reach steady state conditions during centrifugation.

The previous outflow chamber had a large volume chamber with a pressure transducer at the base in order to measure the water pressure at the base of the chamber. The measured pressure could be used to determine the height of water in the chamber and therefore the volume of outflow. The time history of changes in volume in the outflow chamber was used to determine the outflow rate.

The major issue with the previous chamber was that the area was comparatively large, meaning that large outflow volumes were required for a small change in water height (and therefore pressure reading from the transducer). However, the area of the chamber could not simple be reduced to allow more expeditious filling of the chamber because reduced outflow volume would not allow conducting tests of long duration. To solve these issues two modifications were implemented.

First, inserts were developed in order to adjust the area of the outflow chamber. This allows the chamber to have an adjustable volume to target different ranges of flow rates accurately. If a high flow test is being conducted, then a large chamber volume could be used, while a lower chamber volume could be adopted if a low flow rate test is being conducted. The second modification was the inclusion of an electronically controlled solenoid valve, which allows the chamber to be emptied during centrifuge tests. As a result, a relatively low-volume outflow chamber can be used (resulting in high-accuracy readings) without compromising its use in long tests when the outflow chamber could fill up.

The data acquisition system of the CPUS centrifuge did not include the capabilities required for the control of the solenoid. Therefore, an additional control system was designed and included in the centrifuge. A photograph of the system and revised setup is shown in Figure 6.4.

Results from two tests, conducted using influx rates of 10 mL/h and 160 mL/h, are shown in Figure 6.5 and Figure 6.6 respectively. Outflow volume readings from the test conducted with an influx rate of 10 mL/h show some scatter. The main cause of this scatter is small fluctuations in g-level of the centrifuge. When the derivative is taken of outflow volume in order to calculate outflow rate, these small fluctuations result in significant scatter. The pressure readings were subsequently adjusted to correct the outflow rate for fluctuations in g-level, resulting in a significantly lower scatter. This can be seen in Figure 6.5 where the uncorrected flow rate ranged from approximately 0 to 20 mL/h. Once the fluctuations in g-level (red line) were accounted for the scatter is reduced to a range of approximately 7 to 10 mL/h. The accuracy could also be increased by reducing the volume of the outflow chamber so that the same flow rate results in a larger increase in water height and corresponding pressure for the outflow transducer.

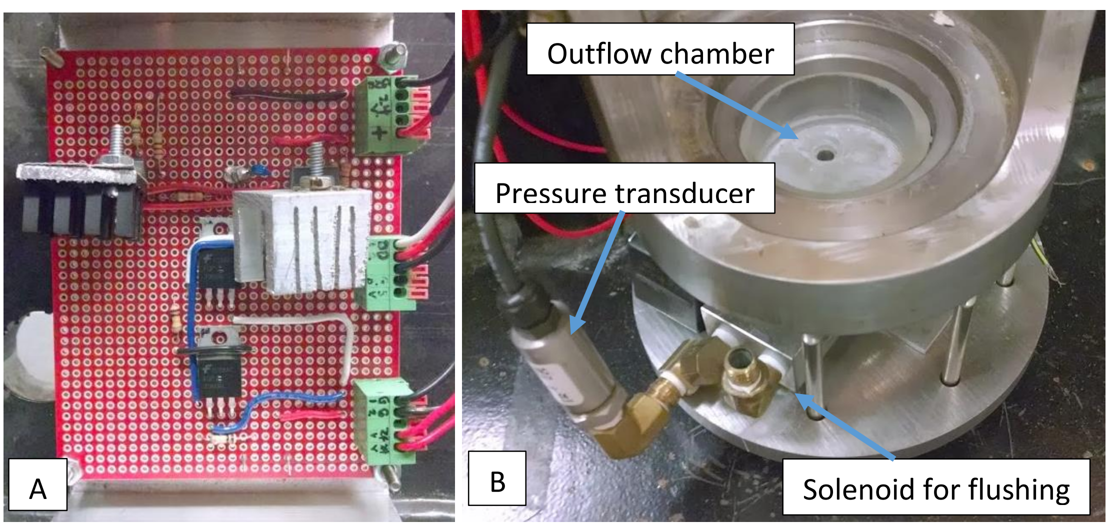

Figure 6.4 - Revised outflow system: a) Control system b) Outflow chamber

The test conducted at 160 mL/h (Figure 6.6) showed much less scatter in the results. The corrected and uncorrected flow rates were both smooth with a range in flow rates of approximately 130 to 150 mL/h. The outflow chamber for Sample 2 reached its full state and the solenoid was opened during the test. The large drop in outflow volume observed in Figure 6.6 corresponds to the volume released by the solenoid.

Some leakage from the outflow chambers was identified, which resulted in lower measured flow rates in the outflow chamber than the rates imposed on the top of the specimens. The flow connections of the outflow chamber were re-sealed in order to reduce leakage. This process is occasionally required in order to reduce leakage.

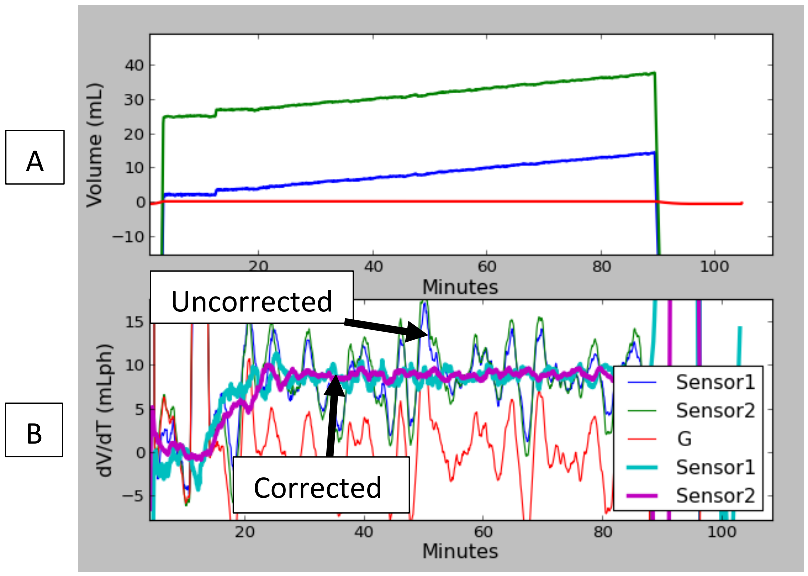

Figure 6.5 - Outflow chamber readout, 10 mL/h inflow: a) volume, b) flow rate

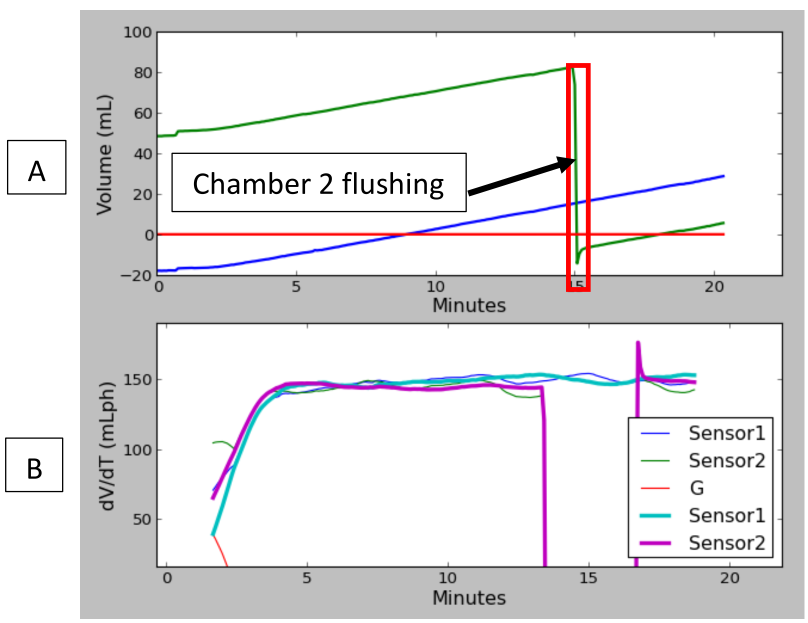

Figure 6.6 - Outflow chamber readout, 160 mL/h infow: a) volume, b) flow rate

7 Testing Series "H": Hydrostatic Procedure

The second series of tests conducted in this research project (Series "H") were completed in order to measure the relationship between void ratio, suction, and volumetric water content the RMA soil. The procedure is referred to as the *Hydrostatic* procedure as it involves allowing a centrifuge sample to reach equilibrium under hydrostatic conditions. Once hydrostatic condition is reached (verified by no outflow from the sample) tests in this series are terminated and the distribution of density and volumetric water content in the sample are measured by slicing the sample and oven drying the specimens.

Each slice results in a direct measurement of gravimetric water content and dry density. These are used to calculate the volumetric water content and void ratio of each slice of the soil sample. The base of the centrifuge testing setup was designed to impose a zero suction boundary at the bottom of centrifuge samples. Due to the sample being at hydrostatic conditions and the base of the sample being a zero suction datum, the suction can be calculated at the center of each slice. This results in a value of VWC, void ratio, and suction for each slice of the sample. These three parameters form a unique relationship referred to as the *soil water retention surface* (SWRS).

7.1 Testing Procedure

A wide range of both suction and void ratio would ideally be measured in order to define a large portion of the SWRS. However, void ratio is difficult to target directly as it is a result of both the initial compaction conditions and the imposed g-level. Increasing g-level resulted in increasing stresses in the centrifuge samples resulting in lower void ratios. Three baseline testing conditions were adopted, which allowed a wide range of both suction and void ratio values to be achieved. These conditions were as follows:

- G-level of 100, sample compacted to 90% relative compaction. This combination resulted in the highest range in suction and a relatively constant (comparatively low) void ratio in the sample.
- G-level of 100, sample compacted to 80% relative compaction. This combination resulted in the highest range in suction and a wide range of void ratios. The void ratio was found to consistently decrease from the top of the sample to its base.
- G-level of 50, sample compacted to 80% relative compaction. This combination resulted in lower ranges in suction and a relatively constant (comparatively high) void ratio throughout the sample.

Resulting distributions of suction and void ratio for the three testing conditions are included in Figure 7.1. When RMA soil samples were tested at all three conditions, it allowed the SWRS to be defined for suction values ranging from approximately 0 to 100 kPa and for void ratios ranging from 0.65 to 1.0. Two samples were simultaneously tested in the centrifuge for each spin. Initially, the two samples were repeat tests. In later testing, the second sample was usually tested at a different density or compaction moisture condition.

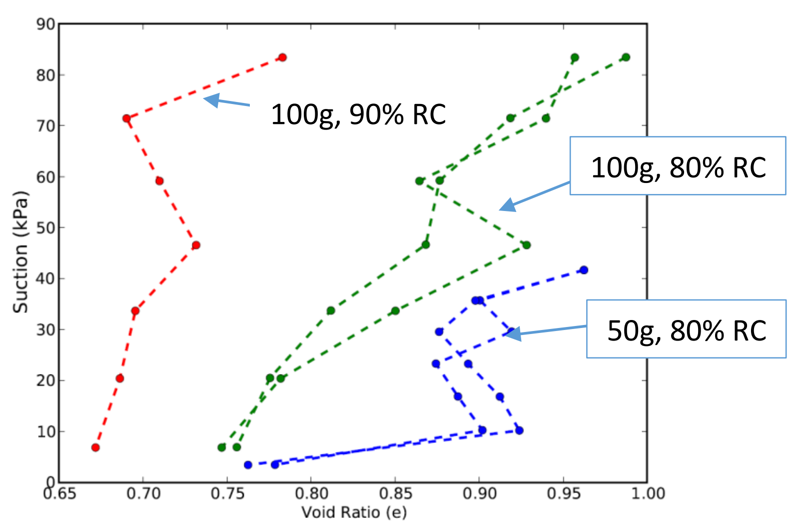

Figure 7.1 – Baseline ranges for suction and void ratio for three testing conditions

7.1.1 Sample Preparation

Soil processing – Soil was spread loosely and air dried at room temperature. After several days the soil was processed using a crusher and sieved using a #10 sieve. Water content of the sieved soil was measured and water was added as needed to bring the soil to the target water content. Testing was conducted on samples compacted at gravimetric water contents of 7.5%, 14.5% and 21.5%. Once the additional water was mixed into the soil it was allowed to rest in a sealed container for at least 48 hours in order to allow uniform moisture distribution.

Compaction – Samples were compacted using 0.5 inch (1.27 cm) lifts using kneading compaction. Generally, eight total compaction lifts were completed for a total sample height of 4 inches (10.16 cm). In some select cases, samples were compacted using a smaller number of lifts resulting in shorter samples. Samples were compacted either to 80% or 90% relative compaction (in relation to standard proctor). The compaction process was as follows:

1. Assemble the centrifuge cup by inserting the ceramic disc in between the base and the main centrifuge cup. Screw the base to the centrifuge cup. Insert the individual rings of the split tube sampler into the centrifuge cup. Place the top cap on the centrifuge cup and screw into place. Place a filter paper on top of the ceramic disc.
2. Calculate the mass of wet soil required for the lift volume based on previously measured gravimetric water content and target void ratio.
3. Measure the mass of the assembled permeameter cup and initial height prior to adding soil for the compaction lift. The initial height should be measured using a mounted caliper and seating dish. The seating dish provides a larger area of measurement so that the measurement is an average of the high points of the area.

4. Loosely place the target mass of soil in the testing cup. Using the small kneading compaction head, begin compacting the soil using a pattern that evenly distributes kneading blows to the sample. A larger kneading compaction head may be used afterwards in order to provide a more even compaction surface for the lift.
5. Measure the achieved height. Iterate between additional kneading compaction (using either the large or small kneading head) and measurement of height until the target height has been reached. The height was deemed acceptable if it was within 0.25 mm of the target (although in select cases a higher error was allowed).
6. Record the total mass of the cup and height of the sample at the end of each compaction lift.
7. Repeat the compaction process for each layer until reaching the target height. Place a filter paper on the surface of the specimen.

The centrifuge required two samples to be tested at once in order to remain balanced. Therefore, two samples were always prepared for simultaneous testing. The two samples were not always prepared at the same compaction conditions (relative compaction or water content).

Later tests used a slightly changed compaction procedure, where half of the soil for the 0.5” layer was inserted into the cup and pressed down with the ¼” kneading compaction rod. The rest of the soil was then compacted on top to the target height. It was found that this method resulted in a more evenly distributed compaction throughout the layer. This method essentially compacted the sample using lifts 0.25” tall. However, the intermediate height was not measured or recorded. Measured relative compaction for samples compacted at 7.5% GWC are shown in Figure 7.2 and the accuracy and scatter is typical of the various compaction conditions used in this testing program.

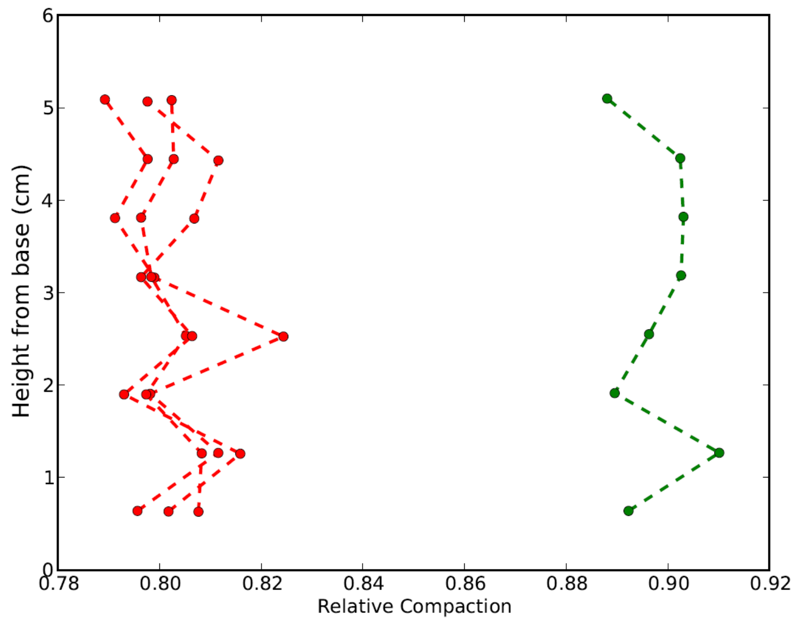

Figure 7.2 - Typical layer compactions (Red – 80% RC target, Green- 90% RC target)

7.1.2 Centrifugation

After both samples were compacted to their target initial conditions they were placed into the centrifuge testing environment. The data acquisition system was initiated and the centrifuge set to the target g-level. The initial water content of the samples was generally well below that corresponding to hydrostatic conditions and the reservoir below the samples was found not to contain enough water to fully wet the samples to their hydrostatic conditions. Therefore, a low flow rate was initially applied to the samples in order to introduce enough water to reach hydrostatic conditions. An illustration of the progression of equilibrium moisture contents in a hydrostatic sample is shown in Figure 7.3. The initial moisture condition is at a low water content relative to hydrostatic conditions. An imposed flow rate is used to wet the sample to steady state conditions. The flow rate is then removed and the sample is then allowed to dry down to hydrostatic conditions. The wetting flow rate was selected based on the target g-level with 20 mL/h at 50g being the baseline conditions. The rates for each G-level used in the testing program are listed in Table 7-1.

Table 7-1 - Wetting front rates

G-Level	Wetting Flow Rate (mL/h)
25	10
50	20
100	40

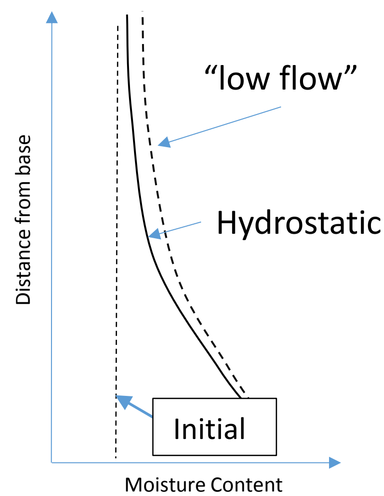

Figure 7.3 - Moisture distribution in hydrostatic sample at different stages

The imposed wetting flow rate was stopped once outflow was registered in the outflow chamber. The samples were then spun for a minimum of 12 hours with no inflow, in order for the samples to dry and reach hydrostatic conditions. Outflow results from a test completed at 100g are shown in Figure 7.4. The pumps were started five minutes into the test. At approximately 45 minutes into the test, outflow was recorded in the chambers of both soil samples. The flow rate was continued for an additional 15 minutes and then the pumps were stopped around 70 minutes into the test. Outflow continued to be recorded after the pumps were stopped, signifying the drying of the sample from the steady state flow condition achieved under the imposed low flow to the hydrostatic conditions. The outflow chamber of the second sample was not properly sealed during testing and showed decreasing total volume due to leakage. No significant outflow was recorded after 500 minutes of testing but centrifugation was continued past 1500 minutes. The centrifuge was then stopped and samples were removed. The final mass and height of the cups were recorded.

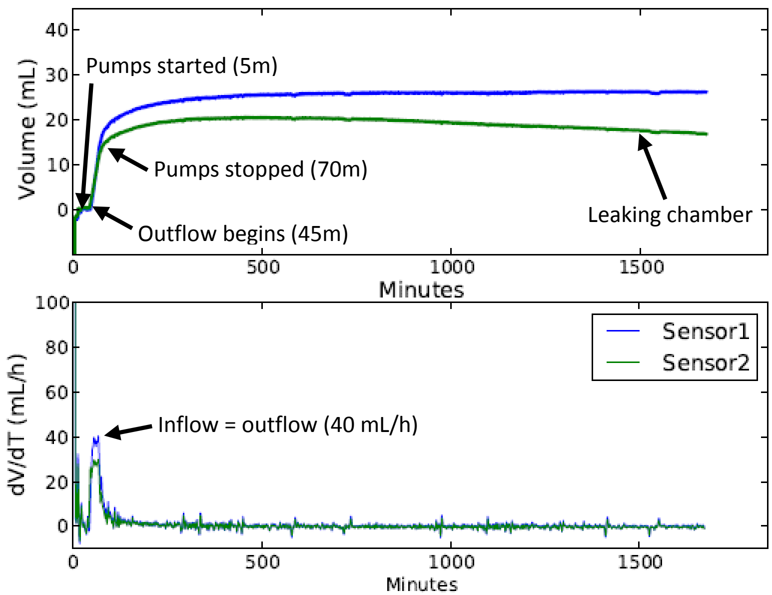

Figure 7.4 - Outflow for hydrostatic test (100g)

7.1.3 Measurement of Water Content and Void Ratio

After centrifugation, the base and top of the centrifuge cup were removed allowing the rings from the split tube sampler to be accessed. The split tube sampler was placed top down onto a metal disc. A plastic disc was also placed on top of the sample in order to maintain some pressure on the soil while slicing the sample. Slicing between the rings was conducted using a wire that was slowly slid between the rings. The rings were often held tightly together and it was difficult to insert the wire in between the rings. In these cases a small flat head screwdriver was used to pry the rings apart a small amount at a location in the rings that was notched in order for the screwdriver to fit in. Photos from the process are included in Figure 7.5.

The height of each specimen was then measured using a mounted caliper (Figure 7.6). This allowed determination of the volume of the specimen as the area of each ring was known. The known volume of the ring was used as a secondary value for the volume of each slice. The top ring of the sample was usually only filled partially with soil. In this case, only the height measured by caliper was used. However, the top slice generally had an irregular surface and measurements of height and volume were often inaccurate. Therefore, the top partially filled ring of the sample was generally neglected from analysis.

Figure 7.5 - Slicing of centrifuge sample

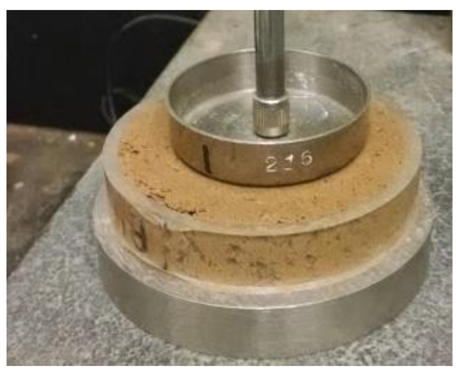

Figure 7.6 - Measurement of slice height

Specimens were then oven dried in order to determine the gravimetric water content and dry density of soil from each ring. These values were then used to calculate the volumetric water content and void ratio of each slice. Typical results from two hydrostatic tests performed at optimum compaction condition are shown in Figure 7.7. The test conducted at 100g resulted in lower water contents near the top of the specimen due to the higher suction reached in the 100g test. The 50g test resulted in slightly lower water contents at the base because of the higher void ratios resulting from comparatively lower stresses.

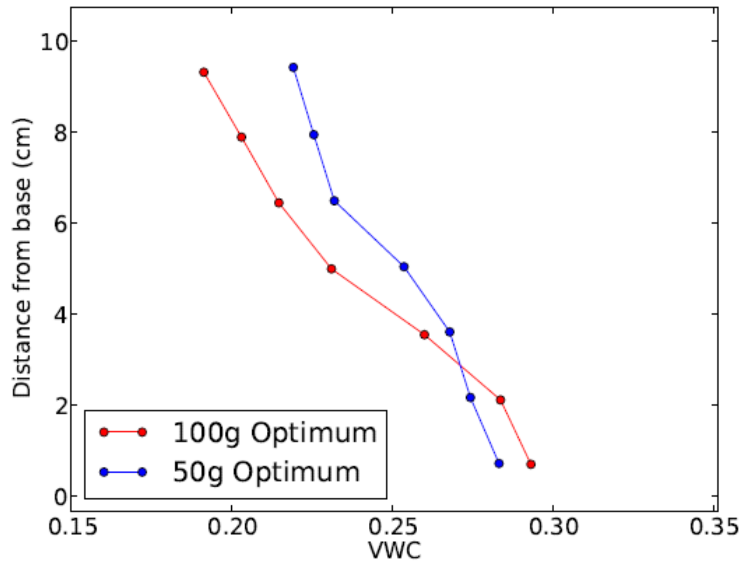

Figure 7.7 - Typical results from two hydrostatic tests

7.1.4 Determination of Suctions for Hydrostatic Conditions

The suction at the middle of a slice is calculated for hydrostatic conditions understanding that the fluid potential does not change throughout the specimen (no flow is occurring). The fluid potential in the centrifuge at an elevation z from the base of the sample is calculated as:

$$\phi(z) = -\frac{1}{2}\omega^2({r_0}^2 - (r_0 - z)^2) - \frac{P(z)}{\rho_w} \tag{23}$$

where ϕ is the fluid potential, ω is the rotational velocity of the centrifuge, $r_0$is the centrifuge radius at the base of the specimen, z is the distance to the point of interest from the base of the sample, $P(z)$ is the pressure at the location z, and ρ_w is the density of water.

The center of the ceramic disc in the base of the centrifuge cup (which should be held at zero suction) is used as the datum in Equation (23). This results in a fluid potential at the base of the sample equal to zero. Due to hydrostatic (no flow) condition the fluid potential does not change across the sample and the suction at a distance z from the base can be calculated as:

$$\psi(z) = \frac{1}{2}\omega^2({r_0}^2 - (r_0 - z)^2)\rho_w \tag{24}$$

where $\psi(z)$ is the suction in the sample (equal to –P(z)).

The calculated suction profiles for 12 centimeter samples under hydrostatic conditions, tested at g-levels of 25, 50, and 100 are plotted in Figure 7.8. The benefits of increased g-level are seen with a maximum suction of slightly over 100 kPa reached at the top of centrifuge samples tested at 100g. However, testing under high g-levels also leads to increased stress and density in samples, so this was considered when defining the scope of the testing program.

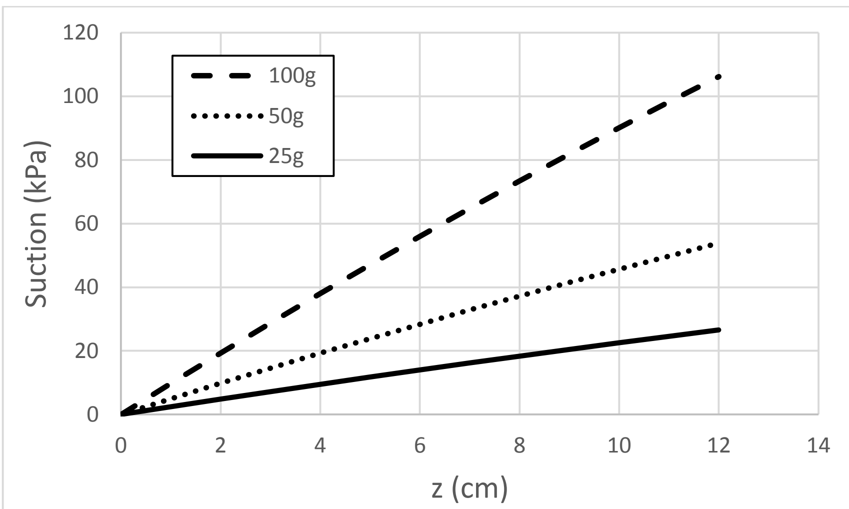

Figure 7.8 - Hydrostatic Suction Profiles

7.2 Scope of Testing Program

In total 29 soil samples were tested as part of the Series "H" testing program. These tests were completed using the hydrostatic procedure and are is listed in Table 7-2. The goals of the testing program were as follows:

- Verify the scaling of suction in the centrifuge with g-level;

- Evaluate the effects of void ratio on the SWRC;
- Evaluate the effects of compaction moisture content on the SWRS;
- Investigate hysteresis in the RMA soil using centrifuge testing.

The results of the testing program are discussed in the following sections.

Table 7-2 - Hydrostatic testing program

Sample	G-level	Compaction Moisture	Relative Compaction	Wetting Flow Rate (mL/h)
RMA41	100	Dry	80%	40
RMA42	100	Dry	80%	40
RMA47	25	Dry	80%	10
RMA48	25	Dry	80%	10
RMA57	50	Dry	80%	20
RMA58	50	Dry	80%	20
RMA76	100	Dry	90%	40
RMA33	25	Optimum	80%	10
RMA35	50	Optimum	80%	20
RMA36	50	Optimum	80%	20
RMA39	100	Optimum	80%	40
RMA40	100	Optimum	80%	40
RMA43	50	Optimum	80%	80
RMA44	50	Optimum	80%	80
RMA45	50	Optimum	80%	5
RMA46	50	Optimum	80%	5
RMA63	100	Optimum	90%	40
RMA64	100	Optimum	90%	40
RMA69	50	Optimum	80%	20
RMA70	50	Optimum	80%	20
RMA75	100	Optimum	90%	40
RMA101	100	Optimum	80%	40
RMA102	100	Optimum	80%	40
RMA59	50	Wet	80%	20
RMA60	50	Wet	80%	20
RMA61	100	Wet	80%	40
RMA62	100	Wet	90%	40
RMA77	100	Wet	80%	40
RMA78	100	Wet	90%	40

7.3 Results from Series "H" Testing Program

The Series "H" (hydrostatic testing) program covered a wide range of testing conditions in order to achieve a wide range of suction and void ratio values. The three main soil properties of interest in the hydrostatic testing are the suction, volumetric water content, and void ratio. These three variables should define a continuous surface. Displaying three variable data sets and 3D surfaces effectively is difficult on a non-interactive 2D medium. Therefore, methods were explored to display the three variable data on traditional 2D graphs. These visualization methods will be briefly discussed followed by methods for fitting 3D surfaces to the hydrostatic results. Detailed analysis of Series "H" testing is presented in Chapter 9.

7.3.1 Visualization methods

One of the main visualization methods used in this dissertation is to color code points on scatter plots so that the 3rd variable corresponds to the color of the point. When the effects of changes in void ratio were of interest, it was found that using void ratio on the x-axis, volumetric water content on the y-axis, and suction as the color coded z-axis was most effective. This plot is similar in layout to those used to display compaction data (e.g. proctor curves) but the x and y axis have been switched. In the hydrostatic testing procedure the void ratio is controlled by g-level and compaction and the water content a result thereof so having the independent variable (void ratio) on the x-axis is convenient for presentation of results involving hydrostatic tests. Data from select hydrostatic tests, plotted using this method, are shown in Figure 7.9a.

It was found to be helpful to add contours on the plots to represent trends in the suction (z-axis) data. This was done manually and is included in Figure 7.9b although fitting algorithms were generally used to automatically calculate these contours in later sections.

A second visualization method also using the color coding methods was to plot suction on the x-axis, volumetric water content on the y-axis, and void ratio as the color coded z-axis. This was particularly useful as the graphical setup was similar to that commonly used to display soil water retention curve data. When contours are included on the plot for different void ratio levels, each contour represents a soil water retention curve for a given void ratio. Hydrostatic test results are shown using this graphical setup in Figure 7.10. Contour lines were included in this figure calculated using the contour() algorithm from the Python library Matplotlib.

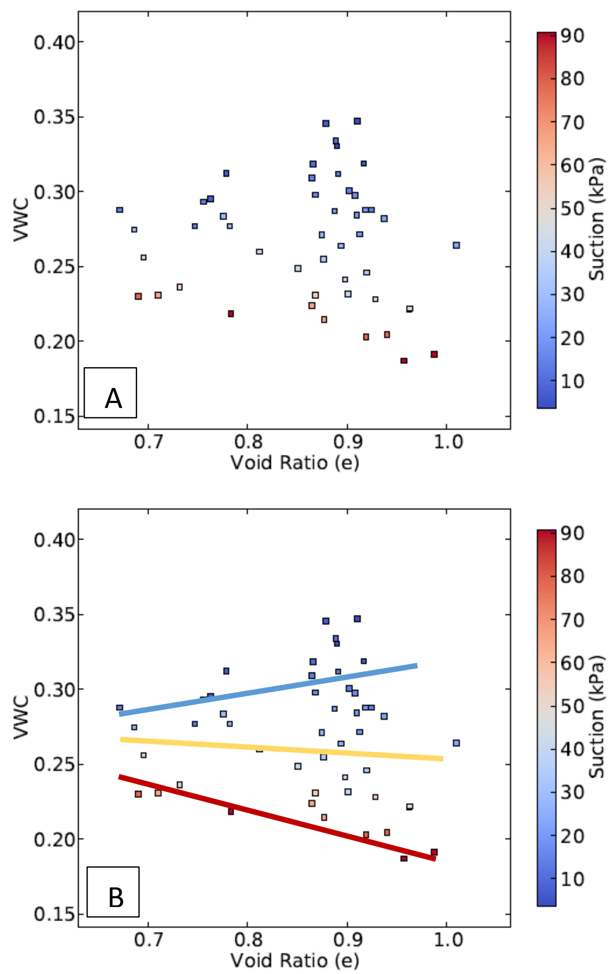

Figure 7.9 – A) Void ratio plot (wet compaction condition) B) Void ratio plot with contours added

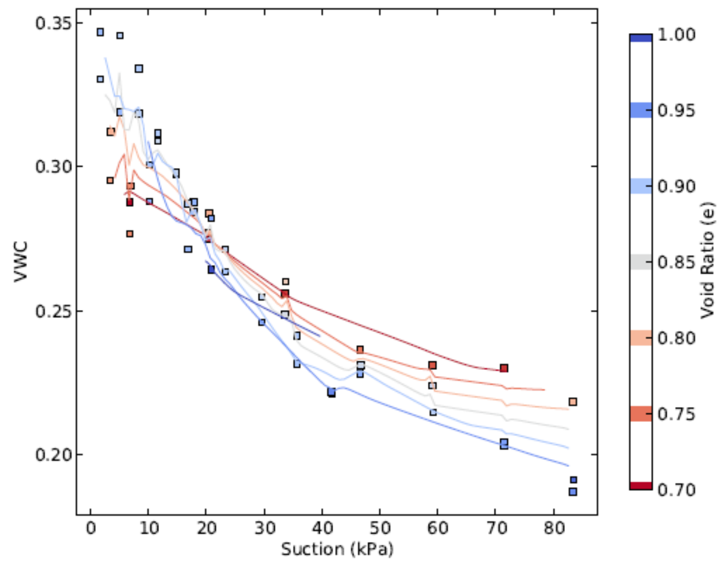

Figure 7.10 - Suction plot with contours from Matplotlib contour()

Finally, using a 3D grid (by itself or with projected contours on the different axis) was found to be effective for illustrating the shape and trends of the 3D surface. Figure 7.11 show a 3D surface that was fit through hydrostatic data with projected contour plots on each axis. The shape and trend of the surface can be easily seen. This type of 3D plot was found to only be effective for visualizing a surface. If individual actual data points were included, it was difficult to determine where they lie within the 3D space.

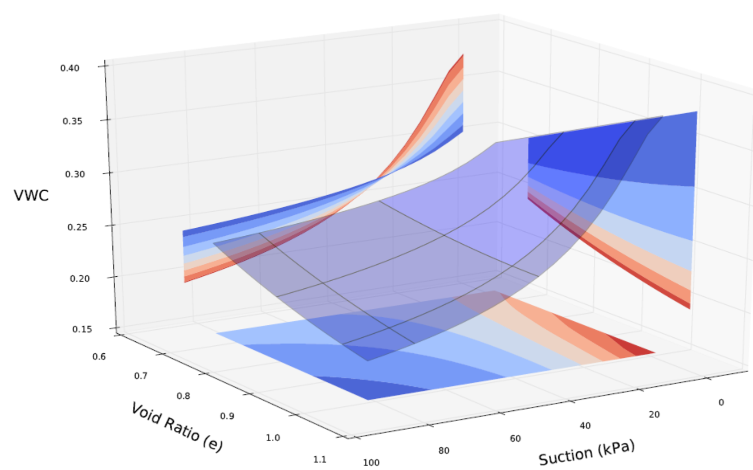

Figure 7.11 - Soil water retention surface, 3D projection plot

7.3.2 Fitting surfaces to hydrostatic data

It is useful to fit continuous functions through soil water retention curve data in order to use the functions to predict the suction of a soil when the VWC is known (or vice versa). The fitting of continuous functions through SWRC data is commonly conducted using functions such as the van Genuchten or the Brookes and Corey functions (Section 2.3). These functions assume a constant void ratio and are not suited for hydrostatic results where void ratios are variable. Methods for fitting the relationship between suction, void ratio, and volumetric water content (soil water retention surface) have not been thoroughly researched and there exists no standard practice for the modeling of the soil water retention surface (SWRS).

Several different methods for modeling the SWRS were evaluated. The first method was based on Kriging (Everitt, 2002), which predicts the value of variables based on known points located nearby. The other methods were based on the principle that any slice of the soil water retention surface (at a constant void ratio) will result in a conventional soil water retention curve for the given void ratio. Since each slice or SWRC can be modeled using common SWRC functions, the entire surface should be able to be fit using conventional SWRC functions but modified to incorporate changes in the SWRC parameters with void ratio.

7.3.2.1 Use of Kriging for prediction

Kriging is a statistical method used for interpolation between known points in a data set. The method, which was originally developed for predicting the location of minerals based on known deposits, has been widely used in a variety of applications.

A Kriging algorithm was adapted from Johnson (2014) for interpretation of the database generated using hydrostatic results. It was found that Kriging was very effective at predicting hydrostatic results as long as there was significant data located around the region where the prediction was of interest. When Kriging was used for prediction near the edges of the data set, the results were inaccurate and resulted in trends in the surface that were obviously incorrect.

The Kriging algorithm is meant for interpolation of data. Consequently, and in order to increase the range where Kriging was effective, a series of points were added to the Kriging data set to represent the line of quasi-saturation (Section 9.1). This resulted in more accurate predictions in the areas of low suction, however there were still significant regions where unreasonable trends were predicted.

Kriging results are shown in Figure 7.12 for the optimum data set. The red dots correspond to the predicted volumetric water contents for a grid of different void ratios and suctions. The predicted water contents defined a smooth surface that appeared to fit the data set very well in the ranges that hydrostatic data was available. When predictions were made slightly outside the range of hydrostatic tests large variations occurred (highlighted by red circles). Some problems with the extrapolated data include increases in volumetric water content with increases in suction or reversals of trends seen in the rest of the data set.

Kriging was also found to be inefficient in the sense that the entire data set must be known in order to make a prediction. Instead of determining a function that best fits the data and reporting the function, the entire data set must be reported and incorporated into a Kriging algorithm for the predictions.

Overall, Kriging was found to be promising but not a fully effective method for modeling the hydrostatic data set. This was mainly a result of a combination of the limited range of data that was measured during hydrostatic testing and the issues with extrapolation using Kriging.

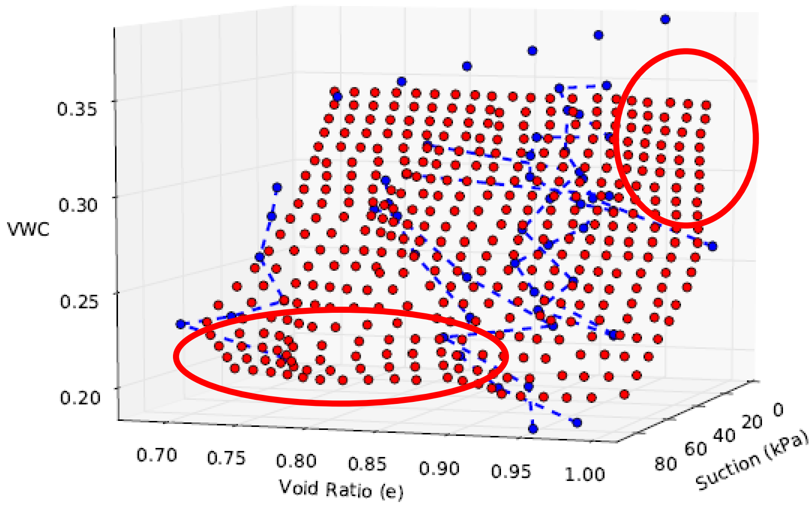

Figure 7.12 - Kriging results with locations of high error (red circles)

7.3.2.2 Use of the van Genuchten function to fit the SWRS

Methods for fitting hydrostatic data were explored that incorporate conventionally used SWRC functions (such as the van Genuchten function) with parameters scaled with void ratio. Prior to fitting surfaces to the hydrostatic data set, the data was grouped based on the three compaction moisture conditions. The data was also trimmed so that no area of the surface had a substantially higher density of points than others. This was done to avoid biasing the fitting process to a certain area due to a higher weight on the measured error due to a higher point density. The resulting grouping of the data set for each compaction moisture condition is listed in Table 7-3.

The fitting methods are discussed in detail using data from samples compacted at the dry moisture condition. Later, results from the fitting procedures on samples compacted at the optimum and wet moisture conditions will be presented.

Table 7-3 - Data set used for surface fitting

Dry	Optimum	Wet
RMA41	RMA63	RMA59
RMA42	RMA64	RMA60
RMA57	RMA103	RMA61
RMA58	RMA104	RMA77
RMA76	RMA35	RMA62
	RMA36	RMA78

7.3.2.2.1 Van Genuchten surface based on isolines

The isoline fitting method was developed as a way to fit the van Genuchten function to the hydrostatic data making no assumptions about how the fitting parameters varied with void ratio. In order to accomplish this, soil water retention curves for different void ratios were interpolated from the data set. Each SWRC was then individually fit using the van Genucthen function.

In order to interpolate the individual SWRCs, the MATPLOTLIB contour() algorithm was used to produce isolines of the set of hydrostatic results. Each isoline is an estimation of the SWRC at a given void ratio based on the given data around that void ratio. The resulting isolines are graphed in Figure 7.13 along with the data set used for fitting. The isolines follow the trends of the raw data closely, although they include variations due to scatter in the data.

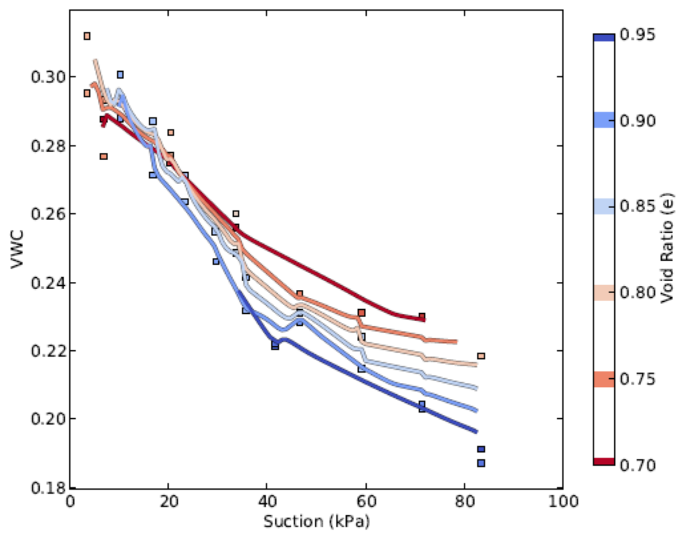

Figure 7.13 - Resulting isolines from Contour(), dry of optimum

Each isoline was then fit with the van Genuchten function using the least squares method with a Powell based optimization. The van Genuchten function is defined as:

$$\theta = \theta_r + (\theta_s - \theta_r)[1 + (\alpha\psi)^N]^{-\left(1-\frac{1}{N}\right)} \tag{25}$$

where θ is the volumetric water content, ψ is the soil suction, θ_r is the residual moisture content, θ_s is the saturated moisture content (porosity), and α and N are function fitting parameters. The following restrictions were applied to the parameters during the fitting process:

- α must be greater than or equal to zero – This is necessary as the van Genuchten function in undefined at α less than zero
- N must be greater than one – at N less than one the curvature of the van Genuchten function is reversed with an increasing VWC with increasing suction
- Each parameter must be within 0.15 of the adjacent lines – this was necessary because some of the isolines had a small ranges in data. When only the small range of data was fit, unreasonable parameters were sometimes obtained.

The van Genucthen curves from the fitting process are plotted on top of their corresponding isoline in Figure 7.14. The fitted curves were found to accurately represent the isolines.

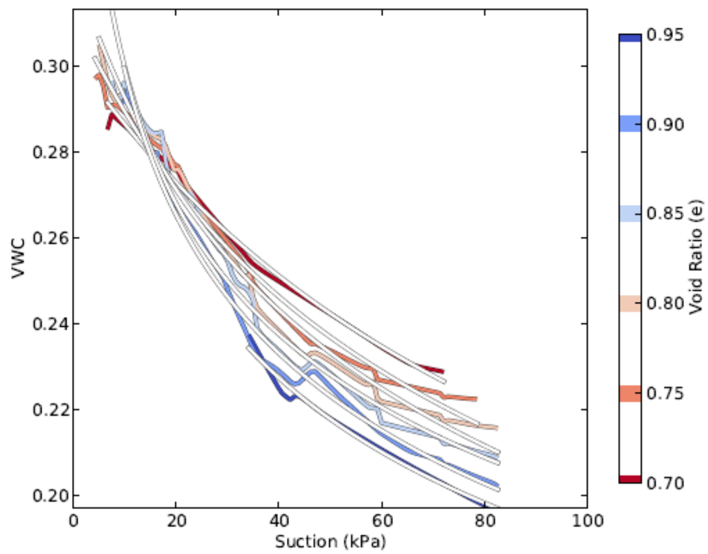

Figure 7.14 - Fitted van Genucthen curves

The fitting parameters from each of curves are shown in Figure 7.15. All of the parameters show an increase in value with increasing void ratio. The change for each parameter was found to be reasonably linear, so fitting methods based on linear changes in function parameters with void ratio are promising.

In order to evaluate the accuracy of the isoline fitting method, a continuous surface was created by linearly interpolating the van Genuchten parameters between the known values for each isoline. The surface was also extended beyond the last isolines by linearly extrapolating based on the previous two isolines. The error between the surface and the measured hydrostatic points was calculated and a filled contour plot of the errors is shown in Figure 7.16.

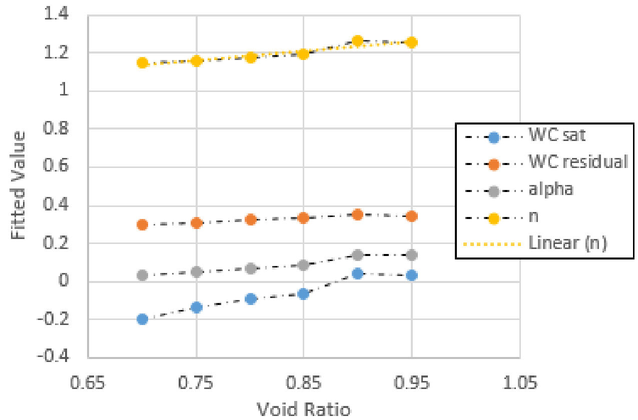

Figure 7.15 - Fitting parameters for van Genuchten curves

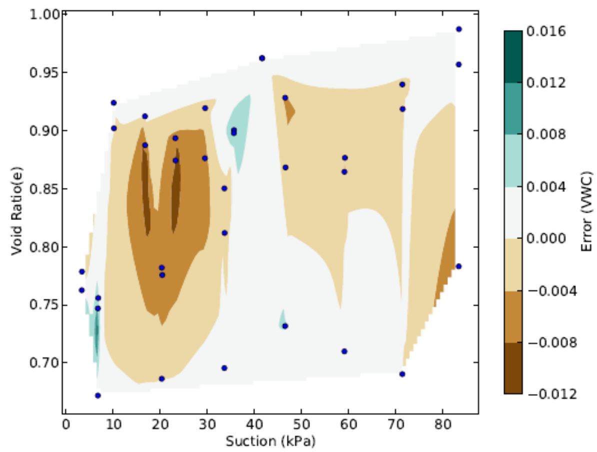

Figure 7.16 - Error of SWRS fitting, dry of optimum (isoline method)

The isoline method resulted in low errors between the predicted surface and the actual data points. The maximum error was under 2% VWC. Some difficulties were identified with the procedure used in the process of fitting of the van Genuchten curve to each isoline. This was a result of the isolines including a relatively narrow range of data, which ranged from 5 to 90 kPa. The narrow range allowed the fitting process to often fit unreasonable SWRCs through the data. Examples of the unreasonable results were:

- Negative values of residual water content
- Very high residual water contents (e.g. 20%)

- Saturated water contents higher than the porosity.
- Saturated water contents well below the porosity or quasi-saturated porosity
- Unusual curvatures

Also, when a surface was created from the different isolines using linear interpolation of the fitting parameters, undesirable jumps or dips were often observed in the surface because of the non-linearity of the van Genuchten function. Overall, it was found that this was an ineffective method for fitting the surface but it was useful for a baseline in order to determine how the van Genuchten parameters changed with void ratio.

7.3.2.2.2 van Genuchten surface with parameters varied linearly

The results obtained using the isoline fitting method suggested that van Genuchten parameters changed approximately linearly with void ratio. The initial attempt for fitting the hydrostatic data using the van Genuchten parameters varied linearly with void ratio was as follows:

$$\theta_s = C_{\theta 1} - C_{\theta 2}\boldsymbol{e}$$

$$\alpha = C_{\alpha 1} - C_{\alpha 2}\boldsymbol{e}$$

$$N = C_{N1} - C_{N2}\boldsymbol{e}$$

The parameter for residual water content was held constant in the fitting process as it was found to have little effect on the surface. Research has also shown that the residual water content is largely independent of the void ratio (McCartney 2007). The surface was fit using a Powell based optimization to solve for the coefficients that resulted in the lowest error between the measured data points and the surface (using least squares method). Contours from the fitted surface are shown with the data set in Figure 7.17. The contours from the van Genuchten surface are found to be smooth and trends are found to be clearly defined.

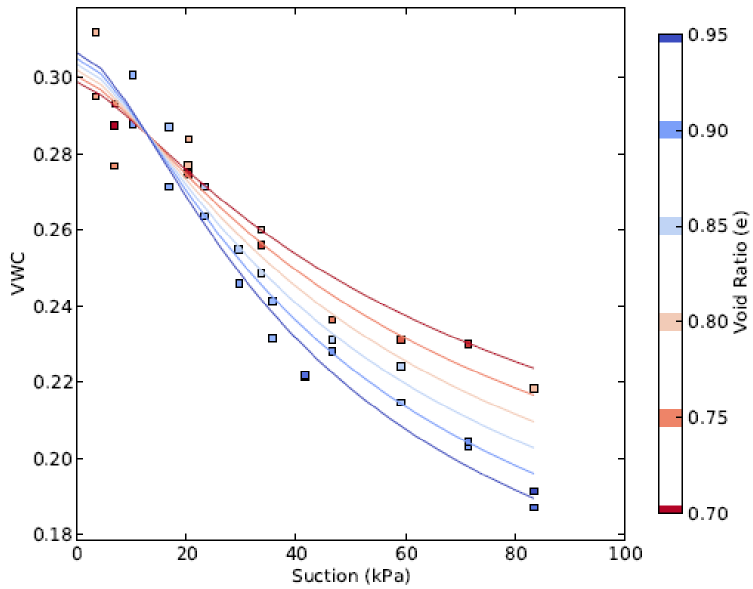

Figure 7.17 - Soil water retention surface, dry of optimum, van Genuchten surface fitting contours

In order to evaluate the accuracy of the surface fit to the data set, a filled contour graph based on the error from each point is shown in Figure 7.18. The blue dots represent the data set used for fitting and the colored areas represent the error between the surface and the data set. Overall the errors were low with a maximum error of 1.7% VWC. No significant trend was seen between the error and the void ratio suggesting the linear change in van Genuchten fitting parameters was adequate for this data set. The average error of the surface was 0.5% VWC, with a maximum of 1.7% VWC. Some trends of the error were observed in relation to suction:

- Errors were relatively high at low suctions however the errors were both over and under predictions.
- Data at “mid” suctions (30-50 kPa) over predicted the water content of samples.
- Data at high suctions (70+ kPa) slightly under predicted the water content of samples.

Attempts were made to minimize these errors by changing the van Genuchten parameters but a better fit could not be identified. The errors were considered to be a result of the adequacy of the van Genuchten function rather than of the specific parameters used.

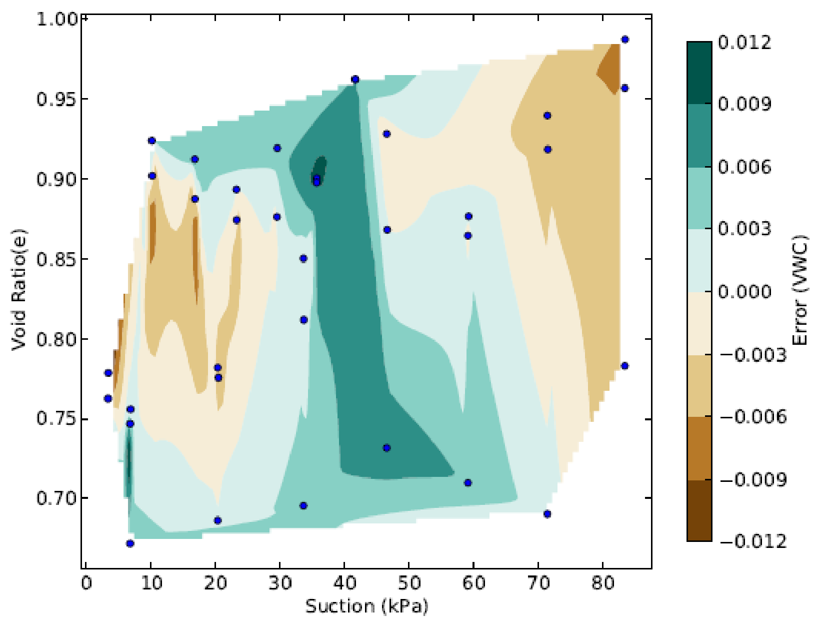

Figure 7.18 - Error of SWRS fitting, dry of optimum

One problem with the global fitting method was that the saturated VWC predicted by the curves often did not match with values of quasi-saturation obtained experimentally (see Section 9.1 for discussion of quasi-saturation of samples). In order to make the surface fit with the quasi-saturated VWC, the parameter for the saturated VWC was fixed such that:

$$\theta_s = 0.195 + 0.1833\boldsymbol{e}$$

This relationship represents the line of quasi-saturation for the dry data set (see Section 9.1). This reduced the number of coefficients to fit from six to four making the optimization less complex. Even with the reduced number of coefficients the Powell based optimization had difficulty converging on optimal solutions. The fitting algorithm was eventually changed to the "Evolutionary" algorithm available in Microsoft Excel's Solver add-in. This algorithm was found to be particularly useful for complex and non-linear functions and was found to be more efficient at determining coefficients that minimized the error between the measured data and predicted surface. The resulting surface from the evolutionary algorithm with fixed coefficients for θ_s is shown in Figure 7.19.

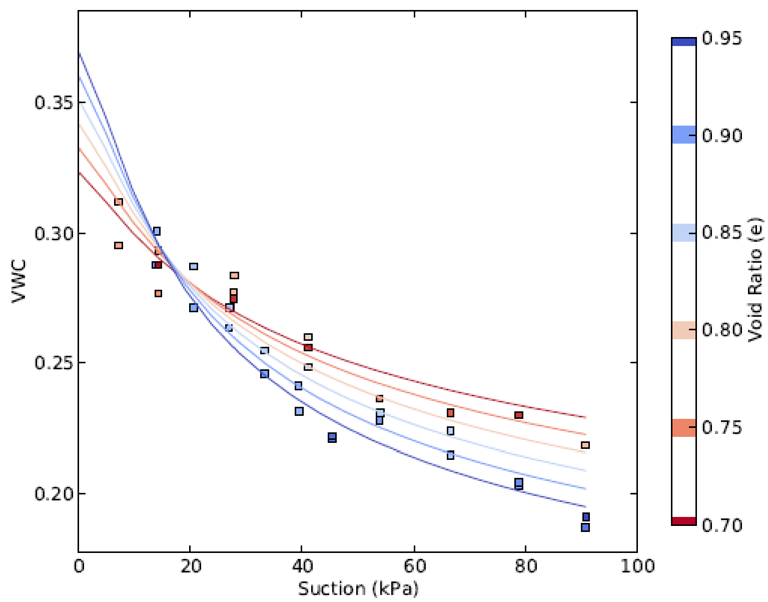

Figure 7.19 - Soil water retention surface, dry of optimum, fixed θ_s relationship and "evolutionary" algorithm

Overall the evolutionary algorithm with fixed θ_s parameters was found to be the best method for fitting a continuous surface through hydrostatic data. This method resulted in the least error and the resulting surfaces followed the general trends and shapes expected from retention results.

7.3.2.3 Fitted 3D surfaces

The data sets for the three compaction moisture conditions were fit with surfaces using the methods described in Section 7.3.2. The surface fit to samples compacted at the dry moisture condition, which was briefly discussed during the description of the fitting process, will be discussed further followed by the discussion of the surfaces fit to samples compacted at the optimum and wet moisture conditions.

Dry Moisture Condition

The resulting surface for samples compacted under dry moisture conditions is shown in Figure 7.20 as a 3D surface. The surface has a smooth shape with trends of decreasing slope and saturated volumetric water content with decreasing void ratio. The same surface is displayed using a contour plot in Figure 7.21. The surface fit the data well with the most error corresponding to suctions between 15 and 25 kPa.

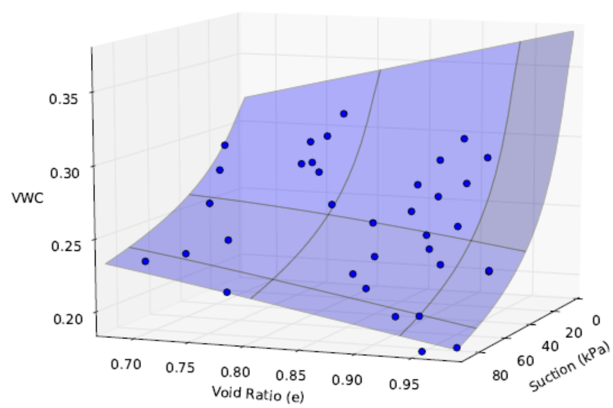

Figure 7.20 – 3D surface for dry hydrostatic data

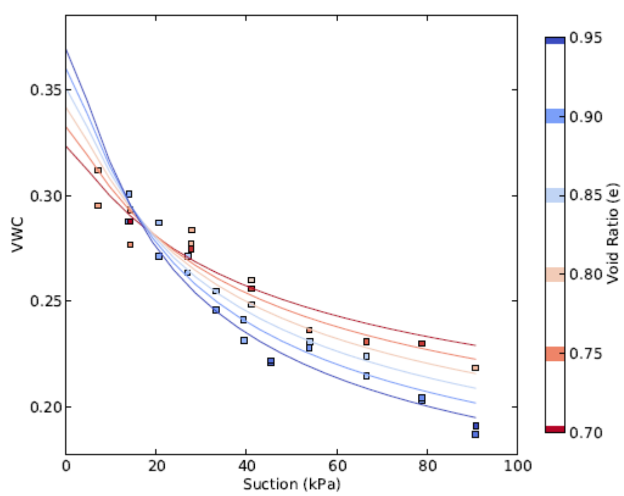

Figure 7.21 - Contours for surface fit to dry hydrostatic data

Filled contour plots for the errors of the surface were defined and are shown in Figure 7.22. The error was calculated in terms of both VWC and suction. Negative errors meant an under-prediction by the surface. Because of the change in curvature of the van Genuchten function areas of the surface can have a low error in VWC prediction but high error in suction prediction or vice versa. Errors ranged from 1.8% to -1.2% VWC and 17 kPa to -12 kPa. Average errors were calculated at 5 kPa and 0.5% VWC.

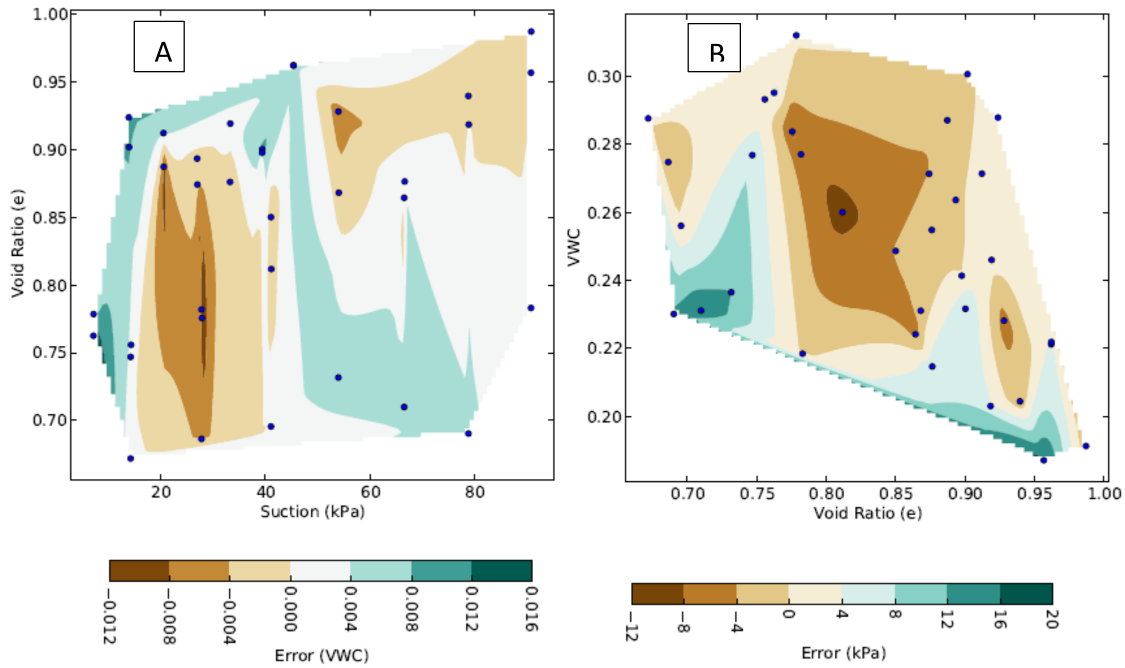

Figure 7.22 - Error contours for fittied surface when predicting - a) VWC, b) Suction

Optimum Moisture Condition

Attempts to fit a surface to the data from samples compacted at the optimum moisture condition were problematic using the procedures discussed in Section 7.3.2.2. The main issue of the fitting process was the inability of the fitted surface to match the behavior of the test results at void ratios of approximately 0.8. The hydrostatic results in this range were higher in water content than any of the fitted surfaced predicted. Surfaces fit to the data set using both the isoline and van Genuchten surface methods are shown in Figure

7.23. Data points circled in red correspond to the region where the fitted surfaces were unable to follow the trends of the hydrostatic data.

The points of high error correspond to the area where the SWRS transitioned from “Zone 1” to “Zone 2” (discussed later in Section 9.3.1). In this transition zone, the relationship between VWC and void ratio reverses and neither of the fitting methods were able to accurately represent this transition in slope. This issue is illustrated in Figure 7.24, where the trend of the fitted surfaces (dashed lines) are shown against the data set. The actual data set shows an increase in VWC with increasing void ratio and then a decrease in VWC with increasing void ratio. The change in behavior is separated by the black dashed line in the figure. The fitted surface essentially fit the general slope of the entire data set with a single line (dashed line) and did not capture the change in slope from positive to negative between zones.

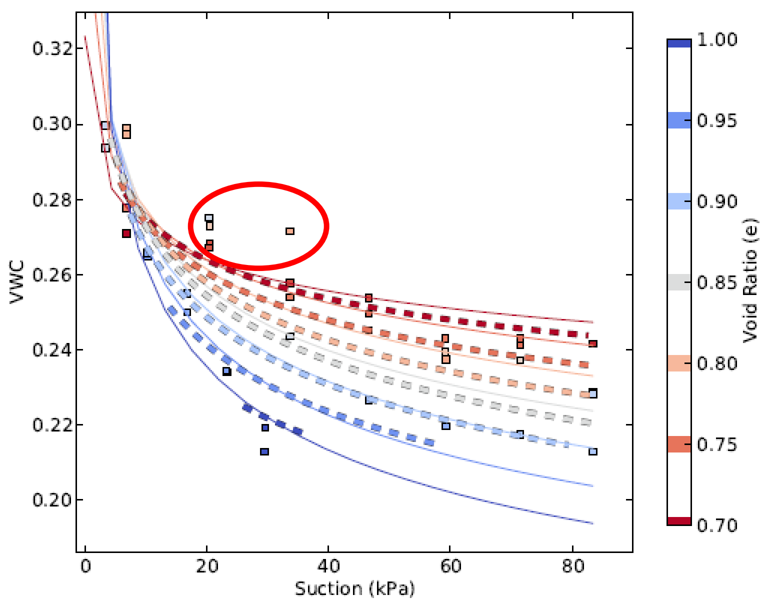

Figure 7.23 - Contours of fitted surfaces for optimum moisture condition, best-fit (solid line), isoline (dashed)

This is probably due to inaccuracies in the assumption of a linear change in van Genuchten parameters with void ratio. The change of VWC with void ratio appeared to be parabolic in this region. Attempts were made to better fit the data using the isoline fitting method, which is not constrained by a linear assumption, but these were also unable to fit the data. This could have been due to issues with the contouring algorithm or the van Genuchten function was simply unable to represent the shape of the retention behavior in this area.

In order to minimize errors, the data was split into two sets. This allowed each side to be fit individually and the algorithms did not have difficulties in transitioning between behaviors. This resulted in a decreased error and better prediction of data in the vicinity of the transition zone. The composite surface is shown in Figure 7.25. A discontinuity is observed between the two surfaces, which is a result of fitting the data with two separate surfaces. A red line is included in Figure 7.25 that represents the shape of the data set that was unable to be modeled using van Genuchten fitting methods.

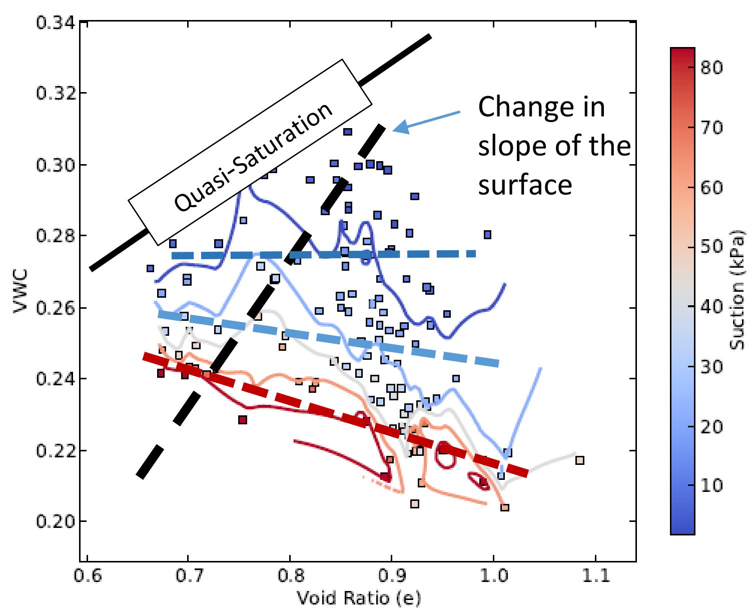

Figure 7.24 - General shape of fitted surfaces (dashed line) vs. actual trends (solid line)

Error contours from the fitted surface are shown in Figure 7.26. The surfaces resulted in low errors when predicting VWC, with an average error of 0.7% VWC. The maximum error, which occurred at the intersection of the surfaces, was 2.7% VWC. The error for suction prediction showed similar trends with the maximum error (48 kPa) occurring at the intersection of the surfaces. The average error was approximately 11 kPa.

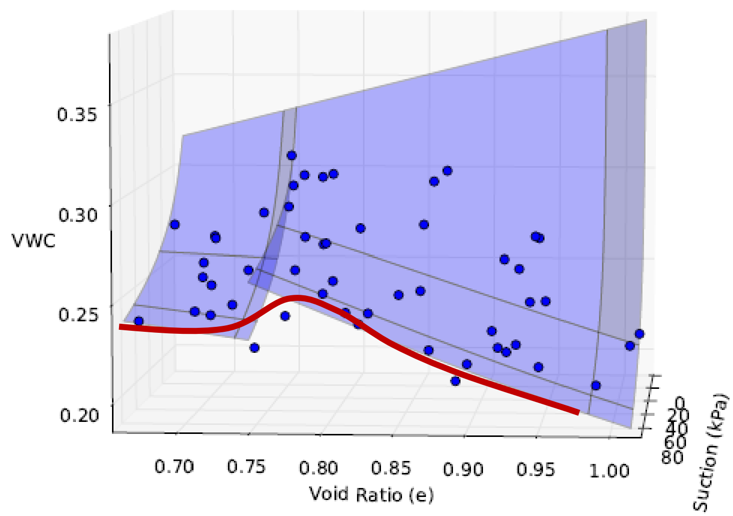

Figure 7.25 – 3D composite surface for optimum data, actual shape of data set illustrated in red line

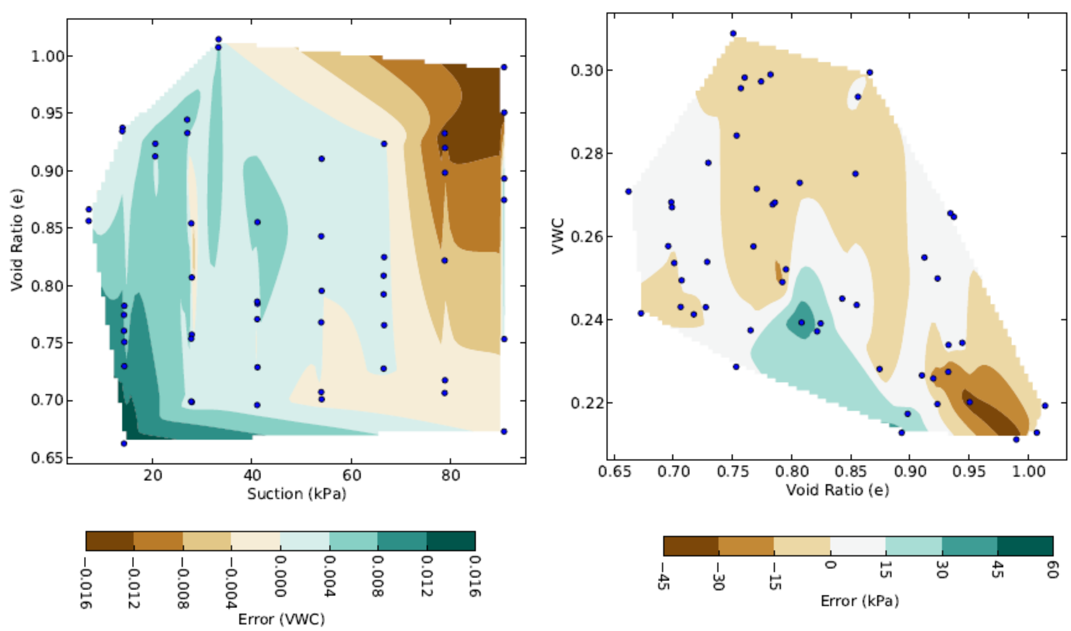

Figure 7.26 - Error plots of optimum surface fitting - a) VWC b) Suction

Wet Moisture Condition

The surface defined for the wet moisture conditions fit the shape of the wet data set well. The wet data set had an area of the plot that showed saturated behavior. In this area increases in suction did not reduce the VWC. Initial attempts to fit the data using Powell base optimizers were unable to model this behavior. Later attempts using Solver's Revolutionary optimizer resulted in a good fit for all areas of the SWRS. The resulting 3D surface is shown in Figure 7.27.

A contour plot of the same surface is shown in Figure 7.28. The transition of the SWRS between a behavior where the VWC reduces quickly with increased suction (blue lines, high void ratio) to an area where increases in suction have no effect (orange lines, low void ratio) is represented well by the contours.

Error plots for this surface are shown in Figure 7.29. The calculated error for VWC is low as the fit is very good. The maximum error was less than 1% VWC with an average of 0.33% VWC. The calculation of error for suction is not possible in some zones, as there is not a unique function between suction and VWC at low void ratios. Also, because the surface is horizontal in this area, a slight change in VWC will produce extremely large changes in the predicted suction. When this area was neglected the suction prediction was found to be very accurate, with most predictions being within 1 kPa of the measured value.

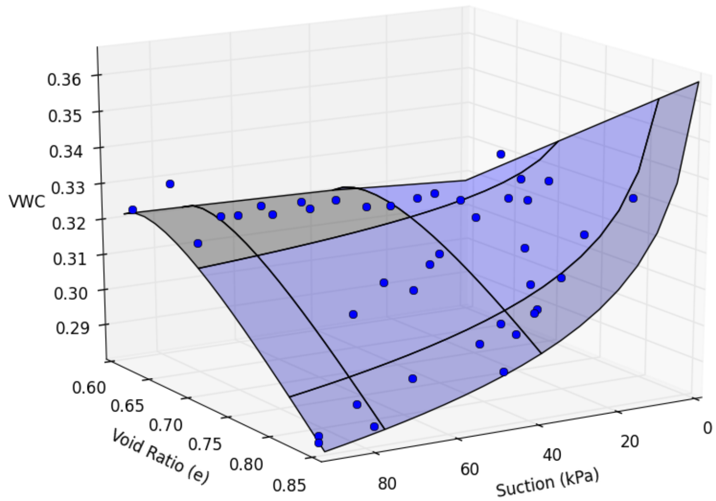

Figure 7.27 – 3D surface for wet hydrostatic data

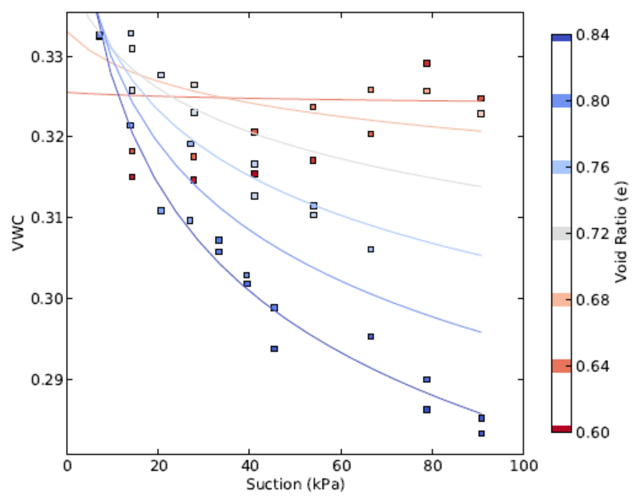

Figure 7.28 - Contour plot of fitted surface to wet hydrostatic data

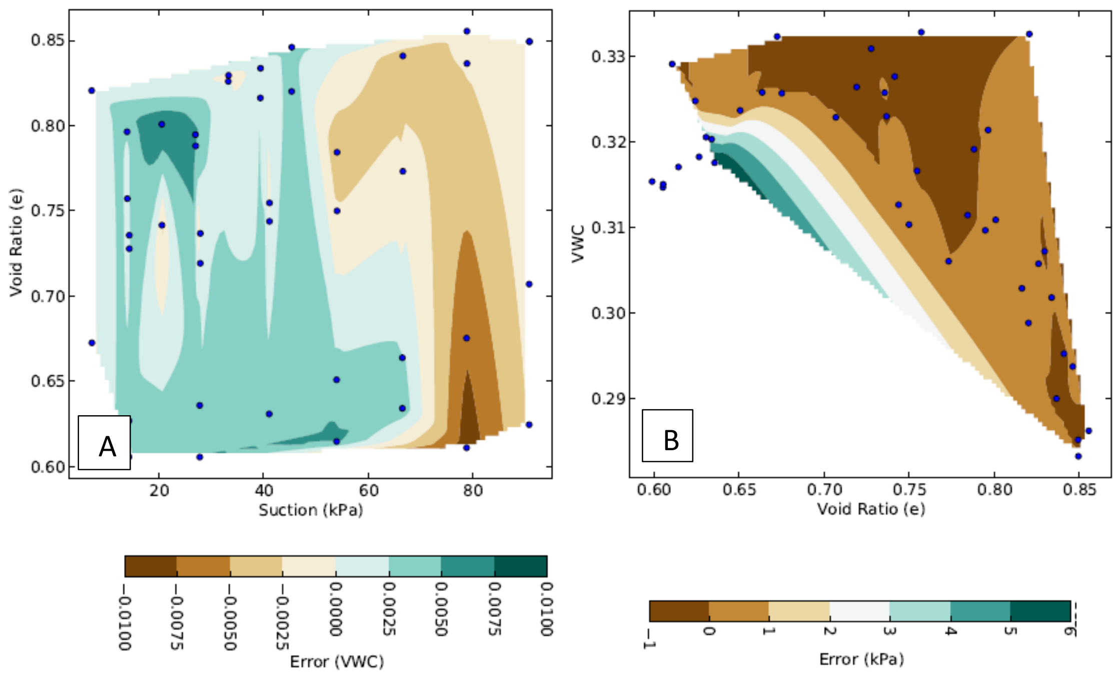

Figure 7.29 - Error plots of wet surface fitting - a) VWC, b) Suction

Summary of Fitted Surfaces

The fitting methods produced surfaces that matched well with the actual data points obtained using the hydrostatic procedure. These surfaces allow the prediction of suction in a centrifuge sample if the void ratio and VWC are known. This allows the suction to be predicted for samples tested under conditions other than hydrostatic, when the suction profile in the samples is unknown. Table 7-4 shows the average and maximum errors for each of the fitted surfaces.

Several locations in the fitted surfaces resulted in large errors and must be taken into account when predictions are made. These locations are:

- The surface for the dry of optimum data set contains an area in the 15-25 kPa suction range that produces larger errors than the rest of the data set. These errors are acceptable but should be noted.

- The optimum data set was modeled using two separate surfaces. The intersection of these surfaces is discontinuous and predictions in this area may result in high error. Errors were also large at comparatively high void ratios, where there was little data for fitting and predictions from this area may be inaccurate.
- The wet data set included an area of quasi-saturation. Points in this area resulted in a range of suctions giving the same VWC meaning that predictions of suctions in this area were not possible. The rest of the surface produced very accurate predictions.

Table 7-4 - Errors of fitted surfaces

	Error in VWC		Error in suction	
	Average Error	Max Error	Average Error	Max Error
Dry	0.52%	1.81%	5 kPa	17 kPa
Opt	0.71%	2.64%	10.8 kPa	47.8 kPa
Wet	0.33%	0.91%	N/A	N/A

7.4 Limitations of the Hydrostatic Procedure

During testing Series “H”, several limitations were identified with the hydrostatic testing procedure. The first limitation was the *lack of in-flight measurement* of soil properties. Soil measurements taken for tests conducted using the hydrostatic procedure were performed after the samples were removed from the centrifuge. The removal from centrifugal acceleration resulted in both a decrease in stress and a change in hydraulic gradient.

The change in gradient promoted flow upwards in the sample. Under the increase gravitational gradient the samples were at equilibrium as the gravitational and suction gradients were equal and opposite. Once the gravitation gradient was reduced to one, the hydraulic gradient was upwards in the sample due to the suction gradient. However, the total time between stopping the centrifugation and slicing of specimens was small (5-

10 minutes) and the hydraulic conductivity of the soils tested was relatively low (<1x10^{-5} cm/s) so the total change in distribution of water content was considered negligible.

The decrease in stress due to removal from centrifugal acceleration likely resulted in changes in void ratio most significantly at the base of specimens where the stress change was the largest. Potential effects of changes in void ratio before measurement were seen when the results were compared with standard test results (Section 9.7.1) and the base of the samples resulted in lower volumetric water content than expected for the measured void ratio.

Another limitation was the inability to directly target a void ratio using the hydrostatic procedure. As the increased stress of centrifugation resulted in changes in void ratio during testing, the compaction void ratio was not the final void ratio for which properties were determined. Once the effects of stress on the void ratio were known for a soil, ranges of void ratio could be targeted. However, if a range of suction was desired to be tested at a constant void ratio (as soil water retention curves typically are) multiple tests were required because single tests decreased in void ratio from the top (under low stresses) to the base (under high stresses).

Another limitation of the hydrostatic procedure was that the stress and suction within the samples were both dependent on the distance above the base of the sample. This resulted in a "coupling" of stress and suction. Low void ratios (high stresses) occurred at the base of samples where low suctions also existed, while high void ratios (low stresses) occurred at the top of samples where high suctions were imposed. These effects can be mitigated by testing samples of different heights. A short sample will result in lower stresses at the base and measurements will be produced for water retention at a relatively low suction and void ratio. However, this process results in significantly fewer data points of the SWRS for a given test due to a shorter sample.

Finally, it was found that the total range of suction for which retention behavior was measureable using the hydrostatic procedure was rather small. Based on the maximum g-level of 100, the highest suction that retention behavior was measured was approximately 90 kPa. This could be increased in future testing by either increasing the sample height and g-level.

7.5 Summary and Findings from Testing Series "H"

A testing procedure was developed that successfully determined the relationship between void ratio, suction, and volumetric water content using centrifuge technology. Suction was applied to samples by use of centrifugal acceleration. This resulted in the suction applied to centrifuge samples being a combination of the distance above the zero suction datum and the g-level.

The distribution of water content and void ratio was determined by slicing samples after testing and was found to provide accurate results. Data was collected, which was suitable to define the relationship between void ratio, suction, and volumetric water content (referred to as the soil water retention surface or SWRS) for suctions ranging from approximately 5 kPa to 90 kPa and for void ratios ranging from 0.7 to 1.0. The resulting volumetric water contents in these ranges was found to range from 18% and 32%.

RMA samples were compacted at three moisture conditions (dry, optimum, and wet) and characterized using the hydrostatic procedure. Each compaction moisture condition produced a unique SWRS. The surfaces were modelled using the van Genuchten function with parameters scaled linearly with void ratio. Fitting the saturated and residual water content to known relations with void ratio and then using optimization algorithms to fit the other parameters in order to reduce errors between the predicted surface and measured data was determined to produce the most reasonable surfaces. The average error between the measured data set and the modeled surface fit each compaction moisture conditions (wet, optimum, dry) was approximately 0.5% VWC.

7.6 Recommendations

In-flight measurement of void ratio and volumetric water content are recommended for future testing. The water content could potentially be measured using resistive water content measurements taken along the height of samples. The void ratio could be measured by using either tell-tales connected to displacement sensors or embedded non-contact displacement sensors. At a very minimum the displacement of the surface of samples should be monitored by linear position sensors during testing. It is recommended that instrumentation be implemented in a way that the methods used in this investigation for measurement of volumetric water content and void ratio can still be conducted.

Improvements to the testing setup are recommended that allow for samples to be wetted using a suction driven wetting process from the base of the sample. Currently the base does not contain sufficient volume in order for the sample to absorb water during centrifugation and wet itself to hydrostatic conditions. If the volume of water stored in the based is increased or flow is routed around the sample to the base, hydrostatic testing can be completed in a true “wetting” method, consistent with pressure plate testing methods.

Testing at higher suction by using increased g-level or elevated suction at the base of samples is recommended. Using a suction boundary at the base of samples has the advantage of not increasing the stress distribution in centrifuge samples any further. The implementation of a suction based lower boundary condition would likely be difficult, however, as a constant air suction must be applied to the outflow chamber.

8 TESTING SERIES "IF": IMPOSED FLOW PROCEDURE

The imposed flow testing method was developed in order to measure the unsaturated hydraulic conductivity of soils in the centrifuge. The testing philosophy is based on the same principles as testing Series "I" (Chapter 5). Flow is imposed on the surface of the centrifuge sample and testing is conducted until steady state flow has been achieved. The base of the sample is a zero suction boundary. Significant changes were made to the testing procedure in order take into account changes in void ratio that result due to increased stresses during centrifugation along with non-uniform distributions of moisture content in samples.

The main improvement over testing conducted in Series "I" was the ability to measure the void ratio of the sample. This was accomplished by changing the centrifuge cup to incorporate a split tube sampler, which allowed the centrifuge sample to be sliced after testing and the void ratio to be measured. Like with the hydrostatic testing procedure (Series "H"), in order to accommodate the split ring sampler it was necessary to remove all instrumentation from the sample. This meant that measurements of water content were taken after testing by oven drying the slices of the sample. This method had the advantage of producing accurate measurements for water content but measurement of the moisture content during centrifugation was not possible, which was a significant disadvantage. However, the removal of instrumentation was considered necessary as the measurement of void ratio in the sample was a fundamental aspect required to accurately classify unsaturated flow characteristics.

The goal of the imposed flow testing procedure, adopted in Series "IF" testing, is to accurately measure the steady state distribution of water content and void ratio in centrifuge samples. Using this information it is possible to determine the hydraulic conductivity of each slice. The simplest scenario for imposed flow testing results is a moisture distribution in which a large portion of the sample is at a constant water content.

This type of distribution is illustrated in Figure 8.1a. A small portion of the sample shows significant changes in water content near the zero suction boundary condition, while the rest of the sample is at a constant water content. This distribution was initially expected for all steady state centrifuge tests when testing Series "I" was conducted. However, when the results were analyzed it was determined that the effects from the zero suction boundary often extend very high into the sample and often covered the entire specimen. The distribution with a large zone at constant water content is simplest because assuming no major changes in void ratio the suction is constant in areas where there is no change in water content. When there is no change in suction, the suction gradient is zero and the total hydraulic gradient equals the imposed gravitational gradient. This means that hydraulic conductivities can be calculated in this region regardless of whether the suction (which would be constant) is known.

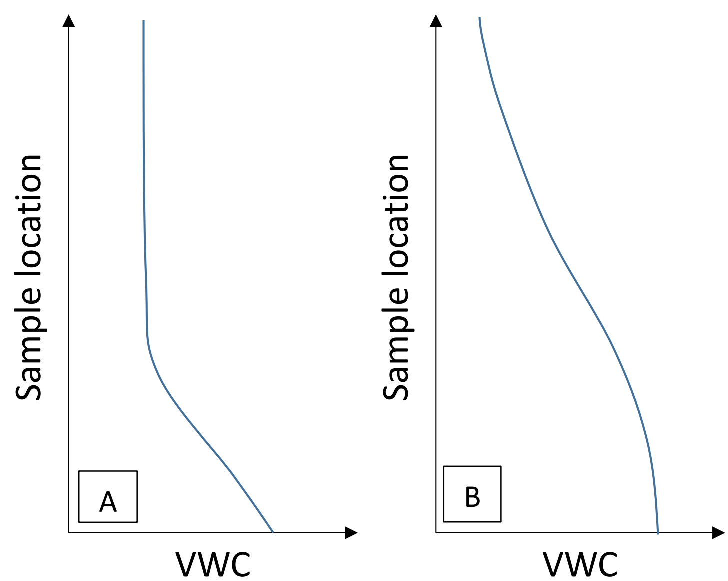

Figure 8.1 - Expected moisture distributions in imposed flow tests

The second distribution, which is more complicated to analyze, is illustrated in Figure 8.1b. In this distribution the water content changes throughout the entire sample and the suction gradient is not equal to zero. In order to calculate the hydraulic conductivity in this type of distribution, the suction must be known in the sample in order to determine the suction gradient. As there is no instrumentation in the sample to measure suction, its value must be predicted using the soil water retention surfaces determined during Series "H" testing using the hydrostatic procedure (Section 7.3.2.3). These surfaces allow the prediction of suction if the volumetric water content and void ratio are known.

The two distributions illustrated in Figure 8.1 are the extreme cases for high and low flow rates and often the distribution of moisture content will be somewhere in between the two. In these cases, part of the sample has a zero suction gradient and hydraulic conductivity can be determined easily due to zero suction gradient and part has a significant suction gradient, which requires the prediction of suction from the soil water retention surface in order to calculate the hydraulic conductivity.

The specific procedure of the imposed flow testing method is discussed in the following sections along with the testing program, analysis, results, and conclusions.

8.1 Testing Procedure

Imposed flow tests were conducted using the same equipment used in the hydrostatic tests (Series "H"). The lower boundary was held at zero suction and flow rates were imposed on the surface of the samples after they were under increased acceleration. Once steady state flow was reached (verified by the outflow chamber) the test was terminated and the moisture content and void ratio was determined throughout each sample. The procedure is discussed in detail in the following sections.

8.1.1 Sample Preparation

Soil processing and compaction was completed using the same procedure as discussed for the hydrostatic procedure. Details can be found in Section 7.1.1.

8.1.2 Centrifugation

Samples were placed into the centrifuge and spun at g-levels of either 25, 50, or 100 with the majority conducted at 50g and 100g. Samples were spun for approximately 5 minutes before the flow pumps were started. A low flow rate was selected (generally between 5 and 10 mL/h) as the first flow rate to be imposed on a given compaction condition. Subsequent samples prepared at the same compaction condition were tested using progressively higher flow rates until saturation was achieved. This process was then repeated for a different compaction condition with the goal of determining the hydraulic conductivity of the soil for a large range of compaction conditions and void ratios.

The initial state of the centrifuge samples involved relatively low water contents, which corresponded to the as-compacted conditions. After flow was imposed on the surface, the moisture in the sample increased to a distribution corresponding to the steady state profile for that given flow rate. The schematic distribution of moisture content at two different flow rates is illustrated in Figure 8.2. The hydrostatic distribution of moisture content is included (black line) for reference and represents the driest state the sample will come to equilibrium for the adopted lower boundary condition. The two blue lines represent the moisture distribution for two imposed flow rates. At the base of the sample these distributions are close to hydrostatic conditions as they both have the same saturated boundary condition. As the distance from the base increases, the distributions diverge and the tests conducted using the imposed flow procedure (Series "IF") transition to a water content corresponding to the flow rate imposed on the surface of the sample. Once steady state conditions were reached the test was terminated. Steady state conditions were verified by measuring the outflow rate from the sample. Specifically, if the outflow was equal to the inflow rate steady state conditions had been met. Testing was continued at least an hour beyond the time when the outflow chamber indicated having reached a constant outflow rate. The extra time was given to ensure the distribution was as close to the steady state profile as possible.

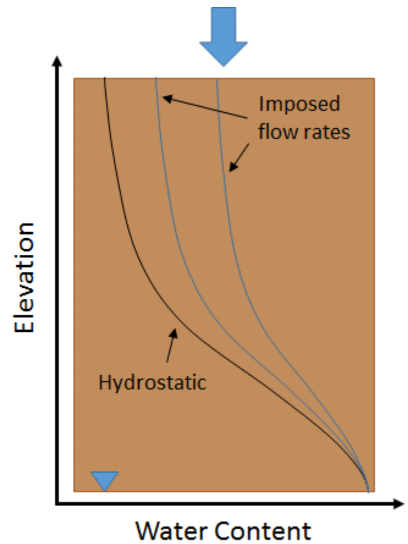

Figure 8.2 - Imposed flow testing setup with moisture distributions

The centrifuge took several minutes to spin down once being turned off. This meant that if flow was stopped at the same time as the centrifuge the sample would dry during the spin down as increased accelerations were still being applied to the sample but no flow was imposed on the surface. In order to minimize the drying effect, the flow pump was manually stepped down following trends consistent with the decreasing g-level. Table 8-1 lists an example step-down procedure completed on an imposed flow test at 100g and 40 mL/h. On the left are the calculated flow rates required for given G-levels. These are the target rates for the flow pump in order to maintain the same flux rate in the sample throughout spin down. As the flow pump cannot be continuously reduced in flow rate, several points were chosen to change the flow pump. These are listed on the right in Table 8-1. These step-down levels and flow rates were chosen so that the average flux rate on the sample remained constant throughout step-down.

Table 8-1 - Example step-down procedure (100g, 40 mL/h)

RPM	G-level	Flow Rate (mL/h)
382	100	40
270	50	20
191	25	10
135	12.5	5

Step-down RPM	G-level	Step-down Flow Rate (mL/h)
331	75	20
234	38	10
165	19	5

8.1.3 Measurement of Water Content and Void Ratio

Once the centrifuge was stopped the void ratio and moisture content distribution in the sample was measured using the same procedure used in the Series "H" tests (hydrostatic testing). This involves slicing the sample using a split tube sampler and oven drying the samples to determine the void ratio and gravimetric water content. Volumetric water content is then determined from these measurements. For a detailed procedure see Section 7.1.

Typical results for the VWC across samples are shown in Figure 8.3 and Figure 8.4. Figure 8.3 shows results of a test completed at a low imposed flow rate. The distribution of moisture content in this scenario was not significantly different than that of the hydrostatic distribution with a total range of approximately 4% VWC across the sample. In cases such as this, the change in water content across the sample means that a suction gradient component must be accounted for when determining unsaturated hydraulic conductivity.

Figure 8.4 shows the results typical of a test completed at a relatively high flow rate. The measured water contents were significantly higher than the hydrostatic distribution. The VWC was more uniform with less than 1% VWC change across the sample meaning that the suction gradient was small in the sample and the flow was dominated by the gravitational gradient.

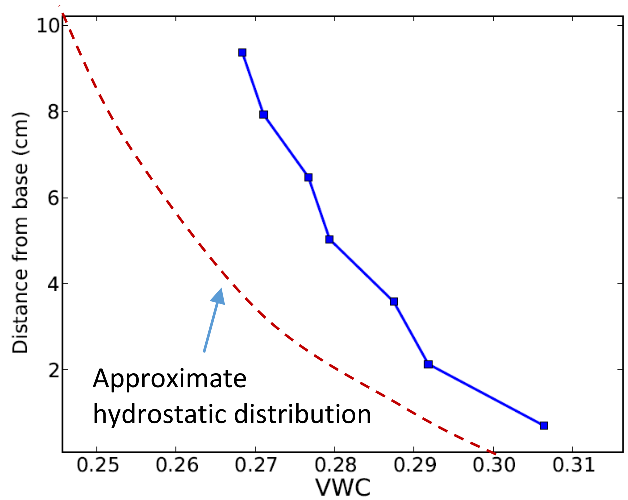

Figure 8.3 - Moisture distribution, low imposed flow rate (RMA52)

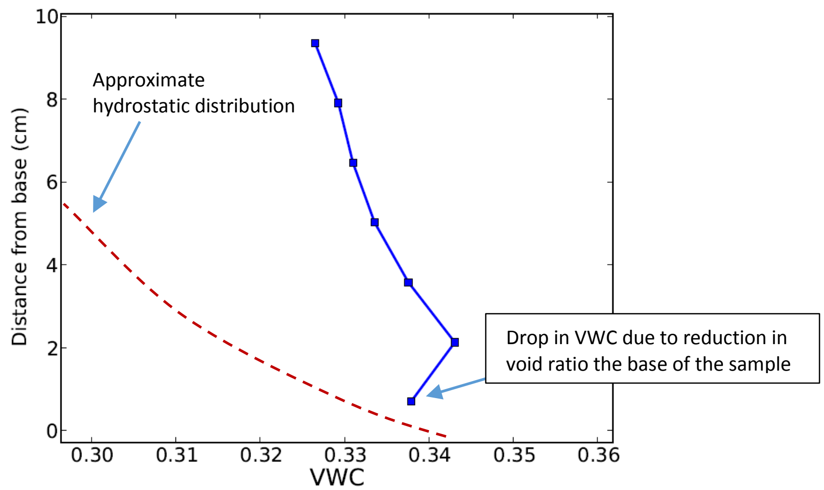

Figure 8.4 - Moisture distribution, high imposed flow rate (RMA54)

8.1.4 Calculation of suction for Series "IF" (Imposed Flow) samples

The volumetric water content and void ratio was determined for each specimen of the Series "IF" (imposed flow) samples. Unlike Series "H" (hydrostatic) tests, where a no-flow condition allowed suction to be determined at any location in the sample, suction was unknown for the imposed flow samples. In order to determine the suction of Series "IF" samples, results from Series "H" (hydrostatic) tests were used. The continuous surfaces that were fit through the Series "H" results (Section 7.3.2.3) allowed prediction of the suction when both the volumetric water content and void ratio were known. That is, for a given void ratio and volumetric water content, suction was determined using relationships such as that shown in Figure 8.5.

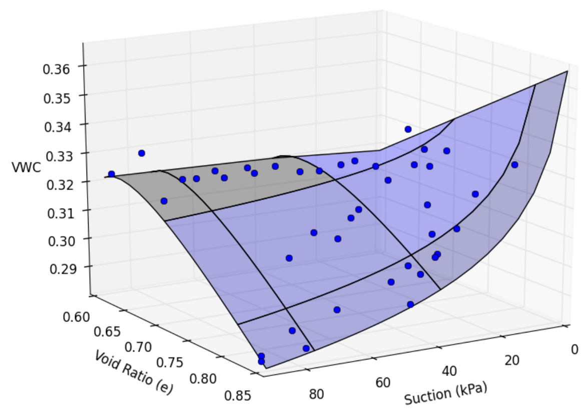

Figure 8.5 - Soil water retention surface fit to Series "H" results (wet compaction moisture condition)

Once the suction was determined for each slice, an exponential function was used to fit the relationship between suction and elevation in each sample. The general form of the function is given in Equation (26. The exponential function was found to fit the shape of the data well for tests conducted at all ranges of flow rate.

$$p = -A(1 - e^{-Bx}) \tag{26}$$

A smooth relationship between the elevation of the sample and suction resulted after fitting the results with the exponential function. The function was also easily differentiable, which allowed the suction gradient to be determined for each slice of the sample.

Fitted exponential curves to a set of imposed flow tests performed on samples compacted at the optimum moisture condition are shown in Figure 8.6. The squares with dashed lines represent the suctions calculated for each slice of the sample from the hydrostatic SWRS. The solid lines of same color show the fitted exponential function to the data. High flow rates resulted in nearly constant suction for the entire sample shown as (A) in

Figure 8.6. Medium flow rates (B in Figure 8.6) resulted in high suction gradients in the lower part of the sample but a nearly constant suction at the top. Finally, tests that were tested at low flow rates resulted in significant suction gradients across the entire sample and are shown as (C).

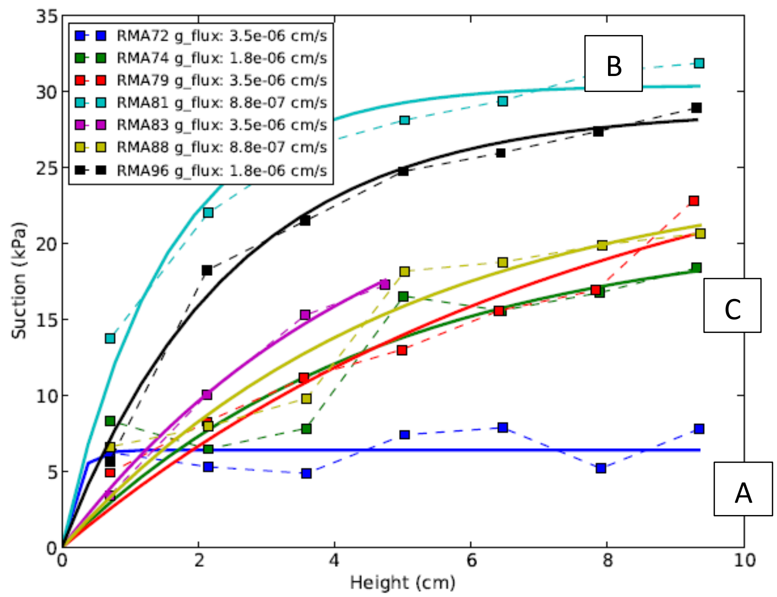

Figure 8.6 - Fitted exponential function to suction profiles

8.1.5 Calculation of hydraulic gradient and hydraulic conductivity

Unsaturated flow in soils is governed by Darcy's law such that,

$$Q = -K\frac{dh}{dl}A \tag{27}$$

where Q is the flow rate, A is the area, K is the hydraulic conductivity, and $\frac{dh}{dl}$ is the hydraulic gradient. When an imposed flow rate is applied to the sample and reaches steady state conditions, it means that the flow rate (Q) through each location of the sample is equal to the imposed flow rate at the surface. Therefore the hydraulic conductivity (K) can be calculated at any location if the hydraulic gradient ($\frac{dh}{dl}$) is known.

In the centrifuge, the flow is parallel to the radius so the formulation for hydraulic gradient can be stated in reference to radius instead of length. The hydraulic gradient is comprised of two components, the pressure and elevation gradients, such that:

$$\frac{dh}{dl} = \frac{dh}{dr} = \frac{dz}{dr} + \frac{dp}{dr} \tag{28}$$

In conventional (1g) experiments the elevation gradient ($\frac{dz}{dr}$) is equal to one however in the centrifuge the gravitational potential is increased such that:

$$\frac{dz}{dr} = \frac{\omega^2 r}{g_1} \tag{29}$$

where ω is the rotational velocity, r is the radius, and g_1 is the gravitational acceleration at 1g.

As discussed in Section 8.1.4, the suction can be determined for each slice of imposed flow tests by knowing the void ratio and VWC, and using these values to determine the corresponding suction using the soil water retention surfaces determined by Series "H" (hydrostatic) testing. The suctions were modeled by an exponential function such that,

$$p = 10.197A(1 - e^{-Bz}) \tag{30}$$

where z is the distance from the base of the sample and A and B are fitting parameters. The factor of 10.197 is used for a conversion of kilopascals (which the functions were fit as) to centimeters of water head (which are used for determining the hydraulic gradient). The fitted pressures were all negative denoting suction in the sample. The base of the sample was located 62.1 centimeters from the center of rotation and therefore the distance z is related to r such that:

$$r = 62.1 - z \tag{31}$$

When Equation (31 is substituted into Equation (30 and differentiated with respect to radius the resulting pressure gradient is:

$$\frac{dp}{dr} = -10.197ABe^{B(r-62.1)} \tag{32}$$

When Equation (32 and Equation (29 are substituted into Equation (28 the total hydraulic gradient is equal to:

$$\frac{dh}{dr} = -10.197ABe^{B(r-62.1)} - \frac{\omega^2 r}{g_1} \tag{33}$$

Once the hydraulic gradient is known, prediction of the hydraulic conductivity of the soil is as follows:

$$K = \frac{Q}{-\frac{dh}{dr}A} \tag{34}$$

where Q, A, and $\frac{dh}{dr}$ are known.

This process was completed using the results obtained after testing sample "RMA96" and the results are discussed below. RMA96 was compacted at the dry moisture condition and tested at 100g with an imposed flow rate of 20 mL/h. This flow rate and g-level produce a target hydraulic conductivity of 1.8×10^{-6} cm/s. Suctions defined for each slice based on the hydrostatic surface and are displayed in Figure 8.7. The exponential function fit to the data is shown as a solid line, which in this case had coefficients of -28.837 (A) and -0.401 (B). Note that the graph displays the information in suction and the coefficients are for pressure (i.e. the signs are reversed). The exponential function fitted the suction data well, with a maximum error of approximately 1 kPa.

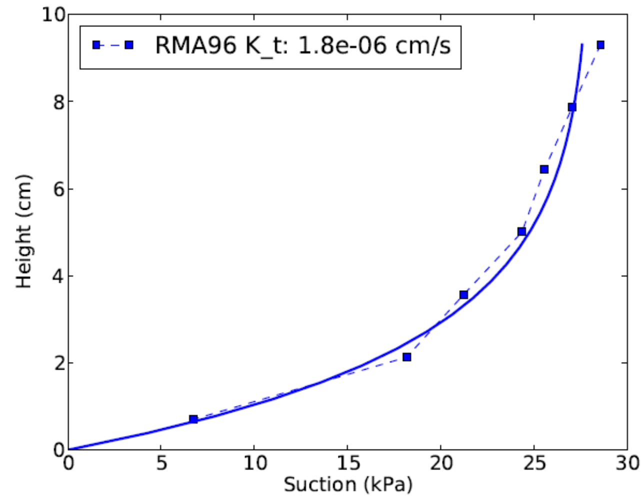

Figure 8.7 - Suction profile of RMA96 (dashed line - calculated suction, solid line - fitted function)

Using the fitted exponential suction and the known gravitational acceleration, the gravitational gradient (Equation (29)) and suction gradient (Equation (32)) could then be calculated for each slice of the sample. The total gradient (the sum of gravitational and suction) could then be calculated. The results are displayed in Figure 8.8. The gravitational gradient decreased in magnitude from the base of the sample to the top as it scales with centrifuge radius. The suction gradient is controlled by the distribution of moisture content and was highest near the base, where the largest changes in moisture content (and suction) occurred. Near the top of the sample the suction gradient had nearly become zero, resulting in the total gradient being dominated by the gravitational gradient.

The total gradient was then used to calculate the hydraulic conductivity for each slice. The results are shown in Figure 8.9. The hydraulic conductivity started high at the base where the sample was wettest and reduced until approximately 6 centimeters from the base where it remained fairly constant up to the last slice. The calculated hydraulic conductivity at the top of the sample is very close to the target hydraulic conductivity of 1.8×10^{-6} cm/s (log value of -5.74) as the suction gradient in this area is nearly zero, which is the assumption of the target hydraulic conductivity.

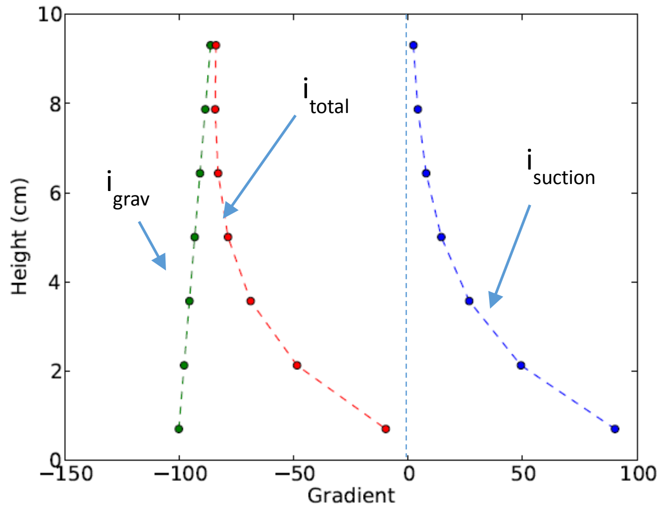

Figure 8.8 - Calculated gradients (with respect to radius) for RMA 96

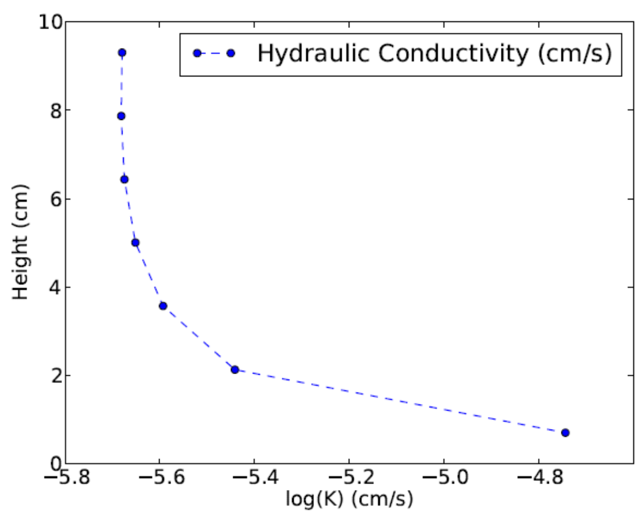

Figure 8.9 - Calculated hydraulic conductivity of RMA96

8.2 Series "IF" Testing Program

In total, 37 soil samples were tested as part of the Series "IF" testing program. These tests were completed using the imposed flow procedure and are is listed in Table 8-2. The goals of the testing program were as follows:

- Determine the relationships among unsaturated hydraulic conductivity, volumetric water content, and void ratio (K-surface);
- Evaluate the effects of compaction moisture content on K-surface.
- Verify the results were in agreement with results obtained from standard testing procedures.

The results of the testing program are discussed in the following sections.

Table 8-2 – Imposed Flow testing program

Sample	Relative Compaction	Compaction Water Content (GWC)	G-level	Imposed flow (mL/h)
RMA100	0.825	0.215	50	20
RMA49	0.8	0.145	50	20
RMA50	0.8	0.145	50	20
RMA51	0.8	0.145	50	5
RMA52	0.8	0.145	50	5
RMA53	0.8	0.145	50	80
RMA54	0.8	0.145	50	80
RMA55	0.8	0.145	25	160
RMA56	0.8	0.145	25	160
RMA65	0.8	0.075	50	20
RMA66	0.8	0.075	50	20
RMA67	0.8	0.215	50	20
RMA68	0.8	0.215	50	20
RMA71	0.9	0.145	100	40
RMA72	0.9	0.075	100	40
RMA73	0.9	0.145	100	20
RMA74	0.9	0.075	100	20
RMA79	0.8	0.075	100	40
RMA80	0.8	0.145	100	40
RMA81	0.8	0.075	100	10
RMA82	0.8	0.145	100	10
RMA83	0.8	0.075	100	40
RMA84	0.8	0.145	100	40
RMA85	0.9	0.145	100	80
RMA86	0.9	0.075	100	80
RMA87	0.9	0.145	100	10
RMA88	0.9	0.075	100	10
RMA89	0.9	0.145	100	160
RMA90	0.9	0.075	100	160
RMA92	0.9	0.215	50	10
RMA93	0.8	0.215	50	10
RMA94	0.8	0.215	50	40
RMA95	0.83	0.145	100	20
RMA96	0.83	0.075	100	20
RMA97	0.85	0.215	100	10
RMA98	0.85	0.215	100	40
RMA99	0.825	0.215	50	10

8.3 SERIES "IF" RESULTS

The Series "IF" (imposed flow) testing program covered a wide range of testing conditions in order to maximize the range of hydraulic conductivity measured. Some testing conditions systematically resulted in poor results and these tests were removed. The process for determining what tests were not considered during analysis is discussed in Section 8.3.1.

The range of void ratio and water content for which unsaturated hydraulic conductivity was measured (for each compaction condition) is then discussed in Section 8.3.2. Finally, fitted surfaces (K-surfaces) to each data set is discussed in Section 8.3.3.

8.3.1 Trimming of Data Set

During analysis of data generated in Series "IF" testing, it was found that there were problematic tests or slices of tests that did not produce results that were consistent with the rest of the data set. These results were grouped into two general categories. These groups included tests that were run use significantly high flow rates and tests that resulted in high suction gradients. They are discussed individually in the following sections.

8.3.1.1 Tests using high flow rates

Samples that were conducted at imposed flow rates that corresponded to hydraulic conductivities larger than the quasi-saturated hydraulic conductivity were found to produce erroneous test results. As the void ratio of the sample varied along the height of the samples, the imposed flow rate was not necessarily above the quasi-saturated hydraulic conductivity over the entire sample, but only over a portion of it.

The simplest method for determining if the tests results were invalid due to too high imposed flow rate was to calculate the hydraulic conductivity for each slice using the procedures discussed in Section 8.1. If the calculated hydraulic conductivity exceeded the quasi-saturated hydraulic conductivity measured by traditional methods for the corresponding void ratio, the test were considered invalid.

However, even without knowing the quasi-saturated hydraulic conductivity, tests conducted at flow rates above the quasi-saturated hydraulic conductivity could be identified. Once the water content and void ratio of the sample were measured, it was found that samples that were tested at imposed flow rates corresponding to hydraulic conductivities above the quasi-saturated hydraulic conductivity showed abnormal results on the top of the sample. One such test result is shown in Figure 8.10 where the top slice of the sample showed a volumetric water content value that was much higher than the rest of the sample. This corresponded with a large increase in void ratio at the surface. This trend was observed in all of the tests that were completed at imposed flow rates corresponding to hydraulic conductivities above the quasi-saturated hydraulic conductivity.

The reduction in void ratio at the surface was likely due to ponding of water on the surface of the sample although ponded water was only observed once at the end of testing. The lack of ponded water may have been due to the centrifuge cup setup that was designed for unsaturated flow. During unsaturated flow the suction in the soil is greater than zero meaning that leakage out of the soil (to zero suction) is unlikely. Accordingly, the centrifuge cup was designed in a manner that facilitated easy and accurate slicing of the sample after testing rather than isolating flow in the sample. When flow rates were encountered that were above the quasi-saturated hydraulic conductivity, the suction in the soil was found to reach zero or even positive pressure values. When this occurred, water may have been lost in between the rings of the split tube sampler, which explains the lack of ponded water on top of the samples even though the quasi-saturated hydraulic conductivity had been exceeded.

Problematic tests could also be identified by comparing results from multiple tests completed at progressively increasing flow rates. A series of tests conducted at flow rates ranging from 10 to 160 mL/h are shown in Figure 8.11. The measured VWC progressively increased between tests conducted at 10, 20, and 40 mL/h and all of the results in this range showed consistent distributions of moisture content. The tests conducted at 80 and 160 mL/h no longer show an increase in VWC, except at the top of the samples where an increase in void ratio was also seen. One data point from the test conducted at 80 mL/h showed abnormal VWC due to a significantly lower void ratio due to over-compaction. The lack of change in VWC in the results obtained from tests conducted using 40, 80, and 160 mL/h suggests that quasi-saturation was reached while running the test conducted at 40 mL/h. Consequently results from tests conducted using flow rates above that value are invalid. When the hydraulic conductivity calculated for these samples is compared with the quasi-saturated hydraulic conductivity (as measured by fixed wall permeameter) the tests conducted at 10 and 20 mL/h result in hydraulic conductivities below the quasi-saturated hydraulic conductivity (from fixed wall permeameters). The results from the test conducted at 40 mL/h result in calculated hydraulic conductivities near the measured quasi-saturated hydraulic conductivity. Finally, results from tests conducted at flow rates of 80 and 160 mL/h result in calculated hydraulic conductivities well above the quasi-saturated value.

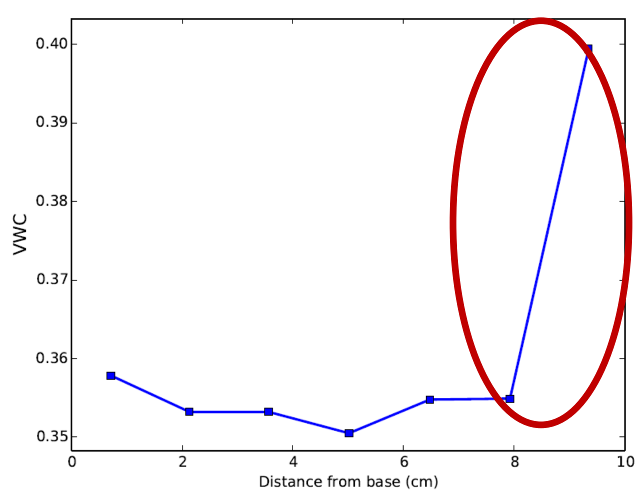

Figure 8.10 - Potential ponding of water on top of sample (RMA55)

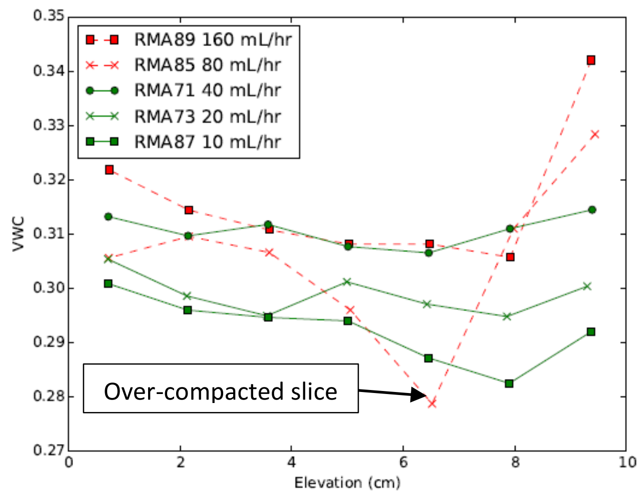

Figure 8.11 - Incrementally increasing flow rates

Consequently, the tests conducted at 80 and 160 mL/h were determined to be invalid independently using three different methods:

- The distribution of moisture in the samples were examined and a large increase in void ratio and water content at the surface was identified, which suggests that ponding of water had occurred;
- The results were compared with other tests conducted at lower flow rates and showed no increase in water content for the sample even though the flow rate was increased;
- The results were compared with the quasi-saturated hydraulic conductivity, obtained using traditional test methods and were found to be higher than the quasi-saturated hydraulic conductivity.

These three methods for detecting tests conducted at imposed flow rates above the quasi-saturated hydraulic conductivity were applied to the entire data set. Overall, thirteen tests were found to be invalid and are listed in Table 8-3. These tests were not used in further analysis.

Table 8-3 - Tests conducted at too high imposed flow rates

Sample	Compaction Condition	Sample	Compaction Condition
RMA72	Dry	RMA89	Opt
RMA86	Dry	RMA97	Wet
RMA90	Dry	RMA98	Wet
RMA55	Opt	RMA92	Wet
RMA56	Opt	RMA99	Wet
RMA71	Opt	RMA100	Wet
RMA85	Opt		

8.3.1.2 High suction gradients

The second group of imposed flow tests that were found to be problematic were those conducted at relatively low flow rates. These tests resulted in distributions of moisture content that were close to hydrostatic conditions. Hydrostatic tests represent a distribution of suction in the sample such that the suction gradient and gravitational gradient are equal and opposite. That is, when imposed flow tests result in distributions close to hydrostatic, the magnitude of the gravitational and suction gradients will be very close each other.

One such tests was RMA52, which was compacted at the optimum moisture condition. The test was conducted at a g-level of approximately 50 and an imposed flow rate of 5 mL/h. The resulting distribution of water content in the sample is shown in Figure 8.12. The lower portion of the sample shows a large change in water content, resulting in a high suction gradient. The suction gradient was calculated as approximately -47 (negative denotes flow towards the surface of the sample). The gravitational gradient was calculated at 51, so the total gradient at this location of the sample was 4. However, with changes in suction as low as 10% the calculated gradient would double or even result in a zero total gradient drastically changing the calculated hydraulic conductivity for this section.

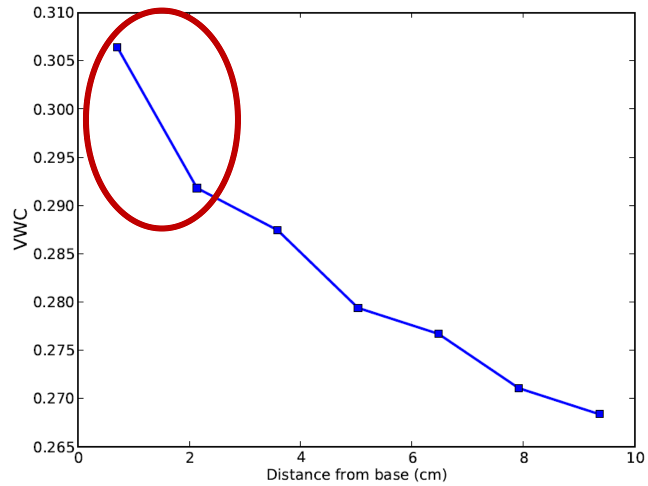

Figure 8.12 - High suction gradient at base of sample (RMA52)

Errors in the calculation of suction gradient could come from a number of sources. The generalized procedure for calculation of gradient was as follows:

- Hydrostatic tests were run at a variety of suctions and void ratios;
- A surface was fit to hydrostatic data;
- Imposed flow tests were run and data measured;
- Suction was predicted using the surface from hydrostatic data;
- An exponential function was fit to suction data versus height, which was used to calculate suction gradients.

Each of these steps includes errors due to fitting, measurement, and soil variability. Accordingly, the accuracy in predicted suction may be compromised. In order to avoid scenarios where a small error in suction gradient drastically changed the calculated hydraulic conductivity, the imposed flow data set was trimmed such that data for which the gravitation gradient exceeded 125% of the suction gradient were considered.

A total of nine tests were identified as having a location within the sample where the gravitational and suction gradients were similar in magnitude. These tests are listed in Table 8-4. For all of the samples listed, only the very base of the sample (slice 6) was determined to be problematic. The remaining slices of the sample remained in the database for analysis.

Table 8-4 - List of samples that slices were removed from due to high suction gradient

RMA65	RMA50
RMA66	RMA51
RMA81	RMA52
RMA96	RMA95
RMA49	

8.3.2 Data Sets for the Three Compaction Conditions

The imposed flow data set for samples compacted at the dry moisture condition is shown in Figure 8.13 in terms of measured volumetric water content and void ratio. The range of the soil water retention surface measured using the hydrostatic testing procedure is also included for reference. Imposed flow test results that were removed from the data set (see Section 8.3.1) are shown as blue "x"s on the graph. The majority of the data that was removed was because the imposed flow rates were too high and the tests resulted in quasi-saturation of the sample. These tests mainly occurred at low void ratios, where the hydraulic conductivity of the samples was comparatively low. The majority of the remaining data set is in the same water content and void ratio range as the hydrostatic data allowing the SWRS from hydrostatic testing to be used to accurately predict suction in these tests.

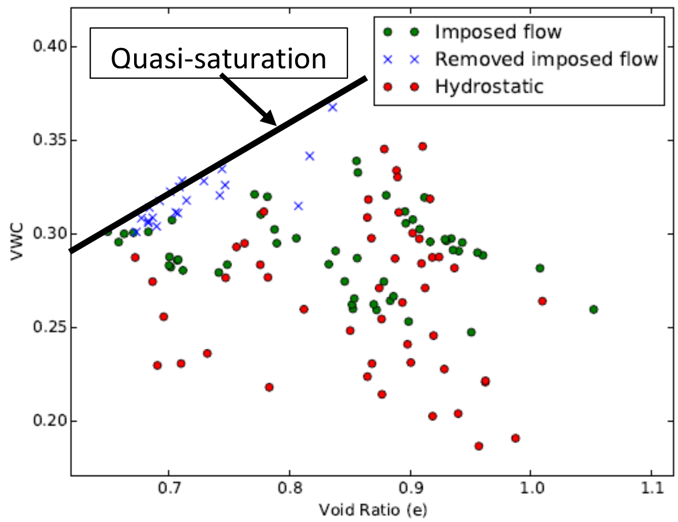

Figure 8.13 - Comparison between imposed flow and hydrostatic tests, dry compaction condition

The data set for Series “IF” (imposed flow) tests conducted on samples compacted at the optimum moisture condition is included as Figure 8.14. In this data set, a larger number of data points were removed due to quasi-saturation. The tests that reached quasi-saturation occurred for a wide range of void ratios and show a well-defined linear trend between void ratio and quasi-saturation. The remaining imposed flow tests still provide a wide range of water content and void ratio for hydraulic conductivity measurement. Some of the imposed flow tests resulted in water contents that were higher than the range measured by hydrostatic testing. This results in the need for extrapolating from the hydrostatic data in order to predict the suction in imposed flow tests. However, the method for fitting a surface to the hydrostatic data incorporated the line of quasi-saturation into the surface. Consequently, while the volumetric water content of these data points was higher than the hydrostatic data, they were in between the data based on the line of quasi-saturation and the hydrostatic data resulting in accurate predictions. This area of the SWRS is also insensitive to changes in VWC (due to large slope between VWC and suction), meaning changes in VWC do not produce significant changes in suction. As a result the suctions predicted for these points were considered sufficiently accurate for calculating hydraulic conductivity.

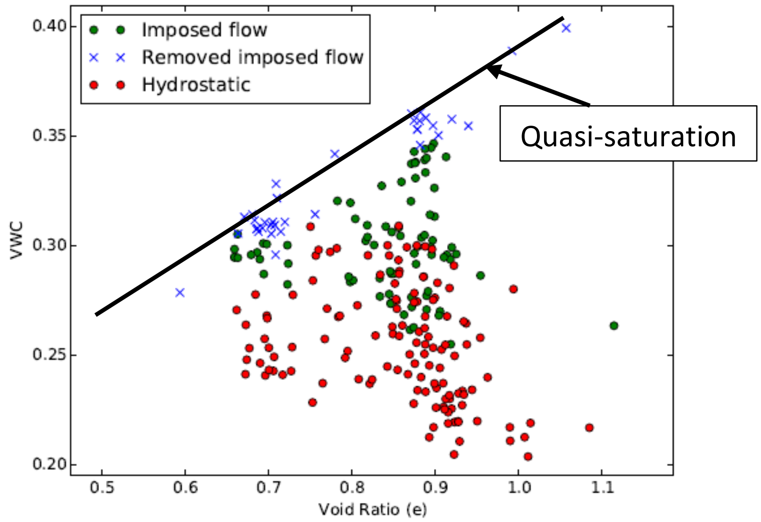

Figure 8.14 - Comparison between imposed flow and hydrostatic tests, optimum compaction condition

The data set for tests conducted on samples compacted at the wet moisture condition is shown in Figure 8.15. As discussed in Chapter 7, Series “H” (hydrostatic) tests conducted on samples compacted at the wet moisture condition exhibited saturated behavior at low void ratios. This meant that measurement of hydraulic conductivity in this region was not possible as the imposed flow testing procedure requires moisture distributions below hydrostatic conditions. The scope of Series “IF” (Imposed flow) tests focused in areas of comparatively high void ratio, where hydrostatic tests resulted in unsaturated specimens. Even in this zone a significant portion of the Series “IF” (Imposed Flow) tests resulted in saturated specimens, which were removed from the data set. The remaining tests conducted on samples compacted at the wet moisture condition were in a narrow range of void ratio. The results were also outside the range of void ratio and VWC measured using the hydrostatic procedure making prediction using the SWRS (from the hydrostatic procedure) questionable. In all four tests were found to have acceptable results but were conducted at very similar void ratios.

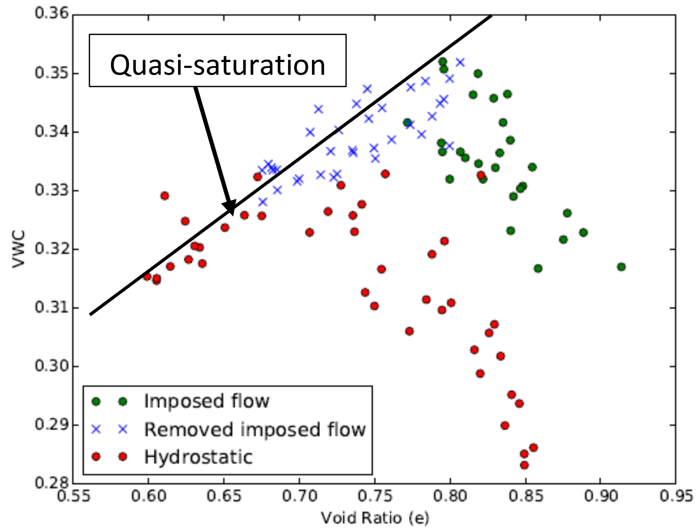

Figure 8.15 - Comparison between imposed flow and hydrostatic tests, wet compaction condition

8.3.3 Hydraulic Conductivity Surfaces

Series "H" (Imposed Flow) testing resulted in values of hydraulic conductivity for a wide range of void ratio and volumetric water content. After trimming (Section 8.3.1), the total data set contained 161 data points. The distribution of points for each compaction moisture condition is listed in Table 8-5.

Table 8-5 - Hydraulic conductivity data set

Condition	Data Points
Dry	52
Optimum	82
Wet	27

The hydraulic conductivity, void ratio, and volumetric water content should form a unique relationship, which will be referred to as the hydraulic conductivity surface or K-surface. The data sets for each compaction moisture condition are discussed individually in the following sections and 3D functions (surfaces) were fit to the data set.

8.3.3.1 *Dry Compaction Condition*

A total of 52 points defined the data set for samples compacted at the dry moisture condition. The relationship between hydraulic conductivity, void ratio, and volumetric water content produced a consistent surface for these points. A filled contour plot of the data is included in Figure 8.16. The line of quasi-saturation is included for reference. The relationship of hydraulic conductivity with the other variables was found to be log-linear. Therefore the fitting and plots are presented with hydraulic conductivity shown with a log based reference system. The calculated hydraulic conductivity for the data varied from approximately $1x10^{-6}$ cm/s to $1.6x10^{-5}$ cm/s. Hydraulic conductivity was found to increase with increasing void ratio and volumetric water content. At a hydraulic conductivity of approximately -5.75 $\log_{10}$ cm/s (or $1.8x10^{-6}$ cm/s) the surface underwent a change in slope denoted by a line on the figure.

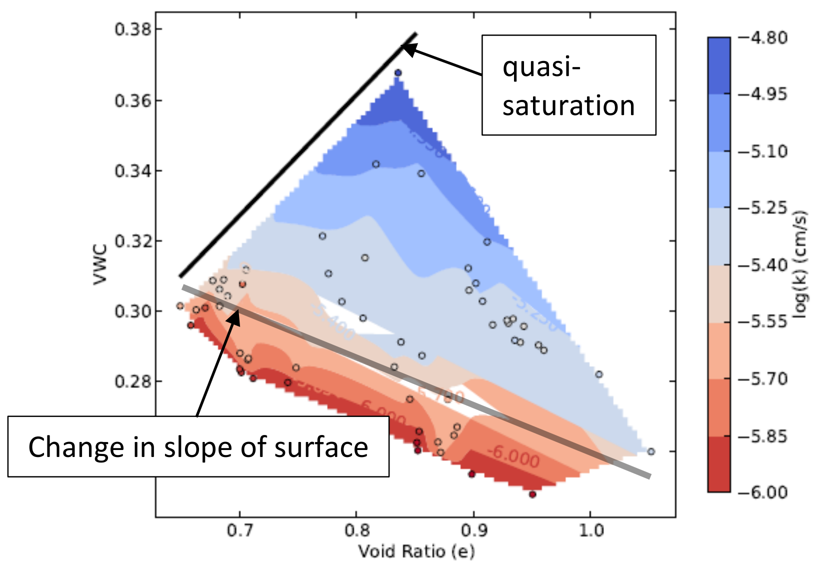

Figure 8.16 - Hydraulic conductivity contour, dry of optimum

A 3D plot of the data is included in Figure 8.17. The view of the 3D plot is oriented so that the K-surface is approximately perpendicular to the page and makes the change of slope in the surface more apparent. The surface is approximately planar except for at a hydraulic conductivity of $1.8x10^{-6}$ cm/s the surface appears to change in slope. The data below the change in slope consists of results from only two tests. Therefore, the lower portion of the surface is not well defined and it is possible that change in slope is due to insufficient test results in this area.

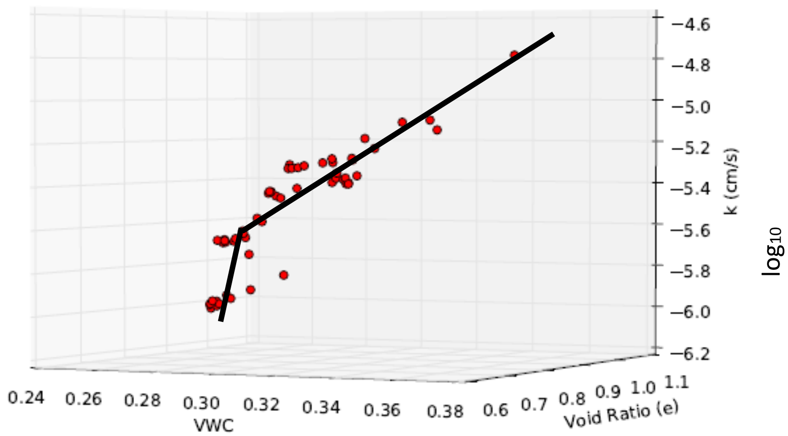

Figure 8.17 - Change in slope of K-surface, dry data set

A plane was fit to the results using the least squares method. This fitting was performed only on the data above the change in slope in order to accurately predict the shape of the surface in this area. Fitting was not performed in the lower section as there was not sufficient data for fitting. The resulting surface is listed as Equation 35 and graphed with the data set in Figure 8.18. The planar surface modeled the data well with comparatively low errors. The mean error was calculated just over 1% with a maximum error of just under 4% (over-prediction).

$$log_{10}(K) = -9.052 + 1.051e + 9.257\,VWC \tag{35}$$

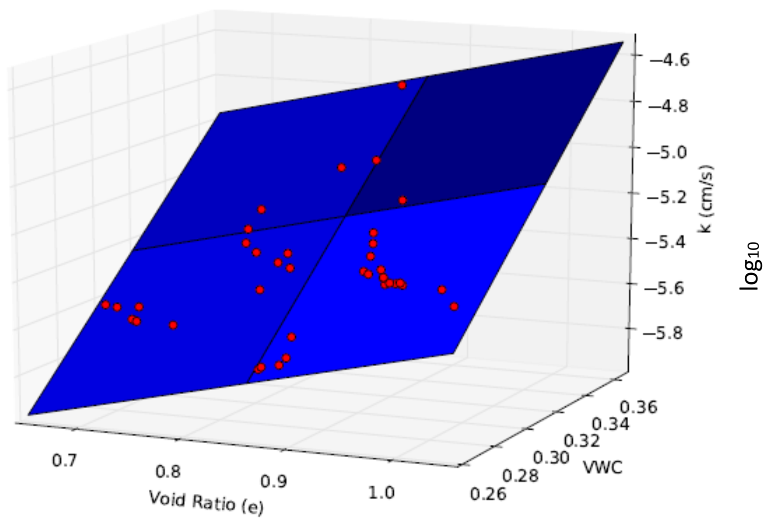

Figure 8.18 - Fitted surface to dry data set above slope change (log10(K)>-5.75)

8.3.3.2 Optimum Compaction Condition

The data set for samples compacted at the optimum moisture condition consisted of 82 data points with hydraulic conductivity ranging from 6.61×10^{-5} to 1×10^{-6} cm/s. The optimum data set had the most data points and was conducted at the greatest range of hydraulic conductivity, void ratio, and volumetric water content. A contour plot of the data is shown in Figure 8.19. The general shape of the surface is planar. The Matplotlib contour() algorithm calculated contours that suggested that near the line of quasi-saturation the void ratio has little effect on the hydraulic conductivity as the contours are horizontal in this region. Further away from quasi-saturation, the contours curve downward representing an increase in hydraulic conductivity with increasing void ratio.

It is possible that there is a change in slope of the surface similar to the change in slope observed in the results from tests conducted at the dry compaction moisture condition. However, such change is much less pronounced in the optimum data set than in the dry data set. A 3D plot of the data set is included as Figure 8.20. A potential change in slope in the surface is shown that occurs at approximately the same hydraulic conductivity value as in the dry data set. Both surfaces showed changes in slope at this location, which supports that this was an actual phenomenon occurring in the soil and not the product of measurement errors or scatter.

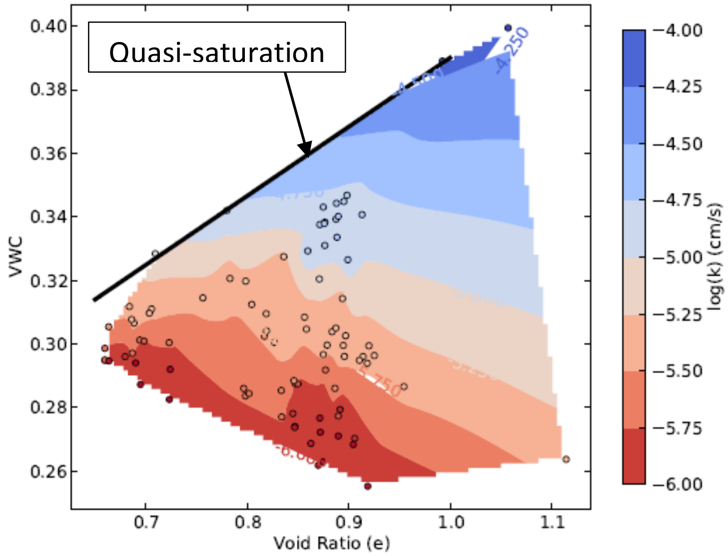

Figure 8.19 - Hydraulic conductivity contours, optimum

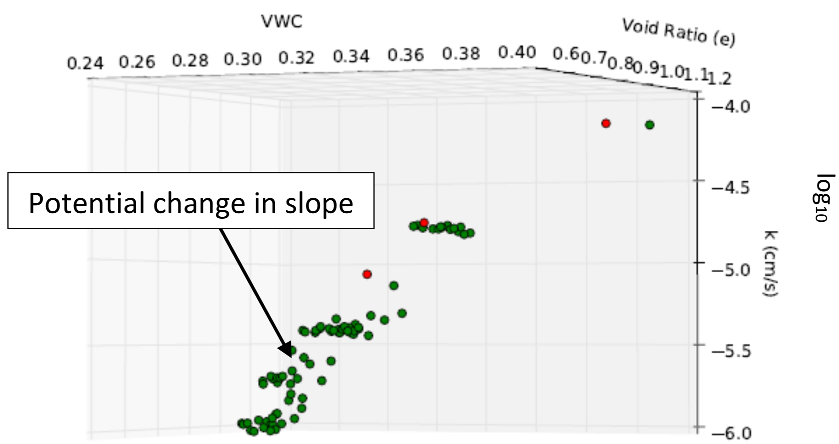

Figure 8.20 - Change in slope of K-surface, optimum data set (red points from potentially saturated tests)

A planar surface was fit to the optimum data set using the same procedures as the dry data. The resulting surface is described by Equation 36 and is shown graphed with the optimum data set in Figure 8.21. The mean error of the surface was 1.6% with a maximum error of 10% (under-prediction). The maximum error occurred at a point that was far away from the majority of the data and is shown on the figure.

$$log_{10}(K) = -10.676 + 1.149e + 14.16\, VWC \quad (36)$$

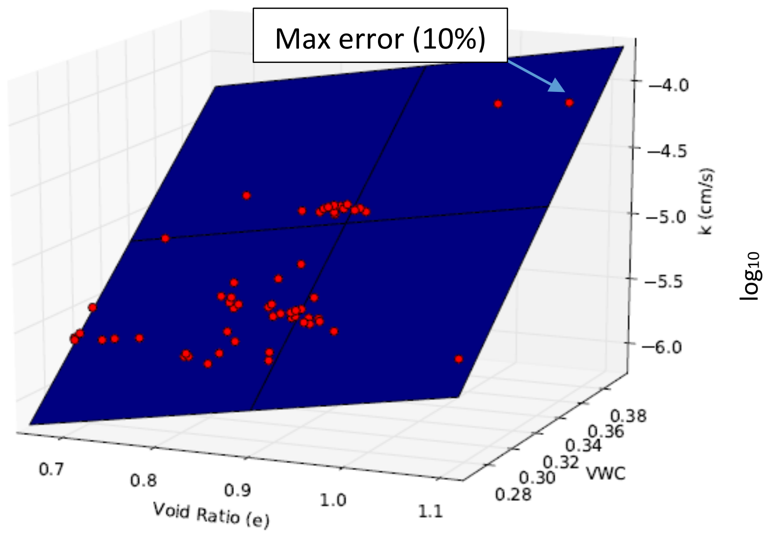

Figure 8.21 - Fitted surface to optimum data set

8.3.3.3 Wet Compaction Condition

Imposed flow testing conducted on samples compacted at the wet moisture condition was problematic due to significant changes in hydraulic conductivity with void ratio. At high relative compaction the soil was homogeneous in structure with no visible voids. At lower relative compactions large voids were visible in the structure in between clods of soil. A large increase in hydraulic conductivity was observed in the samples with large voids. The transition in soil structure occurred at a void ratio between 0.7 and 0.8. The effects of void ratio will be fully discussed in Section 9.3.

When Imposed Flow tests were run on the samples compacted at the wet moisture condition problems were encountered on both sides of this transition. On the low void ratio side of the transition the hydraulic conductivity of the soil was low resulting in quasi-saturation of samples for most of the flow rates tested. On the high void ratio side of the transition the hydraulic conductivity increased dramatically and the same imposed flow rates resulted in distributions of moisture content that produced high suction gradients. In order to calculate the hydraulic conductivity in tests with high suction gradient, the suction gradient must be accurately calculated. However, there was no hydrostatic data in this region and all of the suction predictions were based on extrapolation of the SWRS beyond the range of measured data.

In order to demonstrate these problems, results from three tests conducted on samples compacted at the wet moisture condition using an imposed flow rate of 10 mL/h are shown in Figure 8.22. The tests were run at different relative compactions to target different void ratios. The test run at low void ratio (green) resulted in saturation of the sample. The top of the sample showed a significant increase in water content, which is indicative of ponding water, meaning the results were invalid and the imposed flow rate was too high. The test run at a mid void ratio (red) resulted in moisture uniformly decreasing with height. This meant that the test was not saturated. The changes in moisture were relatively low meaning the suction gradient was also low and hydraulic conductivity was accurately calculated. The third test at high void ratios (blue) resulted in large decreases in moisture content across the entire sample. The suction gradient in this case was high enough that small errors in calculation of suction gradient would result in large errors in the predicted hydraulic conductivity (see Section 8.3.1.2).

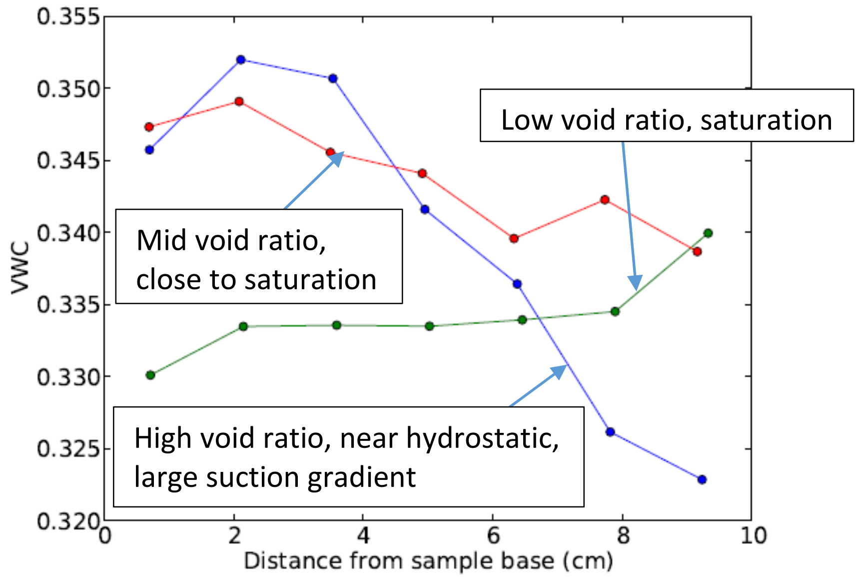

Figure 8.22 - Changes in behavior with void ratio, imposed flow tests at wet condition, 10 mL/h, 50g

In summary the three samples were tested at the same compaction moisture condition but at different void ratios. The results from low void ratios were invalid because the flow rate was too high and water ponded on the surface. The results at "mid" void ratios resulted in acceptable test results. The results at high void ratios were inaccurate due to a flow rate that was too low and resulted in a distribution close to hydrostatic conditions. The total change in void ratio across the three tests was only 0.15. The sensitivity of the soil behavior to void ratio in this region resulted in a significant portion of the test results being unusable.

Creating contour plots and fitting a surface to data from samples compacted at the wet moisture condition was not possible due the small number of data points collected and the large scatter in the results. The data set is shown in Figure 8.23 with some general contours manually drawn. The dashed black line represents the significant change in hydraulic conductivity across the region. Results from hydrostatic tests are included to show that the imposed flow results were at considerably higher water contents than the results from hydrostatic tests. This meant that the predicted suctions of the imposed flow tests (predicted based on the SWRS) were beyond the range at which the hydrostatic data was measured. This extrapolation may have led to errors in the predicted suction.

On both sides of the transition, the general trend was an increasing hydraulic conductivity with increasing water content. Void ratio seemed to have little effect on the hydraulic conductivity at void ratios lower than the void ratio corresponding to the transition in behavior (0.75). At void ratios higher than the transition void ratio, increases in void ratio resulted in increases in hydraulic conductivity. These trends are not well defined due to scatter in the data and the limited range of testing completed.

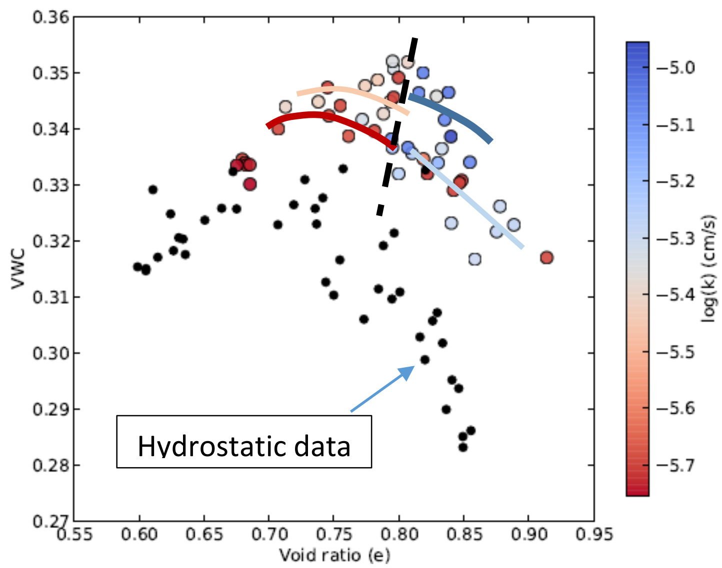

Figure 8.23 - Imposed flow tests on wet samples, hydrostatic data for reference

8.4 Limitations of the Imposed Flow Procedure

The imposed flow procedure relies on many of the same principles as the hydrostatic procedure. As a result, it was found that the imposed flow testing procedure includes many of the same limitations as the hydrostatic procedure. These include:

- The measurement of volumetric water content and void ratio were not taken while the sample was under the centrifugal acceleration. Changes may have occurred between the equilibrium state and measurement.
- Specific ranges of void ratio were difficult to target. The compaction void ratio is reduced in the centrifuge due to increases stresses.

These limitations were discussed in detail in 7.4 and will not be further discussed here.

An additional limitation, which is unique to the Imposed Flow testing procedure (which relies on steady state flow) is the lower boundary condition. The effects of the lower boundary is a limitation of the range of hydraulic conductivity that can be measured using the imposed flow procedure. Theoretical distributions of water content over time are shown for a sample tested using the imposed flow procedure in Figure 8.24. The moisture front advances down the sample at a water content referred to as the transient water content. As the moisture front reaches the zero suction boundary, the moisture content begins to build up near the base in order to reach a water content corresponding to zero suction. Eventually the steady state distribution is reached, which is slightly higher than hydrostatic.

In a steady state distribution such as the one illustrated in Figure 8.24, the gradient required to transmit the imposed flow rate is low. This is a result of the distribution of water content being dominated by the lower boundary condition rather than the imposed flow. The transient water content (labeled $VWC_{transient}$ in the figure) refers to the volumetric water content required to transit the imposed flow rate given the gravitational gradient (acting towards the base). At the steady state distribution the water content, and therefore hydraulic conductivity, has increased from the transient values. As a result the hydraulic gradient must decrease proportionally to the increase in hydraulic conductivity in order to maintain the same flow rate.

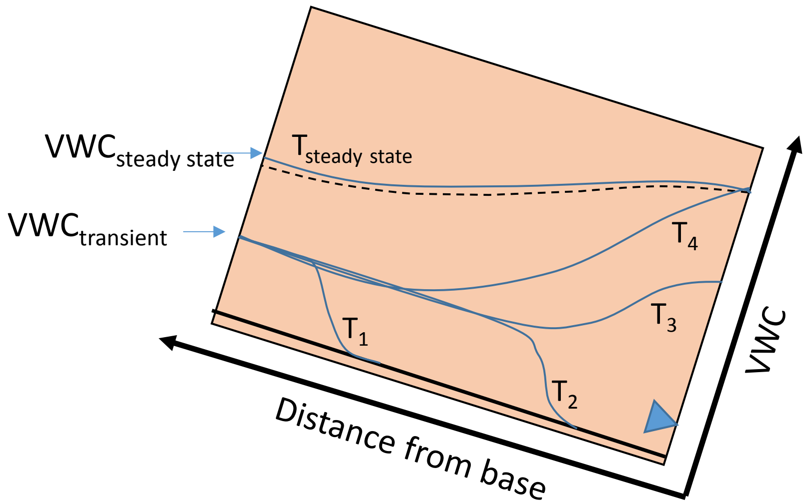

Figure 8.24 – Schematic distributions of moisture content over time of sample tested at low imposed flow rate, dashed line represents hydrostatic distribution of moisture content

The hydraulic conductivity can potentially change orders of magnitude between the transient and steady state water content conditions. This means that the gradient, initially 50 or 100 due to gravitational acceleration at transient conditions, is also reduced several orders of magnitude. Small hydraulic gradients in the Imposed Flow testing setup result when gravitational and suction gradients have similar magnitude (but opposite in direction). This means that small errors in the suction gradient will greatly affect the calculated hydraulic conductivity. For example, assuming sample was tested at a g-level of 50 and the gravitational gradient is only 10% larger than the suction gradient the total gradient is approximately 4.5. If the suction gradient is over-predicted by only 5%, it will result in a 100% increase of the measured hydraulic conductivity. If the total hydraulic gradient is higher (25) the same 5% error in suction gradient only results in a 10% change in hydraulic conductivity. The sensitivity to suction gradient (which must be predicted by hydrostatic tests) at low total gradients limits the effective range of measurement of the imposed flow test to flow rates where the gravitational gradient is significantly larger in magnitude than the suction gradient.

8.5 SUMMARY AND FINDINGS FROM TESTING SERIES "IF"

A testing procedure was developed that successfully determined the relationship between void ratio, volumetric water content, and hydraulic conductivity using centrifuge technology. The procedure was referred to as the Imposed Flow procedure, as constant flow rates are imposed on the surface of samples. After steady state flow was reached, the distribution of water content and void ratio were determined directly by slicing samples after testing.

The suction was calculated for each slice of samples by using the soil water retention surface measured using the hydrostatic procedure. The change in suction across samples tested using the imposed flow procedure was found to be modeled accurately using an exponential function of the form $\psi = A(1 - e^{-Bz})$. This function was also easily differentiable and allowed the suction gradient to be calculated at any point in the sample.

The saturated hydraulic conductivity of the RMA soil was not accurately known for each testing condition prior to completing the testing series. As a result, many of the Imposed Flow tests were conducted using flow rates that were higher than the saturated hydraulic conductivity of the soil. This resulted in erroneous test results, which were removed from the data sets.

Tests that were conducted at very low flow rates procedure produced unreliable hydraulic conductivity measurements when the hydraulic gradient was small. Low hydraulic gradients occurred when the suction gradient and gravitational gradient were similar in magnitude but opposite in direction. In such cases small errors in the prediction of suction gradient resulted in large errors for the calculated hydraulic conductivity.

Samples that were compacted at the wet moisture condition did not produce reliable results for the majority of tests conducted. This was due to large changes in hydraulic conductivity with void ratio. Flow rates imposed on samples of low void ratios were too high and flow rates imposed on samples with high void ratio were too low to reliably measure hydraulic conductivity.

Samples compacted at the optimum compaction moisture condition showed consistent results when tested using the imposed flow procedure. Results were measured for a wide range of unsaturated hydraulic conductivity and void ratio allowing a surface to be created that defined the relationship between K, e, and VWC. The surface was found to be modeled well by a plane and referred to as the K-surface. Likewise, samples compacted at the dry compaction moisture condition showed consistent results when tested using the imposed flow procedure and the results were well modeled well by a plane.

8.6 RECOMMENDATIONS

As with the hydrostatic procedure, it is recommended that future testing include in-flight measurement of volumetric water content and void ratio. This would be important to facilitate that changes due not occur when stress levels and gradients are changed due to removal of centrifugal acceleration.

Measurement of suction at some location in Imposed Flow samples is recommended. This would allow predictions of suction using the SWRS from hydrostatic results to be verified. The current procedure included no direct measurement of the suction profiles.

Some indication of water ponding on samples should be included. This could be accomplished by using a pressure sensor at the surface of samples. In many cases the flow rate imposed on the samples was above the rate that the sample could transmit, resulting in the ponding of water. This was not always observed on the sample as it may have drained by the time samples were removed from the centrifuge.

It is recommended that future testing rely, at least in part, on transient measurements and analysis. The lower boundary condition was shown to have significant effects on the steady state distribution of moisture in the sample. As a result, the effective range of hydraulic conductivity measurement using stead-state methods was limited. In order to improve the effect measurement range, methods of transient analysis should be explored.

9 ANALYSIS OF SERIES "H" AND "IF" RESULTS

9.1 QUASI-SATURATION OF SAMPLES

As discussed in Section 2.5, soil samples that are subjected to soaking or other infiltration processes do not become fully saturated unless back-pressure saturation is used. For fine grained materials it is not uncommon to require large back-pressures (50-100psi) to obtain degrees of saturation above 99% (Mitchell et al 1965).

Samples below 100% degree of saturation may still exhibit behavior which is consistent with a saturated sample. Pressure plate tests conducted on soaked soil samples do not absorb additional water at zero suction and do not expel any water when low suctions are applied. This behavior is expected from saturated samples below the air entry pressure. Hydraulic gradients can also be imposed on soaked samples and flow occurs through them without any increase in the degree of saturation. The maximum water content that can be obtained without back-pressure saturation has been referred to as "quasi-saturation" (Sakaguchi et al. 2005).

Quasi-saturation was observed in samples from both the Series "H" (hydrostatic) and Series "IF" (imposed flow) procedures. Figure 9.1a shows the volumetric water content measured from a sample tested using the hydrostatic procedure. No decreases in water content were seen when suctions up to 95 kPa were applied. A small increase in water content was observed but this was a result of an increase in void ratio near the surface of the sample where the highest suctions occurred. Figure 9.1b shows the distribution of water content from two samples conducted using the imposed flow procedure. One sample (red squares) had an imposed flow rate of almost an order of magnitude higher than the second sample. However, no substantial increase in volumetric water content was measured except at the surface of the sample (where the void ratio was greatly increased due to ponding water). Constant water content with increasing suction (Figure

9.1a) or increasing flow rate (Figure 9.1b) are both indicative of saturated samples. In all three of these samples the measured porosities were above 0.39, so the degree of saturation for the quasi-saturated condition was approximately 80%.

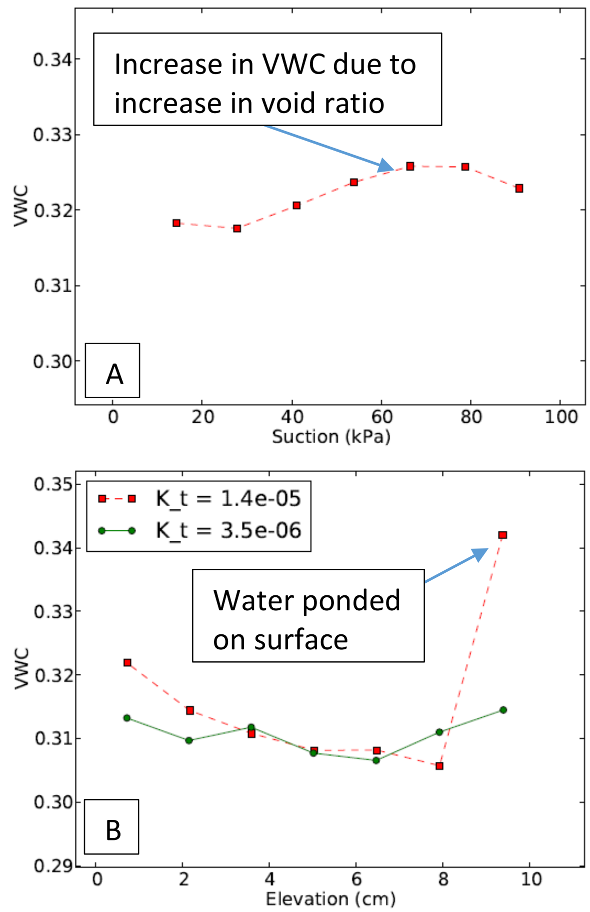

Figure 9.1 - Results exhibiting saturated behavior - a) Hydrostatic results b) Imposed flow results

The volumetric water content required for quasi-saturation was expected to be affected by void ratio. Hydrostatic tests performed on samples compacted at the wet moisture condition are shown in Figure 9.2a. The data is displayed using void ratio on the x-axis and volumetric water content on the y-axis. The suction calculated for each point is represented by color with high suctions as red and low suctions as blue. The data between void ratios of approximately 0.6 and 0.7 show no change in water content with suction meaning that the soil was below the air entry suction and at a quasi-saturated state. A red line was inserted in Figure 9.2a that follows the general trend between the VWC for quasi-saturation and void ratio in this region.

Imposed flow tests run at a similar range of void ratios are shown in Figure 9.2b along with the hydrostatic test results. Several of the imposed flow tests were performed at flow rates above the quasi-saturated hydraulic conductivity, as measured using fixed wall permeameters, and were expected to be at a state of quasi-saturation. The imposed flow test results match well with the line for quasi-saturation previously drawn from hydrostatic tests, suggesting that the volumetric water content required for quasi-saturation is independent of state of flow in the sample (hydrostatic tests were conducted at a no-flow condition while imposed flow results were under steady state infiltration). The relationship between void ratio and the maximum water content achieved without back-pressure saturation will be referred to as the line of quasi-saturation, following the nomenclature used for the line of saturation.

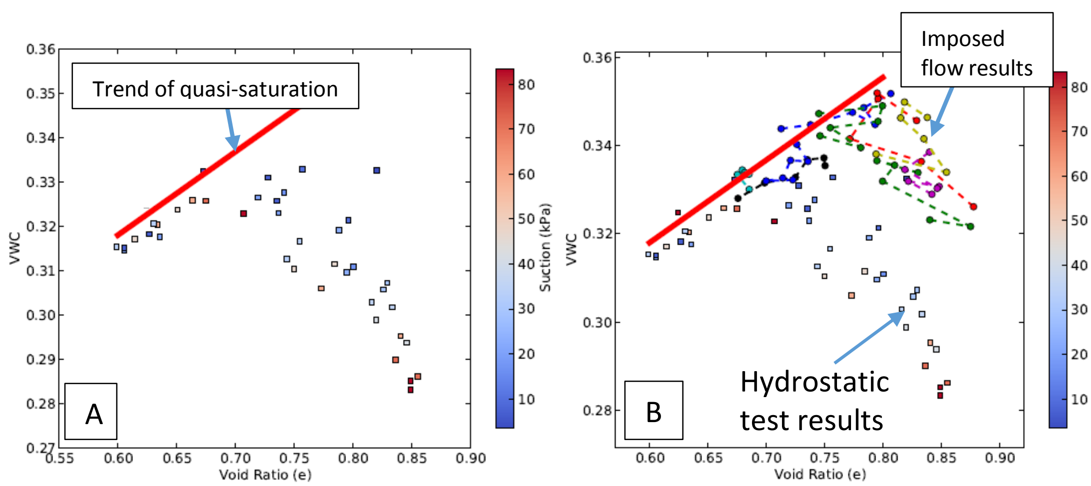

Figure 9.2 – Quasi-saturation of wet compaction condition, a) Hydrostatic b) and Imposed flow

In order to determine whether the volumetric water content at quasi-saturation defined using centrifuge methods was similar to that defined using non-centrifuge results, the results obtained using fixed wall permeameter tests were examined. The fixed wall permeameter tests were performed without back-pressure saturation in order to represent a wetting front that may occur under typical conditions (large pore pressures are not expected for soils where unsaturated flow occurs). Small pressures (between 0.25 at 2psi) were applied to the base of specimens in order to promote flow through the samples and therefore the results are not directly comparable to the centrifuge results, which were under no pressure. The volumetric water content measured at the end of testing using fixed wall permeameters are shown in Figure 9.3. The saturated VWC (porosity) is included for reference. The degree of saturation obtained after completion of the permeameter test was measured below 100%. Samples compacted at the wet compaction moisture condition resulted in the highest degrees of saturation. Specifically, a 93% degree of saturation was obtained for low void ratios and 96% for high void ratios, although there may have been issues with these tests, as will be discussed later. Samples compacted at dry and optimum compaction moisture conditions resulted in significantly lower degrees of saturation ranging from 80 to 88%. The samples compacted at the dry moisture condition resulted in slightly higher degrees of saturation than the samples compacted at the optimum moisture condition.

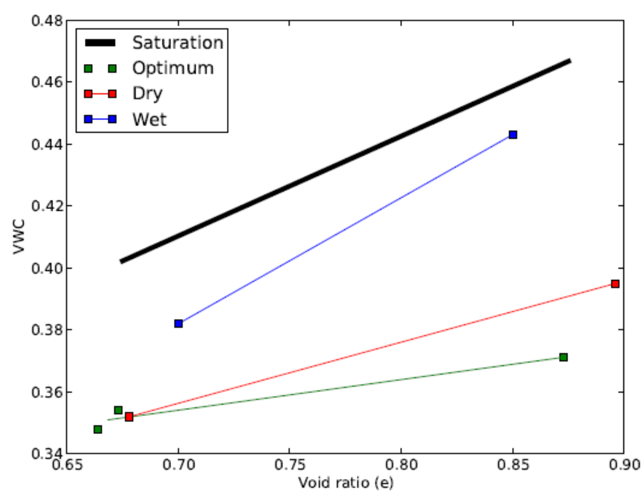

Figure 9.3 - Quasi-saturation lines defined using results from fixed wall permeameter tests

The centrifuge results are plotted against the fixed wall results in Figure 9.4 for all three compaction moisture conditions. When compared with centrifuge, results the fixed wall permeameter tests showed comparatively higher water contents at the end of testing for all compaction conditions. At high void ratios, samples compacted at the dry moisture condition resulted in similar degrees of saturation when tested using both centrifuge and fixed wall permeameter methods. At low void ratios, samples from fixed wall permeameters resulted in higher levels of saturation (~2% VWC). Similarly, samples compacted at the optimum moisture condition showed little difference from the centrifuge results at high void ratios but showed between 3 to 4% higher VWC at low void ratios.

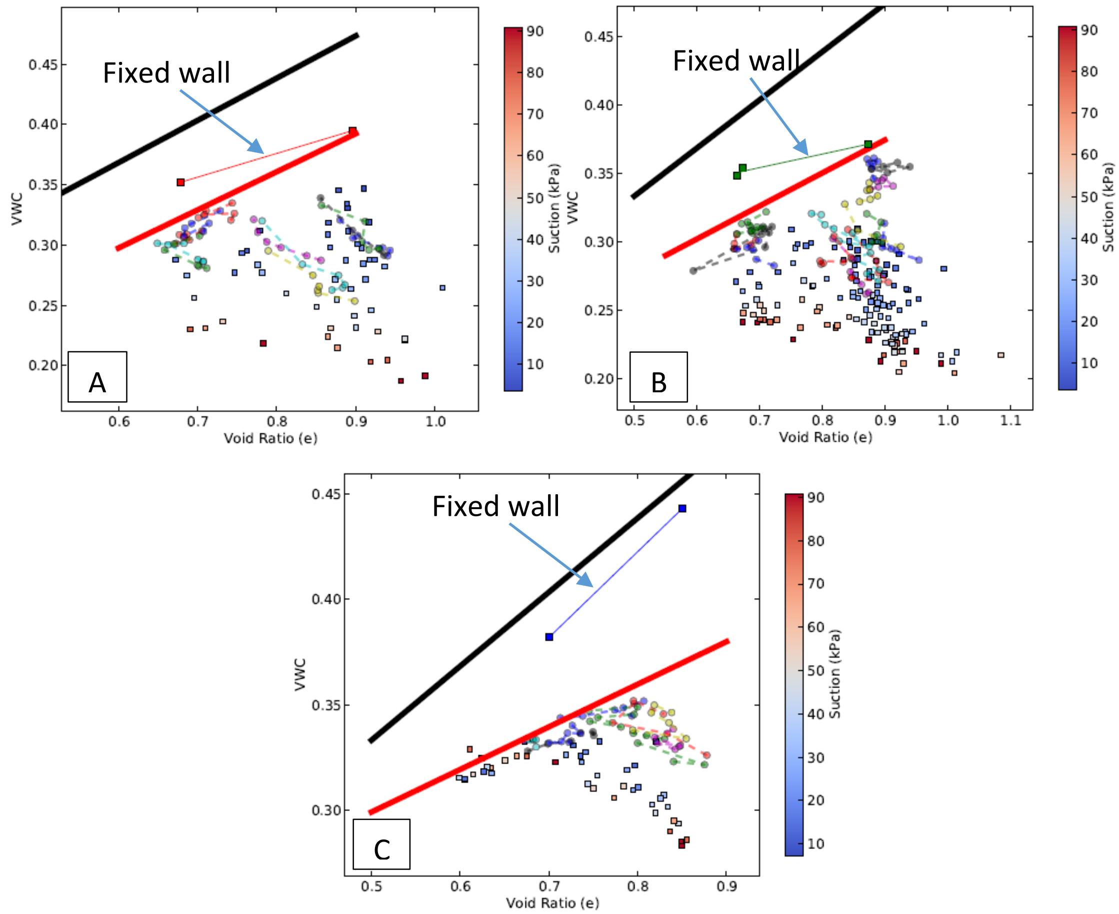

Figure 9.4 - Comparison of saturation of fixed all permeameter tests with centrifuge results (true saturation – black, quasi-saturation – red) a) dry compaction moisture condition, b) optimum compaction moisture condition, c) wet compaction moisture condition

The fixed wall permeameter tests for samples at the wet compaction condition were significantly higher than centrifuge results for both low and high void ratios. The differences ranged from 4% VWC at low void ratios to 8% at high void ratios. It was not apparent why the samples compacted at the wet moisture condition resulted in water contents that were much closer to saturation for the fixed wall permeameter tests.

One possibility is that the increase in saturation may have been due to errors in measurement for the volume of water in the fixed wall samples. In the fixed wall permeameter tests, soil water content was measured before compaction and after permeation was completed. The increase in mass of the sample during permeation was also measured. These three measurements should be in agreement with one another, where the volume of water calculated based on the initial water content plus the increased volume of water in the sample during permeameter (determined by the measured change in mass) should equal the volume of water calculated based on the final water content. In the permeameter tests conducted on the samples compacted and the dry and optimum moisture conditions, this was the case. Only small differences in volume of water (<1% VWC) were calculated depending on whether the initial or final water content measurement was used. For the samples compacted using the wet moisture condition the difference was much larger (>6% VWC).

The results from the fixed wall permeameter tests conducted on the samples compacted at the wet moisture condition are re-plotted in Figure 9.5 using the back-calculated volume of water. The back-calculated results are in better agreement with the results from samples compacted at dry and optimum moisture conditions suggesting that the high degrees of saturation from the samples compacted at the wet moisture content may have been due to an error in measurement of the initial water content. The error in measure of the initial water content also resulted in different void ratios for the samples as the compaction mass was based on the initial measured water content.

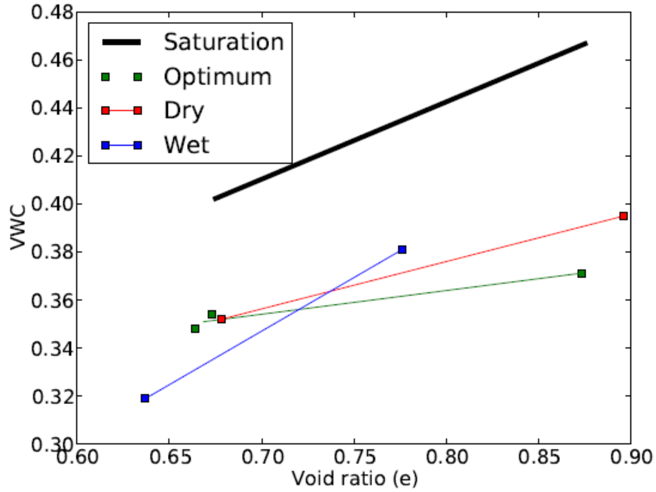

Figure 9.5 - Fixed wall permeameter results, "wet" results based on back-calculated VWC

In summary, results from samples tested in the centrifuge using the hydrostatic and imposed flow procedures were examined. Behavior consistent with saturation was seen in samples from both testing procedures. The measured volumetric water contents of the samples exhibiting saturated behavior was 5-10% below the volumetric water content required for saturation. The difference in volume can be attributed to entrapped air and to inactive air filled voids. The entrapped air was not removed by the flow processes introduced in the centrifuge testing procedures. The wettest state achievable was referred to as the "quasi-saturation" following nomenclature from literature (Sakaguchi et al. 2005).

The volumetric water content required for quasi-saturation varied linearly with void ratio. At a void ratio of 0.6 the volume of entrapped air was approximately 5% of the total volume. The volume of entrapped air increased to around 10% of the total volume at a void ratio of 0.8. The moisture content at compaction was found to have a lesser effect on the volume of entrapped air (changes of 1-2% of the total volume between the different compaction moisture conditions).

The volume of entrapped air in fixed wall permeameter tests was examined. For samples compacted at the dry and optimum moisture conditions, similar volumes of entrapped air were measured between the centrifuge and fixed wall permeameter. The wet moisture condition resulted in a much lower volume of entrapped air in fixed wall permeameter testing compared to the centrifuge results (2-3% of total volume in fixed wall vs. 5-10% in centrifuge). The reduction in measured entrapped air may have been due to measurement errors in the fixed wall permeameter tests conducted on samples compacted at the wet moisture condition.

9.2 Effects of Compaction Water Content

Compaction water content has been shown to have a significant effect on many soil properties including water retention curves (Tinjum et al. 1997) and hydraulic conductivity (Mitchell et al 1965, Benson and Trast 1995). These changes in properties are usually attributed to changes in “soil fabric” or the way the particles are spatially distributed. It has been found that samples compacted wet of optimum result in a more dispersed soil structure where platelets of clay are distributed parallel to each other. Samples compacted dry of optimum results in a more flocculated structure where platelets of clay orient themselves edge-to-face. The distributions of particles does have a major effect on the pore sizes resulting in changes in retention behavior and hydraulic conductivity.

Samples in this study were tested at three compaction moisture conditions. The first was the “dry” condition, which corresponds to 7.5% GWC at compaction. The second was the “optimum” condition, which was determined by standard proctor to be 14.5% GWC. Lastly, a “wet” condition of 21.5% GWC was tested. These compaction conditions are named according to their water content relative to standard proctor optimum water content. As the samples in this study were not prepared following proctor methodologies, the compaction condition names may not necessarily correspond to the actual condition relative to the optimum moisture content of the actual compactive effort used. Samples in this research study were compacted at 80% and 90% of the maximum dry density obtained from standard proctor tests. Depending on the moisture condition and target relative compaction the effort required to compact the specimens may be higher or lower than standard proctor shifting the optimum water content lower or higher respectively.

The moisture condition at compaction had a significant effect on the appearance and behavior of the loose and compacted soil. The wet condition appeared different in consistency as a loose soil than the other two moisture conditions. Loose RMA soil at 21.5% GWC is shown in Figure 9.6. The loose soil was comprised of clumped groups of wet soil particles in a wide range of clump sizes. These groups of soil are referred to as "clods". The clods of soil were much less pronounced in the loose soil at the dry and optimum conditions (Figure 9.7). The dry and optimum moisture compaction conditions appeared to have a more uniform distribution of smaller clod sizes and some individual particles dispersed among the clods.

Figure 9.6 - Loose RMA soil, 21.5% GWC

Figure 9.7 - Loose RMA soil, a) 14.5% GWC b) 7.5% GWC

During compaction the three moisture conditions behaved differently. The soil prepared under wet conditions was very easy to compact to 80% standard proctor density. At this compaction state, large voids were visible in between clods of soil. No voids were visible inside the individual clods of soil. The wet condition was very difficult to compact to 90% relative compaction. At a compaction state slightly below 90% relative compaction, additional compactive effort did not appear to reduce the void ratio. Instead, the soil behaved in a plastic manner where force applied to one area would decrease the height in that specific area but lead to an equal increase in volume in other areas. Visually the soil at this state was uniform with no voids. Samples compacted at the wet moisture condition are shown in clear tubes in Figure 9.8. At 80% RC, voids are clearly visible in the sample. At 90% these large voids have closed and the sample appears to be a near solid mass of soil.

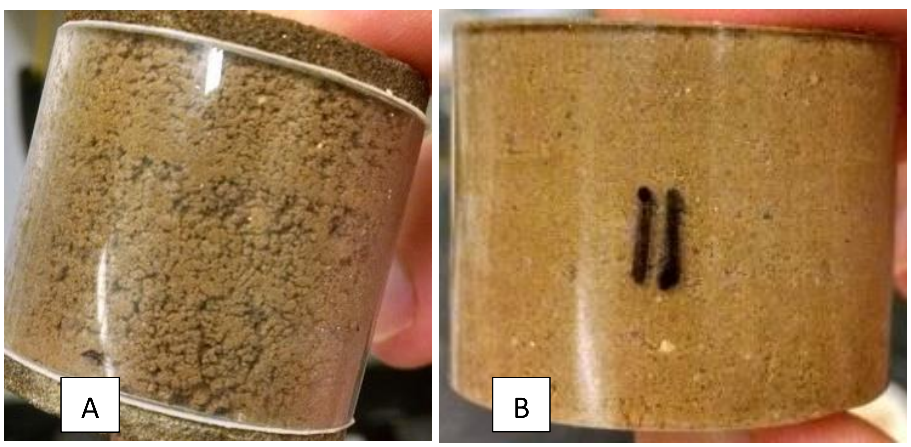

Figure 9.8 - Samples compacted at wet moisture condition - a) 80% RC b) 90% RC

The target compaction state and hydrostatic results of samples compacted at the wet moisture condition targeting 90% relative compaction are shown in Figure 9.9. The initial void ratio corresponds to approximately 88% relative compaction as 90% was not achievable. During centrifugation the samples decreased in void ratio and water content. This was measured both by slicing the specimen and measuring the void ratio and water content and by measuring the height and mass of the entire sample before and after centrifugation. The compaction state started around the line of quasi-saturation and when the stress was increased due to centrifugation water was expelled and the void ratio decreased. The initial and final states both occurred near the line of quasi-saturation. The proximity to the line of quasi-saturation explains why further compaction was difficult to obtain, as the majority of the air voids had already been eliminated from the sample. The air voids that remained corresponded to entrapped air that was not connected to the atmosphere and therefore not expelled during compaction. Difficulties in reaching the target density only occurred for the wet compaction moisture condition, as the optimum and dry moisture conditions contained much less water at compaction and were well below the line of quasi-saturation.

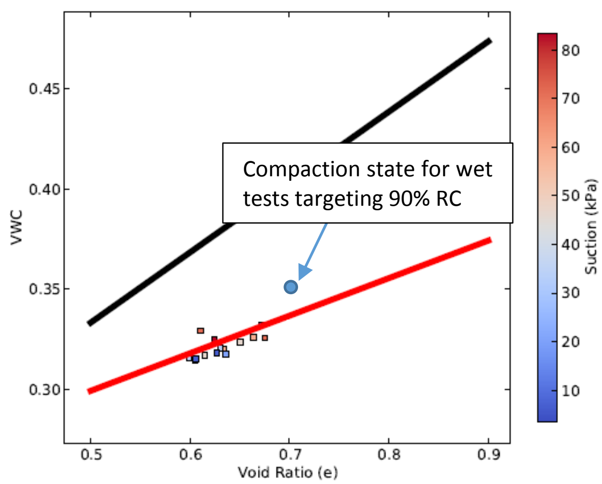

Figure 9.9 – Initial and final conditions of wet tests targeting 90% RC (black line- true saturation, red line – quasi-saturation)

Samples compacted at optimum moisture condition did not have large voids visible at 80% or 90% relative compaction. Some small voids were seen in the samples and photos of samples compacted at the optimum condition are shown as Figure 9.10. Both 80% and 90% relative compaction were easy to achieve using kneading compaction and visually there was little difference between the samples.

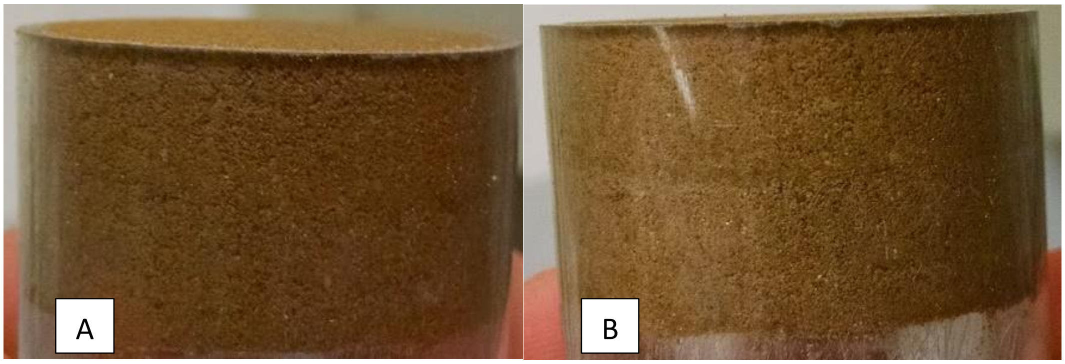

Figure 9.10 - Samples compacted at optimum moisture condition - a) 80% RC b) 90% RC

The dry compaction condition produced a uniform distribution of soil with no significant voids visible in either the 80% or 90% relative compaction condition. Compacted samples at both relative compaction conditions are shown in Figure 9.11. There were no significant visual differences between samples compacted at the dry moisture condition to either 80 or 90% relative compaction. Significant effort was required to achieve 90% relative compaction at the dry moisture condition.

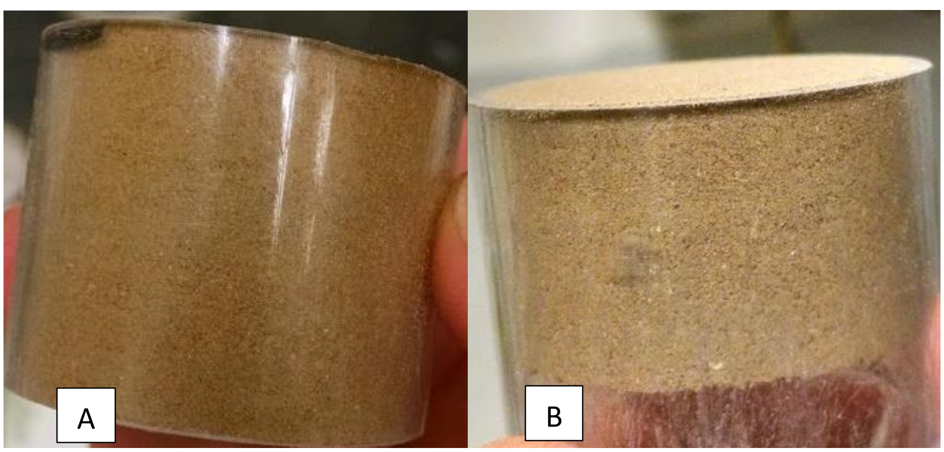

Figure 9.11 - Samples compacted at dry moisture condition - a) 80% RC b) 90% RC

As discussed in Chapters 7 and 8, centrifuge testing was conducted in order to measure the retention behavior and unsaturated hydraulic conductivity of the RMA soil. In the following sections the results are analyzed in order to determine the effects of compaction moisture content on both the soil water retention surface (SWRS) and the unsaturated hydraulic conductivity surface (K-surface).

9.2.1 Effects on the Soil Water Retention Surface

Contours based on the results from Series "H" (hydrostatic) testing were defined for each compaction moisture condition (Figure 9.12). The family of contours for each compaction condition are color-coded with blues representing the wet compaction moisture condition, greens representing the optimum compaction moisture condition, and reds representing the dry compaction moisture condition. The range in void ratio for each family of curves was similar with the results from samples compacted under wet moisture conditions having slightly lower overall void ratios.

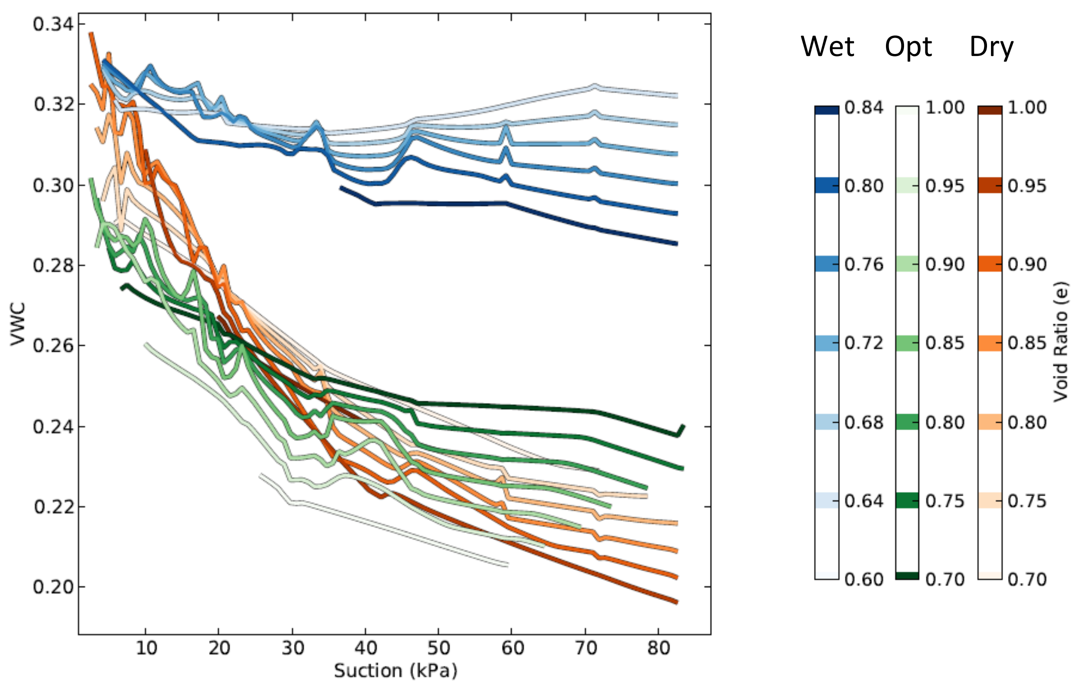

Figure 9.12 - Soil water retention curves at different void ratio for samples prepared using different compaction water contents

Each compaction moisture condition defined a distinct set of curves. Results from samples at the dry and optimum moisture conditions were reasonably similar. The results from the dry moisture condition retained more water than any of the other two compaction conditions at low suctions and less water than the other conditions at high suctions. The results from samples compacted at the wet moisture condition showed the least change across the range of suctions and had significantly higher water contents for suctions greater than 10 kPa.

The retention curves, which range from approximately 5 kPa up to 90 kPa, give information regarding the pore throat sizes corresponding to this range in suction. The total volume of water lost between 5 kPa and 90 kPa represents the volume of pores with pore throat sizes corresponding to that suction range. Using the basic assumption of circular capillary pore throats suctions of 5 and 90 kPa correspond to pore throats with radii of approximately 29 and 1.6 micrometers respectively.

It is also possible to determine information regarding pore sizes of the soil greater than 29 micrometers using the line of quasi-saturation, which was defined for each soil condition in Section 9.1. The total amount of water loss that occurs between 0 kPa (quasi-saturation) and 5 kPa (first measured point in hydrostatic tests) represents the volume of pores that have pore throats larger than 29 micrometers in radius. Likewise it is possible to determine the volume of pores with throats smaller than 1.6 micrometer in radius by calculating the difference between the volumetric water content at 90 kPa and the residual water content for each of the conditions. These values were calculated using results from samples at each compaction moisture content at "high" (0.9) and "low" (0.7) void ratios, as reported in Table 9-1.

Table 9-1 - Change in volumetric water content between different suction ranges for three compaction moisture conditions

	0-5 kPa		5-90 kPa		0-90 kPa		90 kPa+	
	Low *e*	High *e*	Low *e*	High *e*	Low *e*	High *e*	Low *e*	High *e*
Wet	0%	5%	0%	4%	0%	9%	30%	26%
Optimum	3%	5%	4%	10%	7%	15%	20%	16%
Dry	2%	3-5%*	7%	14%	9%	17-19%*	19%	15%

* Line of quasi-saturation estimated in this area

Samples compacted at the dry moisture condition resulted in the largest volume of pores with large throat sizes (defined as emptied by suctions lower than 90 kPa) out of the three compaction conditions. This was true for both high and low void ratios. Samples compacted at the optimum moisture condition resulted in the second most large pores followed by the wet compaction condition, which resulted in the fewest large pores. At low void ratios samples compacted at the wet moisture condition did not have any significant changes in volumetric water content up to 90 kPa meaning that all of the pore throat sizes in the soil were smaller than 1.6 micrometer in radius.

It is reasonable to assume that samples compacted at different moisture conditions but the same void ratio have the same number of particles in them, as the total mass of solids is the same. Some conclusions can then be made regarding the distribution of pore sizes in the samples. If a soil structure is oriented in a manner such that all pores in the soil are of the same size, increases in volume of any single pore must be offset by reduction in size of other pores. Therefore samples compacted at the dry moisture condition, which resulted in the largest volume of large pores, likely also have a large number of small pores to compensate for large pores. Likewise samples compacted to low void ratios at the wet moisture condition, which resulted in no large pore throats, may have a uniform distribution of medium size pores.

9.2.2 Hydraulic Conductivity

The effects of compaction water content on the unsaturated hydraulic conductivity measured during Series "IF" (imposed flow) testing were examined. The comparison between results from samples compacted at the dry and optimum moisture conditions was straightforward as planar K-surfaces could be fit to both data sets. In order to determine the effects of compaction water content, the differences between the different K-surfaces was calculated. A plot with filled contours representing the difference between the K-surfaces of samples compacted at the dry and optimum moisture conditions is shown as Figure 9.13. The data sets for each compaction moisture content are included for reference to illustrate where the data used to fit each K-surface was located.

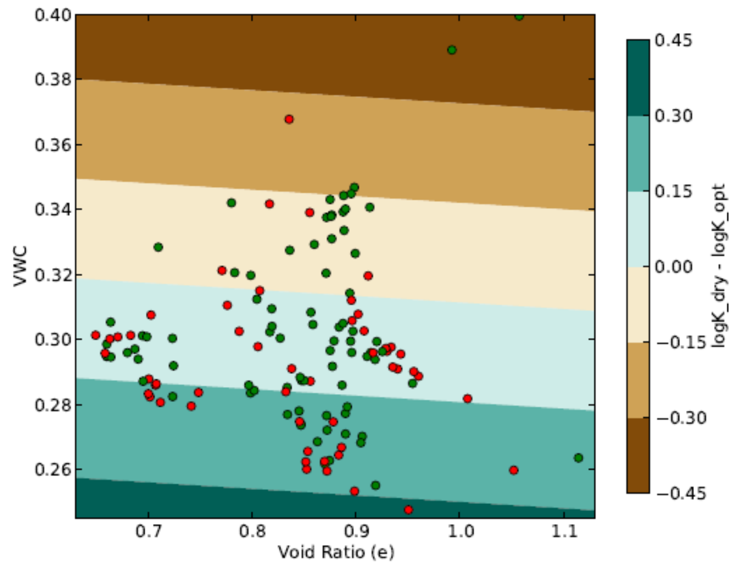

Figure 9.13 – Contours for difference in K-surfaces of dry and optimum conditions (data sets included for reference: dry – red, optimum - green)

At low water contents, samples compacted at the dry moisture condition resulted in higher hydraulic conductivity (denoted by green areas of the contour plot). At a volumetric water content of approximately 32% the two K-surfaces crossed over and reversed the trend in unsaturated hydraulic conductivity between the two compaction conditions. It should be noted that there was limited results for each compacted moisture content above 32% VWC and the change in behavior is not well defined. The data sets were also not perfectly planar and extrapolation past the majority of the data set may lead to significant errors. Therefore the main conclusion from the two data sets is that samples compacted at the dry moisture condition resulted in slightly higher hydraulic conductivities than the samples compacted at the optimum moisture condition over the majority of ranges tested. A few tests conducted at higher flow rates showed a reversal in this behavior but the number of tests conducted was limited and this behavior would need further testing to confirm.

As discussed in Section 8.3.3.3 the data from samples compacted at the wet moisture condition had significant issues and a K-surface was not able to be defined for the data. Therefore it was not possible to compare the data in the same way as for the data sets for the dry and optimum moisture conditions. Instead, select tests were examined in order to determine the relative effects the wet compaction moisture condition had on the hydraulic conductivity. Four test results considered reliable from samples compacted at the wet moisture condition are shown in Figure 9.14 compared with the K-surface fit to data from samples compacted at the optimum moisture condition. The values listed for each of the four "wet" samples (red X's) are the difference between the measured hydraulic conductivity of the "wet" sample and the K-surface for optimum conditions at the same VWC and void ratio. The "wet" samples were below the K-surface fit to samples compacted at the optimum moisture condition in all four cases. At void ratios above 0.8 the difference in hydraulic conductivity was low (20% lower). However at void ratios lower than 0.8 the hydraulic conductivity of samples compacted at the wet moisture condition dropped significantly and the difference between the two compaction conditions became large (80% lower).

In summary the dry compaction condition resulted in the highest measured hydraulic conductivity for the ranges tested. The optimum compaction condition was generally lower, although several points at high volumetric water content showed hydraulic conductivities higher than the dry compaction condition, suggesting there may be a change in behavior at high water contents. The wet compaction condition resulted in the lowest hydraulic conductivities. At high void ratios where the samples compacted at the wet moisture condition had large voids, the difference was relatively minor. At lower void ratios when only small pores were available for flow, the hydraulic conductivity dropped significantly and was nearly an order of magnitude lower than samples compacted at the dry and optimum moisture conditions.

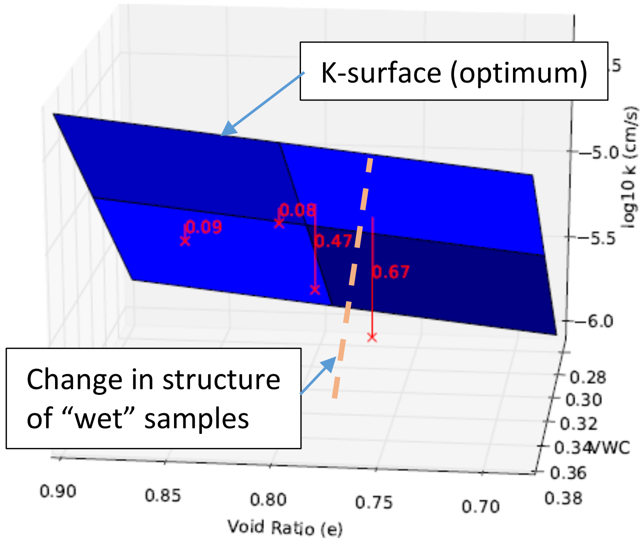

Figure 9.14 - Difference in hydraulic conductivity between wet and optimum compaction conditions (logK_opt - logK_wet)

9.2.3 Summary of the Effects of Compaction Water Content

The effects of compaction moisture content were examined for the RMA soil. Substantial differences in soil structure were visible between the samples compacted at each moisture condition. In particular, samples compacted at the wet moisture condition to 80% relative compaction contained large visible voids in between clods of soil particles, which were not visible in any of the other compaction conditions.

When the hydrostatic testing results were analyzed, large changes in retention behavior were measured. Samples compacted at the dry moisture condition resulted in the highest change in volumetric water content (14%) over the ranges of suction (5-90 kPa) measured using the hydrostatic procedure. The change in water content across the same suction range was reduced to 10% and 4% for samples compacted at the optimum and wet moistures conditions respectively. Samples compacted at the wet moisture condition retained the most water (32% VWC) at the maximum suction measured in the centrifuge (90 kPa). The amount of water retain at 90 kPa by samples compacted the optimum and dry moisture conditions was lower at 20% and 19% respectively. The general trend of compaction water content in the retention results obtained using the hydrostatic procedure was that increases in compaction water content led to reduction in the volume of larger pores in the samples.

Imposed flow testing results showed significant changes in hydraulic conductivity between the different compaction moisture conditions. The unsaturated hydraulic conductivity measured in the centrifuge was highest for samples compacted at the dry compaction condition followed by the optimum and finally wet conditions. This was supported by fixed wall permeameter testing, which showed the same trend in hydraulic conductivity.

Overall, the hydrostatic data and imposed flow data were in agreement with one another regarding changes in pore size of samples compacted at the different moisture conditions. Soils with larger volume of large pores (determined by the hydrostatic procedure) resulted in higher hydraulic conductivity (determined by the imposed flow procedure) for the same porosity. This follows theoretical calculations that large pores should dominate flow processes as the resistant to flow reduces proportionally with radius to the 4th power while volume increases quadratically with radius.

9.3 Effects of Void Ratio

Void ratio has been shown to affect the hydraulic properties of soils (Tinjum et al 1997, Mitchell and Soga 2005, McCartney 2007, Salager et al 2007). Specifically, increases in void ratio have been shown to increase pore sizes resulting in changes in slope to the soil water retention curve along with increases in hydraulic conductivity.

Void ratios between approximately 0.6 and 0.9 were tested during Series “H” and “IF” testing using the hydrostatic and imposed flow testing procedures. The increased stress in centrifuge samples resulted in ranges in void ratio in samples. The void ratios were highest at the top of samples where stresses were lowest and reduced towards the base where stresses were increased. Soils compacted to different relative compactions were also tested in order to increase the range in void ratio tested. The majority of samples were compacted at either 80% or 90% of standard proctor density. Select tests were run in between 80% and 90% relative compaction to characterize soil properties for void ratios that may have been missed using the two standard relative compactions.

9.3.1 Water Retention

The effects of void ratio on the retention characteristics will be discussed individually by compaction moisture condition and then general conclusions will be made.

Dry Moisture Condition

The data set for samples compacted dry of optimum is plotted as Figure 9.15. Contour lines created by the Matplotlib contour() algorithm have been included representing different stages of suction. At quasi-saturation and for low suctions (~<5 kPa) a reduction in void ratio resulted in less water retained (represented by a positive slope between void ratio and VWC). This is consistent with the expected behavior, as there is less pore space available for water to be held as void ratio was reduced. The area of the void ratio-VWC graph where this behavior occurred was referred to as “Zone 1”. At suctions above 5-10 kPa the trend reversed and a reduction in void ratio increased the amount of water retained for a given suction. This area was referred to “Zone 2”. The behavior of Zone 2 can be explained by an increase volume of small pore sizes when the void ratio is reduced. A decrease in void ratio essentially converts large pores into small pores resulting in a higher relative volume of pores filled with decreasing void ratio. In summary for the samples compacted at the dry moisture condition:

- For suctions between 0 and ~10 kPa, a decrease in void ratio resulted in a decrease in volumetric water content (Zone 1).
- For suctions greater than ~10 kPa, a decrease in void ratio resulted in an increase in volumetric water content (Zone 2).

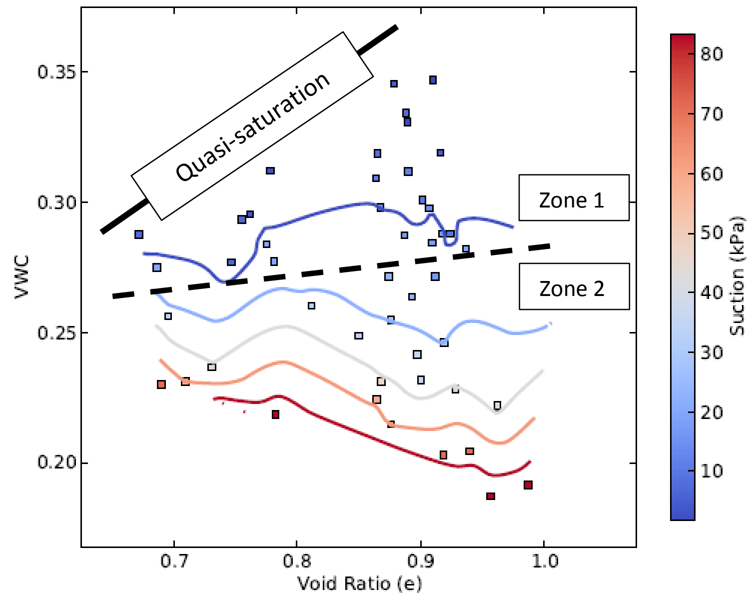

Figure 9.15 - Hydrostatic data, dry of optimum

Optimum Moisture Condition

The same basic behavior seen from samples compacted at the dry moisture condition is seen for samples compacted at optimum water content. The data from tests conducted at optimum water content is shown in Figure 9.16. The data set for samples compacted at optimum moisture condition resulted in the same two distinct zones seen in the "dry" data set. The intersection between the two zones was oriented differently in results from samples compacted at the optimum moisture condition. In the "dry" data set, the intersection occurred at a suction of approximately 10 kPa and appeared to be rather independent of void ratio. For samples compacted at the optimum moisture condition the intersection of the two zones appeared to be highly dependent on void ratio. It is likely that the orientation of the intersection of the two zones is dependent on the location on the soil water retention surface. Using the data from both compaction moisture conditions it can be concluded that increases in void ratio will eventually result in crossing from "zone 1" to "zone 2" as well as increases in suction.

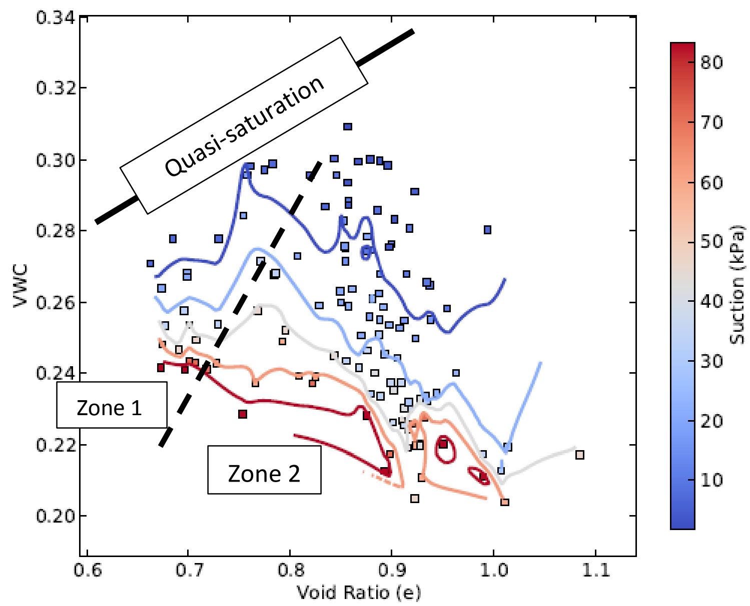

Figure 9.16 - Hydrostatic data, optimum moisture. Dashed line shows border between zones.

The approximate pore throat size of the tests compacted at the optimum moisture condition were calculated by using a bundle of circular capillary tube to represent the soil structure. This assumption relies on the Young–Laplace relationship (Equation (37)) in order to relate the suction of soil to pore throat radius. In an ideal case the radius calculated for a given suction represents the radius of the largest pore throat size that should be filled with water under the given suction. Due to the spatial distribution of pores and effects such as hysteresis this is likely not entirely accurate. However, it is a useful estimate for relating suction to pore throat radius.

$$r = \frac{2\sigma_{aw} cos\gamma}{\psi} \quad (37)$$

The volume of water retained at a suction represents the total volume of pores with throat sizes smaller than radius calculated using the Young-Laplace equation. This information was used to create a phase diagram (Figure 9.17) of the soil at different void ratios.

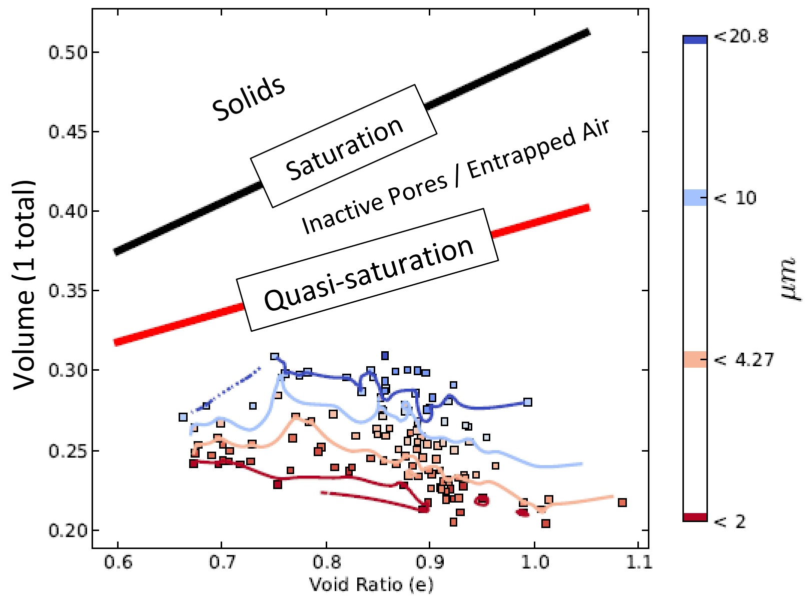

Figure 9.17 - Hydrostatic test results, pore radius / phase diagram

On the phase diagram the line of saturation and quasi-saturation were included. Above the line of saturation represents the volume that was taken up by solid particles. In between the line of saturation and line of quasi-saturation is the relative volume filled by inactive pores or entrapped air. Much of this volume would likely fill under pressure but they remain empty at zero pressure. Below the line of quasi-saturation represents the pore space in the soil that is active and may or may not be filled with water depending on the state of suction in the soil.

The lines of saturation and quasi-saturation follow expected trends with changes in void ratio. An increase in void ratio reduces the percentage of solids in a given volume. Both lines follow similar slopes with void ratio however the line of quasi-saturation is less steep meaning an increase in void ratio also increases the relative volume of entrapped air.

When the active pore space is examined the same trends are seen as when the data was discussed based on suction rather than pore size. Examining the data by pore size rather than suction is useful for explaining what the causes were for trends seen. Contours for several pore throat sizes are included in Figure 9.17 and represent the relative volume of pores with throat sizes smaller than the specific contour. For example the dark blue line represents pores with throats smaller than 20 micrometers in radius. The contour ranges between 0.25 and 0.3 volume meaning that between 25 and 30% of the total volume of the soil is from pores with throat sizes smaller than 20 micrometers.

The same data is shown in Figure 9.18 with the ranges changed in order to focus on the hydrostatic results. The three largest pore throat contours (20.8, 10, 4.27 micrometers) have similar slopes in Zone 2 of the diagram (void ratios between approximately 0.75 and 1). This means that while the total volume of pores with throats smaller than 20.8 is increasing in this range (with a decrease in void ratio) most of the increase is due to an increase of pores with throats smaller than 4.47 micrometers as both contours are increasing equally. This does not mean that the pores with throat sizes between 4.47 and 20.8 are not affected by changes in void ratio but that net change in volume is zero. If pores in this range are decreased in size due to a total reduction in void ratio that volume is replaced by either:

- New pores created in this range due to increased number of particles (lower void ratio)
- Pores with throats larger than 20.8 *u*m being reduced in size to between 4.47 and 20.8 *u*m.

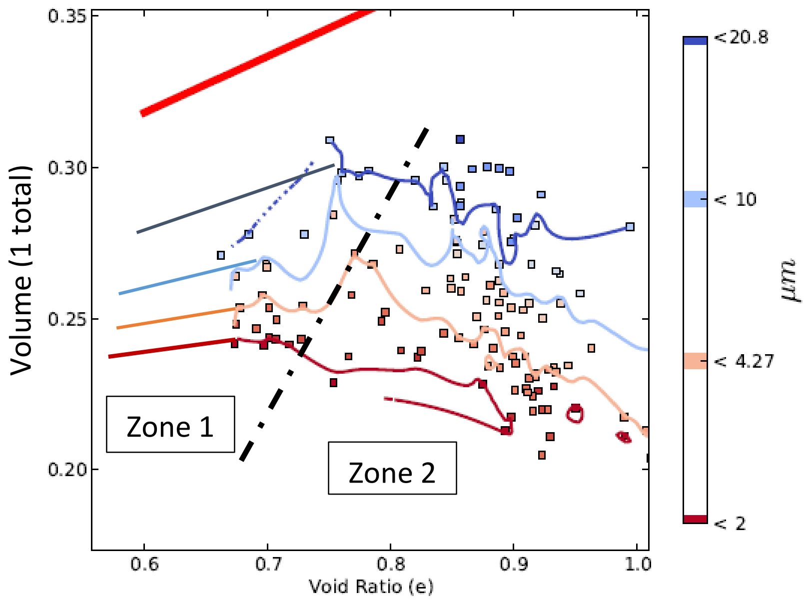

Figure 9.18 - Phase / pore distribution diagram, optimum moisture (zoomed)

All of the pore throat size contours decrease with decreasing void ratio in Zone 1 (void ratios less than ~0.75). The spacing between pore size contours increases with increasing void ratio meaning the pores with throat sizes represented by these contours each individually increase in volume. The slopes of the contours appear as though the contours would eventually converge as the void ratio is decreased. If the trends of the contours continue to low void ratios it suggests that the pores with throat sizes represented by these contours will be eliminated completely (represented by contours intersecting). In such a case the air entry pressure of the soil would be increased to a pressure that could empty pore throats of 2 micrometer or smaller.

The intersection of Zone 1 and Zone 2 represents a change in behavior of the soil as void ratio is increased. An increase in void ratio represents an increase in pore volume in the soil but a reduction in total number of pores due to a lower soil mass and therefore number of soil particles. In order to facilitate this the average pore size must increase with increasing void ratio. In Zone 1 an increase in void ratio increases the total volume of pores with throat sizes below a given contour. This means that the volume lost due to a reduction in the number of total pores is less than the increase in volume due to an increase in average pore size below the contour. In Zone 2 the reverse is true and the volume loss due to reduction in number of pores below the given contour is larger than the increase in average pore size below the contour.

Wet Moisture Condition

As discussed in Section 9.1 a significant portion of the hydrostatic results for samples compacted at the wet moisture condition resulted in quasi-saturation. The hydrostatic results for samples compacted at the wet moisture condition are shown in Figure 9.19 with approximate contours manually added. The large red line represents the line of quasi-saturation. Increases in suction in the area near the line of quasi-saturation did not result in a measureable change in volumetric water content of the soil and as a result all of the contours are together in this area. Increases in void ratio in this area resulted in equal changes in volumetric water content so that the degree of quasi-saturated remained 100%. The zone of quasi-saturation was not seen in results from samples of either of the other compaction moisture conditions (dry and optimum).

Other than the quasi-saturated region the tests conducted using a wet compaction moisture conditions showed similar changes in VWC with void ratio as both the “dry” and “optimum” conditions. Contours in Zone 1 showed an increase in VWC with an increase in void ratio while Zone 2 showed the reverse. The number of data points in this region was very limited so it was difficult to precisely define the transition between the saturated zone, Zone 1, and Zone 2.

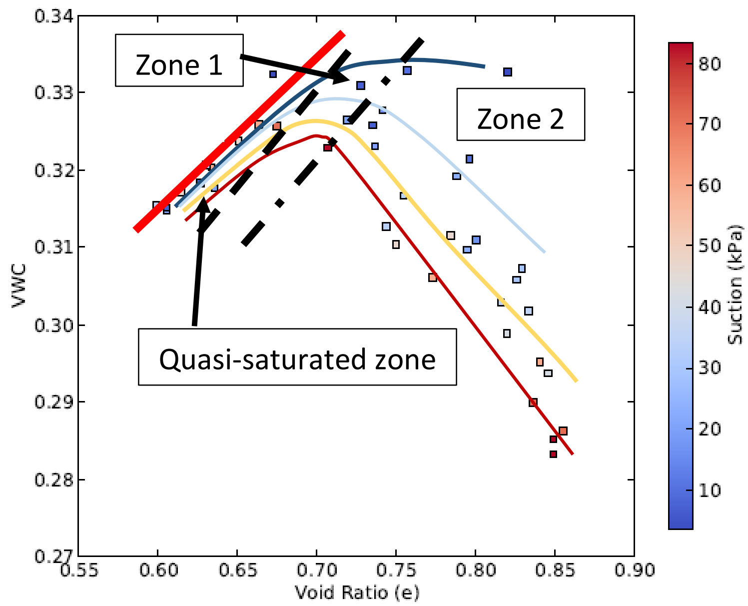

Figure 9.19 - Hydrostatic results, wet of optimum

Summary of Effects of Void Ratio

Three distinct zones were found in the hydrostatic testing data that all show different behavior with regards to changes in void ratio. These were the "saturated zone", "zone 1", and "zone 2". These zones were not seen in all three testing conditions but that was likely due to the limited range of suction and void ratio tested. All three zones should be seen in a fully defined soil water retention surface. The behavior of the three zones was as follows:

- The quasi-saturated zone exhibited saturated behavior for changes in void ratio. Changes in void ratio were compensated by equal changes in volumetric content so that the degree of quasi-saturated remained 100%.
- In "Zone 1" increases in void ratio resulted an increase in volumetric water content. The increases in VWC were less than the increases seen in the quasi-saturated zone resulting in a reduction in the degree of quasi-saturation.
- In "Zone 2" the trends seen in Zone 1 were reversed and increases in void ratio decreased the volumetric water content.

Starting on the soil water retention surface from a state of quasi-saturation, increases in void ratio or suction should eventually move from the zone of quasi-saturation to "Zone 1" and finally "Zone 2".

9.3.2 Hydraulic Conductivity

In all of the testing conditions increases in void ratio resulted in increases in the unsaturated hydraulic conductivity. Imposed flow testing on samples compacted at the dry and optimum moisture condition showed changes in void ratio resulted in the same magnitude change in hydraulic conductivity regardless of where on the K-surface the change occurred. This was expected as each K-surface was well defined by a planar surface. As the hydraulic conductivity was fit using log base ten values the actual relationship between the other parameters is log-linear rather than linear as the planes suggest.

Using the planes fitted to these data sets the change in hydraulic conductivity with void ratio was calculated by taking the partial derivative with respect to void ratio such that:

$$\frac{dlog_{10}K}{de} = 1.051\ (dry)$$

$$\frac{dlog_{10}K}{de} = 1.149\ (optimum)$$

The slopes were very close for the K-surfaces from samples compacted at both of dry and optimum moisture conditions. The K-surface from samples compacted at optimum predicts a slightly higher change of hydraulic conductivity with void ratio. The range of data tested for K-surface was different so the minor change in slope is likely insignificant.

The results from imposed flow tests conducted on samples compacted at the wet moisture condition had significant scatter making quantitative conclusions about void ratio and hydraulic conductivity difficult. Like the data sets from samples compacted at dry and optimum moisture content, samples compacted at the wet moisture condition showed general trends of increasing hydraulic conductivity with void ratio. In one area of the "wet" data set large changes in hydraulic conductivity were seen over a small range of void ratio. The changes in hydraulic conductivity were close to an order of magnitude over a void ratio change of less than 0.1. This is more than ten times the change seen in either the "dry" or "optimum" data sets due to changes in void ratio. The large change in hydraulic conductivity is shown in Figure 9.20. Values for four imposed flow tests conducted on samples compacted at the wet moisture condition are shown in relation to void ratio. The tests conducted at void ratios of 0.76, 0.79, and 0.81 all had the same volumetric water content and a direct comparison based on void ratio was possible. The last data point conducted at a void ratio of 0.86 had a significantly lower volumetric water content than the other three and was not directly comparable. In order to compensate for the difference in volumetric water content the hydraulic conductivity was adjusted according to the relationship between volumetric water content and hydraulic conductivity found in Section 9.4.

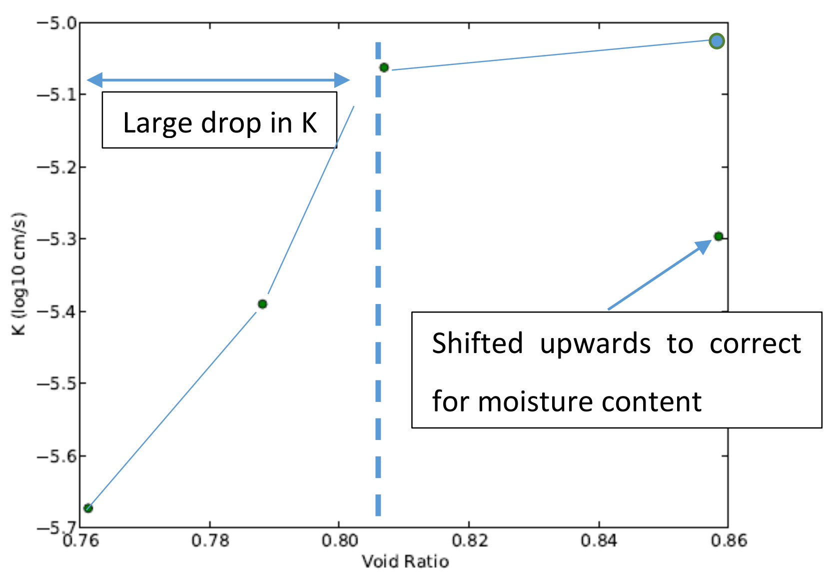

Figure 9.20 - Change in hydraulic conductivity due to void ratio, wet data set

The two test results at void ratios above 0.8 show a change in hydraulic conductivity with void ratio that was consistent with the "dry" and "optimum" K-surfaces. The test results lower than void ratios of 0.8 show much higher changes in hydraulic conductivity with void ratio. The large change in hydraulic conductivity can be explained by examining the soil structure of the wet compaction moisture condition. At low compactive efforts (high void ratios) large clods of soil were visible with voids in between them. When more compactive effort is exerted on the soil (low void ratios) the gaps in between the soil clods close resulting in a different soil structure. The hydraulic conductivity at high void ratios is much higher due to the presence of interconnected voids around the clods that are able to transmit large quantities of water. When the large voids close up due to additional compactive effort (or are no longer interconnected) flow must be carried through the voids in the clods, which are much smaller, and the result is a drastically lower hydraulic conductivity.

9.3.3 Summary of the Effects of Void Ratio

Void ratio was found to have significant effects on results from both the hydrostatic and imposed flow procedures. Void ratio affected the retention behavior differently depending on what area of the SWRS the void ratio change occurred. Three general zones were determined that applied to all three compaction moisture conditions:

- The quasi-saturated zone exhibited saturated behavior for changes in void ratio. Changes in void ratio were compensated by equal changes in volumetric content so that the degree of quasi-saturated remained 100%.
- In “Zone 1” increases in void ratio resulted an increase in volumetric water content. The increases in VWC were less than the increases seen in the quasi-saturated zone resulting in a reduction in the degree of quasi-saturation.
- In “Zone 2” the trends seen in Zone 1 were reversed and increases in void ratio decreased the volumetric water content.

The location of the zones on the soil water retention surface were such that the quasi-saturated zone was located at water contents corresponding to quasi-saturation. Zone 1 bordered the quasi-saturated zone which was then followed by Zone 2.

The unsaturated hydraulic conductivity measured using the imposed flow procedure was found to increase with increasing void ratio. This was found for all areas of the K-surface for each compaction moisture condition. The change in unsaturated hydraulic conductivity with void ratio measured using the imposed flow procedure was similar for the samples compacted at the dry and optimum compaction conditions (approximately a 25% increase in unsaturated hydraulic conductivity per 0.1 change in void ratio). Samples compacted at the wet moisture condition showed a dramatic increase in hydraulic conductivity across a small increase in void ratio (increasing nearly 2 orders of magnitude across 0.05 void ratio). This was determined to be due to a change in structure of the when all of the macro voids in the soil were removed. In other areas of the K-surface samples compacted using the wet moisture condition showed similar changes in unsaturated hydraulic conductivity with void ratio as the dry and optimum conditions.

9.4 Effects of Volumetric Water Content on Unsaturated Hydraulic Conductivity

All of the results from Series "IF" (imposed flow) testing indicate that increases in volumetric water content result in increases in unsaturated hydraulic conductivity. This was expected as increases in volumetric water content represent additional pore space in samples that is filled with water and available to transmit flow. The data from imposed flow testing was split into three sets based on the compaction water content of the samples that were tested. Each set of results formed a unique relationship between volumetric water content, void ratio, and unsaturated hydraulic conductivity known as the "K-surface".

As discussed in Section 8.3.3, planar surfaces were fit to the data sets from samples compacted at the dry and optimum moisture condition tested using the imposed flow procedure. The results from imposed flow testing on samples compacted at the wet moisture condition had many issues (discussed in Section 8.3.3.3) and a surface was unable to be fit to the data set. Consequently, the data from imposed flow tests on samples compacted at the wet moisture condition will be discussed by itself after the other two data sets ("dry" and "optimum").

Using the planes fit to the K-surfaces from the samples compacted at dry and optimum moisture condition (referred to as the "dry" and "optimum" K-surfaces) the change in hydraulic conductivity with volumetric water content was calculated by taking the partial derivative with respect to water content such that:

$$\frac{dlog_{10}K}{dVWC} = 9.257\ (dry)$$

$$\frac{dlog_{10}K}{dVWC} = 14.16\ (optimum)$$

The slopes show that for samples compacted at the optimum moisture condition, unsaturated hydraulic conductivity increases at a greater rate than for samples compacted at the dry moisture condition. As discussed in Section 9.2.2 the "dry" samples showed a higher hydraulic conductivity for low water contents (~25%-30%) but the trend was reversed for high water contents (>~32%). There was not a substantial amount of testing results in the area of the K-surfaces where the cross-ever occurred and may have been due to scatter in the few results for samples compacted at the dry moisture condition in this area. This notion was further supported by fixed wall permeameter testing conducted at quasi-saturation in which samples compacted at the dry moisture condition resulted in higher hydraulic conductivity (contrary to what the K-surfaces would predict if the cross-over was correct). It was therefore concluded that the differences in slope measured between the "dry" and "optimum" K-surfaces was likely due to scatter and that the true relation between volumetric water content and unsaturated hydraulic conductivity was similar for both the dry and optimum compaction moisture conditions.

At low unsaturated hydraulic conductivities the “dry” and “optimum” K-surfaces showed a potential change in shape. The derivatives for slope calculated above are taken from the upper portion of the K-surfaces where the majority of the data was collected and do not include the change in shape. Both K-surfaces are included in a 3D plot as Figure 9.21. The view has been oriented so that surface is perpendicular to the page. The change in slope of the surfaces is shown, which occurred at a hydraulic conductivity of approximately -5.75 (log10 cm/s). Below approximately -5.75 (log10 cm/s), the change in hydraulic conductivity with volumetric water content increases dramatically, from approximately 10 $log_{10}K$ per VWC to 30 $log_{10}K$ per VWC.

The change in relation between hydraulic conductivity and volumetric water content does not match with theoretical predictions for the unsaturated hydraulic conductivity. The most popular models (Mualem, Brookes and Corey) for unsaturated hydraulic conductivity predict a relationship that is close to log-linear between unsaturated hydraulic conductivity and volumetric water content. Both models deviate from the log-linear relationship at volumetric water contents close to the saturated and residual water contents. The change of slope in the “dry” and “optimum” K-surfaces occurs at VWC’s between 25% and 30% which is far from the residual (5-10%) and the saturated (40-45%) volumetric water contents and therefore is contrary to the predictions.

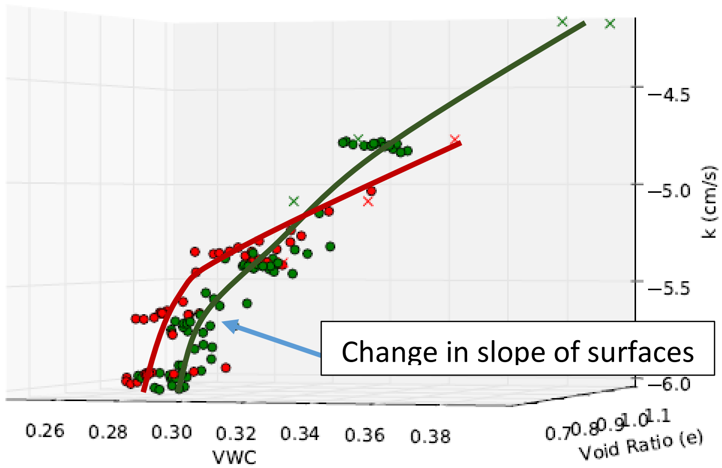

Figure 9.21 - Effects of VWC on hydraulic conductivity (dry - red, optimum - green)

Unsaturated hydraulic conductivity measurements that were performed by McCartney (2007) on a similar low plasticity clay showed changes in relation between hydraulic conductivity and volumetric water content that were consistent with the changes in slope seen in the “dry” and “optimum” K-surfaces. The measurements were performed in one dimensional columns and measured using both transient and steady state techniques. The results are included as Figure 9.22. The soil was compacted to a porosity of approximately 0.5, which is higher than nearly all of the data collected using the imposed flow testing procedure. Two changes in slope of the K-function were seen at volumetric water contents of approximately 15% and 25%. This data supports the changes seen from imposed flow results suggesting that the general shape of the predicted K-functions is insufficient for describing the relationship between unsaturated hydraulic conductivity and volumetric water content.

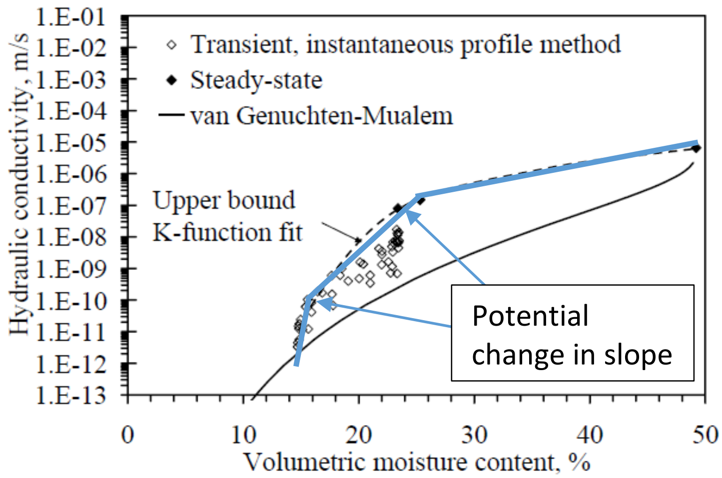

Figure 9.22 - Measured unsaturated hydraulic conductivity using column tests (from McCartney 2007)

The unsaturated hydraulic conductivity results from samples compacted at the wet moisture content increased with increasing water content. Two tests completed at similar void ratios and different imposed flow rates were selected in order to get an estimate of the magnitude of change between volumetric water content and hydraulic conductivity. The calculated hydraulic conductivity and measured water content of these two samples are shown in Figure 9.23. The top three points of each test were selected for analysis as these points should have the lowest suction gradient and result in the most accurate calculated hydraulic conductivities (the suction gradient was used during analysis but the prediction was potentially inaccurate due to problems with the "wet" testing set). The resulting slope was approximately 14 $log_{10}K$/VWC, which was nearly identical in magnitude to relationship determined from the "optimum" K-surface. These tests were selected on the high void ratio side of the change in pore structure (as discussed in Section 8.3.3.3) where the behavior of the samples compacted at the wet moisture condition was most similar with the other compaction conditions. A comparison based on lower void ratios was not possible as insufficient successful tests were conducted in this region on samples compacted at the wet moisture condition.

In summary, results from imposed flow testing were examined for samples compacted at all three moisture conditions. Results from samples compacted at the optimum and dry moisture conditions were compared based on the K-surfaces previously fit to the data sets. For hydraulic conductivities greater than approximately 1.8x10^{-6} cm/s, it was found that hydraulic conductivity increased approximately an order of magnitude for every 10% volumetric water content increase. Select results obtained using the imposed flow procedure were examined for samples compacted at the wet moisture condition. The relationship between unsaturated hydraulic conductivity and volumetric water content was found to be similar to the relationship found for samples compacted at the dry and optimum conditions.

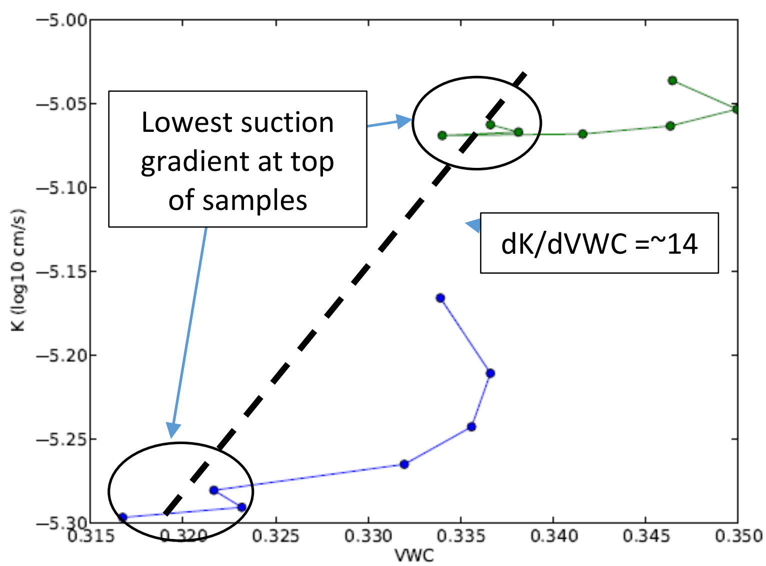

Figure 9.23 - Effect of VWC on K, wet compaction condition

At hydraulic conductivities below approximately 1.8x10^{-6} cm/s, the relationship between hydraulic conductivity and volumetric water content changed. In this area the change of hydraulic conductivity with volumetric water content was much larger (on the order of 2-3 times the changes seen above K=1.8x10^{-6} cm/s). Hydraulic conductivity below 1.8x10^{-6} cm/s was not successfully measured for samples compacted at the wet moisture condition but the increase in slope of the relationship between hydraulic conductivity and volumetric moisture content was seen for samples compacted at both the dry and optimum moisture conditions.

9.5 VERIFICATION OF THE SCALING OF ELEVATION POTENTIAL WITH G-LEVEL

Testing was conducted in order to validate the formulation for increased fluid potential in the centrifuge discussed in Section 2.2. The testing was completed using both the hydrostatic procedure and the imposed flow procedures.

The framework was verified using the hydrostatic procedure by ensuring that the fluid potential (and therefore suction) was increased by g-level. The imposed flow procedure expanded on this and verified that the gradient in fluid potential was also increased by g-level. The testing will be discussed individually in the following sections.

9.5.1 Hydrostatic Procedure

Verification of the scaling of elevation potential with g-level relied on the assumption that there is a unique relationship between suction and volumetric water content, given that samples are at the same void ratio and completed on the same drying path.

The framework for calculating suctions in samples was verified using hydrostatic tests that targeted the same range in suction using different g-levels. Samples at the same suction and void ratio should result in the same measured volumetric water content regardless of the g-level the suction was achieved at. If the sample tested at different g-levels resulted in the same VWC for the same calculated suction it would confirm that the methods for scaling fluid potential with g-level were valid. As an increase in g-level also increases the stresses (decreases void ratio in samples), sample height was varied in order to result in roughly the same stress and void ratio distribution at different g-levels.

Two sets of hydrostatic tests were performed and are listed in Table 9-2. The first set was completed at 50g and 100g. Testing that was conducted at 50g was completed with samples that were compacted to the full height of 10.1 cm. Tested conducted at 100g was completed on samples compacted to heights of 5 cm and 6.4 cm. Samples compacted to 5 cm in height were at a height where it was not sure if compression of the sample during testing would result in a height where only three rings from the split tube sampler would be filled with soil. Three data points was considered too few for comparison so additional samples were compacted to 6.4 cm in order for the sample to cover five full rings of the split tube sampler. After testing was completed it was found that the 5 cm tests resulted in four rings full of soil in the split tube sample (and 4 data points). The second set of tests were completed at 25g and 50g using sample heights of 10.1cm for 25g and 6.4cm for 50g. Additional tests at 5cm sample height were not completed for this data set.

Table 9-2 - Hydrostatic verification tests

Set #	Sample	H (cm)	G
1	RMA26	6.4	100
	RMA27	6.4	100
	RMA69	10.1	50
	RMA70	10.1	50
	RMA101	5	100
	RMA102	5	100
2	RMA35	6.4	50
	RMA36	6.4	50
	RMA33	10.1	25
	RMA34	10.1	25

The first set of tests conducted showed good consistency in resulting volumetric water contents between tests conducted at 50g and 100g. The resulting measured volumetric water contents are shown with the calculated suction in Figure 9.24a. All six of the samples resulted in VWC within approximately 2% of each other. The main contribution to the differences seen in the VWC was likely the range of void ratio in the samples (shown in Figure 9.24b). These samples had a significant range in void ratio due to poor compaction control and the increased stress for the 6.4 cm samples. The increased stress led to lower void ratios, which resulted in higher volumetric water contents (effects of void ratio on retention are discussed in Section 9.3).

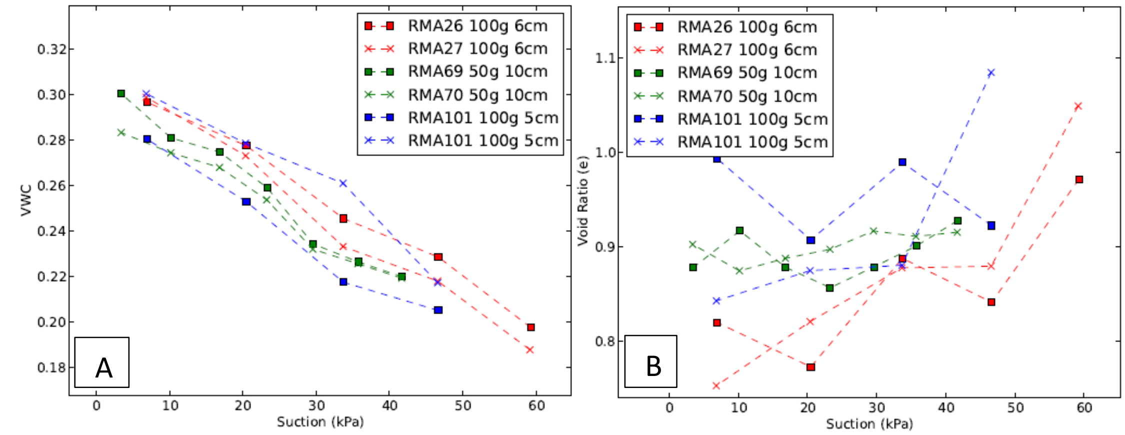

Figure 9.24 - Verification tests for suction scaling (50g/100g) – a) VWC b) Void ratio

The second set of tests completed at 25g and 50g showed even better consistency in the VWC measurements (Figure 9.25a). The majority of the data fill within a 1% range in VWC. There was a trend of the 50g tests resulting in lower VWC than the 25g. When the void ratios in the samples were examined (Figure 9.25b) the 50g tests were at consistently higher void ratios than the 25g tests. Increases in void ratio in this range of suction were found to result in lower VWC (discussed in Section 9.3) and explain the difference in VWC seen between the samples.

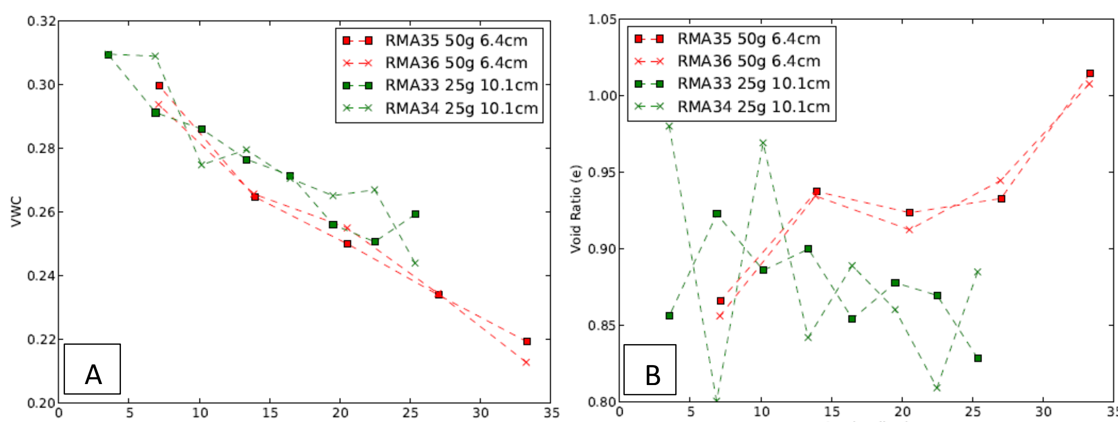

Figure 9.25 - Verification tests for suction scaling (25g/50g) - a) VWC, b) Void ratio

One other set of verification tests were completed early in the research project before the split tube sample was incorporated in the testing procedure. These tests did not allow as accurate measurement of void ratio as the sample were sliced by hand and measured rather than using the rings to obtain a set volume of the sample. Two tests were completed at 50g and two at 100g with sample heights of approximately 12 cm and 6 cm respectively. As the void ratio of the samples were not measured accurately, the tests were compared by gravimetric water content rather than volumetric. If the void ratios of the tests are similar this gives the same comparison as volumetric water content. The results of these verification tests are included as Figure 9.26 and also showed good consistency between scaling tests conducted at different g-levels. In these tests the total range between the four tests was less than 1% GWC.

Overall the testing for verification of the scaling of fluid potential in the centrifuge showed consistent results suggesting that the framework for calculating suction to be correct. The majority of the data fell within 1% VWC for a given suction. This was seen for repeat tests at the same g-level and for scaling tests run at different g-levels. Most of the differences can be explained by inconsistent void ratios. Void ratios ranged in some cases from 0.8 to 1, which was considered a significant range. Effects of changes in void ratios will be discussed in depth in Section 9.3.

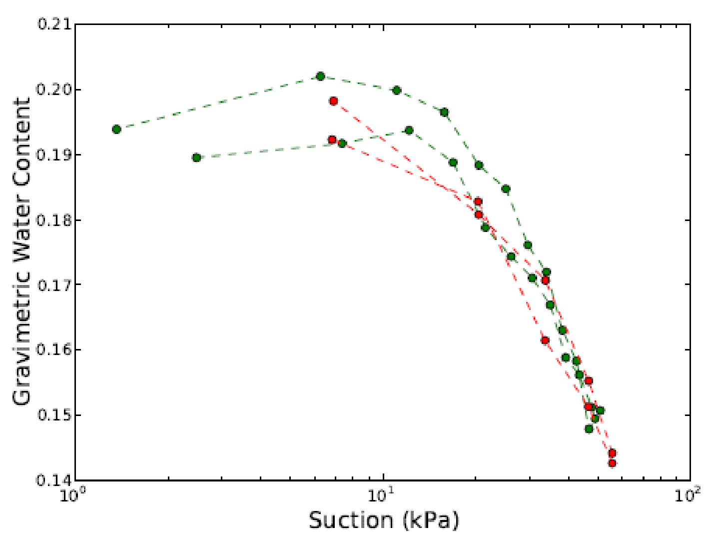

Figure 9.26- Suction verification tests (50g - Green, 100g - Red)

9.5.2 Imposed Flow Procedure

The second method for verification of the scaling of elevation potential with g-level was completed using the imposed flow testing procedure. The goal of the testing was to test two samples where the same hydraulic conductivity was measured using two different g-levels. In order to accomplish the flow rate and g-level were scaled together such that the target hydraulic conductivity, defined as:

$$K_t = \frac{Q}{Ai_g}$$

was constant. The target hydraulic conductivity assume a suction gradient of zero. Therefore the comparison between samples should focus on areas where the suction gradient is lowest.

Tests were completed on samples compacted at the dry moisture condition. In these tests two samples approximately 10 centimeters tall were run at 50g with an imposed flow rate of 20 mL/h. A third test was completed on a sample 6 centimeters tall at 100g with an imposed flow rate of 40 mL/h. In all three samples the target hydraulic conductivity was approximately $3.5\text{x}10^{-6}$. Results from all three tests are shown in Figure 9.27 and have been plotted versus elevation potential. Elevation potential is the potential energy using the base of the sample as the datum (converted to cm of water).

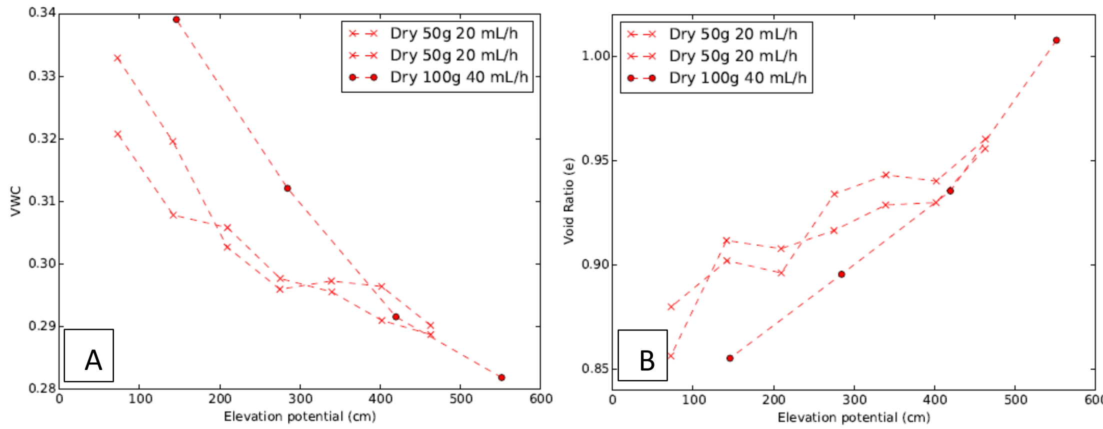

Figure 9.27 - Scaling tests for dry moisture condition - a) VWC b) Void ratio

The moisture content of the test completed at 100g was higher for the lower portion (low elevation potential) of the sample but near the top of the samples the water contents were nearly identical. The differences at the base of the sample can be attributed to differences in void ratio of the sample (Figure 9.27b). The sample tested at 100g resulted in lower void ratios for the majority of the sample compared to the samples completed at 50g, likely due to slightly higher stresses and differences in compaction density. The lower void ratio of the samples tested at 100g near the base means the hydraulic conductivity in this area was lower and required a higher volumetric water content to facilitate the same flow rate.

The second set of tests were completed at the same testing conditions but on samples compacted at optimum moisture conditions and are shown in Figure 9.28. The results are similar with water contents being very similar between all tests at the top of samples but the test conducted at 100g having higher water content at the base. This can once again be explained by lower void ratios seen in this region of the 100g test.

Overall both test groups showed good consistency between tests conducted at different g-levels in the upper portion of the samples. The water contents in this region were very close along with the calculated gradients and resulting hydraulic conductivity. The top of the samples is the area with the lowest suction gradient, meaning the comparison of tests by target hydraulic conductivity is most valid in this area. Between all six tests conducted at the same target hydraulic conductivity (but different g-levels), the volumetric water content at the top of samples varied less than 1%. This supports the scaling of the gravitational portion of the hydraulic gradient with g-level.

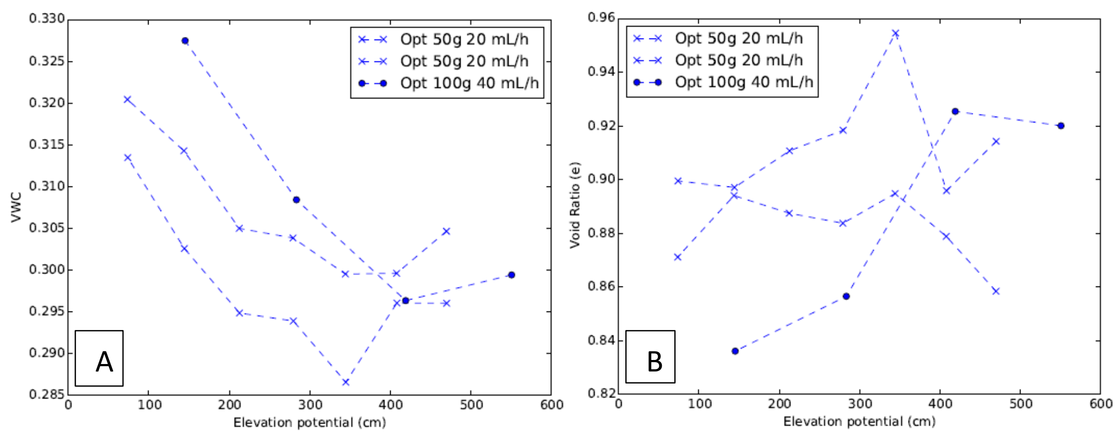

Figure 9.28 - Scaling tests for optimum moisture condition - a) VWC b) Void ratio

9.5.3 Summary of Verification Tests

Testing was conducted using both the hydrostatic and imposed flow procedures. These tests were aimed at verifying the framework for determining the fluid potential of samples in the centrifuge permeameter. Hydrostatic tests were completed in order to measure the same suction in centrifuge samples using different g-levels. The imposed flow tests were completed to target the same fluid potential gradient using different g-levels.

In both testing procedures, the g-level was doubled between tests targeting the same suction or hydraulic gradient. Near the surface of samples, where the void ratio was most consistent, the results were very similar regardless of what g-level they were conducted at. The measured volumetric contents of samples varied less than 2% for hydrostatic tests and less than 1% for imposed flow tests. The consistency between results conducted at different g-levels was indication that the framework used for determining fluid potential in the centrifuge was valid.

9.6 Evaluation of Retention Hysteresis

Traditionally, hysteresis has been evaluated by measuring the retention characteristics of a soil sample using both the “wetting” and “drying” methods. In the wetting method samples are started dry at a high suction and suction is decreased in stages and the moisture content measured at each stage. This same process completed in a drying test however the sample is started saturated and suction incrementally increased. If these testing methods produce different results, which is common in soils, the two curves are combined to form a hysteresis loop bounding the expected condition of the soil.

The centrifuge testing setup was not capable of recreating the wetting and drying process. This was because the size of the water reservoir below the sample was very small and did not hold sufficient volume of water for the sample to wet to a hydrostatic distribution. As a result centrifuge hydrostatic tests were performed by first applying a low flow rate to the sample in order to add enough water to wet the sample to hydrostatic conditions. The flow was then stopped and the sample drains to hydrostatic conditions.

In order to evaluate soil hysteresis using this general procedure, different initial wetting flow rates were imposed on samples and the resulting hydrostatic distributions were measured after flow was stopped and equilibrium occurred. The differences in the resulting distributions were then used to evaluate the hysteresis of the soil. The wetting fronts used in these tests were 5, 20, and 80 mL/h (~4.4×10^{-5} to 7×10^{-4} cm/s). The samples were compacted at a relative compaction of 80% and optimum (14.5%) water content and a centrifugal acceleration of 50g was used during testing. Two samples were tested using the hydrostatic procedure for each wetting from.

The distribution in volumetric moisture content between each sample ranged approximately 2%. The results are shown in Figure 9.29. The hydrostatic tests completed at different wetting flow rates are denoted by the symbol “x” and labeled by the flow rate in milliliters per hour that was applied to the sample before drying occurred. The samples tested at the highest wetting flow rate (blue x's) showed a slightly higher water content than those tested at the lower flow rates (red and green x's).

Imposed flow tests were run at the same flow rates as the hydrostatic tests wetting front. In the imposed flow tests the flow rate remained constant during the entire centrifugation process rather than the flow being stopped and the sample allowed to dry to hydrostatic condition (as done with the hydrostatic procedure). The imposed flow test results show what the water content distribution in the hydrostatic samples were at their wettest state, before the flow was stopped and the samples allowed to dry to hydrostatic conditions. Results from three imposed flow tests at the some flow rates as the initial wetting fronts in the hysteresis samples are also included in the Figure 9.29.

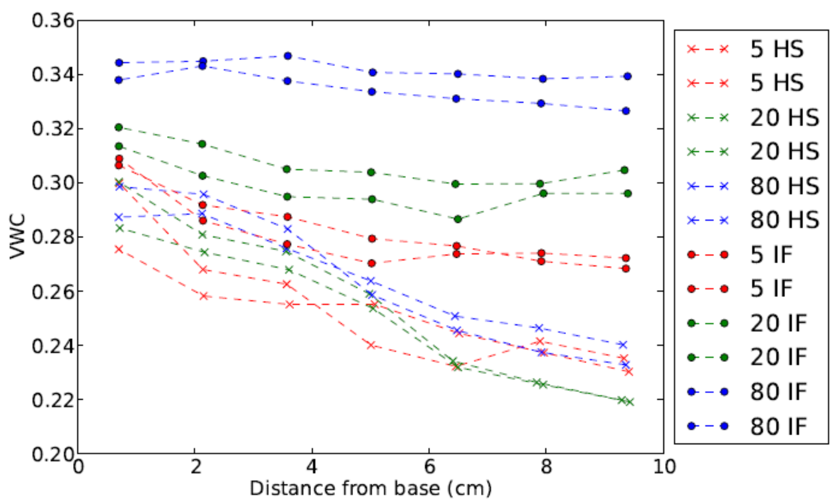

Figure 9.29 - Hysteresis evaluation (legend in mL/h, HS = hydrostatic, IF = imposed flow)

Initially it was thought that a small amount of hysteresis was seen in these results due to the slight correlation between hydrostatic moisture content and wetting flow rate. However when the void ratio of the samples was considered it appears that all of the samples came to equilibrium on the same surface. The sample tested at 80 mL/h experienced the highest total stresses during the wetting process and therefore had a lower void ratio at the end of the test. The lower void ratio resulted in more retained water for the ranges of suction tested (see Section 9.3 for discussion of the effects of void ratio on water retention).

The results from the hydrostatic and imposed flow tests are shown again but in a 3D plot (Figure 9.30) that is rotated so that the soil water retention surface is perpendicular to the page. In this view it is apparent that all of the hydrostatic data falls on the same surface and that no major effects of hysteresis are visible.

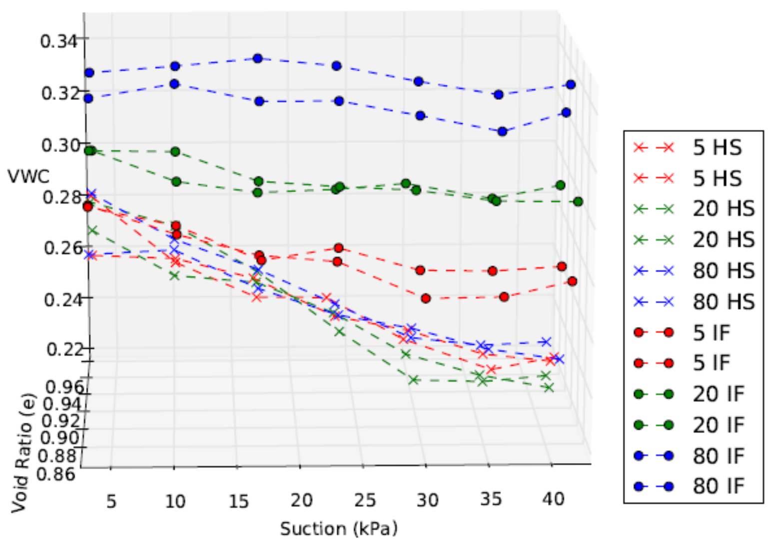

Figure 9.30 - Hysteresis tests (3D) (legend in mL/h, HS = hydrostatic, IF = imposed flow)

Standard retention results determined using pressure plates are shown in Figure 9.31. Samples tested using the “drying” method were soaked at zero suction before incremental levels of suction were applied. The “wetting” tests were compacted at the optimum moisture condition let come to equilibrium at a suction of 80 kPa. The applied suction was then reduced incrementally to the same stages as completed in the “drying” tests. The results from each method form distinct and separate curves which form a hysteresis loop. The two curves are greater than 5% volumetric water content apart for the majority of suctions tested.

Several hypotheses as to why pressure plate testing resulted in significant hysteresis while centrifuge retention results determined using the hydrostatic procedure did not were considered. The first was that no hysteresis was measured in the centrifuge because all of the retention results were actually "drying" curves. The lowest flow rate (5 mL/h) wetted the sample to a distribution of moisture above the hydrostatic distribution. Increases of the wetting flow rate past 5 mL/h did not increase final retention because the sample was already at a moisture state where drying would occur to reach hydrostatic conditions. In order to have hysteresis occur in the centrifuge flow rate would be required that resulted in a distribution of moisture content below the hydrostatic condition.

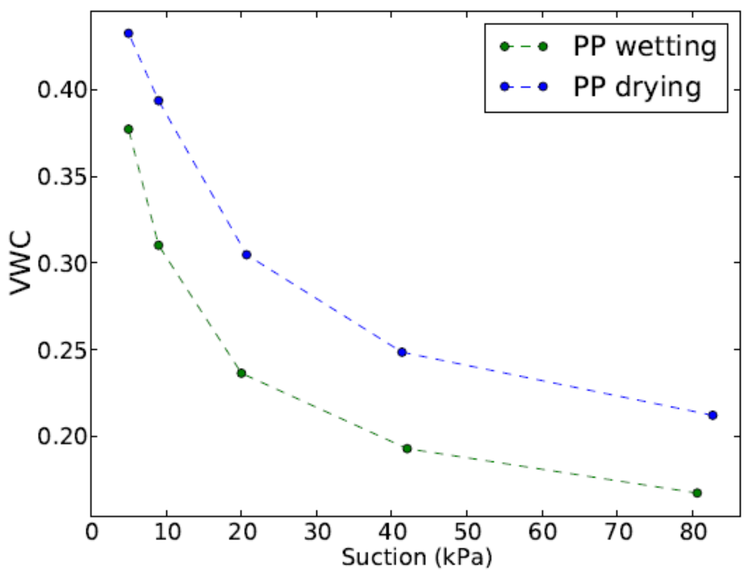

Figure 9.31 - Hysteresis from pressure plate testing

Another hypothesis was that the centrifuge based method of applying suction by using an acceleration field does not result in significant hysteresis when compared to the pressure plate. The pressure plate method of applying suction requires continuity between any water in the sample and the lower boundary condition. The result is that any water in the sample that is isolated from the lower zero suction boundary does not have any suction applied to it. In the centrifuge the acceleration field is applied to the entire sample and moisture in the sample will experience the effect of increased acceleration whether or not the water is isolated. This could lead to less or no hysteresis in the centrifuge.

Finally, it was hypothesized that the centrifuge based method of wetting with a flow rate could in no hysteresis. The use of an infiltration process may give all of the pores of the sample access to water so that no hysteresis occurs.

In summary, a series of tests were conducted in in the centrifuge using the hydrostatic testing procedure. These tests were initially wetted to different moisture conditions by applying different wetting flow rates to each sample. The samples, which started from different initial moisture distributions, were then allowed to dry to hydrostatic conditions.

The results were examined in order to determine if any hysteresis was apparent between the samples. When changes in void ratio due to stress differences were accounted for, all of the samples came to equilibrium on the same soil water retention surface, suggesting that no hysteresis occurred.

Hysteresis testing was conducted using standard testing procedures on the soil at similar void ratios. In these tests a large hysteresis loop was observed. Several hypotheses are proposed as to why the centrifuge results did not show any hysteresis effects (while standard testing procedures did). A summary the hypotheses for lack of hysteresis in the centrifuge are as follows:

- All of the centrifuge tests were completed on a drying path. The magnitude of drying was different but in order for any hysteresis to form true “wetting” and “drying” procedures may be required.
- The application of suction was different. The centrifuge procedure uses an acceleration field to apply suction while the pressure plate device uses a zero water pressure boundary with an increased air pressure. The acceleration field may reduce hysteresis.
- The wetting conditions were different. The centrifuge samples were wetting using a infiltration process, which may give the entire sample access to water reducing the hysteresis effects.

9.7 Comparison of Centrifuge Results with Results from Standard Tests

The retention behavior of the RMA soil measured using the hydrostatic procedure for a wide range of void ratios. In addition the unsaturated hydraulic conductivity was measured using the imposed flow procedure. In order to validate the accuracy of centrifuge measurements select tests were conducted using standard procedures in order to determine the retention behavior and hydraulic conductivity of the RMA soil. The results are compared in the following sections.

9.7.1 Hydrostatic Procedure

Testing results obtained using the hydrostatic procedure were compared to those obtained using a standard pressure plate testing setup. The pressure plate tests were conducted at relative compactions of 80% and 90% while the hydrostatic tests were completed over a range in final void ratios. Both procedures were conducted on samples compacted at the optimum moisture condition. In order to compare the hydrostatic results to the pressure plate results, the hydrostatic data set was trimmed in order to show results that were within 0.03 void ratio of the pressure plate tests. The centrifuge results came from a variety samples tested at different g-levels and heights.

Pressure plate tests were run in both "wetting" and "drying" methods in order to evaluate the hysteresis of the soil. The pressure plate tests conducted at 80% RC are shown with hydrostatic tests of similar void ratio in Figure 9.32. The red data is centrifuge data obtained using the hydrostatic procedure. The blue data is pressure plate drying data while the green is pressure plate wetting data. The pressure plate data points are connected as they were tested on a single sample at different pressures.

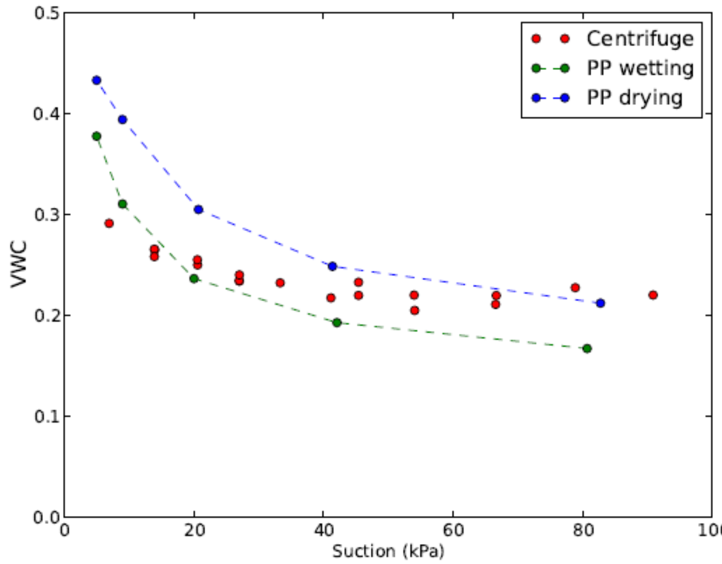

Figure 9.32 - Retention results, optimum moisture, 80% RC

The hydrostatic tests results matched the general magnitude and shape of the pressure plate data. For suctions above approximately 20 kPa the hydrostatic tests resulted in water contents in between those found using the wetting and drying procedures in the pressure plate setup. At low suction (<20 kPa) the hydrostatic tests resulted in lower water contents that those measured by either pressure plate test.

The same trends were seen again with pressure plate tests conducted at 90% and 100% relative compaction. The results are shown in Figure 9.33. Note that each pressure plate measurement for 100% relative compaction was done on different sample rather than measuring multiple suctions on a single sample like at 80% and 90%. The difference in volumetric water content at low suctions between the pressure plate and hydrostatic procedures was slightly smaller than difference seen at 80% relative compaction but the trend of lower water content at low suctions for the hydrostatic tests was still seen.

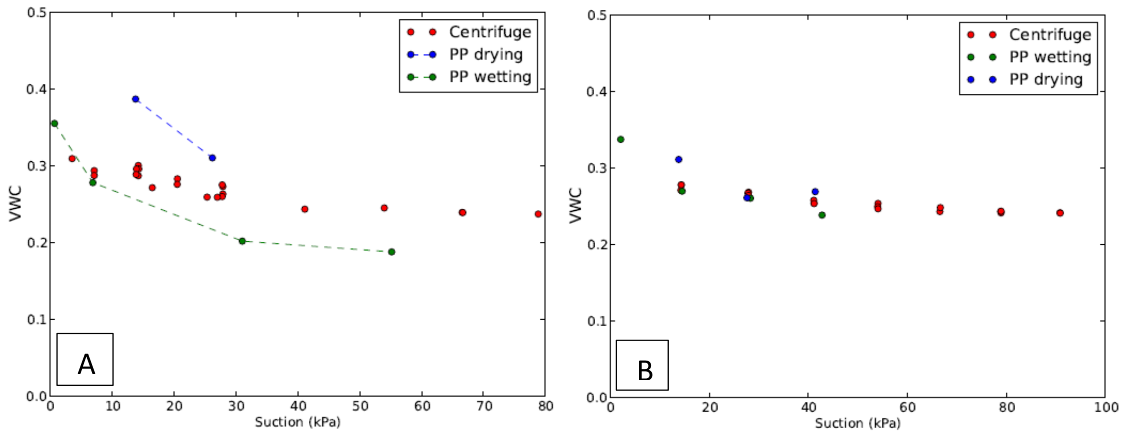

Figure 9.33- Retention results, optimum moisture- A) 90% RC B) 100% RC

Two possible explanations for the differences in volumetric water content at low suctions were considered. The first possibility was that that the zero suction datum was incorrectly chosen. The base of the hydrostatic cup was designed in order to hold pressure at zero approximately 0.75 cm below the base of the sample. This was accomplished by using a spillover port at an elevation in the middle of the ceramic disc located directly below the centrifuge sample. If this spillover port was not functioning properly the zero pressure datum would be shifted to the outflow port of the centrifuge cup base, which was located approximately 0.75 cm below the spillover port. This would move the datum from 0.75 cm below the base of the sample to 1.5 cm increasing the suction on the samples beyond what was calculated for comparison with the pressure plate tests.

The suctions for the hydrostatic data were recalculated based on lower datum and are shown compared with the same pressure plate data in Figure 9.34. The adjusted centrifuge data matched better with the pressure plate data at low suctions although some points still fell slightly below the pressure plate wetting curves.

A second possibility is that the lower boundary condition resulted in additional entrapped air near the base of samples, where the lowest suctions occurred in hydrostatic tests. The ceramic disc at the base of specimens had a high air entry pressure. This meant that as the moisture front progressed down through the sample, the ceramic disc did not allow air to escape from the base of samples. This hypothesis will be discussed further in the next section in conjunction with imposed flow results.

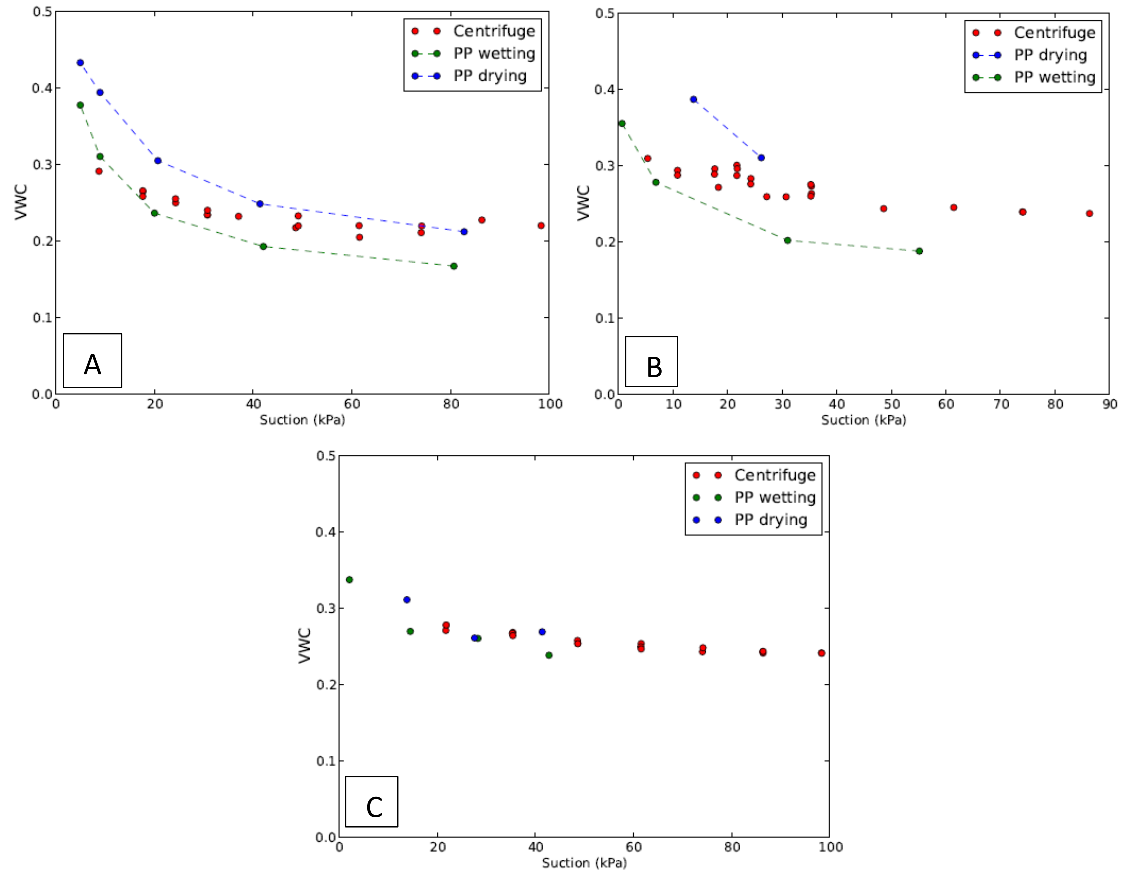

Figure 9.34 - Retention results, optimum moisture, datum adjusted 1 cm- A) 80% RC, B) 90% RC, C) 100% RC

In general, the hydrostatic data matched well with the standard pressure plate tests for all three compaction states tested. The centrifuge data matched best with wetting pressure plate data at low suctions and shifted towards matching the drying pressure plate data at higher suctions. This was likely due to the testing procedure for the hydrostatic test in which a wetting front is used to wet the sample. The effects of the wetting front on hysteresis are discussed in Section 9.6.

9.7.2 Imposed Flow Procedure

Results obtained using the imposed flow procedure were compared with results from fixed wall permeameter tests. The results from the imposed flow procedure defined the relationship between unsaturated hydraulic conductivity and volumetric water content for a range of void ratios (referred to as the K-surface). The imposed flow results defined the quasi-saturated hydraulic conductivity of the soil for the void ratios tested. The results from the fixed wall permeameter define the highest hydraulic conductivity the soil can reach without back-pressure saturation (used in order to remove the entrapped air in the quasi-saturated samples). Therefore, the fixed wall permeameter results should bound the K-surface as the maximum hydraulic conductivity of the surface. As there were insufficient results to define the K-surface for samples compacted at the wet moisture condition only the dry and optimum moisture conditions were compared with fixed wall permeameter tests.

Fixed wall permeameter tests were conducted on samples at compacted at 80% and 90% relative compaction resulting in void ratios of approximately 0.88 and 0.67. In order for comparison imposed flow results were obtained for ranges of similar void ratio. This was completed using two methods. First, the K-surface that was fit to each compaction moisture condition was used to predict the relationship between volumetric water content and hydraulic conductivity for the void ratio of the fixed wall permeameter test. This effectively calculated the K-function for the given void ratio. Second, data from the imposed flow procedure was trimmed to only contain data within void ratios of +/- 0.1 of the fixed wall permeameter test void ratios. This data is displayed in light colors in graphs in this section. The data was further trimmed to only contain data within void ratios of +/- 0.03 of the fixed wall permeameter test void ratios. This data is displayed in bright colors on graphs in this section.

Data from samples compacted at the dry moisture condition at high void ratios is shown in Figure 9.35. The results from the fixed wall permeameter test were at higher hydraulic conductivity and volumetric water content then the ranges measured from the imposed flow testing procedure so direct comparison is not possible. However, the K-function determined from imposed flow testing was extended to the volumetric water content of the fixed wall permeameter test and matches excellently with the results. The differences between the K-function measured using the imposed flow procedure and the fixed wall permeameter results was less than 20%, which was similar to the natural scatter of results seen from the imposed flow test results.

Results from samples compacted at the optimum moisture condition are shown in Figure 9.36 for both the imposed flow procedures and the fixed wall permeameter. The hydraulic conductivity value determined using the fixed wall permeameter was below the K-function determined using the imposed flow procedure. The difference was approximately 35% between the prediction based on the imposed flow results and the measured value in the fixed wall permeameter.

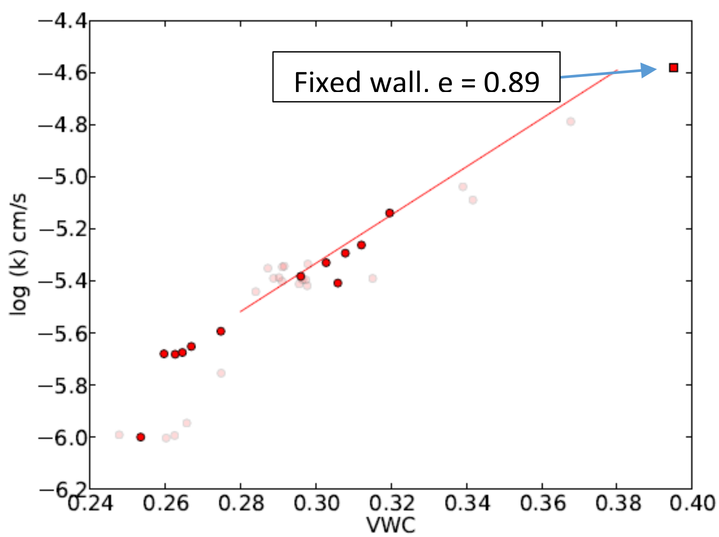

Figure 9.35 - Comparison of imposed flow and fixed wall results (dry compaction condition and high void ratio)

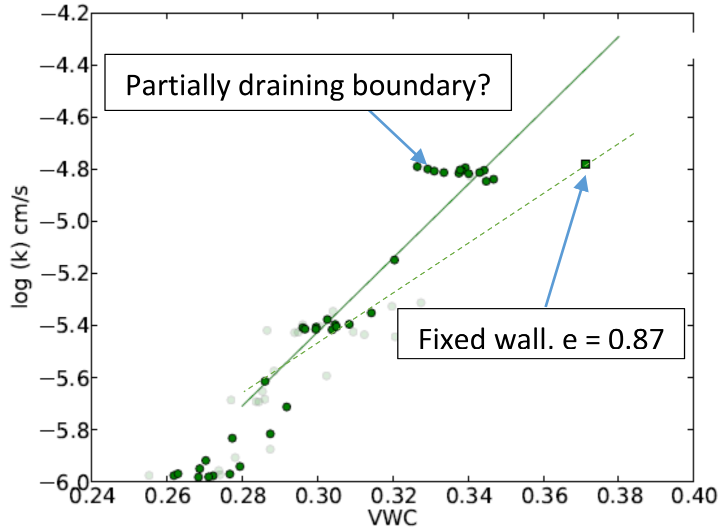

Figure 9.36 - Comparison of imposed flow and fixed wall results (optimum compaction condition and high void ratio)

A group of imposed flow tests were considered questionable as the flow rate through the sample was very close to the permeability of the ceramic disc at the base of the sample. If the permeability of the disc was exceeded and the lower boundary acted as partially draining boundary (instead of a freely draining zero suction boundary), the calculated hydraulic conductivity for these tests would be incorrect and shift downward. This notion is supported by the measured void ratio of the samples from the questionable results. In the samples which may have been tested with a partially draining boundary, the void ratio in the base of the sample is higher than at the top. This is a reverse of the typical trend seen as the base of the sample has the highest stresses due to centrifugation and therefore the lowest void ratio. The increase in void ratio at the base could be explained by a reduction in stress due to increases in pore pressure in the area caused by the partially draining boundary. If the questionable results are ignored, a consistent trend is seen between hydraulic conductivity and volumetric water content for both the results from the imposed flow testing procedure and the fixed wall permeameter (trend denoted by dashed line).

The process above was repeated for the fixed wall permeameter tests conducted at low void ratios. The comparison of samples compacted at the dry moisture condition is shown in Figure 9.37. It should be noted that the K-function displayed is from the K-surface which was fit to data with hydraulic conductivities above -5.75 (log cm/s) and does not match well with the imposed flow data shown, which is from values below -5.75 (log cm/s) (see Section 8.3.3 regarding fitting of K-surface). The measured hydraulic conductivity from fixed wall permeameter was approximately 50% lower than the predicted hydraulic conductivity from the K-function.

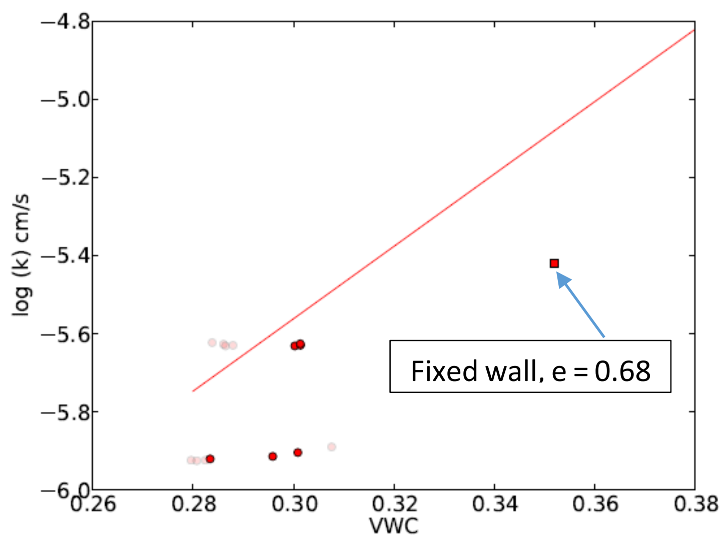

Figure 9.37 - Comparison of imposed flow and fixed wall results (dry compaction condition and low void ratio)

When the results from samples compacted at the optimum moisture condition were examined (shown in Figure 9.38) similar trends were seen. The hydraulic conductivity measured in the fixed wall permeameter was much lower than the conductivity predicted by the K-function from imposed flow testing results. In this case the fixed wall results were 85% lower than the prediction from the K-function which was considered significant.

The centrifuge results from the imposed flow procedure are shown again in Figure 9.39. However, instead of plotting the entire range of hydraulic conductivity measured, only the maximum hydraulic conductivity measured in the centrifuge for a given void ration is shown. The centrifuge results were performed up to flow rates that resulting in ponding on water on the surface of samples and it is expected that these results are from samples at a quasi-saturated state. Fixed wall permeameter results, which were also conducted quasi-saturated specimens, are included (magenta) on the graph for comparison. The relationship between quasi-saturated hydraulic conductivity and void ratio for samples tested using the imposed flow procedure and fixed wall permeameter were nearly identical.

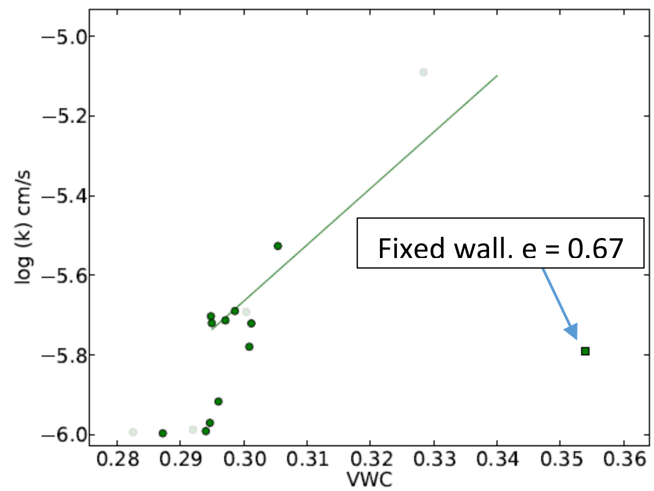

Figure 9.38 - Comparison of imposed flow and fixed wall results (optimum compaction condition and low void ratio)

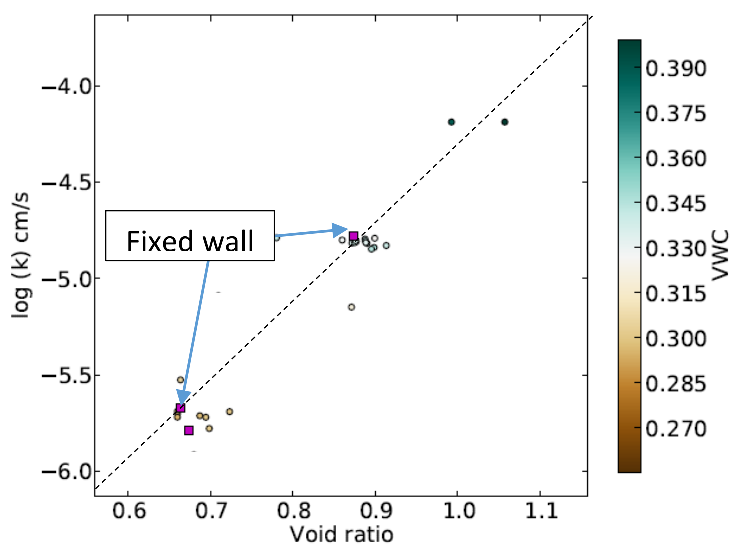

Figure 9.39 - Comparison of fixed wall (magenta squares) and imposed flow results based on void ratio (optimum moisture condition)

In summary the imposed flow procedure and the fixed wall permeameter measured the same relationship between quasi-saturated hydraulic conductivity and void ratio. However, as seen in Figure 9.38, the volumetric water content of samples tested in the fixed wall permeameter was significantly higher at low void ratios. As a result, the fixed wall permeameter results did not match well with the K-function (which relates hydraulic conductivity and volumetric water content) fit to the imposed flow results at low void ratios.

The behavior of lower measured volumetric water content in the centrifuge imposed flow procedure is consistent with the behavior observed in the hydrostatic procedure. In the hydrostatic procedure, measured volumetric water contents were below those measured using conventional methods at low suctions while the difference was observed in the imposed flow results at low void ratios. Both low void ratios and low suctions occur near the base of centrifuge samples. The low void ratios occur due to the highest stresses occurring at the base of samples in centrifuge tests. The low suctions occur at the base due to the imposed zero suction boundary at the base of samples.

It is hypothesized that the discrepancy at the base of samples between conventional procedures and the centrifuge procedures occurred due to an increase in entrapped air at the base of specimens. The changes made to the centrifuge base in order to impose a zero suction boundary is thought to have increased the entrapped air at the base. This is due to the ceramic disc at the base of the centrifuge sample having a high air entry pressure. This effectively created an impermeable boundary at the base of specimens for air flow. As a result, as the infiltration front advanced down the sample there was available exit for the air that was being replaced by water.

Research was performed by Wang et al. (1998) into the effects of the lower boundary condition of infiltration tests. The moisture front was monitored in columns where one boundary was an “open flow” boundary allowing air to escape. The second boundary was “air confined” similar to the lower boundary of the centrifuge. The advancing moisture front was monitored in both setups and is shown in Figure 9.4. In the open flow boundary, the moisture front advanced evenly with no disruptions at the base of the samples. In the testing with the air confined lower boundary, the moisture front began fingering approximately a third of the way down the column and resulted in entrapped air at the base of the specimen.

These results support the hypothesis that the discrepancy between centrifuge and conventional tests was due to an increase in entrapped air at the base of specimens due to the lower boundary condition. Standard pressure plate tests and the fixed wall permeameters were conducted by flowing water up through the specimens. This allowed the air in the soil to escape through the surface of the sample resulting in a lower volume of entrapped air when compared to the base of centrifuge samples.

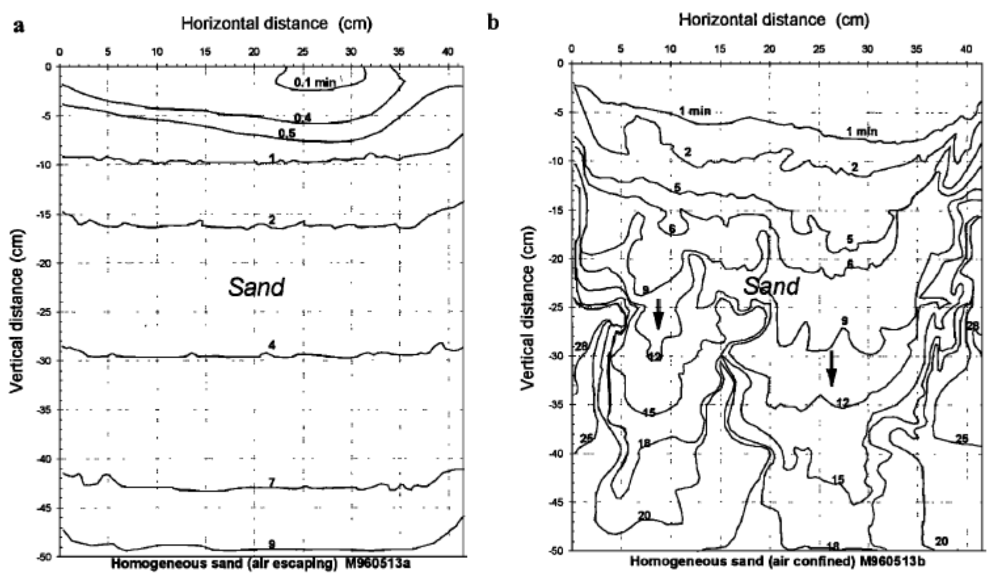

Figure 9.40 - Air entrapment in air confined infiltration test – a) air escaping b) air confined

9.7.3 Summary of the Comparison of Centrifuge Results with Results from Standard Tests

Hydraulic properties of the RMA soil determined using the hydrostatic and imposed flow procedures were compared with results determined using standard testing procedures.

The retention results from the hydrostatic procedure were compared with pressure plate results and the results from the imposed flow procedure were compared with fixed wall permeameter results.

The soil water retention surface determined using the hydrostatic procedure matched well with pressure plate results. The majority of the data collected using the hydrostatic procedure fell between the wetting and drying hysteresis loops measured in pressure plate testing. At low suctions (<20 kPa) the hydrostatic procedure resulted in lower water contents (~5%) than those measured in the pressure plate. At high suctions (>80 kPa) the hydrostatic procedure resulted in slightly higher volumetric water contents (~1%) than the pressure plate results. The differences were a maximum at low void ratios and reduced as void ratio was decreased.

At high void ratios (~0.88), the K-surface determined using the imposed flow testing procedure matched excellently with fixed wall permeameter results for samples compacted at both the dry and optimum moisture conditions. The differences between the measured hydraulic conductivity using fixed wall permeameters and the predicted hydraulic conductivity using the K-surface form imposed flow testing results was less than 20%. At low void ratios the maximum hydraulic conductivity between both testing procedures matched well however the volumetric water content of samples tested in fixed wall permeameters was approximately 5% higher.

The lower water content measured in both centrifuge procedures at low suctions and low void ratios was attributed to increases in entrapped air at the base of specimens due to the lower boundary condition. The ceramic disc at the base of centrifuge specimens did not allow air to escape during infiltration, increasing the volume of entrapped air near the base for both procedures. Further research should be conducted in order to verify this hypothesis by adjusting the lower boundary in order to reduce the volume of entrapped air.

10 Conclusions

Research was completed on the use of centrifuge technology to characterize the unsaturated flow properties of a low plasticity clay (“RMA” soil). Three testing procedures were developed, referred to as the “instrumented”, “hydrostatic”, and “imposed flow” procedures. The “instrumented” procedure focuses on the use on in-flight measurement of the volumetric water content and suction in order to measure the soil water retention curve (SWRC) and hydraulic conductivity function (K-function) of soil samples. The “hydrostatic” and “imposed flow” procedures improve on the “instrumented” procedure by addressing several potential sources on inaccuracy. In addition, the procedures characterize the unsaturated behavior of soil samples over a range of void ratio, resulting in the measurement of the soil water retention surface (SWRS) and unsaturated hydraulic conductivity surface (K-surface).

Conclusions from this research are divided by topic and are presented in the following sections. General conclusions from the research are presented followed by conclusions from each testing series and then conclusions regarding the behavior of the RMA. Finally, recommendations for future research and testing are presented.

10.1 General Conclusions

- The centrifuge was found to increase the hydraulic gradient of soil samples by scaling the gravitational gradient independently of pressure gradient. The independent scaling of gravitational gradient allowed the centrifuge to accelerate unsaturated flow processes without affecting the suction and saturation of soil samples. This is a unique benefit of centrifuge testing as traditional testing methods can only increase the hydraulic gradient by changing the pore pressure at boundaries, which affects the saturation of samples.

- Compaction water content was found to significantly affect the unsaturated hydraulic behavior of the RMA soil. In particular, increases in compaction water content resulted in a decrease of large pore sizes in the soil, resulting in increased water retention and reduced unsaturated hydraulic conductivity.
- Void ratio was found to significantly affect the unsaturated hydraulic behavior of the RMA soil. Specifically, decreases in void ratio were shown to reduce the unsaturated hydraulic conductivity. In addition, decreases in void ratio were shown to result in either increase or decrease on the soil water retention, depending on the level of suction in the soil.
- A good agreement was found between results obtained using standard methods and those from the hydrostatic and imposed flow procedures. Accordingly, steady state centrifuge methods were ultimately found to provide a both expeditious and accurate method for characterizing the unsaturated flow properties of soil.

10.2 Conclusions Regarding Testing Series "I"

- The minimum suction at which the MPS-2 sensors were found to provide reliable measurements was approximately 10 kPa. Suctions below this range occurred in flow tests conducted at target hydraulic conductivities above approximately $3x10^{-5}$ cm/s and corresponded to volumetric water contents above 30%. As a result, the effective range of the instrumented testing procedure was limited to hydraulic conductivities and volumetric water contents below these values.
- The observed accuracy of the moisture content sensors (EC-5) was found to be approximately +/- 4%. This was larger than the manufacturer rated accuracy of +/- 2% for soil a specific calibration.
- The accuracy of the EC-5 sensors was found to be insufficient to measure the changes in volumetric water content needed for this study. The change in volumetric water content that occurred during instrumented testing between different flow rates was on the order of 1-2%. This change is smaller than the

accuracy of the sensors. As a result, the inherent variability of the sensor dominated the sensor reading rather the change in VWC of the soil between flow rates.

- The portion of the moisture content profile that was affected by the lower boundary was significant. In extreme cases the entire sample was affected by the lower boundary. The procedure for calculating the hydraulic conductivity of soil samples in the instrumented testing series assumed the lower boundary did not affect the upper portion of the sample. As a result, a change in procedure (implemented in later testing series) was necessary in order to account for the effects of the lower boundary in the sample
- The density of soil samples was found to vary, often significantly across the sample height (from 1.3 to 1.6 g/cc). The highest density was measured at the base of samples where the highest stresses occurred. The density was not measured in the majority of samples tested during the instrumented testing series. Therefore, the unsaturated soil properties from this series can only be related to a range in density.
- The soil water retention curve measured as part of Series "I" (Instrumented) testing matched well with results from conventional testing procedures that were conducted for similar ranges of density as those found to have occurred in centrifuge tests.

10.3 Conclusions Regarding Testing Series "H"

- The hydrostatic procedure was found to accurately determine the relationship between void ratio, suction, and volumetric water content using centrifuge technology.
- The direct measurement of water content and void ratio involving slicing samples after testing was found to provide accurate data.

- The measurements of water content and void ratio corresponded to the range of suction imposed across the slice. The range of suction across each slice was calculated as approximately 7 kPa and 14 kPa for g-levels of 50 and 100 respectively.
- The minimum suction that the hydrostatic procedure can measure retention behavior was found to be 7 kPa and 14 kPa at g-levels of 50 and 100 respectively. These values correspond to the average suction of the bottom slice of centrifuge samples at these g-levels.
- The maximum suction that the hydrostatic procedure can measure retention behavior is the average suction of the top slice of the centrifuge sample. At the maximum g-level of 100, the resulting average suction of the top slice of the sample is approximately 90 kPa. Suctions of 90 kPa resulted in volumetric want contents as low as 18% for the compaction conditions and ranges in void ratio tested.
- The results from the hydrostatic testing procedure produced consistent data between repeat tests and resulted in a smooth relationship between VWC, void ratio, and suction (referred to as the soil water retention surface or SWRS).
- The following conclusions can be drawn regarding methods for modeling the SWRS determined using the hydrostatic testing procedure:
    - The van Genuchten function with parameters scaled by changes in void ratio was found to be appropriate for fitting a continuous surface to the SWRS from hydrostatic data. Specifically, a linear change in van Genuchten parameters with void ratio fit the hydrostatic data sets well.
    - The best method for fitting the van Genuchten function to hydrostatic results was found to be fitting the saturated and residual water content to known relations with void ratio and then using optimization algorithms to fit the other parameters in order to reduce errors between the predicted surface and measured data.

    - Surfaces fit to each compaction moisture conditions (wet, optimum, dry) resulted in average errors between the measured data set and the modeled surface of approximately 0.5% VWC.
- Hysteresis was not observed to occur in hydrostatic centrifuge tests that were performed in order to evaluate hysteresis.
- Hydrostatic tests that imposed the same levels of suction using different g-levels resulted in similar volumetric water contents. This confirmed the framework used in calculating suction and showed that elevation potential scaled with g-level.
- The hydrostatic procedure produced retention results that generally fell in between the “wetting” and “drying” hysteresis loops from pressure plate results. At low suctions (<20 kPa) the hydrostatic procedure resulted in lower volumetric water contents (~5%) than those measured by pressure plate testing. At high suctions (>80 kPa) the hydrostatic procedure resulted in slightly higher volumetric water contents (~1%) than the pressure plate results. The lower volumetric water content measured in the centrifuge occurred at low suctions, which also occur at the base of centrifuge specimens. The difference in measured volumetric water content is hypothesized to be a result of an increased volume of entrapped air in centrifuge specimens due to the lower boundary condition.
- Some limitations of the hydrostatic procedure were identified as follows:
    - The suction and void ratio of samples tested using the hydrostatic procedure were both a minimum at the base of samples and maximum at the surface of samples. As a result, combinations of high suctions and low void ratios (or vice versa) were difficult to target using the hydrostatic procedure.
    - The void ratio and water content of soil samples tested using the hydrostatic procedure were measured after they were removed from

centrifugation. There was a potential increase in void ratio and movement of moisture towards the top of samples that occurred before the void ratio and water content could be measured.

10.4 Conclusions Regarding Testing Series "IF"

- A testing procedure was developed that allowed the unsaturated hydraulic conductivity of soils to be evaluated using steady state flow and centrifuge technology.
- The change in suction across samples tested using the imposed flow procedure was found to be modeled accurately using an exponential function of the form $\psi = A(1 - e^{-Bz})$. This function is easily differentiable and allowed the suction gradient to be calculated at any point in the sample.
- Many imposed flow tests were conducted at flow rates that were higher than the saturated hydraulic conductivity of the soil. This resulted in erroneous test results, which were removed from the data sets.
- The imposed flow testing procedure produced unreliable hydraulic conductivity measurements when the hydraulic gradient was small. Low hydraulic gradients occurred when the suction gradient and gravitational gradient were similar in magnitude but opposite in direction. In such cases small errors in the prediction of suction gradient resulted in large errors for the calculated hydraulic conductivity.
- Due to large changes in hydraulic conductivity with void ratio, samples compacted at the wet moisture condition were found to not produce reliable results. Flow rates imposed on samples of low void ratios were too high and flow rates imposed on samples with high void ratio were too low to reliably measure hydraulic conductivity.
- Samples compacted at the optimum compaction moisture condition showed consistent results when tested using the imposed flow procedure. Results were

measured for a wide range of unsaturated hydraulic conductivity and void ratio allowing a surface to be created that defined the relationship between K, e, and VWC. The surface was found to be modeled well by a plane and referred to as the K-surface.

- Samples compacted at the dry compaction moisture condition showed consistent results when tested using the imposed flow procedure. The K-surface was also found to be modeled well by a plane.
- Scaling tests targeting the same hydraulic conductivity conducted at different g-levels produced consistent results regarding final water contents and hydraulic conductivity when differences in void ratio were taken into account.
- At high void ratios (0.88), the K-surfaces determined using the imposed flow testing procedure matched excellently with fixed wall permeameter results for samples compacted at both the dry and optimum moisture conditions with differences of less than 20%.
- At low void ratios (0.68), the quasi-saturated hydraulic conductivity measured using the imposed flow procedure matched well with the quasi-saturated hydraulic conductivity measured using fixed wall permeameters. However, the volumetric water content of samples tested in fixed wall permeameters was approximately 5% higher. The difference in volumetric water content is attributed to the lower boundary condition of the centrifuge setup, which increases the volume of entrapped air at the base of centrifuge specimens.
- Some limitations of the imposed flow procedure were found to be:
    - The void ratio and water content of soil samples tested using the imposed flow procedure were measured after they were removed from centrifugation. There was a potential increase in void ratio and movement of moisture towards the base of samples that occurred before the void ratio and water content could be measured.

- The imposed flow testing procedure produced unreliable hydraulic conductivity measurements when the hydraulic gradient was small. This occurred when the suction gradient and gravitational gradient were similar in magnitude but opposite in direction. In such cases small errors in prediction of the suction gradient resulted in large errors for the calculated hydraulic conductivity.

10.5 Conclusions Regarding the Behavior of the RMA Soil

- RMA Samples exhibited behavior consistent with saturation well below water contents corresponding to saturation. Saturated behavior below true saturation was observed in results from both the hydrostatic and imposed flow testing procedures. This was referred to as quasi-saturation and the difference in water content between quasi-saturation and true saturation was attributed to entrapped air.
- The volume of entrapped air in RMA samples varied depending on the void ratio. At a void ratio of 0.6 the volume of entrapped air was approximately 5% of the total volume. The volume of entrapped air increased to around 10% of the total volume at a void ratio of 0.8. Compaction moisture content was found to have a lesser effect on the volume of entrapped air (changes of 1-2% of the total volume).
- The relationship of the RMA soil between quasi-saturation and void ratio in the centrifuge was found to be linear for the ranges of void ratio tested.
- Fixed wall permeameter tests conducted outside the centrifuge resulted in similar volumes of entrapped air as the centrifuge samples in specimens compacted at the dry and optimum moisture conditions. The wet moisture condition resulted in much lower volume of entrapped air in fixed wall permeameter testing compared to the centrifuge results (2-3% of total volume in fixed wall vs. 5-10% in centrifuge). The difference may have been due to

measurement errors and further research is required in order to verify the difference.

- Compaction water content was found to significantly affect the unsaturated hydraulic behavior of the RMA soil. The following conclusions can be drawn regarding compaction water content:
    - Large clods formed when the soil was prepared to the wet compaction moisture content. When samples were prepared at 80% relative compaction at the wet compaction moisture condition large voids were visible in the soil between clods. When compacted at 90% the voids were closed and the soil appeared to be a uniform soil mass.
    - Soil prepared to the dry and optimum moisture conditions did not form significant clods. When soil at these conditions was compacted there were not voids visible in the samples for either the 80% or 90% relative compaction conditions.
    - Changes in compaction water content resulted in significant changes in results from both the hydrostatic and imposed flow procedures.
    - Samples compacted at the dry moisture condition resulted in the highest change in volumetric water content (14%) over the ranges of suction (5-90 kPa) measured using the hydrostatic procedure. The change in volumetric water content across the same suction range was reduced to 10% and 4% for samples compacted at the optimum and wet moistures conditions respectively.
    - Samples compacted at the wet moisture condition retained the most water (32% VWC) at the maximum suction measured in the centrifuge (95 kPa). The volume of water retain at 90 kPa by samples compacted the optimum and dry moisture conditions was lower at 20% and 19% respectively.

- The general trend of compaction water content in the retention results obtained using the hydrostatic procedure is that increases in compaction water content lead to reduction in pore sizes.
- The unsaturated hydraulic conductivity measured in the centrifuge was highest for samples compacted at the dry compaction condition followed by the optimum and finally wet conditions. This was supported by fixed wall permeameter test results, which showed similar trend.
- The hydrostatic data and imposed flow data were in agreement with one another regarding the pore size of samples compacted at different water contents. Soils with larger volume of large pores (determined by the hydrostatic procedure) resulted in higher hydraulic conductivity (determined by the imposed flow procedure) for the same porosity. This follows theoretical calculations that large pores should dominate flow processes as the resistant to flow reduces proportionally with radius to the 4th power while volume increases with the square of radius.

- Void ratio was found to significantly affect the unsaturated hydraulic behavior of the RMA soil. The following conclusions can be drawn the effects of void ratio:
    - Void ratio affected the retention behavior differently depending on what area of the SWRS the void ratio change occurred. Three zones were identified:
        - The quasi-saturated zone exhibited saturated behavior for changes in void ratio. Changes in void ratio were compensated by equal changes in volumetric content so that the degree of quasi-saturated remained 100%.
        - In “Zone 1” increases in void ratio resulted an increase in volumetric water content. The increases in VWC were less than the increases seen in the quasi-saturated zone resulting in a reduction in the degree of quasi-saturation.

        - In "Zone 2" the trends seen in Zone 1 were reversed and increases in void ratio decreases the volumetric water content.
    - Increases in void ratio increased the unsaturated hydraulic conductivity measured using the imposed flow procedure.
    - The change in unsaturated hydraulic conductivity with void ratio measured using the imposed flow procedure was similar for the samples compacted at the dry and optimum compaction conditions (approximately a 25% increase in unsaturated hydraulic conductivity per 0.1 change in void ratio).
    - Samples compacted at the wet moisture condition showed a dramatic increase in hydraulic conductivity across a small increase in void ratio (increasing nearly 2 orders of magnitude across 0.05 void ratio). This was determined to be due to a change in structure of the soil when all of the macro voids of the soil were removed. In other areas of the K-surface, samples compacted using the wet moisture condition showed similar changes in unsaturated hydraulic conductivity with void ratio as the dry and optimum conditions.
- At hydraulic conductivities above 1.8×10^{-6} cm/s, the hydraulic conductivity was found to change approximately an order of magnitude every 10% volumetric water content change. This was consistent for samples compacted at each moisture condition.
- A change in relation between unsaturated hydraulic conductivity and volumetric water content was observed in samples compacted at the dry and optimum moisture condition at an unsaturated hydraulic conductivity of approximately 1.8×10^{-6} cm/s. Below this value, the change in hydraulic conductivity with volumetric water content was around three times larger than above it. Insufficient data was measured on samples compacted at the wet moisture condition to make a comparable conclusion.

10.6 Recommendations for Future Research

Overall, the centrifuge procedures produced results that were in good agreement with conventional test results. However, data collected from the base of samples in centrifuge tests resulted in lower measured water contents (~5% VWC) than from conventional procedures. This different was not seen in results from other areas of the centrifuge samples. It was concluded that this was due to an increase in entrapped air at the base of centrifuge samples due to the lower boundary condition, which was a saturated ceramic disc. This disc had a relatively high air entry pressure and did not allow air to be removed from the sample as it was replaced by water in the infiltration process. As a result, an increase in volume of entrapped air occurred at the base of the specimen, closest to the boundary condition.

Before these procedures be used for further characterization, it is recommended that the lower boundary condition be adjusted in order to allow air to escape more easily from the base of specimens. This can be accomplished by reverting the base design back to a "free draining" boundary. This boundary condition should still result in a zero suction boundary, while allowing air to be removed as the infiltration process advances downward. If such change is confirmed to reduce the volume of entrapped air at the base of centrifuge samples and the results match well with conventional test results, the procedures can be used as is for characterization of unsaturated flow properties. If only the retention characteristics of a soil are desired, the Hydrostatic testing procedure can be used in order to determine these characteristics. If the unsaturated hydraulic conductivity of the soil is of interest, the Hydrostatic procedure must first be used in order to determine the retention characteristics and then the Imposed Flow procedure to determine the unsaturated hydraulic conductivity. This is necessary as the retention characteristics are required for determining the hydraulic gradient during Imposed Flow testing.

Additional changes are recommended that would increase the capabilities of the procedures. In particular, adding non-intrusive instrumentation to the testing setup would provide valuable transient information form the sample during testing. The void ratio of the sample must still be accurately measured so embedded sensors are not recommended. Instead, resistivity or capacitance based sensors on the surface of the soil sample can be used in order to determine the water content of the sample at different locations over time. In addition, it is recommended that the total height of the soil sample be monitored during testing by use of a linear position sensor on the sample surface. This will provide information regarding the deformations that occur when the stresses due to centrifugation are removed.

In order to increase the methods for measurement of retention, changes are suggested to the base of the centrifuge cup in order to allow true "wetting" retention tests to be performed. This can be accomplished by routing flow into the base of the centrifuge cup so that any water absorbed into the centrifuge sample is replaced by flow into the base. This would allow a wide range of hysteresis to be evaluated using the centrifuge procedures, which currently can only be performed using "drying" methods.

An area of research that can be performed after adjusting the procedures to include in-flight measurements is the comparison of the unsaturated hydraulic conductivity measured using transient (e.g. "instant profiling") and steady state methods. The centrifuge methods can be used to provide valuable insight into the accuracy of instant profiling methods, such as determining the sensitivity of results to different parameters of the test (e.g. flow rate).

It is recommended to extend the scope of soils tested using the centrifuge procedures. A single low plasticity clay was characterized as part of this research. It would be valuable to verify the accuracy of the procedures using different soil types such as sands, silts, and high plasticity clays. Sands and silts are not expected to be problematic due to typically having larger hydraulic conductivities compared to the low plasticity clays used in this research. However, high plasticity clays may require adjustments to the testing setup in order to impose smaller flow rates than currently possible in the centrifuge testing setup. In addition, the maximum suction that can be tested using the hydrostatic procedure is approximately 100 kPa. This may be an insignificant suction to de-saturate some high plasticity clays, which can have air entry suctions well above 100 kPa.

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