DISSERTATION

DESIGN PRINCIPLES FOR FOUNDATIONS ON EXPANSIVE SOILS

Submitted by

Kuo-Chieh Chao

Department of Civil and Environmental Engineering

In partial fulfillment of the requirements

for the Degree of Doctor of Philosophy

Colorado State University

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY KUO-CHIEH CHAO ENTITLED "DESIGN PRINCIPLES FOR FOUNDATIONS ON EXPANSIVE SOILS" BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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Co-Advisor

Advisor

Department Head

ABSTRACT OF DISSERTATION

DESIGN PRINCIPLES FOR FOUNDATIONS ON EXPANSIVE SOILS

The design of foundations for sites having expansive soils is one of the greatest challenges facing geotechnical engineers today. Intolerable heave of foundations on expansive soils often affects critical safety aspects of structures. Therefore, it is imperative that design of foundations for expansive soils includes analyses of expected heave and consequences of foundation movement over the design life of the structure.

Current technology generally considers the amount of predicted heave that will ultimately occur at a site. Design of foundations for extreme ultimate conditions is not always practical and economical in engineering practice. When large values of heave are predicted, the depth of potential heave may be very deep, and the time required for the wetting front to reach large depths of potential heave may exceed the design life of the structure. In that case, it is important to consider the rate of water migration in the vadose zone. Thus, design of foundations for buildings on expansive soils must consider the migration of the subsurface water that will occur during the design life of the structure, and the amount of heave that such wetting will produce. Current design procedures that are in common use are deficient in this respect.

Aappropriate design of foundations on expansive soils must consider accurate prediction of soil/bedrock heave and the effect of that heave on foundation movement

over the design life of the structure. It is shown that migration of the subsurface water can be modeled accurately, and that future consequential movement of the foundation system can be accurately predicted.

The hypothesis of this research is that analyses of the expected wetting of the subsoils, and the prediction of amount and nature of heave associated with that wetting, must be a critical part of the design and construction of foundations on expansive soils. In this way, the design methodology for foundations on expansive soils will be improved, and will optimize performance of all elements of the structure.

A major problem in developing the design principles for foundations on expansive soils is that comprehensive field data for a long period of time at a site are usually not available. One building that has been undergoing distress for approximately 15 years is the TRACON building at Denver International Airport, Denver, Colorado. This building is owned by the Federal Aviation Administration and is located on a site having highly expansive soils. Water migration and foundation movement at the TRACON building have been monitored intensely over the past six years. Extensive modeling of the field results has provided particularly useful insight into the behavior of the foundations, and has provided the basis for the development of the design principles for foundations on expansive soils that is presented in this dissertation.

The goal of this research is to advance the state of the art with respect to foundation design by developing a methodology to apply rigorous engineering principles in the design of foundations on expansive soils.

To accomplish the goal, the objectives of this research are:

- to develop a means of installing stable survey benchmarks.
- to develop an accurate methodology to analyze the migration of subsurface water in unsaturated expansive soils. This includes the investigation of the soil water characteristic curve for the expansive bedrock.
- to develop a means of predicting timewise changes in heave based on measured survey data or computer modeling of the water migration.
- to develop a rigorous and appropriate design methodology for foundations on expansive soils.

A water migration study was performed using the VADOSE/W models with the input parameters and boundary conditions calibrated over the period from May 2001 to June 2004 and validated over the period from July 2004 to August 2006 using observed subsurface nuclear gauge data. The results of the analyses have demonstrated that rigorous computer modeling can be performed to analyze the actual migration of subsurface water within the subsoils. Projection of subsurface water migration into the future until the end of the design life of the structure was then possible.

Using the relationship between water content and percent swell developed herein, along with computer modeling of the wetting of the subsoils, heave as a function of time can be predicted. The effects of climate and irrigation must be included in the modeling. The change of heave with time was also predicted by fitting the observed survey data to a hyperbolic equation. In doing so, it was necessary to take into account the maximum ultimate heave predicted using the heave equation.

A design methodology for foundations on expansive soils was proposed based on the field data collected at the TRACON site. This methodology considers the timewise pattern of migration of water within subsoils and the associated heave that such wetting will produce over the design life of a structure. The proposed design methodology was verified over a period of 5 years at the TRACON site. It is believed that the methodology can be applied over the design life of the structure.

The methodology was demonstrated for various design conditions by performing water migration analyses and rate of heave calculations on a hypothetical site. The results of the study indicate that, if the progression of heave over the design life of the structure is considered, the required pier length can be reduced significantly compared to that using the current design methodology. Furthermore, the effect of overexcavating and replacing the upper few meters of expansive soil in combination with installing piers is considered. In summary, the proposed design methodology provides a practical and economical approach to design foundations on expansive soils.

Kuo-Chieh Chao
Department of Civil and Environmental Engineering
Colorado State University
Fort Collins, CO 80523
Spring 2007

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CHAPTER 1

INTRODUCTION

1.1 Hypothesis, Goal, and Objectives

The design of foundations for sites having expansive soils is one of the greatest challenges facing geotechnical engineers today. Intolerable heave of foundations on expansive soils often affects critical safety aspects of structures. Therefore, it is imperative that design of foundations for expansive soils include analyses of expected heave and consequences of foundation movement over the design life of the structure.

Free-field heave is the fundamental parameter for evaluation of the performance of foundations. An important factor to be considered in the computation of predicted heave is the depth of wetting for the soils. Arbitrary depths of wetting have generally been assumed by practicing engineers in the Front Range area of Colorado. Over the last 30 years, the generally assumed depth of wetting has increased from less than 3 meters to a depth of about 6 to 8 meters. Instead of assuming an arbitrary depth of wetting, a conservative and prudent analysis would assume that the entire depth of potential heave is wetted. The depth of potential heave is defined as the depth to which the overburden vertical stress equals the swelling pressure of the soil (Nelson, et al., 2001).

To assume that the entire depth of potential heave will be wetted is not always practical and economical in design of foundations. When large values of heave are predicted, the depth of potential heave may be very deep, and the time required for the subsurface water to reach large depths of potential heave may exceed the design life of the structure. On the other hand, off-site development may introduce deep sources of water such as water bearing coal seams or sandstone strata. These may introduce deep wetting in shorter periods of time. Consequently, design of foundations for buildings on highly expansive soils must consider the pattern and rate of migration of the subsurface water that will occur during the design life of the structure, and the amount of heave that such wetting will produce.

Appropriate design of foundations on expansive soils must consider accurate prediction of soil/bedrock heave, and the effect of that heave on foundation movement over the design life of the structure. It will be shown in this dissertation that migration of the subsurface water can be modeled accurately, and that future consequential movement of the foundation system can be accurately predicted.

The hypothesis of this research is that analyses of the expected wetting of the subsoils, and the prediction of amount and nature of heave associated with that wetting, must be a critical part of the design and construction of foundations on expansive soils. In this way, the design methodology for foundations on expansive soils will be improved, and will optimize performance of all elements of the structure.

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TRACON building have been monitored intensely over the past six years. Extensive modeling of the field results has provided particularly useful insight into the behavior of the foundations, and has provided the basis for the development of the design principles for foundations on expansive soils that is presented in this dissertation.

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- to develop a means of predicting timewise changes in heave based on measured survey data or computer modeling of the water migration.
- to develop a rigorous and appropriate design methodology for foundations on expansive soils.

In design, it is necessary to extend analyses into the future over the design life of the structure. Obviously the actual boundary conditions such as climate, land use, accidents, and others, are not known with accuracy. Therefore, it is necessary to make predictions and assumptions in this regard. To do this one relies on historic data for factors such as climate, irrigation practices, and other factors. It is necessary to extend the analyses over the design life of the structure, even up to periods as much as 100 years.

Based on the results of the analyses, decisions are then made as to foundation types, lengths, and forces to be resisted.

1.2 Site Description

The TRACON building that is the source of the data presented herein is located approximately 2.8 km south of the Denver International Airport Terminals, Denver, Colorado. The location of the TRACON facility is shown in Figure 1-1. "TRACON" stands for "Terminal Radar Approach Control." The TRACON building is owned by the United States, Federal Aviation Administration (FAA) and is a critical part of the FAA National Airspace System (NAS). The NAS is the largest, most complex, and safest air navigation system in the world. The NAS relies on FAA's employees to provide air traffic control, flight service, security, field maintenance, certification, system acquisition, and other essential services. Interruption of operations at the Denver TRACON would have serious consequences for the efficiency and safety of the NAS, not only in the Denver Region but nationwide. This site clearly demonstrates the safety critical aspects of appropriate foundation design for sites with a high expansion potential.

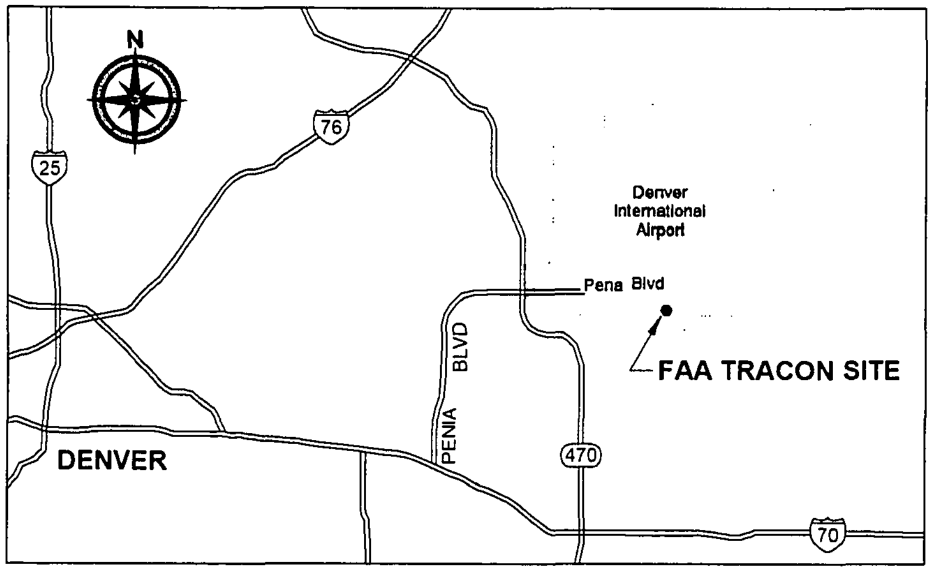


Figure 1-1 Location of FAA Denver TRACON Facility

Chen-Northern (1989) prepared an initial soils report for the TRACON building. The Chen-Northern soils report indicated that subsoils consisted of a thin layer of silty/sandy clay fill, underlain by up to 2.3 meters of sandy/silty clay and claystone bedrock. The maximum boring depth was approximately 11 meters. Testing performed by Chen-Northern (1989) has shown that the claystone bedrock at the site is highly expansive. Chen-Northern (1989) recommended that straight shaft piers be used to support the TRACON building. Piers were recommended to have a minimum length of 5 meters with a minimum penetration of 2.4 meters into the bedrock. The Chen-Northern (1989) soils report stated that slab-on-grade construction may be used, provided that the risk of distress resulting from slab movement is accepted by the owner.

The TRACON building was constructed in 1991. The structure has a footprint of approximately 4,600 m^2 and is two stories in height. An aerial photo of the TRACON facility is shown in Figure 1-2. The TRACON building is located on the northwest portion of the site and the Technical Operations Center (TOC) building is located to the southeast of that. The TRACON building is a steel frame structure supported on a drilled pier and grade beam foundation system with a slab-on-grade floor. The constructed piers range from 7.6 to 8.5 meters in length and from 46 to 76 cm in diameter.

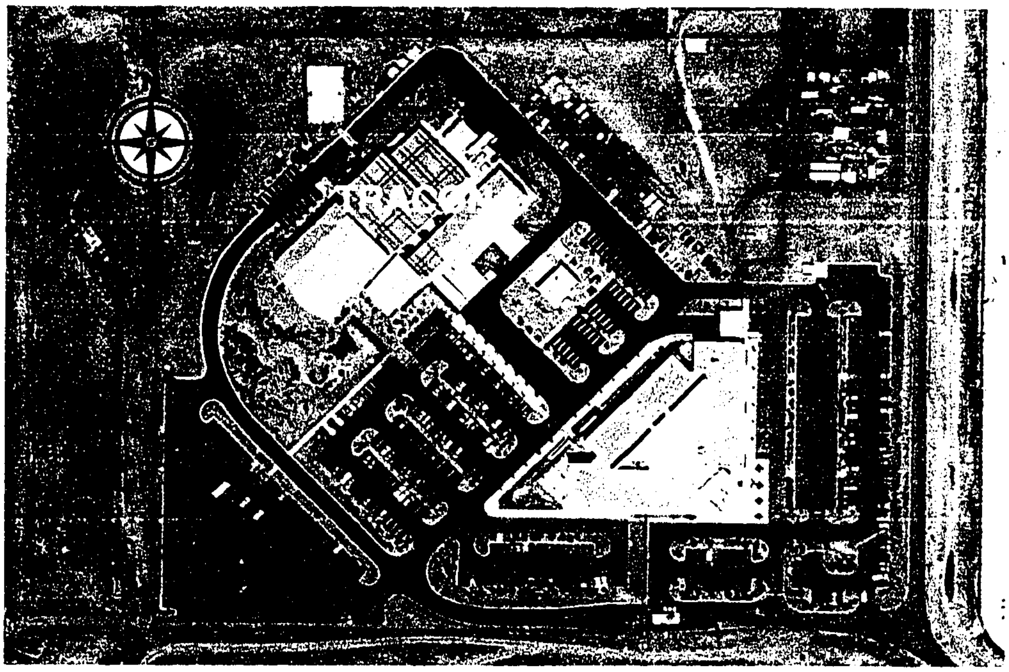


Figure 1-2 Aerial Photo of the TRACON Facility

1.3 Site Geology

The FAA site is located in the Colorado Piedmont section of the Interior Plains physiographic province. More specifically, the site is located in the west-central portion of the Denver Basin, a north-south trending structural basin which encompasses the majority of eastern Colorado from the Front Range of the Rocky Mountains into western Nebraska, Kansas and eastern Wyoming (USGS, 1987). The Denver Basin is an asymmetrical structural basin with a broad, gently sloping eastern flank, and a steeply-dipping and abrupt western flank formed by the uplift of the Front Range beginning in the Late Cretaceous period (Tweto, 1980). Subsequently, the basin was filled with sediments, and today it exhibits little topographic relief, although structural relief is on the order of 5,000 meters in the deepest part of the basin (Tweto, 1980). The TRACON building is immediately underlain by Lower Holocene to Upper Pleistocene windblown sand, silt, and clay from major streams located west and northwest of the site (Trimble and Machette, 1979). These materials immediately overlie the Paleocene and Upper Cretaceous Denver Formation which is approximately 200 meters thick in this area (USGS, 1987).

Hydrogeologically, the TRACON building is located within the Denver groundwater basin, a 17 square-meter area within the structural Denver Basin, extending from the Front Range of the Rocky Mountains east to near Limon, and from Colorado Springs north to near Greeley (USGS, 1987). The TRACON building is located in the north-central portion of the Denver ground water basin, and the surface drainage in the site vicinity is generally to the north. Alluvial aquifers are present in the larger stream valleys in this area and range in thickness from 3 to 50 meters thick (USGS, 1987).

The Denver ground water basin contains four principal aquifers. From deepest to shallowest, these are the Late Cretaceous Laramie-Foxhills aquifer, the Late Cretaceous Arapahoe aquifer, the Late Cretaceous/Early Tertiary Denver aquifer, and the Tertiary Dawson Arkose aquifer (USGS, 1987). These aquifers occur in the Fox Hills Sandstone, Laramie Formation, Arapahoe Formation, Denver Formation and Dawson Arkose (USGS, 1987). All but the Dawson Arkose aquifer are present under the TRACON building. The sedimentary strata in the Denver ground water basin which comprise the principal water-yielding formations are up to 900 meters thick in the deepest part of the basin (CDWR, 2002). The Pierre Shale defines the vertical extent of the aquifers. It underlies the Laramie-Foxhills aquifer and is considered the base of the aquifers because of its thickness (greater than 1,500 meters) and low permeability (USGS, 1987).

The presence of coal seams in the area of Denver International Airport has been publicly documented and widely reviewed. Kirkham and Ladwig (1979) described the area as "one of the major coal- and lignite-bearing regions in Colorado." The USGS report stated that the Denver aquifer consists of a "180 to 300-meters-thick series of interbedded shale, claystone, siltstone, and sandstone in which coal and fossilized plant remains are common." (USGS, 1987). In addition, coal seams have been encountered and noted in several engineering reports prepared as part of the development of the DIA site in around 1989. The report by Colorado Division of Water Resources also indicated that coal seams are commonly encountered in the Denver aquifer (CDWR, 2002).

CHAPTER 2

LITERATURE REVIEW

2.1 Mechanics of Unsaturated Soil

2.1.1 Stress State Variables

The state of stress in a soil is described by combinations of stress parameters that are referred to as stress state variables. The stress state variables are defined as nonmaterial variables required for the characterization of the stress condition (Fredlund and Rahardjo, 1993). To be true stress state variables they must be independent of the soil physical properties and must be expressed in terms of the measurable stresses, such as the total stress, σ, the pore-water pressure, u_w, and the pore-air pressure, u_a. The osmotic suction of a soil is also a valid stress state variable (Miller and Nelson, 2006). Nelson and Miller (1992) stated that a major step in the development of an appropriate framework for macroscale analysis was the definition of the appropriate stress state variables for unsaturated soils.

The effective stress concept has been well documented and used in applications for saturated soils (see, for example, Lambe and Whitman, 1969). Numerous early attempts have been made to develop a similar concept of effective stress for unsaturated soils. Table 2-1 summaries various equations and parameters that were proposed by previous researchers. Table 2-1 indicates that the use of a single-valued effective stress for unsaturated soils has encountered many difficulties since it introduces constitutive parameters into the equations of equilibrium and violates the basic laws of mechanics. In addition, the use of empirical parameters in the description of the stress state is not appropriate.

Fredlund and Morgenstern (1977) verified that $(\sigma - u_w)$, $(\sigma - u_a)$, and $(u_a - u_w)$ are three valid independent stress state variables, since these variables produce no distortion or volume change of an element when the individual components of the stress state variables are modified but the stress state variables themselves are kept constant. Matyas and Radhakrishan (1968), Barden, et al. (1969), Drumright and Nelson (1984), Edgar, et al. (1989), and Fredlund and Morgenstern (1997) have shown that the effective stress equation for unsaturated soils must be separated into two independent stress state variables. The complete form of the stress state for an unsaturated soil can be written as two independent stress tensors as follows:

$$\sigma' = \begin{bmatrix} (\sigma_x - u_a) & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & (\sigma_y - u_a) & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & (\sigma_z - u_a) \end{bmatrix} \qquad \text{Equation (2-1)}$$

and

$$u = \begin{bmatrix} (u_a - u_w) & 0 & 0 \\ 0 & (u_a - u_w) & 0 \\ 0 & 0 & (u_a - u_w) \end{bmatrix} \qquad \text{Equation (2-2)}$$

where σ_x, σ_y, and σ_z are the normal stresses in the x, y, and z directions and the off-diagonal terms (e.g., τ_{xy}) are the shear stresses. For principal directions, the off-diagonal terms in Equation (2-1) would be zero. The off-diagonal terms in Equation (2-2) will be always zero since fluid pressure is isotropic. Figure 2-1 illustrates the two independent tensors acting at a point in an unsaturated soil.

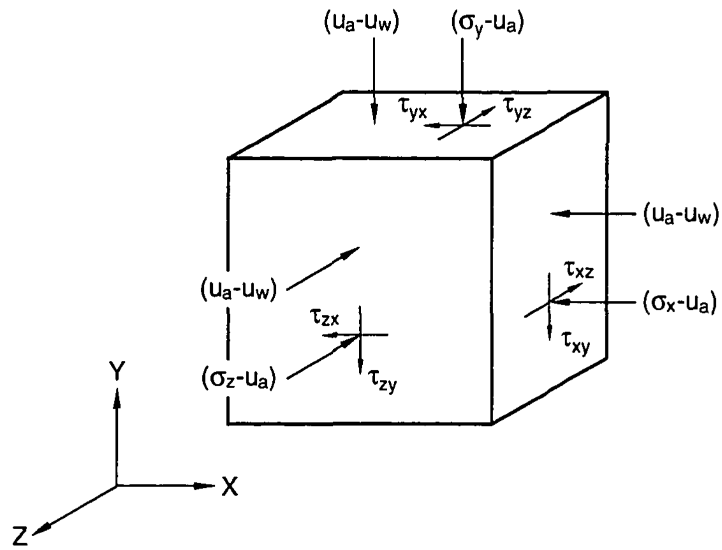


Figure 2-1 Stress State Variables for an Unsaturated Soil

Table 2-1 Effective Stress Equations for Unsaturated Soils (after Nelson and Miller, 1992 and Fredlund Rahardjo, 1993)

Equation	Description of Variables	Reference
$\sigma' = \sigma - \beta' u_w$	β' = holding or bonding factor, which is a measure of the number of bonds under tension, effective in contributing to shear strength of the soil	Croney, et al. (1958)
$\sigma' = (\sigma - u_a) + \chi (u_a - u_w)$	χ = parameter related to the degree of saturation of the soil u_a = the pressure in gas and vapor phase	Bishop (1959) Bishop and Blight (1963)
$\sigma' = \sigma a_m + u_a a_a + u_w a_w + R - A$	a_m = fraction of total area that is mineral a_a = fraction of total area that is air a_w = fraction of total area that is water R = repulsive electrical force A = attractive electrical force	Lambe (1960)
$\sigma' = \sigma + \psi p'$	ψ = parameter with values ranging from zero to one p' = pore-water pressure deficiency	Aitchison (1961)
$\sigma' = \sigma + \beta p'$	β = statistical factor of the same type as the contact area. This factor should be measured experimentally in each case	Jennings (1961)
$\sigma' = \sigma - u_a + \chi_m (h_m + u_a) + \chi_s (h_s + u_a)$	χ_m = effective stress parameter for matric suction h_m = matric suction χ_s = effective stress parameter for solute suction h_s = solute suction	Richards (1966)
$\sigma' = \sigma + \chi_m p''_m + \chi_s p''_m$	p''_m = matric suction p''_m = solute suction	Aitchison (1973)

The stress tensors shown in Equations (2-1) and (2-2) are formulated by using the pore air pressure, u_a, as a reference pressure in the force equilibrium equations for the soil structure. Alternatively, the stress tensors can be expressed by using the pore-water pressure, u_w, or the total normal stress, σ, as a reference pressure in the force equilibrium equations. Therefore, there are three possible combinations of stress state variables for describing the stress state relevant to the soil structure and contractile skin in an unsaturated soil, as shown in Table 2-2 only two of which are independent. Fredlund and Morgenstern (1977) and Fredlund (1979a) indicated that the combination of the two stress state variables, $(\sigma - u_a)$ and $(u_a - u_w)$, appears to be the most satisfactory for use in engineering practice. This combination is advantageous because the effects of a change in the total normal stress can be separated from the effects of a change in the pore water pressure. Additionally, the pore-air pressure is atmospheric (i.e., zero gauge pressure) for most practical engineering problem.

Table 2-2 Combinations of Stress State Variables for an Unsaturated Soil

Reference Pressure	Stress State Variables
Pore-Air Pressure, u_a	$(\sigma - u_a)$ and $(u_a - u_w)$
Pore-Water Pressure, u_w	$(\sigma - u_w)$ and $(u_a - u_w)$
Total Normal Stress, σ	$(\sigma - u_a)$ and $(\sigma - u_w)$

2.1.2 Constitutive Relationships

Various constitutive relationships for an unsaturated soil were studied during the 1960s and 1970s (Blight, 1965; Matyas and Radhakrishna, 1968; Barden, et al., 1969; Fredlund and Morgenstern, 1976; and Fredlund, 1979a). Volume or water content changes of an unsaturated soil can be related to the stress state variables using appropriate constitutive relationships. For an unsaturated soil, void ratio and water content can be used as the deformation state variables for the soil structure and water phase, respectively. For example, the change in void ratio, de, of an unsaturated soil under three-dimensional loading conditions can be described by an equation as follows (Fredlund and Rahardjo, 1993):

$$de = a_t d(\sigma - u_a) + a_m d(u_a - u_w) \qquad \text{Equation (2-3)}$$

where:

a_t = $\partial e / \partial(\sigma - u_a)$ = coefficient of compressibility with respect to a change in net normal stress, $d(\sigma - u_a)$

a_m = $\partial e / \partial(u_a - u_w)$ = coefficient of compressibility with respect to a change in matric suction, $d(u_a - u_w)$

The water content constitutive equation can be expressed as a change in water content with respect to applied stress. For three-dimensional loading conditions, the water content constitutive relationship can be written as the following general form in Equation (2-4). Similar constitutive relationships can be formulated for unloading conditions.

$$dw = b_t d(\sigma - u_a) + b_m d(u_a - u_w) \qquad \text{Equation (2-4)}$$

where:

b_t = $\partial w / \partial(\sigma - u_a)$ = coefficient of water content change with respect to a change in net normal stress, $d(\sigma - u_a)$

b_m = $\partial w / \partial(u_a - u_w)$ = coefficient of water content change with respect to a change in matric suction, $d(u_a - u_w)$

Equations (2-3) and (2-4) show that two constitutive parameters are necessary for defining the constitutive relationships, since two stress state variables are specified separately, as opposed to only one stress state variable, $(\sigma - u_w)$, for a saturated soil. This emphasizes the fact that the stress state variables must be considered independently.

The constitutive relationships presented in Equations (2-3) and (2-4) can be visualized in the form of volume-mass constitutive surfaces on three-dimensional plots, as shown in Figure 2-2. The soil properties, a_t, a_m, b_t, and b_m, shown in Equations (2-3) and (2-4) can be viewed as the slopes of the constitutive surfaces shown in Figure 2-2. The soil properties are moduli that vary as a function of the stress state variables. To define the magnitude of the soil moduli corresponding to any stress state, it is necessary to have constitutive equations describing the entire volume-mass constitutive surfaces. The equations then need to be differentiated with respect to each of the stress state variables to obtain the soil moduli. So far, there are no published equations to represent the entire volume-mass constitutive surfaces (Fredlund, 2000). Once approximate equations are formulated, the derivatives shown in Equations (2-3) and (2-4) will provide values of the soil moduli corresponding to any stress state.

Unsaturated soil properties can be calculated using the volume–mass constitutive surfaces and the basic volume-mass requirement shown in Equation (2-5).

$$Se = wG_s \qquad \text{Equation (2-5)}$$

where:

S	=	degree of saturation
e	=	void ratio
w	=	gravimetric water content, and
G_s	=	specific gravity

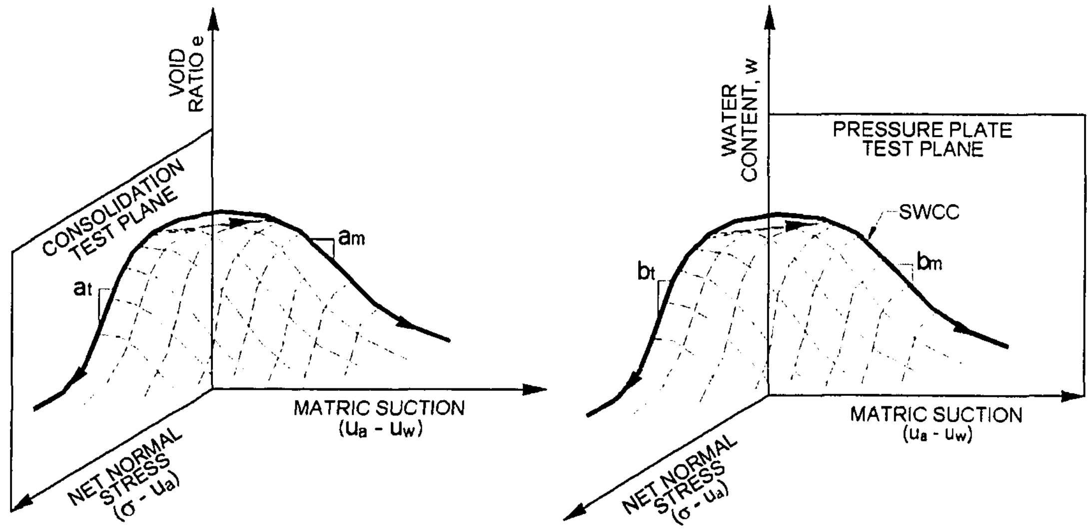


Figure 2-2 Two Independent Volume-Mass Constitutive Surfaces (from Fredlund and Rahardjo, 1993)

Nelson and Miller (1992) showed that the volume-mass constitutive surfaces can be linearized by plotting the volume-mass parameters versus the logarithm of the stress state variables. Nelson and Miller (1992) and Fredlund and Rahardjo (1993) indicated that the constitutive surfaces shown in Figure 2-2 exhibit a symptom of "uniqueness." The "uniqueness" of the constitutive surfaces demonstrates that there is only one relationship between the deformation and stress state variables. In addition, Fredlund (2002) indicated that it is necessary that the soil water characteristic curve may be viewed as a part of the complete water content constitutive surface of the volume–mass constitutive surfaces shown in Figure 2-2.

2.1.3 Soil Suction

The theoretical concept of soil suction was developed in soil physics regarding the soil water-plant system in the early 1900's (Buckingham, 1907; Gardner and Widtsoe, 1921; Richards, 1928, etc.). In soil physics, soil suction is generally referred to as the potential energy state of water in soil (Jury, et al., 1991). The potential energy state of water in soil is defined as the difference in energy per unit quantity of water compared to a reference state, because there is no absolute scale of energy. It is recommended that the reference state can be defined to be the state of pure (no solutes), free (no external forces other than gravity) water at a reference pressure, reference temperature, and reference elevation and is arbitrarily given a value of zero (Bolt, 1976). The use of soil suction in explaining the mechanical behavior of unsaturated soils in relation to engineering problems was introduced by Croney and Coleman (1948), Croney, et al. (1950), and Coleman (1962). In 1965, Aitchison (1965) provided quantitative definitions of soil suction and its components from a thermodynamic context, which have become accepted concepts in geotechnical engineering (Krahn and Fredlund, 1972; Fredlund and Rahardjo, 1988).

2.1.3.1 Matric Suction

Fredlund (1979a) discussed that the capillary phenomenon in soils is affiliated with the matric suction, $(u_a - u_w)$. This is depicted in Figure 2-3 where a column of saturated granular soil is placed in a pan of water and allowed to drain freely. The soil will remain saturated to some height depicted by the point h_d. Below this point, surface tension, T_s, of the air-water interface prevents the water from draining further. The air-water interface in the pore water causes the water pressure to be lower than the air pressure, causing the water to be in tension. The difference between the air and water pressure, $(u_a - u_w)$, quantifies the matric suction, and is a function of the radius of the spherical surface, R, and the surface tension, T_s, as shown in the following equation:

$$(u_a - u_w) = \frac{2T_s}{R}$$ Equation (2-6)

Equation (2-6) indicates that the matric suction is a function of the pore radius, and hence, the grain size of the soil. The matric suction at a point in the soil in terms of head, h_c, is equal to the height of that point above the water table as shown in Figure 2-3(a). The smaller the grain size of the soil, the greater the tension in the water, and the higher will be the capillary rise in the soil.

The capillary head depicted by h_d in Figure 2-3(a) is called the displacement head. This represents the air pressure that would be necessary to displace the water from the pore spaces. This is also called the air entry pressure.

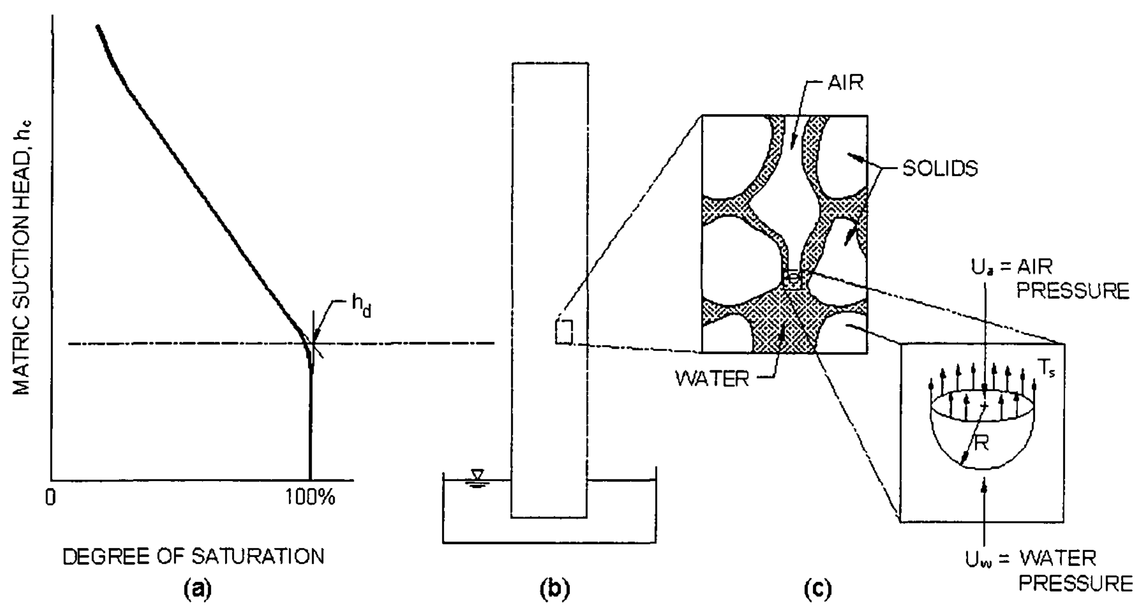


Figure 2-3 Matric Suction in Soil (from Nelson, et al., 2003)

2.1.3.2 Osmotic Suction

Osmotic suction, π, is due to the presence of solutes in the soil water which reduce the energy state of the water in soil. It is related to the salt content in the pore-water which is present in both saturated and unsaturated soils. Figure 2-4 illustrates the nature of osmotic suction by showing a chamber of water divided by a semi-permeable membrane. On one side of the membrane is pure water, and on the other side is a salt solution. The semipermeable membrane will allow water molecules to pass through it but not salt molecules. The concentration of the solution causes an attraction to water molecules and hence, a tendency for the pure water to flow into the salt solution through the semipermeable membrane. The pressure that the salt solution can exert on the pure water depends on the concentration of the salt in the solution. This pressure is called the osmotic pressure. This pressure is represented by h_o in terms of osmotic pressure head in Figure 2-4.

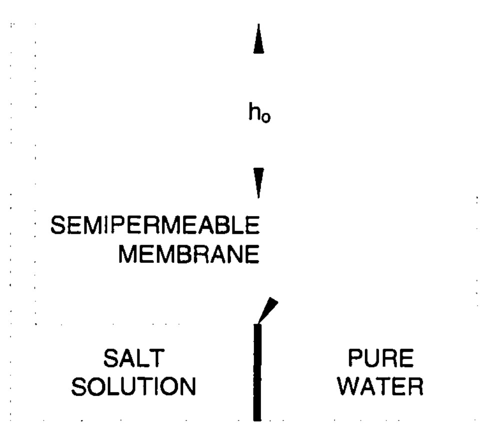


Figure 2-4 Osmotic Pressure Across a Semipermeable Membrane (from Nelson and Miller, 1996)

Two idealized clay particles in close proximity to each other are shown in Figure 2-5. The electrical charges on the faces of the clay particles hold salt cations in close proximity to balance the charges. As a result, the concentration of salt in the water in the space between the particles is higher than that outside of that space. Therefore, the electrical field around the clay particle serves as a "pseudo-semi-permeable" membrane, as shown in Figure 2-5. As water is introduced into the system, the high concentration of salt between the particles causes pressure to be exerted on the water molecules tending to force them into the space between the particles. This pressure is the osmotic suction of the soil.

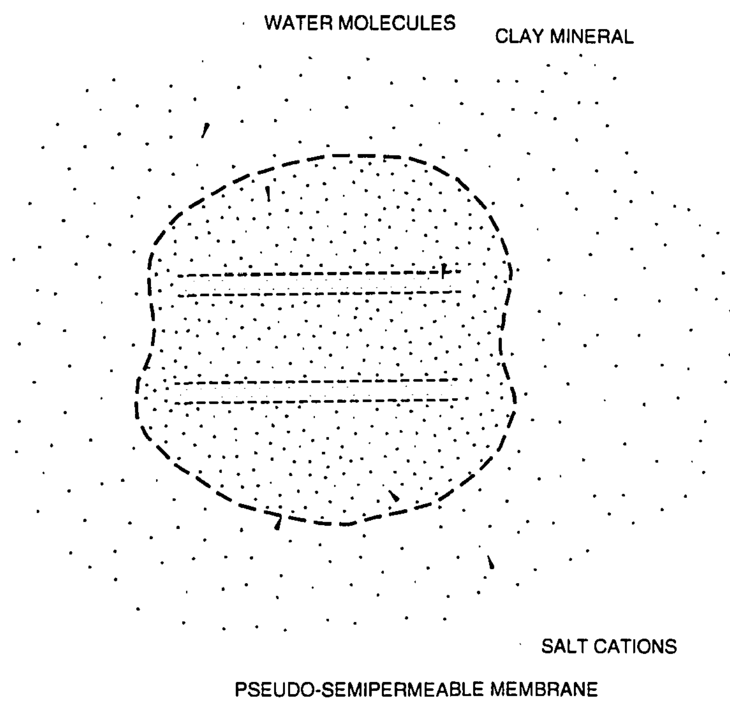


Figure 2-5 Pseudo-Semipermeable Membrane Effect Causing Osmotic Suction in Clay (from Nelson, et al., 2003)

Miller (1996) and Miller and Nelson (2006) showed that osmotic suction, π, is a valid, independent, stress state variable in soils. Thus, the complete rigorous definition of stress state of an unsaturated soil thus requires three independent variables: net normal stress, $(\sigma - u_a)$, matric suction, $(u_a - u_w)$, and osmotic suction, π. Appropriate constitutive parameters must be used to associate changes in these stress state variables with changes in soil volume. In general geotechnical engineering practice, changes in osmotic suction are negligible.

2.1.3.3 Total Suction

The total suction, ψ, is the sum of the matric suction, $(u_a - u_w)$, and the osmotic suction, π. In terms of their effect on the behavior of soil, they must be considered independently (Miller and Nelson, 1993). Figure 2-6 shows experimental data illustrating that the matric suction plus the osmotic suction are about equal to the total suction of the soil, as presented by Krahn and Fredlund (1972). The presented data are for glacial till specimens compacted under modified AASHTO conditions at various initial water contents. Each component of soil suction and the total suction were measured independently. Figure 2-6 indicates that the initial water content of compacted soils is directly related to the matric suction component. The osmotic suction remains fairly consistent with an average value of approximately 300 kPa in the range of water content from 11 to 17%. Consequently, the change in the total suction is quite representative of the change in matric suction within the range of water contents encountered in most practical geotechnical engineering problems.

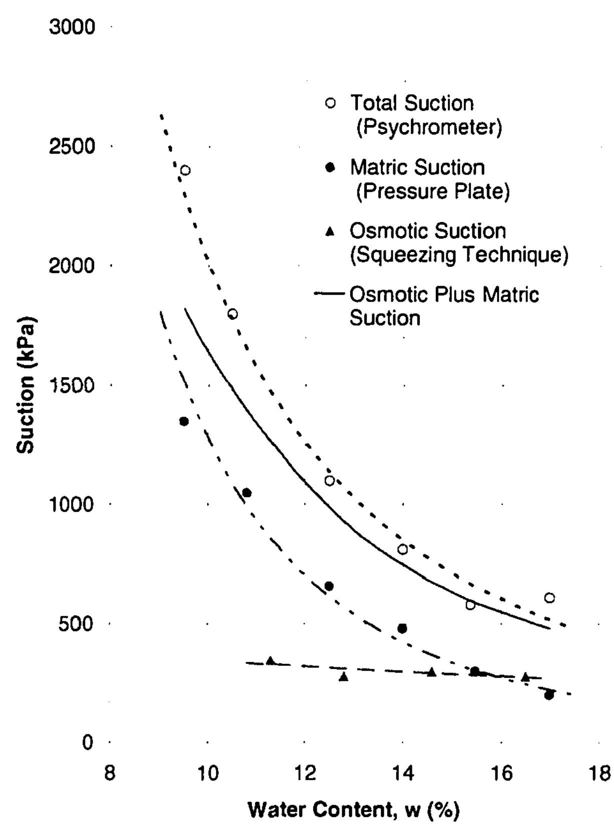


Figure 2-6 Total, Matric, and Osmotic Suctions for Glacial Till (from Krahn and Fredlund, 1972)

2.1.4 Water Flow

2.1.4.1 Steady-State Conditions

Steady-state flow of water in a saturated soil is governed by Darcy's law. Darcy (1856) postulated that the flow rate through porous media is proportional to the head loss and inversely proportional to the length of the flow path. In general one-dimensional form Darcy's law may be written:

$$q = -K\frac{\partial H}{\partial z} = -Ki \qquad \text{Equation (2-7)}$$

where:

q	=	flow rate of water
K	=	coefficient of hydraulic conductivity, assumed to be constant in saturated soil
H	=	hydraulic (total) head
z	=	length of the flow path
i	=	hydraulic gradient

In 1907, Buckingham proposed a modification of Darcy's law to describe water flow through unsaturated soil (Buckingham, 1907). The modification Buckingham made rested primarily on two assumptions:

1. The driving force that causes water to flow in isothermal, rigid, unsaturated soil containing no solute membranes and zero air pressure potential is the sum of the matric and gravitational potentials.
2. The coefficient of hydraulic conductivity of unsaturated soil is a function of the water content or matric potential of the unsaturated soil.

In head units, the general one-dimensional form of Buckingham-Darcy flux law may be expressed as follows:

$$q = -K(h)\frac{\partial H}{\partial z} = -K(h)\frac{\partial}{\partial z}(h + Z) = -K(h)(\frac{\partial h}{\partial z} + 1) \qquad \text{Equation (2-8)}$$

where H is the hydraulic head (= pressure head, h + elevation head, Z) and K(h) is the coefficient of unsaturated hydraulic conductivity.

The form of Equation (2-8) is similar to that of Equation (2-7), except that under conditions of unsaturated flow, the coefficient of unsaturated hydraulic conductivity is no longer a constant, but varies with changes in water content and indirectly varies with changes in pore-water pressure. Therefore, even though Darcy's law was originally derived for a saturated soil, later research has shown that it can also be applied to the flow of water through an unsaturated soil (Richards, 1931; Childs and Collis-George, 1950; McWhorter and Sunada, 1977).

$\partial H/\partial z$ shown in Equation (2-8) is the driving force that causes water to flow in unsaturated soil. Fredlund and Rahardjo (1993) stated that three concepts that engineers have used to explain the driving force are the water content gradient, the matric suction gradient, and the hydraulic head gradient. They stated that water flow in unsaturated soil is more appropriately defined in terms of the hydraulic head gradient.

2.1.4.2 Transient Conditions

The steady-state water flow conditions described in the previous section discussed only a special case of the possible water transport processes in soil. In general, wetting or drying of the soil will change as water flows through the soil, and the matric suction and water content will be functions of time as well as of space. Such transient flows are time dependent and can be mathematically described by the water conservation equation, also called the water mass balance or continuity equation. The water conservation equation is related to water flux, storage changes, and sources or sinks of water. The water conservation equation can be formulated by calculating the mass balance for the one-dimensional system during an arbitrarily small time period Δt between time t and t + Δt as follows (Jury, et al., 1991):

$$\frac{\partial q}{\partial z} + \frac{\partial \theta}{\partial t} + r_w = 0 \qquad \text{Equation (2-9)}$$

where:

θ	=	volumetric water content of soil
t	=	time
r_w	=	sources or sinks of water

A differential equation may be derived by combining Equations (2-8) and (2-9) and assuming $r_w = 0$ to predict the water content in unsaturated soil during transient flow. This differential equation is usually called the Richards equation (Richards, 1931) and is presented in the following one-dimensional form:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)(\frac{\partial h}{\partial z} + 1)\right] \qquad \text{Equation (2-10)}$$

The Richards equation states that the rate of change of the volumetric water content with respect to time is equal to the rate of change of flow in a soil system. Equation (2-10) can not be solved in the form it is in, because it contains two unknowns: θ and h. This difficulty may be overcome by using the soil water characteristic function $h(\theta)$ to eliminate either θ or h from Equation (2-10). Based on experiments, the soil water characteristic function can be estimated and is discussed in details in the following sections.

2.1.5 Migration of Water in Unsaturated Soils

In order to predict the amount of heave that will occur at a particular time, it is important to know what zone of soil is being wetted at that time, and the expansive nature of that soil. This in turn depends on the manner in which the ground water migrates in the soil. Engineers have attempted to determine the zone of soil that is being wetted using different definitions, each of which considers a particular emphasis. Nelson, et al.

(2001) put forth the following four definitions regarding depth of water migration for purposes of clarity and consistency.

1. *Active Zone is that zone of soil that is contributing to heave due to soil expansion at any particular time. The active zone will normally vary with time.*

2. *Zone of Seasonal Moisture Fluctuation is that zone of soil in which water contents change due to climatic changes at the ground surface.*

3. *Depth of Wetting is the depth to which water contents have increased due to the introduction of water from external sources, or due to capillarity after the elimination of evapo-transpiration. The external sources can include such things as irrigation, seepage from ponds or ditches, broken water lines, and others.*

4. *Depth of Potential Heave is the depth to which the overburden vertical stress equals the swelling pressure of the soil. This represents the maximum depth of Active Zone that could occur.*

In general, expansive soil sites are underlain by various strata of claystone and other sedimentary rock, each having a value of hydraulic conductivity. The layers with the lower hydraulic conductivity intercept water moving through the unsaturated zone and this water accumulates on top of the low permeability lenses, thereby forming perched water tables. Practicing engineers generally consider that water will migrate downward from the ground surface, and then perch on the top of a relative low permeable layer, such as claystone. Further downward migration to a lower stratum is often neglected. However, water will continue to move downward as long as the total potential of the soil above the wetting front is higher than that below the wetting front or until a truly impermeable boundary or a water table is reached. For example, Freeze and Cherry

(1979) stated that: "The existence of a low-permeability clay layer ... can lead to the formation of a discontinuous saturated lense, with unsaturated conditions both above and below. ... Saturated zones of this type dissipate with time under the influence of downward percolation and evaporation from the surface." Corey (1994) also discussed flow through stratified media and stated that: "Furthermore, the water is interconnected (continuous) throughout all layers, including at the boundaries between the layers, otherwise there could be no flow." A theoretical formulation of the flow in the various strata was presented in McWhorter and Nelson (1979). Edgar, et al. (1989) presented a theory for modeling flow through several unsaturated layers when heave or compression of the layers and temperature effects are considered. The model presented therein "considers multilayered systems such as natural deposits comprising various strata..." McWhorter and Nelson (1979), Edgar, et al. (1989), and Durkee (2000) all showed that the migration of a wetting front will continue to move downward with time unless bounded by a truly impermeable barrier.

The Colorado Association of Geotechnical Engineers (CAGE) has prescribed a depth of wetting of approximately 6 meters in their guidelines (CAGE, 1996). However, in addition to the findings from the theories described above, experience indicates that many sites exist where depth of wetting has greatly exceeded 6 meters (Overton, et al., 2006, and Chao, et al., 2006). Reed (1985) stated in his conclusions that "The seasonally active zone of soil movement is 1 to 3 meters, however, the zone of movement is influenced by the availability of water to the deeper dry clays. Post construction active zones have been measured as deep as 9 meters." Some practicing engineers in the Front Range of Colorado have used assumptions of depth of wetting much greater than 6 meters (Thompson, 1990; West, 2000; and Cesare, 2005). Diewald (2003) evaluated post-construction data from 133 investigations and determined that the depth of wetting for 7-to-10-year-old residences is approximately 12 meters. Diewald also indicated that there continues to be an increase in the depth of wetting over time. A review of research literature shows that the depth of wetting, and therefore the active zone, can extend to the depth of potential heave depending on site conditions (Durkee, 2000; Nelson, et al., 2001; Overton, et al., 2006, and Chao, et al., 2006).

2.2 Soil Water Characteristics

2.2.1 Characterization of Soil Water Characteristic Curve

The soil water characteristic curve is a relationship between the amount of water in the soil and soil suction under conditions where the normal stress is zero or a small value. Thus, the soil water characteristic curve becomes a special case of the entire water content constitutive surface, as shown in Figure 2-2. The amount of water in the soil is generally quantified in terms of gravimetric water content, volumetric water content, or degree of saturation. All three of these parameters will convey similar information to the engineer provided that the reference volume of the soil remains consistent. Care must be exercised when plotting the soil water characteristic curve for expansive soil to ensure that the correct reference volume is used in both laboratory measurements and mathematical formulations (Durkee, 2000).

A review of the research literature indicates that numerous graphical representations have been used for soil water characteristic curve data. Soil suction has been plotted on the abscissa or on the ordinate, and has been plotted on a logarithmic or arithmetic scale. The same is true for the water content of the soil. Fredlund, et al. (2001) recommended that soil suction be plotted on the abscissa and water content be plotted on the ordinate.

Figure 2-7 defines typical features of the drying (drainage) and wetting (imbibition) portions of the soil water characteristic curves. The air-entry value of the soil is the matric suction where air starts to enter the pores in the soil. The residual water content is the water content where a large suction change is required to remove additional water from the soil (McWhorter and Sunada, 1977; Corey, 1994; Fredlund and Xing, 1994). Figure 2-7 indicates that the residual water content can be approximated as the ordinate of the point at which a tangent line drawn from the inflection point and a tangent line drawn from the high-suction range intersect. Figure 2-7 shows that the soil suction corresponding to zero water content is approximately 10^6 kPa (Fredlund and Xing, 1994). Experimental data by Croney and Coleman (1961) indicate that the maximum suction a soil can reach is slightly below 10^6 kPa. This value is also supported by thermodynamic measurements conducted by Richards (1965).

White, et al. (1970) identified three desaturation stages including the boundary-effect stage, the transition state, and the residual stage of unsaturation along the drying curve (refer to Figure 2-7). It is believed that similar stages apply to the wetting curve (Fredlund, 2000).

The non-uniform pore size distribution in a soil may result in hysteresis in the soil water characteristic curve. Figure 2-7 shows that the water content for the drying curve at a given soil suction is higher than that for the wetting curve. The end point of the wetting curve differs from the starting point of the drying curve because of air entrapment in the soil. In addition, the contact angle at a receding interface during the drying process differs from that at an advancing interface during the wetting process. The above reasons are considered to be the main causes for hysteresis in the soil water characteristic curve (Fredlund and Rahardjo, 1993).

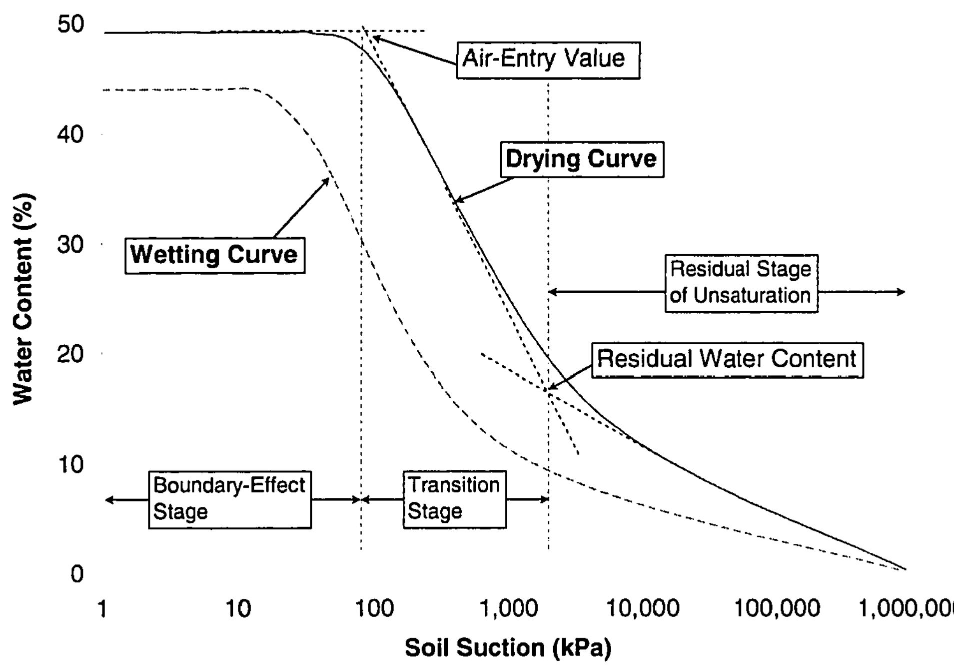


Figure 2-7 Definition of Variables Associated with the Soil Water Characteristic Curve (modified after Fredlund, 2000)

The hysteresis loop associated with the wetting and drying processes of a soil is the indication that the soil water characteristic curve is not unique. The drying and wetting branches, for an unstressed and initially saturated or initially totally dry samples, respectively, form the extreme bounds for any soil water characteristic curve of a particular soil. Depending on the in-situ stress state conditions of a soil, there are a number of intermediate drying or wetting scanning curves, as shown in Figure 2-8. The scanning curves become asymptotic to the boundary drying and wetting curves. In general, either the boundary drying curve or the boundary wetting curve is measured in the laboratory. The laboratory data usually do not represent a soil has a different fabric and is being dried or wetted from some other in-situ stress state with different initial water contents. Hence, the laboratory curve does not accurately represent in-situ conditions in engineering applications.

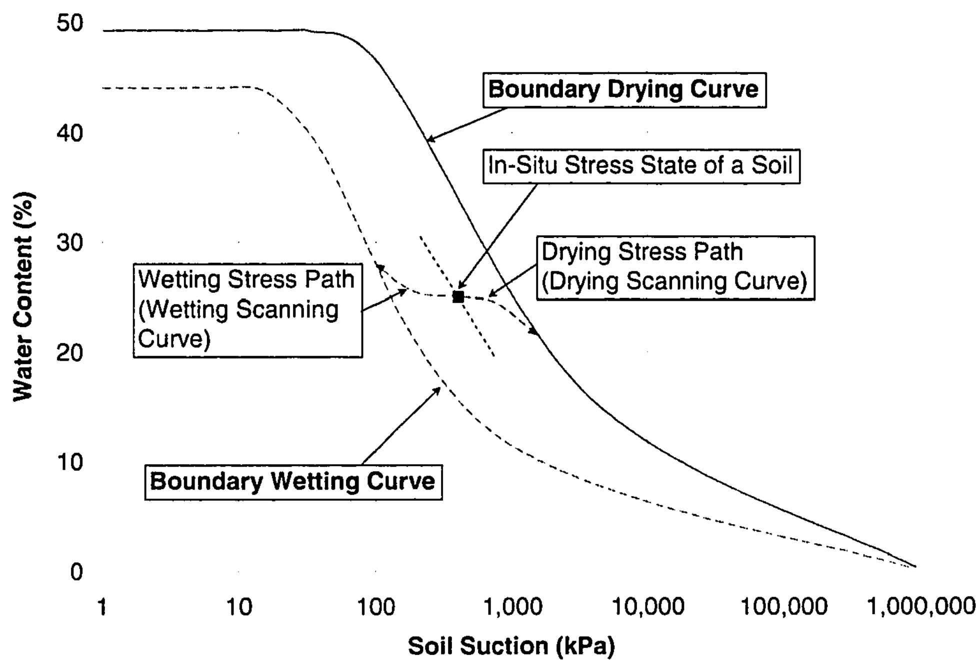


Figure 2-8 Description of Drying and Wetting Curves and Initial Stress State (modified after Fredlund, 2000)

2.2.2 Measurements of Soil Suction

Total suction, matric suction, and osmotic suction can be determined by direct and indirect measurements accomplished by a variety of means. The most commonly used methods include: (1) psychrometers, (2) tensiometers, (3) axis translation technique, (4) filter paper, (5) thermal conductivity sensor, and (6) pore fluid squeezer. Table 2-3 summarizes the suction components and the pressure ranges that these methods can measure.

Table 2-3 Summary of Common Soil Suction Measurement Methods

Measurement Method	**Device**	**Suction Component**	**Approximate Range (kPa)**
Direct	Psychrometers	Total	$0 - 10^6$
	Tensiometers	Matric	0 – 80
	Axis Translation Technique (Pressure Plate Apparatus)	Matric	0 – 1,500
	Fredlund SWCC Device	Matric	0 – 1,500
Indirect	Filter Paper	Total/Matric	10 – 300,000
	Thermal Conductivity Sensors	Matric	0 – 200
	Pore Fluid Squeezing Technique	Osmotic	$0 - 10^6$

The total suction can be determined by measuring the vapor pressure of the soil water or relative humidity in the soil. The direct measurement of relative humidity in the soil can be performed by a psychrometer. Moreover, the relative humidity can be indirectly measured using a filter paper as a measuring sensor.

The matric suction can also be determined by either a direct or indirect manner. A direct measurement of matric suction is commonly obtained with the axis translation technique. A common technique is the pressure plate apparatus. The form of the axis translation technique was proposed by Hilf (1956) to measure matric suction of samples taken from the field. A tensiometer is also commonly used to directly measure the negative pore-water pressure in a soil. The measured pore-water pressure in the tensiometer is numerically equal to the matric suction when the pore-air pressure is atmospheric (i.e., u_a = zero gauge pressure). Recently, the Fredlund SWCC device was developed to directly measure matric suction of samples using the axis translation technique (Perera, et al., 2004). Several types of thermal conductivity sensors can be used for performing indirect measurement of matric suction.

An indirect measurement of osmotic suction can be conducted by measuring the electrical conductivity of the pore-water from the soil. The pore-water in the soil can be extracted using a pore fluid squeezer.

A review of the methods for measuring soil suction is given in Nelson (1985), Nelson and Miller (1992), and Fredlund and Rahardjo (1993). The Fredlund SWCC device and the filter paper method were utilized in this study to obtain the soil water characteristic function for an expansive soil. Consequently, detailed literature review is focused only on these two approaches.

2.2.2.1 Fredlund SWCC Device

The Fredlund SWCC device was designed by Geotechnical Consulting and Testing Systems, Inc. (GCTS, 2004) and is an unsaturated soil testing apparatus with flexibility for controlling the matric suction while applying total stress and measuring volume change. Thus, various stress paths can be followed. The device uses the axis translation technique to control and measure suction for a remolded or undisturbed soil sample. The Fredlund SWCC device can be used to control matric suctions from a value near zero up to 1,500 kPa (i.e., 15 bars).

The device consists of a pressure cell assembly, a pressure panel, and a pneumatic loading frame, as shown in Figure 2-9. The pressure cell assembly is constructed of stainless steel and includes the necessary plumbing and valves for periodic flushing of diffused air to prevent a volume error. The pressure panel contains two volume indicator tubes and two pressure gauges. The volume indicator tubes are graduated to read the amount of water released from or imbibed into soil samples during tests. Flow of water into or out of the soil allows for determination of water content of the samples. The pneumatic loading frame is used to apply normal pressures up to 10 kN to soil samples.

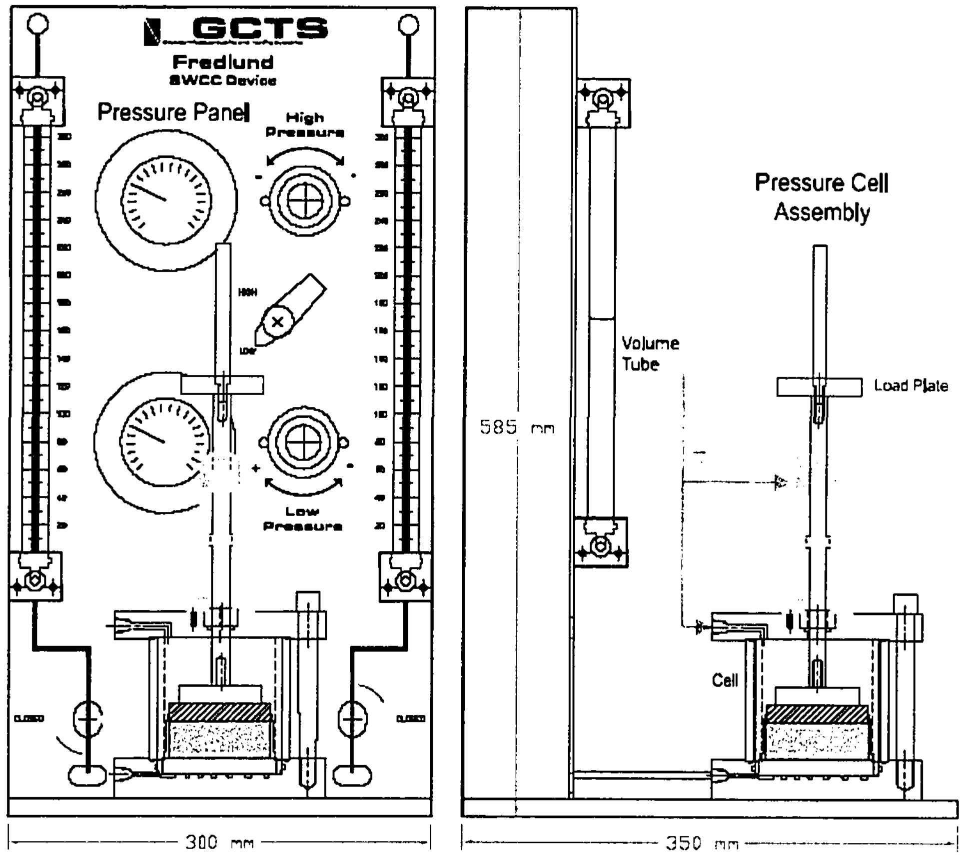


Figure 2-9 Schematic of Fredlund SWCC Device (from GCTS, 2004)

The earlier versions of the pressure plate apparatus require several soil samples to determine a reasonable soil water characteristic curve for a soil. It is almost impossible to obtain several soil samples representing the same soil structure and stress state conditions. The Fredlund SWCC device was designed to overcome this inconvenience. The device allows the use of a single soil specimen to obtain the entire SWCC with any number of data points. Therefore, the possibility of getting the intermediate drying or wetting scanning curves discussed in Section 2.2.1 can be eliminated. Furthermore, the device was designed to measure the overall volume change of the soil specimen during the test. The overall volume change of the soil specimen can be measured by taking measurements of the load plate movement using an attached dial gauge.

2.2.2.2 Filter Paper Method

The filter paper method for measuring soil suction was developed in the agricultural soil science discipline, and has been used routinely by the Water Resources Division of the U.S. Geological Survey for many years (McQueen and Miller, 1968). Attempts have been made to use the filter paper method for engineering applications (McKeen and Nielson, 1978; McKeen, 1981 and 1985; McKeen and Hamberg, 1981; Ching and Fredlund, 1984; Houston, et al., 1994; Bulut, et al., 2001; Leong, et al., 2002; Bulut and Wray, 2005; Oliverira and Fernando, 2006). An advantage of the filter paper method is the wide range of values of soil suction over which it can be used and its simplicity, whereas a disadvantage for the use of this method is the degree of accuracy required for weighing the filter paper.

In this method, a specimen of the soil along with a calibrated filter paper is placed in a closed container that is free of material that could rust. The soil sample and the filter paper are allowed to equilibrate for a period of time at a constant temperature. After equilibrium, the filter paper is removed and the filter paper is weighted by an accurate balance to the nearest 0.0001 g before and after oven drying.

The principle of the filter paper method is the suction of a filter paper will come to equilibrium with that of the soil sample. The relative humidity inside the container will be controlled by the soil suction. Equilibrium can be reached by either liquid or vapor moisture exchange between the filter paper and the soil specimen. Using the filter paper method it is possible to measure either the total or the matric suction of a soil (ASTM D5298-94). When the filter paper is placed in contact with the water in the soil, the soil suction measured at equilibrium will be the matric suction of the soil, because the salt content of the water in the filter paper will be the same as that of the soil water. On the other hand, if the filter paper is not in contact with the soil, the soil suction measured at equilibrium will be the total suction of the soil.

2.2.2.2.1 Calibration Curves

Figure 2-10 presents the range of calibration relationships determined for two most commonly used papers including the Whatman No. 42 paper and the Schleicher and Schnell, No. 589 paper obtained from ASTM D5298-94. Filter papers have a bilinear relationship between suction and filter paper water content on a semi-log scale. McQueen and Miller (1968) attributed that the lower part of the curve to the range where water is held in the filter paper by capillary forces, whereas the upper curve was believed to represent water held by the paper as an adsorbed film.

ASTM D5298-94 reports that the calibration curves shown in Figure 2-10 were obtained from Greacen, et al. (1987). Greacen, et al. (1987) referred to the Fawcett and Collis-George (1967) paper for their calibration data with suction greater than 50 kPa. Fawcett and Collis-George (1967) indicated that the calibration data were determined using pressure plate and vacuum desiccator methods, which implies that the calibration curve is only for matric suction measurement. Fawcett and Collis-George (1967) also indicated that the calibration curve is the wetting curve for the filter paper. Houston, et al. (1994) successfully duplicated the matric suction calibration curve from Fawcett and Collis-George (1967).

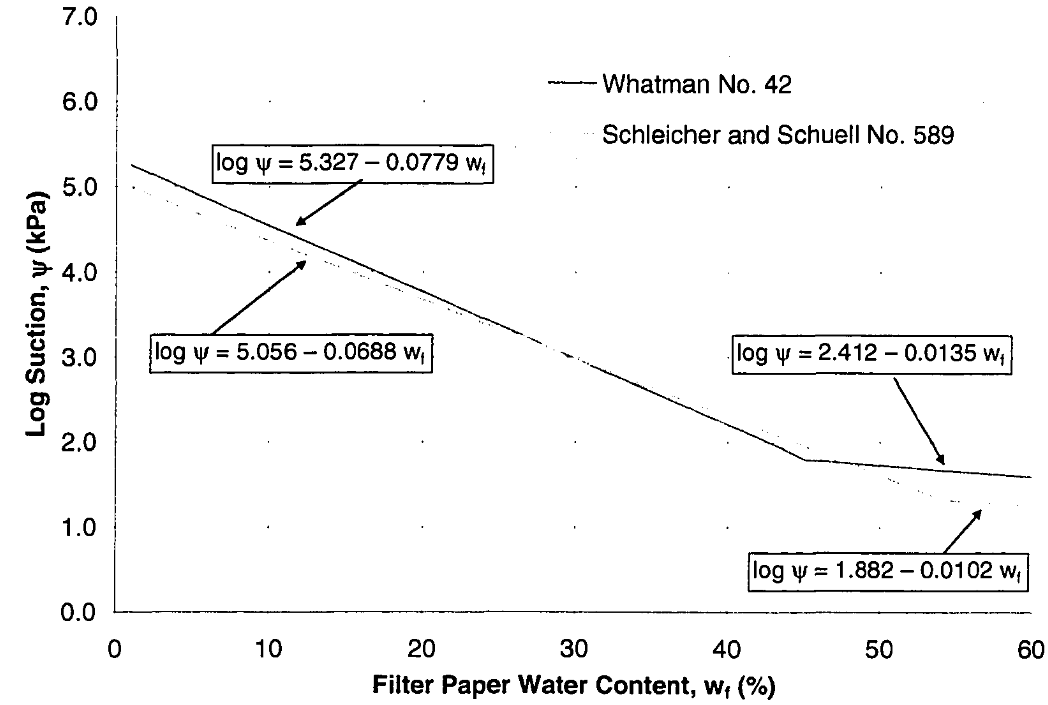


Figure 2-10 Filter Paper Calibration Curves from ASTM D5298-94

The calibration curves shown in ASTM D5298-94 should be used only to obtain matric suction of soil samples via the filter paper contact method. Bulut, et al. (2001) constructed a wetting calibration curve for the total suction measurement using sodium chloride (NaCl) salt solutions and Schleicher & Schuell No. 589-WH filter papers. It was found that the change in the wetting calibration curve is very sensitive to minor changes in filter paper water content below a suction of 1.5 log kPa (2.5 pF). Leong, et al. (2002) developed wetting calibration curves for the total and matric suction measurements using salt solutions of various concentrations in vacuum desiccators. Figure 2-11 shows the calibration curves for the Whatman No. 42 filter paper from Leong, et al. (2002). Figure 2-11 shows that the calibration curves using the contact and non-contact methods converge at a soil suction value of approximately 1,000 kPa. It is also important to note that there is a dramatic decrease of total suction at high filter paper water contents, as shown in Figure 2-11. Bulut, et al. (2001) explained that this dramatic decrease is related to the nature of Kelvin's equation and to the use of the logarithmic scale.

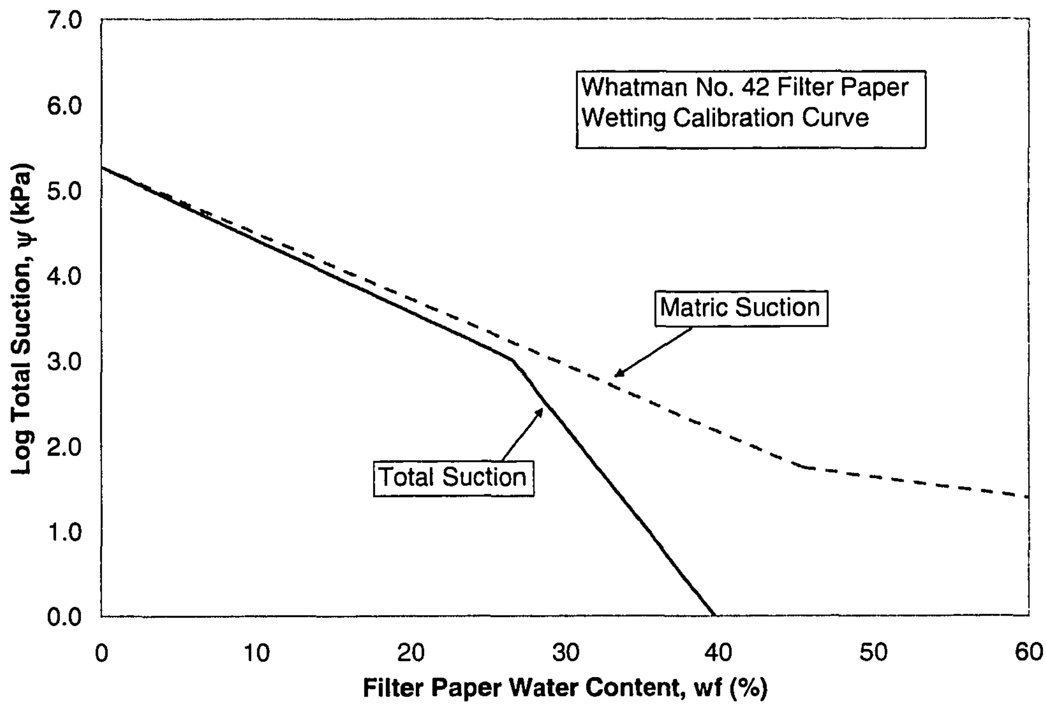


Figure 2-11 Filter Paper Wetting Calibration Curves for Total and Matric Suction Measurements (after Leong, et al., 2002)

Additional calibration curves were constructed by other researchers (Hamblin, 1981; and Chandler and Gutierrez, 1986). A comparison of the wetting calibration curves for the matric suction measurement using the Whatman No. 42 filter paper is presented in Figure 2-12. This figure shows that there are some differences in the calibration curves, even for the same brand of filter paper. Leong, et al. (2002) concluded that the differences in the calibration curves may result from (1) quality of filter paper, (2) suction source used in the calibration process, (3) hysteresis of filter paper, and (4) equilibration time.

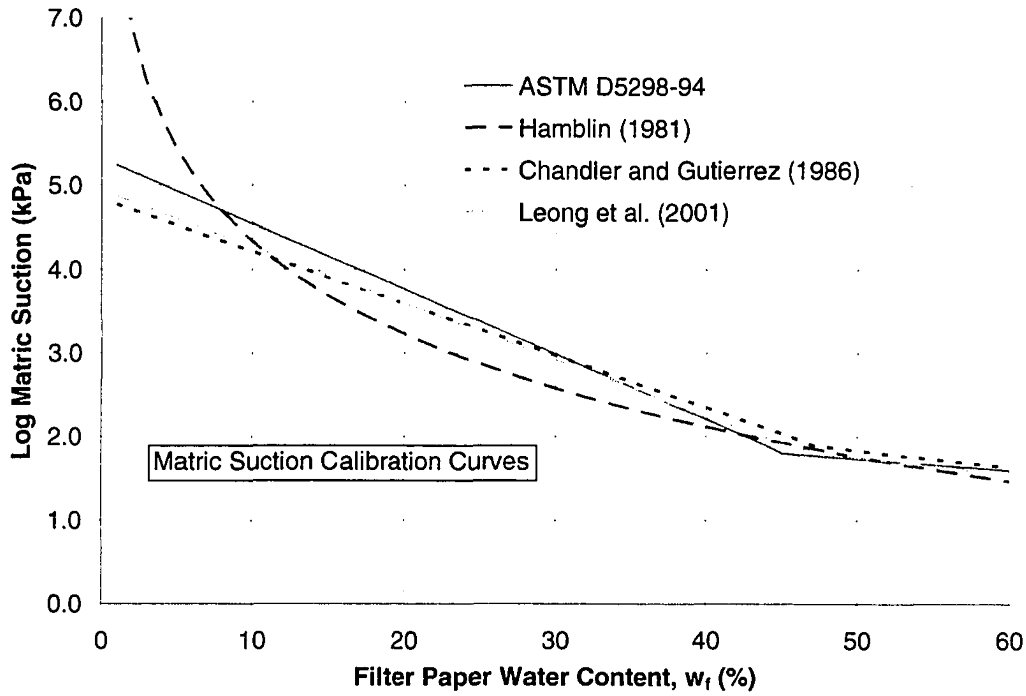


Figure 2-12 Comparison of Calibration Curves for Matric Suction Measurement

2.2.2.2.2 Hysteresis of Filter Paper

The desorption and absorption of a porous medium shows hysteresis, and filter paper is also expect to exhibit hysteretic behavior during the desorption and absorption process. Fawcett and Collis-George (1967) has shown experimental evidence of hysteresis in filter paper. Al-Khafaf and Hanks (1974) suggested that since filter paper was always wetted up during suction measurement, the filter paper should also be calibrated in the same manner to avoid the problem of hysteresis. Leong, et al. (2002) indicated that inadequate equilibration time will lead to larger hysteresis and concluded that hysteresis appears to be minor when equilibration time is sufficient.

2.2.2.2.3 Time for Equilibration

The equilibration time of the filter paper test has been evaluated by various researchers as listed in Table 2-4. ASTM D5294-94 recommends a minimum equilibration time of 7 days for running the filter paper contact and non-contact tests. However, in examining the required time for filter paper to reach equilibrium, it was found that the equilibration time is dependent on suction source, measured suction type (contact or non-contact method), material type, water content of soil specimen (suction level), number of pieces of filter paper used, relative humidity of the air, and soil mass and space in the container, as shown in Table 2-4.

Table 2-4 Summary of Equilibration Time for Filter Paper Test

Reference	Measured Suction Type	Material Type	Time Required for Equilibration (days)
Fawcett and Collis-George (1967)	Matric	-	6 – 7
ASTM D5298-94 (1994)	Total / Matric	-	7
Houston, Houston, and Wagner (1994)	Total / Matric	Sand, Silt, Clay	7
Marinho (1994)	Total	NaCl Solution	>30 days (ψ = 0-100 kPa) 30 days (ψ = 100 – 250 kPa) 15 days (ψ = 250 – 1,000 kPa) 7 days (ψ = 1,000 – 30,000 kPa)
Bulut, Lytton, and Wray (2001)	Total	Fine Clay, Sandy Silt, and Pure Sand	7
Burger and Shackelford (2001a)	Matric	Processed Diatomaceous Earth (CG1 and CG2)	8 days ($u_a - u_w \leq$ 100 kPa) 14 days ($u_a - u_w >$ 100 kPa)
Leong, He, and Rahardjo (2002)	Total	Salt Solution	6
	Matric	Clay (CL)	2 – 5
Bulut and Wray (2005)	Total	Salt Solution	14

2.2.3 Mathematical Forms of SWCC

A number of mathematical equations have been proposed to describe the soil water characteristic curve. Table 2-5 summaries the mathematical equations proposed for the soil water characteristic curve. Most of the SWCC equations shown in Table 2-5 are empirical in nature. The equations were suggested based on the shape of the SWCC. The equations listed in Table 2-5 involve unknown parameters that need to be determined. The saturated volumetric water content, θ_s, is determined by measuring porosity of the soil whereas the residual volumetric water content, θ_r, is not always determined in the laboratory. Table 2-5 shows that the maximum number of the unknown parameters for the equations is six if the saturated volumetric water content is known.

The Gardner (1958) equation was originally proposed for defining the unsaturated hydraulic conductivity function, and its application to the SWCC is inferred. The mathematical equations proposed by Burdine (1953) and Mualem (1976) are three-unknown-parameter equations that become special cases of the more general four-unknown-parameter equation proposed by van Genuchten (1980). Fredlund and Xing (1994) established a theoretical basis of the SWCC by considering the pore-size distribution curve for the soil. They introduced a correction function, $C(\psi)$, in the equation to force the soil water characteristic curve to pass through a soil suction of 10^6 kPa at zero water content. Leong and Rahardjo (1997) indicated that the soil suction value of 10^6 kPa at zero water content is supported by experimental data. However, it has no theoretical basis. Even though each equation has its own limitations, all of the proposed equations provide a reasonable fit of soil water characteristic data in the low and intermediate suction ranges. Leong and Rahardjo (1997) concluded that the equation suggested by Fredlund and Xing (1994) gives the best fit among the equations.

Burger and Shackelford (2001a and 2001b) proposed the use of a bimodal mathematical function to describe the SWCCs of sand-pelletized diatomaceous earth mixtures containing two distinct grain-size distributions. They stated that the measured SWCCs are bimodal due to two distinct pore-size distributions associated with the microscopic and macroscopic porosity regions of the materials. Fredlund, et al. (2000) had previously proposed the use of a bimodal function to describe the grain-size curves of gap-graded soils with two distinct grain-size distributions.

Table 2-5 Summary of Mathematical Equations Proposed for the SWCC

Year	Author(s)	Equation	Unknown Parameters
1953	Burdine	$\theta = \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + a\psi^b\right]^c}$	θ_r, a, b, $c = 2/(1-b)$
1958	Gardner	$\theta = \theta_r + \dfrac{\theta_s - \theta_r}{1 + a\psi^b}$	θ_r, a, b
1964	Brooks and Corey	$\theta = \begin{cases} \theta_s & \psi \le \psi_d \\ \theta_r + (\theta_s - \theta_r)(\alpha \cdot \psi)^{-\lambda} & \psi > \psi_d \end{cases}$	θ_r, α, λ
1976	Mualem	$\theta = \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + a\psi^b\right]^c}$	θ_r, a, b, $c = 1/(1-b)$
1980	van Genuchten	$\theta = \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + a\psi^b\right]^c}$	θ_r, a, b, c
1983	Williams, et al.	$\ln\psi = a + b\ln\theta$	a, b
1984	McKee and Bumb	$\theta = \theta_r + (\theta_s - \theta_r)\exp\left(\dfrac{a - \psi}{b}\right)$	θ_r, a, b
1994	Fredlund and Xing	$\theta = C(\psi)\dfrac{\theta_s}{\left[\ln\left(e + (\frac{\psi}{a})^b\right)\right]^c}$	$C(\psi)$, a, b, c
2001	Burger and Shackelford	$\theta = \begin{cases} C(\psi) = \dfrac{\theta_j}{\left\{\ln\left[e + \left(\frac{\psi}{a'}\right)^{n'}\right]\right\}^{m'}} ; \psi_j < \psi \\ C(\psi) = \dfrac{\theta_s}{\left\{\ln\left[e + \left(\frac{\psi}{a}\right)^{n}\right]\right\}^{m}} ; \psi \le \psi_j \end{cases}$	a, m, n, a', m', n'

where: θ = volumetric water content;

θ_r = residual volumetric water content;

θ_s = saturated volumetric water content (measured in the laboratory, and hence, assumed to be a known parameter);

θ_j = junction volumetric water content;

ψ = soil suction (i.e., matric suction at low suctions and total suction at high suctions);

ψ_j = junction soil suction,

$C(\psi)$ = correction function that forces the volumetric water content to be zero at a soil suction of 10^6 kPa;

e = natural number, 2.71828; and

a, b, c, α,
λ, m, n, a',
m', n' = fitting parameters.

Chao (1995) performed a modified pressure cell test, filter paper test, and CLOD test to estimate soil water characteristic curves for two expansive soils including Pierre Shale and Texas Soil under a zero overburden pressure. Chao, et al. (1998) presented a bilinear semi-logarithmic fit to the observed data for drying and wetting curves of Pierre Shale (refer to Figure 2-13). The regression curves show a good agreement to the observed drying and wetting data for Pierre Shale. The bilinear form also gives a good fit to the observed drying and wetting data for Texas Soil. In addition, a distinct air-entry pressure is not evident on either the drying or wetting curves of the expansive soils tested.

The bilinear relationship of the SWCC for expansive soil has also been reported by others (McKeen and Neilsen, 1978; Marinho, 1994; and Miller, 1996). The change in slope of the SWCC for expansive soil has been attributed to a transition between macropore (capillary) spaces and micropore (diffuse double layer) spaces (Miller, 1996). The physical significance of this apparent transition point may be attributed to the bi-level pore size distribution researched by Al-Mukhtar (1995), Alonso, et al. (1995); and Wan, et al. (1995). It was hypothesized that this bilinear relationship is a manifestation of the transition from macropore spaces, where water retention is governed by capillary mechanisms, to micropore spaces, where water retention is governed by thermodynamic forces (Miller, 1996).

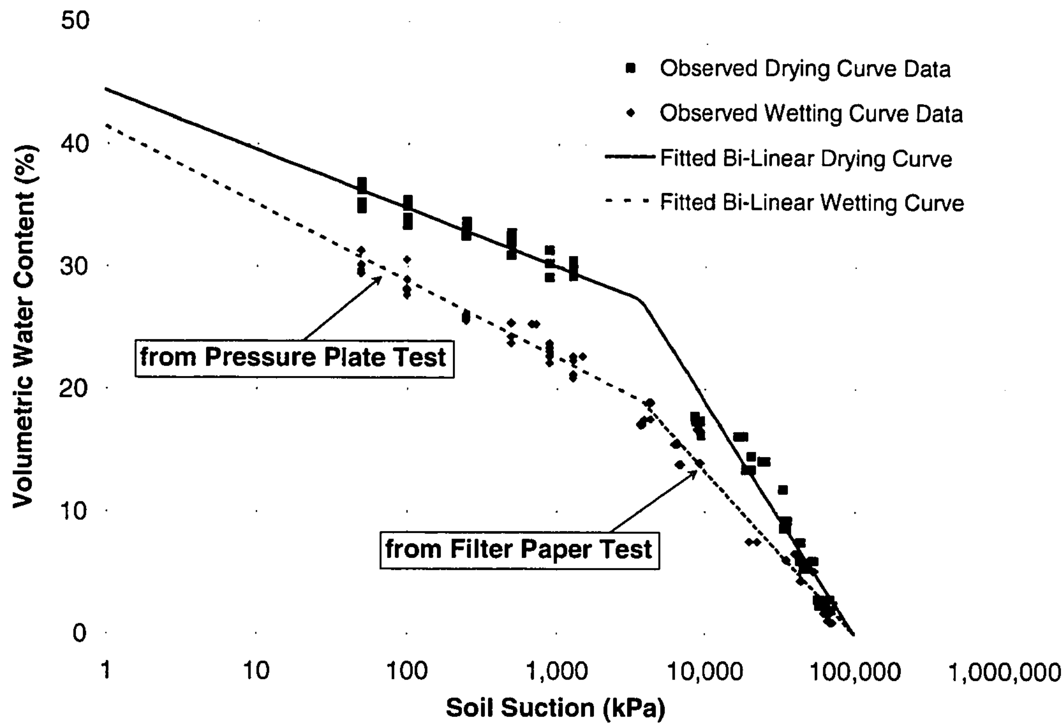


Figure 2-13 Bi-Linear Equation Fitted to Observed Data for Pierre Shale Taking Volume Change into Account

The apparent transition point for Pierre Shale shown in Figure 2-13 occurs at approximately 4,000 kPa. This value is higher than the observed transition value of approximately 50 to 100 kPa for the filter papers shown in Figure 2-10. This higher transition point may be attributed to the wider range of pore sizes in the test soil compared to the filter papers (Miller, 1996).

2.2.4 Influence of Stress State on Soil Water Characteristics

In order to assess and predict the soil water characteristic behavior of an unsaturated soil in the field, it is important to test the specimen in the laboratory simulating the physical state and stress state conditions of the in-situ soil. Vanapalli, et. al. (1998) and Ng and Pang (2000) performed a series of "modified" pressure plate tests with an application of applied stress on soil specimens to account for the influence of the stress state on a soil water characteristic behavior of non-expansive soils. They concluded that unsaturated soil properties can be more accurately estimated using the soil water characteristic curve that has been estimated taking into account the influence of stress state.

Fredlund (2002) conducted a series of laboratory tests to obtain soil water characteristic curves for Regina clay under various overburden pressures. The Regina clay has over 90% silt and clay, more than 75% montmorillonite in the clay fraction, and a liquid limit of about 90%. Figure 2-14 shows the results of the tests in the plot of gravimetric water content versus soil suction. Figure 2-14 indicates that the gravimetric water content at 3 kPa decreases by approximately 41 percent due to the increase of the overburden pressure from 6.2 to 400 kPa. Figure 2-14 indicates that the soil water characteristic curve is affected by the overburden pressure only when the soil suction is below approximately 1,000 kPa (10 bars), which is approximately the boundary between the capillarity and adsorption, as shown in Figure 2-15. Fredlund (2002) stated that matric suction (capillary effects) has been shown to dominate the lower suction portion of a SWCC, while osmotic suction (salt concentration) dominates the high suction portion of the SWCC (refer to Figure 2-15). This is because capillary effects dominate when there is still a significant amount of liquid water in the soil (Edgar, et al., 1989). As the soil becomes dry, liquid flow decreases and vapor flow dominates. This means that the osmotic suction related to hydrated water in the adsorbed salts begins to dominate the behavior of the soil at a high suction range.

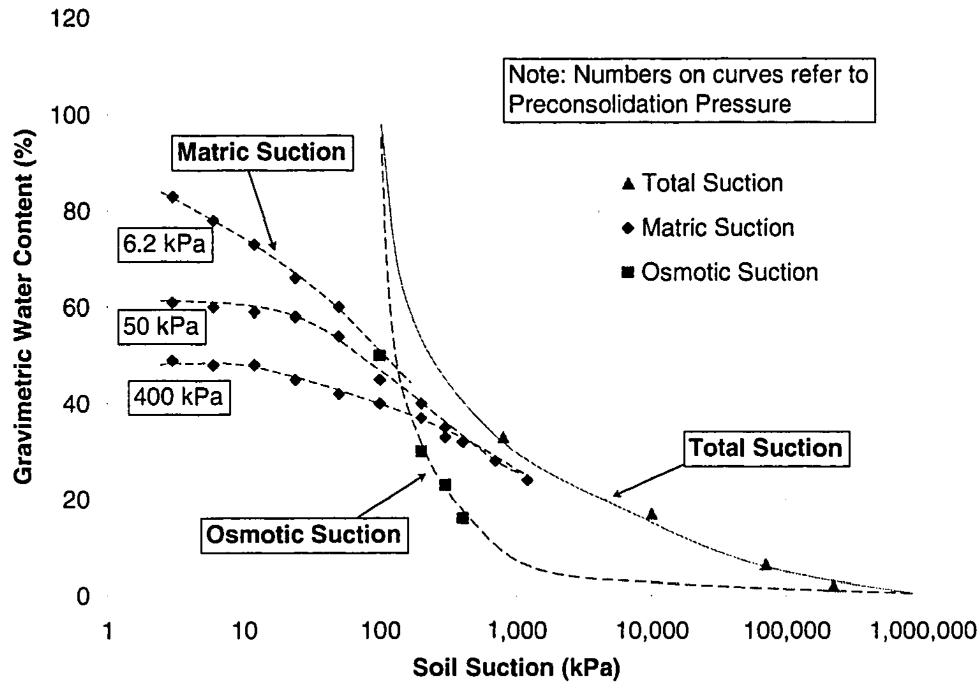


Figure 2-14 Soil Suction vs. Gravimetric Water Content and Illustration of the Influence of the Components of Soil Suction (modified after Fredlund, 2002)

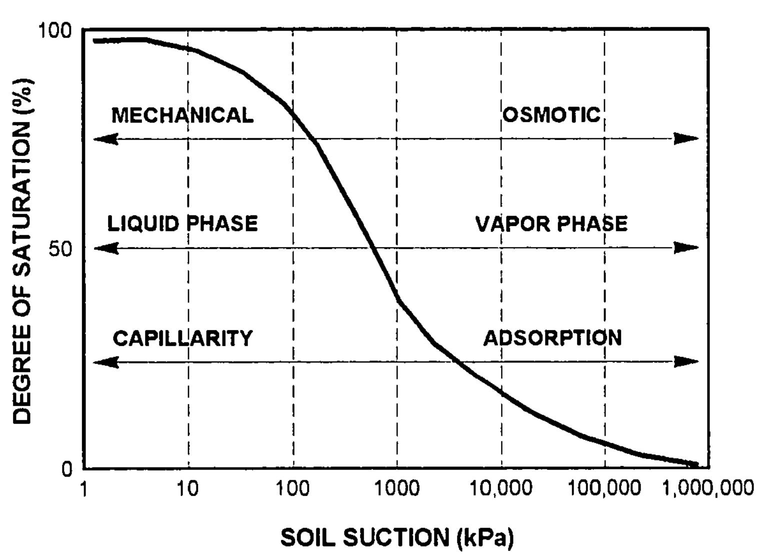


Figure 2-15 Illustration of the Influence of the Components of Soil Suction in Different Ranges of Suction (modified after Barbour, 1999)

2.3 Heave Prediction Methodology

Heave prediction is generally accomplished using one of two methods, viz., (1) the soil suction method, and (2) the oedometer method. In the soil suction method, the soil suction stress state variable is considered to be the fundamental variable affecting heave, and applied effective stress is considered as a percentage of the swelling pressure. Thus, in the soil suction method both oedometer tests and measurements of soil suction are necessary. In the oedometer method, only the effective stress is defined and the soil suction is considered indirectly by assumed that the final value of matric suction of the soil is zero at the end of the inundation process. In this method, only oedometer tests are needed. The oedometer method was used in this research and, therefore, a detailed review of only the oedometer method is provided below.

2.3.1 Evolution of Heave Prediction Methodologies Using the Oedometer Test

Heave prediction methodologies were first developed in the late 1950s, and originated as an extension of methods used to estimate volume change due to settlement in saturated soils using results of one-dimensional oedometer (consolidation) tests. Heave prediction methodologies have been refined continuously as knowledge and understanding of unsaturated soil behavior has increased. Taylor (1948) proposed a mathematical model describing settlement of a layer of saturated soil. Jennings and Knight (1957) first proposed the extension of settlement theory to heave prediction using oedometer tests. Salas and Serratosa (1957) presented the oedometer heave prediction model in terms of the logarithmic pressure, and incorporated the "swelling pressure" of a soil into the equation. Their equation was of the same form as that presented by Taylor (1948).

The "swelling pressure" of a soil was first defined by Palit (1953), as the pressure in an oedometer test required to prevent a soil sample from swelling after being saturated. Fredlund, et al. (1980) set forth the theoretical framework to include soil suction in the prediction of heave. In 1983, Fredlund proposed the modern form of the heave prediction equation for oedometer tests. Fredlund and Rahardjo (1993) also published a heave prediction methodology based on Fredlund (1983). Chen (1988) referenced the method presented in Fredlund (1983) and presented an example of its use to predict heave.

The evolution of heave prediction methodologies using oedometer tests has been largely related to determination of the index parameter used in the heave equation. Burland (1962) first proposed using the slope of the rebound portion of the consolidation-swell curve. Fredlund and Rahardjo (1993) indicated that the slope of the unloading curve from consolidation-swell tests is approximately the same as the slope of the rebound curve determined from constant volume tests. Porter and Nelson (1980) compared the test results of the constant volume (controlled strain) test to those of the consolidation-swell test. Fredlund's method (Fredlund, 1983; Chen, 1988; Fredlund and Rahardjo, 1993) and the method presented in Nelson and Miller (1992) used test results from both the consolidation-swell test and the constant volume test to determine the index parameter. The method presented in Nelson and Miller (1992) uses the same equation as Fredlund (1983). Feng, et al. (1998) presented a thorough comparison of swell pressure as determined by different oedometer test methods. Nelson, et al. (1998) and Bonner (1998) presented a method of estimating the index parameter using test results from only consolidation-swell tests. Nelson, et al. (2006) refined the analysis and developed the methodology for determining the percent swell as a function of the inundation pressure.

2.3.2 Oedometer Test Approach

2.3.2.1 Oedometer Tests

The most common measurement of stress-strain relationship involves the use of the one-dimensional consolidation apparatus, or oedometer. A compression curve obtained from an oedometer test for a saturated soil is a relationship between the amount of volume change in the soil and the normal stress. Thus, the compression curve becomes a special case of the entire void ratio constitutive surface, as shown in Figure 2-2. Numerous test procedures of the oedometer test have been developed to determine the stress-strain relationship for an unsaturated soil. A summary of the test procedures is described in Nelson and Miller (1992). The main differences among the test procedures are loading sequences and applied surcharge pressures in attempts to duplicate in situ stress state conditions. There are two commonly used procedures for conducting oedometer tests for expansive soils, namely, the "consolidation-swell" and "constant volume" tests. The tests on expansive soils differ in the loading procedures that are used. The consolidation-swell and constant volume tests used in geotechnical engineering practice to determine swelling potential for the prediction of heave of expansive soils are described below.

2.3.2.1.1 Consolidation-Swell Test

In the consolidation-swell test, a soil specimen is placed in a consolidation ring and subjected to a prescribed vertical stress, termed the "inundation pressure." After loading under the inundation pressure for a period of time, usually about 24 hours, the specimen is inundated and allowed to swell while still being loaded at the inundation pressure. The inundation pressure may represent the overburden pressure, overburden pressure plus the applied load from the structure, or some other arbitrary value. An inundation pressure of 24 kPa (500 psf) or 48 kPa (1,000 psf) is commonly used in the geotechnical engineering practice of the Front Range area. After swelling, the specimen is subjected to additional load in increments, and may be unloaded in decrements.

Typical stress paths followed in the consolidation-swell test are illustrated in Figure 2-16 on a two-dimensional plot. In Figure 2-16, the percent swell is identified as the increase in void ratio or strain at which the specimen is wetted at the inundation pressure, σ'_i. The swelling pressure, σ'_{cs}, is defined as the vertical stress required to compress the specimen back to the volume it had at the time of inundation. It should be noted that because the excess pore fluid pressures are allowed to dissipate to zero after each load increment, it is not necessary to differentiate between effective and total stress in Figure 2-16. The slope of the loading curve plotted on a semi-logarithmic scale gives the compression index, C_c, which can be related to the coefficient of compressibility, a_t, shown in Figure 2-2.

Figure 2-17 depicts the stress paths followed in the consolidation-swell test on a three-dimensional plot. In Figure 2-17, the initial sampling and seating in the oedometer apparatus are shown by stress path segment 0-1-2. Void ratio can be assumed to remain constant during the stress path segment 0-1-2 if an inundation pressure of 1.0 kPa is used, as suggested by Jennings, et al. (1973). The oedometer test procedure is depicted by stress path 1-2-3-4, where segment 2-3 represents swelling due to soaking under the inundation pressure and segment 3-4 represents consolidation at zero matric suction (100% saturation). The segment 3-4 is shown as a recompression branch of a consolidation curve, since expansive soils are typically highly overconsolidated (Fredlund, 1983). The stress paths shown in Figure 2-17 follow the constitutive surface for void ratio, e, as a function of the two stress state variables, $(\sigma - u_a)$, and $(u_a - u_w)$, similar to the one shown in Figure 2-2 (Nelson, et al., 2006).

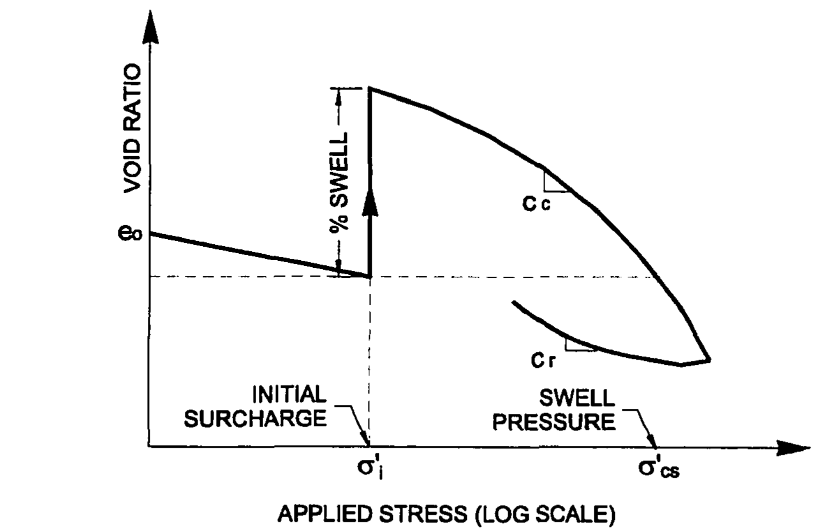
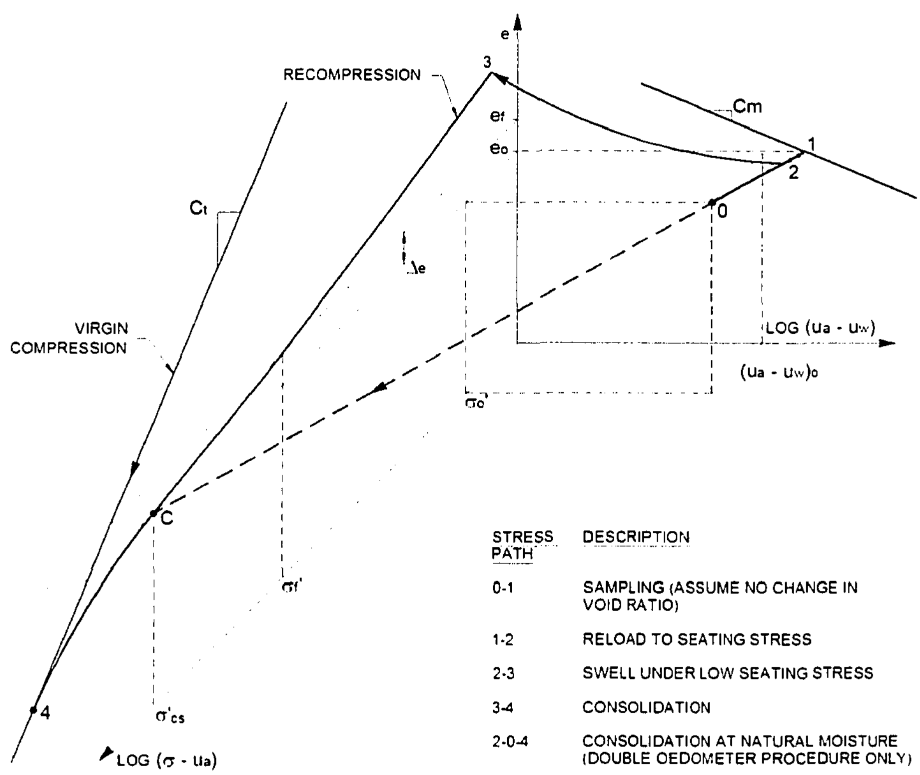


Figure 2-16 Two-Dimensional Consolidation-Swell Test Data



STRESS PATH	DESCRIPTION
0-1	SAMPLING (ASSUME NO CHANGE IN VOID RATIO)
1-2	RELOAD TO SEATING STRESS
2-3	SWELL UNDER LOW SEATING STRESS
3-4	CONSOLIDATION
2-0-4	CONSOLIDATION AT NATURAL MOISTURE (DOUBLE OEDOMETER PROCEDURE ONLY)

Figure 2-17 Three-Dimensional Consolidation-Swell Test Data (from Nelson and Miller, 1992)

2.3.2.1.2 Constant Volume Test

In the constant volume or "strain-controlled" test, the specimen is placed in the oedometer and subjected to a prescribed seating pressure as in the consolidation-swell test. However, when the specimen is inundated, the specimen is prevented from swelling. The swelling pressure, σ'_{cv}, is the maximum applied stress required to maintain no volume change of the specimen. When the swelling pressure stops increasing after inundation, the sample may be rebounded in increments or loaded beyond the swelling pressure (Porter and Nelson, 1980).

Typical stress paths followed for the constant volume test are illustrated in Figure 2-18 on a two-dimensional plot, and Figure 2-19 on a three-dimensional plot. In Figure 2-18, the stress at which water is added is not readily apparent since the applied stress is immediately increased to overcome the swelling tendency of the soil. As a result, the void ratio remains constant until the unloading process begins. Figure 2-19 illustrates that a decrease in matric suction as water is added, even though the void ratio is held constant by increasing the net normal stress.

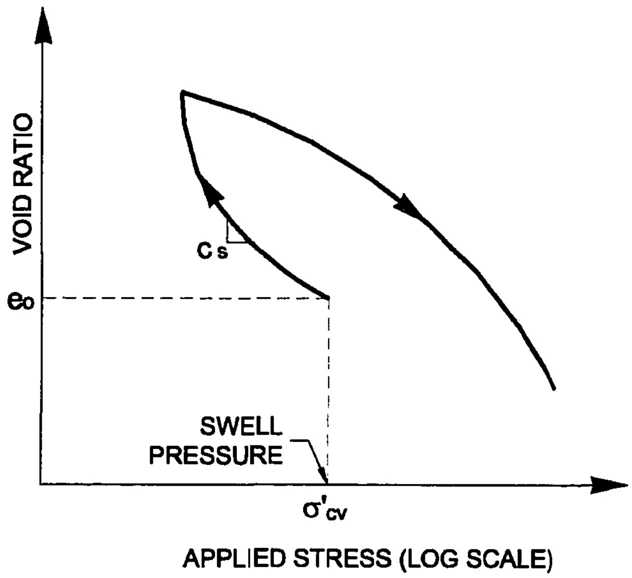
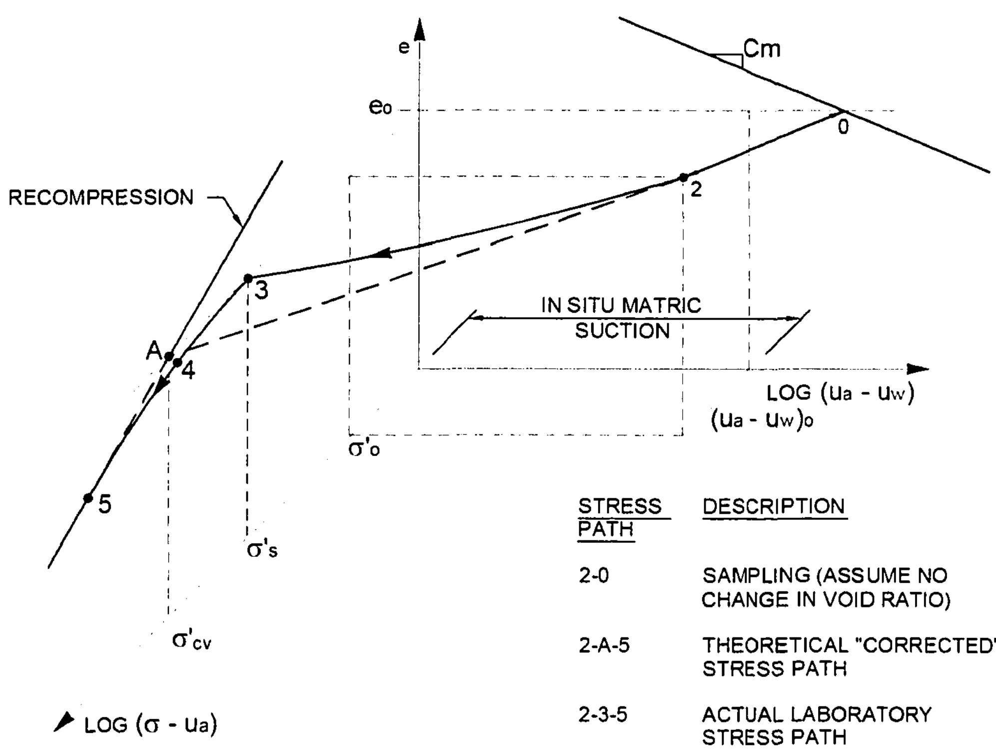


Figure 2-18 Two-Dimensional Constant Volume Test Data



STRESS PATH	DESCRIPTION
2-0	SAMPLING (ASSUME NO CHANGE IN VOID RATIO)
2-A-5	THEORETICAL "CORRECTED' STRESS PATH
2-3-5	ACTUAL LABORATORY STRESS PATH

Figure 2-19 Three-Dimensional Constant Volume Test Data (from Nelson and Miller, 1992)

2.3.2.2 Correction Factors for Oedometer Test Data

The swelling pressure and swelling index determined from the oedometer test may require corrections for more reliable results (Fredlund, 1969; Chen, 1988; Nelson and Miller, 1992; Fredlund and Rahardjo, 1993; and MFG, 2003). Corrected values of the swelling pressure and swelling index may differ significantly from uncorrected values due to (1) specimen disturbance during sampling and (2) compressibility of the testing apparatus, filter paper, and porous stones.

2.3.2.2.1 Corrections for Specimen Disturbance

Fredlund and Rahardjo (1993) indicated that sampling disturbance increases the compressibility of the soil and does not permit the experimental specimen to return to its in-situ void ratio. Nelson and Miller (1992) stated that sampling disturbance causes matric suction to relax more rapidly, which in turn causes the measured swelling pressure to be significantly underestimated. The effect of sample disturbance on the stress paths for the constant volume test can be depicted as shown in Figure 2-19. The initial test conditions of a soil specimen are represented by point O shown in Figure 2-19. The swelling pressure at point A for the undisturbed specimen is significantly larger than that at point 3 for the disturbed specimen. A graphical technique which is similar to Schmertmann's construction for determining the preconsolidation pressure was proposed to correct the measured swelling pressure obtained from the constant volume test (Nelson and Miller, 1992). Fredlund (1979b) reported that a correction for sampling disturbance is not as significant for the consolidation-swell test as it is for the constant volume test.

2.3.2.2.2 Corrections for Compressibility

Other corrections to be applied to the swelling pressure and swelling index account for the effects of the compressibility of the oedometer apparatus, filter paper, and porous stones. The compressibility of the oedometer apparatus is significant because desiccated expansive soils are generally highly imcompressible and have high preconsolidation pressures. Fredlund and Rahardjo (1993) recommended measuring the compressibility of the apparatus with a steel plug substituted for the soil sample. The measured deflections may be subtracted from the measured test data.

Filter paper should be used to prevent the fine particles of clays and silts from entering the pore spaces in the porous stones (ASTM D4546-03). ASTM D2435-96 states that measured vertical deformation must be corrected for apparatus flexibility in all tests where filter paper disks are used and whenever the calibration correction exceeds 5% of the measured deformation. Filter paper is relatively compressible, and exhibits significant hysteresis. Figure 2-20 shows the results of a filter paper correction performed by MFG (MFG, 2003). Figure 2-20 indicates that after several loading and unloading cycles of the filter paper, the hysteresis becomes small. Therefore, it is recommended that the filter paper be subjected to several loading and unloading cycles before calibrating the apparatus and before the consolidation-swell test is performed (MFG, 2003).

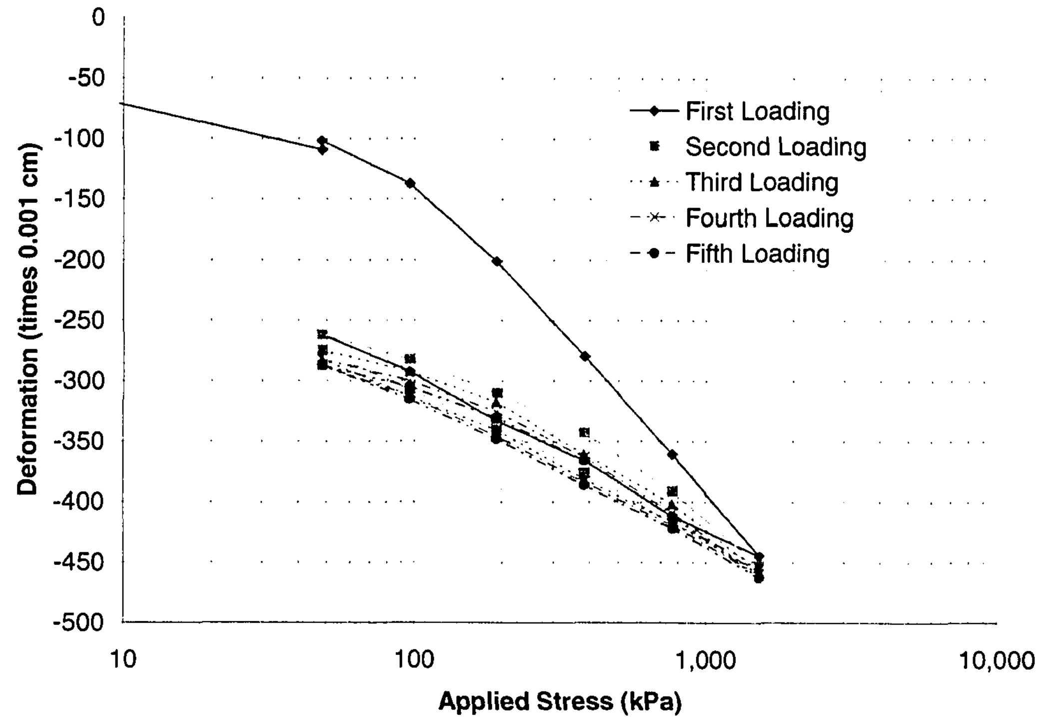


Figure 2-20 Results of Filter Paper Correction (from MFG, 2003)

ASTM D2435-96 recommends that porous stones be used at the top and bottom of the specimen in the oedometer test so that water can imbibe or drain, and thereby dissipate excess hydrostatic pressure. The procedure for measuring the compressibility of the porous stones and the associated correction are similar to those for the oedometer apparatus.

Fredlund (1969) stated that percentage errors without the corrections can be in excess of 100% for the swelling pressure and up to 50% for the swelling index. Chen (1988) reported that it is possible for the corrected values of swelling pressure to be 300% of the measured swelling pressure before correction. MFG (2003) verified the correction factors of the oedometer test data and found that the percentage difference between the corrected and uncorrected swelling pressures could be greater than 80%.

Figure 2-21 shows typical results of the corrections of the consolidation-swell test data obtained from MFG (2003). MFG (2003) concluded that deformation of the testing apparatus is attributed primarily to deformation of the porous stones and filter paper, and to a lesser degree to deformation of the oedometer itself.

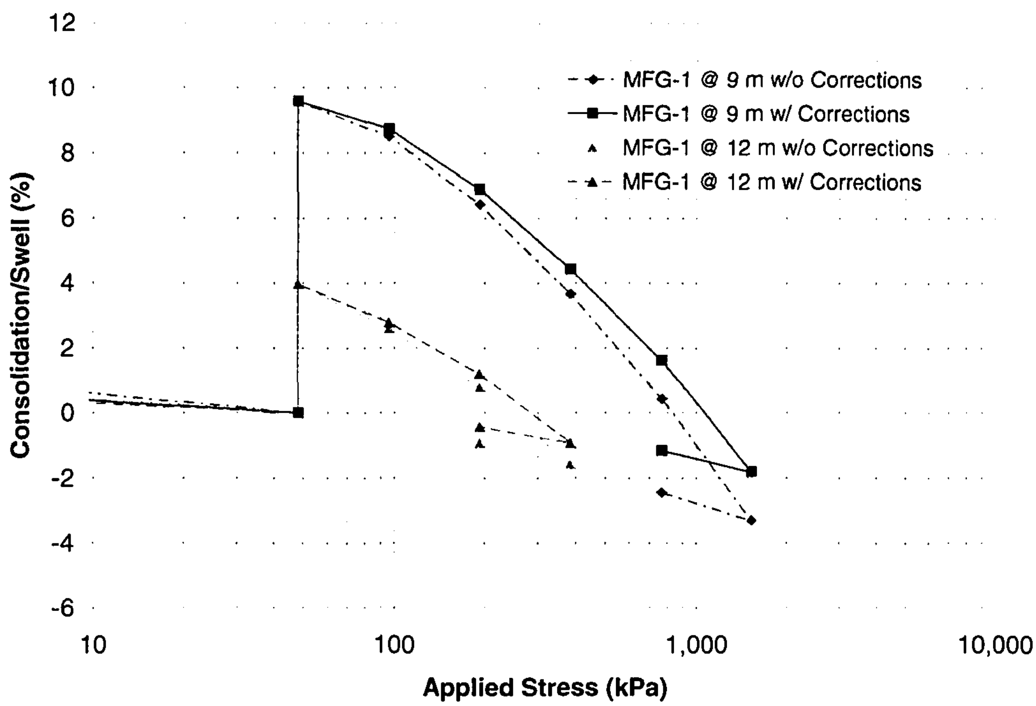


Figure 2-21 Results of Corrections for Oedometer Test Data (from MFG, 2003)

2.3.2.3 Comparison of Swelling Pressures Determined from Consolidation-Swell and Constant Volume Tests

The swelling pressure, σ'_{cs}, determined in the consolidation-swell test is significantly higher than the swelling pressure, σ'_{cv}, measured in the constant volume test (Edil and Alanazy, 1992; Reichler, 1997; and Nelson, et al., 2003 and 2006). Nelson, et al. (2003 and 2006) stated that this is because the specimen imbibes water in the consolidation-swell test, and the swelling pressure includes the work necessary to expel the water. In the constant volume test, the swelling pressure represents only that load necessary to avoid imbibition of water.

Edil and Alanazy (1992) evaluated the difference between the two swelling pressures for a highly plastic clay from Al-Medinah City, Saudi Arabia and concluded that the ratio of σ'_{cv} to σ'_{cs} is approximately 0.7. Research conducted by Reichler (1997) showed that the ratio of σ'_{cv} to σ'_{cs} is approximately 0.8 for Pierre Shale from Fort Collins, Colorado. It has been generally considered that the ratio is approximately 0.5 to 0.6 within the practicing engineering community (Bonner, 1998).

Nelson, et al. (1998 and 2006) proposed a relationship between σ'_{cv} and σ'_{cs} in a form as follows:

$$\sigma'_{cv} = \sigma'_i + \lambda(\sigma'_{cs} - \sigma'_i) \qquad \text{Equation (2-11)}$$

where:

σ'_i = inundation pressure, and

λ = constant.

Nelson, et al. (2006) showed that an appropriate value for λ is in the general range of 0.5 to 0.7. They indicated that a value of 0.6 for the clay soil in the Front Range area of Colorado has been shown to provide reasonably accurate values of predicted heave in cases where actual measurements were possible. The value of λ should be determined for soil on a regional basis.

2.3.2.4 Factors Influencing Swelling Pressure and Percent Swell

Chen (1988) performed a series of consolidation-swell tests on remolded samples to determine the effect of inundation pressure, degree of saturation, sample thickness, initial water content, and initial dry density on swelling pressure and percent swell. The results of his tests are summarized in Table 2-6. He concluded that the swelling pressure is independent of the inundation pressure, the degree of saturation, the sample thickness, and the initial water content. The swelling pressure increases with the increase of initial dry density. The percent swell is dependent on all of the parameters, except the sample thickness, as shown in Table 2-6.

Table 2-6 Summary of Factors Influencing Swelling Pressure and Percent Swell by Chen (1988)

Increased Parameter	Range of Parameter Tested	Swelling Pressure	Percent Swell
Inundation Pressure	48 – 335 kPa	Constant	Decrease
Initial Degree of Saturation	61 – 93%	Constant	Decrease
Sample Thickness	1.28 – 3.81 cm	Constant	Constant
Initial Water Content	5.84 – 19.37%	Constant	Decrease
Initial Dry Density	1.51 – 1.90 Mg/m^3	Increase	Increase

The phenomenon of soil fatigue is another factor affecting the swelling pressure and percent swell of an expansive soil (Chen, 1965; Chu and Mou, 1973; and Popescu, 1980). Chen (1965) observed that expansive soil showed decreasing values of percent swell after each cycle of drying and wetting. Figure 2-22 shows results from his experiments. It was observed that pavements founded on expansive clays which have undergone seasonal movement due to wetting and drying have a tendency to reach a point of stabilization after a number of years (Chen, 1988).

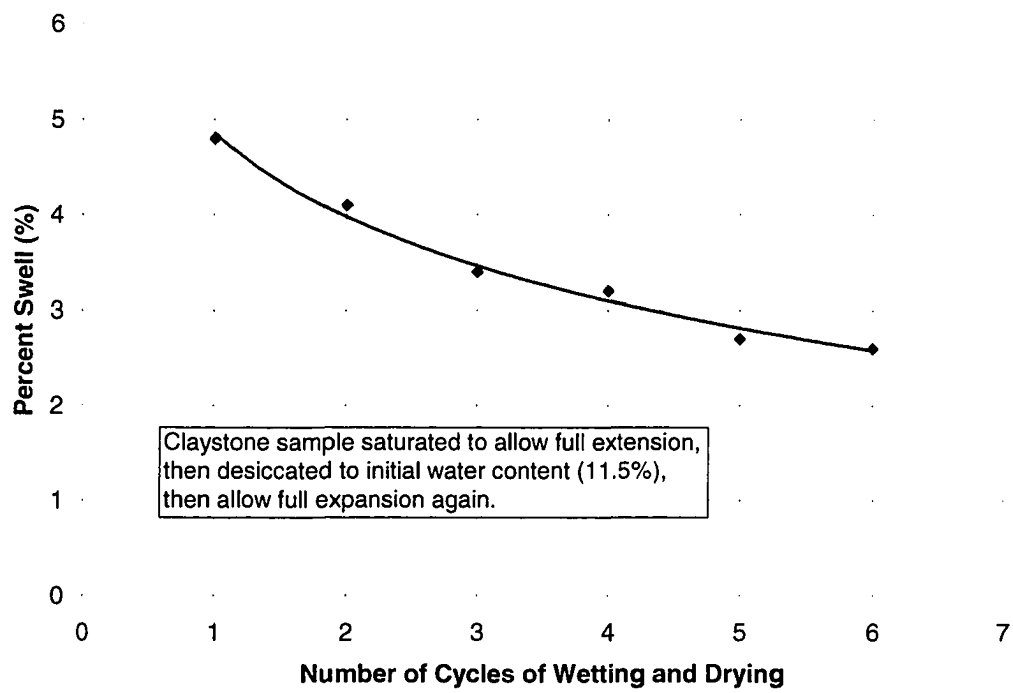


Figure 2-22 Effect of Wetting and Drying Cycles on Percent Swell (after Chen, 1965)

2.3.3 Heave Prediction Equation Using the Oedometer Method

"Free-field" heave is the amount of heave that the ground surface will experience due to wetting of the subsoils with no surface load applied. Because the surface load applied by slab-on-grade floors is very small relative to the swell pressure generated by an expansive soil, the heave of slabs is essentially the same as the free-field heave. To predict the heave of a soil profile, the soil is divided into a number of layers, n, of thickness, z_i. The general equation for predicting heave using the oedometer methods is presented as follows (Nelson and Miller, 1992):

$$\rho = \sum_{1}^{n}\left[\frac{C_p z_i}{(1+e_o)_i}\log\left(\frac{\sigma'_f}{\sigma'_{cv}}\right)_i\right]$$ Equation (2-12)

where:

ρ	=	free-field heave,
C_p	=	heave index,
z_i	=	layer thickness,
e_o	=	initial void ratio,
σ'_f	=	final effective stress state, and
σ'_{cv}	=	swelling pressure from the constant volume test.

It should be noted that the swelling pressure shown in Equation (2-12) is the swelling pressure obtained from the constant volume test.

Nelson, et al. (2006) proposed a refinement of the heave prediction method using the oedometer method as the following equation:

$$\rho = \sum_{1}^{n}\left[C_H z_i \times \log\left(\frac{\sigma'_{cv}}{\sigma'_{vo}}\right)_i\right]$$ Equation (2-12)

where:

C_H	=	heave index, $= \dfrac{\%\text{Swell}}{\log\left(\dfrac{\sigma'_{cv}}{\sigma'_i}\right)}$, and
σ'_{vo}	=	overburden pressure at the midpoint of the layer at depth z.

Nelson, et al. (1998 and 2006) indicated that an accurate method to determine C_H would be to perform several consolidation-swell tests at different inundation pressures and a constant volume test. They noted, however, that doing so is generally not practical nor economical. Therefore, the relationship between σ'_{cv} and σ'_{cs} shown in Equation (2-

11) was proposed so that the value of the heave index, C_H, can be determined from a single consolidation-swell test (Nelson, et al., 2006).

2.4 Design of Pier and Grade Beam Foundations

2.4.1 General Description

Piers have been used extensively for many years as foundations in expansive soils in the Rocky Mountain Front Range area of Colorado. A typical pier and grade beam foundation system that is used in the Front Range area of Colorado is shown in Figure 2-23. The main function of the piers is to provide anchorage in a stable non-swelling stratum sufficient to resist uplift caused by skin friction of expansive soils at shallower depths.

The major concern in the design of any piers in expansive soils is the uplift force exerted by soil swelling along the pier shaft within the active zone. A conservative approach is to consider the ultimate depth of the active zone to be equal to the depth of potential heave.

Straight shaft or belled piers are two commonly used piers. The use of these piers differs in different areas, depending on the soil conditions, depth to bedrock, and ground water conditions (Nelson and Miller, 1992). The pier diameter is typically kept small, usually between 25.4 and 45.7 cm, to minimize the area on which uplift pressures develop.

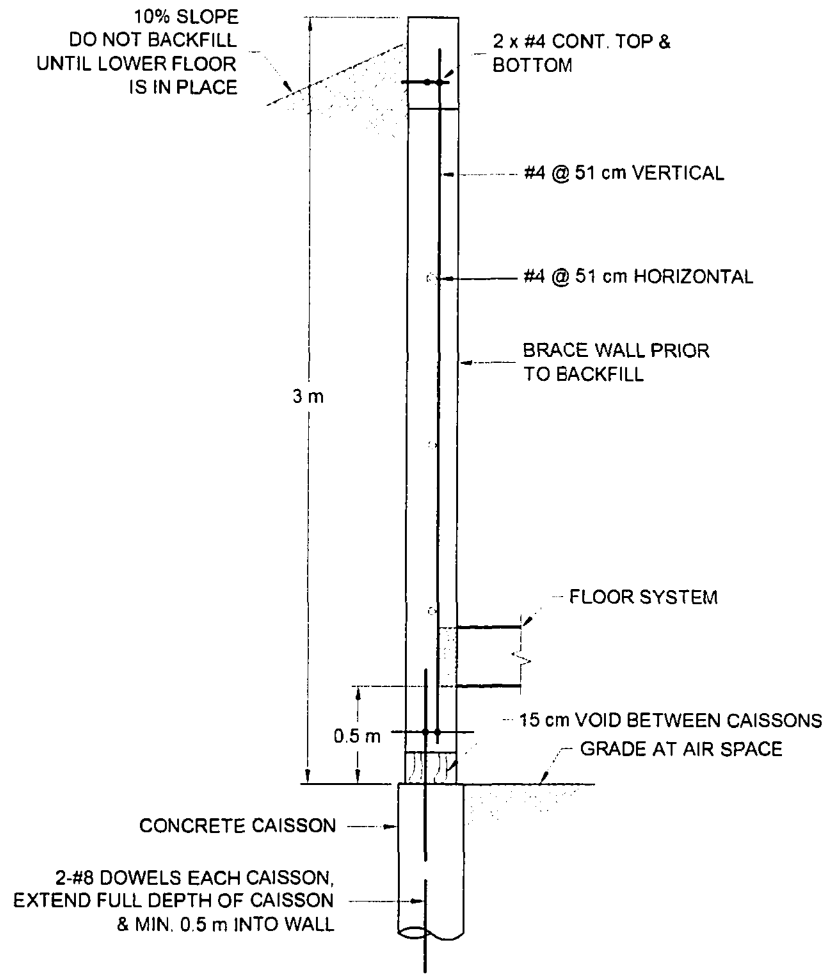


Figure 2-23 Typical Pier and Grade Beam Foundation System

2.4.2 Design Considerations

Two approaches may be taken in the design of piers. If a stable non-expansive stratum exists sufficiently near the surface, the pier may be designed as a rigid member anchored in that stratum so as to prevent movement. This is called the rigid pier design method. However, if the depth of potential heave is large, the required length of pier may be too long to be practical. The pier may then be designed as an elastic member in an elastic medium. The predicted heave of the pier is computed, and the structure must be designed to accommodate that amount of movement. This is called the elastic pier design method. A review of the design methods are provided in the following sections.

2.4.2.1 Rigid Pier Design Method

Nelson and Miller (1992) presented a method of analysis for designing rigid piers based on work by Chen (1988) and O'Neill (1988). The forces acting on a rigid pier are shown in Figure 2-24. The principle of the design is that the negative skin friction below the depth of potential heave plus the dead load, P, must resist the uplift pressures produced by the swelling pressures exerted on the pier above that point. Chen (1988) assumed that the uplift pressures are constant throughout the active zone.

The equation for required length of a rigid straight shaft pier is as follows (Nelson, et al., 2003):

$$L = z_p + \frac{1}{f_s}\left[\alpha_1 \sigma'_{cv} z_p - \frac{P_{dl}}{\pi d}\right] \qquad \text{Equation (2-13)}$$

Where:

z_p	=	depth of potential heave,
f_s	=	negative skin friction below the depth of potential heave,
α_1	=	coefficient of uplift between the pier and the soil,
σ'_{cv}	=	swelling pressure from the constant volume test,
P_{dl}	=	minimum dead load on the pier, and
d	=	diameter of the pier

The coefficient of uplift between the pier and the soil, α_l, is necessary to determine the uplift forces and anchorage forces for the design of the piers. Chen (1988) reported a value of α_l ranging from 0.30 and 0.64 based on results of laboratory experiments. Nelson and Miller (1992) stated that the value of α_l can reasonably be assumed to be between 0.10 and 0.25. Benvenga (2005) found that the value of α_l ranges from 0.3 to 0.8, and stated that the coefficient α_l depends on the nature and strength of the soil, dimensions and method of installation of the pile, time effects, and other factors. The values presented by Benvenga agree more closely with typical factors presented for piers in ordinary soils.

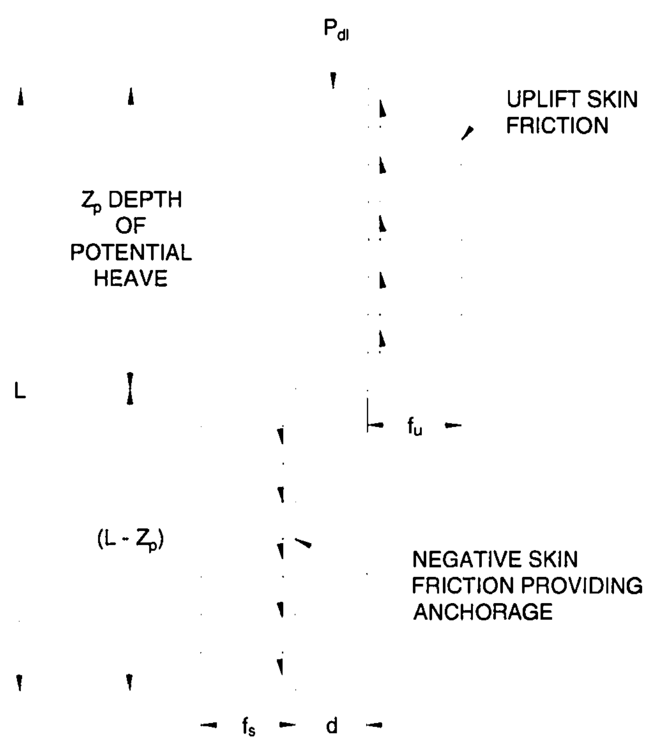


Figure 2-24 Forces Acting on a Rigid Pier in Expansive Soil

The maximum tensile force generated in the pier, P_{max}, generally occurs at a depth of approximately 0.6 of the pier length, L, (Poulos and Davis, 1980) and can be computed as follows:

$$P_{max} = P_{dl@Pmax} - f_u z_p \pi d \qquad \text{Equation (2-14)}$$

$P_{dl@Pmax}$ is the axial force caused by the applied dead load at the point where the maximum tensile force occurs. The coefficient f_u is the uplift skin friction on the pier (= $\alpha_l \sigma'_{cv}$).

2.4.2.1 Elastic Pier Design Method

Design charts that allow prediction of pier movement for an elastic pier and soil are presented in Nelson and Miller (1992) based on solutions developed by Poulos and Davis (1980). These solutions utilize the predicted future free-field heave, as discussed in Section 2.3.3, stiffness of the soil, stiffness of the pier, and the geometry of the system. Nelson and Miller (1992) provided a complete discussion of the elastic pier design method for straight shaft piers and belled piers. The material discussed below is modified from Nelson and Miller (1992) to further facilitate its use by the design engineer.

The uplift skin friction along the side of the pier may be considered to be uniform along the length of the pier, or it may increase with depth. Cases of uniform and linear uplift skin friction along the side of the pier are shown in Figure 2-25 as Cases A and B, respectively. Case A would be the situation where the soil has generally the same swelling pressure throughout the depth of potential heave. Case B would be where a lower swelling soil and/or bedrock stratum overlies a more swelling claystone stratum (Nelson, et al., 2007).

Figure 2-25 shows normalized pier heave plotted as a function of the ratio of pier length to the depth of potential heave for a straight shaft pier (Nelson, et al., 2007). Two curves are presented depending on whether the uplift skin friction is constant with depth or whether it varies linearly with depth. Similar curves are presented in Figure 2-26 for belled piers having a bell diameter twice that of the shaft. Pier heave, ρ_p, can be computed using Figures 2-25 and 2-26 as long as the free-field heave, ρ, depth of potential heave, z_p, and pier length, L, are known.

Figures 2-27 and 2-28 present the normalized maximum tensile force in straight shaft and belled piers as a function of the ratio of pier length to depth of potential heave. The maximum tensile force is normalized to the frictional force, P_{FS}, that would exist if the uplift friction were applied to the entire length of the pier. Nelson, et al. (2007b) provided equations for calculating P_{FS} values for Cases A and B as follows.

Case A: $P_{FS} = -f_u \, L \, \pi \, d$ Equation (2-15)

Case B: $P_{FS} = -0.5 f_u \, L \, \pi \, d$ Equation (2-16)

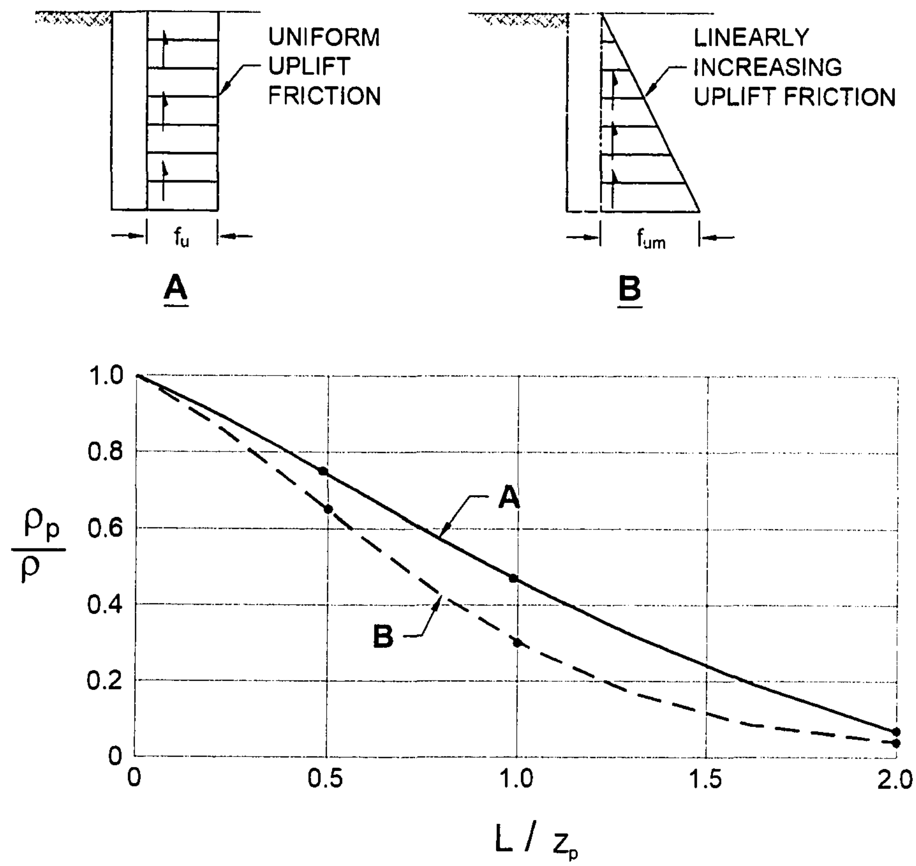


Figure 2-25 Normalized Straight Shaft Pier Heave vs. L/z_p

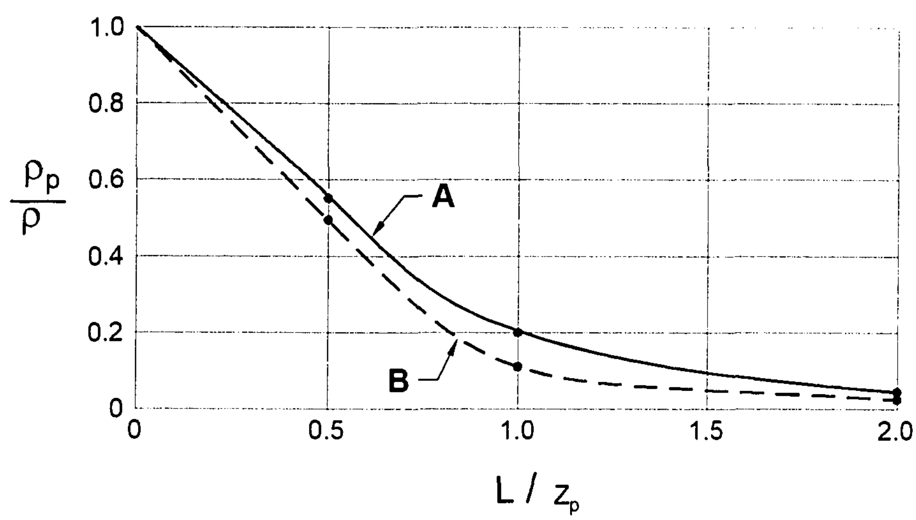


Figure 2-26 Normalized Belled Pier Heave vs. L/z_p

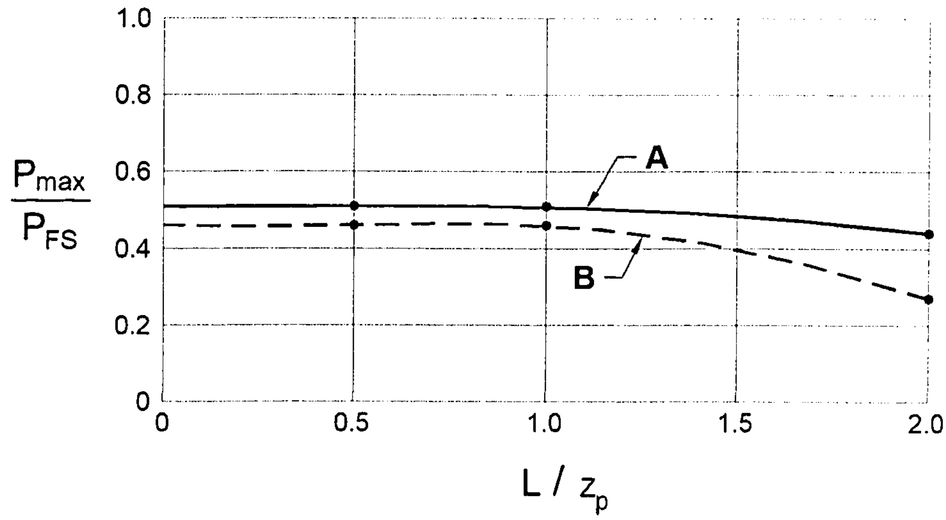


Figure 2-27 Normalized Force in Straight Shaft Piers vs. L/z_p

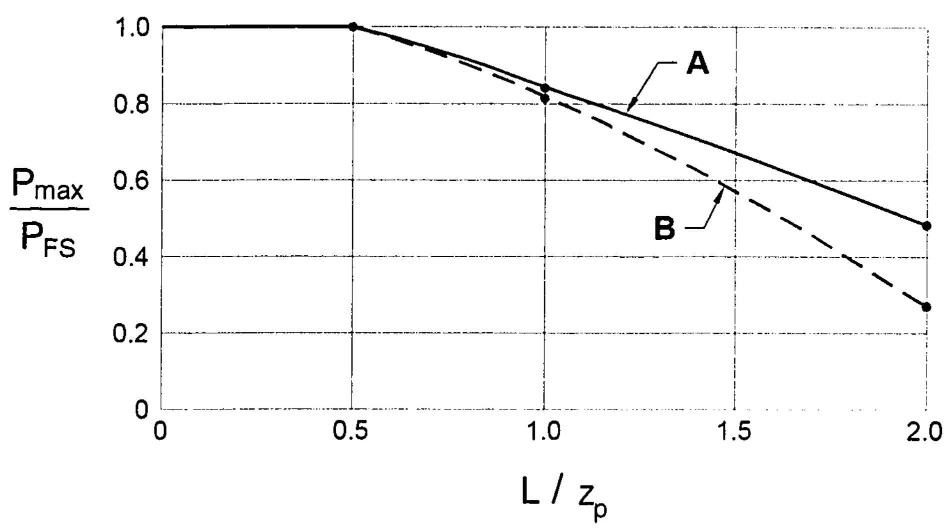


Figure 2-28 Normalized Force in Belled Piers vs. L/z_p

CHAPTER 3

FIELD INVESTIGATION

The field investigation conducted at the TRACON site included the drilling of thirty seven (37) exploratory borings, installation of nine (9) pneumatic piezometers for monitoring the pore water pressure conditions in the coal seams, five (5) standpipe piezometers to the top of the claystone bedrock for monitoring perched water conditions, twelve (12) subsurface nuclear gauge tubes for monitoring water content profiles of the subsoils and bedrock, three (3) deep benchmarks for elevation surveying, and elevation surveying of fifty (50) slab and pier monitoring points within the TRACON building. Table 3-1 summarizes the drilling and installation information including the period of drilling performed, the borehole depths, and the primary purpose of drilling.

3.1 Exploratory Borings

A total of thirty seven (37) exploratory borings were drilled within the TRACON facility to investigate soil/bedrock strata, soil/bedrock properties, and local and regional ground water conditions. The locations of the boreholes are shown on Figure 3-1.

Drilling was performed by Drilling Engineers, Inc., of Fort Collins, Colorado, using a CME 75 drill rig with a 18.4-cm outside diameter hollow-stem auger for the purpose of sampling and installation of the piezometers, and an air rotary drilling technique with a 7.0 or 7.9-cm drag bit for the purpose of installation of the subsurface nuclear gauge tubes. During drilling, the majority of the exploratory borings were sampled continuously using a continuous core sampler. Figure 3-2 shows an example of the continuous core samples obtained from the drilling at the TRACON facility. In addition, 5.1-cm diameter California (CA) samples were collected at 1.5-meter intervals during drilling. Selected CA and bulk samples were tested in the laboratory for geotechnical characteristics.

Table 3-1 Summary of Information of the Drilling and Installation Performed at the TRACON Facility

Borehole I.D.	No. of Boreholes	Period of Drilling Performed	Range of Borehole Depths (m)	Primary Purpose of Drilling
SMI-1 through 7, and 9	8	2/9/1999 – 7/1/2005	12.2 – 22.6	Sampling and Laboratory Testing
SMI-P2, P3, P8, P10 through P15	9	4/29/2002 – 1/21/2003	13.7 – 24.4	Installation of Pneumatic Piezometers
SMI-S2, S3, S8, S14, and S15	5	4/29/2002 – 1/21/2003	1.7 – 3.0	Installation of Standpipe Piezometers
SMI-MA1A, MA1B, MA2A, MA2B, MA3 through MA5, MA8, MA10 through MA13	12	5/18/2000 – 1/15/2003	3.0 – 24.4	Installation of Subsurface Nuclear Gauge Tubes
SMI-BM1 through BM3	3	9/20/1999 – 7/19/2000	30.5 – 36.6	Installation of Benchmarks

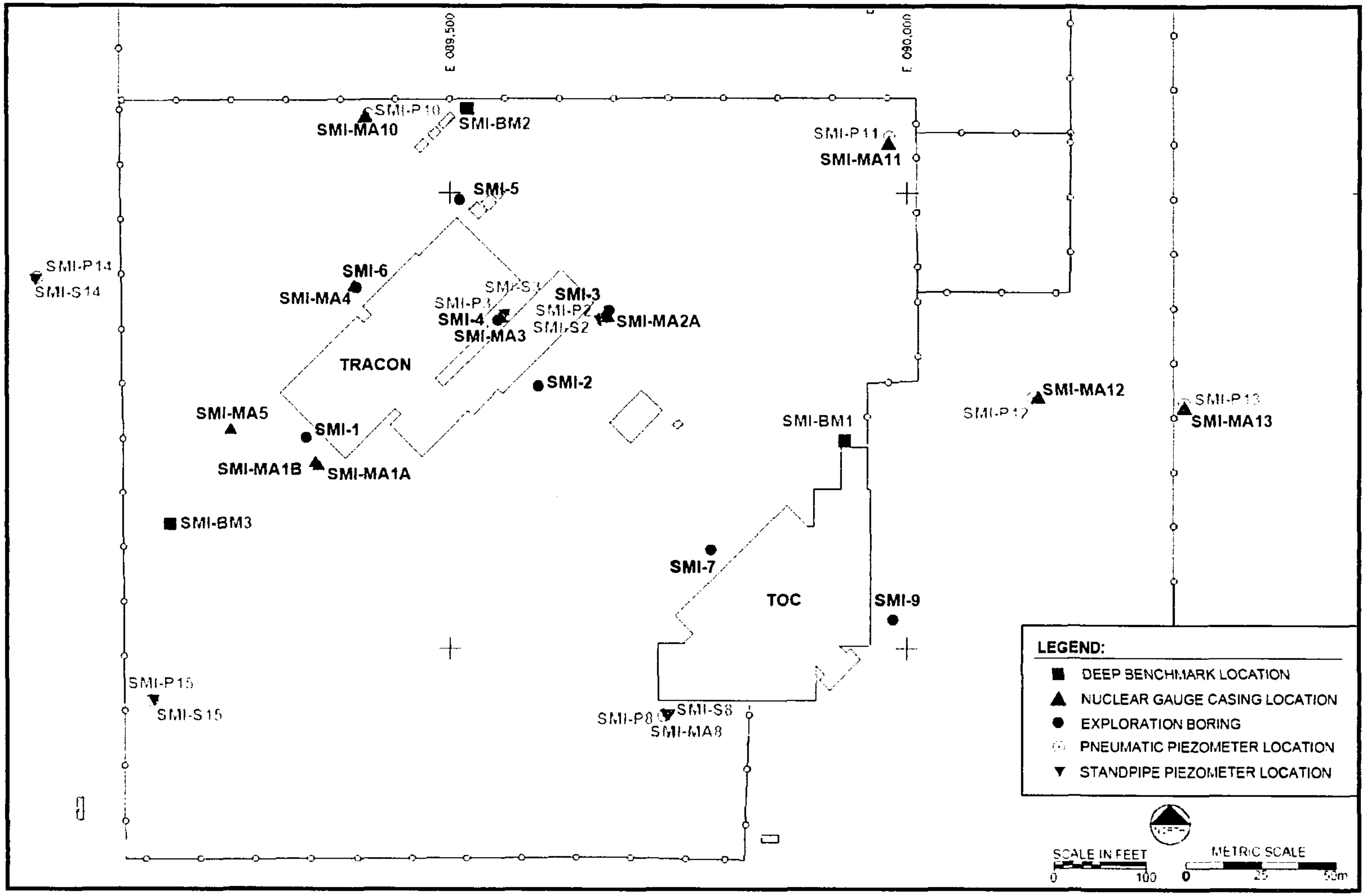


Figure 3-1 **Locations of the Boreholes, Piezometers, Subsurface Nuclear Gauge Tubes, and Deep Benchmarks at the TRACON Facility**

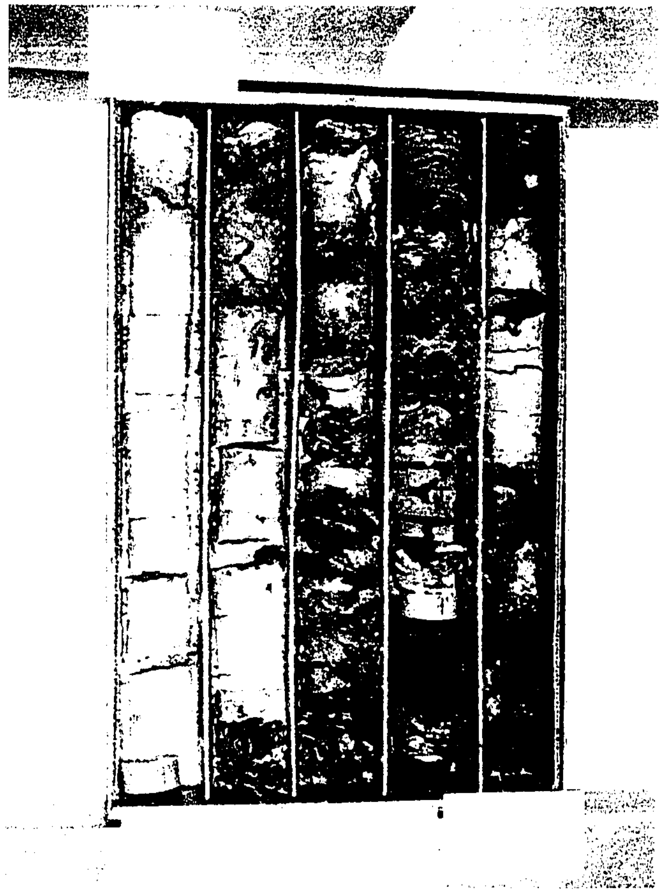


Figure 3-2 Photo of Continuous Core Samples at the TRACON Facility

Subsoils at the site generally consist of 0.3 to 3.4 meters of fill and native soils, underlain by weathered claystone, and interbedded or alternating layers of claystone and sandstone bedrocks. The maximum boring depth in any exploratory boreholes was 36.6 meters. Coal seams were encountered during drilling. A typical soil profile and the primary subsurface units are described in more detail below and are shown in Figure 3-3.

Fill: Fill soils were visually classified as olive brown, yellowish brown and/or dark grayish brown silty and sandy clay. The fill soils were typically dry, slightly moist or moist.

Native Soils: Native soils generally consisted of brown, yellowish to olive or gray brown silty or sandy clay, clayey sand, or sandy silt. The native soils exhibited morphologic features, such as a "blocky" structure, not found in the fill soils.

Claystone Bedrock: Claystone bedrock was dry to slightly moist and consisted of light to very dark gray, or light to dark brown claystone. The claystone samples exhibited high to very high swell potential.

Sandstone Bedrock: Sandstone bedrock was often interbedded with claystone at deeper depths within the borings. The sandstone was generally clayey, dry to slightly moist and brown, yellow, or light gray in color.

Coal: To the extent of the maximum depth of the borings, there are three layers of coal ranging in thickness from approximately 0.9 to 3.4 meters. The top coal seam is approximately 2.4 meters thick on average, and is located at depths ranging from approximately 10.0 to 20.4 meters below the ground surface. The shallower coal layers were usually found to be interbedded with claystone. The coal was generally black or dark greenish black, hard and thinly bedded.

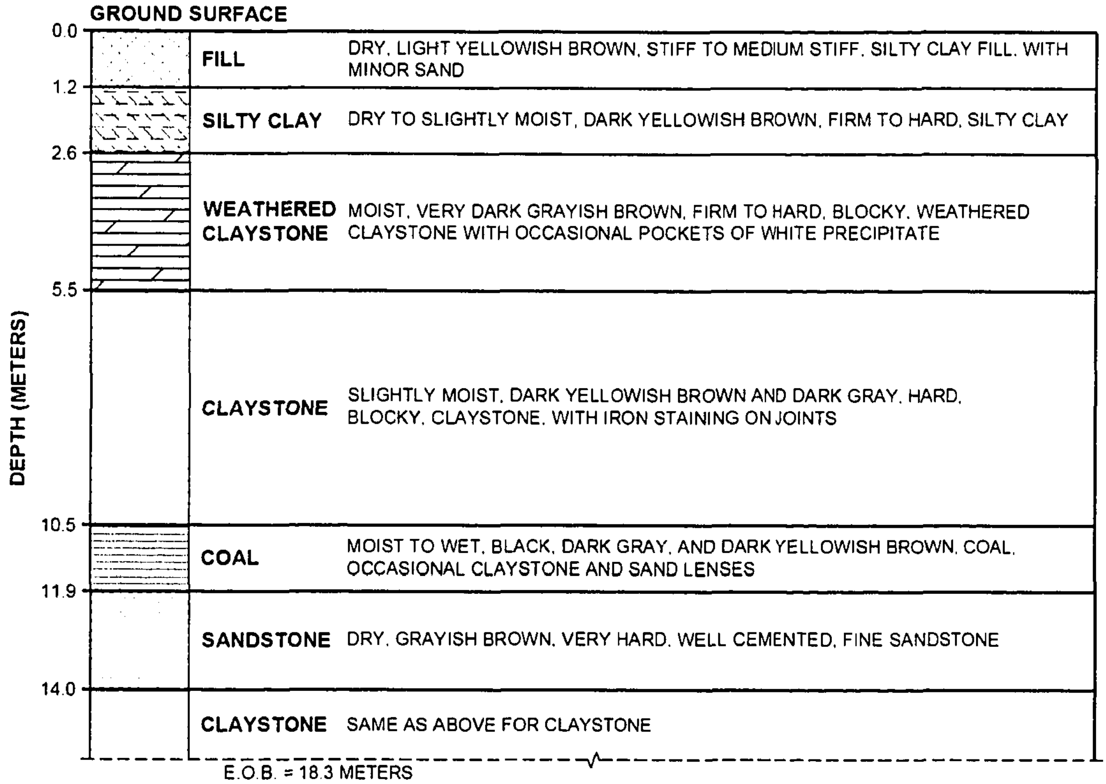


Figure 3-3 Typical Soil Profile and Primary Subsurface Units at the TRACON Facility

3.2 Installation and Monitoring of Piezometers

3.2.1 Pneumatic Piezometers

Pneumatic piezometers were installed at the bottom of the upmost major coal seam encountered in each of the boreholes (SMI-P2, P3, P8, P10 through P15) to monitor the ground water conditions in the coal seams. Figure 3-1 shows the locations of the borings where the pneumatic piezometers were installed. The pneumatic piezometer was attached to a 2.5-cm diameter schedule 40 PVC pipe and was installed in the borehole. The depths of the piezometers SMI-P2, SMI-P3, SMI-P8, and SMI-P10 through P15 are shown in Table 3-2. The piezometers were grouted in place with a Portland

Cement/Bentonite grout mixture. A flush-mounted protective cap was installed at the ground surface.

Measurements of the pneumatic piezometers were taken shortly after installation. The dates for subsequent measurements of the pneumatic piezometers are shown in Table 3-2. A summary of the pneumatic piezometer measurements is presented in Table 3-2. As shown in Table 3-2, the values of the pressure head in the coal seam ranged from approximately 0 to 5.8 meters as of April 2, 2003. SMI-P10 and SMI-P11 were dry during the monitoring period. In general, no significant changes in ground water levels were noted in the pneumatic piezometers during the period of monitoring. The piezometer data show that the regional ground water in the coal seam generally flows to the north or northwest direction within the TRACON site. This regional groundwater flow direction agrees with the findings from USGS (1987), EnecoTech (1994), and CDWR (2002).

Table 3-2 Summary of Pneumatic Piezometer Data

Pneumatic Piezometer	Piezometer Placement (m)		5/6/2002 Water level (m)		6/4/2002 Water level (m)		7/25/2002 Water level (m)		8/20/2002 Water level (m)		10/3/2002 Water level (m)		11/14/2002 Water level (m)	
	BGS[1]	Elev.	BGS	Elev.	BGS	Elev.	BGS	Elev.	BGS	Elev.	BGS	Elev.	BGS	Elev.
SMI-P2	13.3	1628.6	-	-	-	-	-	-	-	-	-	-	-	-
SMI-P3	14.9	1627.1	-	-	-	-	-	-	-	-	-	-	-	-
SMI-P8	18.4	1624.5	-	-	-	-	-	-	-	-	-	-	-	-
SMI-P10	12.1	1627.7	-	-	dry	-	dry	-	dry	-	dry	-	dry	-
SMI-P11	12.1	1631.8	dry	-	dry	-	dry	-	dry	-	dry	-	dry	-
SMI-P12	18.6	1626.0	3.2	1629.3	3.3	1629.3	3.1	1629.3	3.5	1629.6	3.2	1629.3	3.4	1629.5
SMI-P13	21.9	1625.2	3.4	1628.7	3.7	1629.0	3.7	1629.0	3.9	1629.2	3.9	1629.2	3.9	1629.2
SMI-P14	9.1	1624.0	-	-	-	-	-	-	-	-	-	-	-	-
SMI-P15	16.5	1623.8	-	-	-	-	-	-	-	-	-	-	-	-

Note: [1] BGS = Depth Below Ground Surface

Pneumatic Piezometer	Piezometer Placement (m)		1/16/2003 Water level (m)		2/4/2003 Water level (m)		2/10/2003 Water level (m)		2/27/2003 Water level (m)		4/2/2003 Water level (m)	
	BGS	Elev.	BGS	Elev.	BGS	Elev.	BGS	Elev.	BGS	Elev.	BGS	Elev.
SMI-P2	13.3	1628.6	-	-	-	-	-	-	0.5	1629.1	0.0	1628.6
SMI-P3	14.9	1627.1	-	-	-	-	-	-	1.9	1629.0	1.5	1628.6
SMI-P8	18.4	1624.5	-	-	-	-	-	-	5.4	1629.9	5.3	1629.7
SMI-P10	12.1	1627.7	dry	-	dry	-	-	-	dry	-	dry	-
SMI-P11	12.1	1631.8	dry	-	dry	-	-	-	dry	-	dry	-
SMI-P12	18.6	1626.0	-	-	3.6	1629.6	3.5	1629.6	3.7	1629.8	3.7	1629.7
SMI-P13	21.9	1625.2	-	-	4.1	1629.3	-	-	4.4	1629.7	4.1	1629.3
SMI-P14	9.1	1624.0	-	-	3.9	1627.9	4.1	1628.1	4.4	1628.3	4.3	1628.3
SMI-P15	16.5	1623.8	-	-	-	-	-	-	5.8	1629.6	5.8	1629.5

3.2.2 Standpipe Piezometers

A shallow standpipe piezometer was installed in each of the five shallow borings SMI-S2, S3, S8, S14, and S15 to monitor potential perched ground water levels above the existing claystone layer. The locations of the standpipe piezometers are shown on Figure 3-1. The depths of the standpipe piezometers varied from 1.7 to 3.0 meters, as indicated in Table 3-3. The standpipe piezometer consisted of a schedule 40 PVC pipe with a 5.1-cm inside diameter and a 5.7-cm outside diameter. The bottom was screened for a distance of 61 cm with a PVC cap on the end. The borehole was backfilled with silica sand from a depth of 0.1 meters below the screened interval to 0.5 meters above the screened interval. The remainder of the borehole was backfilled with bentonite chips. A flush-mounted protective cap was installed at the ground surface.

Measurements of the standpipe piezometers were taken on January 21, February 4, February 10, February 27, and April 2, 2003. A summary of the standpipe piezometer data is presented in Table 3-3. Perched ground water was not encountered in the standpipe piezometers during the monitoring period, except that perched ground water was encountered in SMI-S14 at a depth of 1.2 meters below the ground surface on February 10, 2003. On April 2, 2003, the level of the perched ground water in SMI-S14 had risen to a depth of 0.04 meters below the ground surface. SMI-S14 is located near a low-lying marsh area where there is usually standing water and/or soft ground visible at the surface. The stormwater outlet from the TRACON facility is located within approximately 60 meters of this area, which indicates that the source of water here is likely the runoff from the parking lots.

EnecoTech (1994) conducted a regional ground water study that included the DIA site. In that study, 35 monitoring wells were located within the DIA site. Perched ground water was encountered in 26 of those 35 monitoring wells. They stated that "at DIA, recent unconsolidated stream and wind deposited sediments (alluvium, loess, eolian sands) provide significant quantities of ground water." The April 29, 2002 Agriculture News from Colorado State University stated that 2002 is the third consecutive year of a drought cycle in Colorado and that the state is in the fifth year of below-average snow pack (CSU, 2002). It is believed that the standpipe piezometers did not show "typical" ground water conditions during the monitoring period due to the drought in Colorado.

Table 3-3 Summary of Standpipe Piezometer Data

Standpipe Piezometer	Depth of Piezometer (m)	1/21/2003 Water level (m)		2/4/2003 Water level (m)		2/10/2003 Water level (m)		2/27/2003 Water level (m)		4/2/2003 Water level (m)	
		BGS[1]	Elev.	BGS	Elev.	BGS	Elev.	BGS	Elev.	BGS	Elev.
SMI-S2	3.0	dry	dry	dry	dry	n/a	n/a	dry	dry	dry	dry
SMI-S3	2.3	dry	dry	dry	dry	n/a	n/a	dry	dry	dry	dry
SMI-S8	2.4	dry	dry	dry	dry	n/a	n/a	dry	dry	dry	dry
SMI-S14	1.7	dry	dry	dry	dry	1.2	1634.6	1.1	1634.8	0.04	1635.8
SMI-S15	2.7	dry	dry	dry	dry	n/a	n/a	dry	dry	dry	dry

Note: (1) BGS = Depth Below Ground Surface

3.3 Installation and Monitoring of Subsurface Nuclear Gauge Tubes

3.3.1 Installation of Subsurface Nuclear Gauge Tubes

Twelve (12) subsurface nuclear gauge tubes were installed within the TRACON facility to evaluate the migration of the subsurface water at the site. Figure 3-1 shows the locations of the subsurface nuclear gauge tubes. Table 3-4 summarizes the installation information for each subsurface nuclear gauge tube. Each subsurface nuclear gauge tube consists of a schedule 40 PVC pipe with a 5.1-cm inside diameter and a 5.7-cm outside diameter. The subsurface nuclear gauge tubes were installed in boreholes using an air rotary drilling technique with a 5.7, 7.0, or 7.9-cm drag bit. As shown in Table 3-4, a 7.0-cm drag bit was used for subsurface nuclear gauge tubes SMI-MA1A, MA4, MA5, MA8, and MA10 through MA13. A 7.9-cm drag bit was used for subsurface nuclear gauge tubes SMI-MA2A and MA3. The annulus between the boring wall and the PVC pipe for these subsurface nuclear gauge tubes was backfilled with slurry consisting of 16 kilograms of bentonite mixed with 303 liters of water. A 5.7-cm drag bit was used for subsurface nuclear gauge tubes SMI-MA1B and MA2B. These nuclear gauge tubes were used for calibration purposes to assess the effect of the grout in the annulus. No backfill was placed between the annulus of the boring wall and the PVC pipe of the shallow nuclear gauge tubes.

Table 3-4 **Installation Information for Subsurface Nuclear Gauge Tubes**

Subsurface Nuclear Gauge Tube I.D.	Borehole Diameter (cm)	Borehole Depth (m)	Tube Depth (m)
SMI-MA1A	7.0	12.2	10.7
SMI-MA1B	5.7	3.0	3.0
SMI-MA2A	7.9	13.7	13.7
SMI-MA2B	5.7	3.0	3.0
SMI-MA3	7.9	13.7	13.7
SMI-MA4	7.0	13.7	10.7
SMI-MA5	7.0	12.2	12.2
SMI-MA8	7.0	19.8	19.8
SMI-MA10	7.0	16.8	16.8
SMI-MA11	7.0	15.2	15.2
SMI-MA12	7.0	20.7	20.7
SMI-MA13	7.0	24.4	24.4

3.3.2 Monitoring with the Subsurface Nuclear Gauge

Monthly measurements using the subsurface nuclear gauge were taken from June 2000 through June 2004. Whitney (2003) and Benvenga (2005) showed the profiles of water content, degree of saturation, and density at each tube location. Additional readings at the locations of SMI-MA2A and MA3 were taken in August 2006. Examples of the water content profiles at the locations of SMI-MA2A and MA3 are shown in Figures 3-4 and 3-5, respectively. SMI-MA2A is located on a bare ground area near the north-east corner of the building, where the greatest amount of slab and pier heave has been observed. Figure 3-4 indicates that changes in water content that have occurred are close to the coal seam and are subject to seasonal fluctuation. This indicated that the coal seam is a water source for the overlying claystone bedrock. SMI-MA3 is located underneath a concrete slab between the TRACON and Environmental Wings, where climatic conditions have no effect on the wetting of the subsoils. Figure 3-5 indicates that the water content in the claystone above the coal seam increased slightly for the same reason that was discussed previously for SMI-MA2A. The water content profiles at SMI-MA2A and MA3 were used for the model calibration and validation process in this study.

The water migration study indicates that the TRACON building has three major sources of water to the subsoils (Whitney, 2003; Benvenga, 2005). The primary source of water is the coal seam. This is observed in SMI-MA2A, MA3, and MA5. The secondary source of water to the subsoils is the perched water zone seen in SMI-MA4 and MA5. The water is located in the sandy or silty clay strata and is perched on top of the weathered claystone. The third major source of water is the localized gravel layer. It was concluded that surface infiltration has had little or no impact on water contents below the TRACON building due to the drought that has been in existence for the past several years. The major source of water to the subsoil appears to be off-site. It appears that control of water from off-site, particularly to the north and northeast, is important in controlling the ground water recharge.

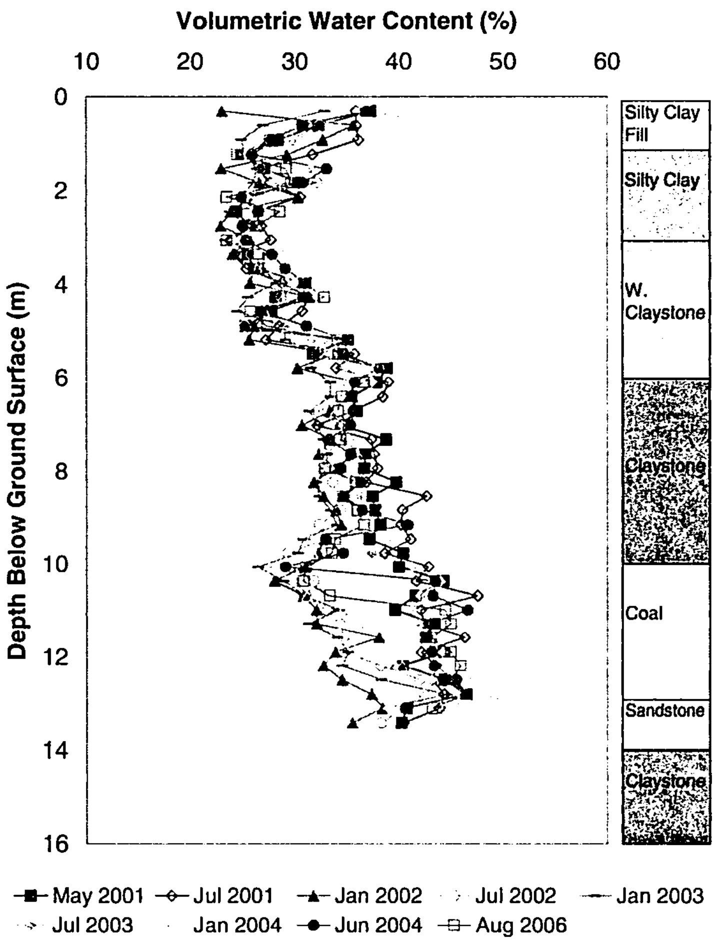


Figure 3-4 Volumetric Water Content Profiles for SMI-MA2A

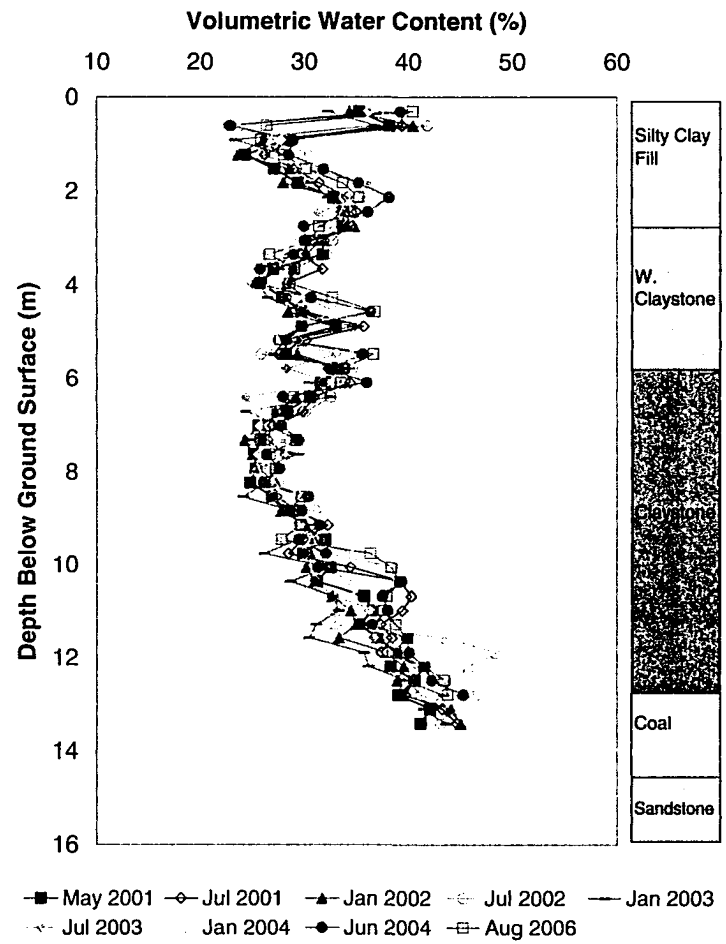


Figure 3-5 Volumetric Water Content Profiles for SMI-MA3

3.4 Elevation Surveying

3.4.1 Design, Installation, and Monitoring of Deep Benchmarks

3.4.1.1 General

Benchmarks are long lasting stable points for which elevations have been determined, and are used to control other surveys and to monitor movement of and within the Earth's crust. Several phenomena can cause benchmark instability. These include, but are not limited to, the following: (1) shrinking and swelling of soil due to changes in water content, (2) frost heave, (3) slope instability, (4) soil consolidation, and (5) physical disturbances. For benchmarks installed into areas with expansive soils, swelling of the soils is the most significant factor that influences the instability of the benchmarks. To prevent the movement of benchmarks due to heaving of expansive soils, benchmarks must be anchored below depths at which these movements originate. The term "deep benchmarks" is used since the benchmarks are anchored at depths such that heave of the expansive soil will not cause movement of the benchmarks.

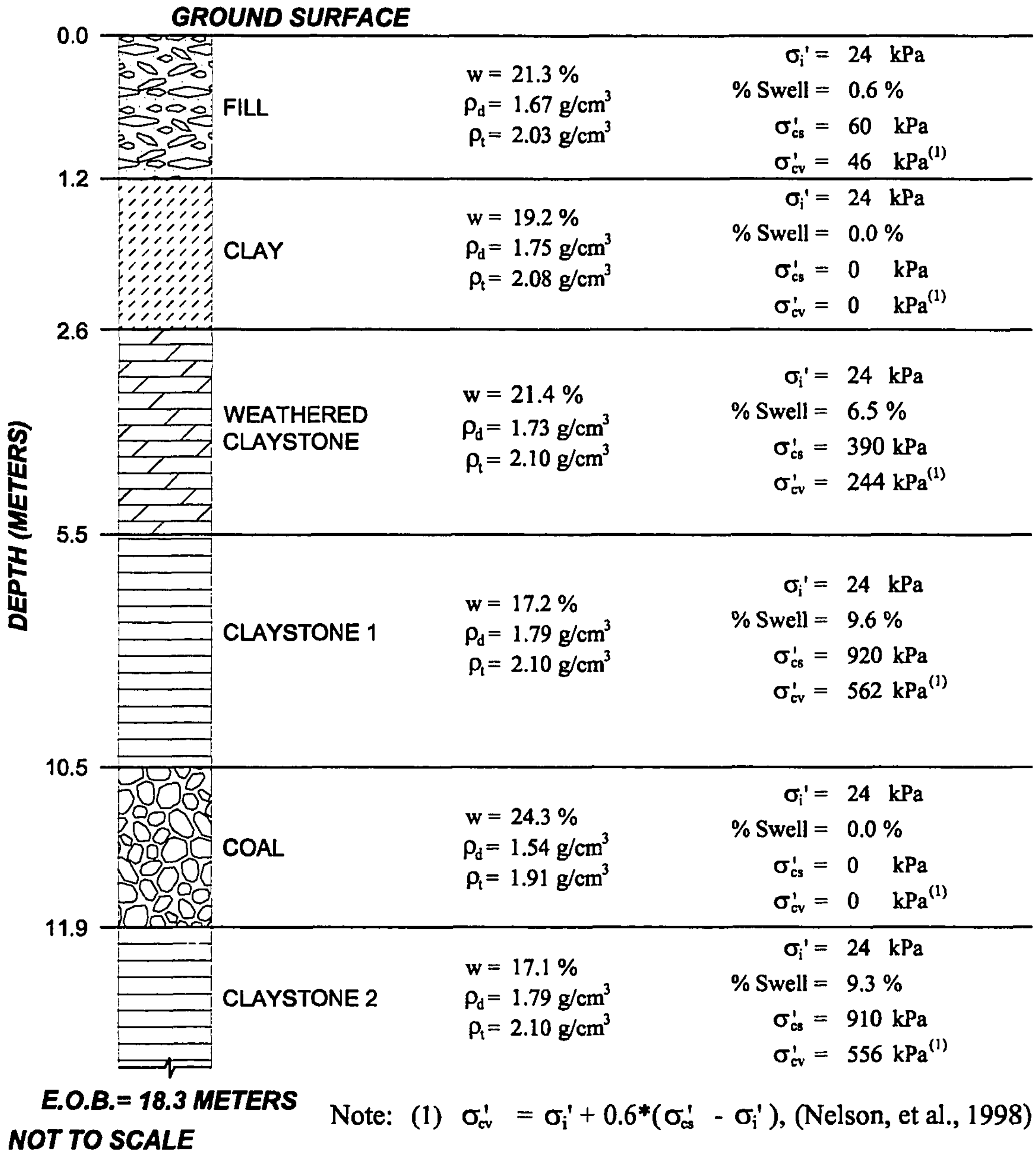
Stable benchmarks were needed at the TRACON building to which elevation monitoring of the building movements could be referenced. A deep benchmark (labeled SMI-BM1) was installed in September 1999 at the site, and two additional benchmarks, SMI-BM2 and SMI-BM3, were installed in July 2000. The performance of the deep benchmarks has been monitored since September 2000. Elevation readings on the three benchmarks have been used to confirm their stability relative to each other.

The procedures for determining the depth of the deep benchmarks, the soil profiles that were observed during installation, steps followed during installation of the benchmarks, verification of the benchmark depth, and results of the benchmark monitoring are presented in the following sections.

3.4.1.2 Calculations of Deep Benchmark Depth

Soil profiles at the six different borehole locations shown in Section 3.1 varied slightly. In order to predict the depth of potential heave for design of the deep benchmark, a generalized soil profile was constructed. Figure 3-6 shows the typical soil profile and soil properties interpreted from the data gathered from six boreholes that had been drilled previously. The soil properties were obtained from laboratory testing and will be discussed in Chapter 4. The soil properties shown in Figure 3-6 represent the most conservative values with respect to soil expansion that were measured.

Table 3-5 shows the computations for depth of potential heave based on the data in Figure 3-6. The maximum depth of potential heave at the site was calculated to be 27.2 meters. To account for uncertainties in the calculations, the required depths of anchorage of the deep benchmarks SMI-BM1, SMI-BM2, and SMI-BM3 were taken to be approximately 37, 30, and 30 meters, respectively. Subsequent test results from testing of samples taken during installation of the deep benchmarks were used to confirm the required depths of anchorage at the actual installed locations.



Note: (1) $\sigma_{cv}' = \sigma_i' + 0.6*(\sigma_{cs}' - \sigma_i')$, (Nelson, et al., 1998)

Figure 3-6 Typical Soil Profile and Properties

Table 3-5 **Calculation of Depth of Potential Heave**

Step	Description	Notes
1	Assuming z_p = Depth of Potential Heave below the Ground Surface	-
2	Calculating Overburden Pressure, σ'_{vo}: $\sigma'_{vo} = (1.2 - 0) \times 2.03 \times 9.81 + (2.6 - 1.2) \times 2.08 \times 9.81 + (5.5 - 2.6) \times 2.10 \times 9.81 + (10.5 - 5.5) \times 2.10 \times 9.81 + (11.9 - 10.5) \times 1.91 \times 9.81 + (z_p - 11.9) \times 2.10 \times 9.81$ $= [241.4 + (z_p - 11.9) \times 20.6]$ kPa	Refer to Figure 3-6 for the soil profile
3	Obtaining Constant Volume Swelling Pressure, σ'_{cv}: σ'_{cv}, = 556 kPa from Claystone 2	Refer to Figure 3-6 for the swelling pressure
4	Solving for z_p: $\because \sigma'_{vo} = \sigma'_{cv}$, Thus, $z_p = 27.2$ meters	-

3.4.1.3 Drilling and Sampling

Three boreholes were drilled at selected locations for installation of the deep benchmarks SMI-BM1, SMI-BM2, and SMI-BM3. The borehole for SMI-BM1 was drilled to a depth of 37 meters and the other two boreholes were drilled to a depth of 30 meters. The boreholes were advanced using an 8.3 cm ID hollow-stem auger powered by a CME-75 drill rig. During drilling, 5.1 cm California samples of the soil and bedrock were taken at 1.5 meter intervals. These samples were tested in the laboratory to confirm assumptions that were made in the calculations for the depths of the benchmarks. In addition, continuous samples were taken using a 5.7 cm diameter CME continuous sampler during drilling.

The actual deep soil/bedrock profile encountered at SMI-BM1 is shown in Figure 3-7. The profiles at the other two benchmark locations were similar. It can be seen that in the deep holes additional strata of claystone, sandstone and coal were observed. After testing the samples, the computed required depth of the benchmark was verified as discussed below.

The testing of the samples requires 2 to 3 weeks for completion. It is not practical to keep the drill hole open for that length of time in order to wait for the verification of the benchmark depth from the test results. Therefore, it was very important that an experienced engineer or geologist be on site to observe the core that was recovered and note any particular deviations from the assumptions used in determining the depth of the benchmark. Also, it was important to be conservative in selecting the depth of anchorage. A general knowledge of the properties of the local bedrock is essential. It must be kept in mind that although a stratum of material with low expansive potential may be encountered at some depth, this may not be the stratum that controls the depth of potential heave. A lower stratum of material with higher expansion potential may govern the depth of potential heave, and, therefore, the depth of anchorage.

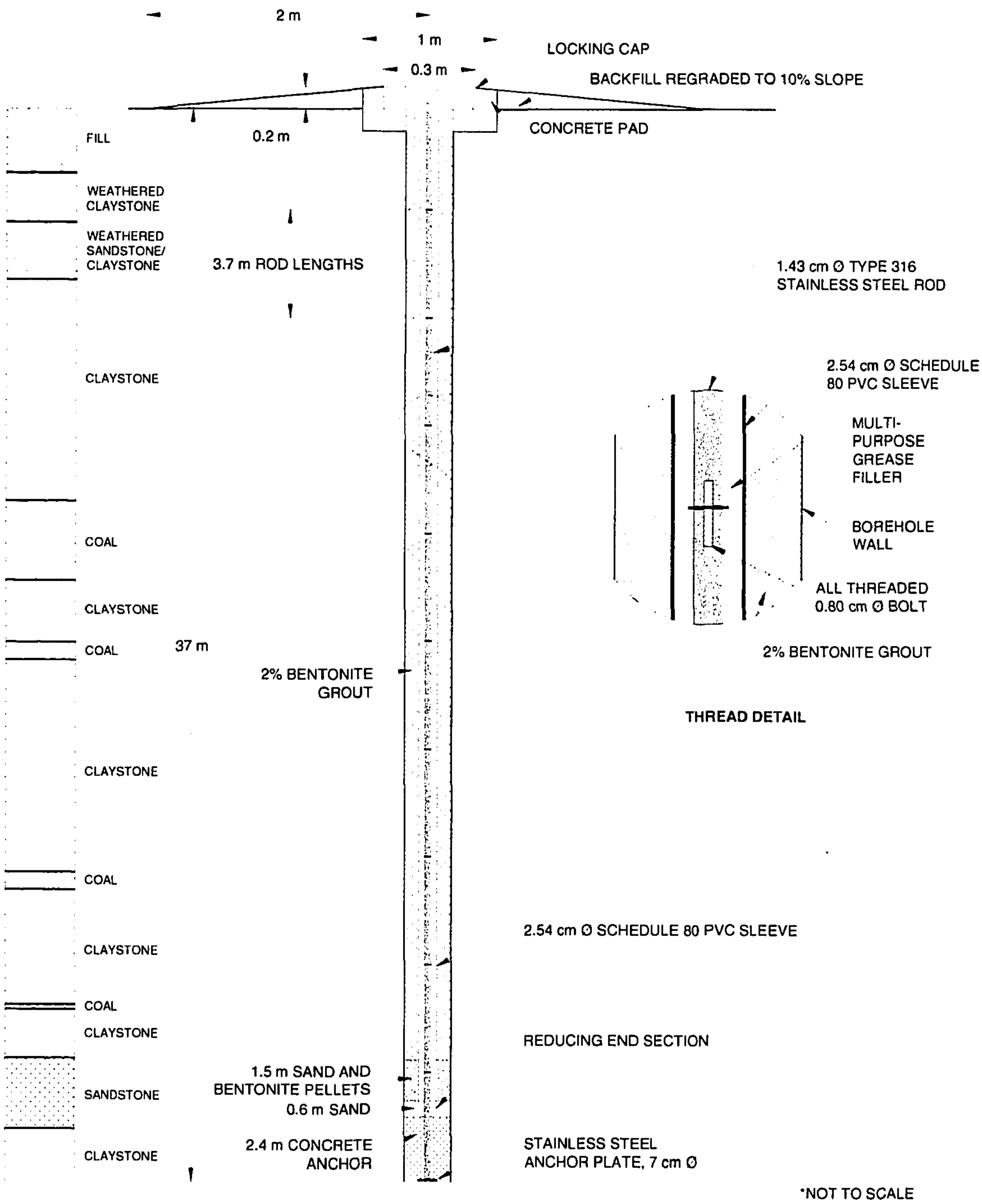


Figure 3-7 SMI-BM1 Soil Profile and Construction of Deep Benchmark

3.4.1.4 Installation of Deep Benchmarks

Following the drilling, the deep benchmarks were installed into the boreholes. The installation procedure of the deep benchmarks was based on the procedure for a class A rod mark established by the National Geodetic Survey (NGS, 1978) but modified for the expansive soil conditions. The construction of the deep benchmarks is shown in Figure 3-7. As shown in Figure 3-7, a rod was assembled from 3.7-meter sections of 1.43-cm-diameter type 316 stainless steel. The type 316 stainless steel has excellent corrosion and oxidation resistance. The coefficient of thermal expansion of the type 316 stainless steel is 15.9 μm/m/°C within a temperature range of 0 to 100 °C.

The rod was anchored in concrete at depths between 34 and 37 meters for SMI-BM1 and at depths between 26 and 30 meters for SMI-BM2 and SMI-BM3. A sleeve made from 2.54-cm schedule 80 polyvinyl chloride (PVC) pipe was placed over the steel rod. The purpose of the sleeve is to isolate the rod from soil movements occurring above the stable stratum. The annular space between the rod and the sleeve was filled with multi-purpose grease made by Lubriplate Division, Fiske Brothers Refining Company, Newark, N.J. A two-percent bentonite grout was tremied between the annulus of the boring wall and the PVC sleeve. The grout provided a low permeability backfill so as to minimize downward migration of water along the borehole. The bentonite served to minimize shrinkage of the grout. The top of the steel rod serves as the datum point. At the surface, a locking cover with a watertight seal was installed in a concrete pad to protect the benchmark from disturbance.

The step-by-step procedure for installing the deep benchmarks is presented below.

1. The proposed boring location was staked out and utility clearance was conducted to prevent any damage of the electrical, gas, water, and sewer lines at the site.
2. After positioning the drill rig, a 30.5-cm diameter hole was drilled to a depth of 0.6 meters. This hole was filled with soil during subsequent operations, but the objective was to loosen the soil in preparation for placing the locking cover.
3. The exploratory boring was drilled with a 18.4-cm OD and 8.3-cm ID hollow stem auger to the required deep benchmark depth. Continuous core and CA samples were taken during drilling for laboratory testing. Results of the laboratory testing were used to verify the selected deep benchmark depths.
4. After the completion of drilling, a 1.43-cm-diameter type 316 stainless steel rod was assembled and lowered through the hollow stem of the auger string to the bottom of the borehole as shown in Figures 3-7 and 3-8. Additionally, a 7-cm-diameter plate was attached to the bottom of the rod to assist in centering the rod and to provide anchorage. To obtain tight joints, the rod was finger tightened and then an additional one-quarter turn was applied using wrenches.

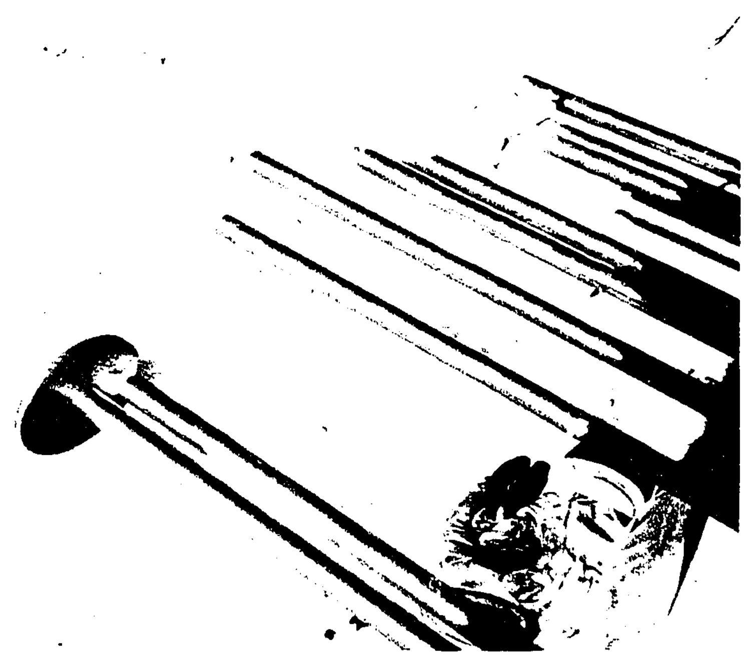


Figure 3-8 Type 316 Stainless Steel Rod and Steel Plate Attached to the Bottom of the Rod

5. Two sections of the augers were pulled up with no rotation to keep the hole clean and prevent caving of the borehole.

6. A temporary PVC pipe was placed over the steel rod. The purpose of the temporary PVC pipe was to prevent concrete that was poured at the next step from adhering to the steel rod.

7. Concrete was prepared and tremied through the hollow stem of the auger string to the bottom of the hole to anchor the steel rod. A total of approximately 3 meters of the concrete was filled. The concrete was allowed to cure overnight to provide good anchorage for the steel rod.

8. The sleeves that were to be placed over the steel rod were filled with multi-purpose grease. The temporary PVC pipe was pulled out of the borehole and the grease-filled sleeves were then placed over the steel rods and pushed down to the point where they rested on the concrete anchor.

9. The grease was injected under pressure into the annular space between the rod and sleeve. The sleeve was lifted slightly to minimize air voids at the bottom and then positioned into place. When the sleeve and the grease were placed, a 1.43-cm ID and 2.54-cm OD O-ring was placed around the rod, just below the top of the sleeve.

10. Two more sections of the augers were pulled up and 0.6 meters of Silica sand followed by 1.5 meters of a Silica sand/bentonite pellet mixture were placed into the annular space between the sleeve and the outside of the hole. These materials were above the concrete anchor to prevent bonding between the concrete and bentonite grout that was put in at the next step.

11. The remaining sections of the augers were pulled out of the borehole at this step. A 2 percent bentonite grout was prepared on site and tremied between the sleeve and the outside of the borehole up to the ground surface.

12. The soil was cleaned out of the 30.5-cm diameter surface hole around the benchmark sleeve to a depth of 0.6 meters. A locking cover with a watertight seal was installed in place with concrete. The joint between the cover and the concrete was sealed.

13. The completed benchmark and cover was set approximately 0.2 meter above the existing ground surface. A 1-meter square concrete pad was placed to surround the benchmark cover (see Figure 3-9). The surface of the concrete pad was finished with a 10 percent slope to drain water away from the benchmark cover. The surface was regraded to a 10 percent slope such that it slopes back to the original ground surface. The removed sod was replaced and the site was cleaned up.

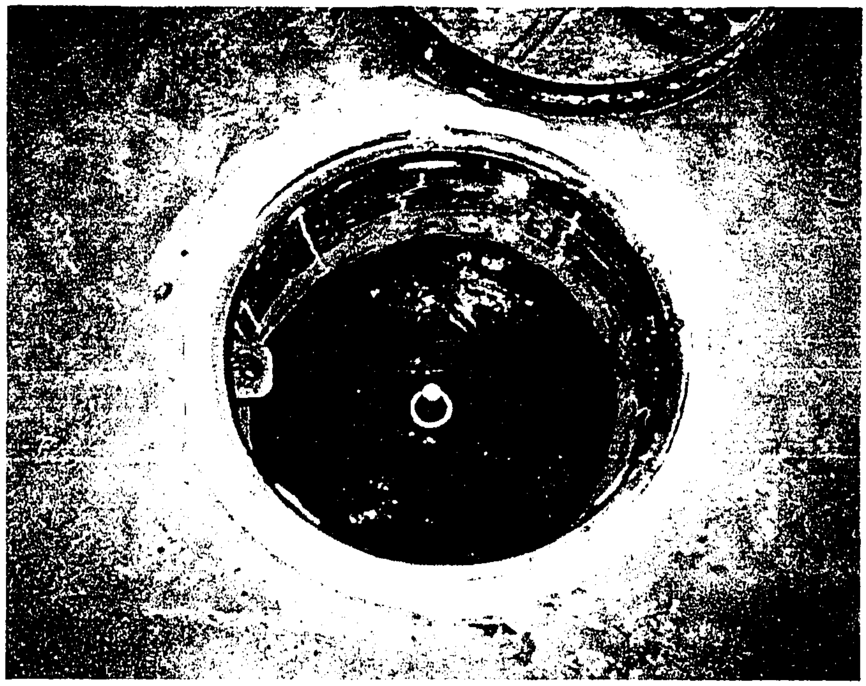


Figure 3-9 Completion of the Deep Benchmark

3.4.1.5 Verification of Deep Benchmark Depth

Laboratory testing was performed on samples of the soil core taken from the benchmark boreholes in order to verify that the anchorage zone was below the depth of potential heave. Laboratory tests including measurements of water content, dry density, and Atterberg limits. Consolidation-swell tests were also conducted. The soil and bedrock properties for selected samples are summarized in Table 3-6. The samples from the deepest depths swelled by amounts up to about 10 percent when inundated at an inundation pressure of 24 kPa. Swelling pressures as high as 1,340 kPa were observed.

The depths of potential heave at the actual locations where the benchmarks were installed were calculated following the procedure shown in Table 3-5. The calculated depths of potential heave for the benchmarks SMI-BM1 through SMI-BM3 are approximately 13.1, 16.5, and 27.3 meters, respectively.

Table 3-6 **Summary of Soil and Bedrock Properties from Boreholes SMI-BM1 through SMI-BM3**

Soil Type	Natural Water Content (%)	Natural Dry Density (Mg/m^3)	Atterberg Limits LL / PL(1) (%)	Consolidation-Swell Test(2) Percent Swell (%)	Swell Pressure (kPa)
Silty/Sandy Clay Fill	25.5	1.57	-	-	-
Silty Clay	-	-	-	-	-
Weathered Claystone	21.6 – 29.0	1.46 – 1.70	71/24	4.4	240
Sandstone	16.0 – 27.3	1.57 – 1.86	-	-	-
Claystone	13.4 – 31.0	1.44 – 1.94	33 – 69/17 – 35	0.2 – 9.9	37 – 1,340
Coal	42.0 – 48.6	1.00 – 1.10	-	-	-

Notes: (1) LL = Liquid Limit, PL = Plastic Limit
(2) Inundation Pressure, σ'_i = 24 kPa

For the benchmarks SMI-BM1 and SMI-BM2, the depths of the anchorages are 34 to 37 meters and 26 to 30 meters, respectively. The anchorage for SMI-BM1 is in sandstone and claystone and for SMI-BM2 it is in claystone. The depths of the anchorages are both greater than the calculated depth of potential heave.

The anchorage for benchmark SMI-BM3 is in interbedded silty claystone, siltstone and sandstone at depths from 26 to 30 meters. The effective overburden stresses are greater than the effective swelling pressures of the bedrock units throughout the entire depth, except for the claystone bedrock at depths between 26.0 and 27.3 meters. At that depth the constant volume swelling pressure was measured to be 814 kPa, and the overburden pressure is 530 kPa. Nevertheless, it is expected that for this limited zone, the effect of heave will be small.

3.4.1.6 Monitoring of Deep Benchmarks

The deep benchmarks have been monitored by Zylstra Baker Surveying, Inc. (ZBSI) since September 2000. A Zeiss digital barcode leveling system was implemented in the monitoring of the benchmarks. A Zeiss DiNi 11 automatic digital level with either a one piece 3 meter alloy invar bar code rod, a one piece 2 meter alloy invar bar code rod or a ½ meter invar strip was used to take survey readings. The digital bar code leveling system can measure precisely to 0.01 mm and has a standard deviation of 0.3 mm per 1 km of double run measurements. A tripod stabilizer was used as the turning points. For purposes of this monitoring, the benchmark SMI-BM1 has been taken as the primary reference point because of its installed depth and the soil expansion properties at that location. The performance of the benchmarks SMI-BM2 and SMI-BM3 were evaluated relative to SMI-BM1. The accuracy of the monitoring was evaluated from the least square adjustment by ZBSI using the standard deviations computed from the adjustment. Values of the accuracy of the monitoring ranged from 0 to 0.05 cm within one standard deviation or within a 95% confidence level.

Figures 3-10 and 3-11 present the results of the deep benchmark monitoring from September 2000 to June 2006 for the benchmarks SMI-BM2 and SMI-BM3, respectively. The actual accuracy of the measurements calculated by ZBSI using the least squares adjustment is included in Figures 3-10 and 3-11. As indicated in Figures 3-10 and 3-11, the benchmark SMI-BM2 was stable with respect to SMI-BM1, whereas the benchmark SMI-BM3 showed a potential movement of about 0.11 cm during the monitoring period.

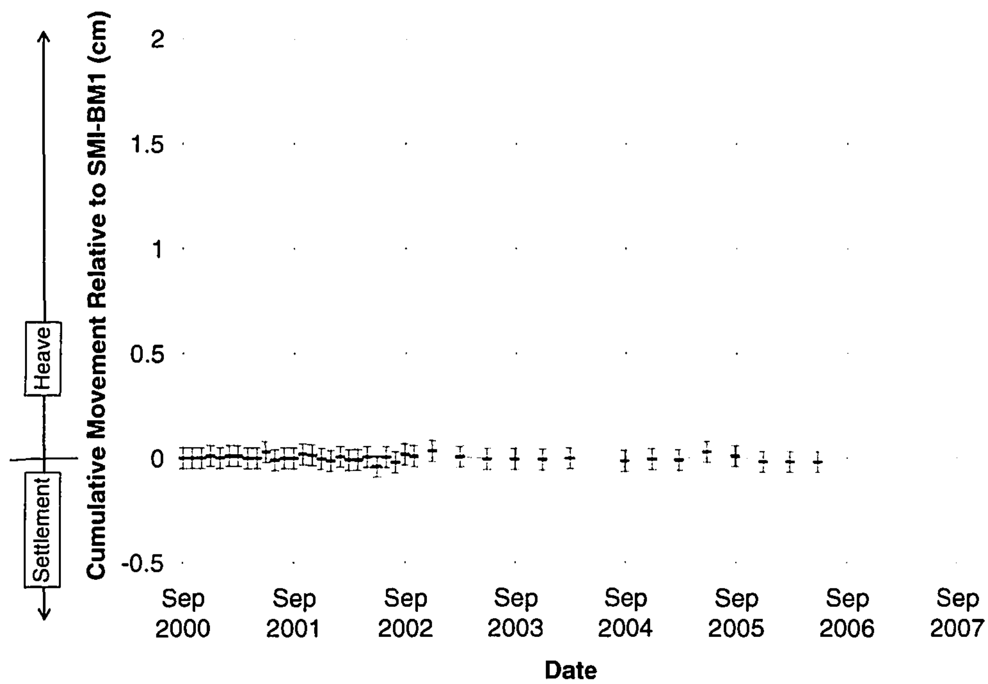


Figure 3-10 SMI-BM2 Deep Benchmark Monitoring Results

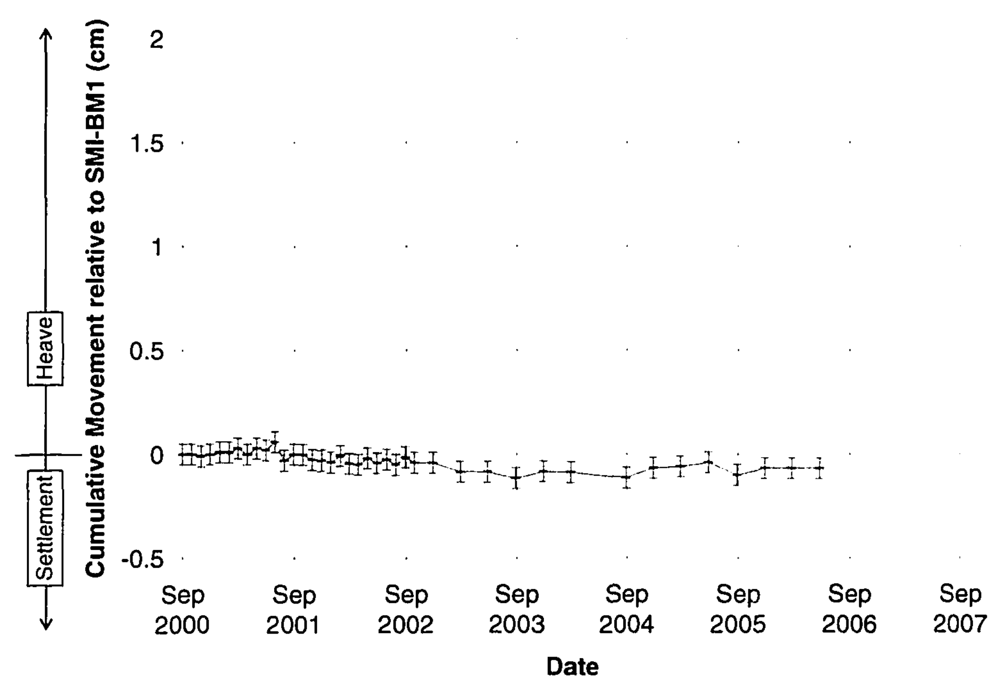


Figure 3-11 SMI-BM3 Deep Benchmark Monitoring Results

The monitoring results indicate that the deep benchmarks were stable during the monitoring period and are reliable to function as good references for elevation monitoring. It is concluded that the design and installation procedure for the deep benchmarks proposed herein provides an ideal opportunity to upgrade the quality of benchmarks installed in expansive soil areas. More precise surveys can be performed in the future providing deep benchmarks are properly designed and installed.

3.4.2 Monitoring of Slab and Pier Movement

ZBSI was contracted by the FAA on July 11, 2000 to perform digital monitoring of the slab and pier movement at the TRACON building. Surveying of the TRACON building was performed at 50 floor and 50 column locations. The locations of the survey points on the columns and floors are shown in Figure 3-12 and were determined to cover critical movement areas at the site. The column points consist of a metal plate attached to the column using a power actuated nailer. A stainless steel rod is attached to the metal plate. The monitoring datum point is rounded. The floor points consist of marked "X's" on various floor locations. In carpeted areas, an approximately 7.6-cm hole with an aluminum disc was placed in the concrete floor slab.

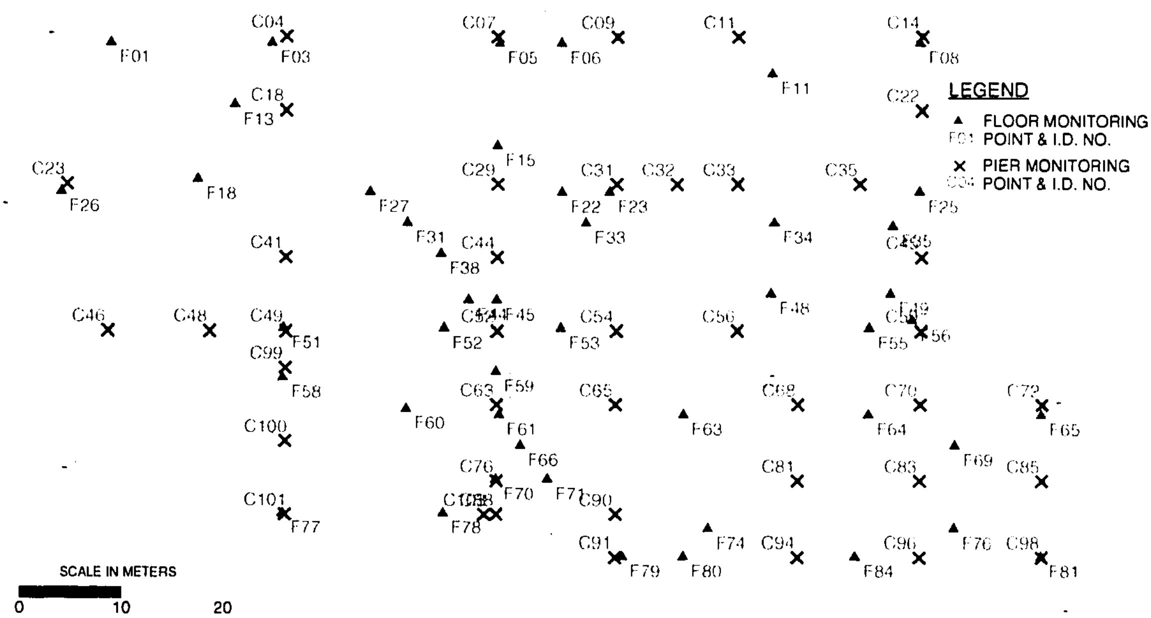


Figure 3-12 Locations of Floor and Column Monitoring Points at the TRACON Building

The survey was designed to achieve an accuracy of ± 0.5 mm as required by the FAA. The actual accuracy of the monitoring points was evaluated from the least square adjustment using the standard deviations computed from the adjustment. Values of the actual accuracy of the monitoring points ranged from 0.00 to 0.50 mm within one standard deviation or within a 95% confidence level. The baseline survey for the TRACON building was completed in September 2000. The elevation survey was performed monthly initially, and quarterly after December 2002. The results of the monitoring are presented in the following sections.

3.4.2.1 Floor Monitoring

Figure 3-13 presents the results of the floor monitoring for the TRACON building from September 2000 through June 2006. Figure 3-13 indicates that the TRACON floor continued to heave throughout the monitoring period. In June 2006, the maximum and average observed heave values of the floor monitoring points since beginning of monitoring were approximately 3.9 and 1.4 cm, respectively. The maximum heave occurred at Floor Monitoring Point F81 in the Environmental Wing (east corner of the TRACON building).

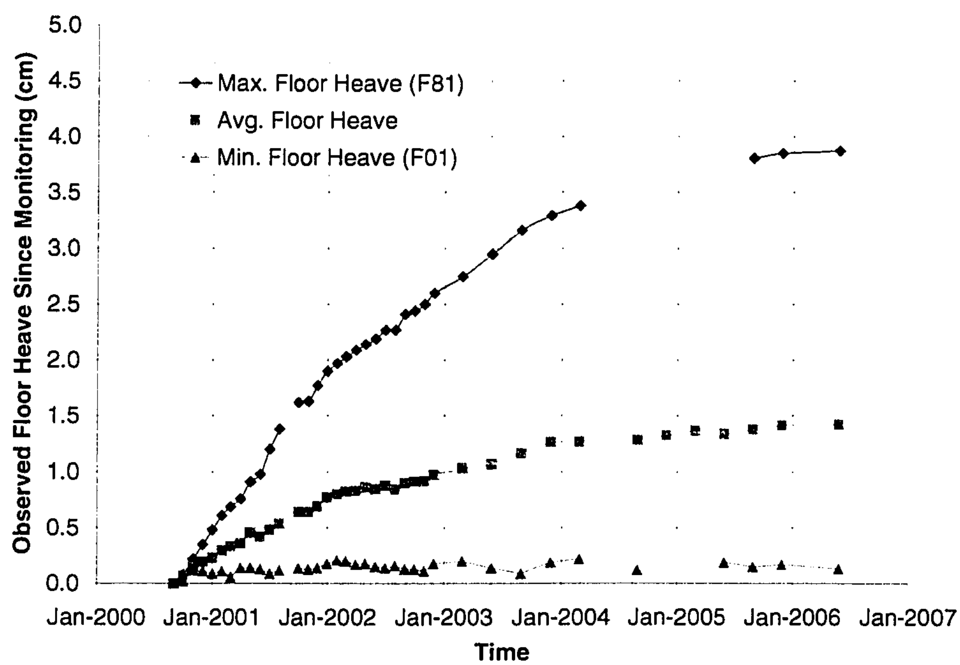


Figure 3-13 Observed Floor Heave Since Beginning of Monitoring

Contours of the observed floor heave since beginning of monitoring and since the time of construction, as of June 2006 are shown in Figures 3-14 and 3-15, respectively. In order to determine the floor heave that has occurred since the time of construction, the as-built elevations of the slab monitoring points were determined by ZBSI using the initial surveying performed by Bell Surveying and/or design drawings (ZBSI, 2001). Figures 3-14 and 3-15 indicate that as of June 2006 the maximum observed floor heave since beginning of monitoring and since the time of construction was 3.9 and 15.1 cm, respectively. The observed floor heave decreases toward the western portion of the building.

The rate of floor heave based on the September 2000 baseline readings through successive readings are shown in Figure 3-16. This figure indicates that the rates of floor heave increased initially and then decreased steadily to the present time. The maximum and average values of the floor heave rate in June 2006 were approximately 0.7 and 0.3 cm/year, respectively.

It should be noted that although the rates of heave are decreasing, the amount of heave is continuing to occur. Also, the year 2002 was one of the driest years on record in Denver.

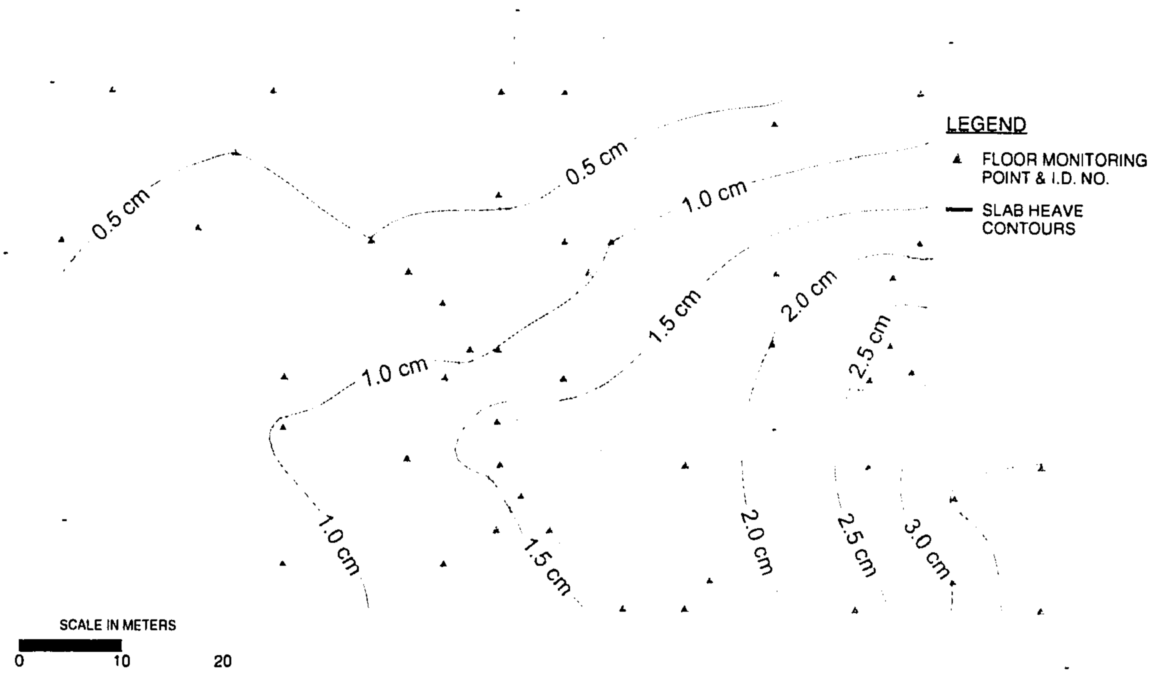


Figure 3-14 Contours of Observed Floor Heave from Initial Monitoring (Sept 2000) to June 2006

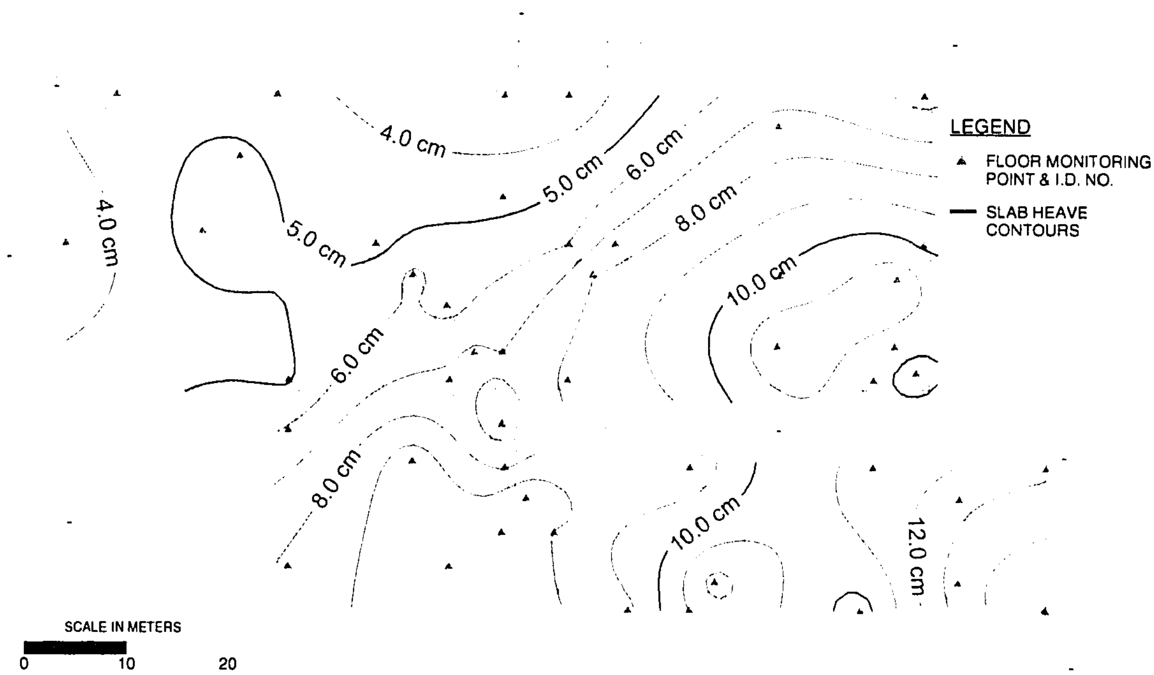


Figure 3-15 Contours of Observed Floor Heave from the Time of Construction (1991) to June 2006

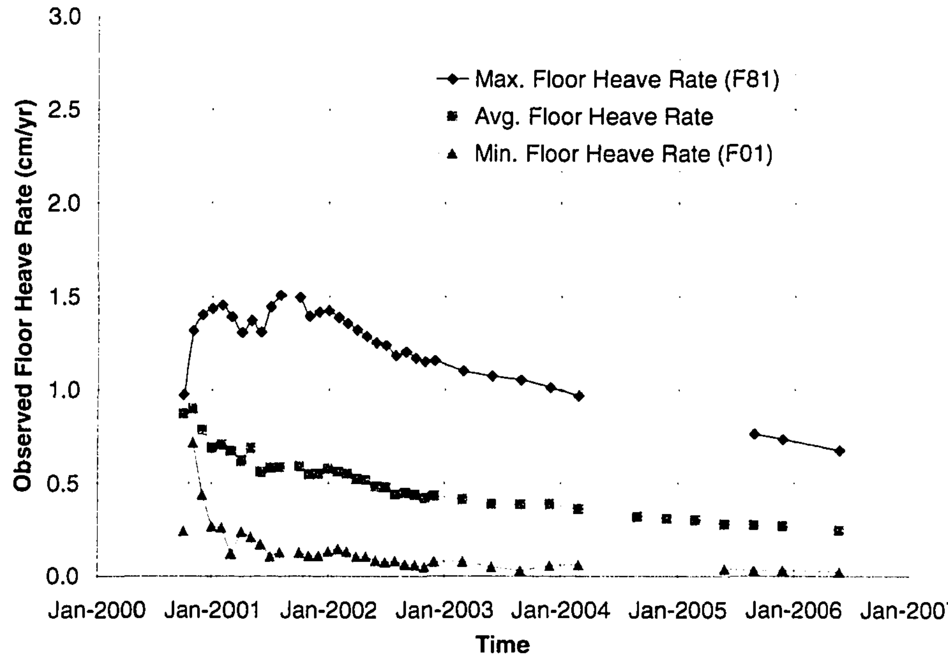


Figure 3-16 Observed Rate of Floor Heave Since Beginning of Monitoring

3.4.2.2 Pier Monitoring

The results of the pier monitoring for the TRACON building from September 2000 through June 2006 are shown in Figure 3-17. This figure indicates that the TRACON piers continued to heave during the monitoring period. The maximum and average heave values of the pier monitoring points since beginning of monitoring are approximately 3.9 and 1.5 cm, respectively. The maximum heave occurred at Pier Point No. C85 in the Environmental Wing (east corner of the TRACON building). This point is located at the point just next to Point F81 where the maximum slab heave was measured.

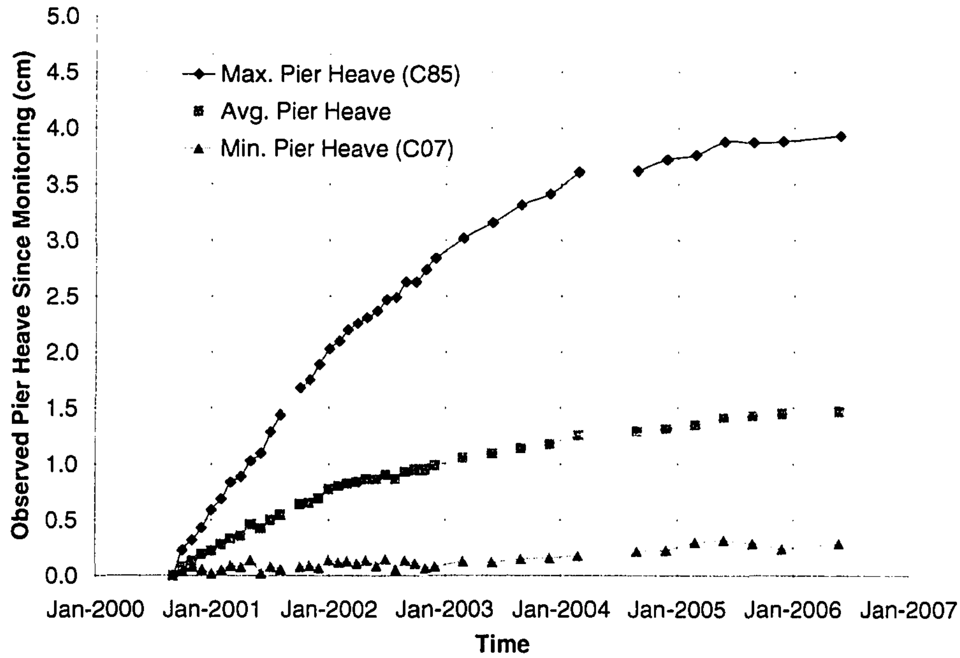


Figure 3-17 Observed Pier Heave Since Beginning of Monitoring

Contours of the observed pier heave as of June 2006 since beginning of monitoring and since the time of construction are presented in Figures 3-18 and 3-19, respectively. As for the floor heave, pier heave since the time of construction was calculated based on the as-built elevations of the pier monitoring points determined by ZBSI using the initial surveying performed by Bell Surveying and/or design drawings (ZBSI, 2001). Figures 3-18 and 3-19 indicate that the maximum observed pier heave as of June 2006 since beginning of monitoring and since the time of construction was 3.9 and 12.3 cm, respectively. As for the floor heave, the observed pier heave also decreases toward the western portion of the building.

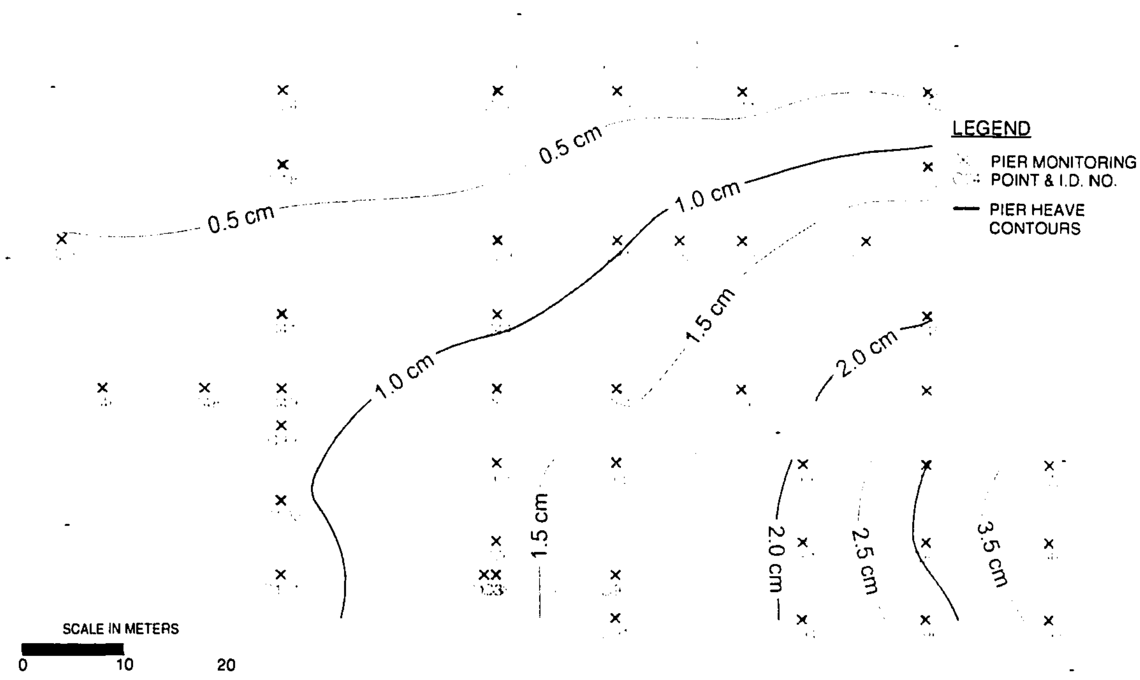


Figure 3-18 **Contours of Observed Pier Heave from Initial Monitoring (September 2000) to June 2006**

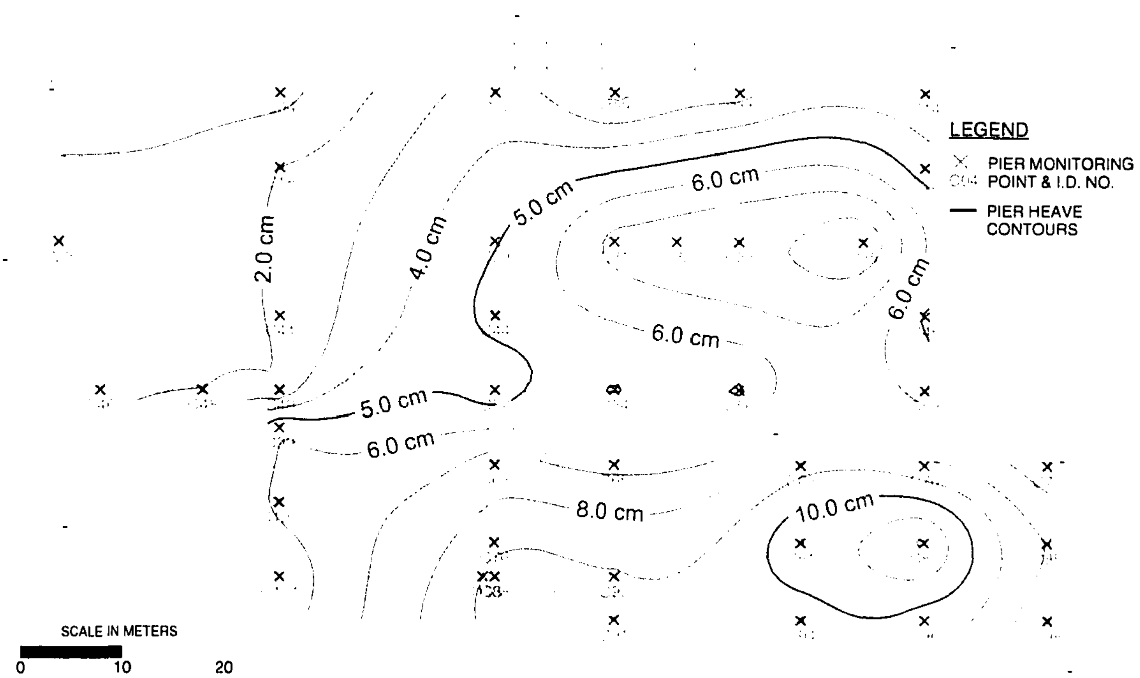


Figure 3-19 **Contours of Observed Pier Heave from the Time of Construction (1991) to June 2006**

Figure 3-20 shows the rate of pier heave for the TRACON building based on September 2000 baseline readings through successive readings. Figure 3-20 indicates that the rate of pier heave has decreased since the initiation of monitoring. The maximum and average values of the pier heave rate in June 2006 were 0.7 and 0.3 cm/year, respectively.

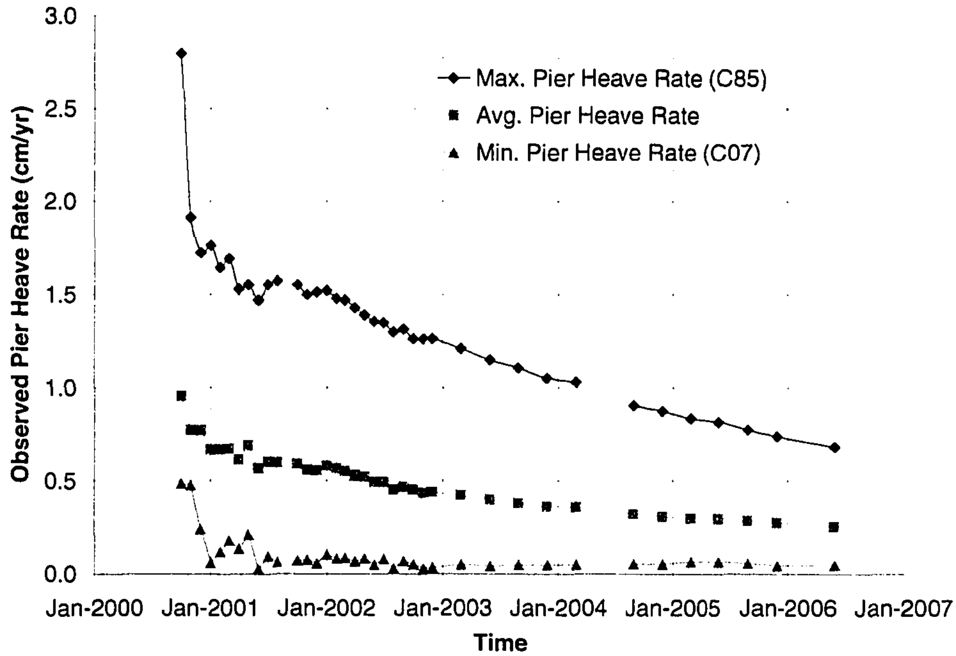


Figure 3-20 Observed Rate of Pier Heave Since Beginning of Monitoring

CHAPTER 4

LABORATORY TESTING PROGRAM

Laboratory testing was conducted on soil/bedrock samples obtained from two sources. One source is the TRACON site. Soil samples were obtained from the drilling of the boreholes around the TRACON building, as described in Section 3.1. Laboratory testing included measurements of natural water content, natural dry density, Atterberg limits, and specific gravity. Consolidation-swell tests were also performed. The results of the laboratory tests were used to perform the total heave prediction, as described in Chapter 7.

The other source of samples was obtained from two local sites in the Front range area of Colorado. The bedrock samples obtained from the local sites consist of two types of geological formations including the Denver and Pierre Shale Formations. For purpose of identification, the site located on the Denver Formation is designated as "Denver Site", and the site located on the Pierre Shale Formation is designated as "Pierre Shale Site."

Besides the laboratory tests described above, filter paper test and Fredlund SWCC test were conducted on the samples obtained from the Denver and Pierre Shale sites to determine the soil water characteristic curve as well as the relationship between water content and swell potential. The results of the laboratory testing were used in the water migration and rate of heave analyses, as described in Chapters 6 and 7. The Denver Formation is the same formation as that at the TRACON site. Although the samples were taken from a different site, it is believed that the SWCC and the functional relationship between water content changes and heave determined therefrom will be representative of the bedrock at the TRACON site. The laboratory testing was conducted for the soil samples obtained from the Pierre Shale site for comparison purposes.

A detailed description of the laboratory testing program for the soil samples from the two sources is provided in the following sections.

4.1 Soil Description and Index and Consolidation-Swell Properties

4.1.1 Soil Samples from TRACON Site

A total of thirty-seven exploratory borings were drilled by SMI/MFG at the TRACON site to investigate soil/bedrock strata, soil/bedrock properties, and local and regional ground water conditions. Subsoils at the site generally consist of 0.3 to 3.4 meters of silty/sandy clay fill, underlain by silty/sandy clay, weathered claystone, claystone bedrock, and sandstone bedrock to the maximum boring depth of 36.6 meters. Coal seams were also encountered in the bedrock. A detailed description of the soil and bedrock was presented in Section 3.1.

Laboratory testing was conducted on selected California (CA) samples obtained from the borings at the TRACON site to determine index and engineering properties of the soils and bedrock. The laboratory testing was conducted by Smith Geotechnical Engineering, Inc., Fort Collins, Colorado. The laboratory testing included water content, dry density, Atterberg limits, specific gravity, and consolidation-swell tests. The results of the laboratory tests are summarized in Table 4-1. The samples of claystone bedrock were classified as low plasticity clay (CL) or high plasticity clay (CH). The claystone exhibited high to very high swell potential.

Table 4-1 Summary of Soil and Bedrock Properties for Soil Samples from the TRACON Site

Soil Type	Natural Water Content (%)	Natural Dry Density (Mg/m^3)	Specific Gravity	Atterberg Limits	Consolidation-Swell Test[2]	
				LL / PL[1] (%)	Percent Swell (%)	Swell Pressure (kPa)
Silty/Sandy Clay Fill	4.0 – 24.4	1.55 – 1.92	-	34/14	0.4 – 0.8	50 – 60
Silty Clay	19.1 – 21.1	1.68 – 1.75	-	-	-	-
Weathered Claystone	19.9 – 28.8	1.49 – 1.76	-	37 – 90/ 18 – 27	4.3 – 8.4	290 – 530
Sandstone	11.5 – 19.9	1.68 – 1.91	-	NP	-	-
Claystone	7.4 – 31.5	1.30 – 2.08	2.66 & 2.71	37 – 87/ 18 – 26	3.0 – 10.2	290 – 1,400
Coal	20.3 – 40.8	0.88 – 1.57		-	-	-

Notes: (1) LL = Liquid Limit, PL = Plastic Limit
(2) Inundation Pressure, σ'_i = 24 kPa

4.1.2 Soil Samples from Denver and Pierre Shale Sites

Claystone samples obtained from the Denver and Pierre Shale sites were used for laboratory testing as part of this research. The samples of the claystone of the Denver Formation were obtained from drilling with a continuous core sampler at a site in Denver, Colorado. The boring log of the claystone of the Denver Formation indicates that the claystone bedrock was slightly moist and consisted of yellowish brown, hard claystone with some oxidation and occasional silty claystone lenses.

The samples of the claystone of the Pierre Shale Formation were obtained from drilling with a continuous core sampler at a site in Littleton, Colorado. This site is located at the Designated Dipping Bedrock Area of the Jefferson County (Jefferson County GIS, 1997). In this area, beds dip toward the east or northeast at approximately 30 to 90 degrees from the horizontal. The boring log of the claystone taken from the Pierre Shale Formation indicates that the claystone bedrock was slightly moist and consisted of light olive brown and gray claystone with oxidation along the bedding planes.

Laboratory testing including water content, dry density, Atterberg limits, Standard Proctor compaction tests, and consolidation-swell tests was conducted on selected CA samples obtained from the borings to provide basic engineering properties of the claystone bedrock. The laboratory testing of the samples from both the Denver and Pierre Shale Formations was conducted in the geotechnical engineering laboratory at Tetra Tech, Inc., Fort Collins, Colorado. The results of the laboratory tests are provided in Table 4-2. The samples of the claystone of both the Denver and Pierre Shale Formations were classified as high plasticity clay (CH). They exhibited moderate to very high swell potential.

Table 4-2 **Summary of Bedrock Properties for Soil Samples from the Denver and Pierre Shale Sites**

Formation of Claystone Bedrock	Natural Water Content (%)	Natural Dry Density (Mg/m³)	Standard Proctor[1] $\rho_{dmax.}$ / $w_{opt.}$ (Mg/m³ / %)	Atterberg Limits	Consolidation-Swell Test[3]	
				LL / PL[2] (%)	Percent Swell (%)	Swell Pressure (kPa)
Denver	20.1 – 26.5	1.54 – 1.67	1.55 / 24.2	56 – 68/ 32 – 43	6.5 – 7.4	1,150 – 2,550
Pierre Shale	15.2 – 16.3	1.81 – 1.92	1.61 / 22.3	60 – 61/ 41 – 42	3.1 – 5.7	710 – 1,300

Notes: (1) $\rho_{dmax.}$ = maximum dry density, $w_{opt.}$ = optimum water content
(2) LL = Liquid Limit, PL = Plastic Limit
(3) Inundation Pressure, σ'_i = 48 kPa

4.2 Filter Paper Test and Fredlund SWCC Test

Filter paper test and Fredlund SWCC test were conducted using the bedrock samples remolded from the continuous core samples obtained from the drillings at the Denver and Pierre Shale sites. The tests were conducted to determine the soil water characteristic curve as well as the relationship between water content and swell potential for the water migration and rate of heave analyses, as described in Chapters 6 and 7. A detailed laboratory testing program including sample preparation, equipment used in the tests, laboratory testing procedures, and the results of the laboratory testing is discussed in the following sections.

4.2.1 Specimen Preparation

A variety of methods have been developed for reconstituting soil specimens in the laboratory. The moist tamping method is one of the successful methods proposed for preparing "identical" soil specimens (Mulilis, et al., 1975). The early implementations of the moist tamping method involved the soil specimen being prepared using a number of layers of equal dry weight and volume wherein each layer was being compacted to the same target density. Mulilis, et al. (1975) found that this could result in the lower portion of the specimen becoming denser than the desired specimen density because the compaction of each overlying layer also resulted in the densification of underlying layers.

Ladd (1978) proposed an "undercompaction" concept to improve this moist tamping method. With this technique, the lower layers are initially compacted looser than the final desired density by predetermined amounts so that the final density of each layer is equal to the target density, even with the effects of compaction of successive overlying layers. The difference in density between successive layers is defined as "percent undercompaction" (Ladd, 1978). It was shown that the undercompaction concept could create more uniform moist-tamped specimens (Ladd, 1978; Frost and Park, 2003).

Noorany (1992 and 2005) noted that the undercompaction concept was impractical especially when the height of the soil sample was small (Noorany, 1992 and 2005). Noorany (2005) proposed to prepare a soil sample with a number of layers of equal soil weight and volume when compacting each layer into a compaction mold, as shown in Figure 4-1. Noorany (2005) found that this modified moist tamping method was successful in preparing uniform soil specimens for the oedometer test.

The modified moist tamping method was utilized to prepare and compact soil specimens for the laboratory testing. The soil specimens were prepared for testing by compacting them to 100% of the maximum Standard Proctor dry density at a water content 3% less than the optimum water content. The sample rings used for the test have dimensions of 6.4 cm in diameter and 3.1 cm in height. The steel plate shown in Figure 4-1 is 0.5 cm in height. Therefore, the soil sample at the completion of compaction within each ring was 2.5 cm in height. In addition, four (4) layers with each layer being 0.6 cm in height were selected for the compaction process in this research. The laboratory data worksheets for the sample preparation are included in Appendix A.

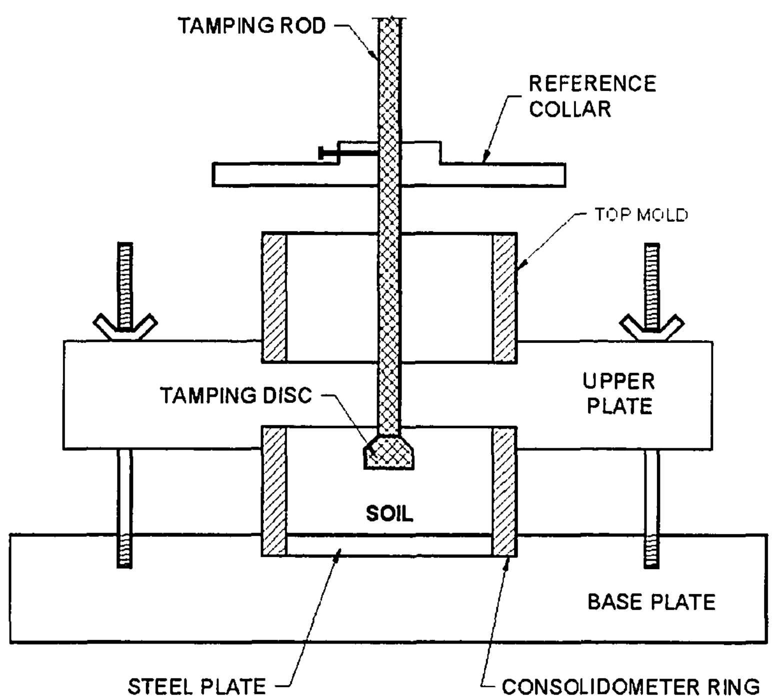


Figure 4-1 Schematic of Moist Tamping System (modified from Noorany, 2005)

The general procedure for the specimen preparation is provided below.

1. The continuous core sample was air-dried and broken down with a mortar and pestle. The air-dry water content of the bulk sample was measured using at least two determinations.
2. The weight of water needed to adjust the water content of the bulk sample to 3% less than the optimum water content was determined. The water was added evenly to the soil sample, and the sample was moisture-cured overnight.

3. The water content of the bulk sample was checked to verify that the desired water content of the sample was reached. The water content was adjusted as necessary.
4. All the necessary parts of the equipment shown in Figure 4-2 were assembled to be used in preparing the soil specimen. Four tamping rods numbered 1 to 4 with decreasing lengths were designed to compact the sample to an appropriate height at each layer.

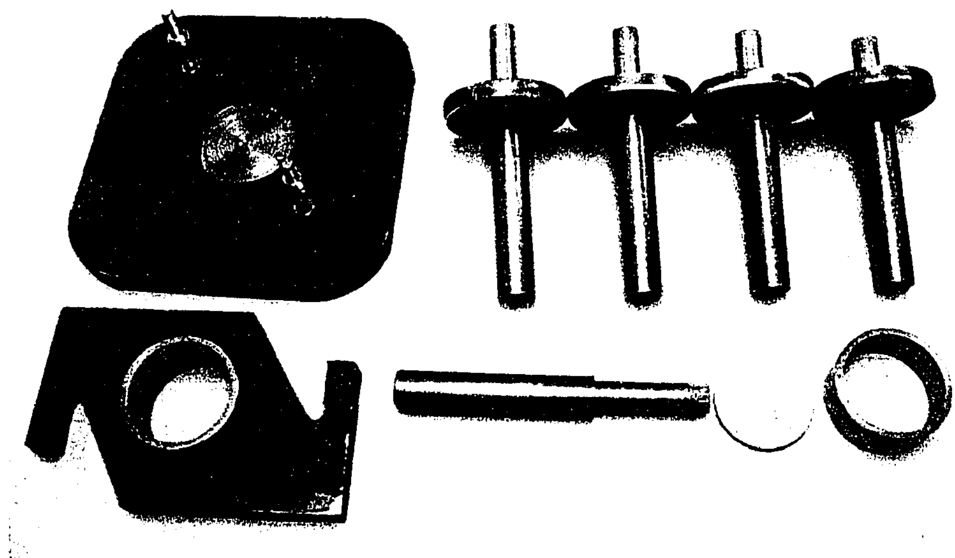


Figure 4-2 Moist Tamping Equipment Used in This Research

5. The volume of material needed for the compaction was calculated based on the measurements described above.
6. The total wet weight of material required for sample preparation was determined. The sample was divided into four parts.
7. The amount of the material for the first layer was placed into the consolidometer ring and compacted with the No. 1 tamping rod. Initially, a light tamping force was used to distribute and seat the material uniformly in the ring. The force was then gradually increased until the reference collar attached to the tamping rod uniformly hit the top of the top mold.
8. Steps 6 and 7 were repeated until the last layer was in place. The soil specimen was ready to be used in the laboratory testing.

4.2.2 Equipment Used in the Testing

4.2.2.1 Fredlund SWCC Device

The Fredlund SWCC device was utilized to determine the soil water characteristic curve as well as the relationship between water content and swell potential for the claystone bedrock. A photo of the Fredlund SWCC device used in this study is shown in Figure 4-3. The sample rings used for the test have dimensions of 6.4 cm in diameter and 2.5 cm in height. The Fredlund SWCC device was calibrated to account for compressibility of the device, filter paper, and porous stone, as discussed in Section 2.3.2.2. Detailed information regarding the Fredlund SWCC device is presented in Section 2.2.2.1.

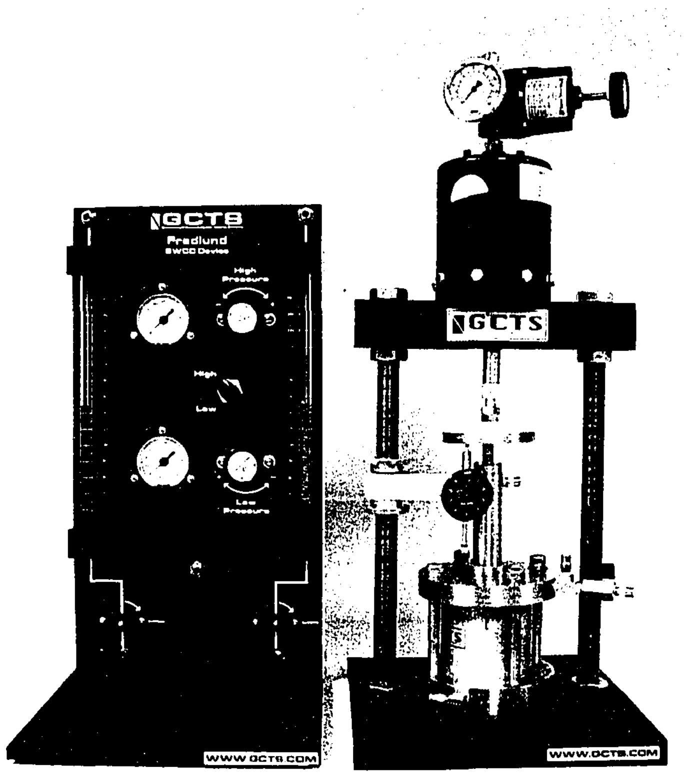


Figure 4-3 Photo of Fredlund SWCC Device with Loading Frame

4.2.2.2 Filter Paper Equipment

The filter paper equipment was utilized to determine the soil water characteristic curve of the entire soil suction range for the claystone bedrock. Figure 4-4 shows the filter paper equipment including filter papers, an analytic balance, a moisture can, a brass ring, a pair of tweezers, and a plastic jar that was used in this study. Whatman No. 42 filter paper was used in this research. The weight of the filter paper was measured to the nearest 0.0001 g during the test. Detailed information regarding the filter paper technique is provided in Section 2.2.2.2.

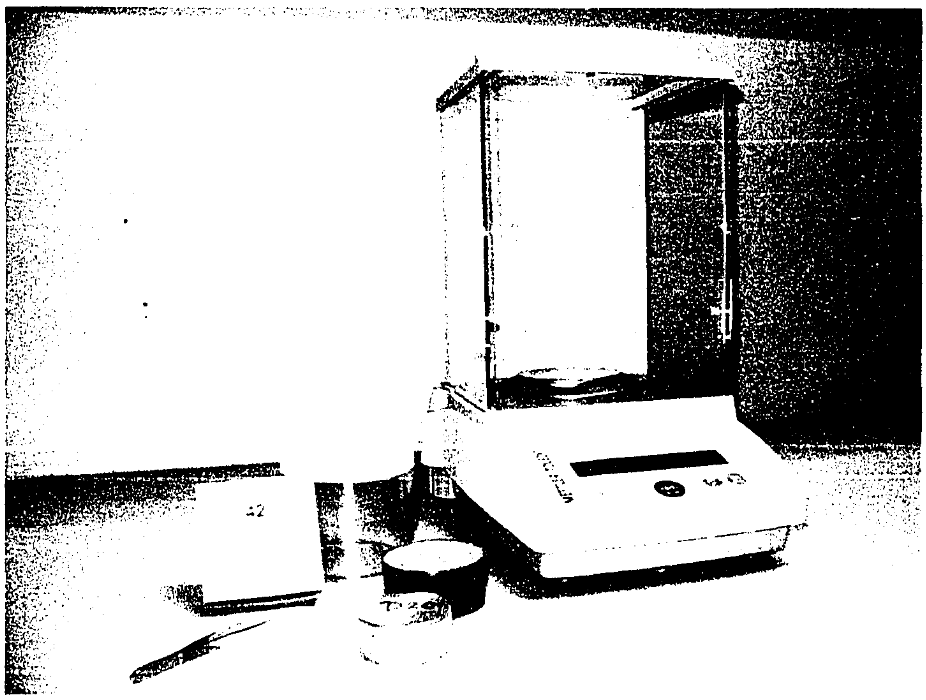


Figure 4-4 Photo of Filter Paper Test Equipment

4.2.3 Laboratory Testing Procedures

4.2.3.1 Procedure for Determination of Filter Paper Calibration Curve

Since the accuracy of the filter paper method is dependent on its water content-suction relationship, the calibration procedure for the filter paper is very important. ASTM D5298-94 recommends that a calibration curve applicable to a specific filter paper be obtained before running the filter paper test. In addition, as described in Section 2.2.2.2, differences in the calibration curve may exist even for the same brand of filter paper. The calibration test for the Whatman No. 42 paper used in this research was performed using sodium chloride (NaCl) salt solutions as an osmotic suction source. Salt concentrations from 0.001 to 2.700 molality were prepared and two filter papers were placed above the salt solutions in sealed containers. Figure 4-5 shows a photo of the calibration test adopted in this research.

Figure 4-5 Photo of Filter Paper Calibration Test

The sealed containers of filter papers and salt solution were put in an insulated chest where a constant temperature of approximately 23.3°C was kept during the equilibration process. An equilibration period of either two or three weeks was used to check the sensitivity of the test to the time for equilibration. The procedure that was adopted for the calibration test is as follows:

1. Filter papers selected for testing were dried at least 16 hours or overnight in the drying oven. The dried filter papers were placed in a desiccant jar over a desiccant after drying for storage until use.
2. Sodium chloride (NaCl) solutions were prepared at values of molality ranging from 0.001 to 2.700.
3. A 400 ml plastic jar was filled with approximately 250 ml of a solution of known molality of NaCl. Then, a small plastic cup was inserted into the plastic jar to serve as a support for the filter papers.
4. Two filter papers were placed on the top of the plastic cup. The plastic jar was sealed tightly with electrical tape to ensure air tightness.
5. Steps 3 and 4 were repeated for each NaCl concentration.
6. The plastic jars with different NaCl concentrations were placed into the insulated chest. After two or three weeks of equilibration time, the water content of the filter paper was measured. The procedure followed for the filter paper water content measurement is discussed in Section 4.2.3.3.
7. The values of osmotic suction for the solutions were calculated using the osmotic coefficients obtained from Hamer and Wu (1972). The calibration curve was established using the calculated osmotic suction and the measured filter paper water content.

4.2.3.2 Procedure for Determination of Equilibration Time for Filter Paper Test

ASTM D5298-94 states that "equilibration of suction between the soil, filter paper and air in the closed container is the desired result of the equilibration period. It must be recognized that the equilibration process is dependent upon the initial suction of the soil, initial relative humidity of the air, soil mass and space in the container. The seven day period is sufficient for conditions normally involved in soil mechanics; however, under many conditions equilibration will be completed more quickly." Research by others presented in Table 2-4 indicates that the equilibration time could be more than 7 days depending on suction source, measured suction type, material type, water content of soil specimen, number of filter papers used, and so on. Therefore, the equilibration time for performing the filter paper test on the remolded claystone samples was evaluated.

The procedure that was adopted for determining time needed for equilibration is provided as follows:

1. Filter papers were dried at least 16 hours or overnight in the drying oven. The dried filter papers were stored in a desiccant jar over a desiccant.
2. Claystone samples were compacted in the oedometer rings using the modified moist tamping method. Samples were compacted to 100% of the maximum Standard Proctor dry density at volumetric water contents ranging from 13.6 to 44.4%.
3. Soil specimens were placed into a plastic specimen container having a resealable lid. Eight filter papers were removed from the desiccator and immediately placed over the samples. The filter papers were isolated from the samples by inserting screen wire between the filter papers and the samples.
4. The lid of the container was put in place and sealed with electrical tape. The container was placed in the insulated chest to minimize temperature fluctuations.
5. Steps 3 and 4 were repeated for the samples compacted at different volumetric water contents.
6. At various increments of time, a pair of tweezers was used to transfer each filter paper from the specimen container into an aluminum weighing can. The water content of the filter paper was measured following the procedure described in Section 4.2.3.3. The corresponding total suction of the filter paper was determined using the calibration curve for that paper.
7. The total suction measured for each filter paper was plotted as a function of the period of time for which the filter paper was exposed to the soil.

4.2.3.3 Procedure for Determination of Soil Water Characteristic Curve

The SWCC of a soil is hysteretic. Therefore, depending on whether the process being simulated in the field is a wetting or drying process, an appropriate wetting or drying curve needs to be determined for the soil. Heaving of expansive soils/bedrock is a wetting process. Consequently, a wetting curve should be utilized in simulations of the migration of water in the subsoils/bedrock for modeling heave phenomena. This research was focused on an evaluation of the wetting curves of the claystone of the Denver and Pierre Shale Formations.

The filter paper method and Fredlund SWCC device were adopted to determine the soil water characteristic curves of the claystone of the Denver and Pierre Shale Formations. The filter paper method was used in accordance with ASTM D5298-94 to obtain the soil water characteristic relationship for a soil suction range of approximately 1 to 175,000 kPa. This range corresponds to a pF of 1.01 to 6.25. The Fredlund SWCC device was used in accordance with the GCTS Operating Instructions (GCTS, 2004) and ASTM D6836-02 to obtain the soil water characteristic relationship for a soil suction range of 2 to 900 kPa. The soil suction ranges from both methods overlapped from 2 to 900 kPa in order to verify the measured laboratory data from each other. The test procedures are summarized in the following sections.

4.2.3.3.1 Filter Paper Test

The filter paper method was adopted to measure total and matric suctions of soil specimens in accordance with both non-contact and contact techniques described in ASTM D5298-94. The soil specimen was compacted into a brass liner with an inside diameter of 6.2 cm following the procedures described in Section 4.2.1. The soil specimen was prepared to be 2.5 cm in height.

For determining the boundary wetting curve as shown in Figure 2-8, the soil specimen was initially air-dried in the laboratory. The weight and volume of the air-dried sample were measured. A filter paper test was performed on the air-dried sample to obtain a soil suction corresponding to the lowest water content of the sample. At the completion of the first filter paper test, water was added to the soil specimen to obtain a desired water content of the sample for the next filter paper test. The values of water content of the sample were increased at intervals of approximately 5%. The wetting curve test continued until the last desired water content of the soil specimen was reached. Measurements of the weight and volume of the sample at equilibrium were taken throughout the test.

The step-by-step procedure for measuring the boundary wetting curve by using the filter paper technique is discussed below.

1. Filter papers selected for testing were dried at least 16 hours or overnight in the drying oven. The dried filter papers were stored in a desiccant jar over a desiccant.
2. Two samples were compacted to the desired initial stress state conditions using the modified moist tamping method described in Section 4.2.1. The samples were placed on a glass plate for several days until a minimum water content of the samples was reached. The weight and volume of each sample were measured.
3. For the measurement of matric suction, three stacked filter papers were "sandwiched" in between the soil specimens (refer to Figure 4-6). The diameter of the outer filter papers was 6.2 cm, and the diameter of the center filter paper was 5.1 cm. The outer filter papers are slightly larger in diameter than the center filter paper to prevent soil contamination of the center filter paper used for analysis of the matric suction. The samples were sealed together with electrical tape after the placement of the stacked filter papers to ensure a close contact between the filter papers and the samples.

4. For the measurement of total suction, the soil specimens were placed into a plastic specimen container having a resealable lid. Three filter papers were removed from the desiccator and immediately placed over the samples. The filter papers were isolated from the samples by inserting screen wire between the filter papers and the soil samples. The lid of the container was put in place and sealed with electrical tape. Figure 4-7 shows the sample setting for the filter paper test.

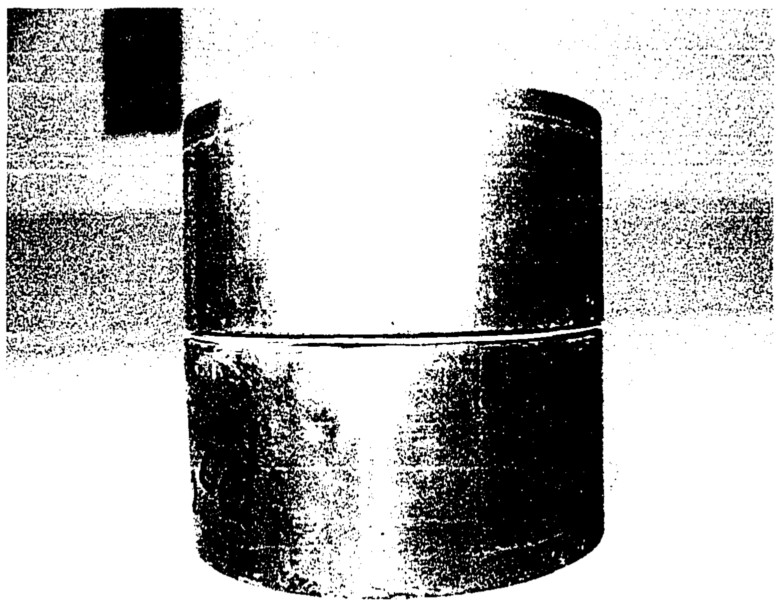


Figure 4-6 Photo of Soil Specimens for Matric Suction Measurement

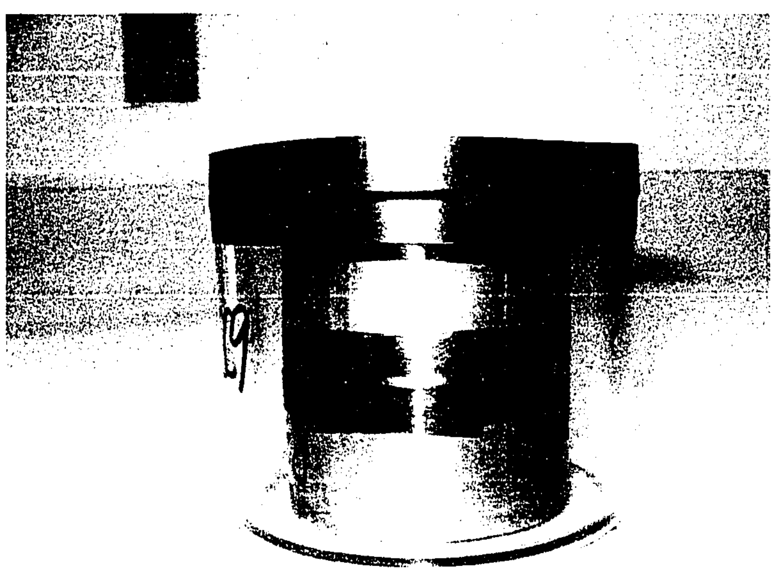


Figure 4-7 Photo of Sample Setting for Filter Paper Test

5. The plastic container was placed into the insulated chest to minimize temperature fluctuations. The system was left for equilibration. The time needed for equilibration was determined based on the results obtained in this research.
6. Five small aluminum weighing cans were weighed at room temperature. The room temperature was monitored and ranged from 22.2 to 23.3°C during testing.
7. At the end of the equilibration period, a pair of tweezers was carefully used to transfer each filter paper from the specimen container into an aluminum weighing can. The entire process was completed in 3 to 5 seconds to minimize moisture loss in the filter paper. Each aluminum weighing can with the filter paper was weighted to the nearest 0.0001 g. Then each aluminum weighing can with the filter paper was oven-dried at 105°C at least 12 hours or overnight.
8. After the filter papers were oven-dried, each aluminum weighing can with the filter paper was closed inside the oven. Each can was then removed from the oven and placed on a metal block for about 30 seconds to cool. The metal block acted as a heat sink and reduced the temperature variation during weighing. The oven-dried weight of each can with the filter paper was determined immediately after the 30 second cooling period. The filter papers were discarded and the weight of each can was measured immediately under a "hot" condition.
9. The weight and volume of each soil specimen were measured at the end of equilibration. Water was then added to each sample to raise its water content by 5%.
10. Steps 3 through 9 were repeated until the wetting process for the sample was completed.
11. At the completion of the wetting curve test, the soil specimens were oven-dried at 105°C at least 12 hours or overnight. The weight and volume of the dry samples were measured. The water content, total suction, and matric suction of the soil at each pressure increment were calculated.

4.2.3.3.2 Fredlund SWCC Test

The Fredlund SWCC device was utilized to obtain the soil water characteristic curve of the claystone of the Denver Formation for a soil suction range of 2 to 900 kPa. This soil suction range overlapped the range used in the filter paper tests to verify the measured laboratory data from each other. Similar to the filter paper test, the soil specimen was compacted to 100% of the maximum Standard Proctor dry density at a water content 3% less than the optimum water content. The soil specimen was compacted into a consolidometer ring with an inside diameter of 6.3 cm. The soil specimen was prepared to be 2.5 cm in height. For determination of the boundary wetting curve, the soil specimen was then air-dried until a minimum water content was reached in the laboratory. The weight and volume of the air-dried sample were measured.

The air-dried soil specimen was transferred to a ceramic stone placed in the pressure cell of the Fredlund SWCC device. The ceramic stone had an air entry pressure of 1,500 kPa (15 bars) such that only water and not air could pass through the ceramic stone. The bottom of the ceramic stone was maintained at atmospheric pressure by connecting the drain holes to two volume indicator tubes filled with water.

A desired air pressure was applied into the pressure cell. The difference between the applied air pressure and the water pressure is equal to the corresponding matric suction. In response to the applied suction the water from the volume indicator tubes moved in the soil specimen through the ceramic stone until the equilibrium was established. The water levels in the tubes showed the amount of water released and ceased to move once the equilibrium was attained. Following equilibrium, the water levels in the volume indicator tubes were recorded. It was possible for air to diffuse through the ceramic stone and collect on the bottom of the cell. Therefore, the diffused air was flushed out before reading the levels in the volume indicator tubes. The water content of the specimen was back-calculated using the volume indicator tube readings. The change in the height of the soil specimen was measured from the attached dial gauge (refer to Figure 4-8). This procedure was repeated for successive pressure decrements to obtain a series of data points on the wetting curve. The pressure values that were used were 900, 400, 100, 10, and 2 kPa (or 9, 4, 1, 0.1, and 0.02 bars). These pressure decrements produced a reasonable uniform distribution of values of volumetric water content. At the end of the wetting curve test, the soil specimen was removed from the cell and its water content and dry density were determined.

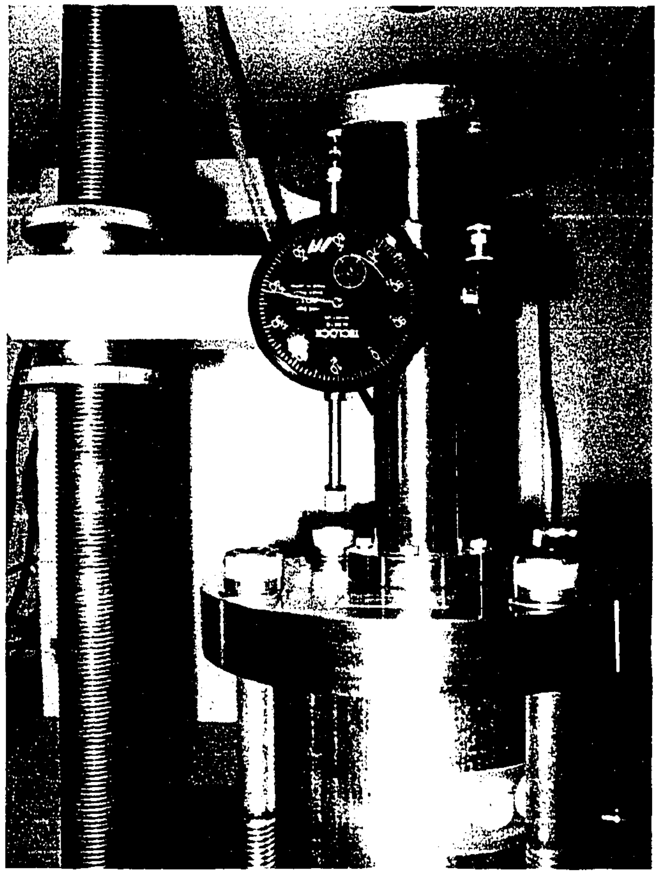


Figure 4-8 Photo of Sample Height Measurement Using the Fredlund SWCC Device

The step-by-step procedure for measuring the wetting SWCC by using the Fredlund SWCC device is provided below. The procedure is determined based on the combination of the procedures from the GCTS Operating Instructions (GCTS, 2004) and ASTM D6836-02.

1. A soil specimen was compacted to the desired initial stress state conditions using the modified moist tamping method described in Section 4.2.1. The soil specimen was placed on a glass plate for several days until a minimum water content of the

sample was reached. The weight and volume of the air-dried sample were measured.

2. The ceramic stone was saturated overnight before using. A ceramic stone was removed from water and mopped to a saturated surface dry (SSD) condition. The weigh of the SSD ceramic stone was measured.

3. The sample was transferred on to the SSD ceramic stone. The sample was examined to ensure a properly centered position of the sample on the ceramic stone. A piece of filter paper and a porous stone were placed on the top of the soil specimen. The filter paper was subjected to several loading and unloading cycles before use, as discussed in Section 2.3.2.2.2.

4. Water was added into the bottom plate of the pressure cell. The ceramic stone and the sample were carefully pressed into the bottom plate. The pressure cell was assembled.

5. The volume indicator tubes were filled with de-ionized water until about half full. A ball pump was used to expel any trapped air in the base until no air bubbles appeared in the tubes during flushing. Water columns should level out in both tubes after flushing. The initial readings in the volume indicator tubes were recorded with the date and time.

6. The first pressure of 900 kPa was applied to the cell. The compensator on the top plate automatically equalized the pressure exerted on the piston by the chamber pressure. The system was checked for any air leaks.

7. The water levels in the tubes and dial gauge readings were taken during the equilibration process. At least two tube readings, typically six to eight hours apart per day were taken. The readings were taken before and after flushing. When the tube readings did not change more than one division over a 12-hour period, the system was considered to have reached equilibrium and the next pressure increment was applied.

8. At the end of the last pressure decrement, the apparatus was disassembled, and the sample was taken out. The weight and volume of the sample were recorded. The sample was then placed in an oven overnight at 105 °C.

9. The ceramic stone was removed from the bottom plate of the device. The ceramic stone was brought to the SSD condition and the weight of the stone was measured. The difference between the initial weight and the final weight of the ceramic stone indicated if water was absorbed or released from the ceramic stone during the test. If the difference existed, the tube readings from the volume indicator tubes were corrected accordingly.

10. Once the dry weight of the sample was available, the water content and volume of the sample at each pressure increment were calculated.

4.2.3.4 Procedure for Determination of Relationship Between Water Content and Swelling Potential

In order to predict timewise variation of heave of the soil/bedrock, it is necessary to understand the relationship between the change in water content and the change in volume of the soil/bedrock. The relationship was determined for the claystone of the Denver Formation using the Fredlund SWCC device. The advantage of using the Fredlund SWCC device instead of the consolidometer to determine this relationship is that water content and volume change of the soil specimen were measured simultaneously during the test.

The soil specimens were remolded to 100% of the maximum Standard Proctor dry density at various values of initial volumetric water content using the modified moist tamping system and then placed in the Fredlund SWCC device. The values of initial volumetric water content that were used were 18, 23, 30, and 38%. A vertical load of approximately 10 kPa was applied on the top of the loading cap to ensure a close contact between the load shaft and the soil specimen. Water was then introduced into the device through the volume indicator tubes and the soil specimen began to swell upon wetting. Volume change and water content of the soil specimen were measured until completion of the swelling process.

A step-by-step procedure for performing the test is provided below. The procedure was determined based on the procedure recommended in ASTM 4546-03 but has been modified for running the test by using the Fredlund SWCC device.

1. A soil specimen was placed on the saturated high air entry pressure ceramic stone and the device was assembled by following Steps 2 through 5 in Section 4.2.3.3.2.

2. A vertical load of approximately 10 kPa was applied on the top of the load shaft to ensure a close contact between the load shaft and the soil specimen. After the application of the seating pressure, the dial gauge was adjusted for the initial reading. The initial readings of the dial gauge and the volume indicator tubes were taken. The soil specimen was ready for the saturation process.
3. Readings of the dial gauge and volume indicator tubes were taken after various elapsed times until the completion of the swelling process. The readings were taken at 0.1, 0.2, 0.5, 1.0, 2.0, 4.0, 8.0, 15.0, and 30.0 minutes and 1, 2, 4, 8, 24, 48, 72, etc., hours.
4. At the completion of the swelling process, the apparatus was disassembled, and the sample was removed. The weight and volume of the sample were recorded. The sample was then placed in an oven overnight at 105 °C. Once the dry weight of the sample was determined, the water content and volume of the sample at each stage were calculated.
5. Steps 1 through 4 were repeated for soil specimens with various initial water contents.

4.2.4 Results of Laboratory Testing

4.2.4.1 Filter Paper Calibration Curve

The filter paper calibration test for the Whatman No. 42 filter paper was conducted using the sodium chloride salt solutions by following the procedure described in Section 4.2.3.1. The calibration test was performed for either a 2 or 3 week equilibration period. The results of the calibration test are shown in Figure 4-9. The laboratory data worksheets for the calibration test are included in Appendix B.

Marinho (1994) concluded that the effect of equilibration time on total suction calibration depends on the imposed level of suction. As shown in Table 2-4, Marinho (1994) concluded that the lower the suction, the longer will be the equilibration time needed to achieve suction equilibrium inside the non-contact filter paper. The equilibration time for suction less than 100 kPa could be longer than 30 days. However, Figure 4-9 indicates that the data points for suction less than 100 kPa obtained from the 3 week equilibration period case are in close agreement with those from the 2 week equilibration period case. Therefore, it is suggested that a 2-week equilibration period for the calibration time is sufficient for the test.

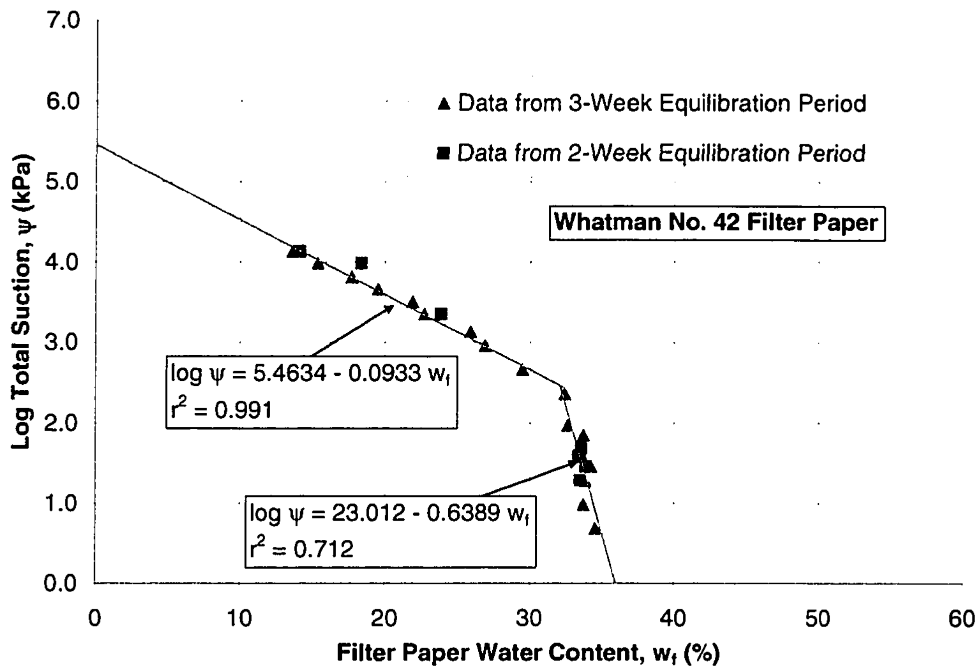


Figure 4-9 Filter Paper Calibration Curve for Total Suction Measurement

The equation for the total suction calibration curve was determined by log-liner regression and is also shown in Figure 4-9. The calibration curve shows the same bilinear relationship as that discussed previously with respect to Figure 2-11. By comparison of Figure 4-9 with Figure 2-10, it is clear that the calibration curve presented in ASTM D5298-94 should be used only for matric suction measurement. Figure 4-9 also shows that the value of r^2 for the low suction range (approximately less than 200 kPa) is less than that for the high suction range. This trend is consistent with the findings from other researchers (Bulut, et al., 2001 and Leong, et al., 2002). Bulut, et al. (2001)

explained the trend by saying that when relative humidity approaches 100 percent, the total suction becomes very sensitive to small changes in humidity.

4.2.4.2 Equilibration Time for Filter Paper Test

The time required for equilibration of the filter paper when measuring the suction of the claystone from the Pierre Shale Formation was evaluated by following the procedure described in Section 4.2.3.2. The claystone samples were remolded to 100 percent of the maximum Standard Proctor dry density at volumetric water content ranging from 13.6 to 44.4 percent. Eight stacked filter papers were placed over the claystone samples in a plastic specimen container. The filter papers were isolated from the samples by inserting screen wire with minimal surface area between the filter papers and the soil samples for the measurement of the total suction. The water content of each filter paper was measured at various time periods to determine the total suction vs. time relationship for the samples. In addition, the values of three oven-dried filter papers were measured to provide the initial point. The results are shown in Figure 4-10. The laboratory data worksheets for the time required to reach equilibrium are included in Appendix C.

The average value of the total suction for the oven-dried filter papers shown in Figure 4-10 is 223,870 ($10^{5.35}$) kPa. The data in Figure 4-10 indicate that equilibrium is achieved quickly for the samples with low water contents, whereas equilibrium is not attained even within the 7 days of the equilibration time recommended by ASTM for the samples with high water contents. Data analyses of the results are provided in Section 5.2.

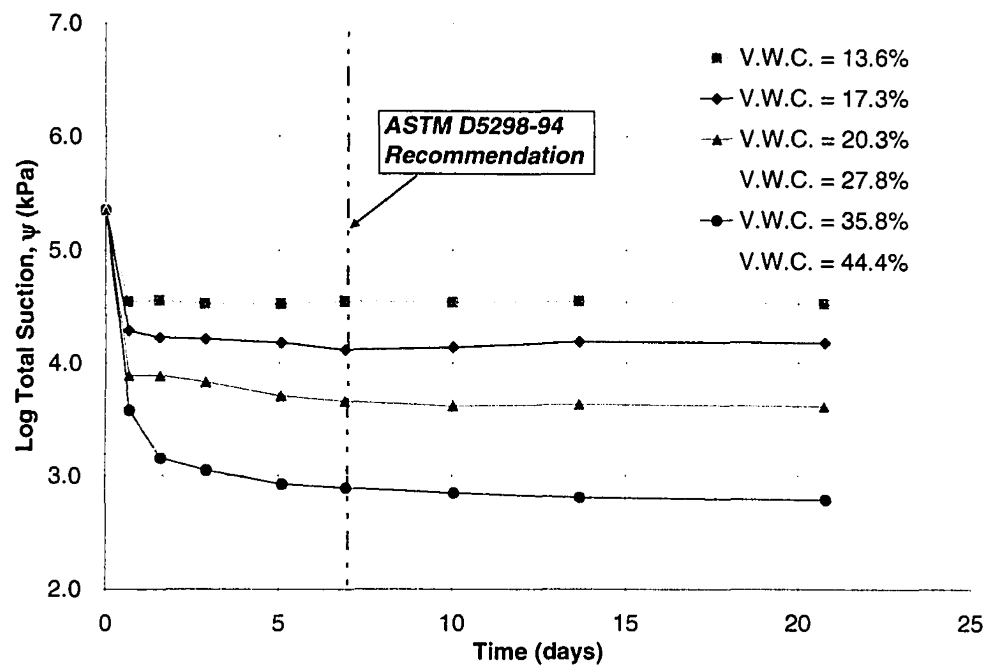


Figure 4-10 Time to Reach Equilibrium for Filter Paper Test

4.2.4.3 Soil Water Characteristic Curves

Soil water characteristic curves for the claystone of the Denver and Pierre Shale Formations were determined using the filter paper method and the Fredlund SWCC device. For determination of the boundary wetting curve, the soil specimens were air-dried to a minimum water content in the laboratory after compaction. The procedures for determining the boundary wetting curves were presented in Sections 4.2.3.3.1 and 4.2.3.3.2. In addition, five remolded samples of the Pierre Shale claystone were oven-dried to obtain the soil suction of the claystone at "zero" water content using the filter paper method. Appendices D and E include the laboratory test data sheets for determining the SWCCs using the filter paper method and the Fredlund SWCC device, respectively.

Figures 4-11 and 4-12 show the SWCCs for the claystone of the Denver Formation in terms of the total and matric suctions, respectively. The average values of the laboratory data are also shown in Figures 4-11 and 4-12. Figures 4-13 and 4-14 present the SWCCs in terms of volumetric water content and degree of saturation, respectively, from the average values of the laboratory data for the claystone of the Denver Formation. The osmotic suction curves shown in Figures 4-13 and 4-14 were computed by subtracting the matric suction values from the total suction values. Similarly, Figures 4-15 through 4-18 present the SWCCs for the claystone of the Pierre Shale Formation.

The soil suction at zero water content is used as a boundary parameter in heave prediction using the soil suction method proposed by McKeen (1992). The soil suction at zero water content has been found by McKeen (1992) to be near 174,385 kPa (6.25 pF). Fredlund and Xing (1994) introduced a correction function, $C(\psi)$, in their SWCC fitting equation to force the SWCC to pass through a soil suction of 10^6 kPa (7.0 pF) at zero water content. Leong and Rahardjo (1997) indicated that the soil suction value of 10^6 kPa at zero water content is supported by experimental data. Leong and Rahardjo (1997) stated that this value has no theoretical basis. The measured average total suction of the five oven-dried claystone samples shown in Figures 4-14 and 4-18 is approximately 245,000 kPa (6.40 pF) at oven-dry water content. The measured soil suction at oven-dry water content is closer to that found by McKeen (1992).

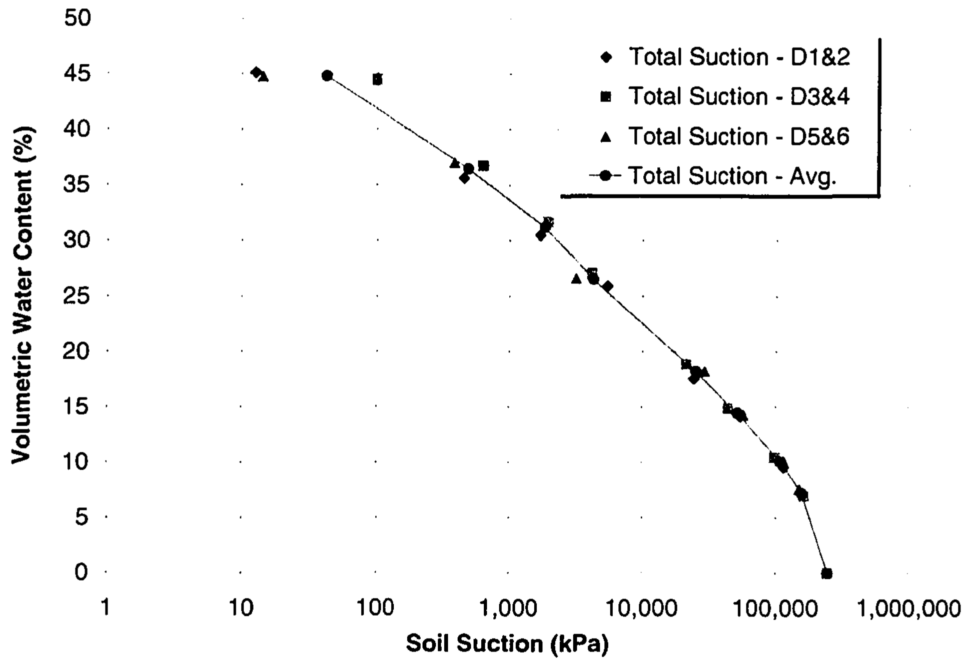


Figure 4-11 Wetting SWCC – Total Suction – Remolded Claystone of Denver Formation

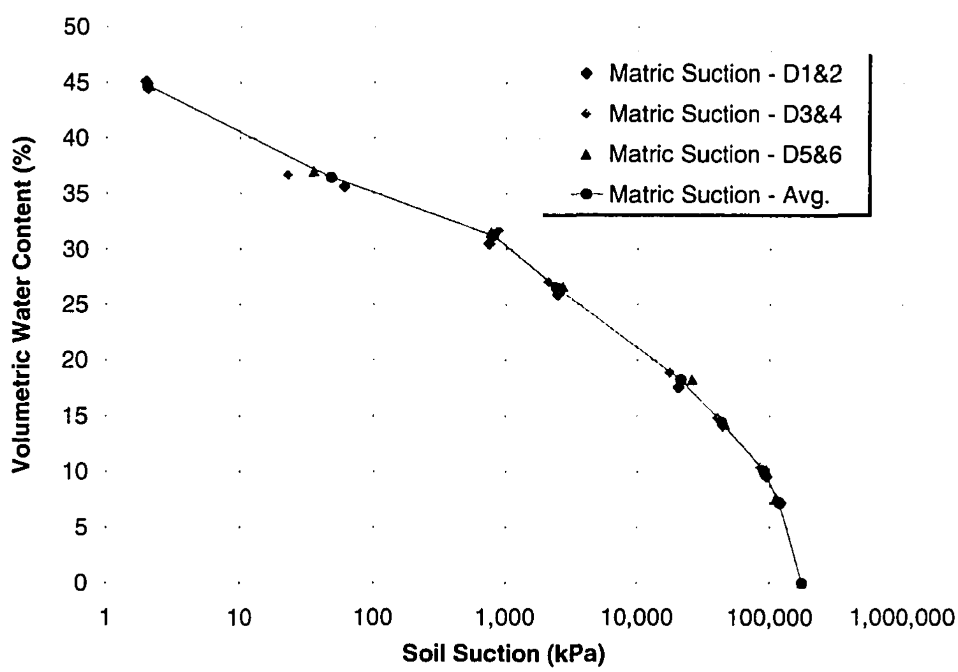


Figure 4-12 Wetting SWCC – Matric Suction – Remolded Claystone of Denver Formation

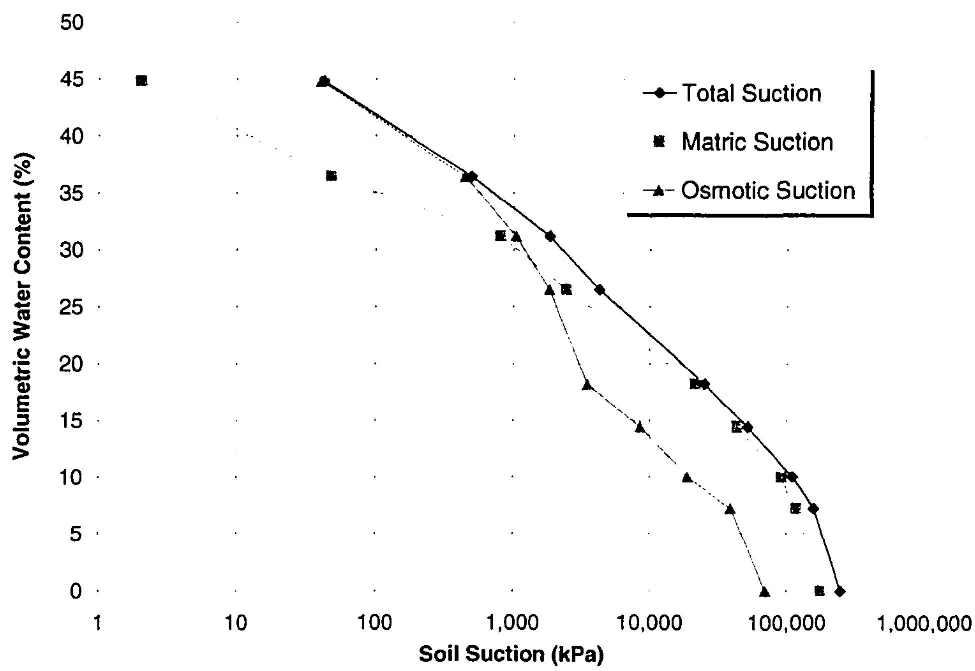


Figure 4-13 Wetting SWCC – Total, Matric, and Osmotic Suctions – Remolded Claystone of Denver Formation

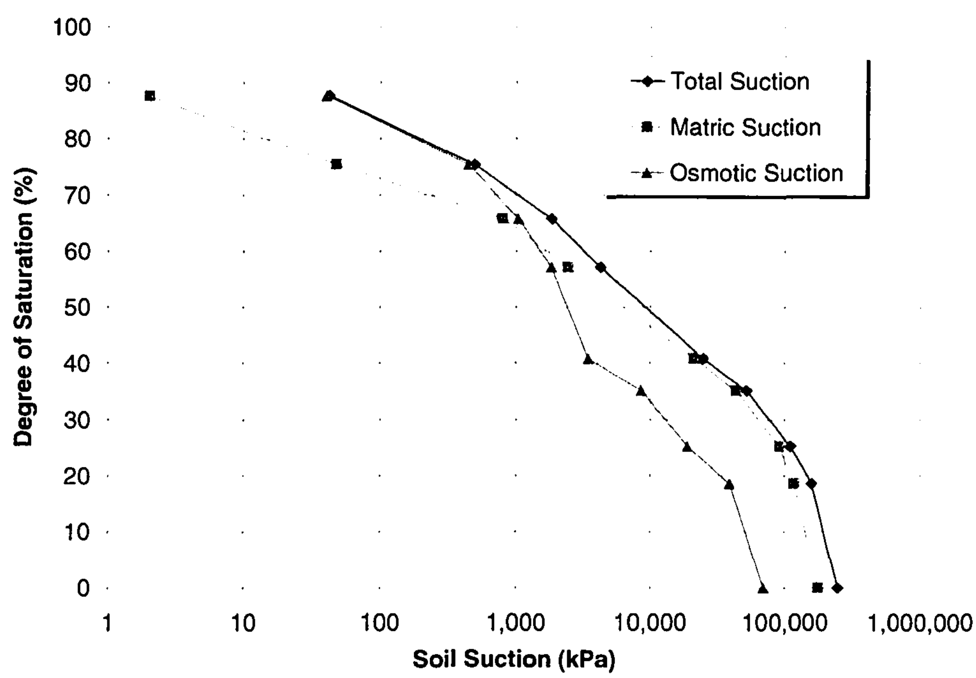


Figure 4-14 Degree of Saturation vs. Soil Suction – Total, Matric, and Osmotic Suctions – Remolded Claystone of Denver Formation

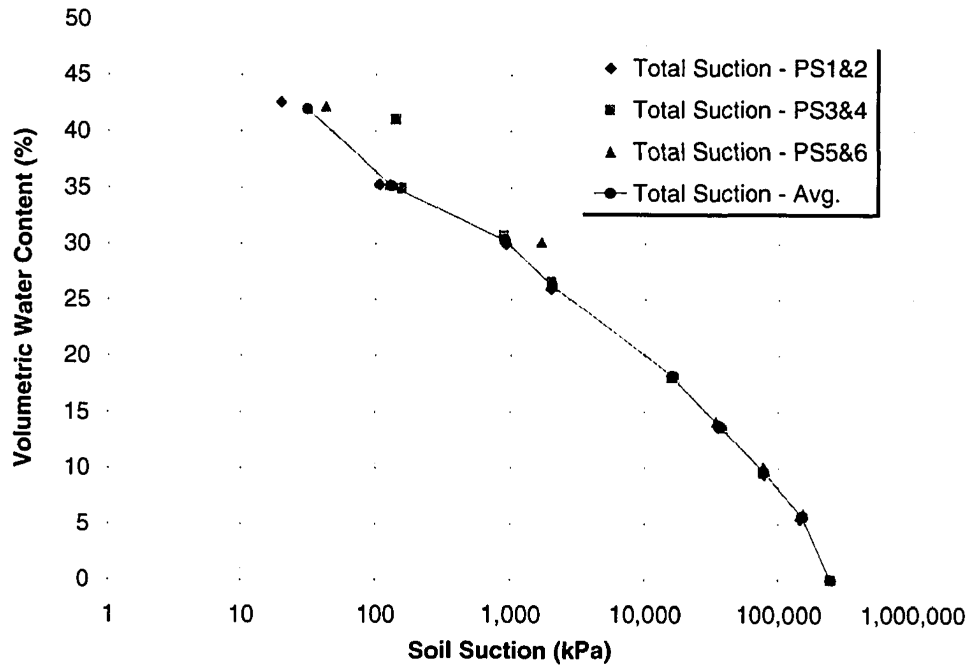


Figure 4-15 Wetting SWCC – Total Suction – Remolded Claystone of Pierre Shale Formation

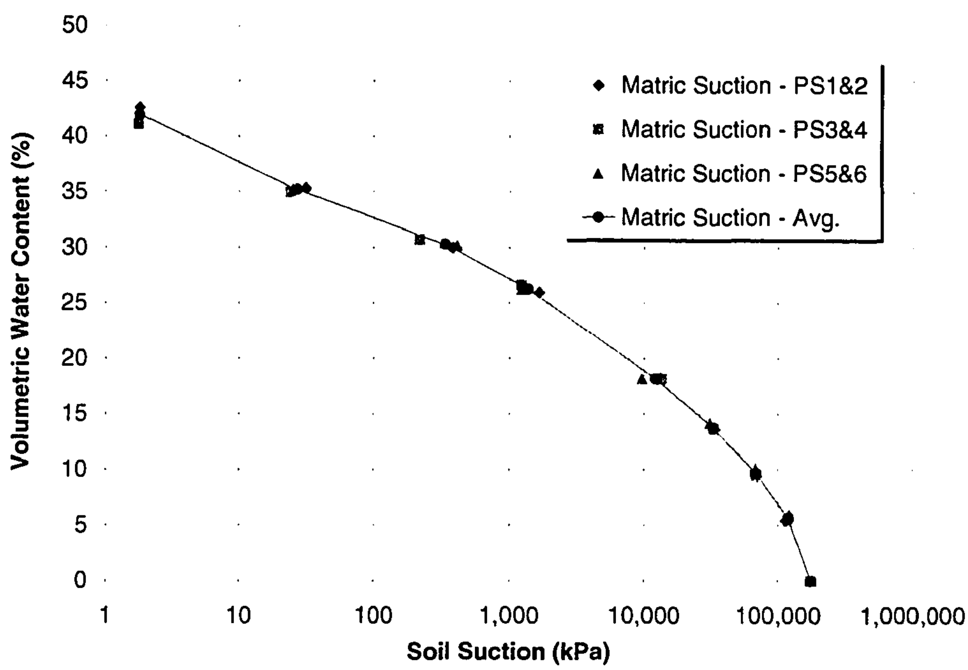


Figure 4-16 Wetting SWCC – Matric Suction – Remolded Claystone of Pierre Shale Formation

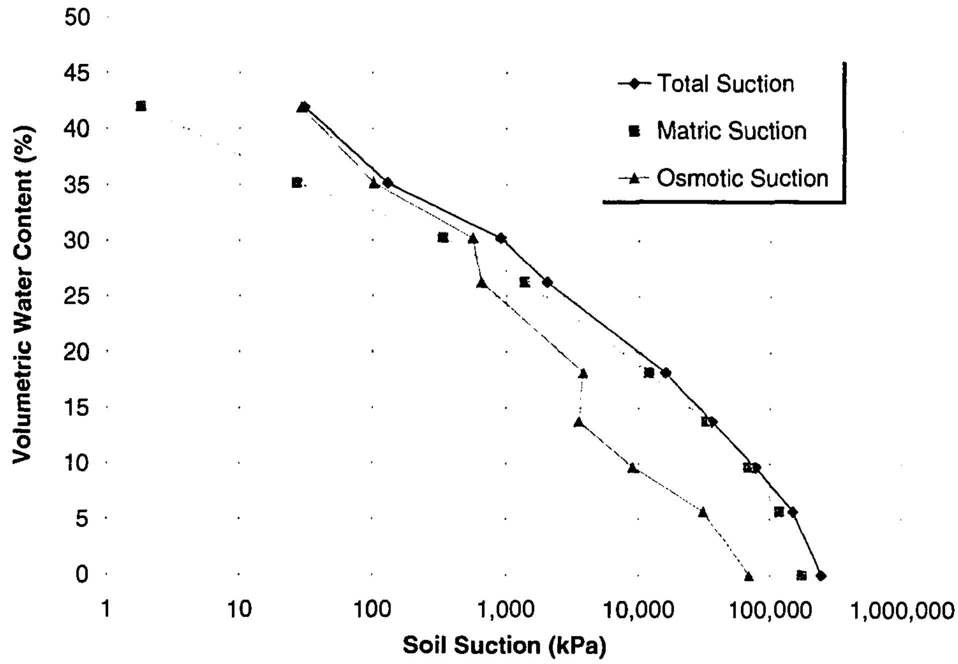


Figure 4-17 Wetting SWCC – Total, Matric, and Osmotic Suctions – Remolded Claystone of Pierre Shale Formation

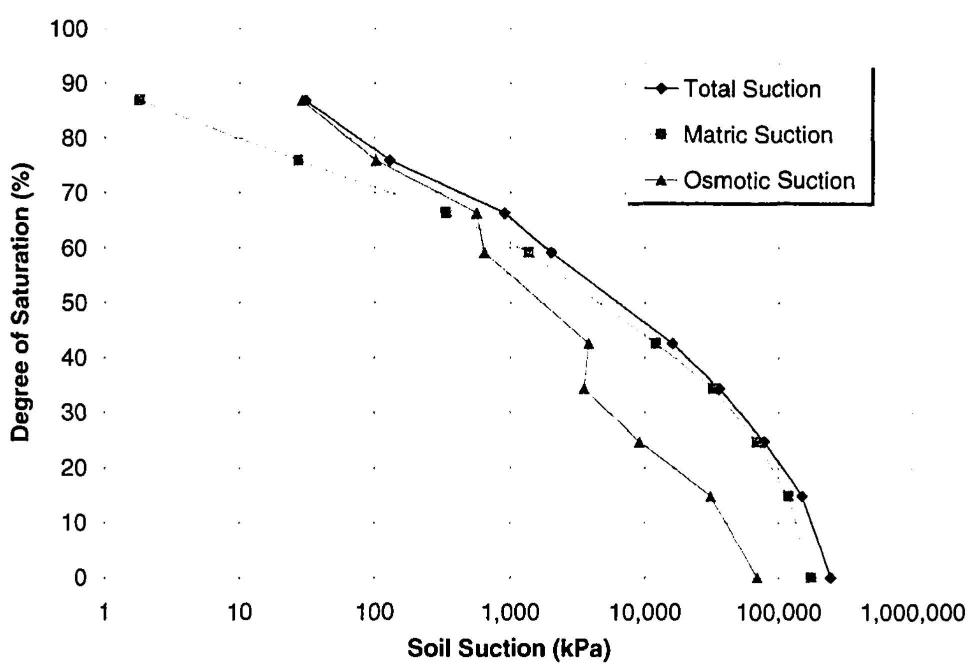


Figure 4-18 Degree of Saturation vs. Soil Suction – Total, Matric, and Osmotic Suctions – Remolded Claystone of Pierre Shale Formation

Fredlund (2002) stated that matric suction has been shown to dominate the lower suction portion of a SWCC, while osmotic suction dominates the high suction portion of the SWCC. Capillary effects dominate when there is a significant amount of liquid water in the soil, whereas the osmotic suction related to the adsorbed salts begins to dominate the behavior of the soil at a high suction range. van der Raadt, et al. (1987) showed that filter paper results used in the contact and noncontact methods were similar for values of suction above 1,000 kPa, but were different for values of suction less than 1,000 kPa. Leong, et al. (2002) suggested that "up to 1,000 kPa suction, the contact filter paper method can be used to measure matric suction reliably, while the noncontact method can be used to measure total suction. Beyond 1,000 kPa suction, the filter paper method measures only total suction, regardless if the contact or the noncontact procedure is used." Review of Figures 4-13 and 4-17 indicates that this limit is much higher (close to 10,000 kPa).

The SWCCs shown in Figures 4-13 and 4-17 for the claystone of both formations do not exhibit an "apparent" displacement pressure head. This trend of not having the apparent displacement pressure head for expansive soil has also been reported by others (Chao, 1995; Al-Mukhtar, 1995; Alonso, et al., 1995; Wan, et al., 1995; and Miller, 1996).

For comparison purposes, the Fredlund SWCC test was conducted on the remolded claystone of the Denver Formation with values of soil suction ranging from 2 to 900 kPa. The results of the Fredlund SWCC test are included in Figure 4-19. This figure demonstrates that the Fredlund SWCC test reproduced the results obtained from the filter paper test. Consequently, it is confident that the wetting soil water characteristic curve shown in Figure 4-19 is reasonable and can be used in the water migration analysis that will be described in Chapter 6.

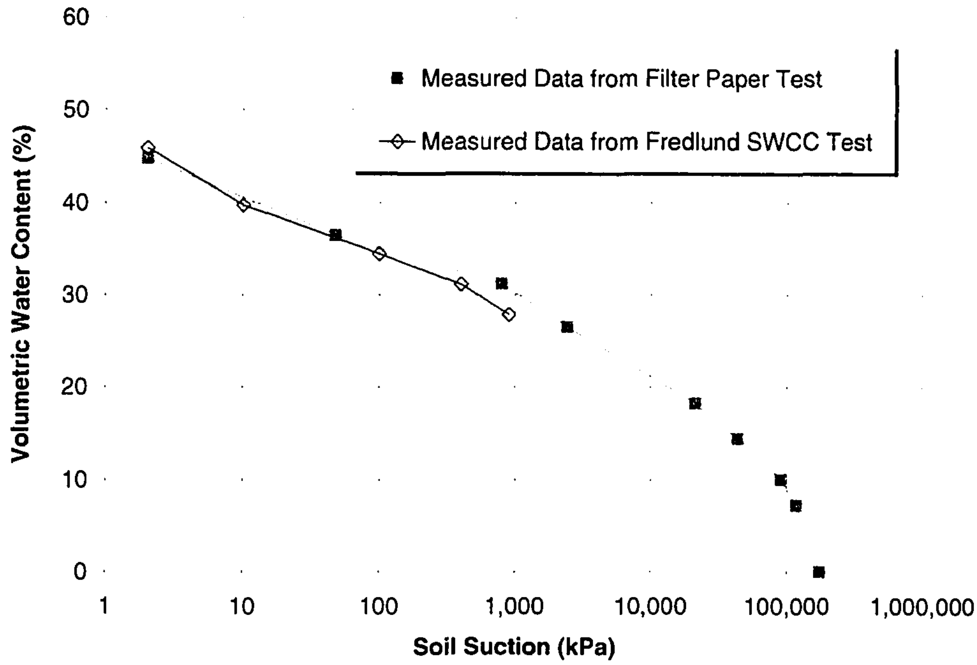


Figure 4-19 Comparison of Wetting SWCCs from Filter Paper Test and Fredlund SWCC Test – Remolded Claystone of Denver Formation

4.2.4.4 Relationship Between Water Content and Swell Potential

The relationship between water content and swell potential for the claystone of the Denver Formation was evaluated. The claystone samples were remolded to the values of initial volumetric water content ranging from 18 to 38 percent. Changes in sample height and water content of the soil samples placed in the Fredlund SWCC device were measured until completion of the swelling process. The laboratory data worksheets for determining the relationship between water content and swell potential are included in Appendix E.

Figure 4-20 presents percent swell as a function of time data for the claystone samples with various initial volumetric water contents. Tangents were drawn to the two straight-line portions of the observed curve for the claystone with the initial water content of 18%. ASTM D4546-03 defines the intersection of the tangent lines as being the end of primary swell. The arrow shown in Figure 4-20 indicates the end of primary swell for the sample with the initial water content of 18%. Values for the time at the end of primary swell for other samples were determined using the same approach. The end of primary swell occurred at approximately 6,400, 8,100, 9,000, and 10,500 minutes for the samples with the initial volumetric water contents of 18, 23, 30, and 38%, respectively.

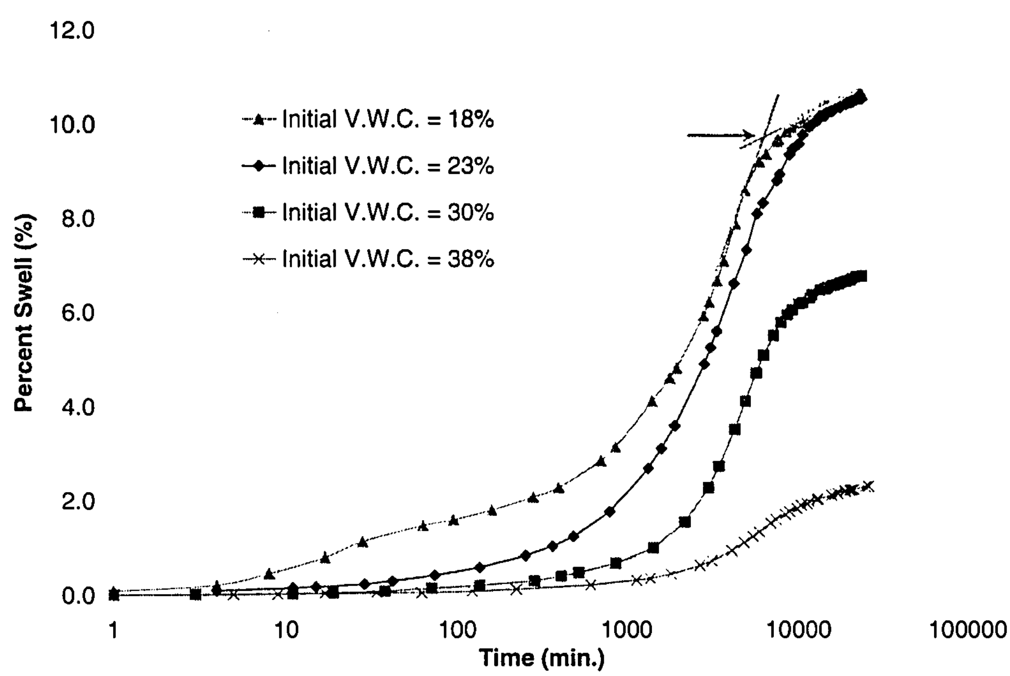


Figure 4-20 Percent Swell vs. Time for Claystone Samples at Various Initial Water Contents

Figure 4-21 shows the laboratory test data of the relationship between water content and percent swell. The percent swell values for each soil specimen shown in Figure 4-21 were normalized to the maximum value of percent swell obtained during the consolidation-swell test for that sample. The observed laboratory data were fitted to second and third order polynomial equations using regression analyses. The results of the regression analyses are shown in Figures 4-21 and 4-22, respectively.

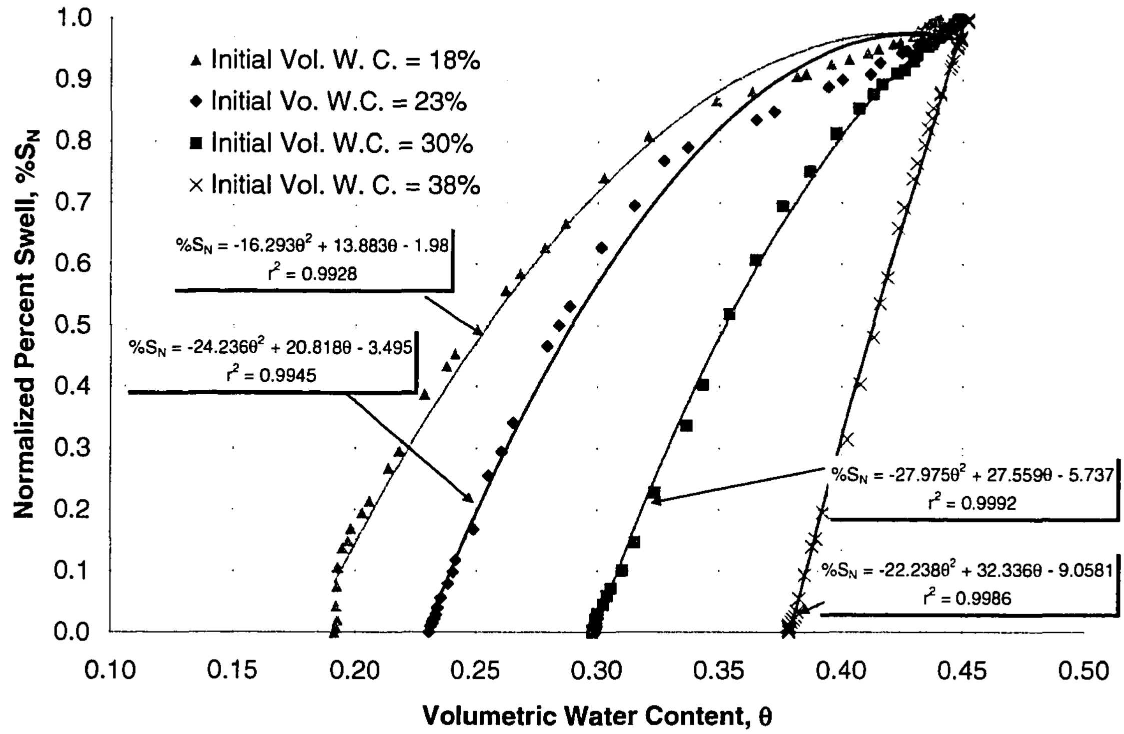


Figure 4-21 Normalized Percent Swell vs. Volumetric Water Content – Second Order Polynomial Equation

Figures 4-21 and 4-22 indicate that the values of r^2 for regression analyses of the second order polynomial equation are very close to those for regression analyses of the third order polynomial equation. The main difference between the second order and third order polynomial equations is the agreement with the observed data in the range from 0.9 to 1.0 Normalized Percent Swell. Inspection of Figures 4-21 and 4-22 shows that the overall effect of using the second order equation would be about 3% inaccuracy in the final stages of the heave process for initially dry soils. In the case of initially wetter soils, the difference between the two equations is negligible. Therefore, the curve fitting results with the second order polynomial equation were selected in this research. Additional analyses of the laboratory data are provided in Section 5.4.

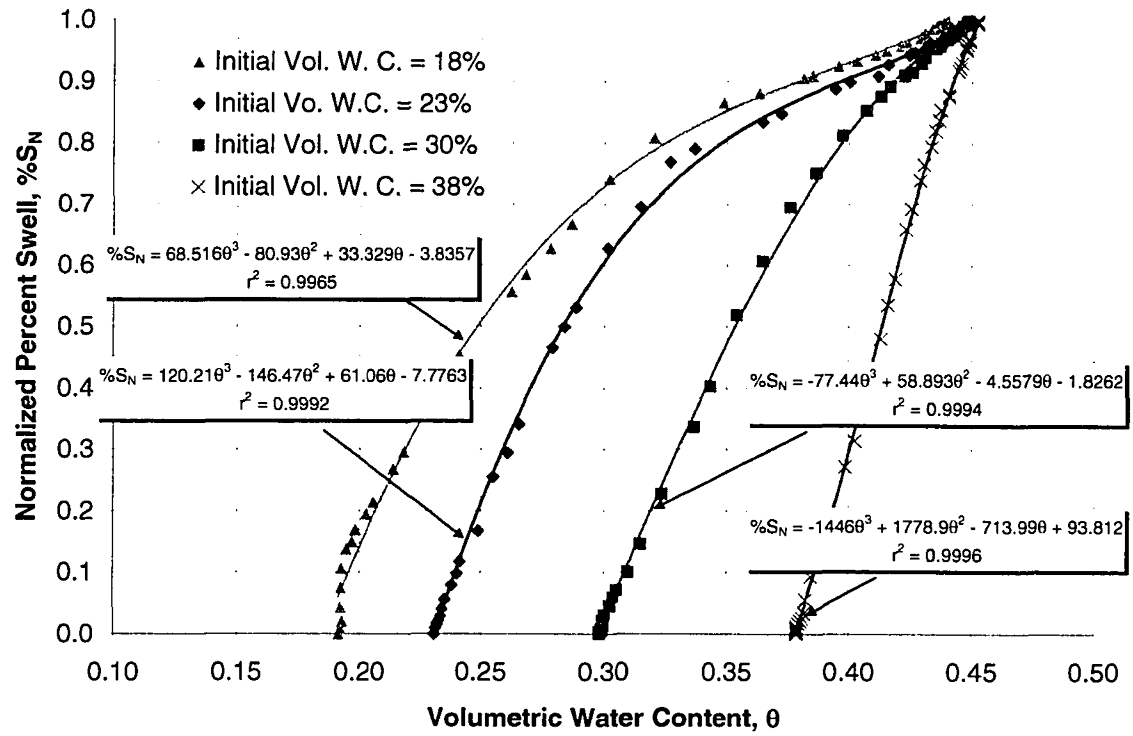


Figure 4-22 Normalized Percent Swell vs. Volumetric Water Content – Third Order Polynomial Equation

CHAPTER 5

ANALYSIS OF LABORATORY TESTING DATA

The primary goal of the experimental testing was to provide the SWCC and the relationship between water content and swelling potential of the claystone for use in the water migration analysis and rate of heave prediction. The results of the experimental testing were presented in Chapter 4. Analysis of the experimental testing data is discussed in this chapter.

5.1 Filter Paper Calibration Curve

Leong, et al. (2002) developed total suction calibration curve for Whatman No. 42 filter paper. The total suction calibration curve was obtained by calibrating initially dry filter papers over salt solutions of various concentrations in vacuum desiccators. The equilibration time of the calibration curve from Leong, et al. (2002) was observed to be between 2 and 5 days. The calibration curve from Leong, et al. (2002) is shown in Figure 5-1 in conjunction with the calibration data obtained from this research. It is shown in Figure 5-1 that the filter paper responses are the same for values of soil suction greater than 1,000 kPa, whereas the calibration curves for soil suction less than 1,000 kPa are somewhat different. The difference in the calibration curves may result from the quality of the filter papers, the differences in the equilibration time, or sensitivity to minor changes in the filter paper water content, as discussed in Section 4.2.4.1.

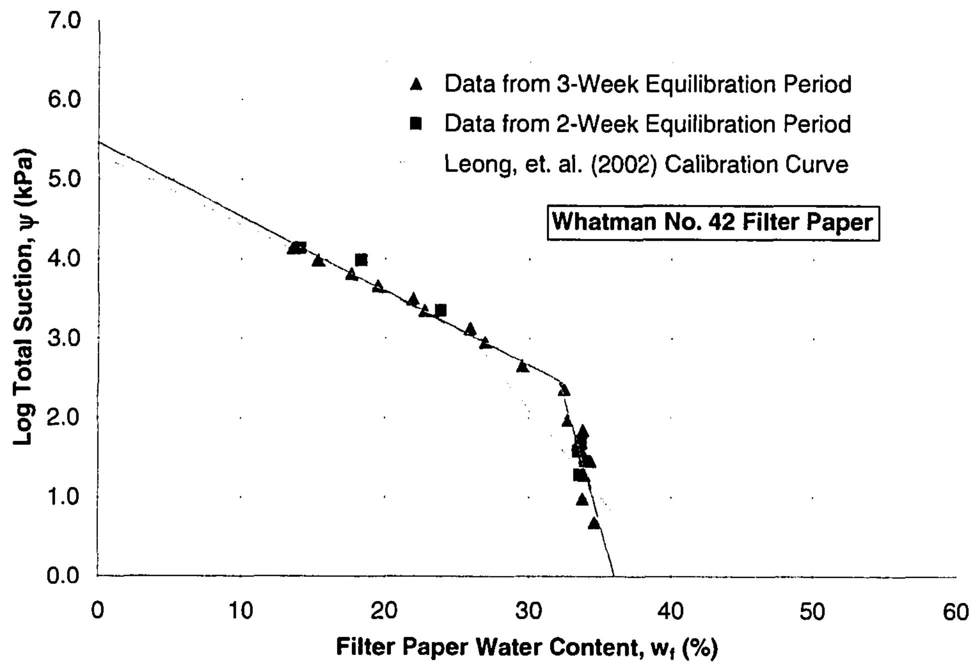


Figure 5-1 Comparison of Filter Paper Calibration Curves for Total Suction Measurement

The calibration curve for total suction obtained from this research is shown in Figure 5-2 in conjunction with the calibration curve for matric suction obtained from ASTM D5298-94. ASTM D5298-94 reports that the calibration curve was obtained from Greacen, et al. (1987). Greacen, et al. (1987) referred to the paper by Fawcett and Collis-George (1967) for their calibration data for values of matric suction greater than 50 kPa. Houston, et al. (1994) successfully duplicated the matric suction calibration curve from Fawcett and Collis-George (1967). Additional calibration curves for the matric suction measurement using the Whatman No. 42 filter paper is presented in Figure 2-12. The difference in the calibration curves from other research is insignificant. Therefore, the matric suction calibration curve obtained from ASTM D5298-94 was adopted in this research.

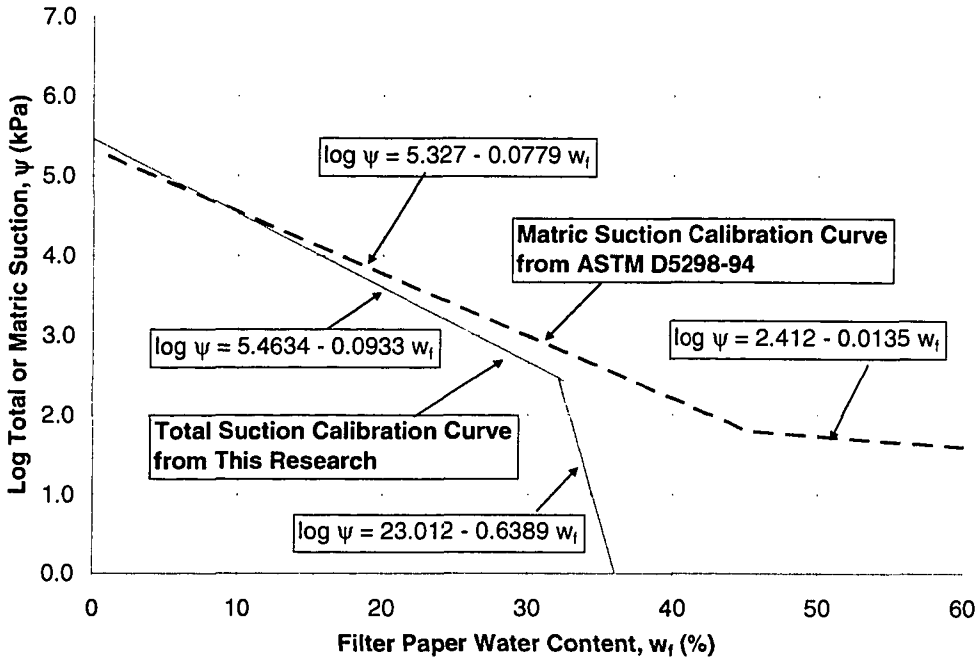


Figure 5-2 Filter Paper Calibration Curves for Whatman No. 42 Filter Paper

Figure 5-2 shows that the calibration curves are different for total and matric suctions. This was also observed by Houston, et al. (1994), Bulut, et al. (2001), Leong, et al. (2002), and Bulut and Wray (2005). The matric suction curve is essentially the same as the total suction curve for a suction value higher than approximately 10,000 kPa.

5.2 Equilibration Time for Filter Paper Test

ASTM D5298-94 recommends a minimum equilibration time of 7 days when measuring suction using the filter paper method. However, various investigators have used different equilibration times, as listed in Table 2-4. Table 2-4 indicates that the equilibration time could be more than 7 days depending on suction source, measured suction type, material type, water content of soil specimen, number of filter papers used, etc. To facilitate determination of the equilibration time for the claystone, the soil suctions observed at a time, t_f, was plotted against that observed at the time, $t_f + 1$. This is shown in Figure 5-3. When equilibrium of the system has been reached, the observed soil suction at $t_f + 1$ will equal to that at t_f. For that case, the data point will plot along a 45° line. Using this approach the time required for equilibration was determined to range from 1 to 10 days for the claystone samples with volumetric water content ranging from 13.6 to 44.4%.

The equilibration times determined for the soil samples with various water contents are depicted in Figure 5-4. It is shown that the time required for equilibration increases as the water content of the sample increases. The equilibration time could be longer than 7 days as recommended by ASTM D5298-94 if the volumetric water content of the sample is higher than 20%. It is interesting to note in Figure 5-4 that a bilinear form of the relationship between equilibration time and water content of the soil gives the best fit to the measured laboratory data. It is also interesting to note that the intersection point of the two points of the bilinear curve corresponds to the ASTM recommendation.

The equilibration time vs. water content relationship developed in Figure 5-4 was used as a guide to determine a minimum time period for running the filter paper test in this research.

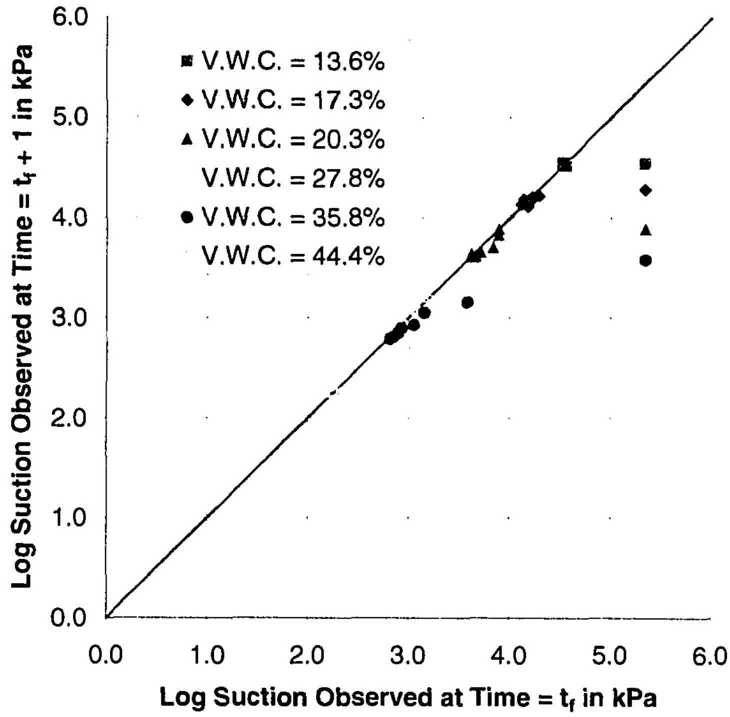


Figure 5-3 Plot of Suction Observed at Time = t_f vs. Time = $t_f + 1$

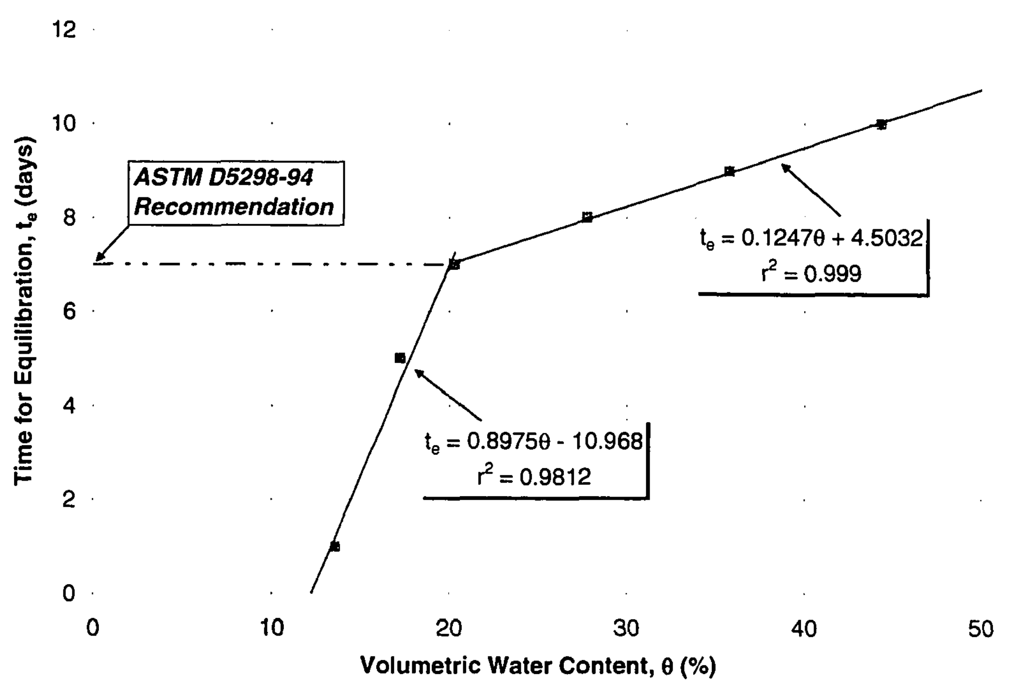


Figure 5-4 Equilibration Time vs. Volumetric Water Content Relationship

5.3 Soil Water Characteristic Curves

Soil water characteristic curves of the claystone of the Denver and Pierre Shale Formations were obtained by means of the filter paper test and the Fredlund SWCC test in this research. The results of the observed experimental data are shown in Figures 4-11 through 4-19. The observed experimental data were used to evaluate the previously proposed mathematical equations of SWCCs described in Table 2-5. Selected mathematical equations include the equations proposed by Burdine (1953), Gardner (1958), Brookes and Corey (1964), Mualem (1976), van Genuchten (1980), and Fredlund & Xing (1994). Figures 5-5 and 5-6 show the results of the curve fitting for the claystone of the Denver Formation. Figures 5-7 and 5-8 show the results of the curve fitting for the claystone of the Pierre Shale Formation. The values of r^2 for regression analyses of the equations are also shown in the figures.

Comparison of Figures 5-5 through 5-8 indicates that the Brooks and Corey equation provides the least agreement with the experimental data among the equations. The reason for the poor fit of the Brooks and Corey equation is that the Brooks and Corey model exhibits a sharp break in the curve at the air entry value which is typically more representative of sandy soil having a relatively narrow grain size distribution. It is seen in Figures 5-5 through 5-8 that the Fredlund and Xing equation exhibits the best agreement with the experimental data among the equations. An interesting observation is that the four-parameter equations (such as the van Genuchten and Fredlund & Xing equations) performed a better curve fitting than the three-parameter equations (such as the Burdine, Brooks and Corey, and Mualem equations). This observation was also made by Leong and Rahardjo (1997) for other soil types.

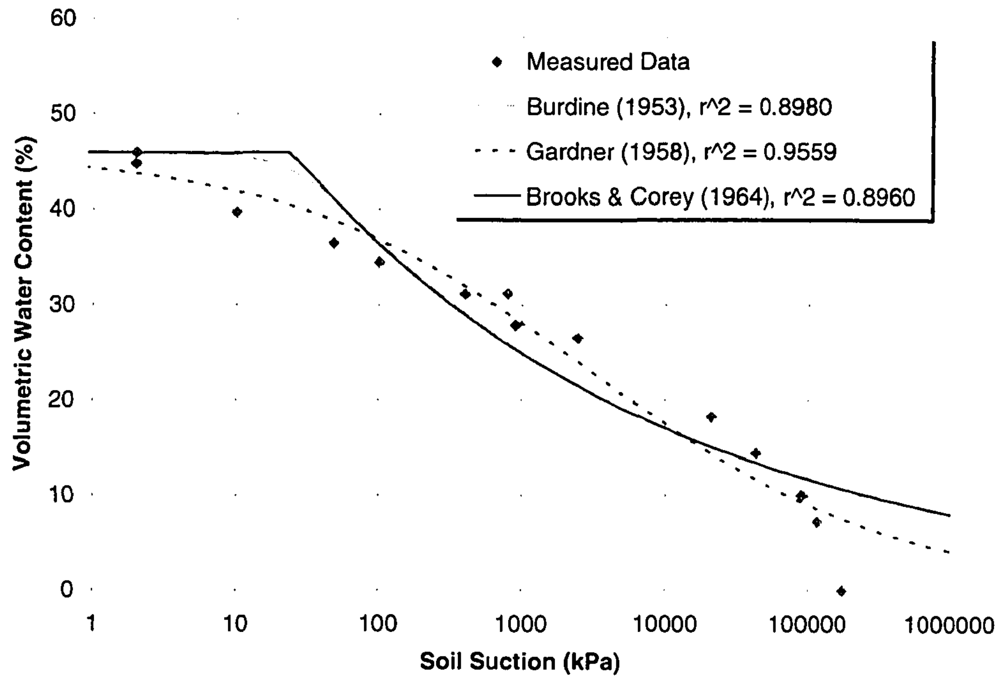


Figure 5-5 **Burdine, Gardner, and Brooks & Corey Equations Fitted to Experimental Data – Claystone of Denver Formation**

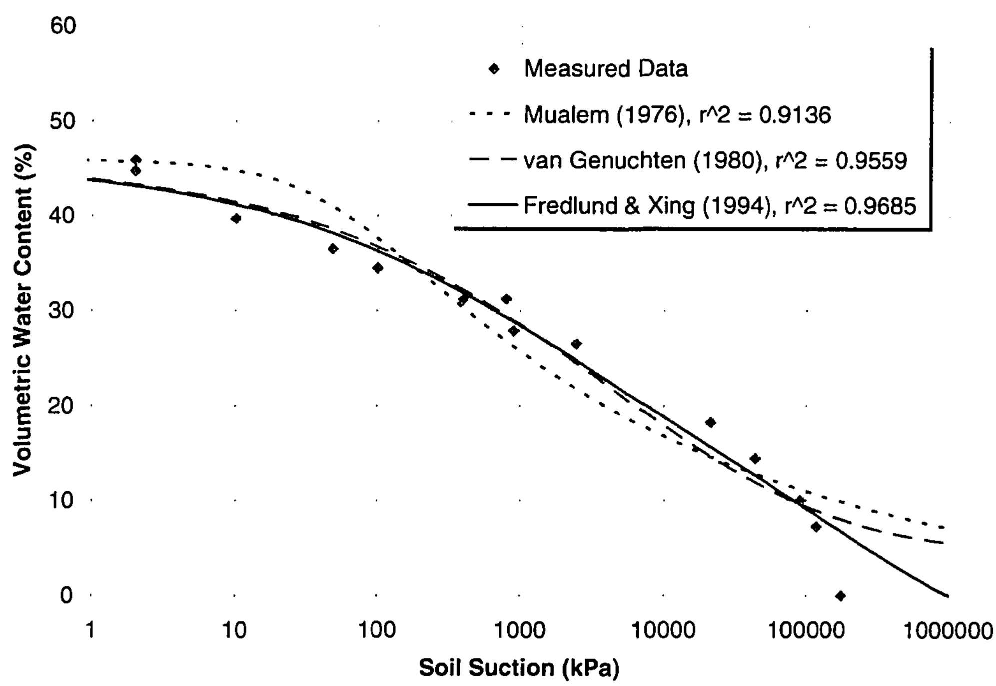


Figure 5-6 **Mualem, van Genuchten, and Fredlund & Xing Equations Fitted to Experimental Data – Claystone of Denver Formation**

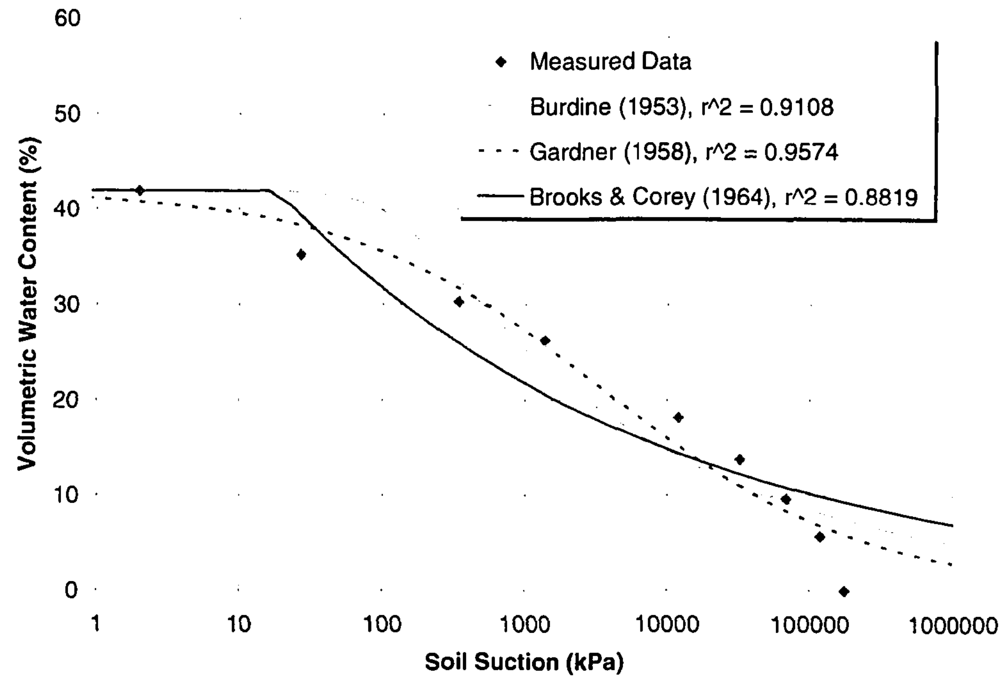


Figure 5-7 **Burdine, Gardner, and Brooks & Corey Equations Fitted to Experimental Data – Claystone of Pierre Shale Formation**

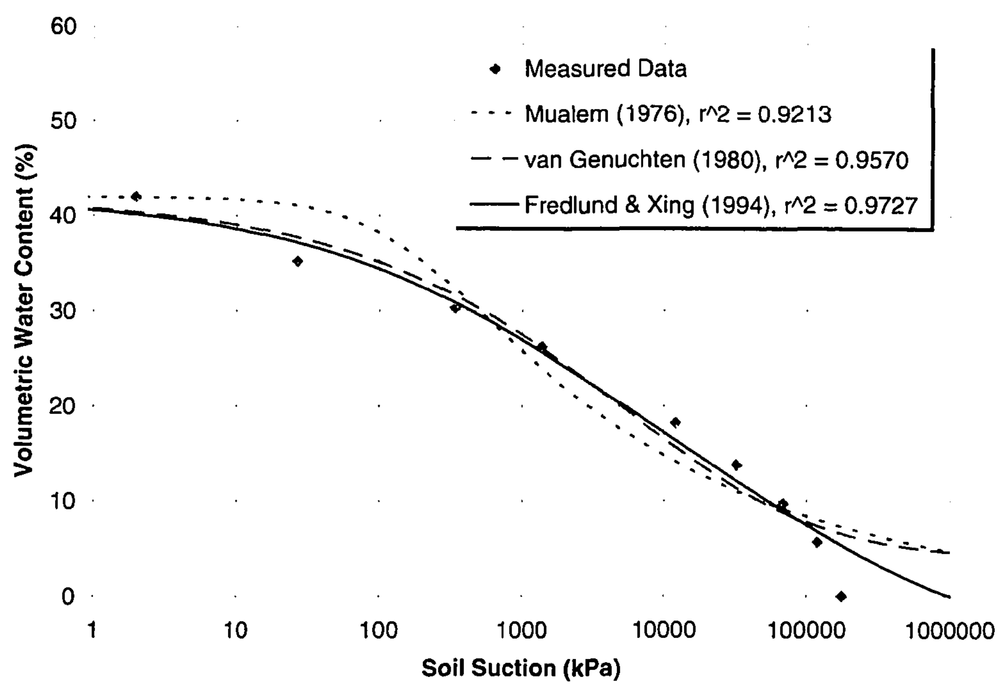


Figure 5-8 **Mualem, van Genuchten, and Fredlund & Xing Equations Fitted to Experimental Data – Claystone of Pierre Shale Formation**

Chao, et al. (1998) indicated that a bilinear form gives a good agreement to the observed experimental data for expansive soils. The bilinear relationship of the SWCC for expansive soils has also been reported by others (McKeen and Neilsen, 1978; Marinho, 1994; and Miller, 1996). The results of the experimental data plotted in the bilinear form are shown in Figures 5-9 and 5-10 for the claystone of the Denver and Pierre Shale Formations, respectively. It is shown in Figures 5-9 and 5-10 that the bilinear form of the SWCC gives the best fit to the measured experimental data compared to the previously proposed mathematical equations discussed previously. The question mark by the point at zero water content indicates that this point was not used in the curve fitting procedure.

As discussed in Section 2.2.3, the change in slope of the SWCC for expansive soil has been attributed to a transition between macropore (capillary) spaces and micropore (diffuse double layer) spaces (Miller, 1996). The physical significance of this apparent transition point may be attributed to the bi-level pore size distribution researched by Al-Mukhtar (1995), Alonso, et al. (1995); and Wan, et al. (1995). Miller (1996) hypothesized that this bilinear relationship is a manifestation of the transition from macropore spaces, where water retention is governed by capillary mechanisms, to micropore spaces, where water retention is governed by thermodynamic forces.

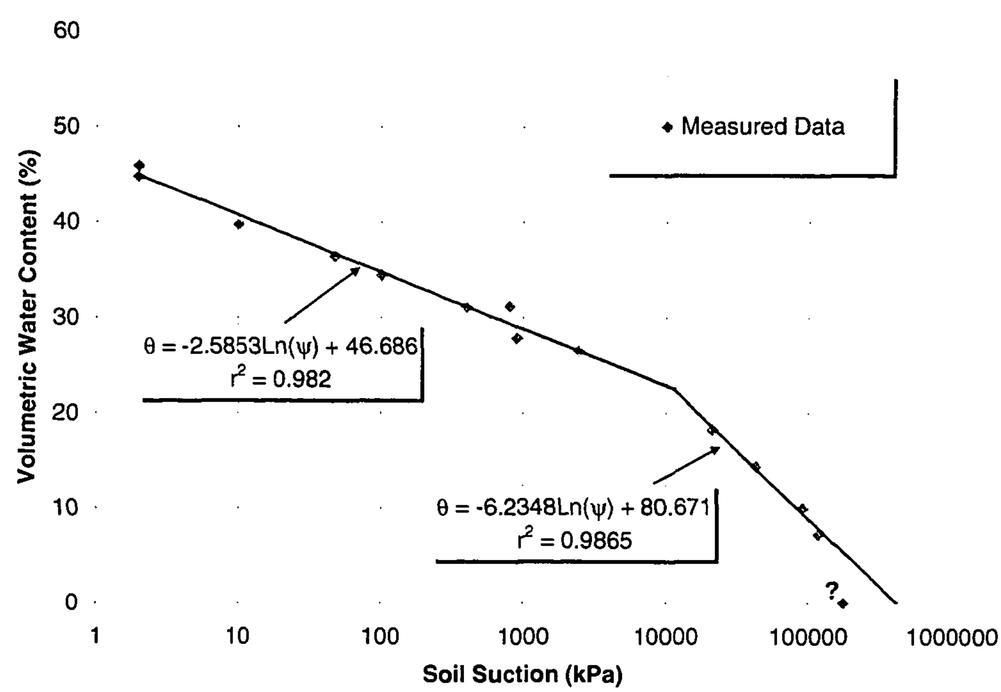


Figure 5-9 **Bilinear Equation Fitted to Laboratory Data – Claystone of Denver Formation**

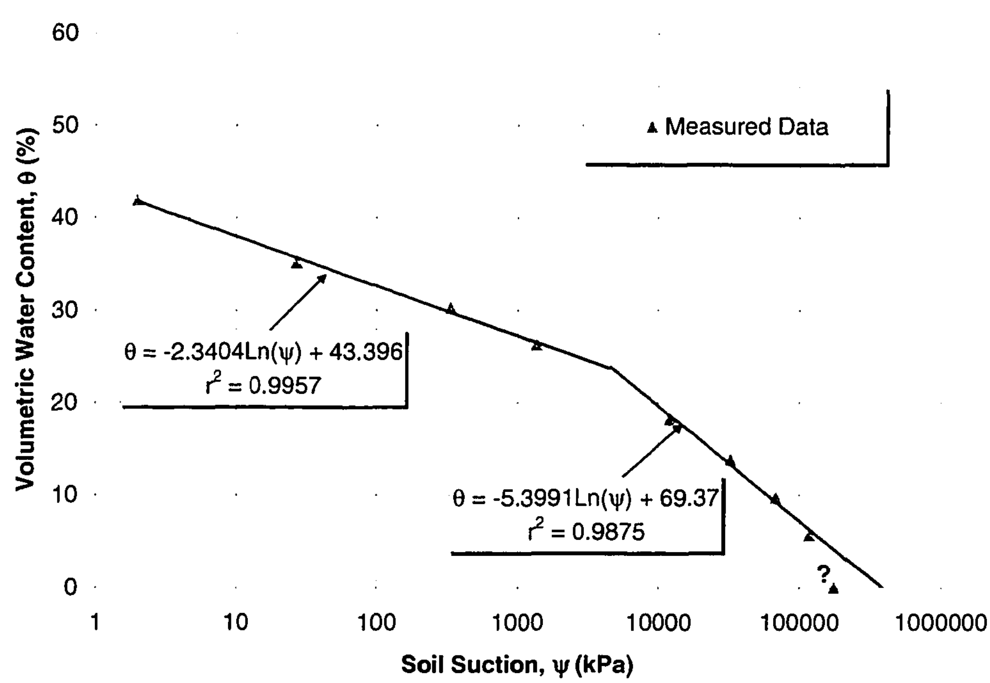


Figure 5-10 **Bilinear Equation Fitted to Laboratory Data – Claystone of Pierre Shale Formation**

5.4 Relationship Between Water Content and Swell Potential

The equations for the curve fitting to the observed experimental data shown in Figure 4-21 are summarized in Table 5-1. Table 5-1 indicates that a second order polynomial equation provides a very reasonable fit to the observed experimental data.

An attempt was made to derive a general form of that polynomial equation. Figure 5-11 plots the values of the coefficients C1, C2, and C3 obtained from Table 5-1 as a function of the initial water contents. Figure 5-11 indicates that the coefficients C1, C2, and C3 can be represented by another second order polynomial equation relating the coefficient to the initial water content. This results in a general form of the normalized percent swell and water content relationship as follows:

$$\begin{aligned}\%S_N &= (850.17\cdot\theta_i^2 - 505.61\cdot\theta_i + 47.14)\cdot\theta^2 \\ &+ (-283.20\cdot\theta_i^2 + 250.35\cdot\theta_i - 21.94)\cdot\theta \\ &+ (-45.70\cdot\theta_i^2 - 9.57\cdot\theta_i + 1.19)\end{aligned} \qquad \text{Equation (5-1)}$$

Where:

$\%S_N$	=	normalized percent swell,
θ_i	=	initial volumetric water content, and
θ	=	volumetric water content.

Equation (5-1) was used for calculations of timewise variation of slab and pier heave in this research.

Table 5-1 Summary of Coefficients of Second Order Polynomial Equations

Initial Volumetric Water (%)	Second Order Polynomial Equation [1] $\%S_N = C_1\theta^2 + C_2\theta + C_3$			r^2 Value for Regression
	Coefficient C_1	Coefficient C_2	Coefficient C_3	
18	-16.293	13.883	-1.980	0.9928
23	-24.236	20.818	-3.495	0.9945
30	-27.975	27.559	-5.737	0.9992
38	-22.238	32.336	-9.058	0.9986

Note: (1) $\%S_N$ = normal percent swell, and θ = volumetric water content

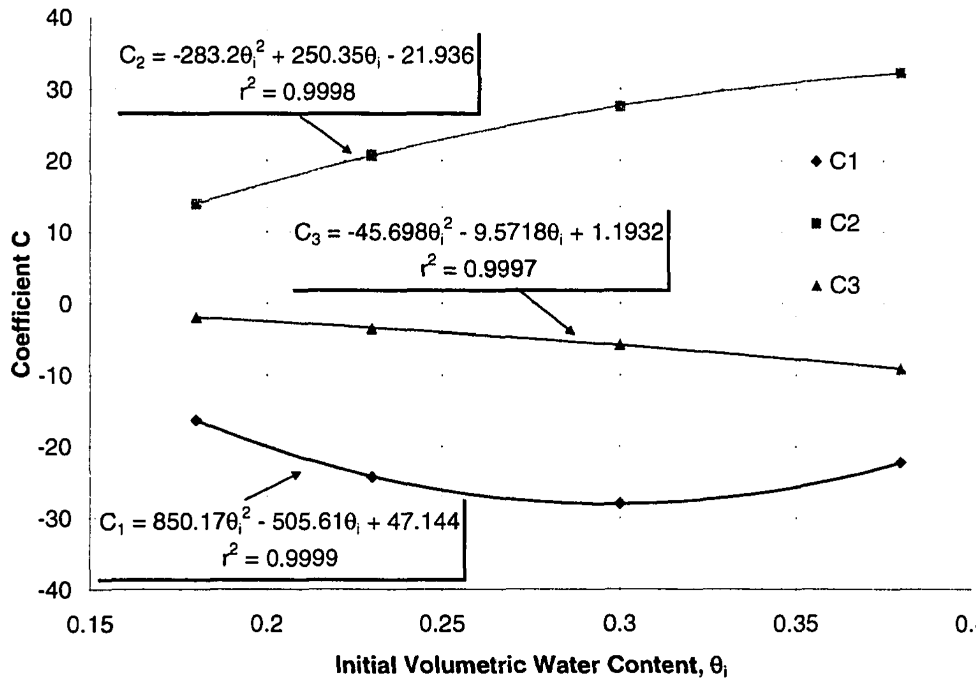


Figure 5-11 Relationship Between Coefficient C and Initial Volumetric Water Content

CHAPTER 6

WATER MIGRATION IN THE VADOSE ZONE

6.1 General

Analyses of the migration of water in the subsoil were conducted for the TRACON facility using VADOSE/W Version 6.20 software (GEO-SLOPE, 2006). VADOSE/W is a finite element program that can be used to model movement and distribution of pore water within porous materials such as soil and bedrock. VADOSE/W can model both saturated and unsaturated flow in response to climatic conditions making it possible to analyze seepage as a function of time while considering infiltration, precipitation, surface water runoff and ponding, plant transpiration, evaporation, and heat flow. The physical relationships required for rigorous calculation of evaporation include fully coupled heat and mass transfer with vapor flow in the soil and across the soil-atmosphere continuum.

The water migration analyses were performed at two soil profiles corresponding to those at the locations of SMI-MA2A and MA3. These two locations were selected for analysis based on the boring logs, elevation survey data provided by Zylstra Baker Surveying, Inc. (ZBSI, 2006), and the subsurface nuclear gauge data provided Whitney (2003) and Benvenga (2005). These two locations represent conditions having natural climate with no irrigation (SMI-MA2A) and no flow at the surface due to pavement (SMI-MA3). The soil profiles analyzed were obtained from boreholes SMI-3 and SMI-4 for the shallower portions of the profiles and deep benchmark SMI-BM1 for the deeper portions of the profiles (SMI, 1999 and 2000).

The time period over which the analysis extended was based on the design life of the foundation. The Housing Facts, Figures, and Trends published by National Association of Home Builders (1997) indicated that the design life for residential foundations should be 200 years. The minimum design life for residential foundations as presented by the U.S. Department of Housing and Urban Development (2002) and Schmatz and Stiemer (1995) is 100 years for foundations. However, FAA personnel expressed that the design life of the TRACON building is approximately 50 years. The TRACON building was constructed in the year 1991. Therefore, the migration of soil water for the soil profiles at SMI-MA2A and MA3 were simulated up to the year 2040 in the seepage analyses. However, for other applications such as design of normal residential structures, a design life of about 100 years should be considered.

6.2 Modeling Procedure

The water migration analyses were performed in four steps. Details of these procedures will be discussed in Section 6.5.

1. Initial Water Content Profiles – The values of water content in May 2001 obtained from the subsurface nuclear gauge tubes SMI-MA2A and MA3 were input into the seepage models as initial water content profiles (CSU, 2004). In addition, the values of water content obtained from the deep benchmark SMI-BM1 were also input into the models for the deeper portions of the soil profile.

2. <u>Model Calibration</u> – The SWCC for the claystone was measured in the laboratory. The SWCC for the weathered claystone was assumed to be the same as that for the claystone. SWCCs and hydraulic conductivity functions for the other soils including the silty clay fill, silty clay, coal, and sandstone bedrock were initially estimated using the soil database program SoilVision, Version 4.14 (SoilVision, 2006). The model was calibrated by varying the input parameters until the predicted water contents match the observed water content data at SMI-MA2A and MA3 from May 2001 to June 2004. In addition, the water observed in the coal seams was input as a pressure head function and was varied until the predicted water content matched the observed water content.

3. <u>Model Validation</u> – Validation of the computer model involves comparison of the values of subsurface water content measured using the downhole nuclear gauge with the results of the computational model. In this way, it is demonstrated that the calibrated model is capable of predicting measured data. Subsurface nuclear gauge readings at the locations of SMI-MA2A and MA3 were taken in August 2006. The model was validated at the locations of SMI-MA2A and MA3 by comparing the computed values of water content with the measured water content data collected in August 2006.

4. <u>Water Migration Simulation</u> – The migration of soil water for the soil profiles at SMI-MA2A and MA3 was simulated from the year 2006 to 2040. VADOSE/W models were calibrated over the period from May 2001 to June 2004 and validated over the period from July 2004 to August 2006.

6.3 Boundary Conditions Specified in the Models

6.3.1 Climate Data

Table 6-1 shows the annual precipitation values for the years 1949 to 2005 recorded at either Stapleton or DIA. The precipitation data were obtained from the National Oceanic and Atmospheric Administration (NOAA). As shown in Table 6-1, the average annual precipitation was 39.0 cm for the years 1949 to 2005. An "average" four year climate scenario was developed by selecting those four years that had annual precipitation closest to the average value. Therefore, climate data obtained from NOAA at Stapleton or DIA for the years 1975, 1989, 1992, and 1998, which had corresponding annual precipitation values of 39.4, 39.3, 39.8, and 40.5 cm, were input one following the other. This sequence was repeated in the seepage models for the entire modeling period. The climate data input in the seepage models include the daily precipitation, the maximum and minimum daily temperature, the maximum and minimum daily relative humidity, and the average daily wind speed. The daily climate data for these years were applied at the ground surface of the VADOSE/W model at the location of SMI-MA2A. This precipitation scenario is termed the "average precipitation" case in this research. SMI-MA3 is located underneath a concrete slab, and therefore, no precipitation data was applied at the ground surface of the model at that location.

Table 6-1 Summary of Annual Precipitation for Denver International Airport

Year	Annual Precipitation (cm)	Year	Annual Precipitation (cm)	Year	Annual Precipitation (cm)
1949	42.6	1968	30.8	1987	50.9
1950	35.4	1969	54.7	1988	38.0
1951	49.4	1970	34.9	1989(1)	39.3
1952	34.1	1971	27.8	1990	42.4
1953	36.1	1972	42.8	1991	51.6
1954	19.1	1973	58.3	1992(1)	39.8
1955	40.8	1974	35.6	1993	37.5
1956	34.8	1975(1)	39.4	1994	27.9
1957	54.8	1976	34.1	1995	45.8
1958	48.0	1977	26.3	1996	26.0
1959	42.0	1978	29.7	1997	49.8
1960	38.0	1979	51.7	1998(1)	40.5
1961	48.3	1980	34.7	1999	53.2
1962	21.5	1981	32.0	2000	37.0
1963	31.1	1982	36.7	2001	42.0
1964	25.8	1983	51.3	2002(3)	19.0
1965	55.5	1984	41.9	2003	35.4
1966	27.5	1985	41.4	2004	37.3
1967(2)	59.2	1986	30.7	2005	32.5

Notes: (1) Years with the annual precipitation approximately equal to the annual precipitation of 39.0 cm
(2) Year with the highest annual precipitation
(3) Year with the lowest annual precipitation

6.3.2 Pressure Head Functions Specified in the Coal Seams

Whitney (2003) and Benvenga (2005) indicated that the primary source of water to the subsoil at the TRACON site is the coal seam. Table 3-2 shows that values of the pressure head in the coal seam ranged from approximately 0 to 5.8 meters during the monitoring period from May 2002 to April 2003. Therefore, it was necessary to estimate the amount of water in the coal seams at the locations of SMI-MA2A and MA3A for the water migration analyses.

As shown in Figure 3-1, piezometer SMI-P2 is located next to the location of SMI-MA2A, but unfortunately, only two water levels were taken and were 0.5 and 0 meters on February 27, 2003 and April 2, 2003. Similarly, piezometer SMI-P3 is located next to the location of SMI-MA3, but only two water levels were taken and were 1.9 and 1.5 meters on February 27, 2003 and April 2, 2003. Therefore, the amount of water in the coal seams at the locations of SMI-MA2A and MA3A was estimated indirectly from the subsurface nuclear gauge tube SMI-MA2A.

The water observed in the coal seams was input into the model in the form of pressure head as a function of time. This input function is termed the "pressure head function." Figure 6-1 shows the pressure head function interpreted from the SWCC of the coal and water content readings from the subsurface nuclear gauge tube SMI-MA2A in the period of May 2001 to April 2002. The pressure head ranges from -0.44 to -1.47 meters. Figure 6-1 indicates that the pressure head fluctuated and reflected wet and dry seasons of the year. The reason that the period of May 2001 to April 2002 was selected is because this period was around one of the driest years on record in Denver. The fluctuation of the function reflecting the wet and dry seasons of the year could be estimated from the nuclear gauge data compared to data from other time periods.

During the model calibration process from May 2001 to June 2004, it was assumed that the pattern of the fluctuation from the estimated pressure head function remained the same, but the magnitude of the pressure head varied. The calibrated pressure head function was varied in the model until the predicted water content of the claystone bedrock above the coal seam matched the observed water content from the subsurface nuclear gauge data at SMI-MA2A. The results of the calibration are discussed in the following section. Additionally, other pressure head functions presented in Figure 6-1 are described in the model sensitivity section.

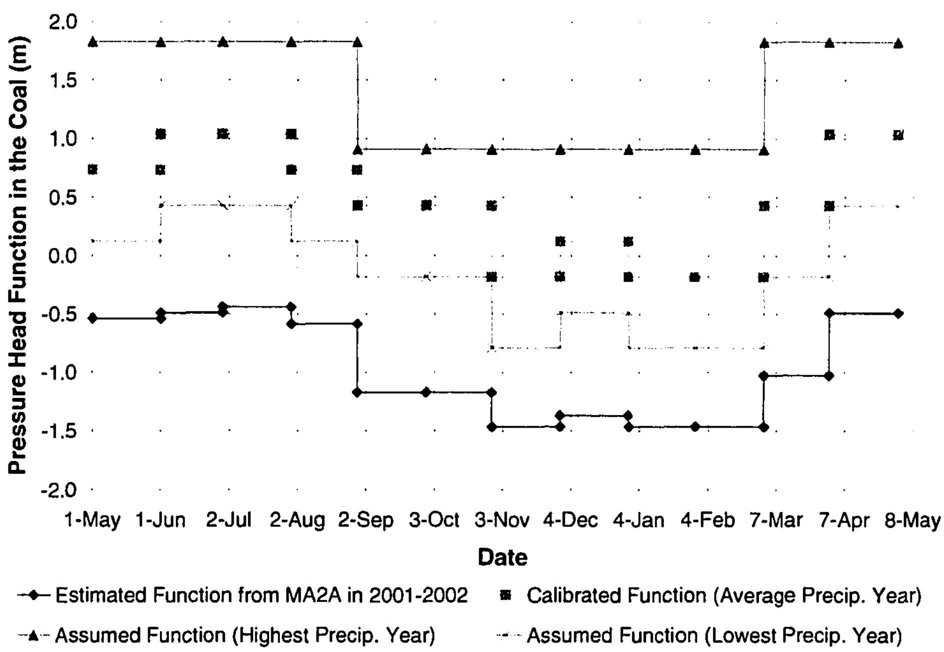


Figure 6-1 Pressure Head Functions Specified in the Coal Seams

6.4 Material Properties Used in the Analyses

Boreholes SMI-MA2A, MA3, and BM1 indicate that the soils at the site consisted of a layer of silty clay fill, underlain by silty clay, weathered claystone, claystone, coal, and sandstone bedrock. The input soil parameters are summarized in Table 6-2. The soil parameters for the materials shown in Table 6-2 were obtained from the laboratory test results, the SoilVision database, and calibrated values.

As shown in Table 6-2, the ratios of hydraulic conductivity in the horizontal direction to that in the vertical direction (K_h:K_v) for the silty clay fill and silty clay were assumed to be 1:1. The K_h:K_v ratio for the weathered claystone, claystone, coal, and sandstone bedrock were assumed to be 10:1 to account for variations due to bedding planes and fractures.

Table 6-2 Summary of Soil Parameters Used in the Seepage Analyses

Soil Type	Saturated Hydraulic Conductivity (cm/sec)	K_h/K_v Ratio	Saturated Volumetric Water Content (vol./vol.)	Residual Volumetric Water Content (vol./vol.)
Silty Clay Fill	1.6×10^{-6}(1)	1(4)	0.40(1)	0.22(1)
Silty Clay	1.0×10^{-6}(2)	1(4)	0.40(1)	0.22(1)
Weathered Claystone	3.6×10^{-7}(3)	10(4)	0.46(5)	0.07(5)
Claystone	8.5×10^{-8}(3)	10(4)	0.46(5)	0.07(5)
Coal	5.0×10^{-4}(3)	10(4)	0.48(1)	0.04(1)
Sandstone	1.5×10^{-5}(1)	10(4)	0.44(1)	0.13(1)

Notes: (1) SoilVision Database
(2) Laboratory data (SMI, 2001)
(3) Calibrated values
(4) Assumed values
(5) Laboratory data in this study

6.5 Results of Analyses

6.5.1 Initial Water Content Profiles

The values of volumetric water content obtained from SMI-MA2A, MA3, and BM1 were input into the VADOSE/W models as the initial water content profiles in May 2001. Figures 6-2 and 6-3 show the observed values of volumetric water content from the boreholes versus the initial water content profiles from the VADOSE/W output for SMI-MA3 and MA2A, respectively. These water content profiles from the VADOSE/W output were utilized as initial conditions for the model calibration process, as discussed in the following section.

6.5.2 Model Calibration

The SWCCs, the hydraulic conductivity functions of the materials, and the estimated pressure head function in the coal seams shown in Figure 6-1 were varied until the computed water content profiles matched the water content data collected between May 2001 and June 2004 at the subsurface nuclear gauge tubes SMI-MA3 and MA2A. Figures 6-4 through 6-7 show the predicted volumetric water content computed by VADOSE/W and the measured water content data for SMI-MA3 in July 2001, July 2002, July 2003, and June 2004, respectively. Figure 6-8 through 6-11 present the predicted volumetric water content computed by VADOSE/W and the measured water content data for SMI-MA2A in July 2001, July 2002, July 2003, and June 2004, respectively. Based on the close agreement between the predicted and observed values of water content, the models were considered calibrated.

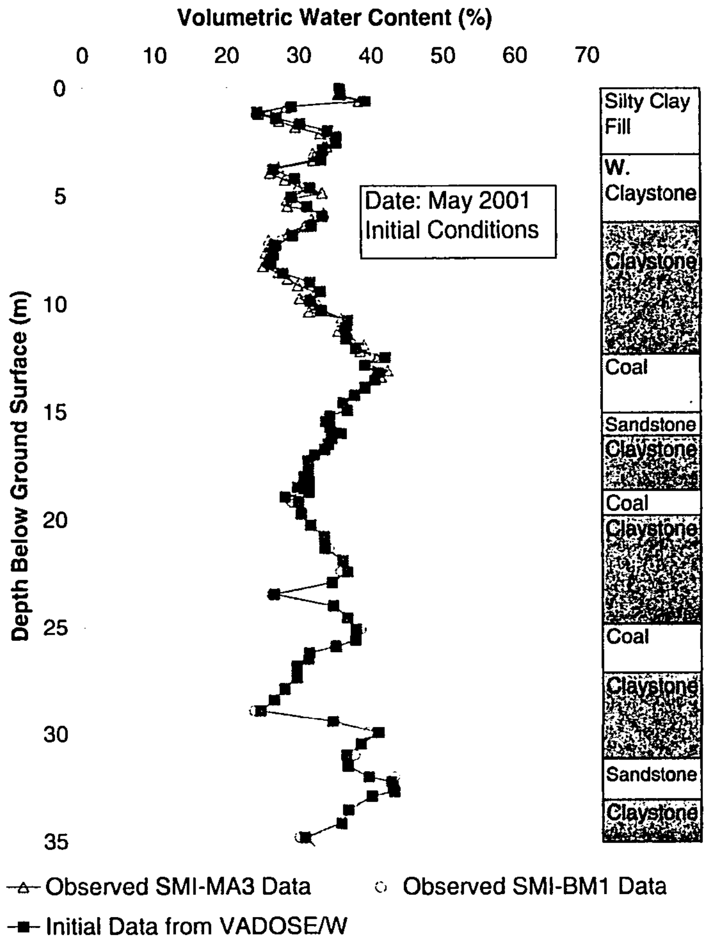


Figure 6-2 Initial Water Content Profile for SMI-MA3

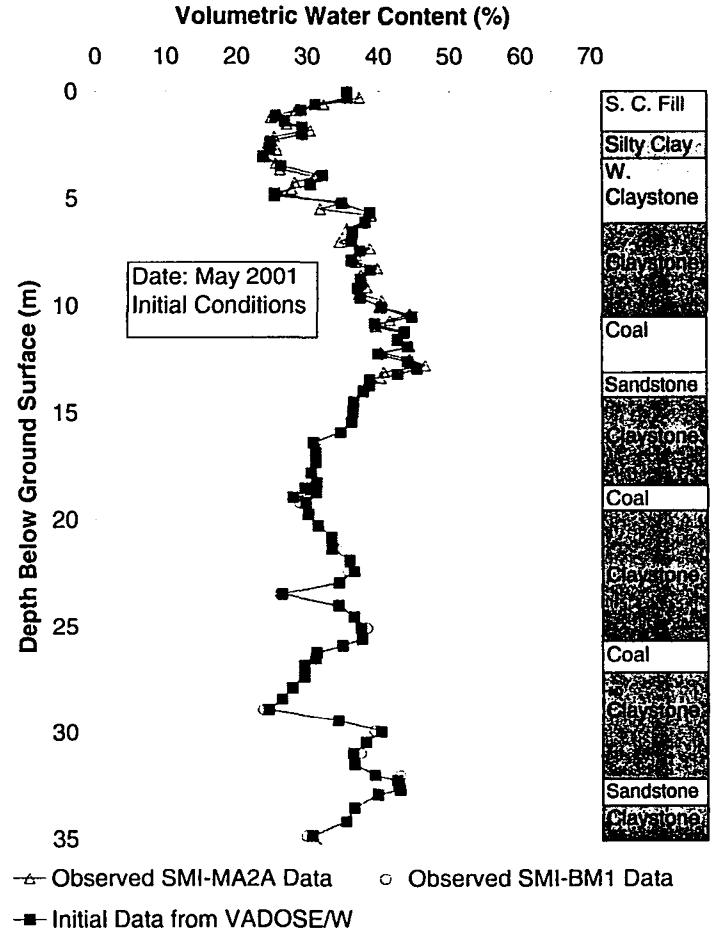


Figure 6-3 Initial Water Content Profile for SMI-MA2A

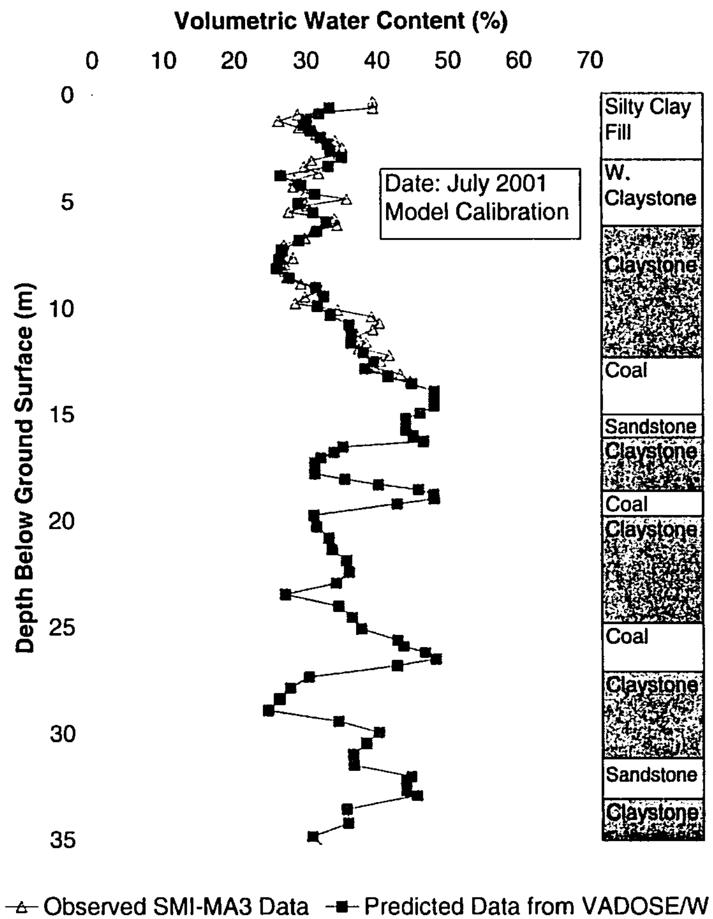


Figure 6-4 **Measured and Predicted Water Content Profiles for SMI-MA3 in July 2001**

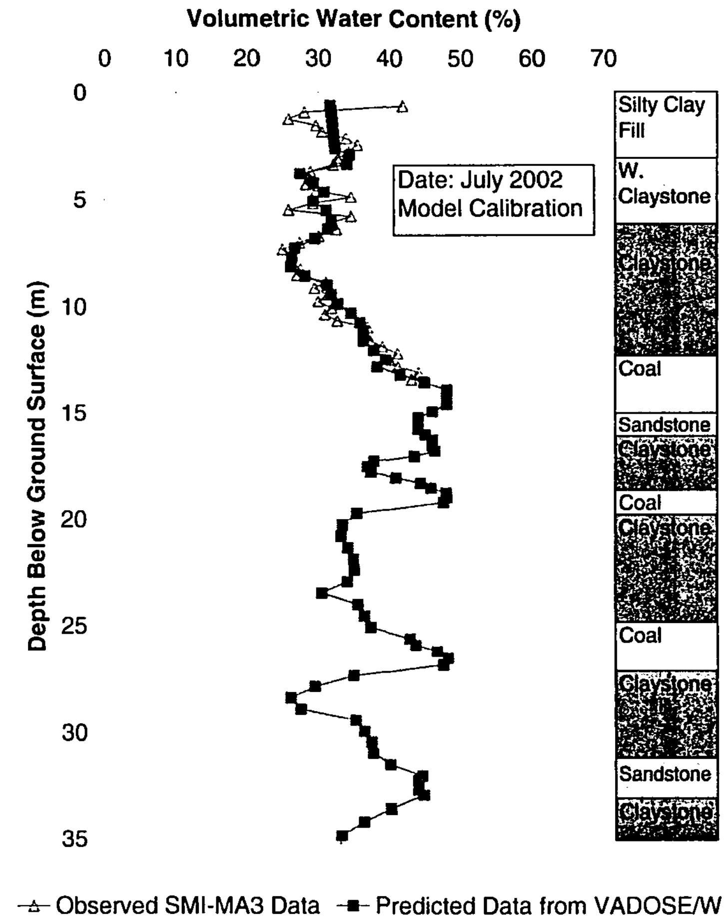


Figure 6-5 **Measured and Predicted Water Content Profiles for SMI-MA3 in July 2002**

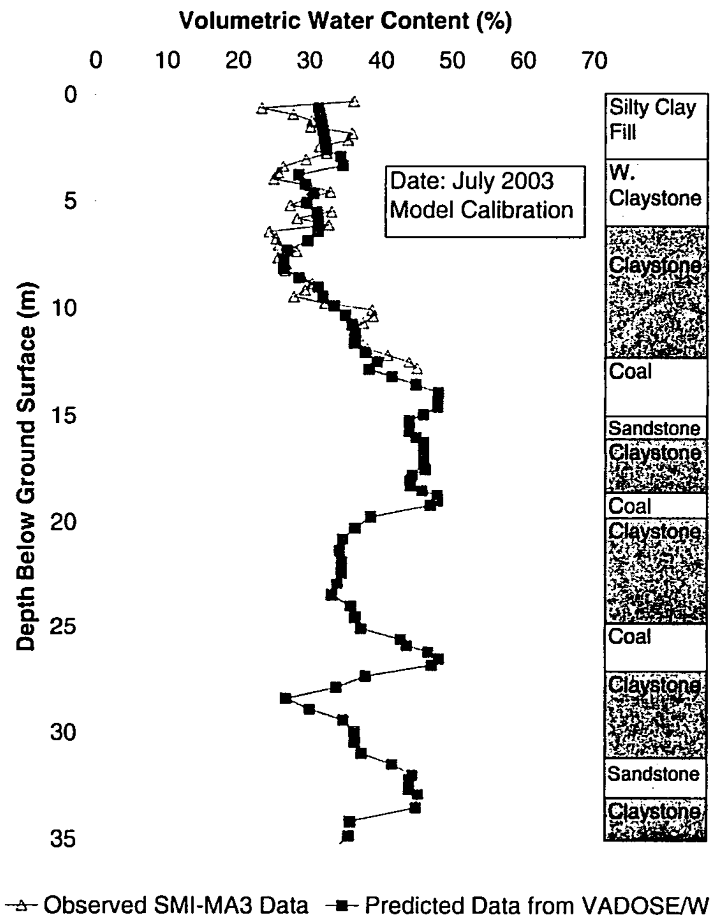


Figure 6-6 Measured and Predicted Water Content Profiles for SMI-MA3 in July 2003

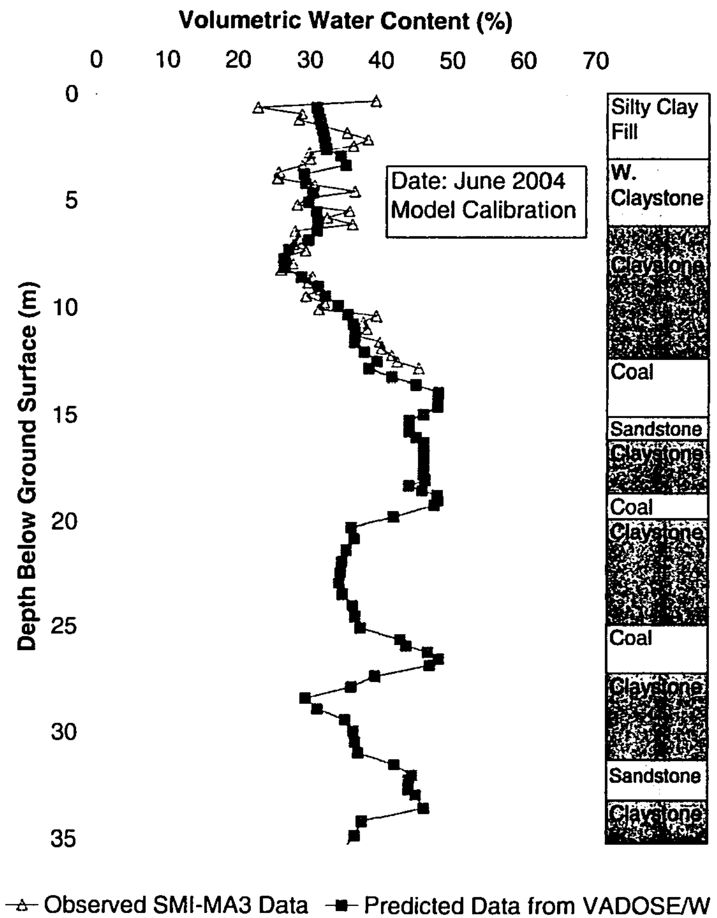


Figure 6-7 Measured and Predicted Water Content Profiles for SMI-MA3 in June 2004

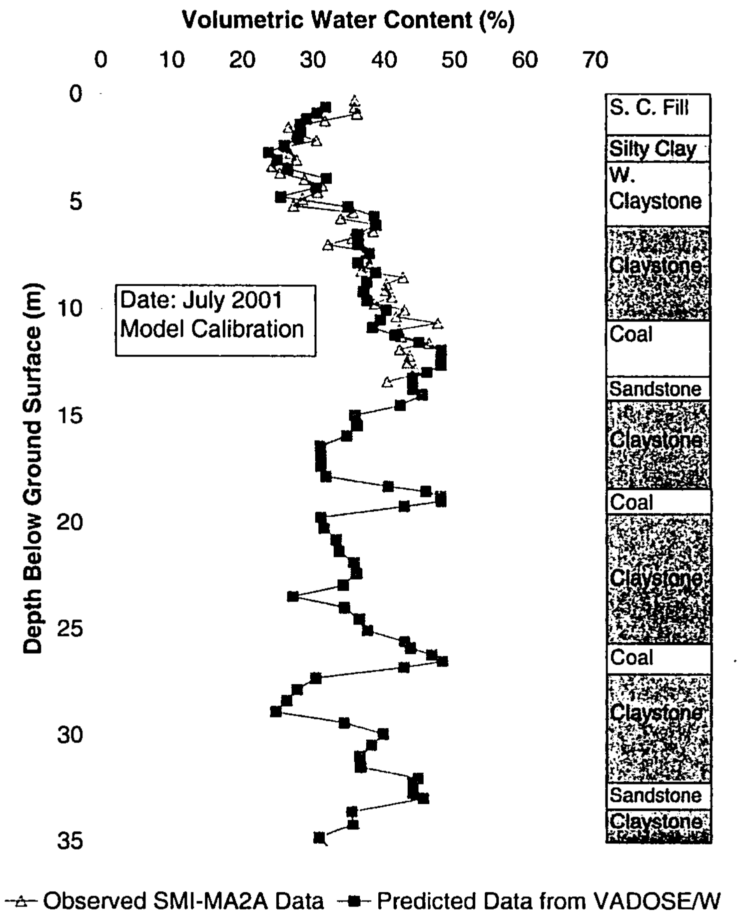


Figure 6-8 Measured and Predicted Water Content Profiles for SMI-MA2A in July 2001

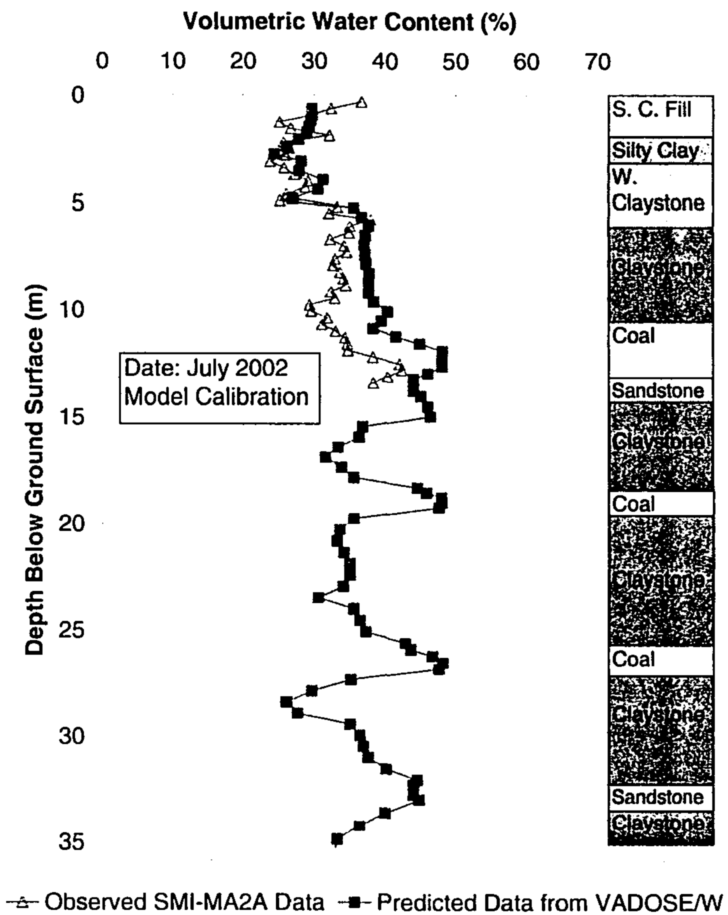


Figure 6-9 Measured and Predicted Water Content Profiles for SMI-MA2A in July 2002

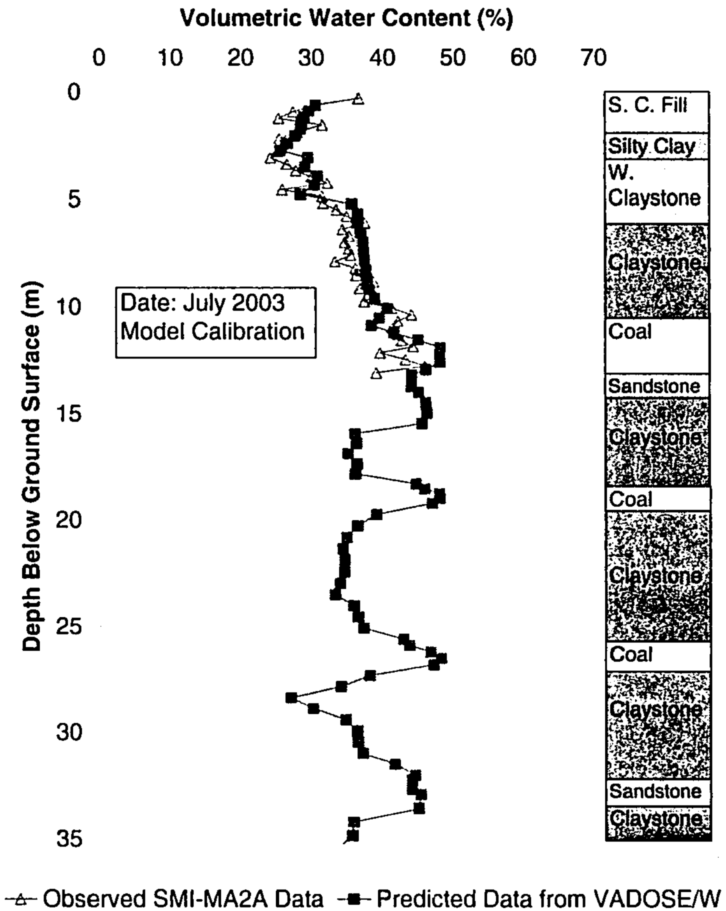


Figure 6-10 Measured and Predicted Water Content Profiles for SMI-MA2A in July 2003

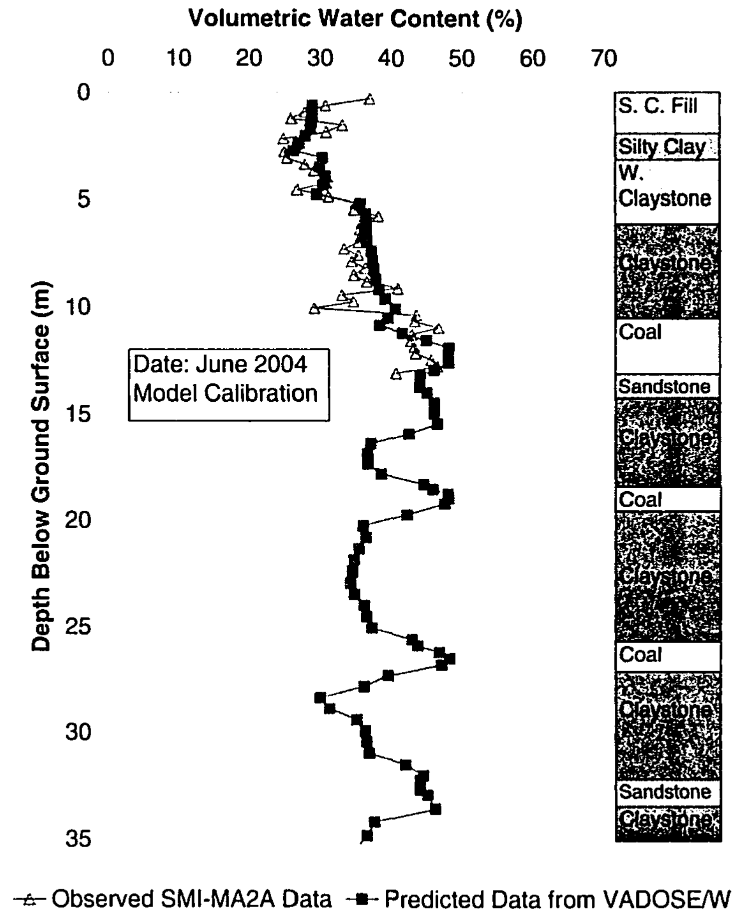


Figure 6-11 Measured and Predicted Water Content Profiles for SMI-MA2A in June 2004

6.5.3 Model Validation

The validation was performed by comparing the model output with downhole nuclear gauge data obtained in August 2006 at the locations of SMI-MA3 and MA2A. Figures 6-12 and 6-13 present the comparison between the predicted and measured volumetric water content profiles at the locations of SMI-MA3 and MA2A, respectively. In general, there is good agreement between the predicted water content distribution and the measured data. This demonstrated the consistency and validation of the model.

6.5.4 Long-Term Water Migration Simulation

The migration of water in the subsoil profile for the case of average precipitation was evaluated by applying climate data for year 1975, 1989, 1992, and 1998 as described previously. Figures 6-14 and 6-15 show the predicted water content profiles through the year 2040 at the locations of SMI-MA3 and MA2A, respectively. These figures indicate that water will continue to migrate within the soils and bedrock through the entire time period. Of particular interest is the fact that the results show that water will migrate both upward and downward from the coal seams and sandstone layers. Comparison of these figures indicates that climate conditions will influence primarily the top 6 meters below the ground surface, whereas the deeper soils are influenced by the deep wetting. This upper 6 m zone represents the zone of seasonal fluctuation.

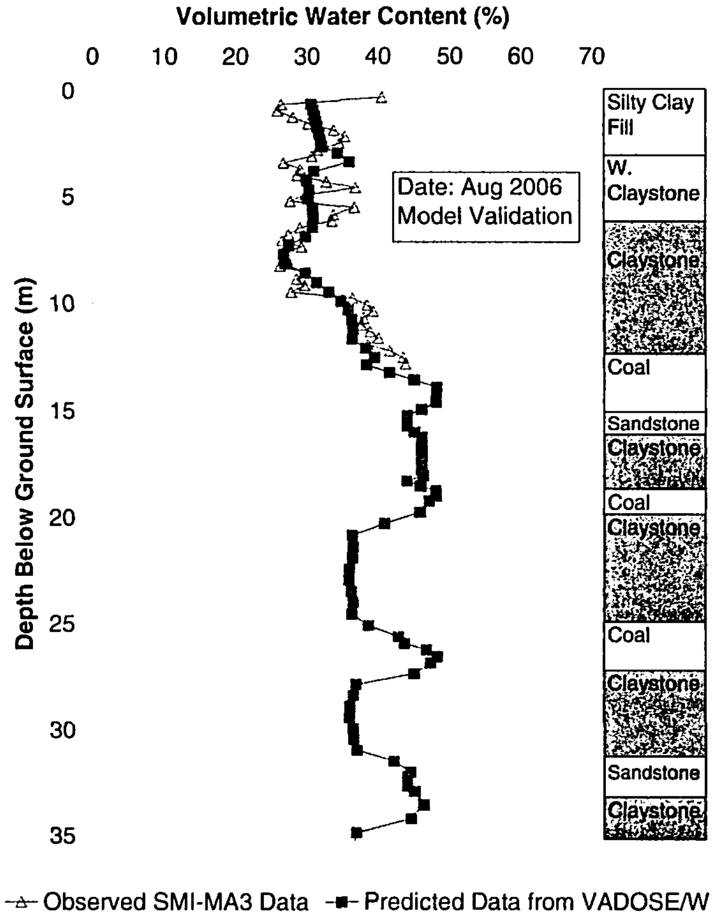


Figure 6-12 Measured and Predicted Water Content Profiles for SMI-MA3 in August 2006

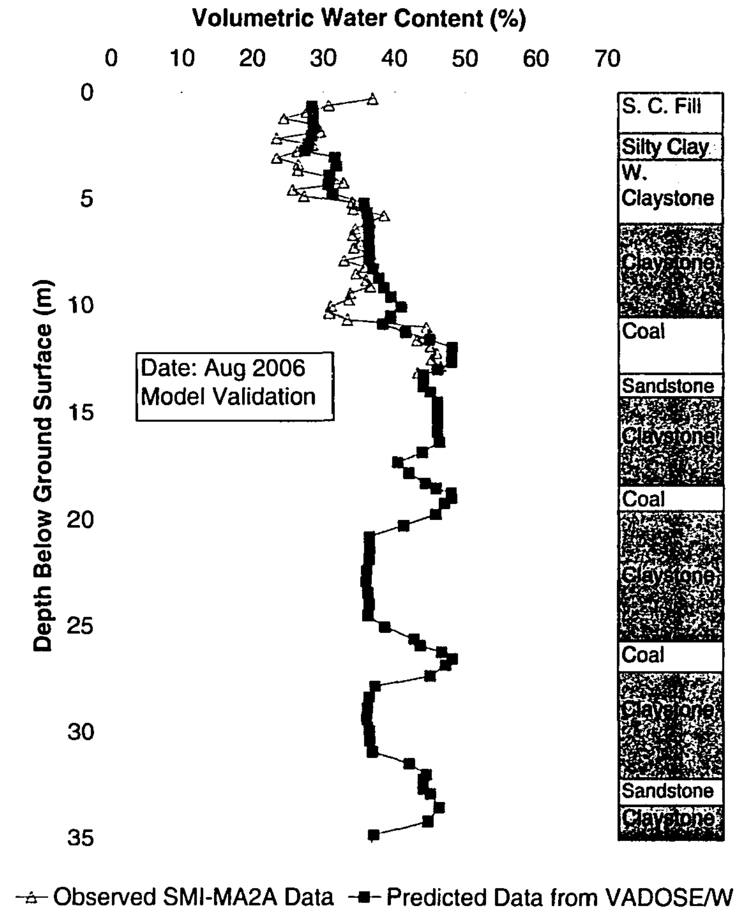


Figure 6-13 Measured and Predicted Water Content Profiles for SMI-MA2A in August 2006

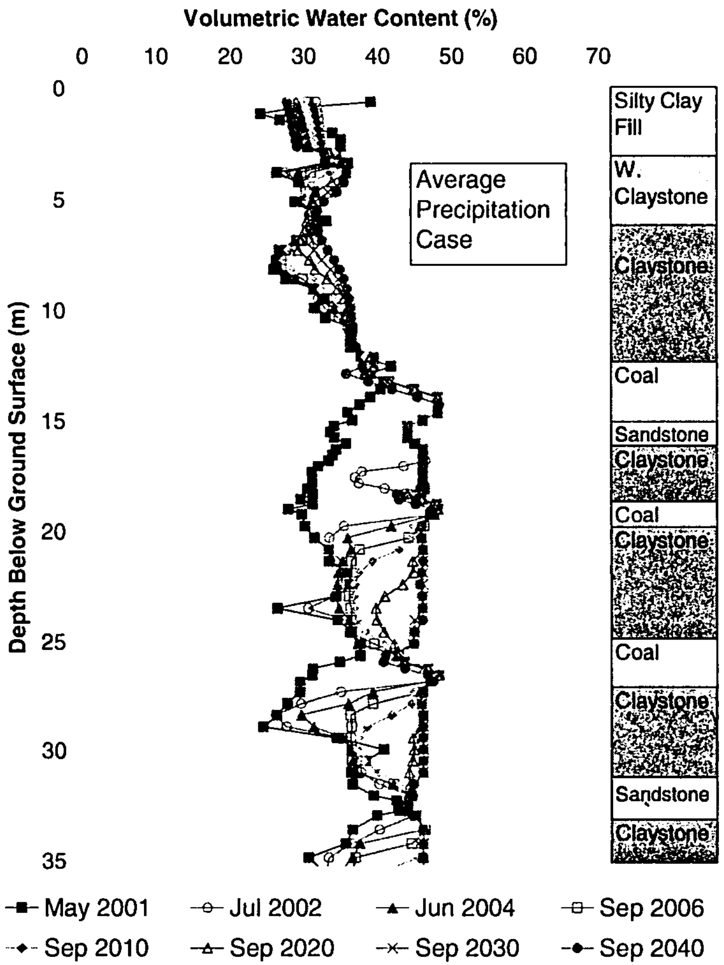


Figure 6-14 Predicted Long-Term Water Content Profiles for SMI-MA3 – Average Precipitation Case

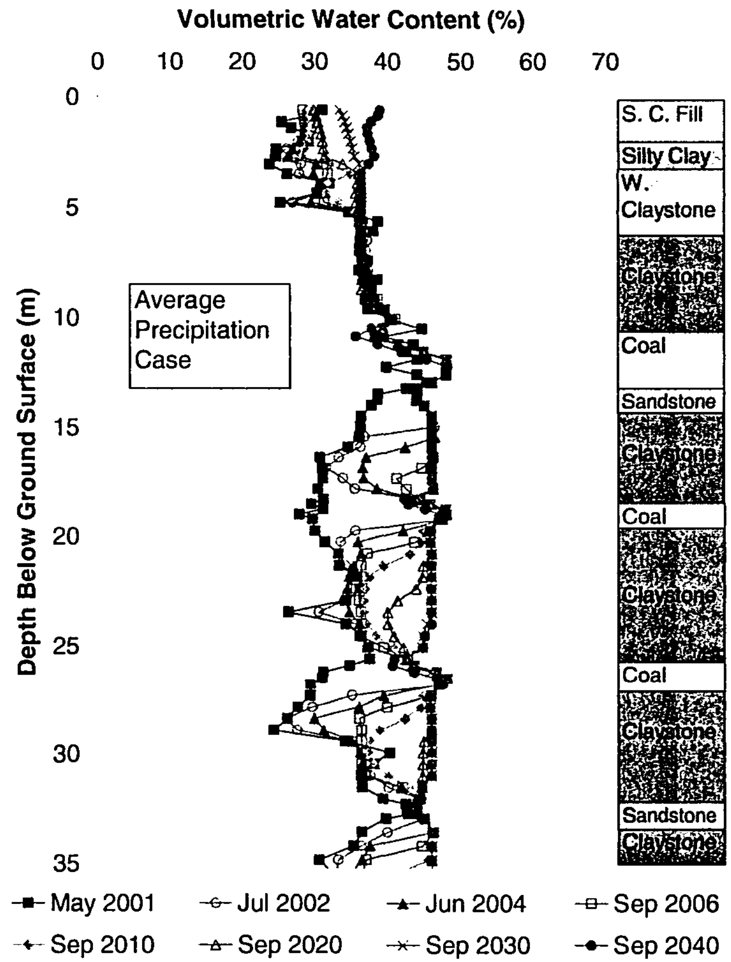


Figure 6-15 Predicted Long-Term Water Content Profiles for SMI-MA2A – Average Precipitation Case

6.6 Effect of Extraordinary Climate and Irrigation

The effects of extraordinary precipitation events and irrigation were also evaluated. Table 6-1 shows the annual precipitation values from the year 1949 to 2005. As indicated in Table 6-1, the years 1967 and 2002 exhibited the highest and lowest annual precipitation values. The annual precipitation values for these years were 59.2 and 19.0 cm, respectively. The annual precipitation for the year 1967 was approximately 52% more than the average value, and the annual precipitation for the year 2002 was approximately 51% less than the average value. Therefore, seepage analyses were conducted to evaluate the migration of soil water for both the highest precipitation year (1967 ± 2 years) and the lowest precipitation year (2002 ± 2 years).

The subsurface nuclear gauge data indicate that the amount of water in the coal seams is sensitive to changes in the amount of the precipitation. For the case of the highest precipitation, the pressure head in the coal seams was assumed to be 1.8 meters during the wet season, and 0.9 meters during the dry season. These values are approximately 1 meter higher than those for the year of average precipitation. In this case, the wet season comprised March, April, May, June, July, and August. For the case of the lowest precipitation, the pressure head in the coal seams was assumed to be 0.6 meters lower than that for the year of average precipitation. The pressure head functions specified in the VADOSE/W models for the cases of the highest and lowest precipitation are shown in Figure 6-1.

Sensitivity of water migration within the soils and bedrock to lawn irrigation was also evaluated in this research. Irrigation was applied to the ground surface in the

VADOSE/W model in addition to the precipitation for the case of average precipitation. The irrigation was applied in the months of April through October at a rate of 130% of the turf grass water requirement (Mecham, 2005).

6.6.1 Highest Precipitation Case

Figures 6-16 and 6-17 show the predicted water content profiles for SMI-MA3 and MA2A through the year 2040 for the case of highest precipitation, respectively. As expected in Figures 6-16 and 6-17, water migrates at a much faster rate within the soils and bedrock through the year 2040, compared to that for the case of average precipitation. If these conditions were to continue year after year, the entire bedrock below the uppermost coal layer would be saturated after the year 2015. Comparison of Figures 6-15 and 6-17 indicates that the top 6 meters below the ground surface is subject to the most change due to the climate conditions.

6.6.2 Lowest Precipitation Case

The predicted water content profiles at the locations of SMI-MA3 and MA2A for the case of the lowest precipitation are shown through the year 2040 in Figures 6-18 and 6-19, respectively. These figures indicate that water migrates at about the same rate as that for the average precipitation case through the year 2040. Comparing Figures 6-15 and 6-19 indicates that there is little difference in the water content profiles, except in the bedrock layer close to the uppermost coal seam, for the average and lowest precipitation cases. The results of the VADOSE/W modeling demonstrate that the primary source of water for the overlying claystone bedrock is the coal seams rather than precipitation.

This was also concluded by Whitney (2003) and Benvenga (2005). Consequently, the presence of a deep water bearing stratum is significant in the migration of the subsurface water within soils and bedrock.

6.6.3 Average Precipitation Plus Irrigation Case

The predicted water content profiles through the year 2040 for the case of average precipitation plus irrigation at the location of SMI-MA2A are shown in Figure 6-20. It is shown that the top 10 meters of the soil layers could be saturated due to irrigation by the year 2020. Review of Figures 6-15 and 6-20 indicates that the water content for the case of average precipitation plus irrigation is significantly greater than that for the case of average precipitation alone. It is evident that irrigation has a significant influence on the migration of the subsurface water within the soils and bedrock.

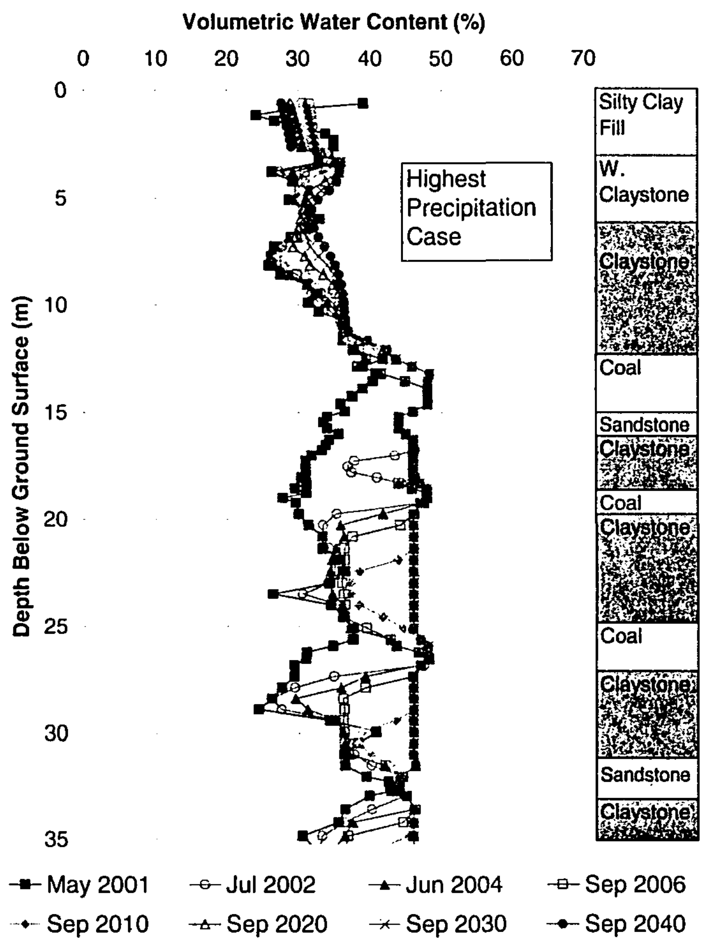


Figure 6-16 Predicted Long-Term Water Content Profiles for SMI-MA3 – Highest Precipitation Case

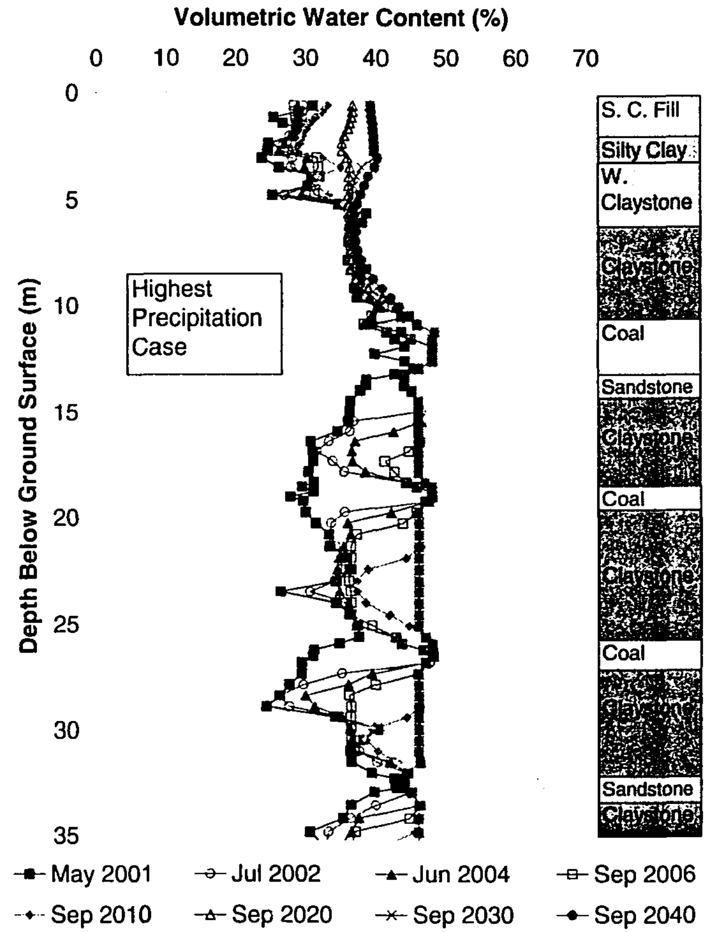


Figure 6-17 Predicted Long-Term Water Content Profiles for SMI-MA2A – Highest Precipitation Case

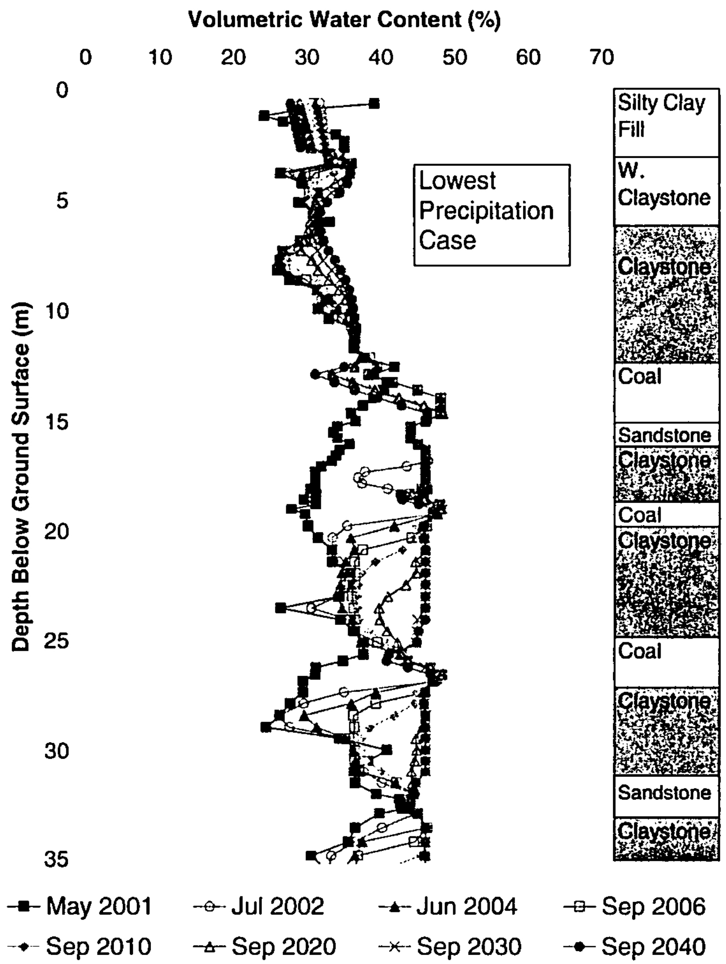


Figure 6-18 Predicted Long-Term Water Content Profiles for SMI-MA3 – Lowest Precipitation Case

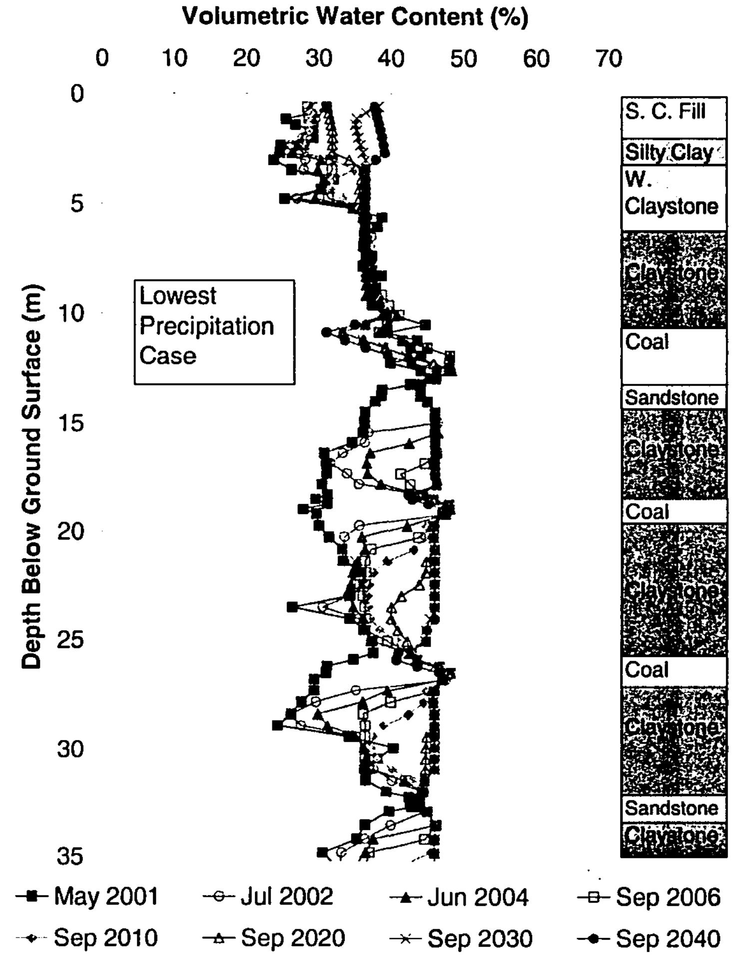


Figure 6-19 Predicted Long-Term Water Content Profiles for SMI-MA2A – Lowest Precipitation Case

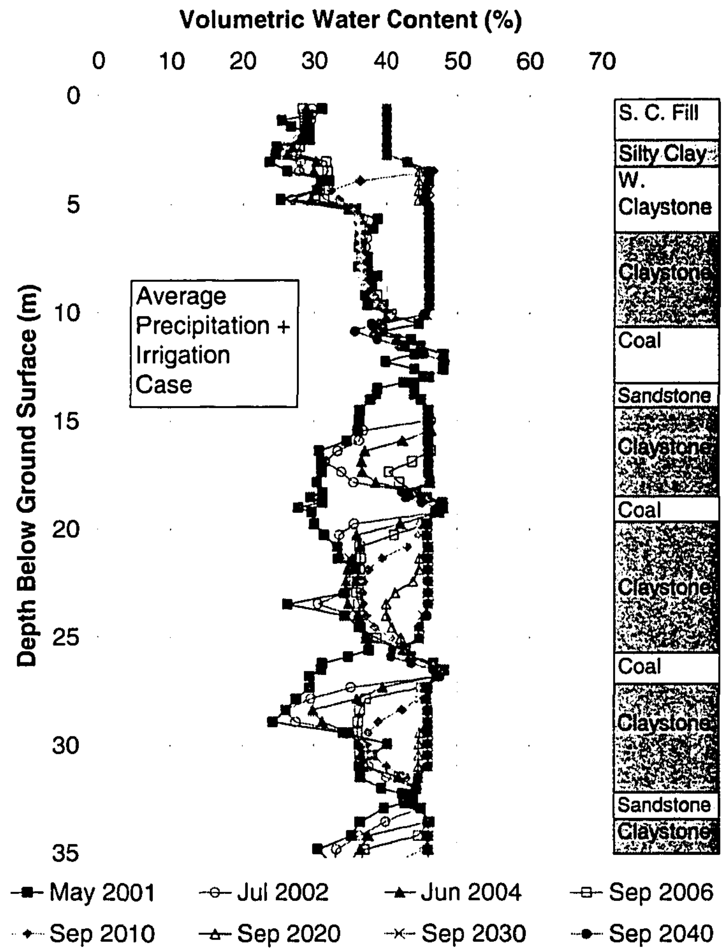


Figure 6-20 Predicted Long-Term Water Content Profiles for SMI-MA2A – Average Precipitation Plus Irrigation Case

6.7 Discussion

The migration of water in the subsoils during the design life of a structure is an important parameter in prediction of slab and pier heave. CAGE guidelines only consider wetting from the surface to a depth of wetting of 6 meters (CAGE, 1996). Practicing engineers in the Front Range area of Colorado often use this arbitrary depth of wetting for their design. Experience has shown that many sites exist where the depth of wetting has exceeded 6 meters (Nelson, et al. 2001; Diewald, 2003). Water will continue to move downward as long as the total potential of the soil above the wetting front is higher than that below the wetting front until a truly impermeable boundary or a water table is reached. It is evident that the actual depth and pattern of wetting that must be considered for design purposes will depend upon subsurface soil and geologic profiles, water sources, irrigation practices, surface grading, as well as other factors.

The coal seam is shown to be the primary water source for the overlying claystone bedrock at the TRACON site. The sensitivity of the results to the pressure head functions specified in the coal seams show that the presence of a deep water bearing stratum is significant in the migration of water within the soils and bedrock. This emphasizes the necessity to identify any deep water bearing stratum during the design process.

The results of the water migration analyses indicate that depth of wetting at the TRACON site will continue to increase throughout the design life of the structure in 2040. Observations of continuous core samples in claystone indicate that soil adjacent to bedding planes is often wet. This demonstrates that water migrates outward from the bedding planes into the zones between the bedding planes. As water continues to migrate into deeper bedding planes along the joints and cracks, an apparent "wetting front" will continue to move downward, and the claystone at deeper depths will increase in water content.

The water migration analyses were performed using calibrated and validated input parameters and boundary conditions in the VADOSE/W models. The results of the validation process show that there is a good agreement between the predicted water content distribution and the measured data demonstrating model consistency and validation with respect to the data set used. Rigorous water migration analyses can be performed to analyze the actual depth of wetting in soils during the design life of a structure. Unless site specific analyses can be performed to accurately determine the rate and pattern of subsoil wetting, a prudent designer should assume that the entire depth of potential heave is wetted during the design life of the structure. Although limitations may be placed on owners of structures regarding grading and irrigation practices, it is important to consider the potential that the owners will use the property in a manner that is not in consistent with the engineering design criteria.

CHAPTER 7

PREDICTION OF CHANGE OF SLAB AND PIER HEAVE WITH TIME

7.1 Total Heave Prediction

7.1.1 Maximum Slab Heave

Free-field heave is a basic parameter for design of foundations for sites on expansive soils. The heave of slabs-on-ground is equal to the free-field heave. Also, predicted pier heave is normalized against free-field heave. Therefore, the first step for design of foundations is to compute predicted free-field heave. Maximum slab heave was predicted using the oedometer methodologies presented in Nelson, et al. (1998 and 2006), as discussed in Section 2.3.3.

Predicted maximum future slab heave since the time of construction (i.e. maximum total heave) was calculated at each pier location of the TRACON building based on the subsoil data obtained from the six boreholes drilled around the building. The amount of heave that had occurred from the time of construction to the time of drilling that was estimated by ZBSI (ZBSI, 2001) was also taken into account. The soil profiles and parameters used to complete the calculations for each pier location were interpolated from the data at the six borehole locations.

Contours of the predicted maximum total slab heave since the time of construction are shown in Figure 7-1. The predicted maximum total slab heave ranges from 22.2 cm at Pier A-4.2 (F03) to 56.2 cm at Pier H-17 (F81). It is predicted that the maximum total slab heave will occur at the eastern corner of the building, and that have will decrease toward the western portion of the building.

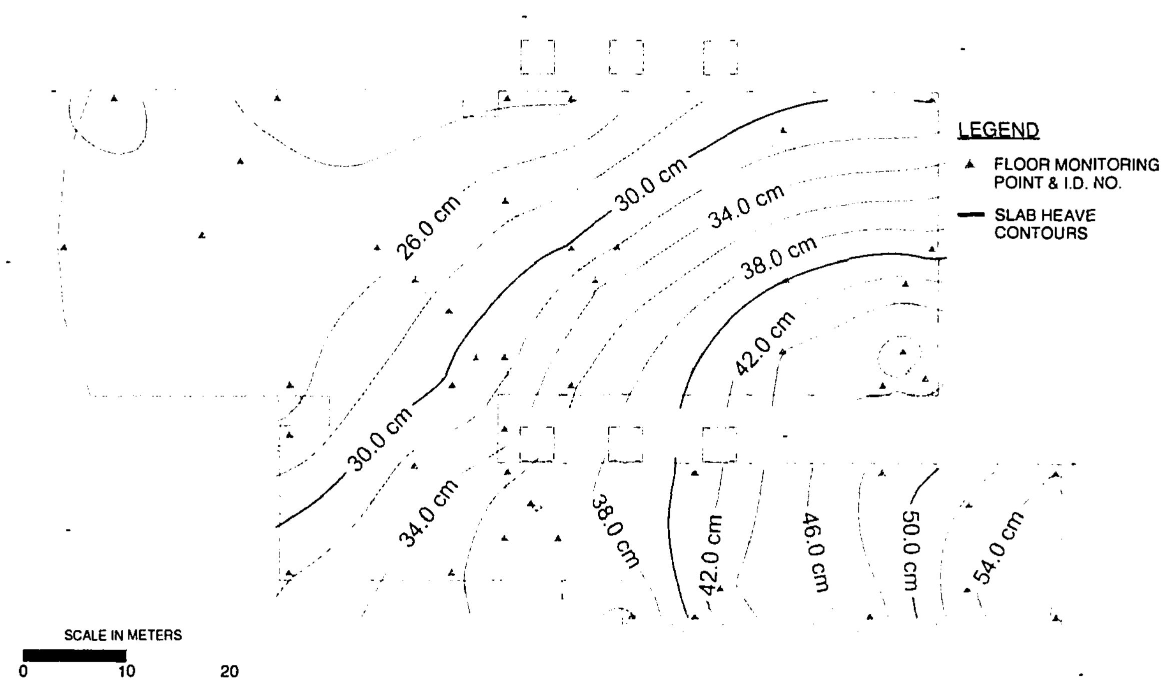


Figure 7-1 Contours of Predicted Maximum Slab Heave Since the Time of Construction

7.1.2 Maximum Pier Heave

A total of 146 straight shaft piers were designed for the TRACON building. In the prediction of pier movement, the pier diameter, pier length, and dead load on the pier were taken into account. According to foundation details of the TRACON design drawings, pier diameters ranged from 46 to 76 cm and pier lengths ranged from 7.6 to 8.5 meters. The dead loads on the piers were computed by the Department of Civil, Environmental and Architectural Engineering, University of Colorado, Boulder, Colorado (CU, 2000). The maximum total pier heave was predicted using the solution for pier movement in an elastic medium that was developed by Poulos and Davis (1980) and modified for design use by Nelson and Miller (1992), and Nelson, et al. (2007b). This was described previously in Section 2.4.2.1. Input data for the calculations were obtained from laboratory test data obtained from soil samples taken from the six boreholes, and the amount of heave that had occurred from the time of construction to the time of drilling as estimated by ZBSI (ZBSI, 2001). Conditions of uniform pier-soil strength within each stratigraphic unit were assumed.

Contours of the predicted maximum future pier heave since the time of construction for the TRACON building are shown in Figure 7-2. Pier heave of the existing 146 piers was predicted to range from 13.0 cm at Pier A-12 (C12) to 50.3 cm at Pier G-15 (C83). Figure 7-2 indicates that the maximum future pier heave will occur at the eastern portion of the building, following a trend similar to that for the maximum slab heave.

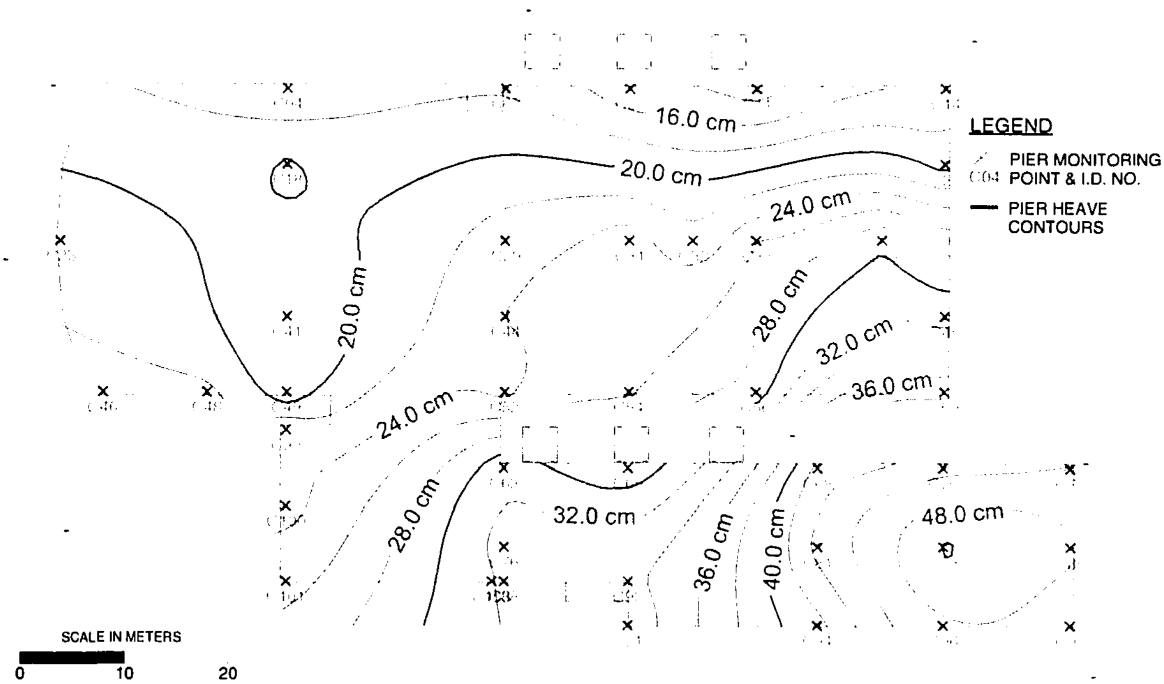


Figure 7-2 Contours of Predicted Maximum Future Pier Heave Since the Time of Construction

7.2 Change of Slab and Pier Heave with Time

Slab and pier heave will vary with time. In soil profiles where shrink-swell behavior is present, heave will occur during wet periods and decrease during dry periods. In the dense, highly expansive claystones existing along the Front Range area of Colorado, shrinkage is small or non-existent. The general pattern of heave in soil/bedrock profiles is for heave to continue to increase with time, although it will occur more rapidly during wet periods and slow down during dry periods. At the TRACON site, the effect of climate on the water present in the coal seams has a large influence.

The change in slab and pier heave with time was analyzed using two different methods of analysis. One was to fit the existing survey data to a hyperbolic equation and then use that to project the predicted heave over time. The second method was to analyze the timewise migration of subsoil water in the manner presented previously, and then relate heave to changes in water content. These methodologies are described below.

7.2.1 Heave Prediction Using Hyperbolic Relationship

7.2.1.1 Methodology of Heave Prediction Using Hyperbolic Relationship

The change of heave of the slabs and piers with time was analyzed by fitting the observed survey data during monitoring to a hyperbolic function. The floor and pier heave since September 2000 was surveyed by ZBSI as discussed previously. The as-built elevations at the slab and pier monitoring points were determined by ZBSI based on the initial surveying performed by Bell Surveying and/or design drawings (ZBSI, 2001). Thus, a function of the following form was used to predict heave as a function of time since the time of construction:

$$\rho = \frac{t}{a + bt} \qquad \text{Equation (7-1)}$$

where:

ρ	=	slab or pier heave since the time of construction,
a and b	=	curve parameters, and
t	=	the time since movement began.

Taking the limit of Equation (7-1) as t approaches infinity shows that the maximum heave approaches a value of 1/b.

Equation (7-1) can be rewritten in the form:

$$\frac{1}{\rho} = \frac{a}{t} + b \qquad \text{Equation (7-2)}$$

Equation (7-2) shows that for this function, $1/\rho$ is a linear function of $1/t$. The curve parameters a and b are the slope and the intercept, respectively, of the linear function. The parameters a and b can then be determined by plotting $1/t$ vs. $1/\rho$ in the form of Equation (7-2). The intercept of the plotted data will equal b and the slope of the line is a.

When plotting the data to Equation (7-2), it is necessary to know the time at which heave at the ground surface actually began. This time, t_o, was not able to be determined accurately by observation. What was known was that it occurred at some time during construction.

Also, it was necessary to assure some bond of the extrapolated data, and therefore, the value of b was taken as the reciprocal of the calculated value of maximum total heave. Thus, the survey data was plotted in the form of Equation (7-2) using the calculated b values for different dates for the point at which $t = 0$. Regression analyses were conducted for the various data plots and the values of a and t_0 that provided the best fit to the linear plots were used to determine the date at which slab or pier movement first began (i.e., the date at which $t = 0$). The TRACON building was built in approximately 1991. Therefore, the first assumed date corresponding to $t = 0$ was January 1991. The data was plotted also for successive dates of t_0 on monthly increments. The data for which the plotted data exhibited the best value of the coefficient of determination, r^2, was taken as the date for t_0.

The rate of heave can be obtained by taking the derivative of Equation (7-1). The first derivative of the Equation (7-1) is.

$$\dot{\rho} = \frac{1}{a + bt} - \frac{bt}{(a + bt)^2} \qquad \text{Equation (7-3)}$$

where: $\dot{\rho}$ = rate of heave

7.2.1.2 Results of Heave Prediction

Heaving of the floor and pier was surveyed by ZBSI from September 2000 to June 2006, a period of 70 months. During this period, 64 sets of data were collected. The slab and pier heave data was initially plotted in the hyperbolic form using only the first 11-month set of survey data from September 2000 to July 2001. The scenario of the 11-month survey data was selected for initial analysis, because this was the data available when the first analysis was done. Also, this is usually the general period of time for which data is available in practice. The effect of using longer survey periods on the results of plotting the data in hyperbolic form will be discussed below.

7.2.1.2.1 Change of Slab Heave with Time

The plot of the slab heave survey data for the first 11-month set of data is shown in Figure 7-3 for the Floor Monitoring Point F81. Monitoring Point F81 was selected for illustration, as it is the floor monitoring point at which the most observed heave has occurred. In Figure 7-3, the parameter, a, is equal to 206.45 days/cm and b is equal to 0.0178 cm^{-1}.

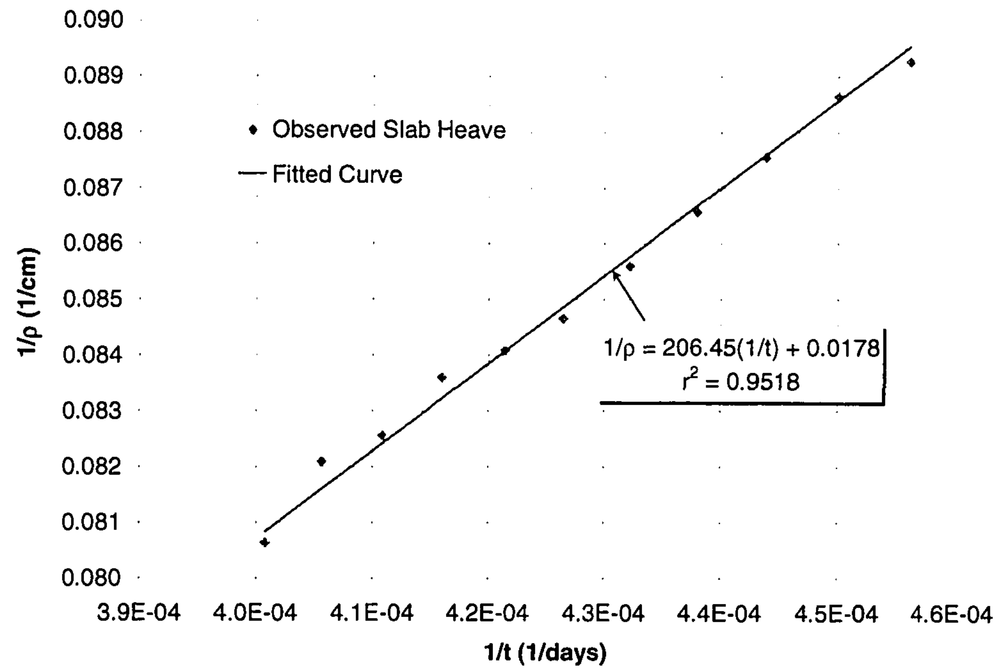


Figure 7-3 Hyperbolic Plot of Slab Heave Since the Time of Construction – Floor Monitoring Point F81

As discussed above, the slab movement at Floor Monitoring Point F81 was initially assumed to have begun in January 1991. Dates for t = 0 were assumed at monthly increments until the best value of r^2 for the regression analysis was obtained. Figure 7-4 shows the various values obtained for r^2 plotted against the date corresponding to t_0. It is seen that the best correlation is obtained for a date of September 1992 for t_0. This indicates that the slab at Point F81 most likely began to heave in September 1992. The dates when the rest of the floor monitoring points began to heave were determined using the same technique. They range from January 1991 to December 1993.

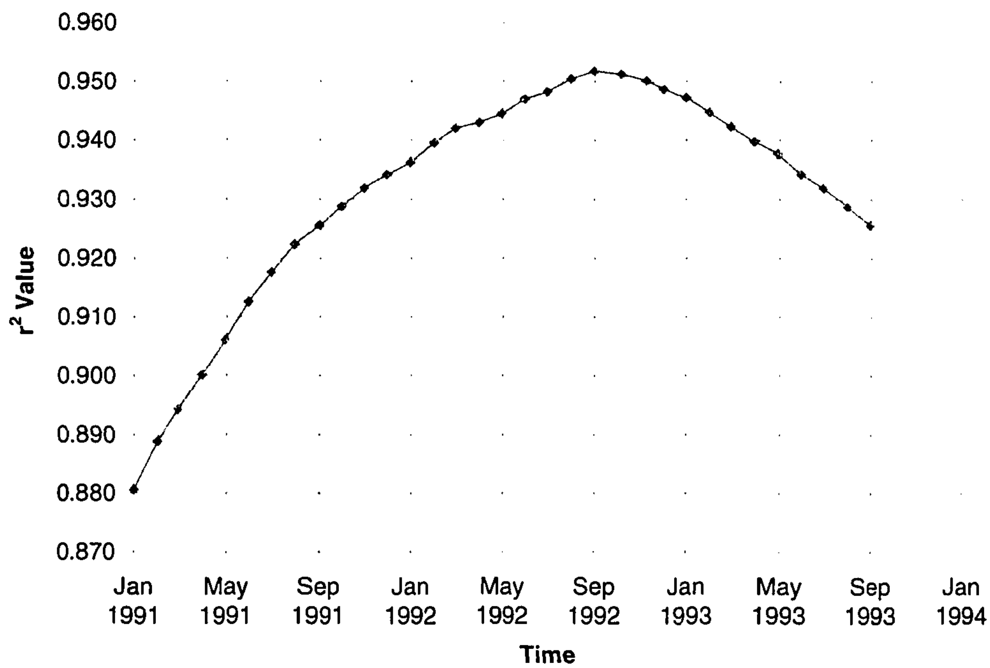


Figure 7-4 **Coefficient of Determination, r^2, vs. Time – Floor Monitoring Point F81**

Figure 7-5 shows the slab heave predicted by Equation (7-1) using the parameters shown in Figure 7-3 along with the observed heave values for the Floor Monitoring Point F81. Figures 7-3 and 7-5 indicate a good match between the observed and fitted curves by using the hyperbolic function. It is interesting to note that the predicted slab heave in 2040 is approximately 58% of the predicted maximum total slab heave at the location of Point F81.

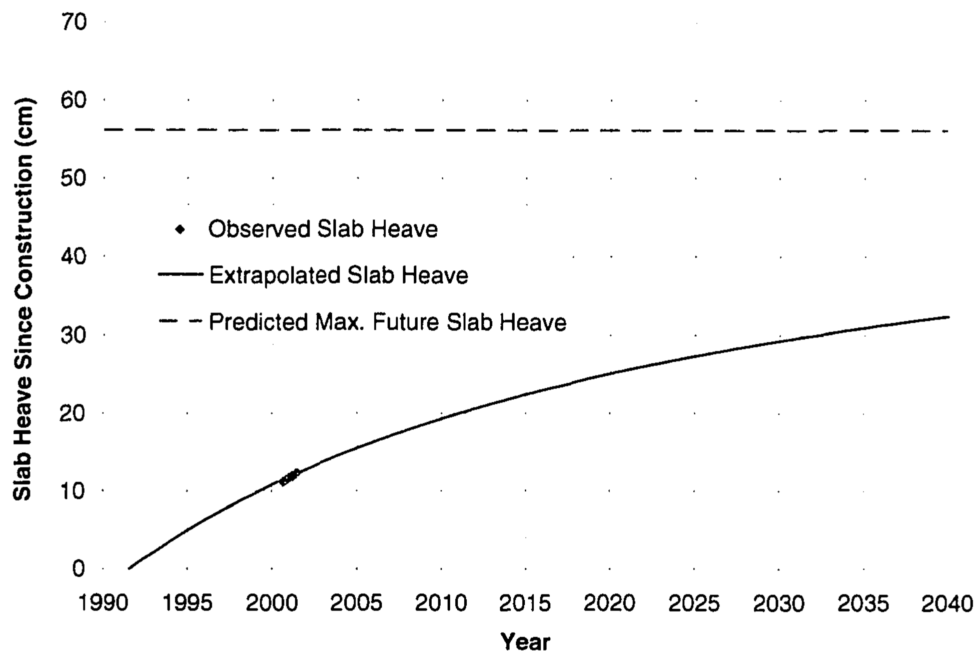


Figure 7-5 Observed and Predicted Slab Heave Since the Time of Construction – Floor Monitoring Point F81

The survey data for total slab heave for all of the 50 floor monitoring points were fitted to the hyperbolic function using the same procedure. Total slab heave for each floor monitoring point was computed from the hyperbolic equation for the time period up to the year 2040. Contours of the total slab heave for the years 2010, 2020, 2030, and 2040 are shown in Figures 7-6 through 7-9, respectively. Figures 7-6 through 7-9 show that the maximum slab heave has occurred at Point F81 in the Environmental Wing. The predicted maximum values of total slab heave as of 2010, 2020, 2030, and 2040 are 19.3, 25.1, 29.3, and 32.5 cm, respectively. Those figures also show that the values of the predicted slab heave generally decreases toward the west of the TRACON building.

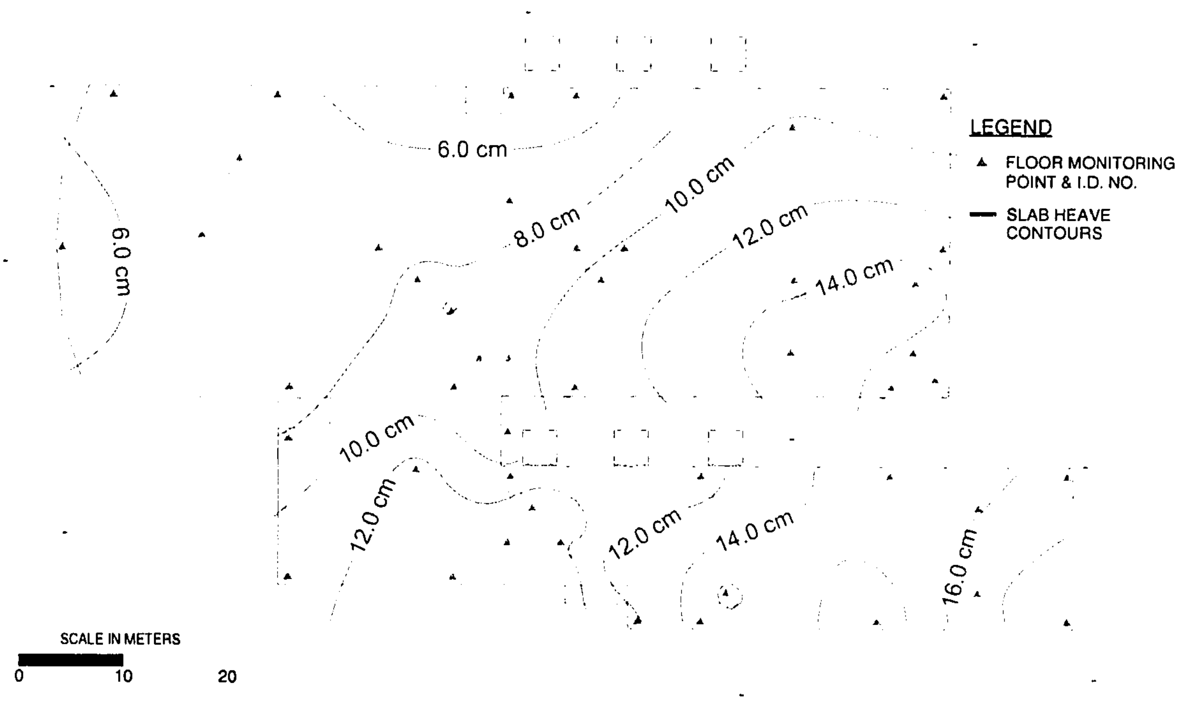


Figure 7-6 **Contours of Predicted Slab Heave from the Time of Construction (1991) to January 2010**

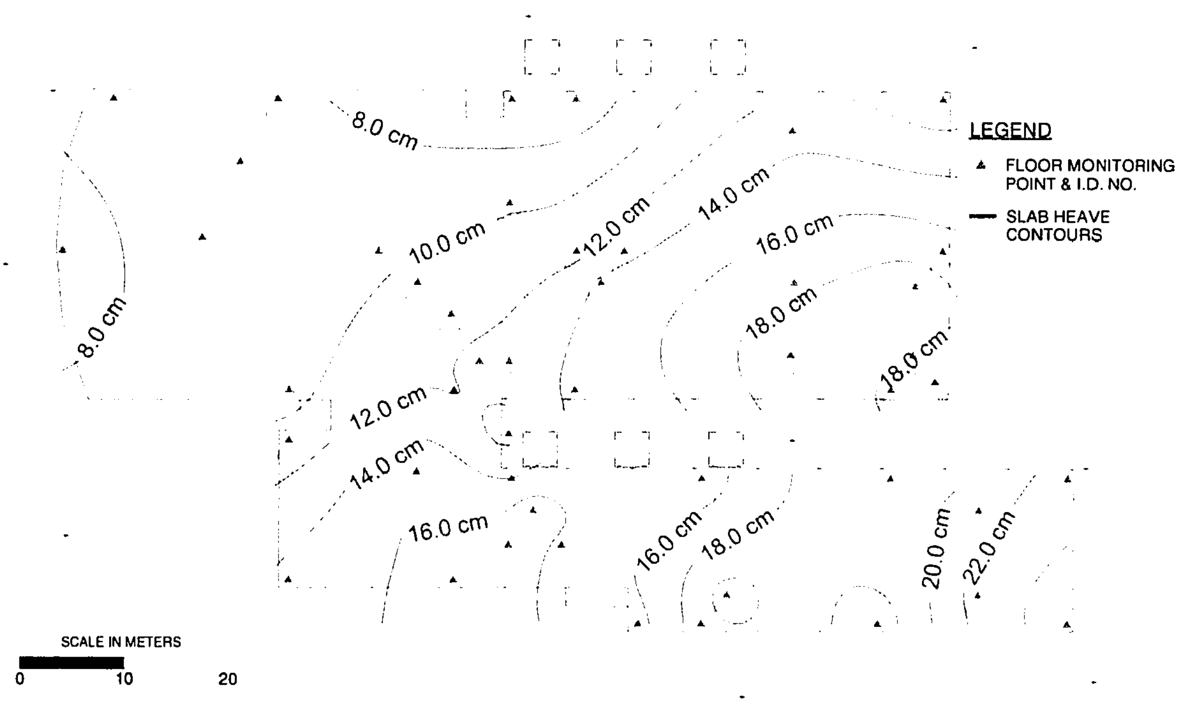


Figure 7-7 **Contours of Predicted Slab Heave from the Time of Construction (1991) to January 2020**

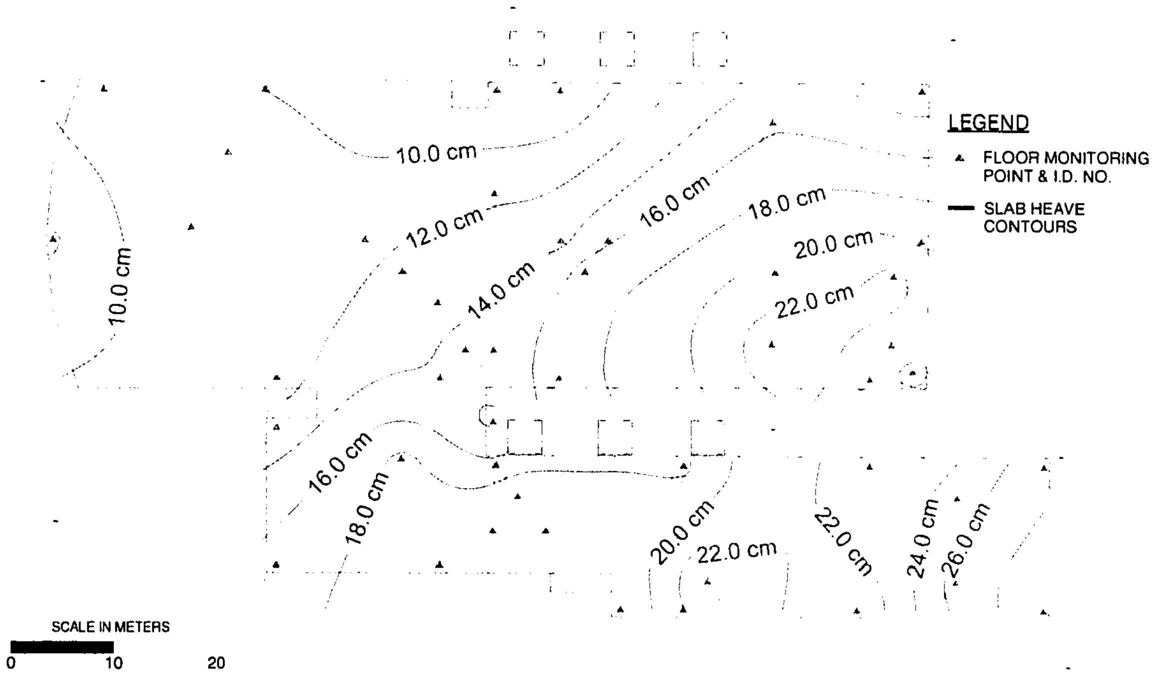


Figure 7-8 Contours of Predicted Slab Heave from the Time of Construction (1991) to January 2030

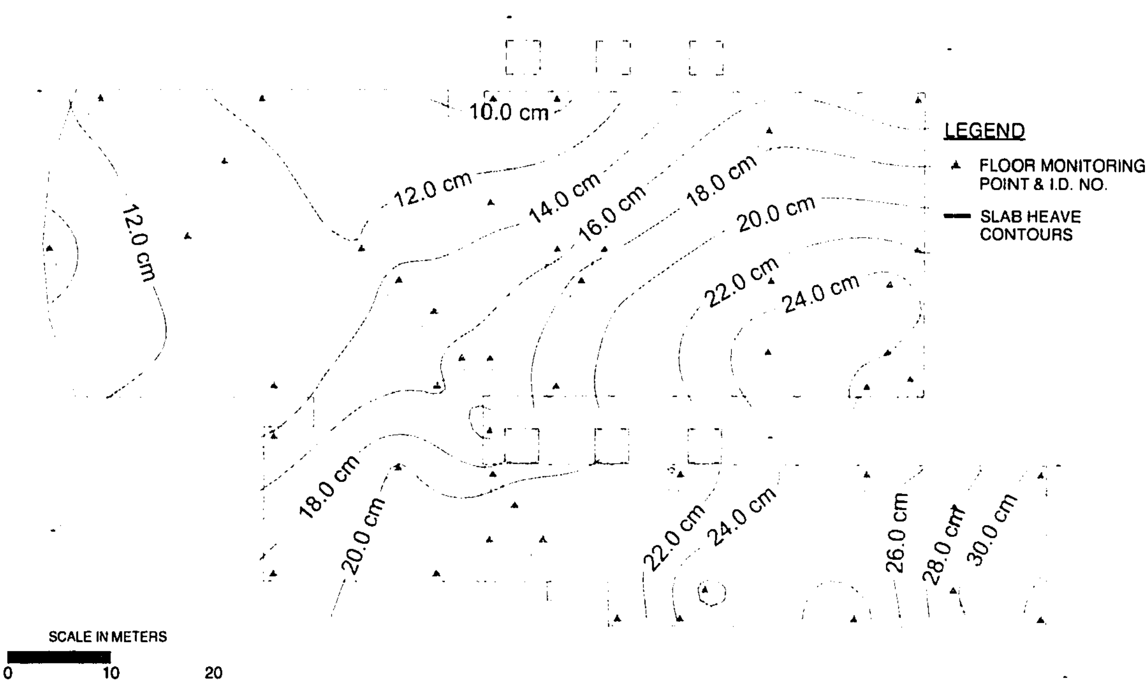


Figure 7-9 Contours of Predicted Slab Heave from the Time of Construction (1991) to January 2040

The rate at which slab heave is occurring, and is predicted to occur in the future, was calculated using Equation (7-3) for several typical floor monitoring points in each wing of the TRACON building. Figure 7-10 shows the rate of slab heave as a function of time. The average heave rate at the time heave began was equal to 0.8 cm/year. The current average slab heave rate is approximately 0.4 cm/year, which is about the same as the observed current heave rate shown in Figure 3-15. The data shown indicates that the average slab heave rate for the TRACON building is expected to reach 0.2 cm/year in approximately 2033. At point F81, the rate of slab heave will be about 0.3 cm/year even at the year 2040, the design life of the structure.

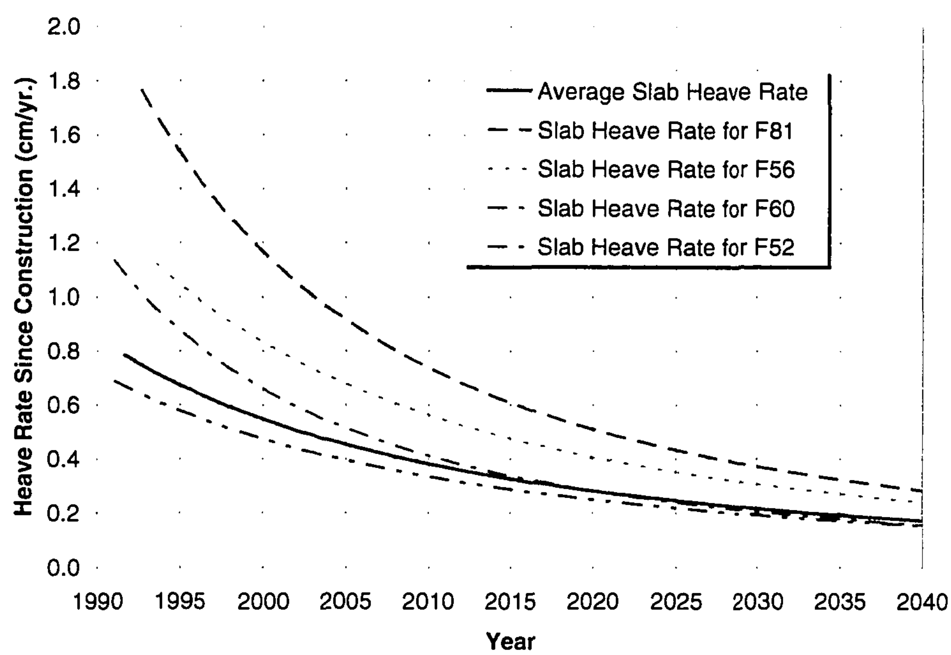


Figure 7-10 Predicted Rate of Slab Heave as a Function of Time

7.2.1.2.2 Change of Pier Heave with Time

The plot of the pier heave survey data for the first 11-month set of data is shown in Figure 7-11 for the Pier Monitoring Point C85. Point C85 is the pier monitoring point at which the greatest amount of heave has been recognized from the beginning of monitoring. Figure 7-11 shows the parameter, a, is equal to 251.65 days/cm and b is equal to 0.0207 cm^{-1}. The dates when the piers began to heave (t = 0) were determined using the same technique as described for the slab heave. The dates range from January 1994 to December 1997. It is important to note that the inception of pier heave lags the slab heave by about 3 to 4 years in this case. Longer lag times are possible depending on soil conditions (Nelson, et al., 2001)

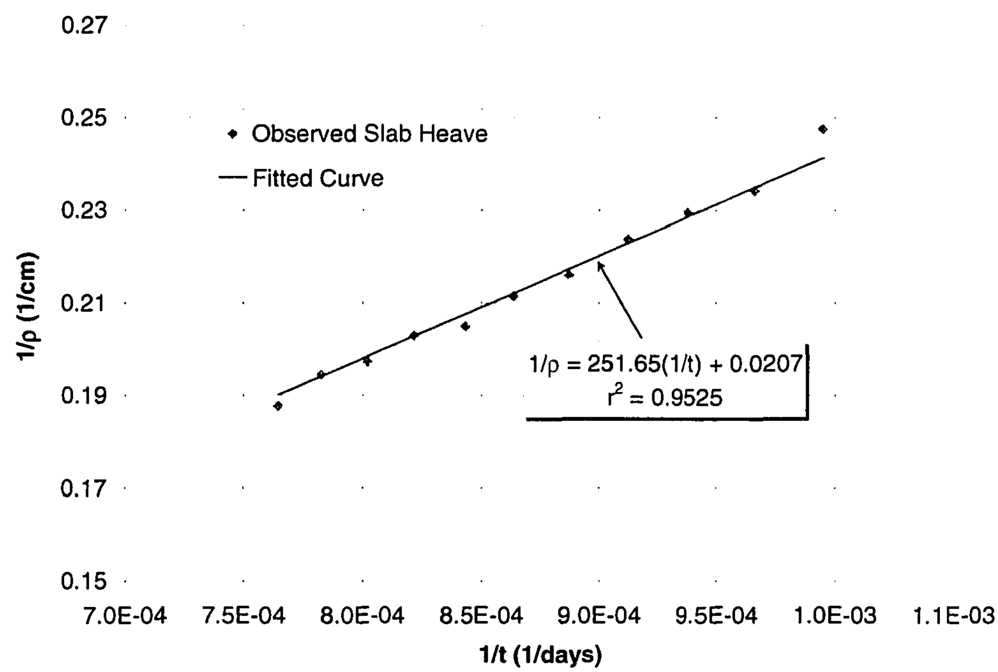


Figure 7-11 Hyperbolic Plot of Pier Heave Since the Time of Construction – Pier Monitoring Point C85

Figure 7-12 shows the observed heave data and the pier heave predicted by Equation (7-1) for Point C85 using the parameters shown in Figure 7-11. Figures 7-11 and 7-12 show a good match between the observed and fitted curves by using the hyperbolic function.

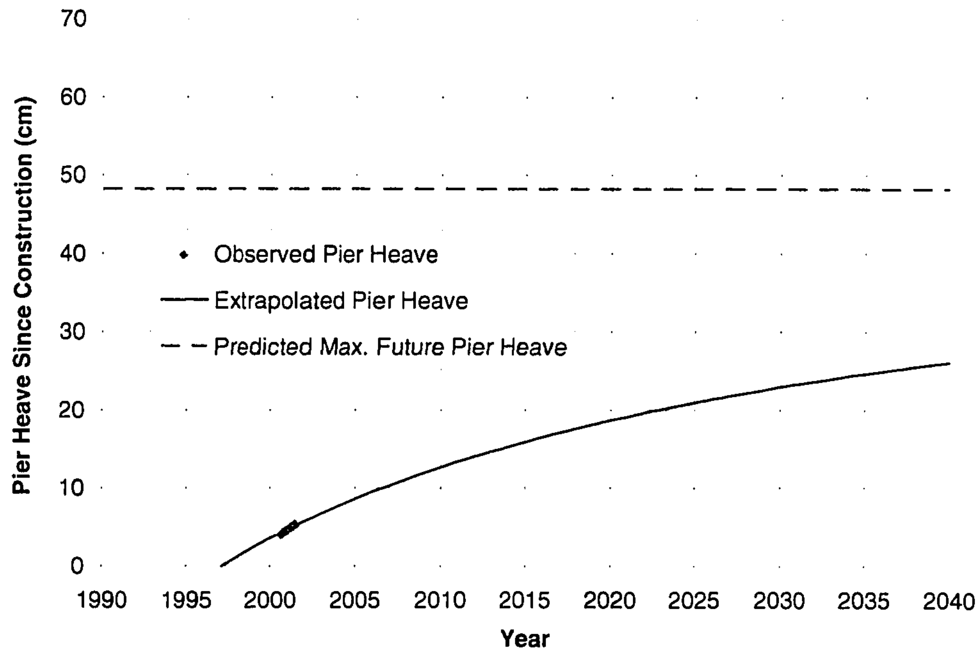


Figure 7-12 Observed and Predicted Pier Heave Since the Time of Construction – Pier Monitoring Point C85

The predicted total pier heave was computed for all of the 50 column monitoring points. Total pier heave at each monitoring point was computed for the time period up to the year 2040. Contours of the total pier heave computed using the hyperbolic equation are shown in Figures 7-13 through 7-16 for the years 2010, 2020, 2030, and 2040, respectively. These figures show that the maximum pier heave occurred at Point C83 in the Environmental Wing. The maximum values of the predicted pier heave as of 2010, 2020, 2030, and 2040 are 17.0, 22.8, 26.9, and 29.9 cm, respectively. These figures also show that the values of the predicted pier heave generally decrease toward the western portion of the TRACON building.

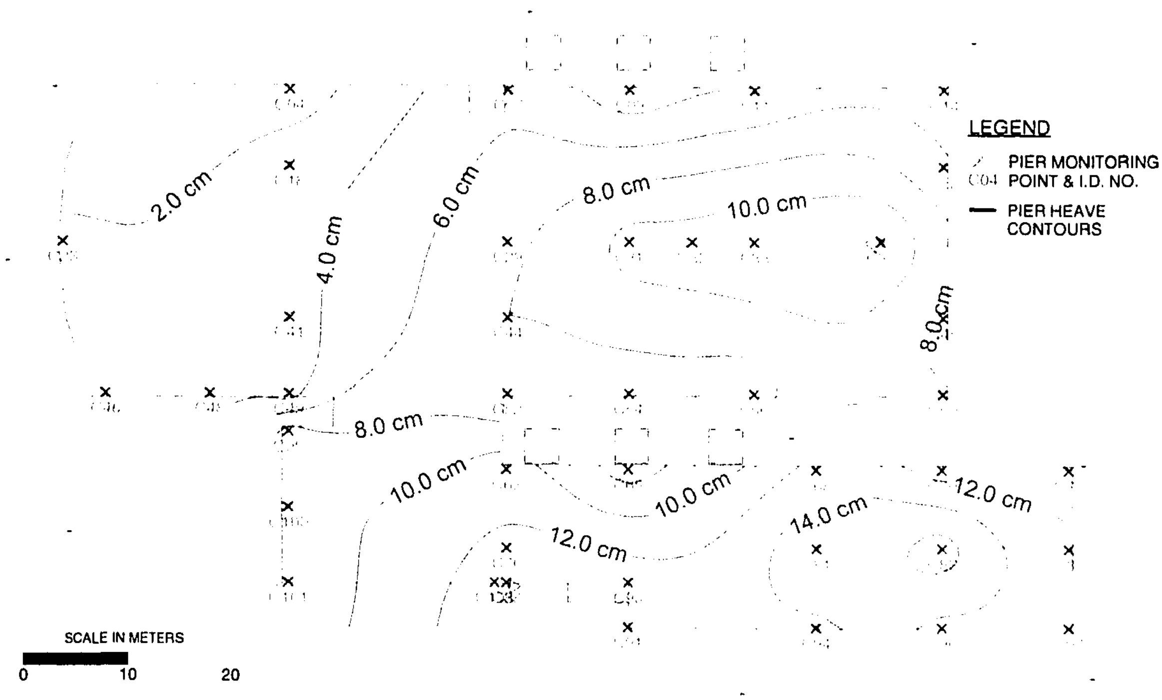


Figure 7-13 Contours of Predicted Pier Heave from the Time of Construction (1991) to January 2010

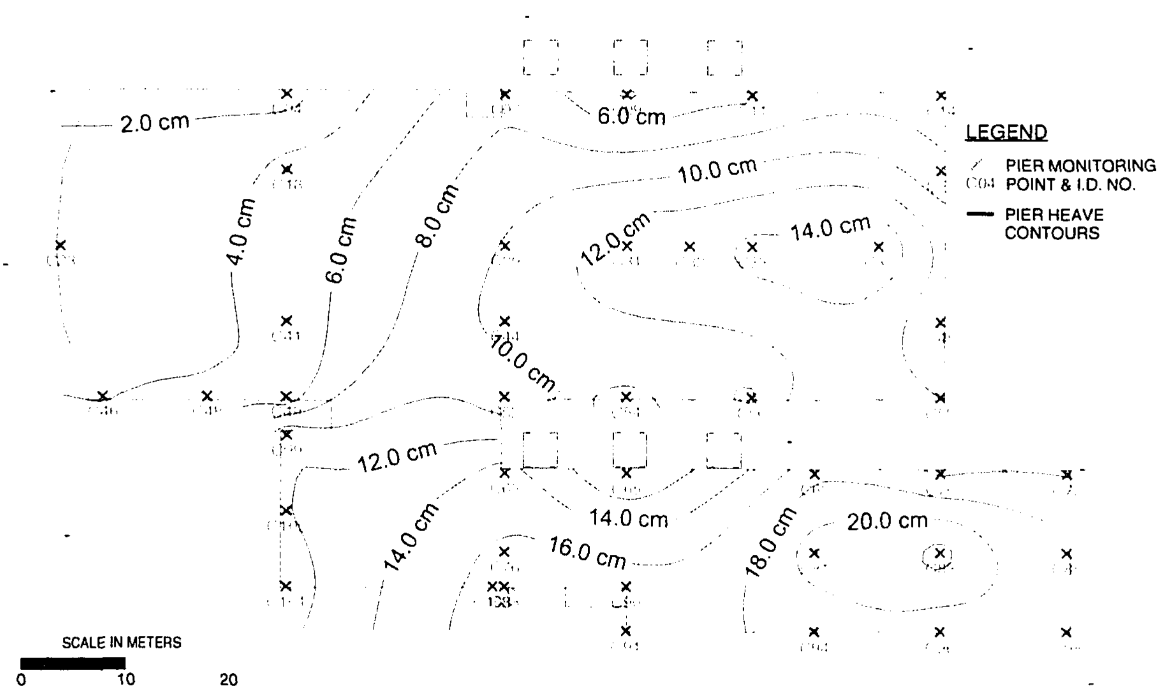


Figure 7-14 Contours of Predicted Pier Heave from the Time of Construction (1991) to January 2020

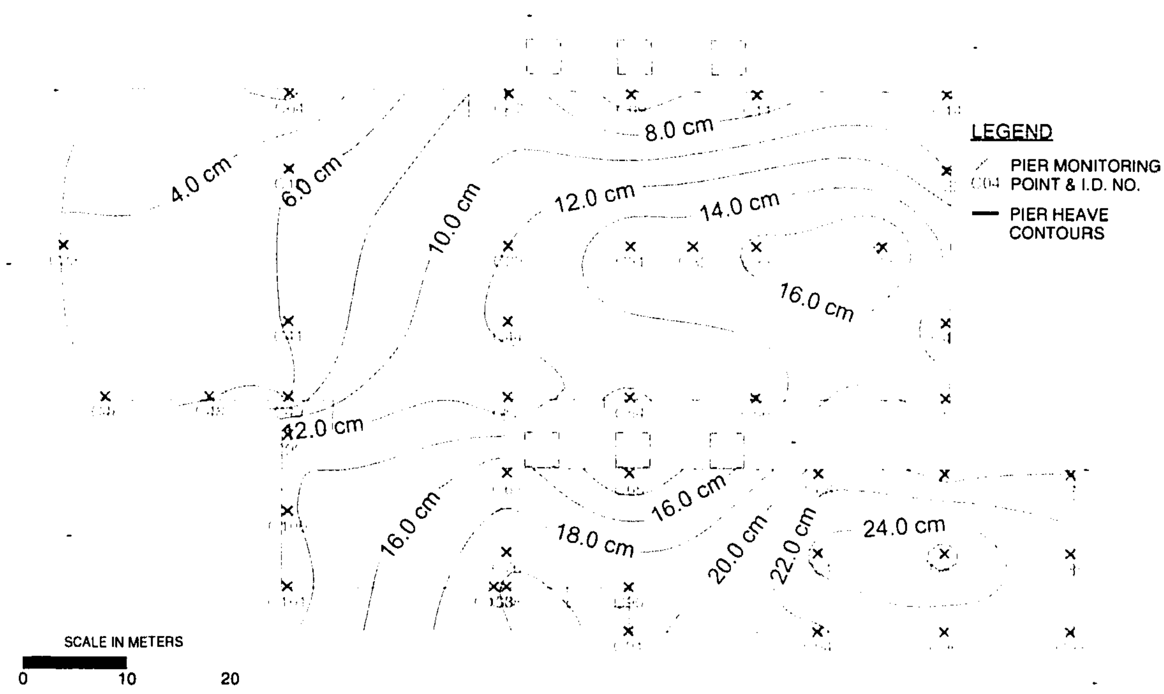


Figure 7-15 Contours of Predicted Pier Heave from the Time of Construction (1991) to January 2030

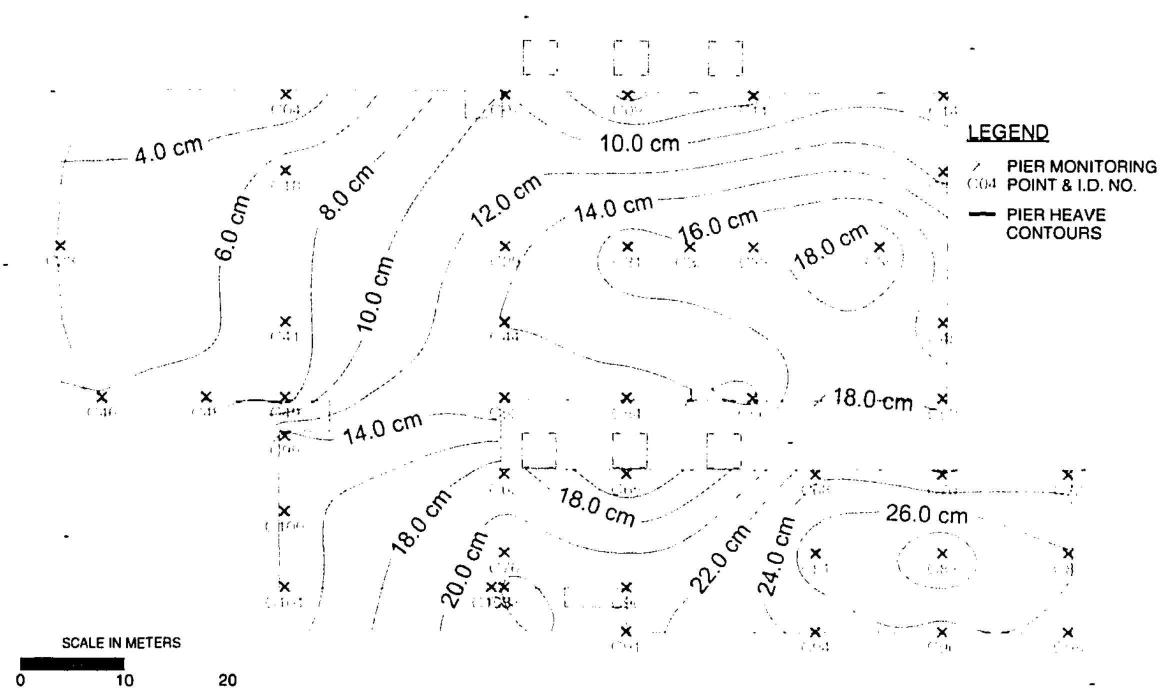


Figure 7-16 Contours of Predicted Pier Heave from the Time of Construction (1991) to January 2040

Figure 7-17 shows the rate at which pier heave is occurring, or expected to occur, as a function of time for several typical pier monitoring points in each wing of the TRACON building. These heave rates were calculated using Equation (7-3). The average heave rate at the time heave began was equal to 0.9 cm/year. The predicted current average pier heave rate is approximately 0.4 cm/year, which is about the same as the observed current heave rate shown in Figure 3-20. Figure 7-17 indicates that the average pier heave rate for the TRACON building will not reach 0.2 cm/year until sometime after the year 2023.

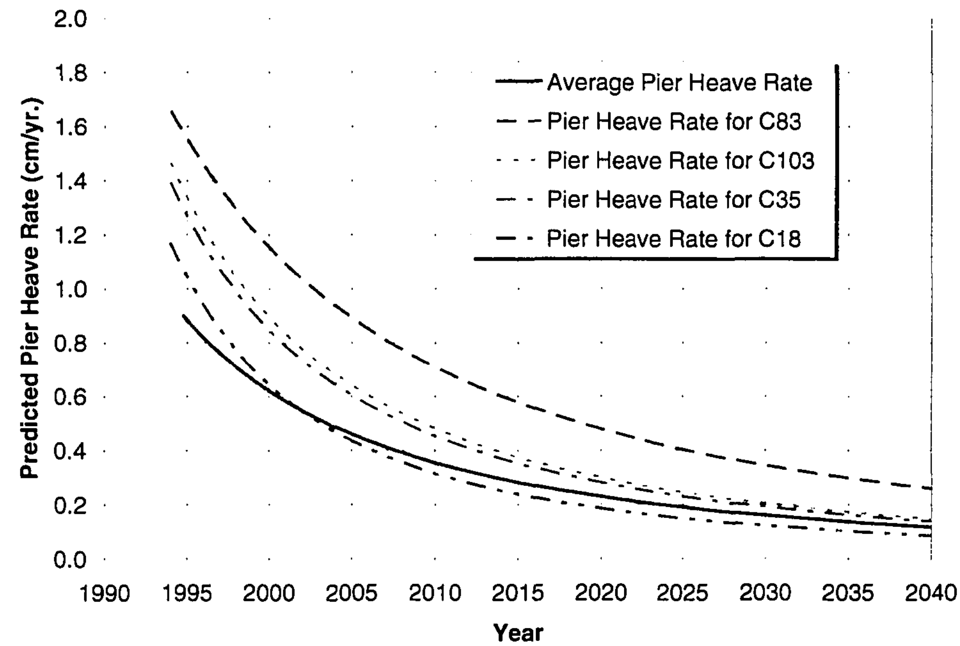


Figure 7-17 Predicted Rate of Pier Heave as a Function of Time

7.2.2 Prediction Using Water Migration Results

7.2.2.1 General

Actual heave rates will be influenced by fluctuations of climate conditions at the ground surface, redistribution of soil water within soil layers, non-uniform heave resulting from the wetting of soil layers, and possibly other factors. It is expected that they will not precisely follow a smooth hyperbolic function over all time. Therefore, another method of predicting heave was used to compute heave based on changes in water content of the subsoils. Water content values were computed using the VADOSE/W modeling. The results of the water migration study were presented previously in Section 6.5. The relationship between water content and swell potential shown in Equation (5-1) was used to compute heave for various water content profiles computed at different points in time. The slab heave at each time step was computed by multiplying the maximum future free-field heave in each soil layer by a factor obtained from Equation (5-1), taking into consideration the changes in volumetric water content from the VADOSE/W output.

Heave prediction was computed for two precipitation scenarios. One scenario considered the average precipitation with no irrigation, and the other considered the average precipitation with irrigation. The rate of slab heave was calculated at the location of Point F81, the point where the greatest amount of heave has been observed.

7.2.2.2 Results of Analyses

Using the values of the volumetric water content obtained from the VADOSE/W modeling, the relationship shown in Equation (5-1), and the calculated value of maximum total free-field heave, the predicted slab heave as a function of time was calculated. The results for Point F81 are shown in Figure 7-18. This figure shows that heaving of the slab will continue to occur and reach a value of about 30 cm at the end of the design life of the building in 2040. This value is about 54% of the predicted maximum total heave. Figure 7-18 also indicates that irrigation may have a significant impact on the slab heave. With irrigation the amount of heave that would occur by the end of the design life of the structure would almost double.

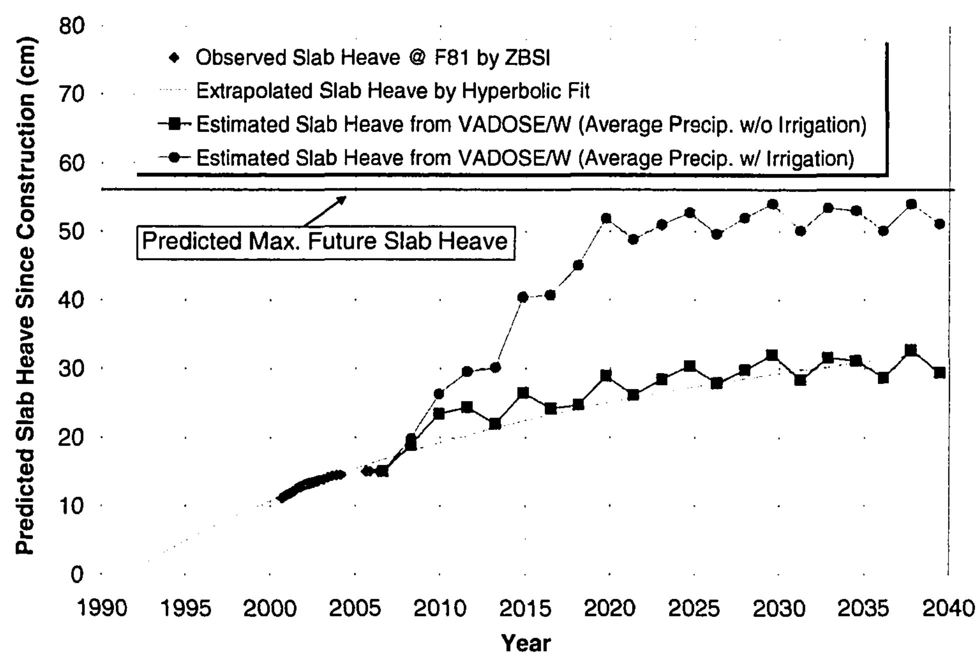


Figure 7-18 Predicted Slab Heave as a Function of Time – Floor Monitoring Point F81

7.3 Accuracy of Heave Prediction

7.3.1 Prediction Using Hyperbolic Relationship

7.3.1.1 Accuracy of Heave Prediction Based on 11-Month Survey Data

The rate of heave was initially predicted by the hyperbolic function derived using data only from the first 11 months of monitoring (from September 2000 to July 2001). The slab heave measured for all monitoring points in June 2006 is compared to the slab heave predicted in June 2006 using the hyperbolic relationship in Figure 7-19. This figure indicates that use of the hyperbolic fit to predict heave with 11 months of data would have overpredicted heave in the year 2006 by approximately 23 percent. This accuracy is likely influenced by the drought cycle in Colorado, particularly the record dry year in 2002. Nevertheless, the ability to predict heave within 23% is considered to be very accurate. Considering the minor difference in the measured and predicted heave, it is evident that the use of the hyperbolic relationship to represent heave vs. time is a good prediction methodology.

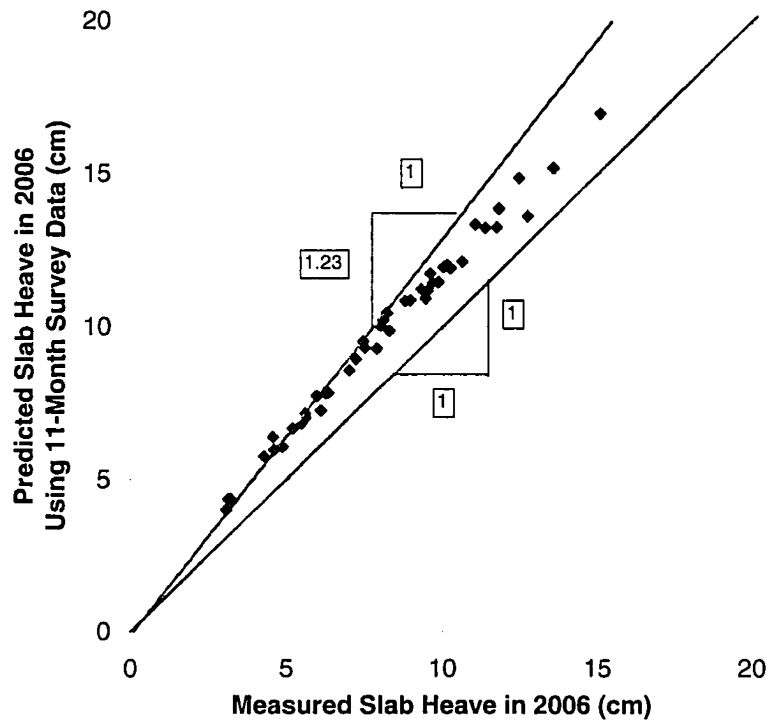


Figure 7-19 Measured Slab Heave in 2006 vs. Predicted Slab Heave in 2006 Using 11-Month Survey Data

7.3.1.2 Comparison of Heave Prediction Using 11, 22, and 70 Month Survey Data

Obviously having a longer period of observation on which to base the development of the hyperbolic relationship will influence the accuracy of the predicted results. After the initial development using the 11 month set of data, the hyperbolic relationship was revised two more times using longer data sets over longer periods of time. Figure 7-20 shows the comparison between predicted and measured slab heave in 2006 using survey data taken over a period of 22 months to fit the hyperbola. Figure 7-20 shows that use of a 22 month set of data instead of the 11 month data increased the accuracy of prediction for the year 2006 to where the predicted data is within 7% of the measured data.

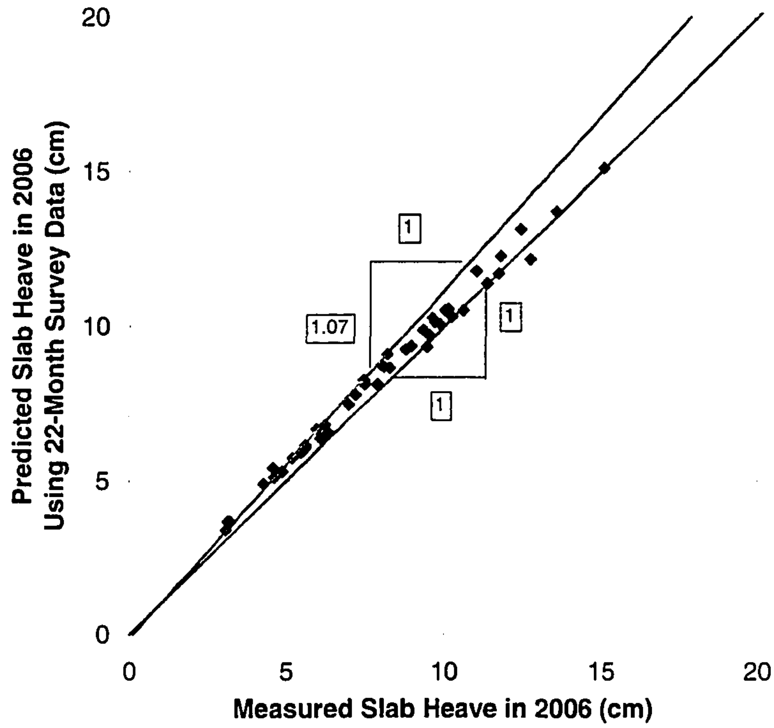


Figure 7-20 Measured Slab Heave in 2006 vs. Predicted Slab Heave in 2006 Using 22-Month Survey Data

The effect of using the entire 70 month set of data to determine the parameters for the hyperbolic function was then investigated. In this case, the entire set of measurements was used to develop the hyperbolic equation, and therefore, there was not a data of measured values with which to compare the predicted values. Therefore, the values of heave predicted for the year 2040 using the equation developed with the 70 month set of data were compared with those values of heave predicted on the basis of 11 months of data. The results are shown in Figure 7-21. From that figure, it is seen that the effect of using the longer data set to determine the hyperbolic parameters was to decrease the predicted values by as much as 13%. Because the equation for the 11 month data set tended to overpredict by as much as 23%, it is evident that the use of the 70 month data set increased the overall accuracy of the prediction method.

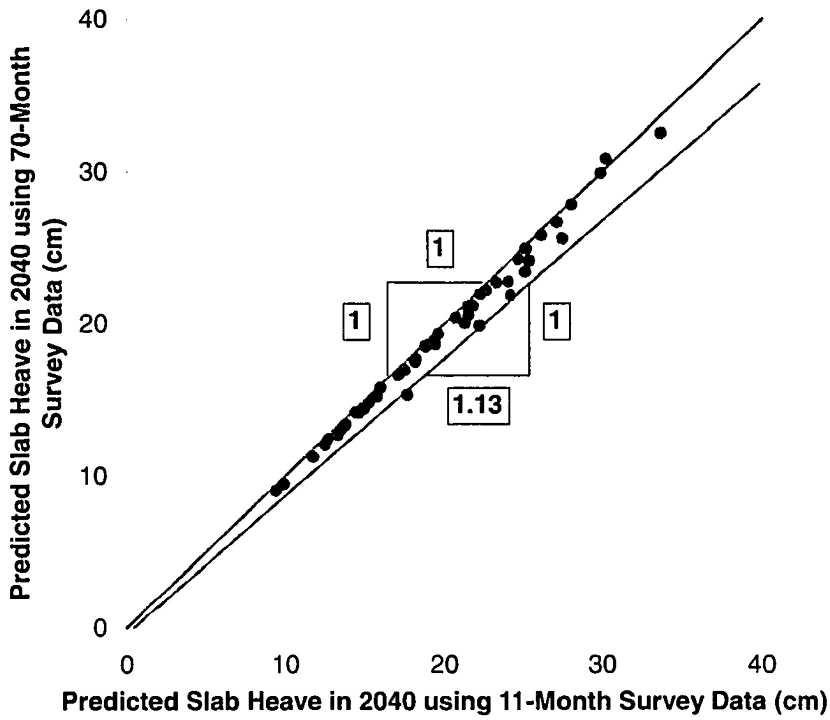


Figure 7-21 Predicted Slab Heave in 2040 Using 11- and 70-Month Survey Data

As would be expected, accuracy of the slab heave prediction will increase as the size of the data base and time over which the data is collected increases. In the case of the data presented in Figure 7-21, some difference is due, at least in part, to the drought cycle that Colorado has experienced over the past few years. Nevertheless, it is evident that the use of a hyperbolic relationship to represent heave vs. time, along with an accurate prediction of maximum total heave, is a good assumption, even only a relatively short period of survey data can be obtained.

7.3.2 Heave Prediction Based on VADOSE/W Modeling of Water Migration

The predicted slab heave as a function of time calculated from the VADOSE/W output was compared to the predicted slab heave using the hyperbolic relationship in Figure 7-18. In general, the heave values predicted by both methods agree quite well. Close examination of Figure 7-18 shows that whereas the heave predicted using VADOSE/W modeling is greater than that predicted by the hyperbolic fit up to about the year 2030, it tends to become smaller after that point. It is believed that heave prediction based on water migration is more realistic in that it considers actual soil profiles, soil properties, and climate conditions. Also, a relatively long period of actual heave monitoring is not needed for that method.

7.4 Differential Pier Heave

A general rule of thumb that has been considered in past years has been that differential movement (heave or settlement) between piers is about equal to half of the maximum movement. To test that hypothesis, the measured differential pier heave between adjacent piers in the year 2006 was plotted against the predicted maximum total pier heave in Figure 7-22. Figure 7-22 indicates that that the measured differential pier heave at some points is already almost as high as 0.5 times the predicted maximum total pier heave. Considering all points the values corresponding to 2 or 3 standard deviations are 0.23 and 0.31, respectively.

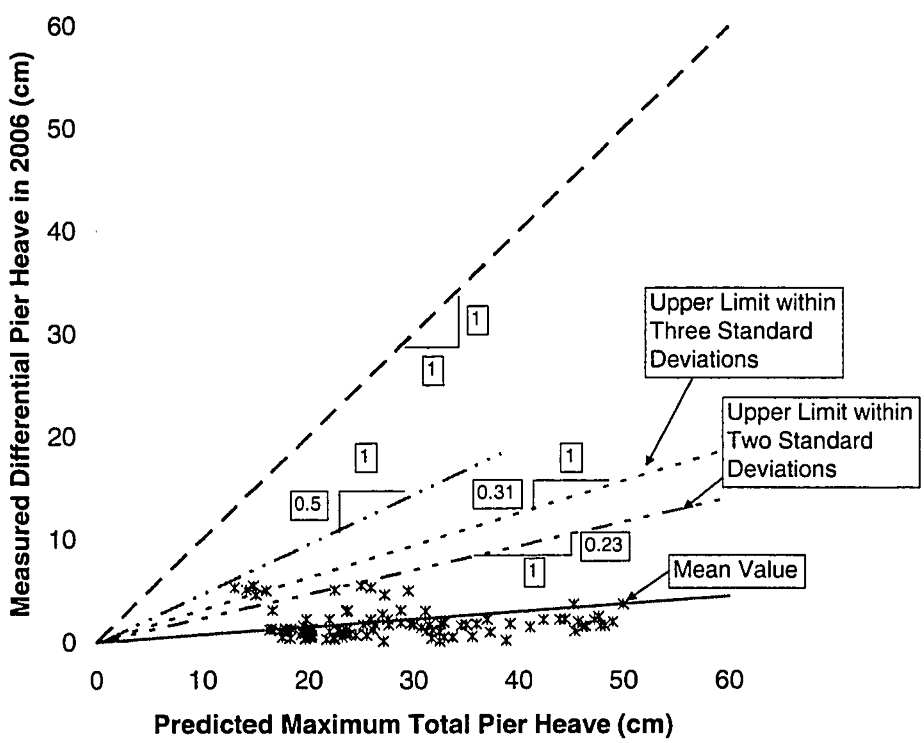


Figure 7-22 Measured Differential Pier Heave in 2006 vs. Predicted Maximum Total Pier Heave

Figure 7-23 shows the predicted total differential pier heave in the year 2040 as a function of the predicted maximum total pier heave. By the end of the design life of the building, the measured differential pier heave at some points is as high as 0.8 times the predicted maximum total pier heave. Considering all points the values corresponding to 2 or 3 standard deviations are 0.47 and 0.63, respectively.

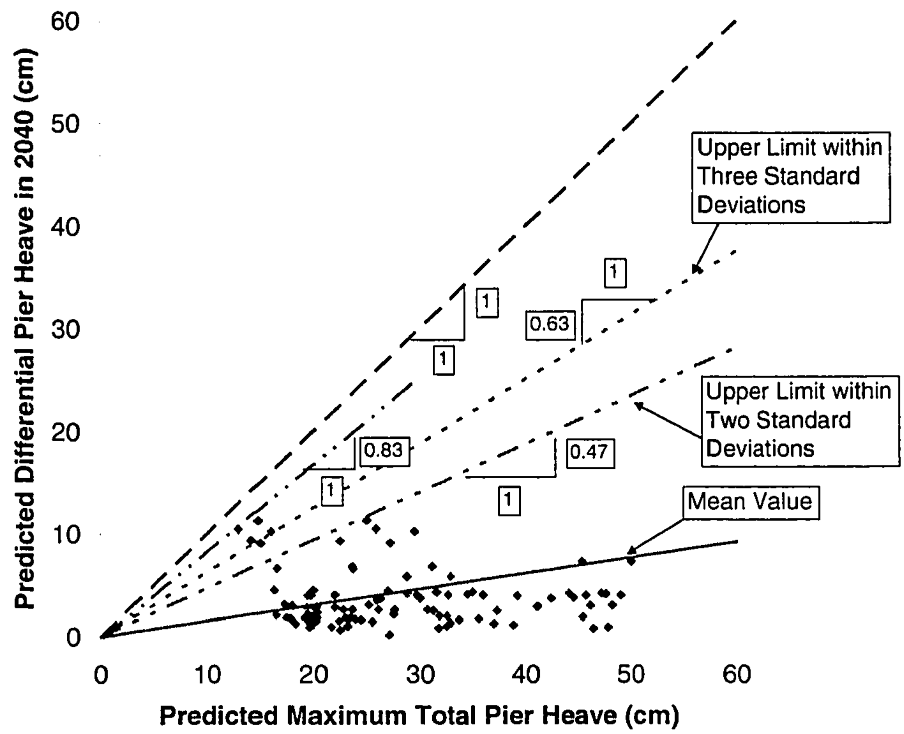


Figure 7-23 Predicted Differential Pier Heave in 2040 vs. Predicted Maximum Total Pier Heave

Figure 7-24 shows the predicted maximum differential pier heave as a function of the predicted maximum total pier heave. Figure 7-24 indicates that the differential heave at some points is predicted to be almost the same as the maximum total pier heave. Based on the results shown in Figure 7-24, it is evident that prudent design would consider that the maximum differential heave could be equal to the maximum heave predicted for the individual pier being considered.

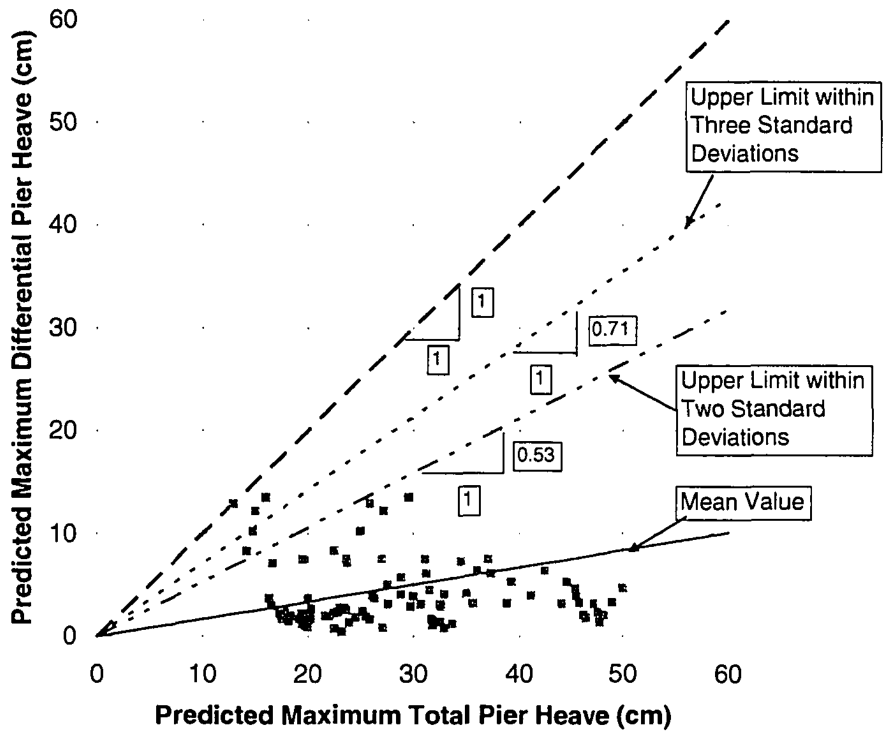


Figure 7-24 Predicted Maximum Differential Pier Heave vs. Predicted Maximum Total Pier Heave

7.5 Angular Distortion Between Piers

Angular distortion between adjacent piers is a more meaningful measure of distress than just differential heave. Therefore, the angular distortion was calculated using the measured and predicted differential heave divided by the span length between adjacent piers. The measured value in 2006 was plotted as a function of the predicted maximum total pier heave in Figure 7-25. The measured angular distortion between adjacent piers in 2006 ranges from 0.02 to 0.49%. The predicted value of angular distortion in 2040 was plotted as a function of the predicted maximum total pier heave in Figure 7-26. The predicted angular distortion between adjacent piers in 2040 ranges from 0.06 to 0.96%.

The Engineer Manual from US Army Corps of Engineers (USACE, 1990) indicated that the critical limit of angular distortion for steel frame structures, such as the TRACON building, with no cracking is 0.33% (1/300). It was also indicated that the maximum allowable angular distortion is 0.66% (1/150) for this type of structure. Figure 7-27 shows the number of data points expressed as a percentage of the whole that exceed the limits of 0.33 and 0.66%. This figure shows that the percentage of points exceeding the limits will continue to increase throughout the design life of the building. Figure 7-27 indicates that about 17% of the data points have already exceeded the limit for no cracking in 2006. This is consistent with observations made within the building.

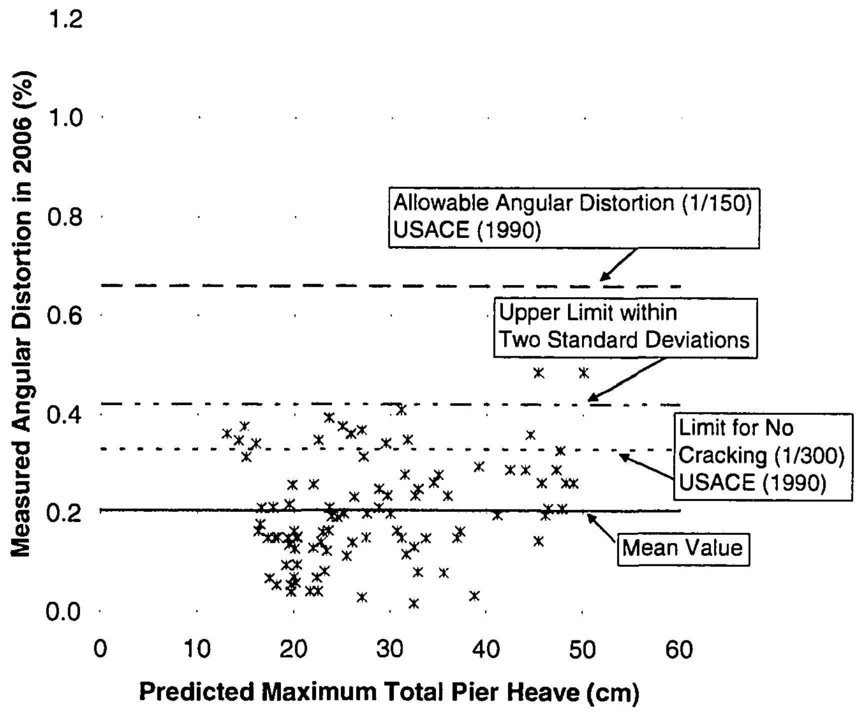


Figure 7-25 Measured Angular Distortion Between Adjacent Piers in 2006 vs. Predicted Maximum Total Pier Heave

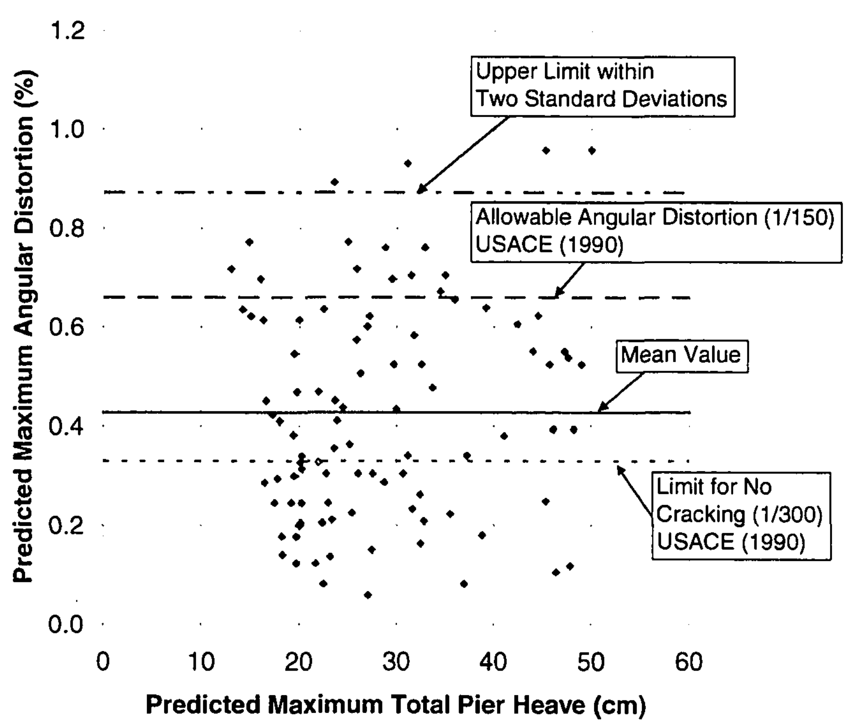


Figure 7-26 Predicted Angular Distortion Between Adjacent Piers in 2040 vs. Predicted Maximum Total Pier Heave

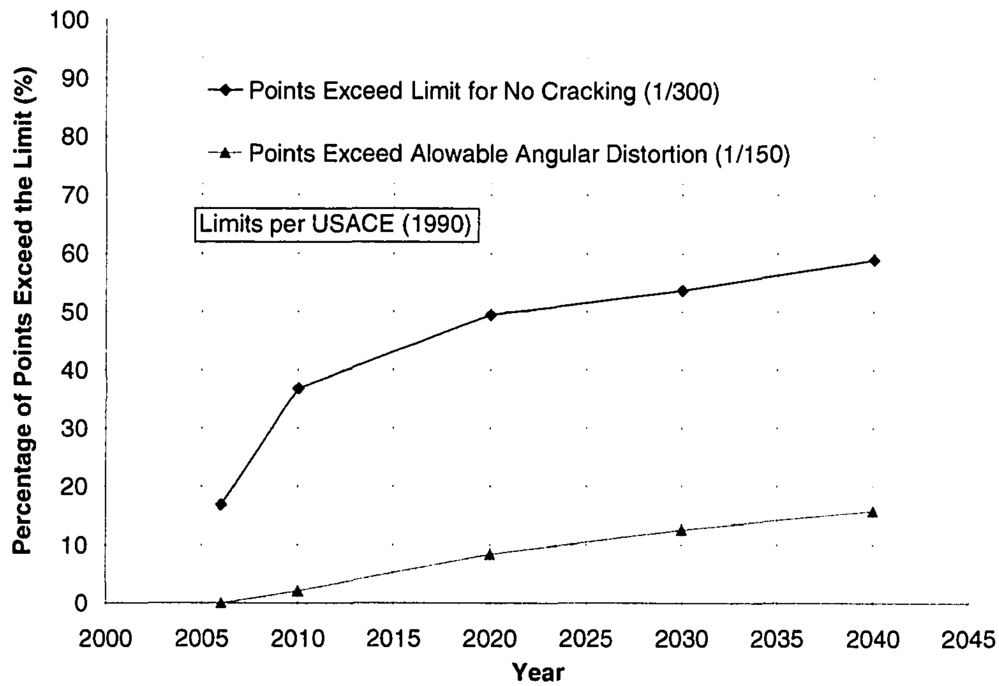


Figure 7-27 Points Exceed Limits of Angular Distortion as a Function of Time

7.6 Discussion

Current design procedures generally consider the maximum amount of predicted heave that will ultimately occur at a site. At sites with highly expansive soils, when large amounts of heave are predicted, it often becomes impractical to design a foundation system for the ultimate amount of heave. Large amounts of heave generally are associated with large depths of potential heave. Over the design life of a structure, those large depths may not realize the full amount of the expansion potential. Consequently, design of foundations for buildings on expansive soils must consider the timewise pattern of migration of water within subsoils and the associated heave that such wetting will produce over time.

The timewise variation of slab and pier heave for the TRACON building was analyzed by extrapolation of measured data using calculated values of predicted maximum total heave along with curve fitting of the measured data to a hyperbolic equation. It was also analyzed by computer modeling of the migration of subsoil water and predicting heave as the water content changed. It was shown that by the year 2040, the design life of the TRACON building, the slabs and piers are expected to heave by about 50 to 60% of the predicted maximum heave.

It is often, not possible to gather measured heave data over a long period of time. It was shown that, by taking into account the calculated value of maximum heave along with the hyperbolic equation, accurate results could be obtained with less than one year's data.

Nevertheless, predicting the timewise variation of heave by modeling of the subsoil water migration is believed to be the more accurate method. It allows for variations in soil profiles, different sources of water, and climate conditions to be taken into account. It was shown that heave will not precisely follow a smooth hyperbolic function over all time. Furthermore, it was shown that the effect of irrigation on the surface will have a large effect.

CHAPTER 8

DESIGN PRINCIPLES FOR FOUNDATIONS ON EXPANSIVE SOILS

8.1 General

The design of foundations for light structures on expansive soils is perhaps one of the most challenging problems facing foundation engineers. Foundations on expansive soils will cost more than foundations on ordinary soils, and most likely the site investigation and foundation design will cost more as well. Owners of structures demand that the foundations be capable of supporting the structure within tolerable movement limits, and at the same time they are reluctant to spend more than they are accustomed to for ordinary soil sites.

The characterization of expansive soil can be conducted on the basis of the Expansion Potential, EP, which is defined on the basis of percent swell exhibited in a consolidation-swell test and the swelling pressure of the soil (Nelson, et al., 2007a). For sites having a low expansion potential, EP, the most common method for foundation design is the use of a spread footing system. However, for sites with moderate to very high EP a variety of foundation systems including pier and grade beam foundation, helical piers, post-tensioned slabs-on-grade, and overexcavation and replacement have been proposed and used.

Current design methodologies consider the amount of predicted maximum heave that will ultimately occur at a site. Design of foundations for the extreme ultimate conditions is not always practical and economical in engineering practice, especially for sites on highly expansive soils. Furthermore, the entire depth of potential heave might not be completely wetted at the end of the design life of a structure. A comprehensive foundation design approach for design of foundations is introduced in this research. This approach considers the rate of water migration in the vadose zone, and designs the foundations in accordance with the amount of expected heave that such wetting will produce at the lifetime of the structure.

An example foundation design was performed using the current and proposed design methodologies. Comparison of the required pier lengths obtained using the current and proposed design methodologies was made. Factors affecting the design of foundations, such as site grading, soil expansion potential, depth of overexcavation, and subsurface water sources, were discussed.

8.2 Current Design Methodology

8.2.1 Maximum Free-Field Heave

Pier heave is normalized against free-field heave. Therefore, the first step for design of foundations on expansive soils is to compute maximum free-field heave. Several methods have been proposed for predicting free-field heave. Two most common methods adopted by practicing engineers in the Front Range area of Colorado are (1) the soil suction method, and (2) the oedometer method.

A method for heave prediction using the soil suction method was developed by McKeen (1992). Heave prediction using the oedometer method was originally presented by Fredlund (1983). It was presented by Nelson and Miller (1992) and modified in Nelson, et al. (1998 and 2006). The oedometer method was used for the design of pier foundations in this research. A detailed review of the heave prediction using the oedometer method was provided in Section 2.3.3.

8.2.2 Pier Design Using Maximum Heave

8.2.2.1 Concrete Pier Design

Two approaches may be taken in the design of concrete piers. The rigid pier approach neglects potential strain in the pier itself and equates the uplift forces to applied load and skin friction. In this way, if the forces are balanced, the pier should not move. The rigid pier approach was discussed in Section 2.4.2.1. The elastic pier theory considers both the pier and soil to be elastic media, and considers that movement of the pier will occur. Design by this method would entail definition of the tolerable amount of pier movement. The elastic pier theory was discussed in Section 2.4.2.2.

8.2.2.2 Helical Pier Design

A number of different configurations of helical piers are available commercially. Figure 8-1 shows a schematic of a helical pier to use for describing the heave prediction methodology. In predicting heave of a helical pier, it is assumed that the skin friction along the shaft is very low. This is considered a reasonable assumption, because as the pier is advanced into the soil, the material in the annulus space above the helix, in which the shaft is centered, is disturbed. It is not recompacted and the swell potential in this area is reduced greatly. Thus, the heave of the top of the pier is limited by the amount by which the helix can move. The helix will move by the amount that the soil at the depth, L_{HP}, will heave. This value can be determined from the calculations of free-field heave.

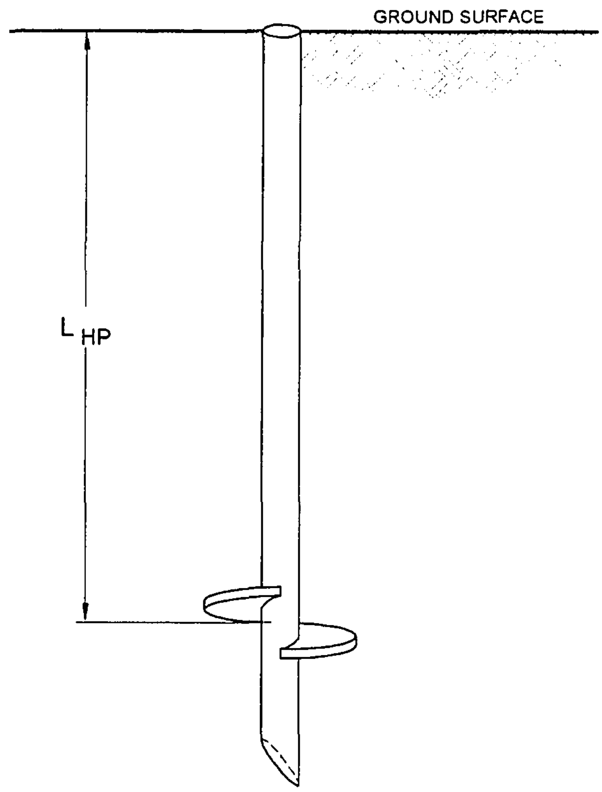


Figure 8-1 Schematic of Helical Pier

8.3 Proposed Design Methodology

Instead of considering the amount of predicted heave that will ultimately occur, the proposed design methodology uses the amount of predicted heave that will occur at the end of design life of a structure. To estimate the predicted heave within the design life of the structure, the following design procedure is proposed:

Step 1. Maximum free-field heave: The maximum free-field heave can be predicted using the oedometer methodologies presented in Nelson, et al.

(1998 and 2006). The heave calculation procedure was described in Section 2.3.3.

Step 2. Water migration analysis: The rate of water migration in the vadose zone throughout the design life of the structure can be analyzed using a computer modeling program, such as VADOSE/W, or other seepage programs that take into account climate, evaporation/transportation, and surface water runoff conditions.

Step 3. Change of heave with time: The change of heave with time throughout the design life of the structure can be calculated using the predicted maximum free-field heave from Step 1, the results of the water migration analysis from Step 2, and the relationship between water content and swell potential shown in Equation (5-1).

Step 4. Foundation Design using the predicted heave for the design life of the structure: Design of foundations can be performed using the elastic design method presented in Nelson and Miller (1992). Nelson, et al. (2007b) somewhat modified the design charts from Nelson and Miller (1992) to further facilitate its use by the design engineer. The depth of wetting from Step 2 and the predicted heave from Step 3 at the end of design life of the structure are used in the design.

8.4 Example Foundation Design

For purposes of illustrating the current and proposed design procedures, a hypothetical subsoil profile has been defined. It consists of a site with 3 meters of native clay over claystone. The soil properties used in the heave calculations are summarized in Table 8-1.

Table 8-1 Summary of Soil Parameters Used in the Heave Calculations

Soil Type	Water Content (%)	Total Density (Mg/m^3)	Consolidation Swell Test(1)		
			Percent Swell (%)	Swelling Pressure (kPa)	Expansion Potential(2)
Native Clay	15.0	1.84	3.0	335	2.0
Claystone	10.0	1.94	4.0	480	3.2

Notes: (1) Inundation Pressure = 48 kPa
(2) Refer to Nelson, et al. (2007a)

For simplicity, the example structure was assumed to have no basement and grade beam. The piers were assumed to be constructed starting from the ground surface. The piers will have a diameter of 25.4 cm. The minimum dead load on the piers will be 50 kN.

The maximum tolerable movement of the foundation was assumed to be 2.5 cm. It should be noted that this is the assumed total movement at that pier location. Experience shows that a differential movement between adjacent piers is usually half to one times of the predicted total heave. Therefore, the assumption of 2.5 cm of the total movement could result in a differential movement of 1.3 to 2.5 cm. The actual maximum tolerable differential movement depends on the type and configuration of the pier and grade beam foundation. Sometimes, an adjustable collar might be needed to be placed on the top of the pier if the predicted total movement is greater than the tolerable heave. The actual maximum tolerable differential movement should be discussed with a structural engineer.

8.4.1 Current Design Methodology

8.4.1.1 Maximum Free-Field Heave

The maximum free-field heave is predicted using the oedometer methodologies presented in Nelson, et al. (1998 and 2006), as discussed in Section 2.3.3. A step-by-step calculation procedure for computing the maximum free-field heave is provided as follows.

The swelling pressure for a constant volume oedometer test is estimated using Equation (2-11). Thus,

$$\sigma'_{cv} = 48 + 0.6 \times (335 - 48) = 220 \text{ kPa for clay}$$
$$\sigma'_{cv} = 48 + 0.6 \times (480 - 48) = 307 \text{ kPa for claystone}$$

C_H can be determined from Equation (2-12):

$$C_H = 3\% / \log(220 / 48) = 0.045 \text{ for clay}$$
$$C_H = 4\% / \log(307 / 48) = 0.050 \text{ for claystone}$$

The depth of potential heave, z_p, is computed by equating the overburden pressure to the swelling pressure. Thus,

$$(1.84 \times 9.81 \times 3) + [1.94 \times 9.81 \times (z_p - 3)] = 307 \text{ kPa}$$
$$z_p = 16.3 \text{ m}$$

In computing heave, the depth of potential heave is divided into several layers and the heave of each layer is computed. The total heave is the sum of heave over all layers. For this example, the soil was divided into 35 layers. Therefore, each layer is then (16.3 m / 35) or 0.47 m thick. The midpoint of the first layer is 0.24 meters below the ground surface. The effective stress at that depth is,

$$\sigma'_{vo} = 1.84 \times 9.81 \times 0.24 = 4.3 \text{ kPa}$$

From Equation (2-12), the heave of that layer is

$$\rho_1 = 0.045 \times 0.47 \times \log(220 / 4.3) = 0.036 \text{ m} = 3.6 \text{ cm}$$

This computation is then repeated for all layers and the increments of heave are summed. These computations lend themselves well to computation by simple spreadsheets. The maximum free-field heave is computed to be 32.0 cm.

8.4.1.2 Pier Design Using Maximum Heave

8.4.1.2.1 Rigid Pier

The example will calculate the required length of a rigid straight shaft pier with no movement. In addition, the required reinforcement steel for the rigid pier will be computed. A step-by-step calculation procedure is provided as follows.

The required length of a rigid pier is calculated by equating the uplift forces shown in Figure 2-24 to the sum of the negative (anchorage) skin friction forces and the dead load.

The uplift skin friction is equal to,

$$f_u = \alpha_l \, \sigma'_{cv}$$

where α_l is a coefficient of uplift between the pier and the soil. The value of α_l can reasonably be assumed to be between 0.10 and 0.25 (Nelson and Miller, 1992). A value of 0.2 was assumed here.

The uplift skin friction forces are,

$$F_u = f_u \, z_p \, \pi \, d$$
$$F_{u1} = (0.2 \times 220) \times 3 \times \pi \times (25.4 / 100) = 105 \text{ kN from clay}$$
$$F_{u2} = (0.2 \times 307) \times (16.3 - 3) \times \pi \times (25.4 / 100) = 651 \text{ kN from claystone}$$
$$\text{Total } F_u = F_{u1} + F_{u2} = 756 \text{ kN}$$

The negative (anchorage) skin friction can be calculated by

$$f_s = \alpha_s \sigma'_h$$

where α_s is a coefficient of negative friction between the pier and the soil, and σ'_h is the lateral stress acting on the pier in the anchorage zone.

The value of α_s should be similar to that of α_l. Whereas that is most likely true in most soils, tests at Colorado State University have shown that it may be somewhat higher in the stiff and, sometimes sandy, claystone in Colorado. Therefore, a value of 0.25 will be used here.

The lateral pressure will be taken as being equal to the swelling pressure of the claystone. Thus,

$$\begin{aligned} F_s &= f_s \, (L - z_p) \, \pi \, d \\ &= (0.25 \times 307) \, (L - 16.3) \, \pi \, (25.4 / 100) \\ &= 61.2L - 998 \text{ kN} \end{aligned}$$

Summing all forces including the dead load,

$$61.2L - 998 + 50 = 756 \text{ kN}$$
$$L_{reqd} = 27.8 \text{ meters}$$

The maximum tensile force in the straight shaft pier generally occurs at a depth of approximately 0.6 of the pier length (Poulos and Davis, 1980), and can be computed using Equation (2-14) as follows:

$$P_{max} = P_{dl@pmax} - f_u z_p \pi d$$

$P_{dl@pmax}$ can be calculated using Figure 5.12 in Nelson and Miller (1992). From Figure 5.12, proportion of the applied dead load transferred to the base is approximately 1 kN. Assuming a linear load distribution with depth, $P_{dl@pmax}$ is calculated to be 30 kN at a depth of 0.6 of the designed pier length of 27.8 m. Thus,

$$P_{max} = 30 - 756 = -726 \text{ kN}$$

The negative sign indicates that the force is tensile. If conventional Grade 60 steel reinforcement, with an allowable design stress of 40 ksi is used, the required area of steel is,

$$(A_s)_{reqd} = 726 \times (0.23 \text{ kips} / 1 \text{ kN}) / 40 = 4.17 \text{ in}^2 = 26.9 \text{ cm}^2$$

8.4.1.2.2 Elastic Pier

The example will calculate the required lengths of elastic straight shaft and belled piers with 2.5 cm of movement. In addition, the required reinforcement steel for the straight shaft and belled piers with 2.5 cm of movement will be computed. A step-by-step calculation procedure is provided below.

8.4.1.2.2.1 Straight Shaft Pier

Figure 2-25 will be used to compute the required length of an elastic straight shaft pier with 2.5 cm of movement. Because the claystone is stiff and has a high swelling pressure, the pier-soil interaction is considered to be uniform with depth. This corresponds to case A in Figure 2-25.

$$\rho_p / \rho = 2.5 / 32.0 = 0.08$$

Using case A in Figure 2-25,

$$L / z_p = 1.9$$

The depth of potential heave, z_p, was previously calculated to be 16.3 meters. Thus, the required pier length, L_{reqd}, is,

$$L_{reqd} = 1.9 \times 16.3 = 31.0 \text{ meters}$$

Figure 2-27 will be used to compute the maximum force in the pier, for use in computing the required amount of reinforcing steel. From Equation (2-15), the value of P_{FS} is calculated to be,

$$P_{FS} = -f_u \, L \, \pi \, d$$
$$P_{FS1} = -(0.2 \times 220) \times 3 \times \pi \times (25.4 / 100) = -105 \text{ kN from clay}$$
$$P_{FS2} = -(0.2 \times 307) \times (31.0 - 3) \times \pi \times (25.4 / 100) = -1{,}371 \text{ kN from claystone}$$
$$\text{Total } P_{FS} = P_{FS1} + P_{FS2} = -1{,}476 \text{ kN}$$

Again, the minus sign indicates that the force is tensile.

From Figure 2-27,

$$P_{max} / P_{FS} = 0.45 \text{ for } L / z_p = 1.90$$
$$P_{max} = 0.45 \times -1{,}476 = -664 \text{ kN}$$

For Grade 60 steel,

$$(As)_{reqd} = 664 \times (0.23 \text{ kips} / 1 \text{ kN}) / 40 = 3.82 \text{ in}^2 = 24.6 \text{ cm}^2$$

8.4.1.2.2.2 Belled Pier

Figure 2-26 will be used to compute the required length of an elastic belled pier with 2.5 cm of movement. Again, the pier-soil interaction is considered to be uniform with depth. This corresponds to case A in Figure 2-26.

Using case A in Figure 2-26,

$$L / z_p = 1.6 \text{ for } \rho_p / \rho = 2.5 / 32.0 = 0.08$$

Thus, the required pier length, L_{reqd}, is,

$$L_{reqd} = 1.6 \times 16.3 = 26.1 \text{ meters}$$

Figure 2-28 will be used to compute the maximum force in the pier, for use in computing the required amount of reinforcing steel. From Equation (2-15), the value of P_{FS} is equal to −1,476 kN, as calculated in Section 8.4.1.2.2.1.

From Figure 2-28,

$$P_{max} / P_{FS} = 0.65 \text{ for } L / z_p = 1.60$$
$$P_{max} = 0.65 \times -1{,}476 = -959 \text{ kN}$$

For Grade 60 steel,

$$(As)_{reqd} = 959 \times (0.23 \text{ kips} / 1 \text{ kN}) / 40 = 5.51 \text{ in}^2 = 35.5 \text{ cm}^2$$

8.4.1.2.3 Helical Pier

The example will calculate the required length of a helical pier with 2.5 cm of movement. As discussed in Section 8.2.3, the helix will move by the amount that the soil at the depth, L_{HP}, will heave. This value can be determined from the calculations of free-field heave. A spreadsheet calculation of the free-field heave was conducted using the free-field heave procedure, as discussed in Section 8.4.1.1. From that spreadsheet, it is predicted that the soil at a depth of 10.7 meters will heave by the amount of 2.5 cm. Consequently, the required length of a helical pier with 2.5 cm of movement is 10.7 meters.

8.4.2 Proposed Design Methodology

The proposed design methodology described in Section 8.3 was used to compute the required pier length for various design conditions. For comparison purposes, the same foundation design example in Section 8.4.1 was used.

8.4.2.1 Maximum Free-Field Heave

The maximum free-field heave can be predicted following the same calculation procedure described in Section 8.4.1.1. The maximum free-field heave of 32.0 cm was calculated for the same design example in that section.

8.4.2.2 Water Migration Study

Chao, et al. (2006) conducted water migration analyses for the example subsoil profile (3 meters of native clay over claystone) using the computer program VADOSE/W (GEO-SLOPE, 2006). Analyses were performed for a site with good drainage consisting of non-irrigated gravel within 1.5 meters of the building and a 10% slope away from the building for the first 3.0 meters, as shown in Figure 8-2. The total width of the building used in the analysis was 13.7 meters determined as the average of 16 residential houses for which data was available.

Consideration was given to the time period of analysis. The minimum design life for residential foundations as presented by the U.S. Department of Housing and Urban Development (2002) and Schmatz and Stiemer (1995) is 100 years for foundations. Consequently, the VADOSE/W analysis was conducted considering 100 years of the design life of the structure.

The results of the water migration analyses at the locations of 6 meters outside of the building and the edge of the building are shown in Figures 8-3 and 8-4, respectively. The results shown in Figures 8-3 and 8-4 indicate that variation exists in the water content profiles considering the location of the profile relative to the structure. The results shown in Figure 8-4 were used for the proposed foundation design example.

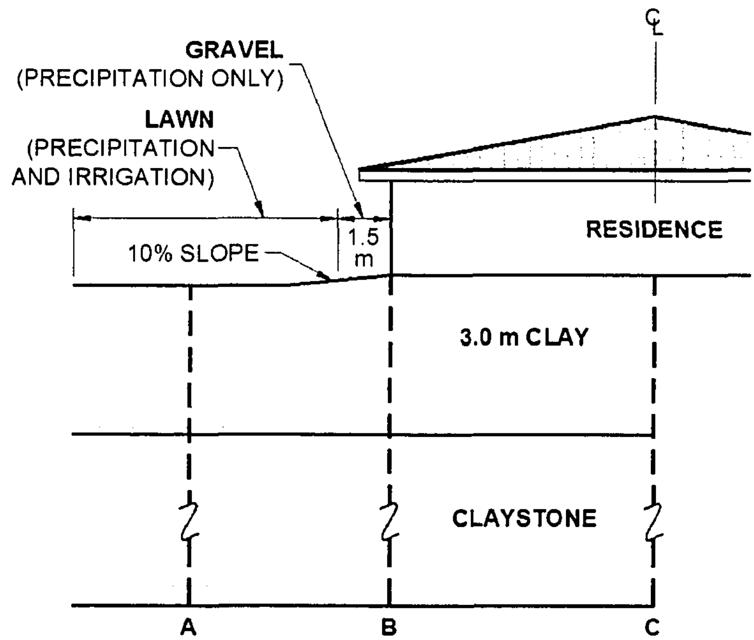


Figure 8-2 Typical Cross Section Used for Modeling Good Drainage Conditions in VADOSE/W analyses

Figure 8-4 indicates that water will continue to migrate down into the subsoil to a depth of approximately 12 meters in 100 years. This depth of wetting is shallower than the depth of potential heave of 16.3 meters computed in Section 8.4.1.1 for the example case. Furthermore, it should be noted that neither the clay nor claystone is completely saturated at the end of design life of the structure in 100 years. This means that the heave prediction method using the consolidation-swell test results and assuming the entire depth of potential heave will be wetted could be conservative for certain circumstances.

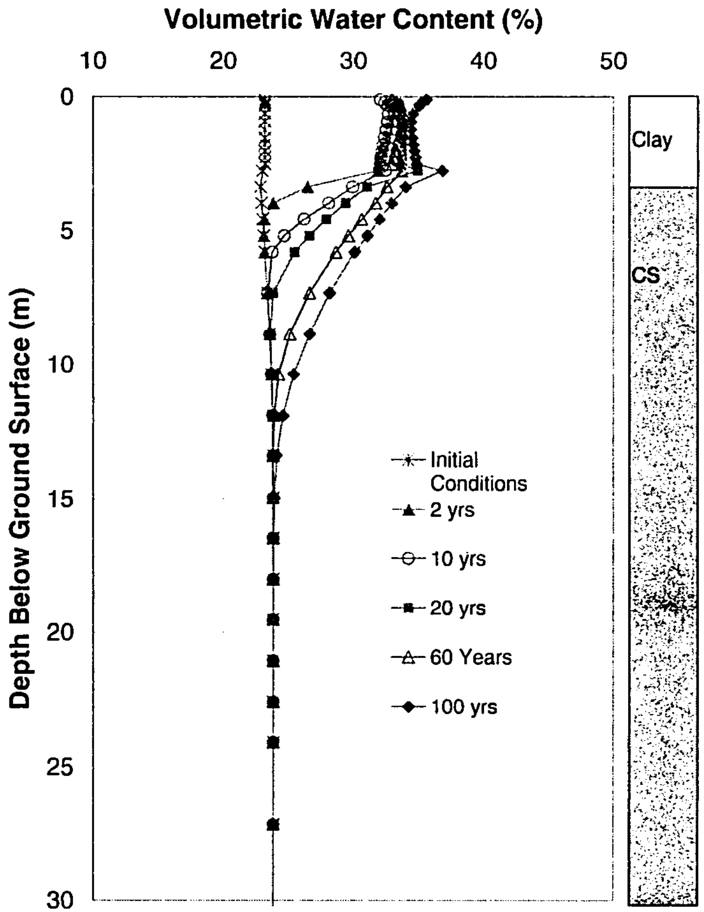


Figure 8-3 Predicted Long-Term Water Content Profiles at 6 Meters Outside of the Building – Good Drainage Conditions

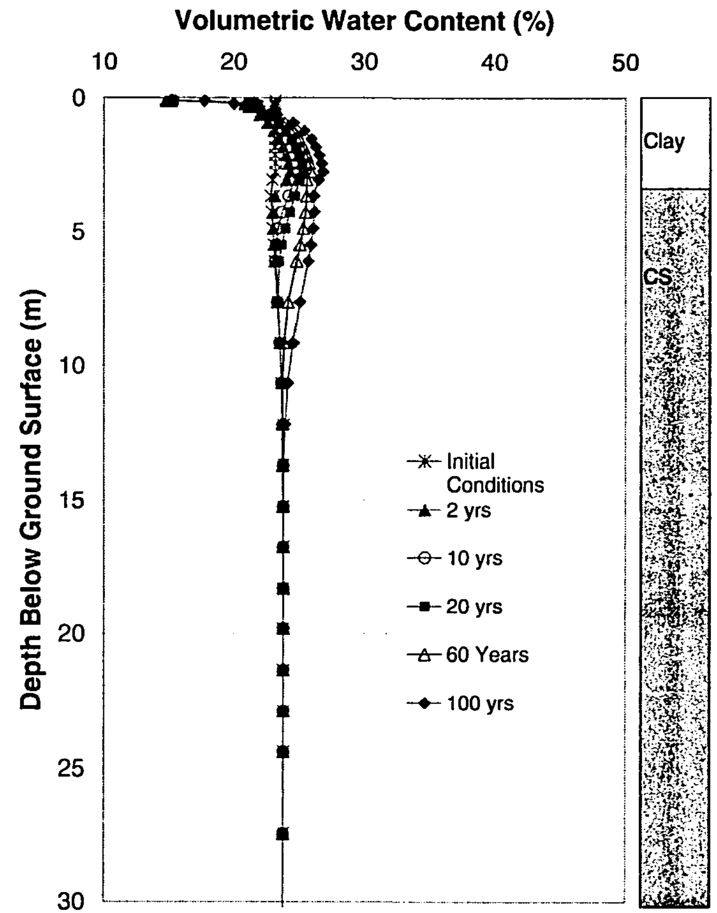


Figure 8-4 Predicted Long-Term Water Content Profiles at the Edge of the Building – Good Drainage Conditions

8.4.2.3 Change of Heave with Time

Using the values of the volumetric water content at each time step shown in Figure 8-4, the relationship between water content and swell potential shown in Equation (5-1), and the predicted maximum free-field heave of 32.0 cm, the predicted slab heave as a function of time was calculated. The calculated rate of free-field heave for the example site at the location of the edge of the structure is presented in Figure 8-5. This figure shows that heaving of the slab will continue to occur and reaches only about 3 cm, which is approximately 9% of the predicted maximum total heave at the end of the design life of the structure.

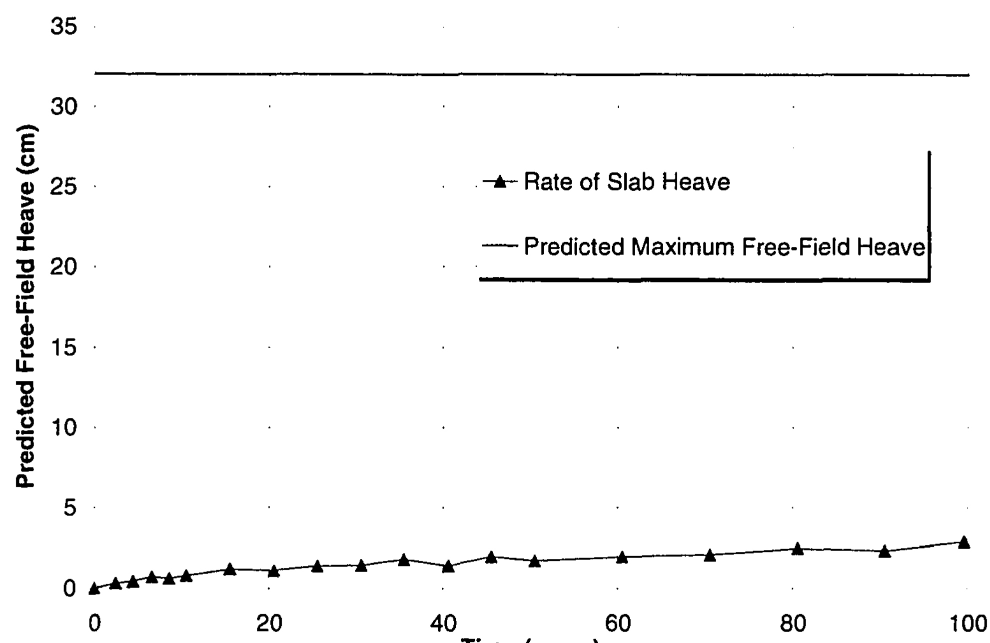


Figure 8-5 Predicted Free-Field Heave as a Function of Time for the Example Site with Good Drainage Conditions

8.4.2.4 Pier Design Using Predicted Heave for the Design Life of a Structure

The required pier length for the design life of the structure was calculated by following the procedure, as described in Section 8.4.1.2, except for the following:

1. The predicted maximum depth of wetting in 100 years instead of the depth of potential heave was used.
2. The predicted heave in 100 years instead of the predicted maximum free-field heave was used.

The required lengths of elastic straight shaft and belled piers with 2.5 cm of movement were calculated. In addition, the required length of a helical pier with 2.5 cm of movement was computed. The required pier lengths of the straight shaft, belled, and helical piers with 2.5 cm of movement were calculated to be 5.8, 2.1, and 1.8 meters.

8.4.3 Comparison of Required Pier Lengths Obtained Using the Current and Proposed Design Methodologies

Table 8-2 summarizes the required pier lengths for the cases computed in Sections 8.4.1 and 8.4.2. For the current design method, Table 8-2 indicates that the required pier length for the straight shaft pier with no movement using the rigid pier method is shorter than that for the straight shaft pier with 2.5 cm of movement using the elastic pier method. Experience indicates that this outcome happens when the soil is highly expansive and the maximum allowable movement of the foundation is small. This outcome is due to the differences in the methods of analyses, and the assumptions made in each method. However, it points out that prediction methods are not exact, and even with the rigid pier design some movement could occur.

Table 8-2 Summary of Required Pier Lengths for the Current and Proposed Design Methodologies

Case No.	Pier Type	Design Method	Required Pier Length Using the Current Design Methodology (m)	Required Pier Length Using the Proposed Design Methodology (m)
1	Straight Shaft Pier with No Movement	Rigid Pier	27.8	N/A
2	Straight Shaft Pier with 2.5 cm of Movement	Elastic Pier	31.0	5.8
3	Belled Pier with 2.5 cm of Movement	Elastic Pier	26.1	2.1
4	Helical Pier with 2.5 cm of Movement	--	10.7	1.8

Table 8-2 indicates that the pier length was reduced up to approximately 64% by using a belled pier instead of a straight shaft pier, if a tolerable movement of 2.5 cm is acceptable for the structure. Comparison of the required pier lengths computed using the current and proposed design methods indicates that by considering rate of heave for the site at the end of design life of the structure, the required pier length can be reduced by 81 to 92%. Among the cases analyzed, the helical pier is the most effective technique in terms of the required pier length for the structure on expansive soils.

8.5 Factors Affecting Design of Foundations on Expansive Soils

The design example discussed in the previous section was conducted assuming the site has good drainage conditions. Chao, et al. (2006) concluded that significant variation exists in the pattern of wetting and the consequential rate of heave if the effects of irrigation practices, poor drainage conditions, deep wetting from underground sources, and other factors are considered. Factors affecting the design of foundations on expansive soils are discussed in the following sections.

8.5.1 Site Grading

The required pier lengths obtained using the proposed design methodology shown in Table 8-2 were calculated for a site with good drainage conditions. Chao, et al. (2006) conducted water migration analyses for the same site, but with poor drainage consisting of flat drainage, non-irrigated gravel within 1.5 meters of the building, and ponding at 1.5 meter away from the building, as shown in Figure 8-6. The long-term water content profiles for this poor drainage case at the edge of the building are shown in Figure 8-7. Comparison of Figure 8-7 with Figure 8-4 indicates that the flat drainage and ponding conditions create a significant increase of water content in soils. The water content profiles at 100 years result in nearly saturated soils from depths of 4 to 17 meters.

The required pier lengths for this condition were computed using the proposed pier design methodology. The same soil properties shown in Table 8-1 were used for the pier design. Figure 8-8 shows the results of the required pier lengths for this case. The required pier lengths computed for the example case with good drainage conditions are also shown in Figure 8-8 for comparison purposes. This figure indicates that the required pier length needs to be increased by up to 92% if the poor drainage conditions exist at the site.

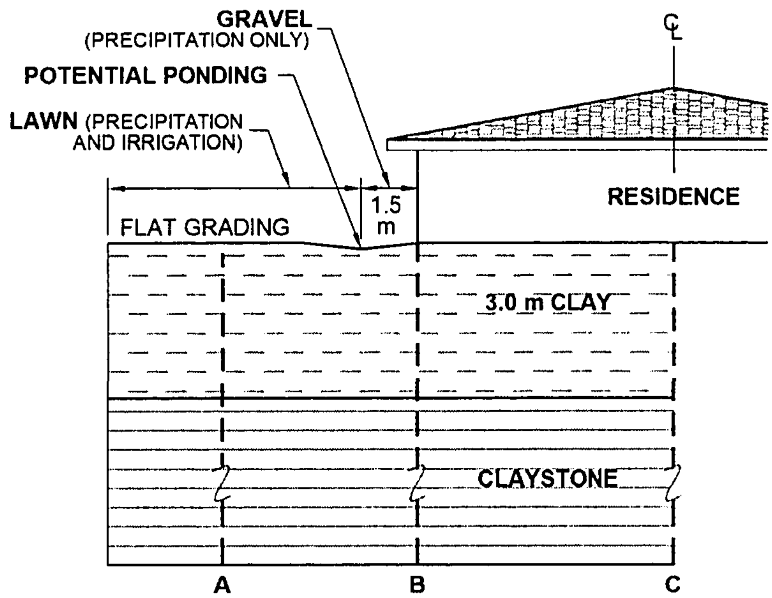


Figure 8-6 Typical Cross Section Used for Modeling Poor Drainage Conditions in VADOSE/W analyses

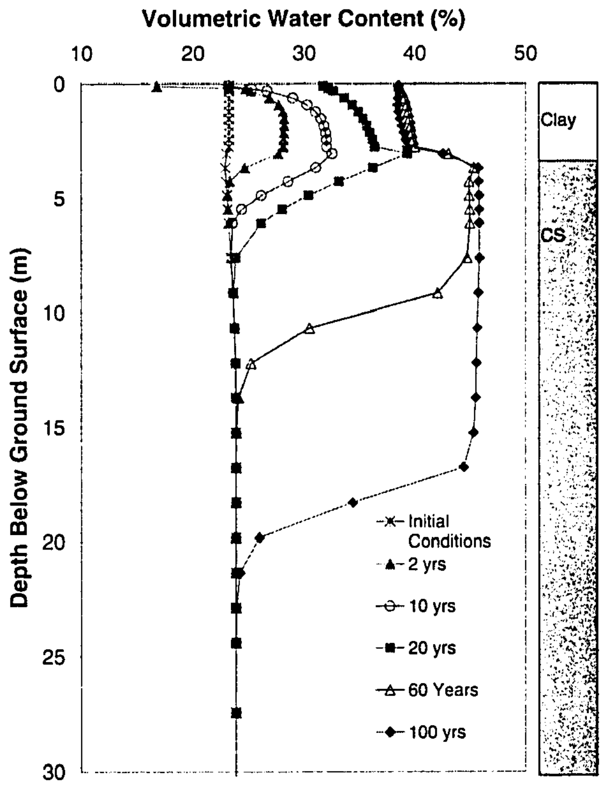


Figure 8-7 Predicted Long-Term Water Content Profiles at the Edge of the Building – Poor Drainage Conditions

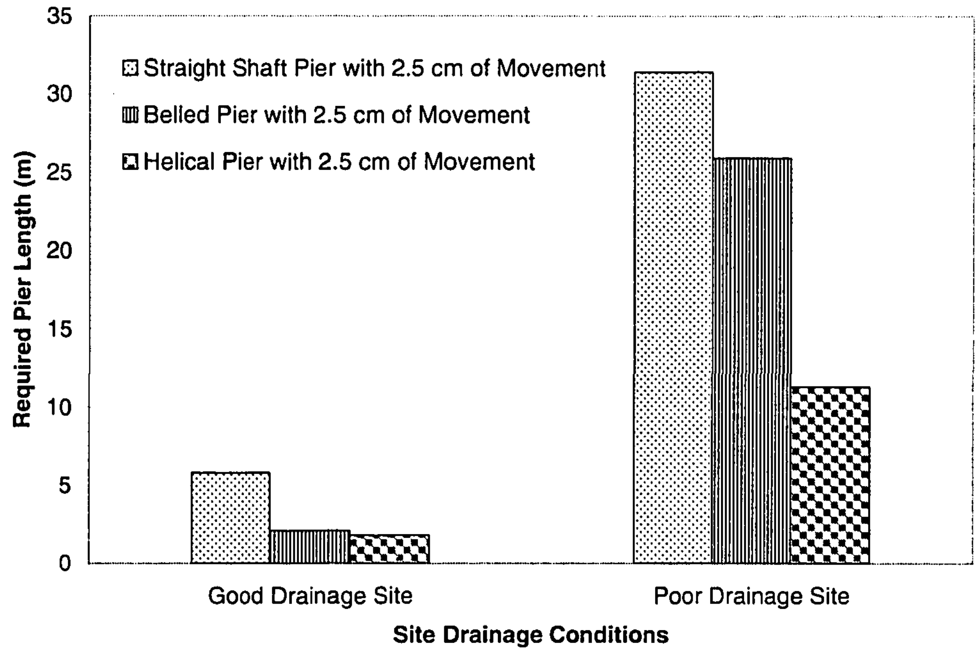


Figure 8-8 Required Pier Lengths for the Site with Good or Poor Drainage Conditions

8.5.2 Soil Expansion Potential

Effect of soil expansion potential to the design of foundations was evaluated in this section. Values of soil expansion potential ranging from 0.5 to 11.9 shown in Table 8-3 were selected for the evaluation. The same soil profile as the example case was used in the calculations. The water content profiles for the site with good drainage conditions shown in Figure 8-4 were used. The results of the required pier lengths using the proposed design methodology are shown in Figure 8-9.

Table 8-3 Summary of EP Values Used in the Heave Calculations

Case No.	Native Clay Consolidation Swell Test[1]			Claystone Consolidation Swell Test[1]		
	Percent Swell (%)	Swelling Pressure (kPa)	Expansion Potential[2]	Percent Swell (%)	Swelling Pressure (kPa)	Expansion Potential[2]
1	1.5	140	0.5	1.5	140	0.5
2	2.0	240	1.1	2.0	240	1.1
3	2.0	240	1.1	3.0	335	2.0
4	3.0	335	2.0	4.0	480	3.2
5	4.0	480	3.2	6.0	720	5.8
6	6.0	720	5.8	10.0	1,200	11.9

Notes: (1) Inundation Pressure = 48 kPa
(2) Refer to Nelson, et al. (2007a)

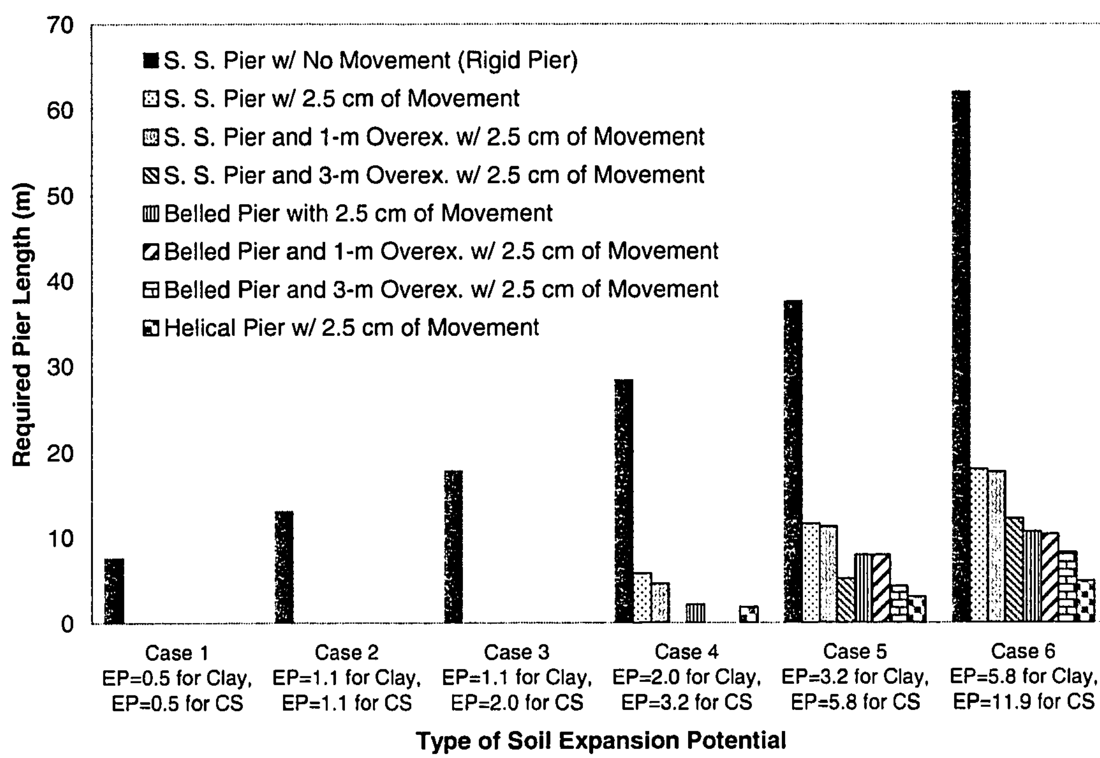


Figure 8-9 Comparison of Required Pier Lengths for Sites with Various EP Values – Good Drainage Conditions

The required pier lengths using the elastic pier method shown in Figure 8-9 were computed considering the amount of predicted heave at the end of design life of the structure. Compared to the required pier lengths assuming the entire depth of potential heave will be wetted (rigid pier) shown in Figure 8-9, the required pier lengths considering the predicted heave at the end of design life of the structure are reduced significantly. Thus, design of foundations on expansive soils for sites with high to very high expansion potential becomes practical and economical in engineering practice.

It is interesting to note in Figure 8-9 that by considering rate of heave for the site at the end of design life of the structure and assuming the maximum tolerable movement of 2.5 cm, no pier is needed for Cases 1, 2, and 3. For these cases, a spread footing foundation could be used for the structure.

For comparison purposes, the water content profiles for the site with poor drainage conditions shown in Figure 8-7 were used for the evaluation. The results of the required pier lengths for the poor drainage site are shown in Figure 8-10. This figure indicates that design of straight shaft and belled pier foundations for Cases 4, 5, and 6 is not practical and economical, even the rate of heave within the design life of the structure is considered.

Among the cases analyzed in Figure 8-10, the helical pier is the most effective technique in terms of the required pier length for the structure on expansive soils.

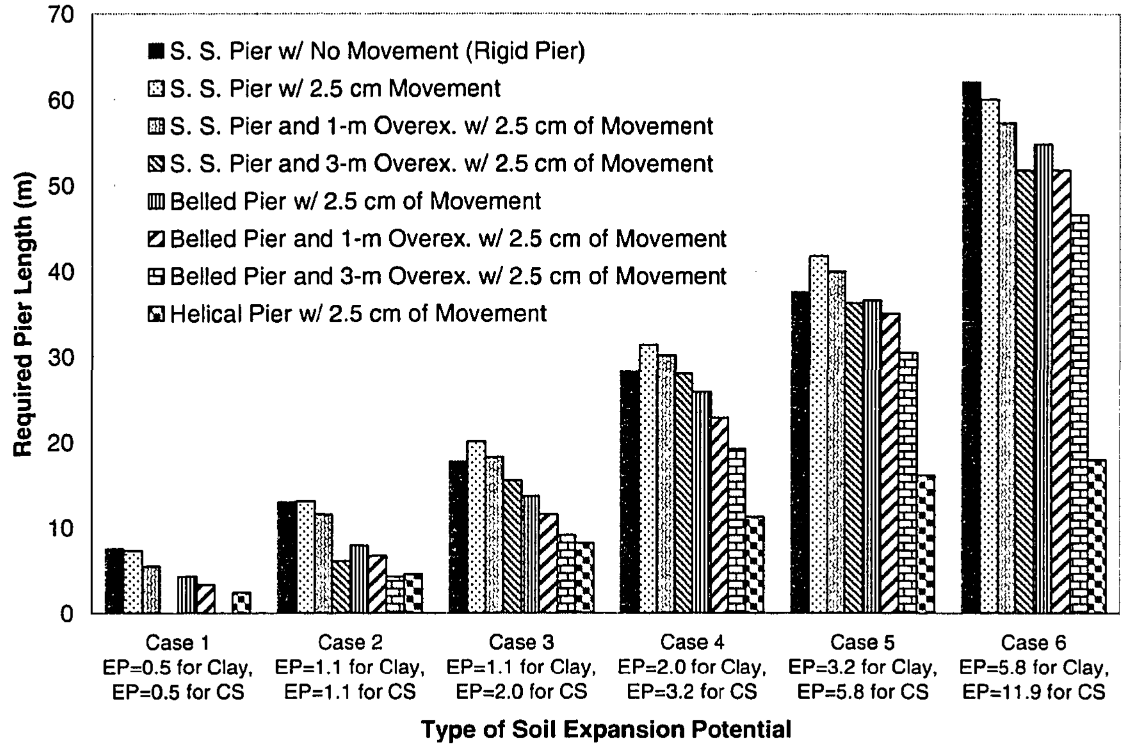


Figure 8-10 Comparison of Required Pier Lengths for Sites with Various EP Values – Poor Drainage Conditions

8.5.3 Overexcavation and Replacement Method

Overexcavation and replacement method is often used in areas of highly swelling soils and bedrock to reduce the amount of total heave and associated differential heave. However, experience indicates that sometimes the use of overexcavation and replacement method by itself can not ensure a structurally sound foundation. Therefore, it is necessary to form a system combining the overexcavation and replacement method and a pier and grade beam foundation for sites with highly expansive soils. The effect of overexcavation and replacement method in combination with a pier and grade beam foundation was evaluated. Both 1 meter and 3 meters of overexcavation are commonly recommended by practicing engineers in the Front Range area of Colorado. Therefore, both depths of overexcavation were evaluated. The results of the evaluation are shown in Figures 8-9 and 8-10 for the site with good or poor drainage conditions, respectively.

Case 4 shown in Figure 8-9 and Case 1 shown in Figure 8-10 indicates that if the 3 meters of overexcavation and replacement method is adopted, no pier is needed within the design life of the structure if 2.5 cm of movement can be tolerated. For these cases, a spread footing foundation could be used for the structure.

Figures 8-9 and 8-10 indicate that by combining the 1 meter of overexcavation and replacement method and a pier and grade beam foundation, the required pier length can be reduced by 0 to 25%. If the 3 meters of the overexcavation and replacement method in combination with a pier and grade beam foundation is adopted, the required pier length can be further reduced by 11 to 53%. As expected, the effect of the overexcavation and replacement method decreases as the soil expansion potential increases.

8.5.4 Subsurface Water Sources

Review of the results of the water migration analyses performed for the TRACON site indicates that the presence of a deep water bearing stratum is significant in the migration of the subsurface water and the associated rate of heave. Therefore, it is necessary to identify any deep water bearing stratum during the design process.

The presence of a deep water bearing stratum affecting the design of foundations was evaluated using the results of the water migration analyses in Chapter 6. The evaluation was performed at two locations of Flooring Monitoring Points F81 and F55. The locations of Points F81 and F55 are adjacent to the locations of subsurface nuclear gauge tubes SMI-MA2A and MA3, respectively. A pier diameter of 61 cm and a design dead load of 1,400 kPa were used in the calculations.

The required pier length was calculated using the proposed design methodology. Figure 8-11 shows the results of the calculations. The constructed lengths of the straight shaft piers at the TRACON building range from 7.6 to 8.5 meters. Figure 8-11 indicates that the straight shaft pier should have been designed to be 30.8 to 40.2 meters, if no foundation movement is allowed. If a 2.5 cm of foundation movement is tolerable, the required straight shaft pier length can be reduced to be 12.8 to 21.3 meters. If a belled pier foundation with a tolerable movement of 2.5 cm had been selected, the required pier length could be further reduced to be 7.0 to 12.2 meters. The length of 7.0 meters is close to the constructed length at the site. However, the constructed piers are straight shaft piers, not belled piers.

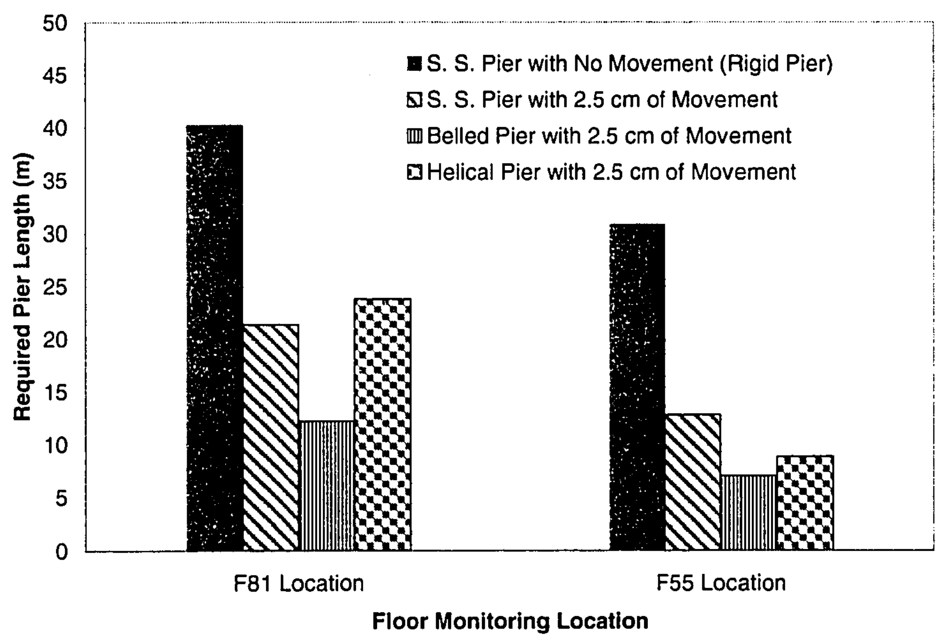


Figure 8-11 Required Pier Lengths at Locations of Floor Monitoring Points F81 and F55

It is interesting to note that among the cases analyzed in the previous sections, the helical pier is the most effective technique in terms of the required pier length. However, that is not the case for the TRACON building. Figure 8-11 shows that the required lengths for the helical pier are longer than those for the belled pier at the both locations analyzed. The required length for the helical pier is even longer than that for the straight shaft pier at the location of Point F81. For the case of wetting occurs outward from a water bearing stratum within subsurface soils, the anchorage zone and the active zone shown in Figure 2-24 are reversed, compared to the case of wetting from the ground surface. As discussed in Section 8.2.2.2, the skin friction along the shaft is neglected in predicting heave of a helical pier. Therefore, the resistance in the anchorage zone is neglected in the helical pier design, whereas the resistance is still considered in the straight shaft or belled pier design. This provides a need for a longer helical pier than a straight shaft or belled pier for the case of water migrating from the subsurface.

8.6 Discussion

The proposed design methodology provides a practical and economical approach to design foundations on expansive soils. This methodology considers the migration of the subsurface water that will occur and the associated heave that such wetting will produce during the design life of the structure. By considering this factor, the required pier length can be reduced significantly, compared to the current design methodology. It is also shown that the use of belled piers may be very effective in some cases.

Another means of mitigating the effects of heave is to overexcavate and replace the upper few meters of expansive soil with non-expansive soil. For sites with low to moderate EP the overexcavation and replacement procedure may even negate the need for piers and spread footings may be used. It is essential that heave calculations be performed to verify if that can be done. For sites with highly expansive soils, the use of overexcavation and replacement method in combination with piers can be very effective in mitigation effects of expansive soils.

For sites with water migrates only from the ground surface, it was found that helical piers might be the most effective foundation system in terms of the required pier length for structures on expansive soils. However, if any subsurface water sources exist at a site, the use of helical piers may become less effective compared to the use of straight shaft or belled piers.

Significant variation exists in the pattern of wetting and the consequential change of heave with time if the effect of irrigation practices, poor drainage conditions, and deep wetting from underground sources are considered. Conditions such as poor drainage and/or excessive lawn irrigation can result in a condition where the entire depth of potential heave is wetted during the life of the structure. This results in the required pier length much longer than that for a site with good drainage conditions. A prudent design engineer should assume that the entire depth of potential heave is wetted during the design life of the structure, unless site specific analyses have been performed to accurately determine the water migration pattern and the resulting change of heave with time. Site specific analyses should consider an appropriate factor of safety, other water sources, and the potential that the owners will use the property in a manner that is not in accordance with good drainage criteria.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The conclusions and accomplishments resulting from this research are categorized in four areas as follows.

9.1.1 Survey Benchmark

9.1.1.1 For benchmarks installed at areas with expansive soils, swelling of the soils is the most significant factor that influences the instability of the benchmarks.

9.1.1.2 The design and installation procedure for the deep benchmark developed in this research provides a means of constructing stable benchmarks.

9.1.2 Water Migration in the Vadose Zone

9.1.2.1 The results of the VADOSE/W analyses demonstrated that rigorous water migration analyses can be performed to analyze the actual depth of wetting in subsoils.

9.1.2.2 The Standard Method of Test ASTM D5298-94 recommends a minimum equilibration time of 7 days when measuring suction using the filter paper method. The results of the equilibration time evaluation indicate that the time required for equilibration increases as the water content of the sample increases. The required equilibration time can be longer than 7 days if the volumetric water content of the sample is greater than 20%.

9.1.2.3 A bilinear form of relationship between equilibration time and water content gives the best fit to the measured laboratory data. It was found that the intersection of the two points of the bilinear curve correspond to the ASTM recommendation of 7 days.

9.1.2.4 For the close form equation of the SWCC, the equation proposed by Fredlund and Xing (1994) provided the best fit when compared to 5 other previously proposed mathematical equations. However, the bilinear form of the SWCC for the expansive bedrock gives the best fit to the measured experimental data overall.

9.1.2.5 The results of the water migration study show that water will continue to migrate within the soils and bedrock through the entire design life period. Climate conditions will influence primarily the top 6 meters below the ground surface. Lawn irrigation can increase the values of water content in the subsoils by a factor of 2 or more.

9.1.2.6 The water content of the subsoils for a site with poor drainage conditions increases significantly compared to that for a site with good drainage conditions. Drainage conditions of the ground surface within the first 3 meters away from foundation walls are a primary factor influencing the rate of water migration.

9.1.3 Prediction of Change of Heave with Time

9.1.3.1 Fitting observed data to a hyperbolic equation provided a means of extending observed heave into the future using monthly survey data. In conducting the curve fitting it was necessary to include the predicted maximum heave in the analysis. Using observed data collected over a period of even less than one year provided reasonable accuracy over the maximum period of observation to date (6 years). The accuracy of this method increased if a longer period of observed data was used.

9.1.3.2 The relationship between water content and percent swell obtained using the Fredlund SWCC device is non-linear. The rate of swell decreases as the water content of the soil sample increases. A general form of the relationship between the normalized percent swell and water content was developed. This general form can be used to predict heave as a function of time.

9.1.3.3 Predicting heave as a function of time using the computer modeling of water migration is more accurate than curve fitting of observed data. This method allows for variations in soil profiles, different sources of water, and climate conditions to be taken into account. The predicted heave rates were influenced by fluctuations of climate conditions, redistribution of soil water within soil layers, and non-uniform heave resulting from the wetting of soil layers.

9.1.4 Foundation Design Principles

9.1.4.1 The maximum amount of predicted heave that will ultimately occur can be very large at highly expansive soil sites. Such large amounts of heave are associated with large depths of potential heave. Over the design life of a structure, those large depths may not become fully wetted so as to realize the full amount of the expansion potential.

9.1.4.2 The predicted heave at the end of design life of the TRACON building was calculated to be up to 60% of the predicted maximum heave. If site conditions were to change, such as the application of lawn irrigation, the predicted heave at the end of design life could reach the predicted maximum heave.

9.1.4.3 The proposed design methodology presented in this research provides a practical and economical approach to design foundations on expansive soils. This methodology considers the timewise pattern of migration of water within subsoils and the associated heave that such wetting will produce during the design life of the structure. Application of the design methodology indicates that the required pier length can be reduced significantly, as compared to the currently used design methodology.

9.1.4.4 The actual depth and pattern of wetting of subsoils that must be considered for design purposes will depend upon subsurface soil and geologic profiles, water sources, irrigation practices, surface grading, and other factors. Deep water bearing strata can have a significant influence on the water migration of the subsoils and must be considered in the design process.

9.1.4.5 Irrigation practices, poor drainage conditions, and deep wetting from underground sources influence significantly the pattern of subsurface water and the consequential change of heave with time. The entire depth of potential heave can become wetted if any of these factors exist. A prudent design concept will assume that the entire depth of potential heave can become wetted during the design life of the structure, unless site specific analyses have been performed to accurately determine the water migration pattern and the resulting change of heave with time. Site specific analyses should consider an appropriate factor of safety, other water sources, and the potential that the owners will use the property in a manner that is not in accordance with the design assumptions.

9.1.4.6 Overexcavating and replacing the upper few meters of expansive soil with non-expansive soil can be effective if properly designed. The use of the overexcavation and replacement method in combination with a pier and grade beam foundation can be very effective even at sites with highly expansive soils.

9.2 Recommendations for Additional Research

Other topics recommended to be further explored include the following:

9.2.1 It was shown that a bilinear form of the relationship between equilibration time and water content of the soil gives the best fit to the measured laboratory data. Also, the intersection of the two points of the bilinear curve corresponds to the ASTM D5298-94 recommendation of 7 days. It is recommended that this bilinear relationship be further investigated.

9.2.2 The bilinear relationship of the SWCC for expansive soils has been attributed to a transition between macropore (capillary) spaces and micropore (diffuse double layer) spaces (Miller, 1996). The physical significance of this apparent transition point may be attributed to the bi-level pore size distribution researched by Al-Mukhtar (1995), Alonso, et al. (1995); and Wan, et al. (1995). The significance of the approximately bilinear shape of the SWCC and the magnitude of the suction at the transition is an important area for future research.

9.2.3 The soil suction at zero water content is used as a boundary parameter in heave prediction using the soil suction method proposed by McKeen (1992). The soil suction at zero water content is reported by McKeen (1992) to be near 174,385 kPa (6.25 pF). Fredlund and Xing (1994) introduced a correction function, $C(\psi)$, in their SWCC fitting equation to force the SWCC to pass through a soil suction of 10^6 kPa (7.0 pF) at zero water content. However, it is not clear in either of these papers whether they are actually referring to oven-dry water content or actual "zero" water content. Because it is virtually impossible to reach actual "zero" water content without changing the mineralogy of the soil, it is assumed that their use of the term "zero" water content actually refers to oven-dry water content.

In the research reported herein, the average measured soil suction value for the claystone samples at oven-dry water content is approximately 245,000 kPa (6.40 pF). It is recommended that this limit of soil suction at oven-dry water content be further evaluated.

9.2.4 A second order polynomial equation was found to provide a very reasonable fit to the observed experimental data for the relationship between water content and swell potential. The remolded claystone of the Denver and Pierre Shale Formations were used in the experiment. More study is needed for this relationship for different kinds of expansive soils/bedrock.

9.2.5 The water migration analyses were conducted using the measured SWCCs and unsaturated permeability functions estimated from the SWCCs. The claystone samples were remolded for the experiment. It is important to test the samples in the laboratory simulating the stress state and physical state conditions of the field. Therefore, it is recommended that additional research be conducted to determine the influence of stress state conditions on the SWCC and the unsaturated permeability function for expansive soils. Furthermore, additional study is necessary to understand the SWCC of fissured and cracked expansive bedrock.

9.2.6 The pier heave calculations were conducted considering each pier acting independently as a single pier. Vesic (1967) indicated that the efficiency of a full pile group in homogeneous sand increased with pile spacing to a maximum at a spacing of three pile diameters and then decreased with a further increase in pile spacing. At the TRACON building, there are six groups of four piers each under the trusses. These truss piers are 76 cm in diameter and were constructed at 2.4-m on-center. The ratio of pier spacing to pier diameter was computed to be 3.2. Elevation surveying performed by ZBSI for these truss piers indicated that these truss piers are heaving less than those piers inside the TRACON building (ZBSI, 2006). It is recommended that additional research be performed on the heave of pier groups in expansive soils.

CHAPTER 10

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APPENDIX A

SPECIMEN PREPARATION
DATA WORKSHEETS

APPENDIX A.1

SPECIMENS FOR FILTER PAPER EQUILIBRATION TIME TEST

REMOLDED SAMPLE PREPARATION DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W10-1
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	12/28/2005	**Notes:**	

Retaining Ring Information		
Ring I.D.		2"R2
Wt. of Ring	(g)	40.51
Ring Diameter	(in)	2.438
Ring Height	(in)	2.400
Spacer Height	(in)	0.376
Volume of Sample	(in^3)	9.449

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	100.5
Opt. Water Content (from Proctor)	(%)	22.30
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	100.5
Target Gravimetric Water Content	(%)	9.60
Change in Gravimetric Water Content	(%)	2.53
Wt. of Water Needed to be Added to Soil Sample	(g)	**8.22**

Existing Soil Water Content (from Microwave)		
Dish I.D.		T2
Wt. of Dish	(g)	157.66
Wt. of Wet Sample + Dish	(g)	214.90
Wt. of Dry Sample + Dish (First Try)	(g)	211.14
Wt. of Dry Sample + Dish (Second Try)	(g)	211.12
% Diff. of Wt. of Dry Sample + Dish	(%)	0.01
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	7.07

Check of Target Water Content (from Microwave)		
Dish I.D.		T5
Wt. of Dish	(g)	161.31
Wt. of Wet Sample + Dish	(g)	197.53
Wt. of Dry Sample + Dish (First Try)	(g)	194.37
Wt. of Dry Sample + Dish (Second Try)	(g)	194.33
% Diff. of Wt. of Dry Sample + Dish	(%)	0.02
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	9.69
Check of Target Gravi. Water Content		**O.K.**

Existing Soil Conditions		
Dish I.D.		W10-1
Wt. of Dish	(g)	34.61
Wt. of Wet Sample + Dish	(g)	382.45
Wt. of Wet Sample	(g)	347.84
Wt. of Dry Sample	(g)	324.87

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	110.24
Wt. of Soil Sample Needed to be Compacted Into Ring	(g)	**273.42**

REMOLDED SAMPLE PREPARATION DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W12-1
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	10/18/2005	**Notes:**	

Retaining Ring Information		
Ring I.D.		2"R2
Wt. of Ring	(g)	40.51
Ring Diameter	(in)	2.438
Ring Height	(in)	2.400
Spacer Height	(in)	0.376
Volume of Sample	(in^3)	9.449

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	100.5
Opt. Water Content (from Proctor)	(%)	22.30
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	100.5
Target Gravimetric Water Content	(%)	12.40
Change in Gravimetric Water Content	(%)	3.51
Wt. of Water Needed to be Added to Soil Sample	(g)	**10.18**

Existing Soil Water Content (from Microwave)		
Dish I.D.		T3
Wt. of Dish	(g)	156.04
Wt. of Wet Sample + Dish	(g)	190.33
Wt. of Dry Sample + Dish (First Try)	(g)	187.55
Wt. of Dry Sample + Dish (Second Try)	(g)	187.53
% Diff. of Wt. of Dry Sample + Dish	(%)	0.01
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	8.89

Check of Target Water Content (from Microwave)		
Dish I.D.		T2
Wt. of Dish	(g)	157.69
Wt. of Wet Sample + Dish	(g)	181.42
Wt. of Dry Sample + Dish (First Try)	(g)	178.70
Wt. of Dry Sample + Dish (Second Try)	(g)	178.69
% Diff. of Wt. of Dry Sample + Dish	(%)	0.01
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	13.00
Check of Target Gravi. Water Content		**O.K.**

Existing Soil Conditions		
Dish I.D.		W12-1
Wt. of Dish	(g)	34.66
Wt. of Wet Sample + Dish	(g)	350.52
Wt. of Wet Sample	(g)	315.86
Wt. of Dry Sample	(g)	290.07

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	113.57
Wt. of Soil Sample Needed to be Compacted Into Ring	(g)	**281.66**

REMOLDED SAMPLE PREPARATION DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W15-1
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	12/28/2005	**Notes:**	

Retaining Ring Information		
Ring I.D.		2"R2
Wt. of Ring	(g)	40.51
Ring Diameter	(in)	2.438
Ring Height	(in)	2.400
Spacer Height	(in)	0.376
Volume of Sample	(in^3)	9.449

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	100.5
Opt. Water Content (from Proctor)	(%)	22.30
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	100.5
Target Gravimetric Water Content	(%)	14.50
Change in Gravimetric Water Content	(%)	7.43
Wt. of Water Needed to be Added to Soil Sample	(g)	**24.23**

Existing Soil Water Content (from Microwave)		
Dish I.D.		T2
Wt. of Dish	(g)	157.66
Wt. of Wet Sample + Dish	(g)	214.90
Wt. of Dry Sample + Dish (First Try)	(g)	211.14
Wt. of Dry Sample + Dish (Second Try)	(g)	211.12
% Diff. of Wt. of Dry Sample + Dish	(%)	0.01
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	7.07

Check of Target Water Content (from Microwave)		
Dish I.D.		T5
Wt. of Dish	(g)	161.32
Wt. of Wet Sample + Dish	(g)	205.46
Wt. of Dry Sample + Dish (First Try)	(g)	200.20
Wt. of Dry Sample + Dish (Second Try)	(g)	200.15
% Diff. of Wt. of Dry Sample + Dish	(%)	0.02
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	13.67
Check of Target Gravi. Water Content		**O.K.**

Existing Soil Conditions		
Dish I.D.		W15-1
Wt. of Dish	(g)	33.81
Wt. of Wet Sample + Dish	(g)	382.97
Wt. of Wet Sample	(g)	349.16
Wt. of Dry Sample	(g)	326.10

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	114.24
Wt. of Soil Sample Needed to be Compacted Into Ring	(g)	**283.35**

REMOLDED SAMPLE PREPARATION DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W19-8
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	12/28/2005	**Notes:**	

Retaining Ring Information		
Ring I.D.		2"R2
Wt. of Ring	(g)	40.51
Ring Diameter	(in)	2.438
Ring Height	(in)	2.400
Spacer Height	(in)	0.376
Volume of Sample	(in^3)	9.449

Existing Soil Water Content (from Microwave)		
Dish I.D.		T2
Wt. of Dish	(g)	157.68
Wt. of Wet Sample + Dish	(g)	218.80
Wt. of Dry Sample + Dish (First Try)	(g)	214.99
Wt. of Dry Sample + Dish (Second Try)	(g)	214.88
% Diff. of Wt. of Dry Sample + Dish	(%)	0.05
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	6.85

Existing Soil Conditions		
Dish I.D.		W19-8
Wt. of Dish	(g)	34.76
Wt. of Wet Sample + Dish	(g)	388.54
Wt. of Wet Sample	(g)	353.78
Wt. of Dry Sample	(g)	331.09

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	100.5
Opt. Water Content (from Proctor)	(%)	22.30
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	100.5
Target Gravimetric Water Content	(%)	19.30
Change in Gravimetric Water Content	(%)	12.45
Wt. of Water Needed to be Added to Soil Sample	(g)	**41.21**

Check of Target Water Content (from Microwave)		
Dish I.D.		T5
Wt. of Dish	(g)	161.31
Wt. of Wet Sample + Dish	(g)	203.42
Wt. of Dry Sample + Dish (First Try)	(g)	197.03
Wt. of Dry Sample + Dish (Second Try)	(g)	196.91
% Diff. of Wt. of Dry Sample + Dish	(%)	0.06
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	18.29
Check of Target Gravi. Water Content		**Check Again**

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	118.88
Wt. of Soil Sample Needed to be Compacted Into Ring	(g)	**294.84**

REMOLDED SAMPLE PREPARATION DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W25-8
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	12/28/2005	**Notes:**	

Retaining Ring Information		
Ring I.D.		2"R2
Wt. of Ring	(g)	40.51
Ring Diameter	(in)	2.438
Ring Height	(in)	2.400
Spacer Height	(in)	0.376
Volume of Sample	(in^3)	9.449

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	100.5
Opt. Water Content (from Proctor)	(%)	22.30
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	100.5
Target Gravimetric Water Content	(%)	24.80
Change in Gravimetric Water Content	(%)	17.73
Wt. of Water Needed to be Added to Soil Sample	(g)	**58.56**

Existing Soil Water Content (from Microwave)		
Dish I.D.		T2
Wt. of Dish	(g)	157.66
Wt. of Wet Sample + Dish	(g)	214.90
Wt. of Dry Sample + Dish (First Try)	(g)	211.14
Wt. of Dry Sample + Dish (Second Try)	(g)	211.12
% Diff. of Wt. of Dry Sample + Dish	(%)	0.01
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	7.07

Check of Target Water Content (from Microwave)		
Dish I.D.		T5
Wt. of Dish	(g)	161.31
Wt. of Wet Sample + Dish	(g)	196.75
Wt. of Dry Sample + Dish (First Try)	(g)	190.23
Wt. of Dry Sample + Dish (Second Try)	(g)	190.12
% Diff. of Wt. of Dry Sample + Dish	(%)	0.06
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	23.01
Check of Target Gravi. Water Content		**Check Again**

Existing Soil Conditions		
Dish I.D.		W25-8
Wt. of Dish	(g)	33.73
Wt. of Wet Sample + Dish	(g)	387.41
Wt. of Wet Sample	(g)	353.68
Wt. of Dry Sample	(g)	330.32

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	123.63
Wt. of Soil Sample Needed to be Compacted Into Ring	(g)	**306.62**

REMOLDED SAMPLE PREPARATION DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W28-1
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	5/27/2006	**Notes:**	

Retaining Ring Information		
Ring I.D.		2"R2
Wt. of Ring	(g)	40.51
Ring Diameter	(in)	2.438
Ring Height	(in)	2.400
Spacer Height	(in)	0.376
Volume of Sample	(in^3)	9.449

Existing Soil Water Content (from Microwave)		
Dish I.D.		F1
Wt. of Dish	(g)	156.03
Wt. of Wet Sample + Dish	(g)	205.87
Wt. of Dry Sample + Dish (First Try)	(g)	203.41
Wt. of Dry Sample + Dish (Second Try)	(g)	203.35
% Diff. of Wt. of Dry Sample + Dish	(%)	0.03
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	5.33

Existing Soil Conditions		
Dish I.D.		W28-1
Wt. of Dish	(g)	33.93
Wt. of Wet Sample + Dish	(g)	398.81
Wt. of Wet Sample	(g)	364.88
Wt. of Dry Sample	(g)	346.43

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	100.5
Opt. Water Content (from Proctor)	(%)	22.30
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	100.5
Target Gravimetric Water Content	(%)	28.00
Change in Gravimetric Water Content	(%)	22.67
Wt. of Water Needed to be Added to Soil Sample	(g)	**78.55**

Check of Target Water Content (from Microwave)		
Dish I.D.		F1
Wt. of Dish	(g)	156.06
Wt. of Wet Sample + Dish	(g)	196.54
Wt. of Dry Sample + Dish (First Try)	(g)	187.05
Wt. of Dry Sample + Dish (Second Try)	(g)	187.04
% Diff. of Wt. of Dry Sample + Dish	(%)	0.01
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	30.66
Check of Target Gravi. Water Content		**Check Again**

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	131.32
Wt. of Soil Sample Needed to be Compacted Into Ring	(g)	**325.69**

APPENDIX A.2

SPECIMENS FOR FILTER PAPER SWCC TEST

APPENDIX A.2.1

SPECIMENS FOR
FILTER PAPER SWCC TEST
DENVER FORMATION

REMOLDED SAMPLE PREPARATION DATA SHEET FOR FILTER PAPER TEST

Sample Source:	Russell Project	**Sample I.D.:**	D-1 and D-2
Soil Type:	Claytone	**Geological Formation:**	Denver Formation
Solution Type:	DI, D-Aired Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	10/29/2005 16:54	**Notes:**	

Retaining Ring Information		
Ring I.D.		2"R2
Wt. of Ring	(g)	40.11
Ring Diameter	(in)	2.438
Ring Height	(in)	2.400
Spacer Height	(in)	0.406
Volume of Sample	(in^3)	9.309

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	96.8
Opt. Water Content (from Proctor)	(%)	24.20
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	96.8
Target Gravimetric Water Content	(%)	21.20
Change in Gravimetric Water Content	(%)	11.49
Wt. of Water Needed to be Added to Soil Sample	(g)	**37.34**

Existing Soil Water Content (from Microwave)		
Dish I.D.		T2
Wt. of Dish	(g)	157.66
Wt. of Wet Sample + Dish	(g)	205.45
Wt. of Dry Sample + Dish (First Try)	(g)	201.23
Wt. of Dry Sample + Dish (Second Try)	(g)	201.22
% Diff. of Wt. of Dry Sample + Dish	(%)	0.00
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	9.71

Check of Target Water Content (from Microwave)		
Dish I.D.		T1
Wt. of Dish	(g)	188.91
Wt. of Wet Sample + Dish	(g)	224.45
Wt. of Dry Sample + Dish (First Try)	(g)	218.39
Wt. of Dry Sample + Dish (Second Try)	(g)	218.38
% Diff. of Wt. of Dry Sample + Dish	(%)	0.00
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	20.60
Check of Target Gravi. Water Content		**O.K.**

Existing Soil Conditions		
Dish I.D.		W19-1
Wt. of Dish	(g)	34.49
Wt. of Wet Sample + Dish	(g)	391.04
Wt. of Wet Sample	(g)	356.55
Wt. of Dry Sample	(g)	324.99

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	116.74
Wt. of Sample Needed to be Compacted Into Two Rings	(g)	285.24
Wt. of Sample Needed to be Compacted Into a Ring	(g)	142.62
Wt. of Sample Needed to be Compacted Into a Layer	(g)	**35.66**

REMOLDED SAMPLE PREPARATION DATA SHEET FOR FILTER PAPER TEST

Sample Source:	Russell Project	**Sample I.D.:**	D-3 and D-4
Soil Type:	Claytone	**Geological Formation:**	Denver Formation
Solution Type:	DI, D-Aired Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	10/29/2005 17:15	**Notes:**	

Retaining Ring Information		
Ring I.D.		2"R2
Wt. of Ring	(g)	40.11
Ring Diameter	(in)	2.438
Ring Height	(in)	2.400
Spacer Height	(in)	0.406
Volume of Sample	(in^3)	9.309

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	96.8
Opt. Water Content (from Proctor)	(%)	24.20
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	96.8
Target Gravimetric Water Content	(%)	21.20
Change in Gravimetric Water Content	(%)	11.43
Wt. of Water Needed to be Added to Soil Sample	(g)	**37.33**

Existing Soil Water Content (from Microwave)		
Dish I.D.		T2
Wt. of Dish	(g)	157.66
Wt. of Wet Sample + Dish	(g)	215.64
Wt. of Dry Sample + Dish (First Try)	(g)	210.52
Wt. of Dry Sample + Dish (Second Try)	(g)	210.48
% Diff. of Wt. of Dry Sample + Dish	(%)	0.02
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	9.77

Check of Target Water Content (from Microwave)		
Dish I.D.		T1
Wt. of Dish	(g)	188.92
Wt. of Wet Sample + Dish	(g)	222.55
Wt. of Dry Sample + Dish (First Try)	(g)	217.04
Wt. of Dry Sample + Dish (Second Try)	(g)	216.98
% Diff. of Wt. of Dry Sample + Dish	(%)	0.03
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	19.85
Check of Target Gravi. Water Content		**Check Again**

Existing Soil Conditions		
Dish I.D.		W19-2
Wt. of Dish	(g)	34.75
Wt. of Wet Sample + Dish	(g)	393.25
Wt. of Wet Sample	(g)	358.50
Wt. of Dry Sample	(g)	326.59

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	116.02
Wt. of Sample Needed to be Compacted Into Two Rings	(g)	283.48
Wt. of Sample Needed to be Compacted Into a Ring	(g)	141.74
Wt. of Sample Needed to be Compacted Into a Layer	(g)	**35.43**

REMOLDED SAMPLE PREPARATION DATA SHEET FOR FILTER PAPER TEST

Sample Source:	Russell Project	**Sample I.D.:**	D-5 and D-6
Soil Type:	Claytone	**Geological Formation:**	Denver Formation
Solution Type:	DI, D-Aired Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	10/29/2005 17:15	**Notes:**	

Retaining Ring Information		
Ring I.D.		2"R2
Wt. of Ring	(g)	40.11
Ring Diameter	(in)	2.438
Ring Height	(in)	2.400
Spacer Height	(in)	0.406
Volume of Sample	(in^3)	9.309

Existing Soil Water Content (from Microwave)		
Dish I.D.		T2
Wt. of Dish	(g)	157.67
Wt. of Wet Sample + Dish	(g)	214.13
Wt. of Dry Sample + Dish (First Try)	(g)	209.42
Wt. of Dry Sample + Dish (Second Try)	(g)	209.34
% Diff. of Wt. of Dry Sample + Dish	(%)	0.04
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	9.27

Existing Soil Conditions		
Dish I.D.		W19-3
Wt. of Dish	(g)	34.59
Wt. of Wet Sample + Dish	(g)	395.80
Wt. of Wet Sample	(g)	361.21
Wt. of Dry Sample	(g)	330.57

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	96.8
Opt. Water Content (from Proctor)	(%)	24.20
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	96.8
Target Gravimetric Water Content	(%)	21.20
Change in Gravimetric Water Content	(%)	11.93
Wt. of Water Needed to be Added to Soil Sample	(g)	**39.44**

Check of Target Water Content (from Microwave)		
Dish I.D.		T1
Wt. of Dish	(g)	188.93
Wt. of Wet Sample + Dish	(g)	235.61
Wt. of Dry Sample + Dish (First Try)	(g)	227.57
Wt. of Dry Sample + Dish (Second Try)	(g)	227.42
% Diff. of Wt. of Dry Sample + Dish	(%)	0.07
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	21.28
Check of Target Gravi. Water Content		**O.K.**

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	117.40
Wt. of Sample Needed to be Compacted Into Two Rings	(g)	286.85
Wt. of Sample Needed to be Compacted Into a Ring	(g)	143.43
Wt. of Sample Needed to be Compacted Into a Layer	(g)	**35.86**

APPENDIX A.2.2

SPECIMENS FOR
FILTER PAPER SWCC TEST
DENVER FORMATION

REMOLDED SAMPLE PREPARATION DATA SHEET FOR FILTER PAPER TEST

Sample Source:	Kim Project	**Sample I.D.:**	PS-1 and PS-2
Soil Type:	Claytone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	10/29/2005 15:33	**Notes:**	

Retaining Ring Information		
Ring I.D.		2"R2
Wt. of Ring	(g)	40.11
Ring Diameter	(in)	2.438
Ring Height	(in)	2.400
Spacer Height	(in)	0.406
Volume of Sample	(in^3)	9.309

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	100.5
Opt. Water Content (from Proctor)	(%)	22.30
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	100.5
Target Gravimetric Water Content	(%)	19.30
Change in Gravimetric Water Content	(%)	9.19
Wt. of Water Needed to be Added to Soil Sample	(g)	**29.95**

Existing Soil Water Content (from Microwave)		
Dish I.D.		T2
Wt. of Dish	(g)	157.67
Wt. of Wet Sample + Dish	(g)	204.29
Wt. of Dry Sample + Dish (First Try)	(g)	200.07
Wt. of Dry Sample + Dish (Second Try)	(g)	200.01
% Diff. of Wt. of Dry Sample + Dish	(%)	0.03
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	10.11

Check of Target Water Content (from Microwave)		
Dish I.D.		T1
Wt. of Dish	(g)	188.88
Wt. of Wet Sample + Dish	(g)	230.50
Wt. of Dry Sample + Dish (First Try)	(g)	224.79
Wt. of Dry Sample + Dish (Second Try)	(g)	224.78
% Diff. of Wt. of Dry Sample + Dish	(%)	0.00
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	15.93
Check of Target Gravi. Water Content		**Check Again**

Existing Soil Conditions		
Dish I.D.		W19-6
Wt. of Dish	(g)	33.75
Wt. of Wet Sample + Dish	(g)	392.58
Wt. of Wet Sample	(g)	358.83
Wt. of Dry Sample	(g)	325.89

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	116.51
Wt. of Sample Needed to be Compacted Into Two Rings	(g)	284.69
Wt. of Sample Needed to be Compacted Into a Ring	(g)	142.35
Wt. of Sample Needed to be Compacted Into a Layer	(g)	**35.59**

REMOLDED SAMPLE PREPARATION DATA SHEET FOR FILTER PAPER TEST

Sample Source:	Kim Project	**Sample I.D.:**	PS-3 and PS-4
Soil Type:	Claytone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	10/29/2005 15:57	**Notes:**	

Retaining Ring Information		
Ring I.D.		2"R2
Wt. of Ring	(g)	40.11
Ring Diameter	(in)	2.438
Ring Height	(in)	2.400
Spacer Height	(in)	0.406
Volume of Sample	(in^3)	9.309

Existing Soil Water Content (from Microwave)		
Dish I.D.		T2
Wt. of Dish	(g)	157.67
Wt. of Wet Sample + Dish	(g)	210.14
Wt. of Dry Sample + Dish (First Try)	(g)	206.74
Wt. of Dry Sample + Dish (Second Try)	(g)	206.66
% Diff. of Wt. of Dry Sample + Dish	(%)	0.04
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	7.10

Existing Soil Conditions		
Dish I.D.		W19-4
Wt. of Dish	(g)	34.89
Wt. of Wet Sample + Dish	(g)	390.54
Wt. of Wet Sample	(g)	355.65
Wt. of Dry Sample	(g)	332.06

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	100.5
Opt. Water Content (from Proctor)	(%)	22.30
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	100.5
Target Gravimetric Water Content	(%)	19.30
Change in Gravimetric Water Content	(%)	12.20
Wt. of Water Needed to be Added to Soil Sample	(g)	**40.50**

Check of Target Water Content (from Microwave)		
Dish I.D.		T1
Wt. of Dish	(g)	188.90
Wt. of Wet Sample + Dish	(g)	236.15
Wt. of Dry Sample + Dish (First Try)	(g)	228.79
Wt. of Dry Sample + Dish (Second Try)	(g)	228.74
% Diff. of Wt. of Dry Sample + Dish	(%)	0.02
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	18.60
Check of Target Gravi. Water Content		**O.K.**

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	119.19
Wt. of Sample Needed to be Compacted Into Two Rings	(g)	291.24
Wt. of Sample Needed to be Compacted Into a Ring	(g)	145.62
Wt. of Sample Needed to be Compacted Into a Layer	(g)	**36.40**

REMOLDED SAMPLE PREPARATION DATA SHEET FOR FILTER PAPER TEST

Sample Source:	Kim Project	**Sample I.D.:**	PS-5 and PS-6
Soil Type:	Claytone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	10/29/2005 16:15	**Notes:**	

Retaining Ring Information	
Ring I.D.	2"R2
Wt. of Ring (g)	40.11
Ring Diameter (in)	2.438
Ring Height (in)	2.400
Spacer Height (in)	0.406
Volume of Sample (in^3)	9.309

Water Needed to be Added to Soil Sample	
Max. Dry Density (from Proctor) (pcf)	100.5
Opt. Water Content (from Proctor) (%)	22.30
Target % of Max. Dry Density (%)	100
Target Dry Density (pcf)	100.5
Target Gravimetric Water Content (%)	19.30
Change in Gravimetric Water Content (%)	10.15
Wt. of Water Needed to be Added to Soil Sample (g)	**32.52**

Existing Soil Water Content (from Microwave)	
Dish I.D.	T2
Wt. of Dish (g)	157.62
Wt. of Wet Sample + Dish (g)	207.60
Wt. of Dry Sample + Dish (First Try) (g)	203.43
Wt. of Dry Sample + Dish (Second Try) (g)	203.41
% Diff. of Wt. of Dry Sample + Dish (%)	0.01
Check of % Diff. of Wt. of Dry Sample + Dish	**O.K.**
Existing Gravimetric Water Content (%)	9.15

Check of Target Water Content (from Microwave)	
Dish I.D.	T1
Wt. of Dish (g)	188.91
Wt. of Wet Sample + Dish (g)	214.31
Wt. of Dry Sample + Dish (First Try) (g)	210.55
Wt. of Dry Sample + Dish (Second Try) (g)	210.51
% Diff. of Wt. of Dry Sample + Dish (%)	0.02
Check of % Diff. of Wt. of Dry Sample + Dish	**O.K.**
Target Gravimetric Water Content (%)	17.59
Check of Target Gravi. Water Content	**Check Again**

Existing Soil Conditions	
Dish I.D.	W19-5
Wt. of Dish (g)	35.20
Wt. of Wet Sample + Dish (g)	384.91
Wt. of Wet Sample (g)	349.71
Wt. of Dry Sample (g)	320.39

Sample Needed to be Compacted into Ring	
Target Total Density (pcf)	118.18
Wt. of Sample Needed to be Compacted Into Two Rings (g)	288.77
Wt. of Sample Needed to be Compacted Into a Ring (g)	144.38
Wt. of Sample Needed to be Compacted Into a Layer (g)	**36.10**

APPENDIX A.3

SPECIMENS FOR
FREDLUND SWCC TEST

REMOLDED SAMPLE PREPARATION DATA SHEET FOR FREDLUND SWCC TEST

Sample Source:	Russell Project	**Sample I.D.:**	D-21
Soil Type:	Claytone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	6/30/2006	**Notes:**	

Retaining Ring Information		
Ring I.D.		R2
Wt. of Ring	(g)	264.57
Ring Diameter	(in)	2.498
Ring Height	(in)	1.200
Spacer Height	(in)	0.207
Volume of Sample	(in^3)	4.867

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	96.8
Opt. Water Content (from Proctor)	(%)	24.20
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	96.8
Target Gravimetric Water Content	(%)	21.20
Change in Gravimetric Water Content	(%)	12.90
Wt. of Water Needed to be Added to Soil Sample	(g)	**121.56**

Existing Soil Water Content (from Microwave)		
Dish I.D.		T5
Wt. of Dish	(g)	161.35
Wt. of Wet Sample + Dish	(g)	212.08
Wt. of Dry Sample + Dish (First Try)	(g)	208.21
Wt. of Dry Sample + Dish (Second Try)	(g)	208.19
% Diff. of Wt. of Dry Sample + Dish	(%)	0.01
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	8.30

Check of Target Water Content (from Microwave)		
Dish I.D.		T5
Wt. of Dish	(g)	161.28
Wt. of Wet Sample + Dish	(g)	201.81
Wt. of Dry Sample + Dish (First Try)	(g)	194.73
Wt. of Dry Sample + Dish (Second Try)	(g)	194.72
% Diff. of Wt. of Dry Sample + Dish	(%)	0.01
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	21.20
Check of Target Gravi. Water Content		**O.K.**

Existing Soil Conditions		
Dish I.D.		W-1
Wt. of Dish	(g)	161.72
Wt. of Wet Sample + Dish	(g)	1182.72
Wt. of Wet Sample	(g)	1021.00
Wt. of Dry Sample	(g)	942.71

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	117.32
Wt. of Sample Needed to be Compacted Into Two Rings	(g)	149.87
Wt. of Sample Needed to be Compacted Into a Ring	(g)	149.87
Wt. of Sample Needed to be Compacted Into a Layer	(g)	**37.47**

REMOLDED SAMPLE PREPARATION DATA SHEET

Sample Source:	Russell Project	**Sample I.D.:**	D-7B and D-8B
Soil Type:	Claytone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	5/1/2006	**Notes:**	

Retaining Ring Information		
Ring I.D.		2"R2
Wt. of Ring	(g)	264.56
Ring Diameter	(in)	2.498
Ring Height	(in)	2.430
Spacer Height	(in)	0.394
Volume of Sample	(in^3)	9.978

Existing Soil Water Content (from Microwave)		
Dish I.D.		F1
Wt. of Dish	(g)	155.98
Wt. of Wet Sample + Dish	(g)	208.69
Wt. of Dry Sample + Dish (First Try)	(g)	205.01
Wt. of Dry Sample + Dish (Second Try)	(g)	204.98
% Diff. of Wt. of Dry Sample + Dish	(%)	0.01
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	7.57

Existing Soil Conditions		
Dish I.D.		W12-1
Wt. of Dish	(g)	34.52
Wt. of Wet Sample + Dish	(g)	434.76
Wt. of Wet Sample	(g)	400.24
Wt. of Dry Sample	(g)	372.07

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	96.8
Opt. Water Content (from Proctor)	(%)	24.20
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	96.8
Target Gravimetric Water Content	(%)	12.00
Change in Gravimetric Water Content	(%)	4.43
Wt. of Water Needed to be Added to Soil Sample	(g)	**16.48**

Check of Target Water Content (from Microwave)		
Dish I.D.		F1
Wt. of Dish	(g)	156.01
Wt. of Wet Sample + Dish	(g)	190.32
Wt. of Dry Sample + Dish (First Try)	(g)	186.63
Wt. of Dry Sample + Dish (Second Try)	(g)	186.62
% Diff. of Wt. of Dry Sample + Dish	(%)	0.01
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	12.09
Check of Target Gravi. Water Content		**O.K.**

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	108.50
Wt. of Soil Sample Needed to be Compacted Into Ring	(g)	**284.19**

REMOLDED SAMPLE PREPARATION DATA SHEET

Sample Source:	Russell Project	**Sample I.D.:**	D-9A, D-9B, and D-10
Soil Type:	Claytone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	6/4/2006	**Notes:**	

Retaining Ring Information		
Ring I.D.		3"R2
Wt. of Ring	(g)	264.56
Ring Diameter	(in)	2.498
Ring Height	(in)	3.645
Spacer Height	(in)	0.591
Volume of Sample	(in^3)	14.967

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	96.8
Opt. Water Content (from Proctor)	(%)	24.20
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	96.8
Target Gravimetric Water Content	(%)	15.00
Change in Gravimetric Water Content	(%)	6.64
Wt. of Water Needed to be Added to Soil Sample	(g)	**38.11**

Existing Soil Water Content (from Microwave)		
Dish I.D.		T5
Wt. of Dish	(g)	161.32
Wt. of Wet Sample + Dish	(g)	220.69
Wt. of Dry Sample + Dish (First Try)	(g)	216.12
Wt. of Dry Sample + Dish (Second Try)	(g)	216.11
% Diff. of Wt. of Dry Sample + Dish	(%)	0.00
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	8.36

Check of Target Water Content (from Microwave)		
Dish I.D.		T1
Wt. of Dish	(g)	188.92
Wt. of Wet Sample + Dish	(g)	234.15
Wt. of Dry Sample + Dish (First Try)	(g)	227.96
Wt. of Dry Sample + Dish (Second Try)	(g)	227.93
% Diff. of Wt. of Dry Sample + Dish	(%)	0.01
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	15.94
Check of Target Gravi. Water Content		**O.K.**

Existing Soil Conditions		
Dish I.D.		W15-1
Wt. of Dish	(g)	64.63
Wt. of Wet Sample + Dish	(g)	686.49
Wt. of Wet Sample	(g)	621.86
Wt. of Dry Sample	(g)	573.89

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	112.23
Wt. of Soil Sample Needed to be Compacted Into Ring	(g)	**440.95**

REMOLDED SAMPLE PREPARATION DATA SHEET

Sample Source:	Russell Project	**Sample I.D.:**	D-11B and D-12B
Soil Type:	Claytone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:	5/18/2006	**Notes:**	

Retaining Ring Information		
Ring I.D.		2"R2
Wt. of Ring	(g)	264.56
Ring Diameter	(in)	2.498
Ring Height	(in)	2.430
Spacer Height	(in)	0.394
Volume of Sample	(in^3)	9.978

Existing Soil Water Content (from Microwave)		
Dish I.D.		T5
Wt. of Dish	(g)	161.31
Wt. of Wet Sample + Dish	(g)	210.61
Wt. of Dry Sample + Dish (First Try)	(g)	207.02
Wt. of Dry Sample + Dish (Second Try)	(g)	206.94
% Diff. of Wt. of Dry Sample + Dish	(%)	0.04
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	8.04

Existing Soil Conditions		
Dish I.D.		W20-1
Wt. of Dish	(g)	33.99
Wt. of Wet Sample + Dish	(g)	423.07
Wt. of Wet Sample	(g)	389.08
Wt. of Dry Sample	(g)	360.12

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	96.8
Opt. Water Content (from Proctor)	(%)	24.20
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	96.8
Target Gravimetric Water Content	(%)	20.00
Change in Gravimetric Water Content	(%)	11.96
Wt. of Water Needed to be Added to Soil Sample	(g)	**43.06**

Check of Target Water Content (from Microwave)		
Dish I.D.		T5
Wt. of Dish	(g)	161.31
Wt. of Wet Sample + Dish	(g)	193.32
Wt. of Dry Sample + Dish (First Try)	(g)	187.97
Wt. of Dry Sample + Dish (Second Try)	(g)	187.94
% Diff. of Wt. of Dry Sample + Dish	(%)	0.02
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	20.20
Check of Target Gravi. Water Content		**O.K.**

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	116.36
Wt. of Soil Sample Needed to be Compacted Into Ring	(g)	**304.76**

REMOLDED SAMPLE PREPARATION DATA SHEET

Sample Source:	Russell Project	**Sample I.D.:**	D-13A, D-13B, and D-14
Soil Type:	Claytone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Date of Preparation:		**Notes:**	

Retaining Ring Information		
Ring I.D.		3"R2
Wt. of Ring	(g)	264.56
Ring Diameter	(in)	2.498
Ring Height	(in)	3.645
Spacer Height	(in)	0.591
Volume of Sample	(in^3)	14.967

Existing Soil Water Content (from Microwave)		
Dish I.D.		T2
Wt. of Dish	(g)	157.64
Wt. of Wet Sample + Dish	(g)	217.43
Wt. of Dry Sample + Dish (First Try)	(g)	213.02
Wt. of Dry Sample + Dish (Second Try)	(g)	212.97
% Diff. of Wt. of Dry Sample + Dish	(%)	0.02
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Existing Gravimetric Water Content	(%)	8.06

Existing Soil Conditions		
Dish I.D.		W25-1
Wt. of Dish	(g)	35.04
Wt. of Wet Sample + Dish	(g)	657.33
Wt. of Wet Sample	(g)	622.29
Wt. of Dry Sample	(g)	575.87

Water Needed to be Added to Soil Sample		
Max. Dry Density (from Proctor)	(pcf)	96.8
Opt. Water Content (from Proctor)	(%)	24.20
Target % of Max. Dry Density	(%)	100
Target Dry Density	(pcf)	96.8
Target Gravimetric Water Content	(%)	25.00
Change in Gravimetric Water Content	(%)	16.94
Wt. of Water Needed to be Added to Soil Sample	(g)	**97.55**

Check of Target Water Content (from Microwave)		
Dish I.D.		T2
Wt. of Dish	(g)	157.67
Wt. of Wet Sample + Dish	(g)	192.94
Wt. of Dry Sample + Dish (First Try)	(g)	185.76
Wt. of Dry Sample + Dish (Second Try)	(g)	185.73
% Diff. of Wt. of Dry Sample + Dish	(%)	0.02
Check of % Diff. of Wt. of Dry Sample + Dish		**O.K.**
Target Gravimetric Water Content	(%)	25.69
Check of Target Gravi. Water Content		**O.K.**

Sample Needed to be Compacted into Ring		
Target Total Density	(pcf)	121.67
Wt. of Soil Sample Needed to be Compacted Into Ring	(g)	**478.03**

APPENDIX B

FILTER PAPER CALIBRATION CURVE DATA WORKSHEETS

Table B-1 Osmotic Suction of Sodium Chloride Solution at 23 Degrees Celsius (3 Week Testing Period)

Date of Testing Began =	6/2/2006
Date of Testing Completed =	6/24/2006
Salt Solution =	NaCl
Mol. Weight of NaCl =	58 g/mole
Total volume of the container =	400 ml
Volume of distilled water in the container =	250 ml
Number of ions from one molecule of salt, v =	2 for NaCl
Temperature, t =	74.0 Degrees Fahrenheit
	23.3 Degrees Celsius
Absolute temperature, T =	296.5 K
Universal gas constant, R =	8.31443 kPa/(mol.K)

Osmotic Suction Calculations								Top Filter Paper				
Sample I.D.	Container I.D.	Molality [1]	Weight of NaCl needed for 1000 ml of water	Weight of NaCl needed for 250 ml of water	Osmotic Coefficient [2]	Osmotic Suction	Log Osmotic Suction	Moisture Tin I.D.	Wt. of Cold Tare, T	Wt. of Wet Filter Paper + Cold Tare, M_1	Wt. of Dry Filter Paper + Hot Tare, M_2	Wt Ta
		(m)	(g)	(g)		(kPa)	(Log kPa)		(g)	(g)	(g)	
FPC-1	C15	0.001	0.058	0.015	0.988	5	0.69	D5	15.3079	15.7822	15.6579	
FPC-2	C16	0.002	0.116	0.029	0.984	10	0.99	D4	15.4031	15.8657	15.7472	
FPC-3	C17	0.004	0.232	0.058	0.979	19	1.29	D7	15.4488	15.9144	15.7937	
FPC-4	C19	0.006	0.348	0.087	0.974	29	1.46	D16	15.2784	15.7424	15.6207	
FPC-5	C20	0.008	0.464	0.116	0.971	38	1.58	D2	15.3337	15.8021	15.6818	
FPC-6	C21	0.010	0.580	0.145	0.968	48	1.68	D8	15.4150	15.8886	15.7675	
FPC-7	C22	0.015	0.870	0.218	0.962	71	1.85	D1	15.3395	15.8151	15.6944	
FPC-8	C23	0.020	1.160	0.290	0.959	95	1.98	D18	15.4310	15.9061	15.7869	
FPC-9	C24	0.050	2.900	0.725	0.944	233	2.37	D22	15.2674	15.7243	15.6104	
FPC-10	C25	0.100	5.800	1.450	0.933	460	2.66	D12	15.1729	15.6340	15.5260	
FPC-11	C26	0.200	11.600	2.900	0.924	911	2.96	D20	15.3630	15.8155	15.7167	
FPC-12	C27	0.300	17.400	4.350	0.921	1362	3.13	D6	15.4260	15.8628	15.7713	
FPC-13	C28	0.500	29.000	7.250	0.921	2270	3.36	D19	15.4373	15.8744	15.7907	
FPC-14	C29	0.700	40.600	10.150	0.926	3196	3.50	D24	15.3156	15.7573	15.6761	
FPC-15	C30	1.000	58.000	14.500	0.936	4615	3.66	D13	15.4458	15.8637	15.7934	
FPC-16	C31	1.400	81.200	20.300	0.953	6578	3.82	D10	15.4618	15.8852	15.8175	
FPC-17	C32	2.000	116.000	29.000	0.984	9703	3.99	D11	15.4313	15.8456	15.7909	
FPC-18	C33	2.700	156.600	39.150	1.026	13658	4.14	D25	15.4140	15.8132	15.7622	

Notes: (1) Molality = mole / 1000 ml of water. Thus, 1 molality of NaCl = 58 g of NaCl / 1000 ml of water
(2) from Hamer and Wu (1972)

					Bottom Filter Paper								Average
of Dry Paper + Tare, M_2	Wt. of Hot Tare, T_h	Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$	Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$	Water Content of Filter Paper, $W_f = (M_w / M_f)$	Moisture Tin I.D.	Wt. of Cold Tare, T_c	Wt. of Wet Filter Paper + Cold Tare, M_1	Wt. of Dry Filter Paper + Hot Tare, M_2	Wt. of Hot Tare, T_h	Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$	Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$	Water Content of Filter Paper, $W_f = (M_w / M_f)$	Avg. Water Content of Filter Paper
(g)	(g)	(g)	(g)	(%)		(g)	(g)	(g)	(g)	(g)	(g)	(%)	(%)
15.6579	15.3057	0.3522	0.1221	34.67	D9	15.4230	15.9041	15.7791	15.4213	0.3578	0.1233	34.46	34.5
15.7472	15.4010	0.3462	0.1164	33.62	D30	15.4385	15.9139	15.7918	15.4367	0.3551	0.1203	33.88	33.7
15.7937	15.4462	0.3475	0.1181	33.99	D31	15.3163	15.7998	15.6761	15.3146	0.3615	0.1220	33.75	33.8
15.6207	15.2756	0.3451	0.1189	34.45	D34	15.3919	15.8681	15.7445	15.3894	0.3551	0.1211	34.10	34.2
15.6818	15.3314	0.3504	0.1180	33.68	D14	15.1954	15.6672	15.5466	15.1936	0.3530	0.1188	33.65	33.6
15.7675	15.4124	0.3551	0.1185	33.37	D29	15.4342	15.8987	15.7788	15.4306	0.3482	0.1163	33.40	33.3
15.6944	15.3386	0.3558	0.1198	33.67	D3	15.4041	15.8785	15.7568	15.4023	0.3545	0.1199	33.82	33.7
15.7869	15.4290	0.3579	0.1172	32.75	D21	15.4063	15.8629	15.7486	15.4043	0.3443	0.1123	32.62	32.6
15.6104	15.2653	0.3451	0.1118	32.40	D36	15.4025	15.8605	15.7451	15.3996	0.3455	0.1125	32.56	32.4
15.5260	15.1700	0.3560	0.1051	29.52	D15	15.4258	15.8776	15.7724	15.4234	0.3490	0.1028	29.46	29.4
15.7167	15.3606	0.3561	0.0964	27.07	D33	15.3598	15.8102	15.7133	15.3579	0.3554	0.0950	26.73	26.9
15.7713	15.4244	0.3469	0.0899	25.92	D23	15.4613	15.8846	15.7955	15.4591	0.3364	0.0869	25.83	25.8
15.7907	15.4358	0.3549	0.0822	23.16	D28	15.3563	15.7785	15.6994	15.3541	0.3453	0.0769	22.27	22.7
15.6761	15.3128	0.3633	0.0784	21.58	D32	15.3343	15.7673	15.6879	15.3336	0.3543	0.0787	22.21	21.9
15.7934	15.4439	0.3495	0.0684	19.57	D17	15.4524	15.8691	15.7989	15.4501	0.3488	0.0679	19.47	19.5
15.8175	15.4586	0.3589	0.0645	17.97	D26	15.3847	15.8101	15.7449	15.3825	0.3624	0.0630	17.38	17.6
15.7909	15.4303	0.3606	0.0537	14.89	D35	15.3593	15.7685	15.7104	15.3571	0.3533	0.0559	15.82	15.3
15.7622	15.4114	0.3508	0.0484	13.80	D27	15.2534	15.6576	15.6072	15.2509	0.3563	0.0479	13.44	13.6

Table B-2 Osmotic Suction of Sodium Chloride Solution at 23 Degrees Celsius (2 Week Testing Period)

Date of Testing Began =	5/19/2006
Date of Testing Completed =	6/2/2006
Salt Solution =	NaCl
Mol. Weight of NaCl =	58 g/mole
Total volume of the container =	400 ml
Volume of distilled water in the container =	250 ml
Number of ions from one molecule of salt, v =	2 for NaCl
Temperature, t =	74.0 Degrees Fahrenheit
	23.3 Degrees Celsius
Absolute temperature, T =	296.5 K
Universal gas constant, R =	8.31443 kPa/(mol.K)

Osmotic Suction Calculations / **Top Filter Paper**

Sample I.D.	Container I.D.	Molality [(1)]	Weight of NaCl needed for 1000 ml of water	Weight of NaCl needed for 250 ml of water	Osmotic Coefficient [(2)]	Osmotic Suction	Log Osmotic Suction	Moisture Tin I.D.	Wt. of Cold Tare, T_c	Wt. of Wet Filter Paper + Cold Tare, M_1	Wt. of Dry Filter Paper + Hot Tare, M_2	Wt. of Hot Tare, T_h	Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$	W… M_w
		(m)	(g)	(g)		(kPa)	(Log kPa)		(g)	(g)	(g)	(g)	(g)	
FPC-3	C17	0.004	0.232	0.058	0.979	19	1.29	D5	15.3084	15.7878	15.6622	15.3037	0.3585	
FPC-4	C19	0.006	0.348	0.087	0.974	29	1.46	D7	15.4489	15.9369	15.8085	15.4453	0.3632	
FPC-5	C20	0.008	0.464	0.116	0.971	38	1.58	D9	15.4236	15.9025	15.7796	15.4202	0.3594	
FPC-6	C21	0.010	0.580	0.145	0.968	48	1.68	D11	15.4321	15.8923	15.7734	15.4288	0.3446	
FPC-13	C28	0.500	29.000	7.250	0.921	2270	3.36	D25	15.4142	15.8592	15.7696	15.4101	0.3595	
FPC-17	C32	2.000	116.000	29.000	0.984	9703	3.99	D33	15.3599	15.7916	15.7216	15.3568	0.3648	
FPC-18	C33	2.700	156.600	39.150	1.026	13658	4.14	D35	15.3595	15.7499	15.6993	15.3569	0.3424	

Notes: (1) Molality = mole / 1000 ml of water. Thus, 1 molality of NaCl = 58 g of NaCl / 1000 ml of water
(2) from Hamer and Wu (1972)

					Bottom Filter Paper									Average
. of Dry ' Paper + Tare, M_2	Wt. of Hot Tare, T_h	Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$	Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$	Water Content of Filter Paper, $W_f = (M_w / M_f)$	Moisture Tin I.D.	Wt. of Cold Tare, T_c	Wt. of Wet Filter Paper + Cold Tare, M_1	Wt. of Dry Filter Paper + Hot Tare, M_2	Wt. of Hot Tare, T_h	Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$	Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$	Water Content of Filter Paper, $W_f = (M_w / M_f)$	Avg. Water Content of Filter Paper
(g)	(g)	(g)	(g)	(%)		(g)	(g)	(g)	(g)	(g)	(g)	(%)	(%)
15.6622	15.3037	0.3585	0.1209	33.72	D6	15.4269	15.9048	15.7801	15.4217	0.3584	0.1195	33.34	33.53
15.8085	15.4453	0.3632	0.1248	34.36	D8	15.4145	15.8836	15.7625	15.4122	0.3503	0.1188	33.91	33.91
15.7796	15.4202	0.3594	0.1195	33.25	D10	15.4624	15.9341	15.8108	15.4578	0.3530	0.1187	33.63	33.44
15.7734	15.4288	0.3446	0.1156	33.55	D12	15.1730	15.6569	15.5317	15.1697	0.3620	0.1219	33.67	33.61
15.7696	15.4101	0.3595	0.0855	23.78	D26	15.3845	15.8369	15.7471	15.3820	0.3651	0.0873	23.91	23.85
15.7216	15.3568	0.3648	0.0669	18.34									18.34
15.6993	15.3569	0.3424	0.0480	14.02	D36	15.4021	15.8147	15.7600	15.3987	0.3613	0.0513	14.20	14.11

APPENDIX C

FILTER PAPER EQUILIBRATION TIME TEST DATA WORKSHEETS

Table C-1 Summary of Equilibration Time for Filter Paper Test								
Sample ID	Time of Test Began	Time of Test Ended	Time	Gravimetric Water Content	Volumetric Water Content	Total Suction	Total Suction	Total Suction
			(days)	(%)	(%)	(kPa)	(Log kPa)	(pF)
W28-1	5/28/06 6:40 PM	5/28/06 6:40 PM	0.00	26.87	44.35	221,640	5.35	6.35
		5/29/06 8:52 AM	0.59			2,923	3.47	4.47
		5/30/06 8:57 AM	1.60			1,030	3.01	4.02
		5/31/06 5:43 PM	2.96			451	2.65	3.66
		6/2/06 5:05 PM	4.93			314	2.50	3.51
		6/4/06 5:18 PM	6.94			209	2.32	3.33
		6/7/06 5:38 PM	9.96			182	2.26	3.27
		6/11/06 5:40 PM	13.96			184	2.26	3.27
		6/18/06 9:02 PM	21.10			195	2.29	3.30
W25-8	1/1/06 6:56 PM	1/1/06 6:56 PM	0.00	21.94	35.76	221,640	5.35	6.35
		1/2/06 11:42 AM	0.70			3,819	3.58	4.59
		1/3/06 9:13 AM	1.60			1,438	3.16	4.17
		1/4/06 4:40 PM	2.91			1,128	3.05	4.06
		1/6/06 9:22 PM	5.10			848	2.93	3.94
		1/8/06 5:54 PM	6.96			784	2.89	3.90
		1/11/06 8:24 PM	10.06			705	2.85	3.86
		1/15/06 11:23 AM	13.69			643	2.81	3.82
		1/22/06 2:05 PM	20.80			614	2.79	3.80
W19-8	1/1/06 7:25 PM	1/1/06 7:25 PM	0.00	16.98	27.77	221,640	5.35	6.35
		1/2/06 11:45 AM	0.68			4,022	3.60	4.61
		1/3/06 9:15 AM	1.58			1,763	3.25	4.25
		1/4/06 4:43 PM	2.89			1,472	3.17	4.18
		1/6/06 9:25 PM	5.08			1,276	3.11	4.11
		1/8/06 5:58 PM	6.94			1,124	3.05	4.06
		1/11/06 8:27 PM	10.04			1,244	3.09	4.10
		1/15/06 11:32 AM	13.67			1,059	3.02	4.03
		1/22/06 2:15 PM	20.78			1,053	3.02	4.03
W15-1	1/1/06 7:45 PM	1/1/06 7:45 PM	0.00	12.42	20.31	221,640	5.35	6.35
		1/2/06 11:47 AM	0.67			7,788	3.89	4.90
		1/3/06 9:17 AM	1.56			7,759	3.89	4.90
		1/4/06 4:45 PM	2.88			6,826	3.83	4.84
		1/6/06 9:26 PM	5.07			5,134	3.71	4.72
		1/8/06 6:00 PM	6.93			4,602	3.66	4.67
		1/11/06 8:29 PM	10.03			4,182	3.62	4.63
		1/15/06 11:36 AM	13.66			4,331	3.64	4.65
		1/22/06 1:52 PM	20.75			4,131	3.62	4.62
W12-1	1/1/06 8:07 PM	1/1/06 8:07 PM	0.00	10.49	17.25	221,640	5.35	6.35
		1/2/06 11:51 AM	0.66			19,416	4.29	5.30
		1/3/06 9:19 AM	1.55			16,829	4.23	5.23
		1/4/06 4:46 PM	2.86			16,314	4.21	5.22
		1/6/06 9:28 PM	5.06			15,216	4.18	5.19
		1/8/06 6:02 PM	6.91			13,139	4.12	5.13
		1/11/06 8:31 PM	10.02			13,806	4.14	5.15
		1/15/06 11:40 AM	13.65			15,511	4.19	5.20
		1/22/06 2:09 PM	20.75			15,133	4.18	5.19
W10-1	1/1/06 8:16 PM	1/1/06 8:16 PM	0.00	8.19	13.58	221,640	5.35	6.35
		1/2/06 11:54 AM	0.65			35,152	4.55	5.55
		1/3/06 9:21 AM	1.55			35,918	4.56	5.56
		1/4/06 4:48 PM	2.86			33,572	4.53	5.53
		1/6/06 9:32 PM	5.05			33,622	4.53	5.54
		1/8/06 6:05 PM	6.91			35,362	4.55	5.56
		1/11/06 8:33 PM	10.01			34,578	4.54	5.55
		1/15/06 11:42 AM	13.64			35,430	4.55	5.56
		1/22/06 2:00 PM	20.74			33,533	4.53	5.53

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W-Dry
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	72 Degrees F.
Time of Beginning:	11/13/05 4:36 PM	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	11/14/05 5:00 PM	**Notes:**	Oven-Dried Filter Paper

Table 1 Measurements of Soil Suction

Measurements	*Total Suction*		
	Total (Top)	*Total (Middle)*	*Total (Bottom)*
Moisture Tin I.D.	C3	4	C8
Wt. of Cold Tare, T_c (g)	15.4608	15.4256	15.4409
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8164	15.7716	15.7884
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.8067	15.7624	15.7811
Wt. of Hot Tare, T_h (g)	15.4560	15.4208	15.4374
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3507	0.3416	0.3437
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0049	0.0044	0.0038
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	1.40	1.29	1.11
Soil Suction (kPa)	215,298	220,406	229,217
Soil Suction (pF)	6.34	6.35	6.37

Table 2 Calculations of Soil Suction

Average Total Suction	221,640 (kPa)	6.35 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W28-1
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI. D-Aired Water	**Room Temperature:**	73 Degrees F
Time of Beginning:	5/28/2006 18 40	**Filter Paper Type:**	Whatman No 42
Time of Completion:	--	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D for Top Sample	R27	Wt. of Top Wet Sample + Ring (g)	202 43	Pan I D. for Top Sample	DC-8
Wt. of Ring for Top Sample (g)	40 62	Height of Top Sample (in)	1 00	Wt of Pan for Top Sample (g)	13 26
Ring Diameter for Top Sample (in)	2 438	Wt. of Bottom Wet Sample + Ring (g)	201 26	Wt of Top Wet Sample + Ring + Pan (g)	214 53
Ring I D. for Bottom Sample	R32	Height of Bottom Sample (in)	1 00	Wt. of Top Dry Sample + Ring + Pan (g)	181 10
Wt of Ring for Bottom Sample (g)	40 29	***End of the Test:***		Pan I D for Bottom Sample	DC-3
Ring Diameter for Bottom Sample (in)	2 438	Wt. of Top Wet Sample + Ring (g)	201 27	Wt of Pan for Bottom Sample (g)	13.26
Sample Container I D	C7	Height of Top Sample (in)	1 00	Wt of Bottom Wet Sample + Ring + Pan (g)	213 83
Wt of Sample Container (g)	114 07	Wt. of Bottom Wet Sample + Ring (g)	200 57	Wt of Bottom Dry Sample + Ring + Pan (g)	179 29
		Height of Bottom Sample (in)	1 00		

Table 2 Calculations of Soil Sample Properties

Soil Property	***Top Sample***	***Bottom Sample***	***Average***
Wt. of Wet Sample (g)	160 65	160 28	160 47
Wt. of Dry Sample (g)	127 22	125 74	126 48
Wt. of Water (g)	33 43	34 54	33 99
Gravimetric Water Conter (%)	26 28	27 47	26 87
Volume of Sample (in^3)	4 67	4 67	4 67
Volumetric Water Content (%)	43 63	45 08	44.35

Table 3 Measurements of Soil Suction

Measurements	**Total Suction**							
	5/29/2006 8:52	5/30/2006 8:57	5/31/2006 17.43	6/2/2006 17.05	6/4/2006 17 18	6/7/2006 17:38	6/11/2006 17 40	6/18/2006 21:02
Moisture Tin I.D.	Total (Middle)	A10	B8	A9	D28	D7	D10	D21
Wt. of Cold Tare, T_c (g)	15 2762	15.3541	15 3057	15 4885	15 3538	15 4463	15 4601	15 4058
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15 7049	15 8185	15 7745	15.9399	15 8247	15 9219	15 9325	15 8774
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15 6254	15 7184	15 6639	15 8273	15 7077	15 8035	15 8145	15 7611
Wt. of Hot Tare, T_h (g)	15.2723	15 3506	15 3036	15 4848	15.3520	15 4445	15 4579	15 4050
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0 3531	0 3678	0 3603	0 3425	0 3557	0 3590	0 3566	0 3561
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0756	0.0966	0.1085	0 1089	0 1152	0 1166	0 1158	0 1155
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	21 41	26.26	30 11	31 80	32 39	32 48	32 47	32 43
Soil Suction (kPa)	2,923	1.030	451	314	209	182	184	195
Soil Suction (pF)	4.47	4.02	3 66	3 51	3 33	3 27	3 27	3 30

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W25-8
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI. D-Aired Water	**Room Temperature:**	73 Degrees F
Time of Beginning:	1/1/2006 18 56	**Filter Paper Type:**	Whatman No 42
Time of Completion:	--	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I D for Top Sample	R21	Wt. of Top Wet Sample + Ring (g)	193 13	Pan I D for Top Sample	KD19
Wt of Ring for Top Sample (g)	40 27	Height of Top Sample (in)	1 00	Wt of Pan for Top Sample (g)	16 22
Ring Diameter for Top Sample (in)	2 438	Wt. of Bottom Wet Sample + Ring (g)	193 26	Wt. of Top Wet Sample + Ring + Pan (g)	208 55
Ring I D for Bottom Sample	R30	Height of Bottom Sample (in)	1 00	Wt of Top Dry Sample + Ring + Pan (g)	181 20
Wt of Ring for Bottom Sample (g)	40 10	*End of the Test:*		Pan I D for Bottom Sample	KD10
Ring Diameter for Bottom Sample (in)	2 438	Wt of Top Wet Sample + Ring (g)	192 33	Wt of Pan for Bottom Sample (g)	15 65
Sample Container I D	C3	Height of Top Sample (in)	1 00	Wt. of Bottom Wet Sample + Ring + Pan (g)	208 33
Wt. of Sample Container (g)	114 43	Wt. of Bottom Wet Sample + Ring (g)	192 68	Wt. of Bottom Dry Sample + Ring + Pan (g)	180 87
		Height of Bottom Sample (in)	1 00		

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt of Wet Sample (g)	152 06	152 58	152 32
Wt of Dry Sample (g)	124 71	125 12	124 92
Wt of Water (g)	27 35	27 46	27 41
Gravimetric Water Conter (%)	21 93	21 95	21 94
Volume of Sample (in^3)	4 67	4 67	4 67
Volumetric Water Content (%)	35 69	35 84	35 76

Table 3 Measurements of Soil Suction

Measurements	Total Suction							
	1/2/2006 11.42	1/3/2006 9 13	1/4/2006 16 40	1/6/2006 21 22	1/8/2006 17 54	1/11/2006 20 24	1/15/2006 11 23	1/22/2006 14 05
Moisture Tin I.D.	C1	C2	C2	B1	C1	C3	C1	A12
Wt. of Cold Tare, T_c (g)	15 4905	15 4118	15 4115	15 3689	15 4263	15 4611	15 4260	15 3969
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15 9100	15 8544	15 8478	15 8117	15 8640	15 9156	15 8675	15 8470
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15 8374	15 7646	15 7570	15 7129	15 7653	15 8135	15 7667	15 7403
Wt. of Hot Tare, T_h (g)	15 4883	15 4097	15 4103	15 3647	15 4221	15 4585	15 4230	15 3905
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0 3491	0 3549	0 3467	0 3482	0 3432	0 3550	0 3437	0 3498
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0 0704	0 0877	0 0896	0 0946	0 0945	0 0995	0 0978	0 1003
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	20 17	24 71	25 84	27 17	27 53	28 03	28 46	28 67
Soil Suction (kPa)	3,819	1,438	1,128	848	784	705	643	614
Soil Suction (pF)	4 59	4 17	4 06	3 94	3 90	3 86	3 82	3 80

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W19-8
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	73 Degrees F
Time of Beginning:	1/1/2006 19 25	**Filter Paper Type:**	Whatman No 42
Time of Completion:	--	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R16	Wt. of Top Wet Sample + Ring (g)	187 56	Pan I D for Top Sample	Total (Middle)
Wt of Ring for Top Sample (g)	40.31	Height of Top Sample (in)	1 00	Wt of Pan for Top Sample (g)	15 55
Ring Diameter for Top Sample (in)	2 438	Wt. of Bottom Wet Sample + Ring (g)	187 50	Wt of Top Wet Sample + Ring + Pan (g)	202 14
Ring I.D. for Bottom Sample	R22	Height of Bottom Sample (in)	1 00	Wt of Top Dry Sample + Ring + Pan (g)	180 69
Wt. of Ring for Bottom Sample (g)	40 15	***End of the Test:***		Pan I.D for Bottom Sample	Total (Middle)
Ring Diameter for Bottom Sample (in)	2 438	Wt of Top Wet Sample + Ring (g)	186 59	Wt of Pan for Bottom Sample (g)	15 29
Sample Container I.D.	C13	Height of Top Sample (in)	1 00	Wt. of Bottom Wet Sample + Ring + Pan (g)	202 40
Wt of Sample Container (g)	113 45	Wt. of Bottom Wet Sample + Ring (g)	187 11	Wt of Bottom Dry Sample + Ring + Pan (g)	181.29
		Height of Bottom Sample (in)	1 00		

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt of Wet Sample (g)	146 28	146.96	146 62
Wt. of Dry Sample (g)	124 83	125 85	125.34
Wt. of Water (g)	21 45	21 11	21 28
Gravimetric Water Conter (%)	17 18	16.77	16 98
Volume of Sample (in^3)	4 67	4 67	4 67
Volumetric Water Content (%)	27.99	27.55	27 77

Table 3 Measurements of Soil Suction

Measurements	Total Suction							
	1/2/2006 11:45	1/3/2006 9:15	1/4/2006 16:43	1/6/2006 21:25	1/8/2006 17:58	1/11/2006 20:27	1/15/2006 11 32	1/22/2006 14 15
Moisture Tin I.D.	B4	4	4	B2	A12	C12	B3	A2
Wt. of Cold Tare, T_c (g)	15.3445	15.3216	15.3212	15 3232	15 3976	15 4190	15 3077	15 4166
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7580	15.7466	15.7461	15 7560	15 8327	15 8561	15 7493	15 8641
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15 6861	15 6627	15 6591	15 6657	15 7393	15 7651	15 6552	15 7694
Wt. of Hot Tare, T_h (g)	15 3413	15 3193	15 3181	15 3202	15 3936	15 4165	15 3051	15 4147
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0 3448	0 3434	0 3410	0 3455	0 3457	0 3486	0 3501	0 3547
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0 0687	0 0816	0 0839	0 0873	0 0894	0 0885	0 0915	0 0928
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	19 92	23 76	24 60	25 27	25.86	25 39	26 14	26 16
Soil Suction (kPa)	4,022	1,763	1.472	1,276	1,124	1,244	1,059	1,053
Soil Suction (pF)	4 61	4.25	4 18	4 11	4 06	4 10	4.03	4 03

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W15-1
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI. D-Aired Water	**Room Temperature:**	73 Degrees F
Time of Beginning:	1/1/2006 19.45	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	--	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R13	Wt. of Top Wet Sample + Ring (g)	181.94	Pan I.D. for Top Sample	KD25
Wt. of Ring for Top Sample (g)	40.30	Height of Top Sample (in)	1.00	Wt. of Pan for Top Sample (g)	15.53
Ring Diameter for Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring (g)	181.72	Wt. of Top Wet Sample + Ring + Pan (g)	196.82
Ring I.D. for Bottom Sample	R17	Height of Bottom Sample (in)	1.00	Wt. of Top Dry Sample + Ring + Pan (g)	181.36
Wt. of Ring for Bottom Sample (g)	40.36	*End of the Test:*		Pan I.D. for Bottom Sample	MG3
Ring Diameter for Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring (g)	181.29	Wt. of Pan for Bottom Sample (g)	13.56
Sample Container I.D.	C12	Height of Top Sample (in)	1.00	Wt. of Bottom Wet Sample + Ring + Pan (g)	194.80
Wt. of Sample Container (g)	113.15	Wt. of Bottom Wet Sample + Ring (g)	181.24	Wt. of Bottom Dry Sample + Ring + Pan (g)	179.13
		Height of Bottom Sample (in)	1.00		

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	140.99	140.88	140.94
Wt. of Dry Sample (g)	125.53	125.21	125.37
Wt. of Water (g)	15.46	15.67	15.57
Gravimetric Water Conter (%)	12.32	12.51	12.42
Volume of Sample (in^3)	4.67	4.67	4.67
Volumetric Water Conten (%)	20.18	20.45	20.31

Table 3 Measurements of Soil Suction

Measurements	Total Suction							
	1/2/2006 11.47	1/3/2006 9.17	1/4/2006 16.45	1/6/2006 21.26	1/8/2006 18.00	1/11/2006 20.29	1/15/2006 11.36	1/22/2006 13.52
Moisture Tin I.D.	C8	C6	C6	B9	C4	C1	C4	B4
Wt. of Cold Tare, T_c (g)	15.2803	15.3826	15.3824	15.3014	15.2150	15.4262	15.2148	15.3052
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.6867	15.8025	15.7981	15.7130	15.6329	15.8356	15.6301	15.7130
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6254	15.7395	15.7339	15.6457	15.5628	15.7645	15.5613	15.6415
Wt. of Hot Tare, T_h (g)	15.2776	15.3802	15.3800	15.2992	15.2125	15.4226	15.2140	15.3011
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3478	0.3593	0.3539	0.3465	0.3503	0.3419	0.3473	0.3404
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0586	0.0606	0.0618	0.0651	0.0676	0.0675	0.0680	0.0674
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	16.85	16.87	17.46	18.79	19.30	19.74	19.58	19.80
Soil Suction (kPa)	7,788	7,759	6,826	5,134	4,602	4,182	4,331	4,131
Soil Suction (pF)	4.90	4.90	4.84	4.72	4.67	4.63	4.65	4.62

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W12-8
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	73 Degrees F
Time of Beginning:	1/1/2006 20 07	**Filter Paper Type:**	Whatman No 42
Time of Completion:	--	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I D. for Top Sample	R10	Wt. of Top Wet Sample + Ring (g)	179 75	Pan I D for Top Sample	Total (Middle)
Wt. of Ring for Top Sample (g)	40 15	Height of Top Sample (in)	1 00	Wt of Pan for Top Sample (g)	15 27
Ring Diameter for Top Sample (in)	2 438	Wt. of Bottom Wet Sample + Ring (g)	180 15	Wt. of Top Wet Sample + Ring + Pan (g)	194 45
Ring I D. for Bottom Sample	R28	Height of Bottom Sample (in)	1 00	Wt of Top Dry Sample + Ring + Pan (g)	181 31
Wt of Ring for Bottom Sample (g)	40 16	*End of the Test:*		Pan I.D for Bottom Sample	KD12
Ring Diameter for Bottom Sample (in)	2 438	Wt. of Top Wet Sample + Ring (g)	179 18	Wt of Pan for Bottom Sample (g)	15 46
Sample Container I D	C14	Height of Top Sample (in)	1 00	Wt of Bottom Wet Sample + Ring + Pan (g)	195 15
Wt of Sample Container (g)	112 92	Wt. of Bottom Wet Sample + Ring (g)	179 69	Wt of Bottom Dry Sample + Ring + Pan (g)	181 85
		Height of Bottom Sample (in)	1 00		

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	139 03	139 53	139 28
Wt. of Dry Sample (g)	125 89	126 23	126 06
Wt. of Water (g)	13.14	13 30	13 22
Gravimetric Water Conte (%)	10.44	10.54	10 49
Volume of Sample (in^3)	4 67	4 67	4.67
Volumetric Water Conten (%)	17.15	17 36	17.25

Table 3 Measurements of Soil Suction

Measurements	Total Suction							
	1/2/2006 11:51	1/3/2006 9:19	1/4/2006 16.46	1/6/2006 21:28	1/8/2006 18.02	1/11/2006 20 31	1/15/2006 11 40	1/22/2006 14 09
Moisture Tin I.D.	C4	B8	B8	C10	C9	C9	C9	B10
Wt. of Cold Tare, T_c (g)	15 3800	15 2652	15 2651	15 4245	15.3675	15 3675	15 3673	15 3352
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15 7742	15 6572	15 6669	15.8229	15 7747	15 7668	15 7680	15 7189
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7287	15 6077	15 6163	15 7730	15.7216	15 7151	15.7181	15 6703
Wt. of Hot Tare, T_h (g)	15 3786	15 2616	15 2620	15 4227	15 3657	15 3654	15 3655	15 3330
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0 3501	0.3461	0 3543	0 3503	0 3559	0 3497	0 3526	0 3373
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0 0441	0 0459	0 0475	0 0481	0 0513	0 0496	0 0481	0 0464
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	12 60	13 26	13 41	13 73	14 41	14 18	13 64	13 76
Soil Suction (kPa)	19.416	16.829	16.314	15.216	13.139	13.806	15.511	15.133
Soil Suction (pF)	5 30	5 23	5 22	5 19	5 13	5 15	5 20	5 19

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W10-1
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI. D-Aired Water	**Room Temperature:**	73 Degrees F
Time of Beginning:	1/1/2006 20 16	**Filter Paper Type:**	Whatman No 42
Time of Completion:	--	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I D for Top Sample	R6	Wt of Top Wet Sample + Ring (g)	177 74	Pan I D for Top Sample	KD6
Wt of Ring for Top Sample (g)	40 15	Height of Top Sample (in)	1 00	Wt of Pan for Top Sample (g)	15 65
Ring Diameter for Top Sample (in)	2 438	Wt. of Bottom Wet Sample + Ring (g)	178 53	Wt. of Top Wet Sample + Ring + Pan (g)	192 89
Ring I.D for Bottom Sample	R19	Height of Bottom Sample (in)	1 00	Wt of Top Dry Sample + Ring + Pan (g)	182 60
Wt. of Ring for Bottom Sample (g)	40.35	*End of the Test:*		Pan I D. for Bottom Sample	MG2
Ring Diameter for Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring (g)	177 24	Wt of Pan for Bottom Sample (g)	13 51
Sample Container I D	C16	Height of Top Sample (in)	1.00	Wt. of Bottom Wet Sample + Ring + Pan (g)	191.68
Wt. of Sample Container (g)	113 32	Wt. of Bottom Wet Sample + Ring (g)	178 17	Wt of Bottom Dry Sample + Ring + Pan (g)	181 16
		Height of Bottom Sample (in)	1.00		

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	137 09	137 82	137 46
Wt. of Dry Sample (g)	126 80	127 30	127 05
Wt. of Water (g)	10 29	10 52	10 41
Gravimetric Water Conter (%)	8 12	8 26	8 19
Volume of Sample (in^3)	4 67	4 67	4.67
Volumetric Water Conten (%)	13.43	13.73	13 58

Table 3 Measurements of Soil Suction

Measurements	Total Suction							
	1/2/2006 11:54	1/3/2006 9:21	1/4/2006 16 48	1/6/2006 21:32	1/8/2006 18 05	1/11/2006 20:33	1/15/2006 11.42	1/22/2006 14 00
Moisture Tin I.D.	A11	B10	B10	A6	C12	B8	C12	A9
Wt. of Cold Tare, T_c (g)	15 3597	15 2475	15 2476	15 3389	15 4190	15 3080	15 4181	15 4904
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15 7484	15.6421	15.6419	15 7192	15 7975	15 6984	15.8070	15 8867
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15 7119	15 6041	15 6027	15 6822	15 7602	15 6612	15 7706	15 8462
Wt. of Hot Tare, T_h (g)	15 3580	15 2445	15.2444	15 3366	15 4155	15 3060	15 4164	15 4861
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0 3539	0 3596	0 3583	0 3456	0 3447	0 3552	0 3542	0 3601
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0 0348	0.0350	0 0360	0 0347	0 0338	0 0352	0 0347	0 0362
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	9 83	9 73	10 05	10 04	9 81	9 91	9 80	10 05
Soil Suction (kPa)	35.152	35.918	33.572	33.622	35,362	34.578	35.430	33.533
Soil Suction (pF)	5.55	5.56	5 53	5 54	5 56	5.55	5 56	5.53

APPENDIX D

FILTER PAPER SWCC TEST DATA WORKSHEETS

APPENDIX D.1

DENVER FORMATION

Table D-1 Summary of Results of Soil Water Characteristic Curve

Curve Type: Wetting Curve
Formation: Denver Formation

Sample I.D.	Gravimetric Water Content (%)	Volumetric Water Content (%)	Wt. of Dry Sample (g)	Volume of Sample (in^3)	Dry Density (pcf)	Specific Gravity	Degree of Saturation (%)	Total Suction (kPa)	Matric Suction (kPa)	Osmotic Suction (kPa)	Notes
D-1&2	0.00	0.00				2.76	0.00	244,584	175,038	69,546	Avg. of Oven Dried Samples
	4.33	7.22	117.91	4.30	104.37		18.36	157,066	120,123	36,943	Air Dried Sample
	5.80	9.58	117.91	4.35	103.31		23.98	115,157	94,443	20,714	
	8.77	14.16	117.91	4.45	101.02		34.32	54,401	44,084	10,318	
	11.54	17.60	117.91	4.71	95.33		39.49	24,384	20,426	3,959	
	17.54	25.93	117.91	4.86	92.48		56.12	5,450	2,489	2,961	
	21.07	30.51	117.91	4.96	90.52		64.44	1,698	749	949	
	25.11	35.63	117.91	5.06	88.73		73.65	458	60	399	
	33.81	45.15	117.91	5.38	83.49		87.82	13	2	11	
D-3&4	0.00	0.00					0.00	244,584	175,038	69,546	Avg. of Oven Dried Samples
	4.18	6.97	117.23	4.28	104.40		17.74	161,795	120,103	41,692	Air Dried Sample
	6.35	10.43	117.23	4.35	102.74		25.90	99,349	84,330	15,019	
	9.27	14.88	117.23	4.45	100.33		35.72	44,110	40,134	3,976	
	12.53	18.88	117.23	4.74	94.27		41.81	21,195	17,561	3,634	
	18.57	27.06	117.23	4.90	91.11		57.57	4,173	2,124	2,049	
	22.09	31.69	117.23	4.98	89.70		66.28	1,947	876	1,071	
	26.06	36.73	117.23	5.07	88.13		75.38	639	23	616	
	33.36	44.43	117.23	5.36	83.26		86.18	100	2	98	
D-5&6	0.00	0.00					0.00	244,584	175,038	69,546	Avg. of Oven Dried Samples
	4.51	7.61	117.77	4.25	105.66		19.74	149,951	111,126	38,825	Air Dried Sample
	6.08	10.17	117.77	4.29	104.52		25.93	114,534	93,651	20,882	
	8.75	14.31	117.77	4.38	102.32		35.34	57,440	46,149	11,291	
	11.93	18.25	117.77	4.69	95.68		41.16	28,749	25,877	2,872	
	17.98	26.64	117.77	4.84	92.63		57.76	3,178	2,714	464	
	21.72	31.49	117.77	4.95	90.67		66.64	1,857	773	1,084	
	25.90	37.02	117.77	5.02	89.36		77.07	386	36	351	
	32.80	44.79	117.77	5.25	85.39		89.02	14	2	12	
Average	0.00	0.00					0.00	244,584	175,038	69,546	
	4.34	7.27	117.64	4.28	104.81		18.60	156271	117117	39,153	
	6.08	10.06	117.64	4.33	103.52		25.27	109680	90808	18,872	
	8.93	14.45	117.64	4.43	101.22		35.13	51984	43456	8,528	
	12.00	18.24	117.64	4.71	95.09		40.83	24776	21288	3,488	
	18.03	26.54	117.64	4.87	92.07		57.16	4267	2442	1,825	
	21.63	31.23	117.64	4.96	90.30		65.79	1834	799	1,035	
	25.69	36.46	117.64	5.05	88.74		75.36	494	48	447	
	33.33	44.79	117.64	5.33	84.04		87.65	42	2	40	

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-1 (Top), D-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	11/9/2005	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	12/9/2005	**Notes:**	Air Dried Sample

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R33	Wt. of Top Wet Sample + Ring (g)	163.10	Wt. of Bottom Wet Sample + Ring (g)	163.25
Wt. of Ring for Top Sample (g)	39.95	Height of Top Sample (in)	0.984	Height of Bottom Sample (in)	0.983
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.361	Diameter of Bottom Sample (in)	2.360
Ring I.D. for Bottom Sample	R34	Wt. of Bottom Wet Sample + Ring (g)	163.39	Pan I.D. for Top Sample	KD-3
Wt. of Ring for Bottom Sample (g)	40.21	Height of Bottom Sample (in)	0.983	Wt. of Pan for Top Sample (g)	15.64
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.360	Wt. of Top Wet Sample + Ring + Pan (g)	178.57
Sample Container I.D.	C5	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	173.69
Wt. of Sample Container (g)	114.63	Wt. of Top Wet Sample + Ring (g)	162.93	Pan I.D. for Bottom Sample	KD-17
		Height of Top Sample (in)	0.984	Wt. of Pan for Bottom Sample (g)	15.70
		Diameter of Top Sample (in)	2.361	Wt. of Bottom Wet Sample + Ring + Pan (g)	178.95
				Wt. of Bottom Dry Sample + Ring + Pan (g)	173.63

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	122.98	123.04	123.01
Wt. of Dry Sample (g)	118.10	117.72	117.91
Wt. of Water (g)	4.88	5.32	5.10
Gravimetric Water Conten (%)	4.13	4.52	4.33
Volume of Sample (in^3)	4.31	4.30	4.30
Volumetric Water Content (%)	6.90	7.54	7.22

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B1	B2	B3	B7	8
Wt. of Cold Tare, T_c (g)	15.3117	15.2054	15.1954	15.3277	15.3934
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.6522	15.5596	15.5524	15.5438	15.6062
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6393	15.5447	15.5402	15.5348	15.5956
Wt. of Hot Tare, T_h (g)	15.3082	15.2007	15.1929	15.3253	15.3894
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3311	0.3440	0.3473	0.2095	0.2062
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0094	0.0102	0.0097	0.0066	0.0066
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	2.84	2.97	2.79	3.15	3.20
Soil Suction (kPa)	157,950	153,729	159,520	120,667	119,580
Soil Suction (pF)	6.21	6.20	6.21	6.09	6.09

Table 4 Calculations of Soil Suction

Average Total Suction	157,066 (kPa)	6.20 (pF)
Average Matric Suction	120,123 (kPa)	6.09 (pF)
Osmotic Suction	36,943 (kPa)	5.58 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-1 (Top), D-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	12/12/2005	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	1/7/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R33	Wt. of Top Wet Sample + Ring (g)	164.94	Wt. of Bottom Wet Sample + Ring (g)	164.93
Wt. of Ring for Top Sample (g)	39.95	Height of Top Sample (in)	0.987	Height of Bottom Sample (in)	0.986
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.369	Diameter of Bottom Sample (in)	2.369
Ring I.D. for Bottom Sample	R34	Wt. of Bottom Wet Sample + Ring (g)	165.31	Pan I.D. for Top Sample	KD-3
Wt. of Ring for Bottom Sample (g)	40.21	Height of Bottom Sample (in)	0.986	Wt. of Pan for Top Sample (g)	15.64
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.369	Wt. of Top Wet Sample + Ring + Pan (g)	180.36
Sample Container I.D.	C5	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	173.69
Wt. of Sample Container (g)	114.63	Wt. of Top Wet Sample + Ring (g)	164.72	Pan I.D. for Bottom Sample	KD-17
		Height of Top Sample (in)	0.987	Wt. of Pan for Bottom Sample (g)	15.70
		Diameter of Top Sample (in)	2.369	Wt. of Bottom Wet Sample + Ring + Pan (g)	180.63
				Wt. of Bottom Dry Sample + Ring + Pan (g)	173.63

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	124.77	124.72	124.75
Wt. of Dry Sample (g)	118.10	117.72	117.91
Wt. of Water (g)	6.67	7.00	6.84
Gravimetric Water Conten (%)	5.65	5.95	5.80
Volume of Sample (in^3)	4.35	4.35	4.35
Volumetric Water Content (%)	9.34	9.81	9.58

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	A1	B3	A8	A9	A11
Wt. of Cold Tare, T_c (g)	15.4175	15.3083	15.4314	15.4904	15.3187
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7828	15.6758	15.7875	15.7265	15.5570
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7637	15.6572	15.7687	15.7120	15.5440
Wt. of Hot Tare, T_h (g)	15.4133	15.3052	15.4272	15.4861	15.3160
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3504	0.3520	0.3415	0.2259	0.2280
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0149	0.0155	0.0146	0.0102	0.0103
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	4.25	4.40	4.28	4.52	4.52
Soil Suction (kPa)	116,590	112,866	116,016	94,463	94,424
Soil Suction (pF)	6.08	6.06	6.07	5.98	5.98

Table 4 Calculations of Soil Suction

Average Total Suction	115,157 (kPa)	6.07 (pF)
Average Matric Suction	94,443 (kPa)	5.98 (pF)
Osmotic Suction	20,714 (kPa)	5.32 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-1 (Top), D-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	1/8/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	1/22/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R33	Wt. of Top Wet Sample + Ring (g)	168.25	Wt. of Bottom Wet Sample + Ring (g)	168.42
Wt. of Ring for Top Sample (g)	39.95	Height of Top Sample (in)	1.008	Height of Bottom Sample (in)	1.008
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.370	Diameter of Bottom Sample (in)	2.370
Ring I.D. for Bottom Sample	R34	Wt. of Bottom Wet Sample + Ring (g)	169.25	Pan I.D. for Top Sample	KD-3
Wt. of Ring for Bottom Sample (g)	40.21	Height of Bottom Sample (in)	1.008	Wt. of Pan for Top Sample (g)	15.64
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.370	Wt. of Top Wet Sample + Ring + Pan (g)	183.87
Sample Container I.D.	C5	*End of the Test:*		Wt. of Top Dry Sample + Ring + Pan (g)	173.69
Wt. of Sample Container (g)	114.63	Wt. of Top Wet Sample + Ring (g)	168.23	Pan I.D. for Bottom Sample	KD-17
		Height of Top Sample (in)	1.008	Wt. of Pan for Bottom Sample (g)	15.70
		Diameter of Top Sample (in)	2.370	Wt. of Bottom Wet Sample + Ring + Pan (g)	184.12
				Wt. of Bottom Dry Sample + Ring + Pan (g)	173.63

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	128.28	128.21	128.25
Wt. of Dry Sample (g)	118.10	117.72	117.91
Wt. of Water (g)	10.18	10.49	10.34
Gravimetric Water Conten (%)	8.62	8.91	8.77
Volume of Sample (in^3)	4.45	4.45	4.45
Volumetric Water Content (%)	13.95	14.37	14.16

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	A3	C6	C8	C10	A11
Wt. of Cold Tare, T_c (g)	15.2488	15.3335	15.4414	15.4242	15.3191
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.6323	15.7163	15.8262	15.6754	15.5730
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6000	15.6841	15.7945	15.6519	15.5484
Wt. of Hot Tare, T_h (g)	15.2445	15.3287	15.4376	15.4210	15.3149
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3555	0.3554	0.3569	0.2309	0.2335
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0280	0.0274	0.0279	0.0203	0.0204
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	7.88	7.71	7.82	8.79	8.74
Soil Suction (kPa)	53,524	55,474	54,206	43,866	44,301
Soil Suction (pF)	5.74	5.75	5.74	5.65	5.65

Table 4 Calculations of Soil Suction

Average Total Suction	54,401 (kPa)	5.74 (pF)
Average Matric Suction	44,084 (kPa)	5.65 (pF)
Osmotic Suction	10,318 (kPa)	5.02 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-1 (Top), D-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	1/24/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	3/14/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R33	Wt. of Top Wet Sample + Ring (g)	172.15	Wt. of Bottom Wet Sample + Ring (g)	171.52
Wt. of Ring for Top Sample (g)	39.95	Height of Top Sample (in)	1.021	Height of Bottom Sample (in)	1.028
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.420	Diameter of Bottom Sample (in)	2.420
Ring I.D. for Bottom Sample	R34	Wt. of Bottom Wet Sample + Ring (g)	172.10	Pan I.D. for Top Sample	KD-3
Wt. of Ring for Bottom Sample (g)	40.21	Height of Bottom Sample (in)	1.028	Wt. of Pan for Top Sample (g)	15.64
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.420	Wt. of Top Wet Sample + Ring + Pan (g)	187.32
Sample Container I.D.	C5	*End of the Test:*		Wt. of Top Dry Sample + Ring + Pan (g)	173.69
Wt. of Sample Container (g)	114.63	Wt. of Top Wet Sample + Ring (g)	171.68	Pan I.D. for Bottom Sample	KD-17
		Height of Top Sample (in)	1.021	Wt. of Pan for Bottom Sample (g)	15.70
		Diameter of Top Sample (in)	2.420	Wt. of Bottom Wet Sample + Ring + Pan (g)	187.22
				Wt. of Bottom Dry Sample + Ring + Pan (g)	173.63

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	131.73	131.31	131.52
Wt. of Dry Sample (g)	118.10	117.72	117.91
Wt. of Water (g)	13.63	13.59	13.61
Gravimetric Water Conten (%)	11.54	11.54	11.54
Volume of Sample (in^3)	4.70	4.73	4.71
Volumetric Water Content (%)	17.68	17.51	17.60

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B1	B2	A8	A10	A12
Wt. of Cold Tare, T_c (g)	15.3676	15.3233	15.4322	15.3555	15.3966
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7694	15.7105	15.8317	15.5889	15.6335
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7231	15.6670	15.7865	15.5576	15.6040
Wt. of Hot Tare, T_h (g)	15.3640	15.3197	15.4274	15.3513	15.3943
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3591	0.3473	0.3591	0.2063	0.2097
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0427	0.0399	0.0404	0.0271	0.0272
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	11.89	11.49	11.25	13.14	12.97
Soil Suction (kPa)	22,594	24,633	25,926	20,123	20,728
Soil Suction (pF)	5.36	5.40	5.42	5.31	5.33

Table 4 Calculations of Soil Suction

Average Total Suction	24,384	(kPa)	5.40	(pF)
Average Matric Suction	20,426	(kPa)	5.32	(pF)
Osmotic Suction	3,959	(kPa)	4.61	(pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-1 (Top), D-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	3/15/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	4/9/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R33	Wt. of Top Wet Sample + Ring (g)	179.23	Wt. of Bottom Wet Sample + Ring (g)	178.95
Wt. of Ring for Top Sample (g)	39.95	Height of Top Sample (in)	1.033	Height of Bottom Sample (in)	1.048
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R34	Wt. of Bottom Wet Sample + Ring (g)	179.14	Pan I.D. for Top Sample	KD-3
Wt. of Ring for Bottom Sample (g)	40.21	Height of Bottom Sample (in)	1.048	Wt. of Pan for Top Sample (g)	15.64
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	194.02
Sample Container I.D.	C5	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	173.69
Wt. of Sample Container (g)	114.63	Wt. of Top Wet Sample + Ring (g)	178.38	Pan I.D. for Bottom Sample	KD-17
		Height of Top Sample (in)	1.033	Wt. of Pan for Bottom Sample (g)	15.70
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	194.65
				Wt. of Bottom Dry Sample + Ring + Pan (g)	173.63

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	138.43	138.74	138.59
Wt. of Dry Sample (g)	118.10	117.72	117.91
Wt. of Water (g)	20.33	21.02	20.68
Gravimetric Water Conten (%)	17.21	17.86	17.54
Volume of Sample (in^3)	4.82	4.89	4.86
Volumetric Water Content (%)	25.68	26.18	25.93

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	A1	C2	B4	C9	C11
Wt. of Cold Tare, T_c (g)	15.4172	15.3306	15.3052	15.3677	15.3147
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8283	15.7495	15.7214	15.6244	15.5794
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7565	15.6797	15.6542	15.5693	15.5227
Wt. of Hot Tare, T_h (g)	15.4113	15.3262	15.3015	15.3632	15.3110
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3452	0.3535	0.3527	0.2061	0.2117
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0659	0.0654	0.0635	0.0506	0.0530
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	19.09	18.50	18.00	24.55	25.04
Soil Suction (kPa)	4,811	5,461	6,076	2,597	2,381
Soil Suction (pF)	4.69	4.75	4.79	4.42	4.39

Table 4 Calculations of Soil Suction

Average Total Suction	5,450 (kPa)	4.74 (pF)
Average Matric Suction	2,489 (kPa)	4.40 (pF)
Osmotic Suction	2,961 (kPa)	4.48 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-1 (Top), D-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	4/9/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	5/4/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R33	Wt. of Top Wet Sample + Ring (g)	183.20	Wt. of Bottom Wet Sample + Ring (g)	182.33
Wt. of Ring for Top Sample (g)	39.95	Height of Top Sample (in)	1.058	Height of Bottom Sample (in)	1.068
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R34	Wt. of Bottom Wet Sample + Ring (g)	183.70	Pan I.D. for Top Sample	KD-3
Wt. of Ring for Bottom Sample (g)	40.21	Height of Bottom Sample (in)	1.068	Wt. of Pan for Top Sample (g)	15.64
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	198.99
Sample Container I.D.	C5	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	173.69
Wt. of Sample Container (g)	114.63	Wt. of Top Wet Sample + Ring (g)	183.35	Pan I.D. for Bottom Sample	KD-17
		Height of Top Sample (in)	1.058	Wt. of Pan for Bottom Sample (g)	15.70
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	198.03
				Wt. of Bottom Dry Sample + Ring + Pan (g)	173.63

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	143.40	142.12	142.76
Wt. of Dry Sample (g)	118.10	117.72	117.91
Wt. of Water (g)	25.30	24.40	24.85
Gravimetric Water Conten (%)	21.42	20.73	21.07
Volume of Sample (in^3)	4.94	4.99	4.96
Volumetric Water Content (%)	31.21	29.82	30.51

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B1	B5	A6	A8	A9
Wt. of Cold Tare, T_c (g)	15.3671	15.2763	15.3387	15.4309	15.4889
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7914	15.7047	15.7662	15.7226	15.7963
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7055	15.6185	15.6791	15.6497	15.7169
Wt. of Hot Tare, T_h (g)	15.3630	15.2716	15.3357	15.4266	15.4846
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3425	0.3469	0.3434	0.2231	0.2323
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0818	0.0815	0.0841	0.0686	0.0751
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	23.88	23.49	24.49	30.75	32.33
Soil Suction (kPa)	1,718	1,868	1,508	854	644
Soil Suction (pF)	4.24	4.28	4.19	3.94	3.82

Table 4 Calculations of Soil Suction

Average Total Suction	1,698 (kPa)	4.24 (pF)
Average Matric Suction	749 (kPa)	3.88 (pF)
Osmotic Suction	949 (kPa)	3.99 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-1 (Top), D-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	72 Degrees F.
Time of Beginning:	5/6/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	5/27/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R33	Wt. of Top Wet Sample + Ring (g)	188.70	Wt. of Bottom Wet Sample + Ring (g)	187.40
Wt. of Ring for Top Sample (g)	39.95	Height of Top Sample (in)	1.086	Height of Bottom Sample (in)	1.083
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R34	Wt. of Bottom Wet Sample + Ring (g)	188.16	Pan I.D. for Top Sample	KD-3
Wt. of Ring for Bottom Sample (g)	40.21	Height of Bottom Sample (in)	1.083	Wt. of Pan for Top Sample (g)	15.64
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	203.44
Sample Container I.D.	C5	*End of the Test:*		Wt. of Top Dry Sample + Ring + Pan (g)	173.69
Wt. of Sample Container (g)	114.63	Wt. of Top Wet Sample + Ring (g)	187.80	Pan I.D. for Bottom Sample	KD-17
		Height of Top Sample (in)	1.086	Wt. of Pan for Bottom Sample (g)	15.70
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	203.10
				Wt. of Bottom Dry Sample + Ring + Pan (g)	173.63

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	147.85	147.19	147.52
Wt. of Dry Sample (g)	118.10	117.72	117.91
Wt. of Water (g)	29.75	29.47	29.61
Gravimetric Water Conten (%)	25.19	25.03	25.11
Volume of Sample (in^3)	5.07	5.06	5.06
Volumetric Water Content (%)	35.75	35.51	35.63

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B2	B3	C4	C7	B8
Wt. of Cold Tare, T_c (g)	15.3228	15.3076	15.2144	15.5137	15.3054
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7933	15.7732	15.6607	15.8458	15.6245
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6808	15.6615	15.5563	15.7351	15.5224
Wt. of Hot Tare, T_h (g)	15.3199	15.3035	15.2122	15.5115	15.3036
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3609	0.3580	0.3441	0.2236	0.2188
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.1096	0.1076	0.1022	0.1085	0.1003
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	30.37	30.06	29.70	48.52	45.84
Soil Suction (kPa)	427	456	492	57	62
Soil Suction (pF)	3.64	3.67	3.70	2.77	2.80

Table 4 Calculations of Soil Suction

Average Total Suction	458 (kPa)	3.67 (pF)
Average Matric Suction	60 (kPa)	2.78 (pF)
Osmotic Suction	399 (kPa)	3.61 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-1 (Top), D-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	72 Degrees F.
Time of Beginning:	5/29/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	6/17/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R33	Wt. of Top Wet Sample + Ring (g)	199.02	Wt. of Bottom Wet Sample + Ring (g)	197.95
Wt. of Ring for Top Sample (g)	39.95	Height of Top Sample (in)	1.152	Height of Bottom Sample (in)	1.153
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R34	Wt. of Bottom Wet Sample + Ring (g)	199.75	Pan I.D. for Top Sample	KD-3
Wt. of Ring for Bottom Sample (g)	40.21	Height of Bottom Sample (in)	1.153	Wt. of Pan for Top Sample (g)	15.64
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	213.41
Sample Container I.D.	C5	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	173.69
Wt. of Sample Container (g)	114.63	Wt. of Top Wet Sample + Ring (g)	197.77	Pan I.D. for Bottom Sample	KD-17
		Height of Top Sample (in)	1.152	Wt. of Pan for Bottom Sample (g)	15.70
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	213.65
				Wt. of Bottom Dry Sample + Ring + Pan (g)	173.63

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	157.82	157.74	157.78
Wt. of Dry Sample (g)	118.10	117.72	117.91
Wt. of Water (g)	39.72	40.02	39.87
Gravimetric Water Conten (%)	33.63	34.00	33.81
Volume of Sample (in^3)	5.38	5.38	5.38
Volumetric Water Content (%)	45.00	45.30	45.15

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	D3	D11	D15	D19	D32
Wt. of Cold Tare, T_c (g)	15.4043	15.4312	15.4257	15.4378	15.3344
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8793	15.9223	15.9166	15.9805	15.9093
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7566	15.7965	15.7881	15.6447	15.5580
Wt. of Hot Tare, T_h (g)	15.4026	15.4306	15.4233	15.4353	15.3327
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3540	0.3659	0.3648	0.2094	0.2253
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.1210	0.1252	0.1261	0.3333	0.3496
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	34.18	34.22	34.57	159.17	155.17
Soil Suction (kPa)	15	14	8	2	2
Soil Suction (pF)	2.18	2.16	1.94	1.27	1.33

Table 4 Calculations of Soil Suction

Average Total Suction	13 (kPa)	2.11 (pF)
Average Matric Suction	2 (kPa)	1.30 (pF)
Osmotic Suction	11 (kPa)	2.03 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-3 (Top), D-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	11/9/2005	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	12/9/2005	**Notes:**	Air Dried Sample

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R35	Wt. of Top Wet Sample + Ring (g)	162.19	Wt. of Bottom Wet Sample + Ring (g)	162.41
Wt. of Ring for Top Sample (g)	40.05	Height of Top Sample (in)	0.980	Height of Bottom Sample (in)	0.980
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.358	Diameter of Bottom Sample (in)	2.357
Ring I.D. for Bottom Sample	R37	Wt. of Bottom Wet Sample + Ring (g)	162.55	Pan I.D. for Top Sample	KD-10
Wt. of Ring for Bottom Sample (g)	40.13	Height of Bottom Sample (in)	0.980	Wt. of Pan for Top Sample (g)	15.68
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.357	Wt. of Top Wet Sample + Ring + Pan (g)	177.70
Sample Container I.D.	C6	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	172.82
Wt. of Sample Container (g)	114.17	Wt. of Top Wet Sample + Ring (g)	162.02	Pan I.D. for Bottom Sample	KD-4
		Height of Top Sample (in)	0.980	Wt. of Pan for Bottom Sample (g)	15.40
		Diameter of Top Sample (in)	2.358	Wt. of Bottom Wet Sample + Ring + Pan (g)	177.81
				Wt. of Bottom Dry Sample + Ring + Pan (g)	172.90

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	121.97	122.28	122.13
Wt. of Dry Sample (g)	117.09	117.37	117.23
Wt. of Water (g)	4.88	4.91	4.90
Gravimetric Water Conten (%)	4.17	4.18	4.18
Volume of Sample (in^3)	4.28	4.28	4.28
Volumetric Water Content (%)	6.95	7.00	6.97

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	5	6	7	9	C11
Wt. of Cold Tare, T_c (g)	15.3922	15.4094	15.3824	15.2398	15.3879
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7430	15.7623	15.7372	15.4551	15.5979
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7302	15.7491	15.7236	15.4442	15.5886
Wt. of Hot Tare, T_h (g)	15.3887	15.4057	15.3781	15.2357	15.3849
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3415	0.3434	0.3455	0.2085	0.2037
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0093	0.0095	0.0093	0.0068	0.0063
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	2.72	2.77	2.69	3.26	3.09
Soil Suction (kPa)	161,927	160,432	163,027	118,287	121,919
Soil Suction (pF)	6.22	6.21	6.22	6.08	6.09

Table 4 Calculations of Soil Suction

Average Total Suction	161,795 (kPa)	6.22 (pF)
Average Matric Suction	120,103 (kPa)	6.09 (pF)
Osmotic Suction	41,692 (kPa)	5.63 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-3 (Top), D-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	12/12/2005	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	1/7/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R35	Wt. of Top Wet Sample + Ring (g)	164.82	Wt. of Bottom Wet Sample + Ring (g)	164.97
Wt. of Ring for Top Sample (g)	40.05	Height of Top Sample (in)	0.985	Height of Bottom Sample (in)	0.985
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.371	Diameter of Bottom Sample (in)	2.370
Ring I.D. for Bottom Sample	R37	Wt. of Bottom Wet Sample + Ring (g)	165.26	Pan I.D. for Top Sample	KD-10
Wt. of Ring for Bottom Sample (g)	40.13	Height of Bottom Sample (in)	0.985	Wt. of Pan for Top Sample (g)	15.68
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.370	Wt. of Top Wet Sample + Ring + Pan (g)	180.23
Sample Container I.D.	C6	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	172.82
Wt. of Sample Container (g)	114.17	Wt. of Top Wet Sample + Ring (g)	164.55	Pan I.D. for Bottom Sample	KD-4
		Height of Top Sample (in)	0.985	Wt. of Pan for Bottom Sample (g)	15.40
		Diameter of Top Sample (in)	2.371	Wt. of Bottom Wet Sample + Ring + Pan (g)	180.37
				Wt. of Bottom Dry Sample + Ring + Pan (g)	172.90

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	124.50	124.84	124.67
Wt. of Dry Sample (g)	117.09	117.37	117.23
Wt. of Water (g)	7.41	7.47	7.44
Gravimetric Water Conten (%)	6.33	6.36	6.35
Volume of Sample (in^3)	4.35	4.35	4.35
Volumetric Water Content (%)	10.38	10.47	10.43

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	A5	A6	A7	C8	C10
Wt. of Cold Tare, T_c (g)	15.1991	15.3396	15.4221	15.4415	15.4247
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.5616	15.7064	15.7836	15.6765	15.6529
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.5393	15.6849	15.7648	15.6617	15.6388
Wt. of Hot Tare, T_h (g)	15.1947	15.3369	15.4187	15.4386	15.4214
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3446	0.3480	0.3461	0.2231	0.2174
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0179	0.0188	0.0154	0.0119	0.0108
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	5.19	5.40	4.45	5.33	4.97
Soil Suction (kPa)	95,227	91,068	111,752	81,562	87,098
Soil Suction (pF)	5.99	5.97	6.06	5.92	5.95

Table 4 Calculations of Soil Suction

Average Total Suction	99,349 (kPa)	6.01 (pF)
Average Matric Suction	84,330 (kPa)	5.93 (pF)
Osmotic Suction	15,019 (kPa)	5.19 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-3 (Top), D-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	1/8/2005	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	1/22/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R35	Wt. of Top Wet Sample + Ring (g)	168.25	Wt. of Bottom Wet Sample + Ring (g)	168.55
Wt. of Ring for Top Sample (g)	40.05	Height of Top Sample (in)	1.009	Height of Bottom Sample (in)	1.009
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.370	Diameter of Bottom Sample (in)	2.370
Ring I.D. for Bottom Sample	R37	Wt. of Bottom Wet Sample + Ring (g)	169.04	Pan I.D. for Top Sample	KD-10
Wt. of Ring for Bottom Sample (g)	40.13	Height of Bottom Sample (in)	1.009	Wt. of Pan for Top Sample (g)	15.68
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.370	Wt. of Top Wet Sample + Ring + Pan (g)	183.51
Sample Container I.D.	C6	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	172.82
Wt. of Sample Container (g)	114.17	Wt. of Top Wet Sample + Ring (g)	167.83	Pan I.D. for Bottom Sample	KD-4
		Height of Top Sample (in)	1.009	Wt. of Pan for Bottom Sample (g)	15.40
		Diameter of Top Sample (in)	2.370	Wt. of Bottom Wet Sample + Ring + Pan (g)	183.95
				Wt. of Bottom Dry Sample + Ring + Pan (g)	172.90

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	127.78	128.42	128.10
Wt. of Dry Sample (g)	117.09	117.37	117.23
Wt. of Water (g)	10.69	11.05	10.87
Gravimetric Water Conten (%)	9.13	9.41	9.27
Volume of Sample (in^3)	4.45	4.45	4.45
Volumetric Water Content (%)	14.63	15.12	14.88

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B2	B5	A7	B9	C12
Wt. of Cold Tare, T_c (g)	15.3227	15.2775	15.4215	15.3003	15.4173
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7110	15.6679	15.8089	15.5392	15.6665
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6747	15.6312	15.7741	15.5147	15.6415
Wt. of Hot Tare, T_h (g)	15.3183	15.2733	15.4165	15.2958	15.4138
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3564	0.3579	0.3576	0.2189	0.2277
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0319	0.0325	0.0298	0.0200	0.0215
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	8.95	9.08	8.33	9.14	9.44
Soil Suction (kPa)	42,492	41,321	48,518	41,234	39,035
Soil Suction (pF)	5.64	5.62	5.69	5.62	5.60

Table 4 Calculations of Soil Suction

Average Total Suction	44,110 (kPa)	5.65 (pF)
Average Matric Suction	40,134 (kPa)	5.61 (pF)
Osmotic Suction	3,976 (kPa)	4.61 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-3 (Top), D-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	1/24/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	3/14/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R35	Wt. of Top Wet Sample + Ring (g)	172.54	Wt. of Bottom Wet Sample + Ring (g)	172.20
Wt. of Ring for Top Sample (g)	40.05	Height of Top Sample (in)	1.031	Height of Bottom Sample (in)	1.029
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.420	Diameter of Bottom Sample (in)	2.420
Ring I.D. for Bottom Sample	R37	Wt. of Bottom Wet Sample + Ring (g)	172.49	Pan I.D. for Top Sample	KD-10
Wt. of Ring for Bottom Sample (g)	40.13	Height of Bottom Sample (in)	1.029	Wt. of Pan for Top Sample (g)	15.68
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.420	Wt. of Top Wet Sample + Ring + Pan (g)	187.49
Sample Container I.D.	C6	*End of the Test:*		Wt. of Top Dry Sample + Ring + Pan (g)	172.82
Wt. of Sample Container (g)	114.17	Wt. of Top Wet Sample + Ring (g)	171.81	Pan I.D. for Bottom Sample	KD-4
		Height of Top Sample (in)	1.031	Wt. of Pan for Bottom Sample (g)	15.40
		Diameter of Top Sample (in)	2.420	Wt. of Bottom Wet Sample + Ring + Pan (g)	187.60
				Wt. of Bottom Dry Sample + Ring + Pan (g)	172.90

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	131.76	132.07	131.92
Wt. of Dry Sample (g)	117.09	117.37	117.23
Wt. of Water (g)	14.67	14.70	14.69
Gravimetric Water Conten (%)	12.53	12.52	12.53
Volume of Sample (in^3)	4.74	4.73	4.74
Volumetric Water Content (%)	18.85	18.92	18.88

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	C3	A4	C7	C8	B12
Wt. of Cold Tare, T_c (g)	15.4613	15.4260	15.5126	15.4412	15.2811
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8601	15.8101	15.9162	15.6913	15.5300
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.8120	15.7635	15.8681	15.6572	15.4964
Wt. of Hot Tare, T_h (g)	15.4560	15.4219	15.5081	15.4381	15.2774
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3560	0.3416	0.3600	0.2191	0.2190
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0428	0.0425	0.0436	0.0310	0.0299
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	12.02	12.44	12.11	14.15	13.65
Soil Suction (kPa)	21,964	20,073	21,549	16,781	18,341
Soil Suction (pF)	5.35	5.31	5.34	5.23	5.27

Table 4 Calculations of Soil Suction

Average Total Suction	21,195 (kPa)	5.33 (pF)
Average Matric Suction	17,561 (kPa)	5.25 (pF)
Osmotic Suction	3,634 (kPa)	4.57 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-3 (Top), D-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	3/15/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	4/9/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R35	Wt. of Top Wet Sample + Ring (g)	179.38	Wt. of Bottom Wet Sample + Ring (g)	179.56
Wt. of Ring for Top Sample (g)	40.05	Height of Top Sample (in)	1.052	Height of Bottom Sample (in)	1.048
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R37	Wt. of Bottom Wet Sample + Ring (g)	179.72	Pan I.D. for Top Sample	KD-10
Wt. of Ring for Bottom Sample (g)	40.13	Height of Bottom Sample (in)	1.048	Wt. of Pan for Top Sample (g)	15.68
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	194.30
Sample Container I.D.	C6	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	172.82
Wt. of Sample Container (g)	114.17	Wt. of Top Wet Sample + Ring (g)	178.62	Pan I.D. for Bottom Sample	KD-4
		Height of Top Sample (in)	1.052	Wt. of Pan for Bottom Sample (g)	15.40
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	194.96
				Wt. of Bottom Dry Sample + Ring + Pan (g)	172.90

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	138.57	139.43	139.00
Wt. of Dry Sample (g)	117.09	117.37	117.23
Wt. of Water (g)	21.48	22.06	21.77
Gravimetric Water Conten (%)	18.34	18.80	18.57
Volume of Sample (in^3)	4.91	4.89	4.90
Volumetric Water Content (%)	26.65	27.47	27.06

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	C1	B5	C4	B8	C10
Wt. of Cold Tare, T_c (g)	15.4267	15.2772	15.2149	15.3066	15.4250
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8364	15.6969	15.6184	15.5833	15.7280
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7637	15.6240	15.5473	15.5261	15.6568
Wt. of Hot Tare, T_h (g)	15.4225	15.2729	15.2101	15.3024	15.4215
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3412	0.3511	0.3372	0.2237	0.2353
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0685	0.0686	0.0663	0.0530	0.0677
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	20.08	19.54	19.66	23.69	28.77
Soil Suction (kPa)	3,893	4,370	4,255	3,029	1,218
Soil Suction (pF)	4.60	4.65	4.64	4.49	4.09

Table 4 Calculations of Soil Suction

Average Total Suction	4,173 (kPa)	4.63 (pF)
Average Matric Suction	2,124 (kPa)	4.34 (pF)
Osmotic Suction	2,049 (kPa)	4.32 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-3 (Top), D-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	4/9/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	5/4/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R35	Wt. of Top Wet Sample + Ring (g)	183.40	Wt. of Bottom Wet Sample + Ring (g)	183.97
Wt. of Ring for Top Sample (g)	40.05	Height of Top Sample (in)	1.067	Height of Bottom Sample (in)	1.066
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R37	Wt. of Bottom Wet Sample + Ring (g)	184.80	Pan I.D. for Top Sample	KD-10
Wt. of Ring for Bottom Sample (g)	40.13	Height of Bottom Sample (in)	1.066	Wt. of Pan for Top Sample (g)	15.68
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	198.15
Sample Container I.D.	C6	*End of the Test:*		Wt. of Top Dry Sample + Ring + Pan (g)	172.82
Wt. of Sample Container (g)	114.17	Wt. of Top Wet Sample + Ring (g)	182.47	Pan I.D. for Bottom Sample	KD-4
		Height of Top Sample (in)	1.067	Wt. of Pan for Bottom Sample (g)	15.40
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	199.37
				Wt. of Bottom Dry Sample + Ring + Pan (g)	172.90

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	142.42	143.84	143.13
Wt. of Dry Sample (g)	117.09	117.37	117.23
Wt. of Water (g)	25.33	26.47	25.90
Gravimetric Water Conten (%)	21.63	22.55	22.09
Volume of Sample (in^3)	4.98	4.98	4.98
Volumetric Water Content (%)	30.98	32.41	31.69

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B2	C3	B4	B10	B11
Wt. of Cold Tare, T_c (g)	15.3232	15.4611	15.3044	15.3342	15.2601
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7447	15.8973	15.7248	15.6182	15.5478
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6612	15.8143	15.6419	15.5478	15.4761
Wt. of Hot Tare, T_h (g)	15.3191	15.4580	15.3012	15.3300	15.2562
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3421	0.3563	0.3407	0.2178	0.2199
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0794	0.0799	0.0797	0.0662	0.0678
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	23.21	22.42	23.39	30.39	30.83
Soil Suction (kPa)	1,986	2,350	1,909	910	842
Soil Suction (pF)	4.31	4.38	4.29	3.97	3.93

Table 4 Calculations of Soil Suction

Average Total Suction	1,947	(kPa)	4.30	(pF)
Average Matric Suction	876	(kPa)	3.95	(pF)
Osmotic Suction	1,071	(kPa)	4.04	(pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-3 (Top), D-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	72 Degrees F.
Time of Beginning:	5/6/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	5/27/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R35	Wt. of Top Wet Sample + Ring (g)	188.42	Wt. of Bottom Wet Sample + Ring (g)	188.20
Wt. of Ring for Top Sample (g)	40.05	Height of Top Sample (in)	1.088	Height of Bottom Sample (in)	1.083
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R37	Wt. of Bottom Wet Sample + Ring (g)	189.28	Pan I.D. for Top Sample	KD-10
Wt. of Ring for Bottom Sample (g)	40.13	Height of Bottom Sample (in)	1.083	Wt. of Pan for Top Sample (g)	15.68
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	203.22
Sample Container I.D.	C6	*End of the Test:*		Wt. of Top Dry Sample + Ring + Pan (g)	172.82
Wt. of Sample Container (g)	114.17	Wt. of Top Wet Sample + Ring (g)	187.54	Pan I.D. for Bottom Sample	KD-4
		Height of Top Sample (in)	1.088	Wt. of Pan for Bottom Sample (g)	15.40
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	203.60
				Wt. of Bottom Dry Sample + Ring + Pan (g)	172.90

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	147.49	148.07	147.78
Wt. of Dry Sample (g)	117.09	117.37	117.23
Wt. of Water (g)	30.40	30.70	30.55
Gravimetric Water Conten (%)	25.96	26.16	26.06
Volume of Sample (in^3)	5.08	5.06	5.07
Volumetric Water Content (%)	36.46	36.99	36.73

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	C1	C5	A8	A10	C12
Wt. of Cold Tare, T_c (g)	15.4255	15.3596	15.4306	15.3546	15.4162
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8758	15.7997	15.8860	15.7654	15.8032
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7702	15.6991	15.7820	15.5768	15.6353
Wt. of Hot Tare, T_h (g)	15.4209	15.3558	15.4273	15.3513	15.4136
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3493	0.3433	0.3547	0.2255	0.2217
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.1010	0.0968	0.1007	0.1853	0.1653
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	28.91	28.20	28.39	82.17	74.56
Soil Suction (kPa)	583	680	653	20	25
Soil Suction (pF)	3.77	3.84	3.82	2.31	2.41

Table 4 Calculations of Soil Suction

Average Total Suction	639	(kPa)	3.81	(pF)
Average Matric Suction	23	(kPa)	2.37	(pF)
Osmotic Suction	616	(kPa)	3.80	(pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-3 (Top), D-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	72 Degrees F.
Time of Beginning:	5/29/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	6/17/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R35	Wt. of Top Wet Sample + Ring (g)	197.53	Wt. of Bottom Wet Sample + Ring (g)	196.36
Wt. of Ring for Top Sample (g)	40.05	Height of Top Sample (in)	1.138	Height of Bottom Sample (in)	1.160
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R37	Wt. of Bottom Wet Sample + Ring (g)	198.03	Pan I.D. for Top Sample	KD-10
Wt. of Ring for Bottom Sample (g)	40.13	Height of Bottom Sample (in)	1.160	Wt. of Pan for Top Sample (g)	15.68
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	212.18
Sample Container I.D.	C6	*End of the Test:*		Wt. of Top Dry Sample + Ring + Pan (g)	172.82
Wt. of Sample Container (g)	114.17	Wt. of Top Wet Sample + Ring (g)	196.50	Pan I.D. for Bottom Sample	KD-4
		Height of Top Sample (in)	1.138	Wt. of Pan for Bottom Sample (g)	15.40
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	211.76
				Wt. of Bottom Dry Sample + Ring + Pan (g)	172.90

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	156.45	156.23	156.34
Wt. of Dry Sample (g)	117.09	117.37	117.23
Wt. of Water (g)	39.36	38.86	39.11
Gravimetric Water Conten (%)	33.62	33.11	33.36
Volume of Sample (in^3)	5.31	5.42	5.36
Volumetric Water Content (%)	45.14	43.72	44.43

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	D14	D20	D25	D26	D36
Wt. of Cold Tare, T_c (g)	15.1963	15.3632	15.4140	15.3849	15.4025
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.6523	15.8455	15.8693	15.9455	15.9659
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.5391	15.7231	15.7541	15.6026	15.6191
Wt. of Hot Tare, T_h (g)	15.1951	15.3608	15.4122	15.3829	15.3998
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3440	0.3623	0.3419	0.2197	0.2193
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.1120	0.1200	0.1134	0.3409	0.3441
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	32.56	33.12	33.17	155.17	156.91
Soil Suction (kPa)	162	71	66	2	2
Soil Suction (pF)	3.22	2.86	2.83	1.33	1.30

Table 4 Calculations of Soil Suction

Average Total Suction	100	(kPa)	3.01	(pF)
Average Matric Suction	2	(kPa)	1.31	(pF)
Osmotic Suction	98	(kPa)	3.00	(pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-5 (Top), D-6 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	11/9/2005	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	12/9/2005	**Notes:**	Air Dried Sample

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R3	Wt. of Top Wet Sample + Ring (g)	163.82	Wt. of Bottom Wet Sample + Ring (g)	163.35
Wt. of Ring for Top Sample (g)	40.61	Height of Top Sample (in)	0.979	Height of Bottom Sample (in)	0.974
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.354	Diameter of Bottom Sample (in)	2.352
Ring I.D. for Bottom Sample	R7	Wt. of Bottom Wet Sample + Ring (g)	163.52	Pan I.D. for Top Sample	KD-25
Wt. of Ring for Bottom Sample (g)	40.26	Height of Bottom Sample (in)	0.974	Wt. of Pan for Top Sample (g)	15.57
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.352	Wt. of Top Wet Sample + Ring + Pan (g)	179.23
Sample Container I.D.	C1	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	173.72
Wt. of Sample Container (g)	113.68	Wt. of Top Wet Sample + Ring (g)	163.66	Pan I.D. for Bottom Sample	KD-28
		Height of Top Sample (in)	0.979	Wt. of Pan for Bottom Sample (g)	16.24
		Diameter of Top Sample (in)	2.354	Wt. of Bottom Wet Sample + Ring + Pan (g)	179.59
				Wt. of Bottom Dry Sample + Ring + Pan (g)	174.49

Table 2 Calculations of Soil Sample Properties

Soil Property	***Top Sample***	***Bottom Sample***	***Average***
Wt. of Wet Sample (g)	123.05	123.09	123.07
Wt. of Dry Sample (g)	117.54	117.99	117.77
Wt. of Water (g)	5.51	5.10	5.30
Gravimetric Water Conten (%)	4.69	4.32	4.51
Volume of Sample (in^3)	4.26	4.23	4.25
Volumetric Water Content (%)	7.88	7.34	7.61

Table 3 Measurements of Soil Suction

Measurements	***Total or Matric Suction***				
	Total (Top)	***Total (Middle)***	***Total (Bottom)***	***Matric (Top)***	***Matric (Bottom)***
Moisture Tin I.D.	C5	C7	C9	B9	B11
Wt. of Cold Tare, T_c (g)	15.4158	15.3523	15.3360	15.1969	15.2449
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7711	15.7095	15.6985	15.4161	15.4588
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7564	15.6958	15.6831	15.4047	15.4465
Wt. of Hot Tare, T_h (g)	15.4123	15.3481	15.3321	15.1934	15.2398
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3441	0.3477	0.3510	0.2113	0.2067
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0112	0.0095	0.0115	0.0079	0.0072
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	3.25	2.73	3.28	3.74	3.48
Soil Suction (kPa)	144,451	161,615	143,786	108,580	113,671
Soil Suction (pF)	6.17	6.22	6.17	6.04	6.06

Table 4 Calculations of Soil Suction

Average Total Suction	149,951 (kPa)	6.18 (pF)
Average Matric Suction	111,126 (kPa)	6.05 (pF)
Osmotic Suction	38,825 (kPa)	5.60 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-5 (Top), D-6 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	12/12/2005	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	1/7/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R3	Wt. of Top Wet Sample + Ring (g)	165.74	Wt. of Bottom Wet Sample + Ring (g)	165.22
Wt. of Ring for Top Sample (g)	40.61	Height of Top Sample (in)	0.982	Height of Bottom Sample (in)	0.978
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.362	Diameter of Bottom Sample (in)	2.361
Ring I.D. for Bottom Sample	R7	Wt. of Bottom Wet Sample + Ring (g)	165.38	Pan I.D. for Top Sample	KD-25
Wt. of Ring for Bottom Sample (g)	40.26	Height of Bottom Sample (in)	0.978	Wt. of Pan for Top Sample (g)	15.57
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.361	Wt. of Top Wet Sample + Ring + Pan (g)	181.08
Sample Container I.D.	C1	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	173.72
Wt. of Sample Container (g)	113.68	Wt. of Top Wet Sample + Ring (g)	165.51	Pan I.D. for Bottom Sample	KD-28
		Height of Top Sample (in)	0.982	Wt. of Pan for Bottom Sample (g)	16.24
		Diameter of Top Sample (in)	2.362	Wt. of Bottom Wet Sample + Ring + Pan (g)	181.46
				Wt. of Bottom Dry Sample + Ring + Pan (g)	174.49

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	124.90	124.96	124.93
Wt. of Dry Sample (g)	117.54	117.99	117.77
Wt. of Water (g)	7.36	6.97	7.16
Gravimetric Water Conten (%)	6.26	5.91	6.08
Volume of Sample (in^3)	4.30	4.28	4.29
Volumetric Water Content (%)	10.42	9.92	10.17

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B4	B7	B10	C11	B12
Wt. of Cold Tare, T_c (g)	15.3065	15.3279	15.3368	15.3151	15.2822
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.6726	15.6850	15.6965	15.5531	15.5029
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6524	15.6666	15.6779	15.5397	15.4885
Wt. of Hot Tare, T_h (g)	15.3016	15.3246	15.3328	15.3116	15.2779
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3508	0.3420	0.3451	0.2281	0.2106
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0153	0.0151	0.0146	0.0099	0.0101
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	4.36	4.42	4.23	4.34	4.80
Soil Suction (kPa)	113,887	112,580	117,133	97,476	89,827
Soil Suction (pF)	6.06	6.06	6.08	6.00	5.96

Table 4 Calculations of Soil Suction

Average Total Suction	114,534 (kPa)	6.07 (pF)
Average Matric Suction	93,651 (kPa)	5.98 (pF)
Osmotic Suction	20,882 (kPa)	5.33 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-5 (Top), D-6 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	1/8/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	1/22/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R3	Wt. of Top Wet Sample + Ring (g)	169.11	Wt. of Bottom Wet Sample + Ring (g)	168.32
Wt. of Ring for Top Sample (g)	40.61	Height of Top Sample (in)	1.003	Height of Bottom Sample (in)	1.000
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.359	Diameter of Bottom Sample (in)	2.363
Ring I.D. for Bottom Sample	R7	Wt. of Bottom Wet Sample + Ring (g)	168.63	Pan I.D. for Top Sample	KD-25
Wt. of Ring for Bottom Sample (g)	40.26	Height of Bottom Sample (in)	1.000	Wt. of Pan for Top Sample (g)	15.57
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.363	Wt. of Top Wet Sample + Ring + Pan (g)	184.25
Sample Container I.D.	C1	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	173.72
Wt. of Sample Container (g)	113.68	Wt. of Top Wet Sample + Ring (g)	168.68	Pan I.D. for Bottom Sample	KD-28
		Height of Top Sample (in)	1.003	Wt. of Pan for Bottom Sample (g)	16.24
		Diameter of Top Sample (in)	2.359	Wt. of Bottom Wet Sample + Ring + Pan (g)	184.56
				Wt. of Bottom Dry Sample + Ring + Pan (g)	174.49

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	128.07	128.06	128.07
Wt. of Dry Sample (g)	117.54	117.99	117.77
Wt. of Water (g)	10.53	10.07	10.30
Gravimetric Water Conten (%)	8.96	8.53	8.75
Volume of Sample (in^3)	4.38	4.39	4.38
Volumetric Water Content (%)	14.63	13.99	14.31

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	A1	B3	A10	B11	B12
Wt. of Cold Tare, T_c (g)	15.4176	15.3074	15.3557	15.2602	15.2811
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8060	15.6877	15.7417	15.4907	15.5212
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7733	15.6567	15.7097	15.4687	15.4985
Wt. of Hot Tare, T_h (g)	15.4127	15.3021	15.3513	15.2567	15.2768
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3606	0.3546	0.3584	0.2120	0.2217
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0278	0.0257	0.0276	0.0185	0.0184
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	7.71	7.25	7.70	8.73	8.30
Soil Suction (kPa)	55,477	61,263	55,578	44,383	47,915
Soil Suction (pF)	5.75	5.80	5.75	5.66	5.69

Table 4 Calculations of Soil Suction

Average Total Suction	57,440	(kPa)	5.77	(pF)
Average Matric Suction	46,149	(kPa)	5.67	(pF)
Osmotic Suction	11,291	(kPa)	5.06	(pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-5 (Top), D-6 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	1/24/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	3/14/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R3	Wt. of Top Wet Sample + Ring (g)	172.86	Wt. of Bottom Wet Sample + Ring (g)	172.13
Wt. of Ring for Top Sample (g)	40.61	Height of Top Sample (in)	1.019	Height of Bottom Sample (in)	1.020
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.420	Diameter of Bottom Sample (in)	2.420
Ring I.D. for Bottom Sample	R7	Wt. of Bottom Wet Sample + Ring (g)	172.54	Pan I.D. for Top Sample	KD-25
Wt. of Ring for Bottom Sample (g)	40.26	Height of Bottom Sample (in)	1.020	Wt. of Pan for Top Sample (g)	15.57
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.420	Wt. of Top Wet Sample + Ring + Pan (g)	187.94
Sample Container I.D.	C1	*End of the Test:*		Wt. of Top Dry Sample + Ring + Pan (g)	173.72
Wt. of Sample Container (g)	113.68	Wt. of Top Wet Sample + Ring (g)	172.37	Pan I.D. for Bottom Sample	KD-28
		Height of Top Sample (in)	1.019	Wt. of Pan for Bottom Sample (g)	16.24
		Diameter of Top Sample (in)	2.420	Wt. of Bottom Wet Sample + Ring + Pan (g)	188.37
				Wt. of Bottom Dry Sample + Ring + Pan (g)	174.49

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	131.76	131.87	131.82
Wt. of Dry Sample (g)	117.54	117.99	117.77
Wt. of Water (g)	14.22	13.88	14.05
Gravimetric Water Conten (%)	12.10	11.76	11.93
Volume of Sample (in^3)	4.69	4.69	4.69
Volumetric Water Content (%)	18.48	18.02	18.25

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B3	C4	C5	A6	B9
Wt. of Cold Tare, T_c (g)	15.3089	15.2147	15.3601	15.3397	15.2991
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7049	15.6040	15.7553	15.5749	15.5362
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6623	15.5625	15.7141	15.5464	15.5083
Wt. of Hot Tare, T_h (g)	15.3045	15.2120	15.3567	15.3359	15.2961
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3578	0.3505	0.3574	0.2105	0.2122
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0382	0.0388	0.0378	0.0247	0.0249
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	10.68	11.07	10.58	11.73	11.73
Soil Suction (kPa)	29,329	26,951	29,966	25,878	25,876
Soil Suction (pF)	5.48	5.44	5.49	5.42	5.42

Table 4 Calculations of Soil Suction

Average Total Suction	28,749 (kPa)	5.47 (pF)
Average Matric Suction	25,877 (kPa)	5.42 (pF)
Osmotic Suction	2,872 (kPa)	4.47 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-5 (Top), D-6 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	3/15/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	4/9/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R3	Wt. of Top Wet Sample + Ring (g)	179.91	Wt. of Bottom Wet Sample + Ring (g)	179.48
Wt. of Ring for Top Sample (g)	40.61	Height of Top Sample (in)	1.035	Height of Bottom Sample (in)	1.040
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R7	Wt. of Bottom Wet Sample + Ring (g)	179.72	Pan I.D. for Top Sample	KD-25
Wt. of Ring for Bottom Sample (g)	40.26	Height of Bottom Sample (in)	1.040	Wt. of Pan for Top Sample (g)	15.57
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	194.84
Sample Container I.D.	C1	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	173.72
Wt. of Sample Container (g)	113.68	Wt. of Top Wet Sample + Ring (g)	179.27	Pan I.D. for Bottom Sample	KD-28
		Height of Top Sample (in)	1.035	Wt. of Pan for Bottom Sample (g)	16.24
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	195.72
				Wt. of Bottom Dry Sample + Ring + Pan (g)	174.49

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	138.66	139.22	138.94
Wt. of Dry Sample (g)	117.54	117.99	117.77
Wt. of Water (g)	21.12	21.23	21.18
Gravimetric Water Conten (%)	17.97	17.99	17.98
Volume of Sample (in^3)	4.83	4.86	4.84
Volumetric Water Content (%)	26.63	26.64	26.64

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	A4	C5	C6	A11	C12
Wt. of Cold Tare, T_c (g)	15.4266	15.3597	15.3332	15.3181	15.4169
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8460	15.7854	15.7535	15.5905	15.6912
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7670	15.7068	15.6766	15.5325	15.6347
Wt. of Hot Tare, T_h (g)	15.4208	15.3546	15.3294	15.3135	15.4139
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3462	0.3522	0.3472	0.2190	0.2208
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0732	0.0735	0.0731	0.0534	0.0535
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	21.14	20.87	21.05	24.38	24.23
Soil Suction (kPa)	3,095	3,284	3,155	2,676	2,751
Soil Suction (pF)	4.50	4.52	4.51	4.44	4.45

Table 4 Calculations of Soil Suction

Average Total Suction	3,178	(kPa)	4.51	(pF)
Average Matric Suction	2,714	(kPa)	4.44	(pF)
Osmotic Suction	464	(kPa)	3.68	(pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-5 (Top), D-6 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	4/9/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	5/4/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R3	Wt. of Top Wet Sample + Ring (g)	184.40	Wt. of Bottom Wet Sample + Ring (g)	184.07
Wt. of Ring for Top Sample (g)	40.61	Height of Top Sample (in)	1.055	Height of Bottom Sample (in)	1.065
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R7	Wt. of Bottom Wet Sample + Ring (g)	184.60	Pan I.D. for Top Sample	KD-25
Wt. of Ring for Bottom Sample (g)	40.26	Height of Bottom Sample (in)	1.065	Wt. of Pan for Top Sample (g)	15.57
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	199.06
Sample Container I.D.	C1	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	173.72
Wt. of Sample Container (g)	113.68	Wt. of Top Wet Sample + Ring (g)	183.49	Pan I.D. for Bottom Sample	KD-28
		Height of Top Sample (in)	1.055	Wt. of Pan for Bottom Sample (g)	16.24
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	200.31
				Wt. of Bottom Dry Sample + Ring + Pan (g)	174.49

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	142.88	143.81	143.35
Wt. of Dry Sample (g)	117.54	117.99	117.77
Wt. of Water (g)	25.34	25.82	25.58
Gravimetric Water Conten (%)	21.56	21.88	21.72
Volume of Sample (in^3)	4.93	4.97	4.95
Volumetric Water Content (%)	31.35	31.64	31.49

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B3	C4	B8	B9	A11
Wt. of Cold Tare, T_c (g)	15.3069	15.2139	15.3056	15.2979	15.3170
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7419	15.6524	15.7360	15.5894	15.6197
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6545	15.5673	15.6515	15.5185	15.5430
Wt. of Hot Tare, T_h (g)	15.3044	15.2114	15.3021	15.2956	15.3135
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3501	0.3559	0.3494	0.2229	0.2295
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0849	0.0826	0.0810	0.0686	0.0732
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	24.25	23.21	23.18	30.78	31.90
Soil Suction (kPa)	1,588	1,986	1,997	850	696
Soil Suction (pF)	4.21	4.31	4.31	3.94	3.85

Table 4 Calculations of Soil Suction

Average Total Suction	1,857 (kPa)	4.28 (pF)
Average Matric Suction	773 (kPa)	3.90 (pF)
Osmotic Suction	1,084 (kPa)	4.04 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-5 (Top), D-6 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	72 Degrees F.
Time of Beginning:	5/6/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	5/27/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R3	Wt. of Top Wet Sample + Ring (g)	189.45	Wt. of Bottom Wet Sample + Ring (g)	188.59
Wt. of Ring for Top Sample (g)	40.61	Height of Top Sample (in)	1.059	Height of Bottom Sample (in)	1.092
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R7	Wt. of Bottom Wet Sample + Ring (g)	189.55	Pan I.D. for Top Sample	KD-25
Wt. of Ring for Bottom Sample (g)	40.26	Height of Bottom Sample (in)	1.092	Wt. of Pan for Top Sample (g)	15.57
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	204.37
Sample Container I.D.	C1	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	173.72
Wt. of Sample Container (g)	113.68	Wt. of Top Wet Sample + Ring (g)	188.80	Pan I.D. for Bottom Sample	KD-28
		Height of Top Sample (in)	1.059	Wt. of Pan for Bottom Sample (g)	16.24
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	204.83
				Wt. of Bottom Dry Sample + Ring + Pan (g)	174.49

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	148.19	148.33	148.26
Wt. of Dry Sample (g)	117.54	117.99	117.77
Wt. of Water (g)	30.65	30.34	30.50
Gravimetric Water Conten (%)	26.08	25.71	25.90
Volume of Sample (in^3)	4.94	5.10	5.02
Volumetric Water Content (%)	37.77	36.26	37.02

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	A2	A5	B5	B9	B12
Wt. of Cold Tare, T_c (g)	15.4159	15.1982	15.2761	15.2982	15.2803
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.9015	15.6585	15.7392	15.6554	15.6237
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7733	15.5462	15.6267	15.5140	15.4871
Wt. of Hot Tare, T_h (g)	15.4121	15.1946	15.2725	15.2963	15.2768
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3612	0.3516	0.3542	0.2177	0.2103
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.1244	0.1087	0.1089	0.1395	0.1331
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	34.44	30.92	30.75	64.08	63.29
Soil Suction (kPa)	10	379	393	35	36
Soil Suction (pF)	2.02	3.59	3.60	2.56	2.57

Table 4 Calculations of Soil Suction

Average Total Suction	386 (kPa)	3.60 (pF)
Average Matric Suction	36 (kPa)	2.56 (pF)
Osmotic Suction	351 (kPa)	3.55 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Russell	**Sample I.D.:**	D-5 (Top), D-6 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	72 Degrees F.
Time of Beginning:	5/29/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	6/17/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R3	Wt. of Top Wet Sample + Ring (g)	198.34	Wt. of Bottom Wet Sample + Ring (g)	196.63
Wt. of Ring for Top Sample (g)	40.61	Height of Top Sample (in)	1.120	Height of Bottom Sample (in)	1.131
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R7	Wt. of Bottom Wet Sample + Ring (g)	198.07	Pan I.D. for Top Sample	KD-25
Wt. of Ring for Bottom Sample (g)	40.26	Height of Bottom Sample (in)	1.131	Wt. of Pan for Top Sample (g)	15.57
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	212.59
Sample Container I.D.	C1	*End of the Test:*		Wt. of Top Dry Sample + Ring + Pan (g)	173.72
Wt. of Sample Container (g)	113.68	Wt. of Top Wet Sample + Ring (g)	197.02	Pan I.D. for Bottom Sample	KD-28
		Height of Top Sample (in)	1.120	Wt. of Pan for Bottom Sample (g)	16.24
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	212.87
				Wt. of Bottom Dry Sample + Ring + Pan (g)	174.49

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	156.41	156.37	156.39
Wt. of Dry Sample (g)	117.54	117.99	117.77
Wt. of Water (g)	38.87	38.38	38.63
Gravimetric Water Conten (%)	33.07	32.53	32.80
Volume of Sample (in^3)	5.23	5.28	5.25
Volumetric Water Content (%)	45.29	44.29	44.79

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	D17	D18	D31	D33	D35
Wt. of Cold Tare, T_c (g)	15.4529	15.4364	15.3210	15.3603	15.3590
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.9451	15.8949	15.8090	15.9007	15.9226
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.8177	15.7708	15.6777	15.5711	15.5775
Wt. of Hot Tare, T_h (g)	15.4511	15.4291	15.3142	15.3585	15.3582
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3666	0.3417	0.3635	0.2126	0.2193
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.1256	0.1168	0.1245	0.3278	0.3443
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	34.26	34.18	34.25	154.19	157.00
Soil Suction (kPa)	13	15	13	2	2
Soil Suction (pF)	2.13	2.18	2.14	1.34	1.30

Table 4 Calculations of Soil Suction

Average Total Suction	14 (kPa)	2.16 (pF)
Average Matric Suction	2 (kPa)	1.32 (pF)
Osmotic Suction	12 (kPa)	2.09 (pF)

APPENDIX D.2

PIERRE SHALE FORMATION

Table D-2 Summary of Results of Soil Water Characteristic Curve

Curve Type: Wetting Curve

Formation: Pierre Shale Formation

Sample I.D.	Gravimetric Water Content (%)	Volumetric Water Content (%)	Wt. of Dry Sample (g)	Volume of Sample (in^3)	Dry Density (pcf)	Specific Gravity	Degree of Saturation (%)	Total Suction (kPa)	Matric Suction (kPa)	Osmotic Suction (kPa)	Notes
PS-1&2	0.00	0.00				2.76	0.00	244,584	175,038	69,546	Avg. of Oven Dried Samples
	3.25	5.45	122.45	4.45	104.90		13.98	144,883	113,801	31,083	Air Dried Sample
	5.70	9.44	122.45	4.51	103.53		23.71	78,657	69,643	9,014	
	8.41	13.62	122.45	4.61	101.24		33.11	35,711	33,650	2,061	
	11.57	18.24	122.45	4.73	98.61		42.77	15,678	13,102	2,576	
	16.95	25.99	122.45	4.86	95.90		58.77	1,993	1,659	334	
	19.93	29.96	122.45	4.96	94.00		66.11	916	382	534	
	23.73	35.30	122.45	5.02	93.00		76.89	105	32	74	
	29.63	42.59	122.45	5.19	89.90		89.31	20	2	18	
PS-3&4	0.00	0.00					0.00	244,584	175,038	69,546	Avg. of Oven Dried Samples
	3.27	5.64	122.47	4.32	107.90		15.14	150,688	120,232	30,456	Air Dried Sample
	5.63	9.56	122.47	4.40	106.09		24.95	77,090	68,473	8,617	
	8.16	13.64	122.47	4.46	104.53		34.77	38,311	33,028	5,282	
	11.44	18.15	106.68	4.10	99.22		42.91	16,391	13,473	2,917	
	17.37	26.63	106.68	4.24	95.93		60.29	2,010	1,227	783	
	20.69	30.73	106.68	4.37	93.06		67.13	884	219	664	
	23.95	34.97	106.68	4.44	91.55		74.99	154	24	130	
	29.30	41.08	106.68	4.62	87.94		84.38	140	2	138	
PS-5&6	0.00	0.00					0.00	244,584	175,038	69,546	Avg. of Oven Dried Samples
	3.53	5.98	121.92	4.38	105.97		15.57	152,764	121,124	31,640	Air Dried Sample
	6.09	10.15	121.92	4.45	104.31		25.80	77,770	68,257	9,513	
	8.64	14.21	121.92	4.51	102.87		35.36	34,149	30,866	3,284	
	11.61	18.21	121.92	4.74	98.04		42.36	15,632	9,649	5,983	
	17.24	26.24	121.92	4.88	95.16		58.75	2,049	1,233	816	
	20.23	30.19	121.92	4.98	93.29		65.99	1,680	410	1,270	
	24.02	35.29	121.92	5.06	91.87		75.80	126	25	101	
	29.82	42.20	121.92	5.25	88.48		86.97	42	2	41	
Average	0.00	0.00					0.00	244,584	175,038	69,546	
	3.35	5.69	122.28	4.38	106.24		14.89	149445	118386	31,059	
	5.81	9.72	122.28	4.45	104.63		24.81	77839	68791	9,048	
	8.40	13.82	122.28	4.53	102.86		34.39	36057	32515	3,542	
	11.54	18.20	117.01	4.52	98.59		42.65	15900	12075	3,825	
	17.18	26.28	117.01	4.66	95.65		59.25	2017	1373	644	
	20.28	30.29	117.01	4.77	93.47		66.44	900	337	563	
	23.90	35.19	117.01	4.84	92.16		75.93	128	27	101	
	29.59	41.96	117.01	5.02	88.80		86.92	31	2	29	

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W10-1
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	73 Degrees F.
Time of Beginning:	1/23/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	3/4/2006	**Notes:**	Oven-Dried Sample

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R6	Wt. of Top Wet Sample + Ring (g)	166.95	Wt. of Bottom Wet Sample + Ring (g)	167.64
Wt. of Ring for Top Sample (g)	40.15	Height of Top Sample (in)		Height of Bottom Sample (in)	
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)		Diameter of Bottom Sample (in)	
Ring I.D. for Bottom Sample	R19	Wt. of Bottom Wet Sample + Ring (g)	167.65	Pan I.D. for Top Sample	
Wt. of Ring for Bottom Sample (g)	40.35	Height of Bottom Sample (in)		Wt. of Pan for Top Sample (g)	
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)		Wt. of Top Wet Sample + Ring + Pan (g)	
Sample Container I.D.	C16	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	
Wt. of Sample Container (g)	113.32	Wt. of Top Wet Sample + Ring (g)	166.90	Pan I.D. for Bottom Sample	
		Height of Top Sample (in)		Wt. of Pan for Bottom Sample (g)	
		Diameter of Top Sample (in)		Wt. of Bottom Wet Sample + Ring + Pan (g)	
				Wt. of Bottom Dry Sample + Ring + Pan (g)	

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)			
Wt. of Dry Sample (g)			
Wt. of Water (g)			
Gravimetric Water Conten (%)			
Volume of Sample (in^3)			
Volumetric Water Content (%)			

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	C1	B2	C3	A8	A10
Wt. of Cold Tare, T_c (g)	15.4268	15.3233	15.4607	15.4320	15.3544
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7901	15.6787	15.8253	15.6521	15.5844
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7841	15.6727	15.8181	15.6462	15.5780
Wt. of Hot Tare, T_h (g)	15.4236	15.3201	15.4569	15.4287	15.3535
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3605	0.3526	0.3612	0.2175	0.2245
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0028	0.0028	0.0034	0.0026	0.0055
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	0.78	0.79	0.94	1.20	2.45
Soil Suction (kPa)	245,999	245,081	237,452	171,348	136,821
Soil Suction (pF)	6.40	6.40	6.38	6.24	6.14

Table 4 Calculations of Soil Suction

Average Total Suction	242,844 (kPa)	6.39 (pF)
Average Matric Suction	154,084 (kPa)	6.20 (pF)
Osmotic Suction	88,760 (kPa)	5.96 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W12-8
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	73 Degrees F.
Time of Beginning:	1/23/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	3/4/2006	**Notes:**	Oven-Dried Sample

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R10	Wt. of Top Wet Sample + Ring (g)	166.04	Wt. of Bottom Wet Sample + Ring (g)	166.32
Wt. of Ring for Top Sample (g)	40.15	Height of Top Sample (in)		Height of Bottom Sample (in)	
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)		Diameter of Bottom Sample (in)	
Ring I.D. for Bottom Sample	R28	Wt. of Bottom Wet Sample + Ring (g)	166.39	Pan I.D. for Top Sample	
Wt. of Ring for Bottom Sample (g)	40.16	Height of Bottom Sample (in)		Wt. of Pan for Top Sample (g)	
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)		Wt. of Top Wet Sample + Ring + Pan (g)	
Sample Container I.D.	C14	*End of the Test:*		Wt. of Top Dry Sample + Ring + Pan (g)	
Wt. of Sample Container (g)	112.92	Wt. of Top Wet Sample + Ring (g)	166.06	Pan I.D. for Bottom Sample	
		Height of Top Sample (in)		Wt. of Pan for Bottom Sample (g)	
		Diameter of Top Sample (in)		Wt. of Bottom Wet Sample + Ring + Pan (g)	
				Wt. of Bottom Dry Sample + Ring + Pan (g)	

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)			
Wt. of Dry Sample (g)			
Wt. of Water (g)			
Gravimetric Water Conten (%)			
Volume of Sample (in^3)			
Volumetric Water Content (%)			

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	A1	C7	C8	C9	A11
Wt. of Cold Tare, T_c (g)	15.4165	15.5120	15.4412	15.3675	15.3180
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7730	15.8802	15.8036	15.5875	15.5407
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7669	15.8742	15.7982	15.5827	15.5357
Wt. of Hot Tare, T_h (g)	15.4141	15.5088	15.4382	15.3640	15.3148
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3528	0.3654	0.3600	0.2187	0.2209
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0037	0.0028	0.0024	0.0013	0.0018
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	1.05	0.77	0.67	0.59	0.81
Soil Suction (kPa)	232,034	246,550	251,884	190,851	183,452
Soil Suction (pF)	6.37	6.40	6.41	6.29	6.27

Table 4 Calculations of Soil Suction

Average Total Suction	243,489 (kPa)	6.39 (pF)
Average Matric Suction	187,152 (kPa)	6.28 (pF)
Osmotic Suction	56,338 (kPa)	5.76 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W15-1
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	73 Degrees F.
Time of Beginning:	1/23/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	3/4/2006	**Notes:**	Oven-Dried Sample

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R13	Wt. of Top Wet Sample + Ring (g)	165.83	Wt. of Bottom Wet Sample + Ring (g)	165.50
Wt. of Ring for Top Sample (g)	40.30	Height of Top Sample (in)		Height of Bottom Sample (in)	
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)		Diameter of Bottom Sample (in)	
Ring I.D. for Bottom Sample	R17	Wt. of Bottom Wet Sample + Ring (g)	165.57	Pan I.D. for Top Sample	
Wt. of Ring for Bottom Sample (g)	40.36	Height of Bottom Sample (in)		Wt. of Pan for Top Sample (g)	
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)		Wt. of Top Wet Sample + Ring + Pan (g)	
Sample Container I.D.	C12	*End of the Test:*		Wt. of Top Dry Sample + Ring + Pan (g)	
Wt. of Sample Container (g)	113.15	Wt. of Top Wet Sample + Ring (g)	165.80	Pan I.D. for Bottom Sample	
		Height of Top Sample (in)		Wt. of Pan for Bottom Sample (g)	
		Diameter of Top Sample (in)		Wt. of Bottom Wet Sample + Ring + Pan (g)	
				Wt. of Bottom Dry Sample + Ring + Pan (g)	

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)			
Wt. of Dry Sample (g)			
Wt. of Water (g)			
Gravimetric Water Conten (%)			
Volume of Sample (in^3)			
Volumetric Water Content (%)			

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	A7	B8	B9	Total (Middle)	C12
Wt. of Cold Tare, T_c (g)	15.4208	15.3059	15.2987	15.3140	15.4158
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7894	15.6611	15.6590	15.5321	15.6360
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7820	15.6564	15.6530	15.5281	15.6319
Wt. of Hot Tare, T_h (g)	15.4166	15.3038	15.2956	15.3124	15.4135
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3654	0.3526	0.3574	0.2157	0.2184
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0032	0.0026	0.0029	0.0024	0.0018
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	0.88	0.74	0.81	1.11	0.82
Soil Suction (kPa)	240,820	248,086	244,171	173,910	183,146
Soil Suction (pF)	6.39	6.40	6.40	6.25	6.27

Table 4 Calculations of Soil Suction

Average Total Suction	244,359 (kPa)	6.40 (pF)
Average Matric Suction	178,528 (kPa)	6.26 (pF)
Osmotic Suction	65,831 (kPa)	5.83 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W19-8
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	73 Degrees F.
Time of Beginning:	1/23/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	3/4/2006	**Notes:**	Oven-Dried Sample

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R16	Wt. of Top Wet Sample + Ring (g)	165.14	Wt. of Bottom Wet Sample + Ring (g)	165.96
Wt. of Ring for Top Sample (g)	40.31	Height of Top Sample (in)		Height of Bottom Sample (in)	
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)		Diameter of Bottom Sample (in)	
Ring I.D. for Bottom Sample	R22	Wt. of Bottom Wet Sample + Ring (g)	166.00	Pan I.D. for Top Sample	
Wt. of Ring for Bottom Sample (g)	40.15	Height of Bottom Sample (in)		Wt. of Pan for Top Sample (g)	
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)		Wt. of Top Wet Sample + Ring + Pan (g)	
Sample Container I.D.	C13	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	
Wt. of Sample Container (g)	113.45	Wt. of Top Wet Sample + Ring (g)	165.12	Pan I.D. for Bottom Sample	
		Height of Top Sample (in)		Wt. of Pan for Bottom Sample (g)	
		Diameter of Top Sample (in)		Wt. of Bottom Wet Sample + Ring + Pan (g)	
				Wt. of Bottom Dry Sample + Ring + Pan (g)	

Table 2 Calculations of Soil Sample Properties

Soil Property	***Top Sample***	***Bottom Sample***	***Average***
Wt. of Wet Sample (g)			
Wt. of Dry Sample (g)			
Wt. of Water (g)			
Gravimetric Water Conten (%)			
Volume of Sample (in^3)			
Volumetric Water Content (%)			

Table 3 Measurements of Soil Suction

Measurements	***Total or Matric Suction***				
	Total (Top)	***Total (Middle)***	***Total (Bottom)***	***Matric (Top)***	***Matric (Bottom)***
Moisture Tin I.D.	B1	C2	C4	Total (Middle)	B11
Wt. of Cold Tare, T_c (g)	15.3674	15.3314	15.2144	15.3272	15.2631
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7254	15.6943	15.5709	15.5458	15.4684
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7201	15.6886	15.5647	15.5414	15.4631
Wt. of Hot Tare, T_h (g)	15.3646	15.3282	15.2112	15.3246	15.2595
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3555	0.3604	0.3535	0.2168	0.2036
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0025	0.0025	0.0030	0.0018	0.0017
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	0.70	0.69	0.85	0.83	0.83
Soil Suction (kPa)	249,913	250,426	242,226	182,946	182,791
Soil Suction (pF)	6.41	6.41	6.39	6.27	6.27

Table 4 Calculations of Soil Suction

Average Total Suction	247,522 (kPa)	6.40 (pF)
Average Matric Suction	182,869 (kPa)	6.27 (pF)
Osmotic Suction	64,653 (kPa)	5.82 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	W25-8
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI, D-Aired Water	**Room Temperature:**	73 Degrees F.
Time of Beginning:	1/23/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	3/4/2006	**Notes:**	Oven-Dried Sample

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R21	Wt. of Top Wet Sample + Ring (g)	164.98	Wt. of Bottom Wet Sample + Ring (g)	165.18
Wt. of Ring for Top Sample (g)	40.27	Height of Top Sample (in)		Height of Bottom Sample (in)	
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)		Diameter of Bottom Sample (in)	
Ring I.D. for Bottom Sample	R30	Wt. of Bottom Wet Sample + Ring (g)	165.22	Pan I.D. for Top Sample	
Wt. of Ring for Bottom Sample (g)	40.10	Height of Bottom Sample (in)		Wt. of Pan for Top Sample (g)	
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)		Wt. of Top Wet Sample + Ring + Pan (g)	
Sample Container I.D.	C3	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	
Wt. of Sample Container (g)	114.43	Wt. of Top Wet Sample + Ring (g)	164.95	Pan I.D. for Bottom Sample	
		Height of Top Sample (in)		Wt. of Pan for Bottom Sample (g)	
		Diameter of Top Sample (in)		Wt. of Bottom Wet Sample + Ring + Pan (g)	
				Wt. of Bottom Dry Sample + Ring + Pan (g)	

Table 2 Calculations of Soil Sample Properties

Soil Property	***Top Sample***	***Bottom Sample***	***Average***
Wt. of Wet Sample (g)			
Wt. of Dry Sample (g)			
Wt. of Water (g)			
Gravimetric Water Conten (%)			
Volume of Sample (in^3)			
Volumetric Water Content (%)			

Table 3 Measurements of Soil Suction

Measurements	***Total or Matric Suction***				
	Total (Top)	***Total (Middle)***	***Total (Bottom)***	***Matric (Top)***	***Matric (Bottom)***
Moisture Tin I.D.	B3	B4	A9	C10	B12
Wt. of Cold Tare, T_c (g)	15.3073	15.3050	15.4892	15.4248	15.2811
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.6655	15.6651	15.8400	15.6450	15.4984
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6592	15.6578	15.8333	15.6401	15.4931
Wt. of Hot Tare, T_h (g)	15.3037	15.3007	15.4853	15.4223	15.2784
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3555	0.3571	0.3480	0.2178	0.2147
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0027	0.0030	0.0028	0.0024	0.0026
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	0.76	0.84	0.80	1.10	1.21
Soil Suction (kPa)	246,910	242,671	244,529	174,245	170,869
Soil Suction (pF)	6.40	6.39	6.40	6.25	6.24

Table 4 Calculations of Soil Suction

Average Total Suction	244,704 (kPa)	6.40 (pF)
Average Matric Suction	172,557 (kPa)	6.25 (pF)
Osmotic Suction	72,147 (kPa)	5.87 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-1 (Top), PS-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	11/9/2005	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	12/9/2005	**Notes:**	Air Dried Sample

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R11	Wt. of Top Wet Sample + Ring (g)	167.38	Wt. of Bottom Wet Sample + Ring (g)	166.49
Wt. of Ring for Top Sample (g)	40.50	Height of Top Sample (in)	0.995	Height of Bottom Sample (in)	0.995
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.387	Diameter of Bottom Sample (in)	2.384
Ring I.D. for Bottom Sample	R15	Wt. of Bottom Wet Sample + Ring (g)	166.87	Pan I.D. for Top Sample	KD5
Wt. of Ring for Bottom Sample (g)	40.30	Height of Bottom Sample (in)	0.995	Wt. of Pan for Top Sample (g)	15.58
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.384	Wt. of Top Wet Sample + Ring + Pan (g)	182.74
Sample Container I.D.	C4	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	178.68
Wt. of Sample Container (g)	113.15	Wt. of Top Wet Sample + Ring (g)	167.16	Pan I.D. for Bottom Sample	DC12
		Height of Top Sample (in)	0.995	Wt. of Pan for Bottom Sample (g)	13.34
		Diameter of Top Sample (in)	2.387	Wt. of Bottom Wet Sample + Ring + Pan (g)	179.83
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.93

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	126.66	126.19	126.43
Wt. of Dry Sample (g)	122.60	122.29	122.45
Wt. of Water (g)	4.06	3.90	3.98
Gravimetric Water Conten (%)	3.31	3.19	3.25
Volume of Sample (in^3)	4.45	4.44	4.45
Volumetric Water Content (%)	5.56	5.35	5.45

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B4	B5	B10	A11	B12
Wt. of Cold Tare, T_c (g)	15.3048	15.2776	15.3350	15.3185	15.2811
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.6596	15.6345	15.6987	15.5306	15.4973
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6455	15.6200	15.6849	15.5205	15.4878
Wt. of Hot Tare, T_h (g)	15.3030	15.2737	15.3321	15.3160	15.2784
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3425	0.3463	0.3528	0.2045	0.2094
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0123	0.0106	0.0109	0.0076	0.0068
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	3.59	3.06	3.09	3.72	3.25
Soil Suction (kPa)	134,381	150,597	149,673	109,017	118,585
Soil Suction (pF)	6.14	6.19	6.18	6.05	6.08

Table 4 Calculations of Soil Suction

Average Total Suction	144,883 (kPa)	6.17 (pF)
Average Matric Suction	113,801 (kPa)	6.06 (pF)
Osmotic Suction	31,083 (kPa)	5.50 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-1 (Top), PS-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	12/12/2005	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	1/7/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R11	Wt. of Top Wet Sample + Ring (g)	170.55	Wt. of Bottom Wet Sample + Ring (g)	169.45
Wt. of Ring for Top Sample (g)	40.50	Height of Top Sample (in)	0.998	Height of Bottom Sample (in)	0.999
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.398	Diameter of Bottom Sample (in)	2.396
Ring I.D. for Bottom Sample	R15	Wt. of Bottom Wet Sample + Ring (g)	169.86	Pan I.D. for Top Sample	KD5
Wt. of Ring for Bottom Sample (g)	40.30	Height of Bottom Sample (in)	0.999	Wt. of Pan for Top Sample (g)	15.58
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.396	Wt. of Top Wet Sample + Ring + Pan (g)	185.78
Sample Container I.D.	C4	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	178.68
Wt. of Sample Container (g)	113.15	Wt. of Top Wet Sample + Ring (g)	170.20	Pan I.D. for Bottom Sample	DC12
		Height of Top Sample (in)	0.998	Wt. of Pan for Bottom Sample (g)	13.34
		Diameter of Top Sample (in)	2.398	Wt. of Bottom Wet Sample + Ring + Pan (g)	182.79
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.93

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	129.70	129.15	129.43
Wt. of Dry Sample (g)	122.60	122.29	122.45
Wt. of Water (g)	7.10	6.86	6.98
Gravimetric Water Conten (%)	5.79	5.61	5.70
Volume of Sample (in^3)	4.51	4.50	4.51
Volumetric Water Content (%)	9.60	9.28	9.44

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	C1	A3	C4	B9	A12
Wt. of Cold Tare, T_c (g)	15.4263	15.2503	15.2151	15.3014	15.3974
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7967	15.6150	15.5797	15.5300	15.6320
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7712	15.5917	15.5558	15.5135	15.6142
Wt. of Hot Tare, T_h (g)	15.4223	15.2472	15.2126	15.2984	15.3932
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3489	0.3445	0.3432	0.2151	0.2210
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0215	0.0202	0.0214	0.0135	0.0136
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	6.16	5.86	6.24	6.28	6.15
Soil Suction (kPa)	77,351	82,476	76,144	68,879	70,407
Soil Suction (pF)	5.90	5.92	5.89	5.85	5.86

Table 4 Calculations of Soil Suction

Average Total Suction	78,657	(kPa)	5.90	(pF)
Average Matric Suction	69,643	(kPa)	5.85	(pF)
Osmotic Suction	9,014	(kPa)	4.96	(pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-1 (Top), PS-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	1/8/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	1/22/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R11	Wt. of Top Wet Sample + Ring (g)	173.75	Wt. of Bottom Wet Sample + Ring (g)	173.35
Wt. of Ring for Top Sample (g)	40.50	Height of Top Sample (in)	1.016	Height of Bottom Sample (in)	1.016
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.402	Diameter of Bottom Sample (in)	2.404
Ring I.D. for Bottom Sample	R15	Wt. of Bottom Wet Sample + Ring (g)	173.52	Pan I.D. for Top Sample	KD5
Wt. of Ring for Bottom Sample (g)	40.30	Height of Bottom Sample (in)	1.016	Wt. of Pan for Top Sample (g)	15.58
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.404	Wt. of Top Wet Sample + Ring + Pan (g)	188.52
Sample Container I.D.	C4	*End of the Test:*		Wt. of Top Dry Sample + Ring + Pan (g)	178.68
Wt. of Sample Container (g)	113.15	Wt. of Top Wet Sample + Ring (g)	172.94	Pan I.D. for Bottom Sample	DC12
		Height of Top Sample (in)	1.016	Wt. of Pan for Bottom Sample (g)	13.34
		Diameter of Top Sample (in)	2.402	Wt. of Bottom Wet Sample + Ring + Pan (g)	186.69
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.93

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	132.44	133.05	132.75
Wt. of Dry Sample (g)	122.60	122.29	122.45
Wt. of Water (g)	9.84	10.76	10.30
Gravimetric Water Conten (%)	8.03	8.80	8.41
Volume of Sample (in^3)	4.60	4.61	4.61
Volumetric Water Content (%)	13.02	14.21	13.62

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	C5	A4	B7	C7	C11
Wt. of Cold Tare, T_c (g)	15.3605	15.4252	15.3279	15.5134	15.3149
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7450	15.8154	15.7149	15.7565	15.5479
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7062	15.7772	15.6771	15.7287	15.5245
Wt. of Hot Tare, T_h (g)	15.3561	15.4217	15.3243	15.5089	15.3126
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3501	0.3555	0.3528	0.2198	0.2119
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0344	0.0347	0.0342	0.0233	0.0211
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	9.83	9.76	9.69	10.60	9.96
Soil Suction (kPa)	35,209	35,703	36,221	31,712	35,588
Soil Suction (pF)	5.56	5.56	5.57	5.51	5.56

Table 4 Calculations of Soil Suction

Average Total Suction	35,711 (kPa)	5.56 (pF)
Average Matric Suction	33,650 (kPa)	5.54 (pF)
Osmotic Suction	2,061 (kPa)	4.32 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-1 (Top), PS-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	1/24/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	3/14/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R11	Wt. of Top Wet Sample + Ring (g)	177.60	Wt. of Bottom Wet Sample + Ring (g)	176.86
Wt. of Ring for Top Sample (g)	40.50	Height of Top Sample (in)	1.021	Height of Bottom Sample (in)	1.036
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.420	Diameter of Bottom Sample (in)	2.420
Ring I.D. for Bottom Sample	R15	Wt. of Bottom Wet Sample + Ring (g)	177.54	Pan I.D. for Top Sample	KD5
Wt. of Ring for Bottom Sample (g)	40.30	Height of Bottom Sample (in)	1.036	Wt. of Pan for Top Sample (g)	15.58
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.420	Wt. of Top Wet Sample + Ring + Pan (g)	192.74
Sample Container I.D.	C4	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	178.68
Wt. of Sample Container (g)	113.15	Wt. of Top Wet Sample + Ring (g)	177.16	Pan I.D. for Bottom Sample	DC12
		Height of Top Sample (in)	1.021	Wt. of Pan for Bottom Sample (g)	13.34
		Diameter of Top Sample (in)	2.420	Wt. of Bottom Wet Sample + Ring + Pan (g)	190.20
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.93

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	136.66	136.56	136.61
Wt. of Dry Sample (g)	122.60	122.29	122.45
Wt. of Water (g)	14.06	14.27	14.17
Gravimetric Water Conten (%)	11.47	11.67	11.57
Volume of Sample (in^3)	4.70	4.77	4.73
Volumetric Water Content (%)	18.24	18.24	18.24

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	C2	A9	B10	B11	C12
Wt. of Cold Tare, T_c (g)	15.3312	15.4900	15.3351	15.2614	15.4163
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7283	15.8902	15.7362	15.5143	15.6581
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6767	15.8386	15.6849	15.4769	15.6230
Wt. of Hot Tare, T_h (g)	15.3275	15.4863	15.3314	15.2581	15.4136
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3492	0.3523	0.3535	0.2188	0.2094
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0479	0.0479	0.0476	0.0341	0.0324
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	13.72	13.60	13.47	15.59	15.47
Soil Suction (kPa)	15,262	15,662	16,110	12,970	13,233
Soil Suction (pF)	5.19	5.20	5.22	5.12	5.13

Table 4 Calculations of Soil Suction

Average Total Suction	15,678 (kPa)	5.20 (pF)
Average Matric Suction	13,102 (kPa)	5.13 (pF)
Osmotic Suction	2,576 (kPa)	4.42 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-1 (Top), PS-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	3/15/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	4/9/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R11	Wt. of Top Wet Sample + Ring (g)	184.22	Wt. of Bottom Wet Sample + Ring (g)	183.74
Wt. of Ring for Top Sample (g)	40.50	Height of Top Sample (in)	1.026	Height of Bottom Sample (in)	1.058
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R15	Wt. of Bottom Wet Sample + Ring (g)	184.29	Pan I.D. for Top Sample	KD5
Wt. of Ring for Bottom Sample (g)	40.30	Height of Bottom Sample (in)	1.058	Wt. of Pan for Top Sample (g)	15.58
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	199.03
Sample Container I.D.	C4	*End of the Test:*		Wt. of Top Dry Sample + Ring + Pan (g)	178.68
Wt. of Sample Container (g)	113.15	Wt. of Top Wet Sample + Ring (g)	183.45	Pan I.D. for Bottom Sample	DC12
		Height of Top Sample (in)	1.026	Wt. of Pan for Bottom Sample (g)	13.34
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	197.08
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.93

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	142.95	143.44	143.20
Wt. of Dry Sample (g)	122.60	122.29	122.45
Wt. of Water (g)	20.35	21.15	20.75
Gravimetric Water Conten (%)	16.60	17.29	16.95
Volume of Sample (in^3)	4.79	4.94	4.86
Volumetric Water Content (%)	25.88	26.09	25.99

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B2	B3	A7	A8	B10
Wt. of Cold Tare, T_c (g)	15.3227	15.3072	15.4210	15.4315	15.3346
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7522	15.7416	15.8541	15.7131	15.6063
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6692	15.6574	15.7686	15.6487	15.5462
Wt. of Hot Tare, T_h (g)	15.3207	15.3041	15.4176	15.4266	15.3328
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3485	0.3533	0.3510	0.2221	0.2134
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0810	0.0811	0.0821	0.0595	0.0583
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	23.24	22.95	23.39	26.79	27.32
Soil Suction (kPa)	1,972	2,097	1,910	1,738	1,581
Soil Suction (pF)	4.30	4.33	4.29	4.25	4.21

Table 4 Calculations of Soil Suction

Average Total Suction	1,993 (kPa)	4.31 (pF)
Average Matric Suction	1,659 (kPa)	4.23 (pF)
Osmotic Suction	334 (kPa)	3.53 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-1 (Top), PS-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	4/9/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	5/4/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R11	Wt. of Top Wet Sample + Ring (g)	187.80	Wt. of Bottom Wet Sample + Ring (g)	187.54
Wt. of Ring for Top Sample (g)	40.50	Height of Top Sample (in)	1.052	Height of Bottom Sample (in)	1.074
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R15	Wt. of Bottom Wet Sample + Ring (g)	188.40	Pan I.D. for Top Sample	KD5
Wt. of Ring for Bottom Sample (g)	40.30	Height of Bottom Sample (in)	1.074	Wt. of Pan for Top Sample (g)	15.58
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	202.54
Sample Container I.D.	C4	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	178.68
Wt. of Sample Container (g)	113.15	Wt. of Top Wet Sample + Ring (g)	186.96	Pan I.D. for Bottom Sample	DC12
		Height of Top Sample (in)	1.052	Wt. of Pan for Bottom Sample (g)	13.34
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	200.88
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.93

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	146.46	147.24	146.85
Wt. of Dry Sample (g)	122.60	122.29	122.45
Wt. of Water (g)	23.86	24.95	24.41
Gravimetric Water Conten (%)	19.46	20.40	19.93
Volume of Sample (in^3)	4.91	5.01	4.96
Volumetric Water Content (%)	29.60	30.32	29.96

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	A3	C5	C7	C11	C12
Wt. of Cold Tare, T_c (g)	15.2473	15.3597	15.5128	15.3148	15.4169
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.6915	15.8009	15.9555	15.6008	15.7072
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.5946	15.7048	15.8545	15.5225	15.6303
Wt. of Hot Tare, T_h (g)	15.2443	15.3558	15.5066	15.3127	15.4142
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3503	0.3490	0.3479	0.2098	0.2161
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0939	0.0922	0.0948	0.0762	0.0742
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	26.81	26.42	27.25	36.32	34.34
Soil Suction (kPa)	917	997	834	315	449
Soil Suction (pF)	3.97	4.01	3.93	3.51	3.66

Table 4 Calculations of Soil Suction

Average Total Suction	916 (kPa)	3.97 (pF)
Average Matric Suction	382 (kPa)	3.59 (pF)
Osmotic Suction	534 (kPa)	3.74 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-1 (Top), PS-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	72 Degrees F.
Time of Beginning:	5/6/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	5/27/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R11	Wt. of Top Wet Sample + Ring (g)	192.64	Wt. of Bottom Wet Sample + Ring (g)	191.60
Wt. of Ring for Top Sample (g)	40.50	Height of Top Sample (in)	1.070	Height of Bottom Sample (in)	1.079
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R15	Wt. of Bottom Wet Sample + Ring (g)	192.99	Pan I.D. for Top Sample	KD5
Wt. of Ring for Bottom Sample (g)	40.30	Height of Bottom Sample (in)	1.079	Wt. of Pan for Top Sample (g)	15.58
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	207.79
Sample Container I.D.	C4	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	178.68
Wt. of Sample Container (g)	113.15	Wt. of Top Wet Sample + Ring (g)	192.21	Pan I.D. for Bottom Sample	DC12
		Height of Top Sample (in)	1.070	Wt. of Pan for Bottom Sample (g)	13.34
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	204.94
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.93

Table 2 Calculations of Soil Sample Properties

Soil Property	***Top Sample***	***Bottom Sample***	***Average***
Wt. of Wet Sample (g)	151.71	151.30	151.51
Wt. of Dry Sample (g)	122.60	122.29	122.45
Wt. of Water (g)	29.11	29.01	29.06
Gravimetric Water Conten (%)	23.74	23.72	23.73
Volume of Sample (in^3)	5.00	5.04	5.02
Volumetric Water Content (%)	35.50	35.09	35.30

Table 3 Measurements of Soil Suction

Measurements	***Total or Matric Suction***				
	Total (Top)	***Total (Middle)***	***Total (Bottom)***	***Matric (Top)***	***Matric (Bottom)***
Moisture Tin I.D.	C2	C6	A7	C9	C10
Wt. of Cold Tare, T_c (g)	15.3305	15.3324	15.4201	15.3666	15.4250
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7899	15.8151	15.8927	15.7438	15.7679
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6733	15.6917	15.7741	15.5838	15.6334
Wt. of Hot Tare, T_h (g)	15.3278	15.3288	15.4178	15.3645	15.4238
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3455	0.3629	0.3563	0.2193	0.2096
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.1139	0.1198	0.1163	0.1579	0.1333
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	32.97	33.01	32.64	72.00	63.60
Soil Suction (kPa)	89	83	144	28	36
Soil Suction (pF)	2.96	2.93	3.17	2.45	2.56

Table 4 Calculations of Soil Suction

Average Total Suction	105	(kPa)	3.03	(pF)
Average Matric Suction	32	(kPa)	2.51	(pF)
Osmotic Suction	74	(kPa)	2.88	(pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-1 (Top), PS-2 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	72 Degrees F.
Time of Beginning:	5/29/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	6/17/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R11	Wt. of Top Wet Sample + Ring (g)	199.60	Wt. of Bottom Wet Sample + Ring (g)	199.78
Wt. of Ring for Top Sample (g)	40.50	Height of Top Sample (in)	1.097	Height of Bottom Sample (in)	1.126
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R15	Wt. of Bottom Wet Sample + Ring (g)	202.27	Pan I.D. for Top Sample	KD5
Wt. of Ring for Bottom Sample (g)	40.30	Height of Bottom Sample (in)	1.126	Wt. of Pan for Top Sample (g)	15.58
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	214.05
Sample Container I.D.	C4	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	178.68
Wt. of Sample Container (g)	113.15	Wt. of Top Wet Sample + Ring (g)	198.47	Pan I.D. for Bottom Sample	DC12
		Height of Top Sample (in)	1.097	Wt. of Pan for Bottom Sample (g)	13.34
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	213.12
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.93

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	157.97	159.48	158.73
Wt. of Dry Sample (g)	122.60	122.29	122.45
Wt. of Water (g)	35.37	37.19	36.28
Gravimetric Water Conten (%)	28.85	30.41	29.63
Volume of Sample (in^3)	5.12	5.26	5.19
Volumetric Water Content (%)	42.08	43.10	42.59

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	D9	D12	D28	D30	D34
Wt. of Cold Tare, T_c (g)	15.4232	15.1724	15.3559	15.4390	15.3919
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.9153	15.6522	15.8039	16.0036	15.9784
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7888	15.5279	15.6866	15.6558	15.6137
Wt. of Hot Tare, T_h (g)	15.4212	15.1698	15.3527	15.4359	15.3911
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3676	0.3581	0.3339	0.2199	0.2226
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.1245	0.1217	0.1141	0.3447	0.3639
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	33.87	33.98	34.17	156.75	163.48
Soil Suction (kPa)	24	20	15	2	2
Soil Suction (pF)	2.38	2.31	2.19	1.30	1.21

Table 4 Calculations of Soil Suction

Average Total Suction	20 (kPa)	2.30 (pF)
Average Matric Suction	2 (kPa)	1.26 (pF)
Osmotic Suction	18 (kPa)	2.26 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-3 (Top), PS-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	11/9/2005	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	12/9/2005	**Notes:**	Air Dried Sample

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R20	Wt. of Top Wet Sample + Ring (g)	166.76	Wt. of Bottom Wet Sample + Ring (g)	166.61
Wt. of Ring for Top Sample (g)	40.21	Height of Top Sample (in)	0.991	Height of Bottom Sample (in)	0.981
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.367	Diameter of Bottom Sample (in)	2.359
Ring I.D. for Bottom Sample	R26	Wt. of Bottom Wet Sample + Ring (g)	166.82	Pan I.D. for Top Sample	DC-8
Wt. of Ring for Bottom Sample (g)	40.02	Height of Bottom Sample (in)	0.981	Wt. of Pan for Top Sample (g)	13.27
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.359	Wt. of Top Wet Sample + Ring + Pan (g)	179.84
Sample Container I.D.	C18	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.56
Wt. of Sample Container (g)	114.23	Wt. of Top Wet Sample + Ring (g)	166.57	Pan I.D. for Bottom Sample	KD-A
		Height of Top Sample (in)	0.991	Wt. of Pan for Bottom Sample (g)	15.50
		Diameter of Top Sample (in)	2.367	Wt. of Bottom Wet Sample + Ring + Pan (g)	182.11
				Wt. of Bottom Dry Sample + Ring + Pan (g)	178.38

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	126.36	126.59	126.48
Wt. of Dry Sample (g)	122.08	122.86	122.47
Wt. of Water (g)	4.28	3.73	4.00
Gravimetric Water Conten (%)	3.51	3.04	3.27
Volume of Sample (in^3)	4.36	4.29	4.32
Volumetric Water Content (%)	5.98	5.30	5.64

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	C1	C2	C4	C6	B8
Wt. of Cold Tare, T_c (g)	15.4262	15.3306	15.2145	15.3333	15.3072
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7848	15.6880	15.5668	15.5467	15.5167
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7700	15.6740	15.5532	15.5354	15.5069
Wt. of Hot Tare, T_h (g)	15.4219	15.3273	15.2114	15.3287	15.3037
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3481	0.3467	0.3418	0.2067	0.2032
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0105	0.0107	0.0105	0.0067	0.0063
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	3.02	3.09	3.07	3.24	3.10
Soil Suction (kPa)	152,045	149,780	150,240	118,712	121,753
Soil Suction (pF)	6.19	6.18	6.19	6.08	6.09

Table 4 Calculations of Soil Suction

Average Total Suction	150,688 (kPa)	6.19 (pF)
Average Matric Suction	120,232 (kPa)	6.09 (pF)
Osmotic Suction	30,456 (kPa)	5.49 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-3 (Top), PS-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	12/12/2005	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	1/7/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R20	Wt. of Top Wet Sample + Ring (g)	169.79	Wt. of Bottom Wet Sample + Ring (g)	169.48
Wt. of Ring for Top Sample (g)	40.21	Height of Top Sample (in)	0.995	Height of Bottom Sample (in)	0.987
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.380	Diameter of Bottom Sample (in)	2.374
Ring I.D. for Bottom Sample	R26	Wt. of Bottom Wet Sample + Ring (g)	169.88	Pan I.D. for Top Sample	DC-8
Wt. of Ring for Bottom Sample (g)	40.02	Height of Bottom Sample (in)	0.987	Wt. of Pan for Top Sample (g)	13.27
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.374	Wt. of Top Wet Sample + Ring + Pan (g)	182.76
Sample Container I.D.	C18	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.56
Wt. of Sample Container (g)	114.23	Wt. of Top Wet Sample + Ring (g)	169.49	Pan I.D. for Bottom Sample	KD-A
		Height of Top Sample (in)	0.995	Wt. of Pan for Bottom Sample (g)	15.50
		Diameter of Top Sample (in)	2.380	Wt. of Bottom Wet Sample + Ring + Pan (g)	184.98
				Wt. of Bottom Dry Sample + Ring + Pan (g)	178.38

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	129.28	129.46	129.37
Wt. of Dry Sample (g)	122.08	122.86	122.47
Wt. of Water (g)	7.20	6.60	6.90
Gravimetric Water Conten (%)	5.90	5.37	5.63
Volume of Sample (in^3)	4.43	4.37	4.40
Volumetric Water Content (%)	9.91	9.20	9.56

Table 3 Measurements of Soil Suction

Measurements	***Total or Matric Suction***				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	C3	B5	C6	C12	C9
Wt. of Cold Tare, T_c (g)	15.4610	15.2774	15.3345	15.4191	15.3673
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8209	15.6340	15.6971	15.6602	15.5916
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7979	15.6096	15.6724	15.6422	15.5764
Wt. of Hot Tare, T_h (g)	15.4594	15.2734	15.3308	15.4161	15.3648
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3385	0.3362	0.3416	0.2261	0.2116
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0214	0.0204	0.0210	0.0150	0.0127
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	6.32	6.07	6.15	6.63	6.00
Soil Suction (kPa)	74,741	78,936	77,595	64,594	72,352
Soil Suction (pF)	5.88	5.91	5.90	5.82	5.87

Table 4 Calculations of Soil Suction

Average Total Suction	77,090 (kPa)	5.90 (pF)
Average Matric Suction	68,473 (kPa)	5.84 (pF)
Osmotic Suction	8,617 (kPa)	4.94 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-3 (Top), PS-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	1/8/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	1/22/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R20	Wt. of Top Wet Sample + Ring (g)	173.12	Wt. of Bottom Wet Sample + Ring (g)	172.44
Wt. of Ring for Top Sample (g)	40.21	Height of Top Sample (in)	1.008	Height of Bottom Sample (in)	1.007
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.374	Diameter of Bottom Sample (in)	2.376
Ring I.D. for Bottom Sample	R26	Wt. of Bottom Wet Sample + Ring (g)	172.93	Pan I.D. for Top Sample	DC-8
Wt. of Ring for Bottom Sample (g)	40.02	Height of Bottom Sample (in)	1.007	Wt. of Pan for Top Sample (g)	13.27
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.376	Wt. of Top Wet Sample + Ring + Pan (g)	185.98
Sample Container I.D.	C18	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.56
Wt. of Sample Container (g)	114.23	Wt. of Top Wet Sample + Ring (g)	172.71	Pan I.D. for Bottom Sample	KD-A
		Height of Top Sample (in)	1.008	Wt. of Pan for Bottom Sample (g)	15.50
		Diameter of Top Sample (in)	2.374	Wt. of Bottom Wet Sample + Ring + Pan (g)	187.94
				Wt. of Bottom Dry Sample + Ring + Pan (g)	178.38

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	132.50	132.42	132.46
Wt. of Dry Sample (g)	122.08	122.86	122.47
Wt. of Water (g)	10.42	9.56	9.99
Gravimetric Water Conten (%)	8.54	7.78	8.16
Volume of Sample (in^3)	4.46	4.46	4.46
Volumetric Water Content (%)	14.23	13.04	13.64

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	C1	C2	C3	C4	C9
Wt. of Cold Tare, T_c (g)	15.4260	15.3302	15.4606	15.2144	15.3679
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8138	15.7182	15.8528	15.4665	15.6033
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7764	15.6810	15.8148	15.4402	15.5790
Wt. of Hot Tare, T_h (g)	15.4221	15.3259	15.4569	15.2125	15.3651
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3543	0.3551	0.3579	0.2277	0.2139
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0335	0.0329	0.0343	0.0244	0.0215
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	9.46	9.26	9.58	10.72	10.05
Soil Suction (kPa)	38,126	39,717	37,089	31,062	34,994
Soil Suction (pF)	5.59	5.61	5.58	5.50	5.55

Table 4 Calculations of Soil Suction

Average Total Suction	38,311 (kPa)	5.59 (pF)
Average Matric Suction	33,028 (kPa)	5.53 (pF)
Osmotic Suction	5,282 (kPa)	4.73 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-3 (Top), PS-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	1/24/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	3/14/2006	**Notes:**	Bottom sample is only 3/4 of normal height

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R20	Wt. of Top Wet Sample + Ring (g)	176.89	Wt. of Bottom Wet Sample + Ring (g)	141.63
Wt. of Ring for Top Sample (g)	40.21	Height of Top Sample (in)	1.021	Height of Bottom Sample (in)	0.760
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.420	Diameter of Bottom Sample (in)	2.420
Ring I.D. for Bottom Sample	R26	Wt. of Bottom Wet Sample + Ring (g)	142.45	Pan I.D. for Top Sample	DC-8
Wt. of Ring for Bottom Sample (g)	40.02	Height of Bottom Sample (in)	0.760	Wt. of Pan for Top Sample (g)	13.27
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.420	Wt. of Top Wet Sample + Ring + Pan (g)	189.67
Sample Container I.D.	C18	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.56
Wt. of Sample Container (g)	114.23	Wt. of Top Wet Sample + Ring (g)	176.40	Pan I.D. for Bottom Sample	DC-3
		Height of Top Sample (in)	1.021	Wt. of Pan for Bottom Sample (g)	13.25
		Diameter of Top Sample (in)	2.420	Wt. of Bottom Wet Sample + Ring + Pan (g)	154.88
				Wt. of Bottom Dry Sample + Ring + Pan (g)	144.55

Table 2 Calculations of Soil Sample Properties

Soil Property	***Top Sample***	***Bottom Sample***	***Average***
Wt. of Wet Sample (g)	136.19	101.61	118.90
Wt. of Dry Sample (g)	122.08	91.28	106.68
Wt. of Water (g)	14.11	10.33	12.22
Gravimetric Water Conten (%)	11.56	11.32	11.44
Volume of Sample (in^3)	4.70	3.50	4.10
Volumetric Water Content (%)	18.30	18.00	18.15

Table 3 Measurements of Soil Suction

Measurements	***Total or Matric Suction***				
	Total (Top)	***Total (Middle)***	***Total (Bottom)***	***Matric (Top)***	***Matric (Bottom)***
Moisture Tin I.D.	A1	B4	B5	C6	A11
Wt. of Cold Tare, T_c (g)	15.4177	15.3054	15.2774	15.3334	15.3184
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8223	15.7112	15.6765	15.5813	15.5726
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7698	15.6601	15.6257	15.5443	15.5350
Wt. of Hot Tare, T_h (g)	15.4136	15.3018	15.2735	15.3295	15.3146
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3562	0.3583	0.3522	0.2148	0.2204
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0484	0.0475	0.0469	0.0331	0.0338
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	13.59	13.26	13.32	15.41	15.34
Soil Suction (kPa)	15,691	16,847	16,634	13,384	13,563
Soil Suction (pF)	5.20	5.23	5.23	5.14	5.14

Table 4 Calculations of Soil Suction

Average Total Suction	16,391 (kPa)	5.22 (pF)
Average Matric Suction	13,473 (kPa)	5.14 (pF)
Osmotic Suction	2,917 (kPa)	4.47 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-3 (Top), PS-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	3/15/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	4/8/2006	**Notes:**	Bottom sample is only 3/4 of normal height

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R20	Wt. of Top Wet Sample + Ring (g)	183.87	Wt. of Bottom Wet Sample + Ring (g)	147.34
Wt. of Ring for Top Sample (g)	40.21	Height of Top Sample (in)	1.034	Height of Bottom Sample (in)	0.781
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R26	Wt. of Bottom Wet Sample + Ring (g)	148.01	Pan I.D. for Top Sample	DC-8
Wt. of Ring for Bottom Sample (g)	40.02	Height of Bottom Sample (in)	0.781	Wt. of Pan for Top Sample (g)	13.27
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	196.52
Sample Container I.D.	C18	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.56
Wt. of Sample Container (g)	114.23	Wt. of Top Wet Sample + Ring (g)	183.25	Pan I.D. for Bottom Sample	DC-3
		Height of Top Sample (in)	1.034	Wt. of Pan for Bottom Sample (g)	13.25
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	160.59
				Wt. of Bottom Dry Sample + Ring + Pan (g)	144.55

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	143.04	107.32	125.18
Wt. of Dry Sample (g)	122.08	91.28	106.68
Wt. of Water (g)	20.96	16.04	18.50
Gravimetric Water Conten (%)	17.17	17.57	17.37
Volume of Sample (in^3)	4.83	3.65	4.24
Volumetric Water Content (%)	26.45	26.80	26.63

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	A3	C7	C8	A9	B12
Wt. of Cold Tare, T_c (g)	15.2483	15.5127	15.4415	15.4894	15.2810
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.6871	15.9616	15.8848	15.7810	15.5597
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6005	15.8715	15.7992	15.7025	15.4934
Wt. of Hot Tare, T_h (g)	15.2432	15.5075	15.4398	15.4855	15.2769
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3573	0.3640	0.3594	0.2170	0.2165
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0815	0.0849	0.0839	0.0746	0.0622
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	22.81	23.32	23.34	34.38	28.73
Soil Suction (kPa)	2,164	1,938	1,929	446	1,227
Soil Suction (pF)	4.34	4.30	4.29	3.66	4.10

Table 4 Calculations of Soil Suction

Average Total Suction	2,010 (kPa)	4.31 (pF)
Average Matric Suction	1,227 (kPa)	4.10 (pF)
Osmotic Suction	783 (kPa)	3.90 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-3 (Top), PS-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	4/9/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	5/4/2006	**Notes:**	Bottom sample is only 3/4 of normal height

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R20	Wt. of Top Wet Sample + Ring (g)	187.50	Wt. of Bottom Wet Sample + Ring (g)	150.47
Wt. of Ring for Top Sample (g)	40.21	Height of Top Sample (in)	1.058	Height of Bottom Sample (in)	0.813
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R26	Wt. of Bottom Wet Sample + Ring (g)	151.70	Pan I.D. for Top Sample	DC-8
Wt. of Ring for Bottom Sample (g)	40.02	Height of Bottom Sample (in)	0.813	Wt. of Pan for Top Sample (g)	13.27
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	200.44
Sample Container I.D.	C18	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.56
Wt. of Sample Container (g)	114.23	Wt. of Top Wet Sample + Ring (g)	187.17	Pan I.D. for Bottom Sample	DC-3
		Height of Top Sample (in)	1.058	Wt. of Pan for Bottom Sample (g)	13.25
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	163.72
				Wt. of Bottom Dry Sample + Ring + Pan (g)	144.55

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	146.96	110.45	128.71
Wt. of Dry Sample (g)	122.08	91.28	106.68
Wt. of Water (g)	24.88	19.17	22.03
Gravimetric Water Conten (%)	20.38	21.00	20.69
Volume of Sample (in^3)	4.94	3.80	4.37
Volumetric Water Content (%)	30.69	30.77	30.73

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	C1	C2	A7	A10	B12
Wt. of Cold Tare, T_c (g)	15.4256	15.3305	15.4210	15.3545	15.2809
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8610	15.7691	15.8738	15.6533	15.6015
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7652	15.6729	15.7736	15.5687	15.5058
Wt. of Hot Tare, T_h (g)	15.4227	15.3275	15.4166	15.3508	15.2766
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3425	0.3454	0.3570	0.2179	0.2292
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0929	0.0932	0.0958	0.0809	0.0914
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	27.12	26.98	26.83	37.13	39.88
Soil Suction (kPa)	856	883	911	272	166
Soil Suction (pF)	3.94	3.95	3.97	3.44	3.23

Table 4 Calculations of Soil Suction

Average Total Suction	884	(kPa)	3.95	(pF)
Average Matric Suction	219	(kPa)	3.35	(pF)
Osmotic Suction	664	(kPa)	3.83	(pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-3 (Top), PS-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	72 Degrees F.
Time of Beginning:	5/6/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	5/27/2006	**Notes:**	Bottom sample is only 3/4 of normal height

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R20	Wt. of Top Wet Sample + Ring (g)	191.78	Wt. of Bottom Wet Sample + Ring (g)	153.40
Wt. of Ring for Top Sample (g)	40.21	Height of Top Sample (in)	1.071	Height of Bottom Sample (in)	0.831
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R26	Wt. of Bottom Wet Sample + Ring (g)	154.78	Pan I.D. for Top Sample	DC-8
Wt. of Ring for Bottom Sample (g)	40.02	Height of Bottom Sample (in)	0.831	Wt. of Pan for Top Sample (g)	13.27
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	204.47
Sample Container I.D.	C18	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.56
Wt. of Sample Container (g)	114.23	Wt. of Top Wet Sample + Ring (g)	191.20	Pan I.D. for Bottom Sample	DC-3
		Height of Top Sample (in)	1.071	Wt. of Pan for Bottom Sample (g)	13.25
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	166.65
				Wt. of Bottom Dry Sample + Ring + Pan (g)	144.55

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	150.99	113.38	132.19
Wt. of Dry Sample (g)	122.08	91.28	106.68
Wt. of Water (g)	28.91	22.10	25.51
Gravimetric Water Conten (%)	23.68	24.21	23.95
Volume of Sample (in^3)	5.00	3.88	4.44
Volumetric Water Content (%)	35.23	34.71	34.97

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B1	A3	C8	A9	C11
Wt. of Cold Tare, T_c (g)	15.3673	15.2479	15.4413	15.4894	15.3143
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8132	15.7305	15.9195	15.8713	15.6992
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7029	15.6071	15.7968	15.7022	15.5297
Wt. of Hot Tare, T_h (g)	15.3650	15.2440	15.4378	15.4845	15.3125
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3379	0.3631	0.3590	0.2177	0.2172
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.1080	0.1195	0.1192	0.1642	0.1677
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	31.96	32.91	33.20	75.42	77.21
Soil Suction (kPa)	303	97	63	25	23
Soil Suction (pF)	3.49	2.99	2.81	2.40	2.38

Table 4 Calculations of Soil Suction

Average Total Suction	154	(kPa)	3.20	(pF)
Average Matric Suction	24	(kPa)	2.39	(pF)
Osmotic Suction	130	(kPa)	3.12	(pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-3 (Top), PS-4 (Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	72 Degrees F.
Time of Beginning:	5/29/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	6/17/2006	**Notes:**	Bottom sample is only 3/4 of normal height

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		*Beginning of the Test:*		*End of the Test (continued):*	
Ring I.D. for Top Sample	R20	Wt. of Top Wet Sample + Ring (g)	199.80	Wt. of Bottom Wet Sample + Ring (g)	158.11
Wt. of Ring for Top Sample (g)	40.21	Height of Top Sample (in)	1.107	Height of Bottom Sample (in)	0.873
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R26	Wt. of Bottom Wet Sample + Ring (g)	159.49	Pan I.D. for Top Sample	DC-8
Wt. of Ring for Bottom Sample (g)	40.02	Height of Bottom Sample (in)	0.873	Wt. of Pan for Top Sample (g)	13.27
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	211.25
Sample Container I.D.	C18	*End of the Test:*		Wt. of Top Dry Sample + Ring + Pan (g)	175.56
Wt. of Sample Container (g)	114.23	Wt. of Top Wet Sample + Ring (g)	197.98	Pan I.D. for Bottom Sample	DC-3
		Height of Top Sample (in)	1.107	Wt. of Pan for Bottom Sample (g)	13.25
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	171.36
				Wt. of Bottom Dry Sample + Ring + Pan (g)	144.55

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	157.77	118.09	137.93
Wt. of Dry Sample (g)	122.08	91.28	106.68
Wt. of Water (g)	35.69	26.81	31.25
Gravimetric Water Conten (%)	29.23	29.37	29.30
Volume of Sample (in^3)	5.17	4.08	4.62
Volumetric Water Content (%)	42.08	40.08	41.08

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	D1	D4	D6	D7	D10
Wt. of Cold Tare, T_c (g)	15.3403	15.4035	15.4265	15.4487	15.4622
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8094	15.8826	15.9001	16.0122	16.0387
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6902	15.7627	15.7817	15.6622	15.6811
Wt. of Hot Tare, T_h (g)	15.3368	15.4007	15.4245	15.4460	15.4597
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3534	0.3620	0.3572	0.2162	0.2214
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.1157	0.1171	0.1164	0.3473	0.3551
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	32.74	32.35	32.59	160.64	160.39
Soil Suction (kPa)	124	221	156	2	2
Soil Suction (pF)	3.10	3.35	3.20	1.25	1.26

Table 4 Calculations of Soil Suction

Average Total Suction	140	(kPa)	3.15	(pF)
Average Matric Suction	2	(kPa)	1.25	(pF)
Osmotic Suction	138	(kPa)	3.15	(pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-5 (Top), PS-6(Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	11/9/2005	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	12/9/2005	**Notes:**	Air Dried Sample

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R25	Wt. of Top Wet Sample + Ring (g)	166.51	Wt. of Bottom Wet Sample + Ring (g)	166.56
Wt. of Ring for Top Sample (g)	40.26	Height of Top Sample (in)	0.993	Height of Bottom Sample (in)	0.989
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.370	Diameter of Bottom Sample (in)	2.376
Ring I.D. for Bottom Sample	R29	Wt. of Bottom Wet Sample + Ring (g)	166.77	Pan I.D. for Top Sample	DC-21
Wt. of Ring for Bottom Sample (g)	40.19	Height of Bottom Sample (in)	0.989	Wt. of Pan for Top Sample (g)	13.34
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.376	Wt. of Top Wet Sample + Ring + Pan (g)	179.66
Sample Container I.D.	C9	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.10
Wt. of Sample Container (g)	113.72	Wt. of Top Wet Sample + Ring (g)	166.32	Pan I.D. for Bottom Sample	DC-22
		Height of Top Sample (in)	0.993	Wt. of Pan for Bottom Sample (g)	13.35
		Diameter of Top Sample (in)	2.370	Wt. of Bottom Wet Sample + Ring + Pan (g)	179.91
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.87

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	126.06	126.37	126.22
Wt. of Dry Sample (g)	121.50	122.33	121.92
Wt. of Water (g)	4.56	4.04	4.30
Gravimetric Water Conten (%)	3.75	3.30	3.53
Volume of Sample (in^3)	4.38	4.39	4.38
Volumetric Water Content (%)	6.34	5.61	5.98

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	C3	4	B6	C8	C12
Wt. of Cold Tare, T_c (g)	15.4613	15.1709	15.3366	15.4412	15.5343
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8081	15.5240	15.6914	15.6570	15.7468
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7952	15.5105	15.6769	15.6477	15.7360
Wt. of Hot Tare, T_h (g)	15.4578	15.1680	15.3328	15.4386	15.5298
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3374	0.3425	0.3441	0.2091	0.2062
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0094	0.0106	0.0107	0.0067	0.0063
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	2.79	3.09	3.11	3.20	3.06
Soil Suction (kPa)	159,759	149,502	149,031	119,507	122,742
Soil Suction (pF)	6.21	6.18	6.18	6.09	6.10

Table 4 Calculations of Soil Suction

Average Total Suction	152,764 (kPa)	6.19 (pF)
Average Matric Suction	121,124 (kPa)	6.09 (pF)
Osmotic Suction	31,640 (kPa)	5.51 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-5 (Top), PS-6(Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	12/12/2005	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	1/7/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R25	Wt. of Top Wet Sample + Ring (g)	169.84	Wt. of Bottom Wet Sample + Ring (g)	169.70
Wt. of Ring for Top Sample (g)	40.26	Height of Top Sample (in)	0.997	Height of Bottom Sample (in)	0.993
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.385	Diameter of Bottom Sample (in)	2.389
Ring I.D. for Bottom Sample	R29	Wt. of Bottom Wet Sample + Ring (g)	170.00	Pan I.D. for Top Sample	DC-21
Wt. of Ring for Bottom Sample (g)	40.19	Height of Bottom Sample (in)	0.993	Wt. of Pan for Top Sample (g)	13.34
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.389	Wt. of Top Wet Sample + Ring + Pan (g)	182.76
Sample Container I.D.	C9	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.10
Wt. of Sample Container (g)	113.72	Wt. of Top Wet Sample + Ring (g)	169.42	Pan I.D. for Bottom Sample	DC-22
		Height of Top Sample (in)	0.997	Wt. of Pan for Bottom Sample (g)	13.35
		Diameter of Top Sample (in)	2.385	Wt. of Bottom Wet Sample + Ring + Pan (g)	183.05
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.87

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	129.16	129.51	129.34
Wt. of Dry Sample (g)	121.50	122.33	121.92
Wt. of Water (g)	7.66	7.18	7.42
Gravimetric Water Conten (%)	6.30	5.87	6.09
Volume of Sample (in^3)	4.45	4.45	4.45
Volumetric Water Content (%)	10.48	9.83	10.15

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B1	B2	A4	B8	A10
Wt. of Cold Tare, T_c (g)	15.3686	15.3229	15.4325	15.3069	15.3573
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7398	15.6867	15.7970	15.5482	15.6032
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7136	15.6628	15.7715	15.5311	15.5830
Wt. of Hot Tare, T_h (g)	15.3639	15.3200	15.4232	15.3039	15.3520
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3497	0.3428	0.3483	0.2272	0.2310
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0215	0.0210	0.0162	0.0141	0.0149
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	6.15	6.13	4.65	6.21	6.45
Soil Suction (kPa)	77,585	77,955	107,015	69,752	66,762
Soil Suction (pF)	5.90	5.90	6.04	5.85	5.83

Table 4 Calculations of Soil Suction

Average Total Suction	77,770	(kPa)	5.90	(pF)
Average Matric Suction	68,257	(kPa)	5.84	(pF)
Osmotic Suction	9,513	(kPa)	4.99	(pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-5 (Top), PS-6(Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	1/8/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	1/22/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R25	Wt. of Top Wet Sample + Ring (g)	173.07	Wt. of Bottom Wet Sample + Ring (g)	172.91
Wt. of Ring for Top Sample (g)	40.26	Height of Top Sample (in)	1.014	Height of Bottom Sample (in)	1.014
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.381	Diameter of Bottom Sample (in)	2.381
Ring I.D. for Bottom Sample	R29	Wt. of Bottom Wet Sample + Ring (g)	173.20	Pan I.D. for Top Sample	DC-21
Wt. of Ring for Bottom Sample (g)	40.19	Height of Bottom Sample (in)	1.014	Wt. of Pan for Top Sample (g)	13.34
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.381	Wt. of Top Wet Sample + Ring + Pan (g)	185.77
Sample Container I.D.	C9	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.10
Wt. of Sample Container (g)	113.72	Wt. of Top Wet Sample + Ring (g)	172.43	Pan I.D. for Bottom Sample	DC-22
		Height of Top Sample (in)	1.014	Wt. of Pan for Bottom Sample (g)	13.35
		Diameter of Top Sample (in)	2.381	Wt. of Bottom Wet Sample + Ring + Pan (g)	186.26
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.87

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	132.17	132.72	132.45
Wt. of Dry Sample (g)	121.50	122.33	121.92
Wt. of Water (g)	10.67	10.39	10.53
Gravimetric Water Conten (%)	8.78	8.49	8.64
Volume of Sample (in^3)	4.51	4.51	4.51
Volumetric Water Content (%)	14.40	14.02	14.21

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B1	A5	A6	B8	A8
Wt. of Cold Tare, T_c (g)	15.3661	15.1980	15.3397	15.3078	15.4337
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7565	15.5846	15.7275	15.5486	15.6708
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7165	15.5467	15.6884	15.5215	15.6436
Wt. of Hot Tare, T_h (g)	15.3620	15.1948	15.3356	15.3043	15.4293
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3545	0.3519	0.3528	0.2172	0.2143
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0359	0.0347	0.0350	0.0236	0.0228
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	10.13	9.86	9.92	10.87	10.64
Soil Suction (kPa)	33,003	34,946	34,499	30,239	31,492
Soil Suction (pF)	5.53	5.55	5.55	5.49	5.51

Table 4 Calculations of Soil Suction

Average Total Suction	34,149	(kPa)	5.54	(pF)
Average Matric Suction	30,866	(kPa)	5.50	(pF)
Osmotic Suction	3,284	(kPa)	4.52	(pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-5 (Top), PS-6(Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	1/24/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	3/14/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R25	Wt. of Top Wet Sample + Ring (g)	176.78	Wt. of Bottom Wet Sample + Ring (g)	176.61
Wt. of Ring for Top Sample (g)	40.26	Height of Top Sample (in)	1.034	Height of Bottom Sample (in)	1.026
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.420	Diameter of Bottom Sample (in)	2.420
Ring I.D. for Bottom Sample	R29	Wt. of Bottom Wet Sample + Ring (g)	176.96	Pan I.D. for Top Sample	DC-21
Wt. of Ring for Bottom Sample (g)	40.19	Height of Bottom Sample (in)	1.026	Wt. of Pan for Top Sample (g)	13.34
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.420	Wt. of Top Wet Sample + Ring + Pan (g)	189.33
Sample Container I.D.	C9	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.10
Wt. of Sample Container (g)	113.72	Wt. of Top Wet Sample + Ring (g)	175.99	Pan I.D. for Bottom Sample	DC-22
		Height of Top Sample (in)	1.034	Wt. of Pan for Bottom Sample (g)	13.35
		Diameter of Top Sample (in)	2.420	Wt. of Bottom Wet Sample + Ring + Pan (g)	189.96
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.87

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	135.73	136.42	136.08
Wt. of Dry Sample (g)	121.50	122.33	121.92
Wt. of Water (g)	14.23	14.09	14.16
Gravimetric Water Conten (%)	11.71	11.52	11.61
Volume of Sample (in^3)	4.76	4.72	4.74
Volumetric Water Content (%)	18.23	18.19	18.21

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	C1	A5	B7	C9	C10
Wt. of Cold Tare, T_c (g)	15.4268	15.1995	15.3275	15.3678	15.4247
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8335	15.6097	15.7322	15.6317	15.6879
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7800	15.5566	15.6810	15.5887	15.6468
Wt. of Hot Tare, T_h (g)	15.4222	15.1954	15.3247	15.3640	15.4219
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3578	0.3612	0.3563	0.2247	0.2249
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0489	0.0490	0.0484	0.0392	0.0383
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	13.67	13.57	13.58	17.45	17.03
Soil Suction (kPa)	15,427	15,765	15,704	9,290	10,009
Soil Suction (pF)	5.20	5.21	5.20	4.98	5.01

Table 4 Calculations of Soil Suction

Average Total Suction	15,632 (kPa)	5.20 (pF)
Average Matric Suction	9,649 (kPa)	4.99 (pF)
Osmotic Suction	5,983 (kPa)	4.79 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-5 (Top), PS-6(Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	3/15/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	4/9/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R25	Wt. of Top Wet Sample + Ring (g)	183.39	Wt. of Bottom Wet Sample + Ring (g)	183.88
Wt. of Ring for Top Sample (g)	40.26	Height of Top Sample (in)	1.054	Height of Bottom Sample (in)	1.037
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R29	Wt. of Bottom Wet Sample + Ring (g)	184.09	Pan I.D. for Top Sample	DC-21
Wt. of Ring for Bottom Sample (g)	40.19	Height of Bottom Sample (in)	1.037	Wt. of Pan for Top Sample (g)	13.34
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	195.77
Sample Container I.D.	C9	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.10
Wt. of Sample Container (g)	113.72	Wt. of Top Wet Sample + Ring (g)	182.43	Pan I.D. for Bottom Sample	DC-22
		Height of Top Sample (in)	1.054	Wt. of Pan for Bottom Sample (g)	13.35
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	197.23
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.87

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	142.17	143.69	142.93
Wt. of Dry Sample (g)	121.50	122.33	121.92
Wt. of Water (g)	20.67	21.36	21.02
Gravimetric Water Conten (%)	17.01	17.46	17.24
Volume of Sample (in^3)	4.92	4.84	4.88
Volumetric Water Content (%)	25.59	26.88	26.24

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	B1	C3	A6	B9	A10
Wt. of Cold Tare, T_c (g)	15.3676	15.4609	15.3406	15.3000	15.3556
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.7972	15.8983	15.7738	15.6022	15.6421
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7104	15.8105	15.6865	15.5223	15.5729
Wt. of Hot Tare, T_h (g)	15.3613	15.4556	15.3340	15.2949	15.3503
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3491	0.3549	0.3525	0.2274	0.2226
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0805	0.0825	0.0807	0.0748	0.0639
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	23.06	23.25	22.89	32.89	28.71
Soil Suction (kPa)	2,051	1,970	2,125	582	1,233
Soil Suction (pF)	4.32	4.30	4.34	3.77	4.10

Table 4 Calculations of Soil Suction

Average Total Suction	2,049 (kPa)	4.32 (pF)
Average Matric Suction	1,233 (kPa)	4.10 (pF)
Osmotic Suction	816 (kPa)	3.92 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-5 (Top), PS-6(Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	4/9/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	5/4/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R25	Wt. of Top Wet Sample + Ring (g)	187.50	Wt. of Bottom Wet Sample + Ring (g)	187.38
Wt. of Ring for Top Sample (g)	40.26	Height of Top Sample (in)	1.079	Height of Bottom Sample (in)	1.054
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R29	Wt. of Bottom Wet Sample + Ring (g)	187.70	Pan I.D. for Top Sample	DC-21
Wt. of Ring for Bottom Sample (g)	40.19	Height of Bottom Sample (in)	1.054	Wt. of Pan for Top Sample (g)	13.34
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	199.57
Sample Container I.D.	C9	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.10
Wt. of Sample Container (g)	113.72	Wt. of Top Wet Sample + Ring (g)	186.23	Pan I.D. for Bottom Sample	DC-22
		Height of Top Sample (in)	1.079	Wt. of Pan for Bottom Sample (g)	13.35
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	200.73
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.87

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	145.97	147.19	146.58
Wt. of Dry Sample (g)	121.50	122.33	121.92
Wt. of Water (g)	24.47	24.86	24.67
Gravimetric Water Conten (%)	20.14	20.32	20.23
Volume of Sample (in^3)	5.04	4.92	4.98
Volumetric Water Content (%)	29.60	30.78	30.19

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	A1	A4	C6	C8	C9
Wt. of Cold Tare, T_c (g)	15.4162	15.4253	15.3327	15.4405	15.3665
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8452	15.8562	15.7717	15.7349	15.6677
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7607	15.7690	15.6821	15.6570	15.5866
Wt. of Hot Tare, T_h (g)	15.4139	15.4216	15.3289	15.4378	15.3642
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3468	0.3474	0.3532	0.2192	0.2224
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.0822	0.0835	0.0858	0.0752	0.0788
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	23.70	24.04	24.29	34.31	35.43
Soil Suction (kPa)	1,786	1,663	1,574	451	369
Soil Suction (pF)	4.26	4.23	4.21	3.66	3.58

Table 4 Calculations of Soil Suction

Average Total Suction	1,680 (kPa)	4.23 (pF)
Average Matric Suction	410 (kPa)	3.62 (pF)
Osmotic Suction	1,270 (kPa)	4.11 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-5 (Top), PS-6(Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	72 Degrees F.
Time of Beginning:	5/6/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	5/27/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R25	Wt. of Top Wet Sample + Ring (g)	192.19	Wt. of Bottom Wet Sample + Ring (g)	191.75
Wt. of Ring for Top Sample (g)	40.26	Height of Top Sample (in)	1.096	Height of Bottom Sample (in)	1.070
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R29	Wt. of Bottom Wet Sample + Ring (g)	192.65	Pan I.D. for Top Sample	DC-21
Wt. of Ring for Bottom Sample (g)	40.19	Height of Bottom Sample (in)	1.070	Wt. of Pan for Top Sample (g)	13.34
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	204.44
Sample Container I.D.	C9	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.10
Wt. of Sample Container (g)	113.72	Wt. of Top Wet Sample + Ring (g)	191.10	Pan I.D. for Bottom Sample	DC-22
		Height of Top Sample (in)	1.096	Wt. of Pan for Bottom Sample (g)	13.35
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	205.10
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.87

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	150.84	151.56	151.20
Wt. of Dry Sample (g)	121.50	122.33	121.92
Wt. of Water (g)	29.34	29.23	29.29
Gravimetric Water Conten (%)	24.15	23.89	24.02
Volume of Sample (in^3)	5.12	5.00	5.06
Volumetric Water Content (%)	34.94	35.65	35.29

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	A1	C3	A4	A11	A12
Wt. of Cold Tare, T_c (g)	15.4166	15.4605	15.4255	15.3176	15.3970
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8670	15.9348	15.9072	15.6979	15.7798
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.7540	15.8109	15.7793	15.5326	15.6136
Wt. of Hot Tare, T_h (g)	15.4113	15.4564	15.4208	15.3144	15.3953
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3427	0.3545	0.3585	0.2182	0.2183
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.1077	0.1198	0.1232	0.1621	0.1645
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	31.43	33.79	34.37	74.29	75.36
Soil Suction (kPa)	340	26	11	26	25
Soil Suction (pF)	3.54	2.43	2.06	2.42	2.40

Table 4 Calculations of Soil Suction

Average Total Suction	126 (kPa)	3.11 (pF)
Average Matric Suction	25 (kPa)	2.41 (pF)
Osmotic Suction	101 (kPa)	3.01 (pF)

FILTER PAPER TEST DATA SHEET

Sample Source:	Kim Project	**Sample I.D.:**	PS-5 (Top), PS-6(Bottom)
Soil Type:	Claystone	**Geological Formation:**	Pierre Shale
Solution Type:	DI Water	**Room Temperature:**	72 Degrees F.
Time of Beginning:	5/29/2006	**Filter Paper Type:**	Whatman No. 42
Time of Completion:	6/17/2006	**Notes:**	

Table 1 Summary of Sample and Equipment Information

Steel Rings and Sample Container:		***Beginning of the Test:***		***End of the Test (continued):***	
Ring I.D. for Top Sample	R25	Wt. of Top Wet Sample + Ring (g)	199.85	Wt. of Bottom Wet Sample + Ring (g)	198.77
Wt. of Ring for Top Sample (g)	40.26	Height of Top Sample (in)	1.126	Height of Bottom Sample (in)	1.123
Ring Diameter for Top Sample (in)	2.438	Diameter of Top Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438
Ring I.D. for Bottom Sample	R29	Wt. of Bottom Wet Sample + Ring (g)	200.25	Pan I.D. for Top Sample	DC-21
Wt. of Ring for Bottom Sample (g)	40.19	Height of Bottom Sample (in)	1.123	Wt. of Pan for Top Sample (g)	13.34
Ring Diameter for Bottom Sample (in)	2.438	Diameter of Bottom Sample (in)	2.438	Wt. of Top Wet Sample + Ring + Pan (g)	211.57
Sample Container I.D.	C9	***End of the Test:***		Wt. of Top Dry Sample + Ring + Pan (g)	175.10
Wt. of Sample Container (g)	113.72	Wt. of Top Wet Sample + Ring (g)	198.23	Pan I.D. for Bottom Sample	DC-22
		Height of Top Sample (in)	1.126	Wt. of Pan for Bottom Sample (g)	13.35
		Diameter of Top Sample (in)	2.438	Wt. of Bottom Wet Sample + Ring + Pan (g)	212.12
				Wt. of Bottom Dry Sample + Ring + Pan (g)	175.87

Table 2 Calculations of Soil Sample Properties

Soil Property	*Top Sample*	*Bottom Sample*	*Average*
Wt. of Wet Sample (g)	157.97	158.58	158.28
Wt. of Dry Sample (g)	121.50	122.33	121.92
Wt. of Water (g)	36.47	36.25	36.36
Gravimetric Water Conten (%)	30.02	29.63	29.82
Volume of Sample (in^3)	5.26	5.24	5.25
Volumetric Water Content (%)	42.27	42.13	42.20

Table 3 Measurements of Soil Suction

Measurements	*Total or Matric Suction*				
	Total (Top)	*Total (Middle)*	*Total (Bottom)*	*Matric (Top)*	*Matric (Bottom)*
Moisture Tin I.D.	D2	D5	D8	D16	D29
Wt. of Cold Tare, T_c (g)	15.3341	15.3079	15.4149	15.2789	15.4337
Wt. of Wet Filter Paper + Cold Tare, M_1 (g)	15.8155	15.7817	15.8905	15.8380	16.0243
Wt. of Dry Filter Paper + Hot Tare, M_2 (g)	15.6930	15.6604	15.7675	15.4951	15.6559
Wt. of Hot Tare, T_h (g)	15.3328	15.3045	15.4122	15.2771	15.4317
Wt. of Dry Filter Paper, $M_f = (M_2 - T_h)$ (g)	0.3602	0.3559	0.3553	0.2180	0.2242
Wt. of Water in Filter Paper, $M_w = (M_1 - M_2 - T_c + T_h)$ (g)	0.1212	0.1179	0.1203	0.3411	0.3664
Water Content of Filter Paper, $W_f = (M_w / M_f)$ (%)	33.65	33.13	33.86	156.47	163.43
Soil Suction (kPa)	33	70	24	2	2
Soil Suction (pF)	2.52	2.86	2.39	1.31	1.21

Table 4 Calculations of Soil Suction

Average Total Suction	42 (kPa)	2.64 (pF)
Average Matric Suction	2 (kPa)	1.26 (pF)
Osmotic Suction	41 (kPa)	2.62 (pF)

APPENDIX E

FREDLUND SWCC TEST DATA WORKSHEETS

APPENDIX E.1

SOIL WATER CHARACTERISTIC CURVE

SWCC TEST DATA SHEET

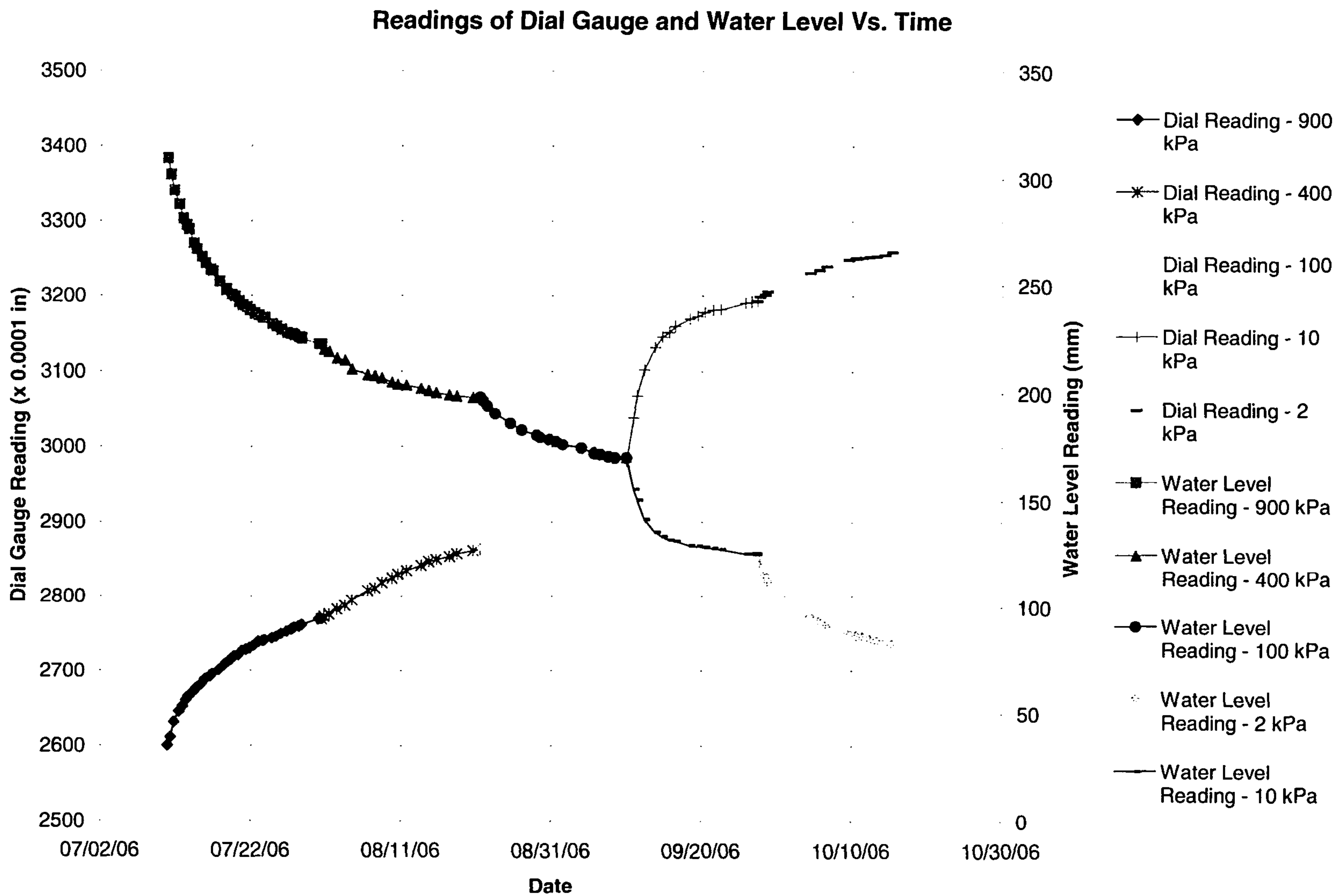
Sample Source:	Russell Project	**Sample I.D.:**	D-21
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
SWCC Curve Type:	Wetting Curve	**Target Suction:**	900, 400, 100, 10, 2 kPa
Date of Testing:	7/10/2006	**Notes:**	Air-Dried Condition at Beginning

Steel Ring:		*Beginning of the Test:*		*End of the Test:*	
Ring I.D.	R2	Wt. of Wet Sample + Ring (g)	397.37	Wt. of Wet Sample + Ring + CS (g)	568.60
Wt. of Ring (g)	264.57	Height of Sample (in)	0.995	Pan I.D.	DC-2
Ring Diameter (in)	2.498	Diameter of Sample (in)	2.419	Wt. of Pan (g)	13.28
				Wt. of Wet Sample + Pan (g)	175.02
				Wt. of Dry Sample + Pan (g)	135.85
Ceramic Stone (CS):		*Overburden:*		*Notes:*	
I.D. / Rating	15 bar	Applied Overburden Pressure (kPa)	-		
Initial Wt. of SSD CS (g)	144.72	Diameter of Metal Plate (in)	-		
Final Wt. of SSD CS (g)	144.70	Friction Compensat. (lbf)	-		

Applied Suction (kPa)	Date/Clock Time	Dial Gauage Reading (x 0.0001 in)	Water Level Reading: Left Column (mm)	Water Level Reading: Right Column (mm)
900	7/10/2006 22:08	2600	197	197
	7/11/2006 7:29	2611	189.5	189.5
	7/11/2006 18:50	2631	182	182
	7/12/2006 10:07	2645	175.5	175.5
	7/12/2006 23:54	2652	169	169
	7/13/2006 9:56	2660	166	166
	7/13/2006 17:07	2665	164	164
	7/14/2006 8:57	2671	157.5	157.5
	7/14/2006 18:24	2676	154.5	154.5
	7/15/2006 11:12	2682	151	151
	7/15/2006 22:05	2688	148	148
	7/16/2006 12:38	2692	145	145
	7/16/2006 19:55	2695	144.5	144.5
	7/17/2006 17:41	2701	139.5	139.5
	7/18/2006 14:57	2709	136	136
	7/19/2006 8:25	2715	133.5	133.5
	7/19/2006 18:42	2719	132.5	132.5
	7/20/2006 7:51	2721	130	130
	7/20/2006 19:31	2726	128.5	128.5
	7/21/2006 9:27	2728	127.5	127.5
	7/21/2006 18:55	2730	126	126
	7/22/2006 10:17	2734	124.5	124.5

Applied Suction (kPa)	Date/Clock Time	Dial Gauage Reading (x 0.0001 in)	Water Level Reading Left Column (mm)	Water Level Reading Right Column (mm)
900	7/22/2006 23:30	2738	123.5	123.5
	7/23/2006 13:04	2739	122.5	122.5
	7/23/2006 19:08	2740	122.5	122.5
	7/24/2006 18:58	2743	119.5	119.5
	7/25/2006 7:58	2745	118.5	118.5
	7/25/2006 23:32	2749	117	117
	7/26/2006 17:52	2752	115.5	115.5
	7/27/2006 9:21	2755	115	115
	7/27/2006 16:57	2757	114.5	114.5
	7/28/2006 8:53	2759	113.5	113.5
	7/28/2006 17:04	2761	113	113
	7/30/2006 23:58	2769	110.5	110.5
	7/31/2006 9:12	2769	110.5	110.5
400	7/31/2006 9:25	2769	185	185
	7/31/2006 17:13	2772	182.5	182.5
	8/1/2006 8:56	2775	181.5	181.5
	8/2/2006 9:34	2782	178.5	178.5
	8/3/2006 11:13	2787	177.5	177.5
	8/4/2006 9:28	2794	173.5	173.5
	8/6/2006 11:41	2808	171	171
	8/7/2006 10:37	2811	170.5	170.5
	8/8/2006 9:23	2819	169.5	169.5
	8/9/2006 17:17	2825	167.5	167.5
	8/10/2006 12:03	2830	166.5	166.5
	8/11/2006 16:04	2835	166	166
	8/13/2006 14:00	2842	164.5	164.5
	8/14/2006 14:43	2847	163.5	163.5
	8/15/2006 14:12	2850	162.5	162.5
	8/17/2006 9:00	2854	161.5	161.5
	8/18/2006 8:17	2858	161	161
	8/20/2006 13:06	2862	160.5	160.5
	8/21/2006 11:34	2864	160.5	160.5
100	8/21/2006 11:37	2864	198	198
	8/21/2006 20:08	2872	196.5	196.5
	8/22/2006 10:12	2880	194	194
	8/23/2006 9:42	2889	190.5	190.5
	8/25/2006 10:45	2908	186	186
	8/26/2006 22:30	2920	183	183
	8/28/2006 22:30	2930	180.5	180.5
	8/29/2006 9:34	2938	179.5	179.5
	8/30/2006 13:50	2942	178.5	178.5
	8/31/2006 12:25	2949	177.5	177.5
	9/1/2006 9:29	2952	176	176

Applied Suction (kPa)	Date/Clock Time	Dial Gauage Reading (x 0.0001 in)	Water Level Reading Left Column (mm)	Right Column (mm)
100	9/3/2006 21:35	2965	174.5	174.5
	9/5/2006 14:05	2971	172	172
	9/6/2006 9:45	2972	171.5	171.5
	9/7/2006 12:47	2975	170.5	170.5
	9/8/2006 8:39	2978	170	170
	9/9/2006 21:43	2980	170	170
10	9/9/2006 21:45	2980	170	170
	9/10/2006 20:49	3039	155.5	155.5
	9/11/2006 8:36	3068	150.5	150.5
	9/12/2006 7:46	3103	141.5	141.5
	9/13/2006 18:16	3132	135.5	135.5
	9/14/2006 17:15	3146	133.5	133.5
	9/15/2006 14:47	3152	132	132
	9/16/2006 9:57	3160	131.5	131.5
	9/18/2006 8:42	3170	129.5	129.5
	9/19/2006 9:55	3173	129	129
	9/20/2006 8:55	3178	128.5	128.5
	9/21/2006 10:50	3181	128	128
	9/22/2006 11:15	3182	127.5	127.5
	9/25/2006 17:58	3191	125.5	125.5
	9/26/2006 13:35	3192	125.5	125.5
	9/27/2006 8:43	3193	125.5	125.5
2	9/27/2006 8:45	3193	125.5	125.5
	9/27/2006 16:41	3199	121	121
	9/28/2006 8:38	3202	115.5	115.5
	9/28/2006 16:26	3206	112.5	112.5
	10/4/2006 8:56	3231	96	96
	10/5/2006 14:12	3235	93.5	93.5
	10/6/2006 12:45	3240	91.5	91.5
	10/9/2006 13:00	3248	87.5	87.5
	10/10/2006 13:16	3250	86.5	86.5
	10/11/2006 8:47	3251	86	86
	10/12/2006 8:41	3252	85	85
	10/13/2006 8:40	3253	84	84
	10/14/2006 10:45	3255	83	83
	10/15/2006 10:16	3259	82.5	82.5



Readings of Dial Gauge and Water Level Vs. Time
3500
3400
3300
3200
3100
3000
2900
2800
2700
2600
2500
Dial Gauge Reading (x 0.0001 in)
350
300
250
200
150
100
50
0
Water Level Reading (mm)
07/02/06
07/22/06
08/11/06
08/31/06
09/20/06
10/10/06
10/30/06
Date
Dial Reading - 900 kPa
Dial Reading - 400 kPa
Dial Reading - 100 kPa
Dial Reading - 10 kPa
Dial Reading - 2 kPa
Water Level Reading - 900 kPa
Water Level Reading - 400 kPa
Water Level Reading - 100 kPa
Water Level Reading - 2 kPa
Water Level Reading - 10 kPa

CALCULATIONS OF WETTING CURVE DATA

Project Name:	Russell Project	**Project No.:**	D-21
Sample I.D.:	Claystone	**Station I.D.**	Denver Formation
SWCC Curve Type:	Wetting Curve	**Target Suction:**	900, 400, 100, 10, 2 kPa

(I) Initial Soil Conditions:

Wt. of Wet Sample + Ring (g)	Wt. of Ring (g)	Wt. of Wet Sample (g)	Wt. of Dry Sample + Pan (g)	Wt. of Pan (g)	Wt. of Dry Sample (g)	Initial Wt. of Water (g)	Initial Gravimetric Water Content (%)	Initial Sample Diameter (in)	Initial Height of Sample (in)	Initial Volume of Sample (in^3)	Initial Volumetric Water Content (%)	Initial Wet Density (pcf)	Initial Dry Density (pcf)	Specific Gravity	Initial Degree of Saturation (%)
397.37	264.57	132.8	135.85	13.28	122.57	10.23	8.35	2.419	0.995	4.573	13.63	110.4	101.9	2.76	33.38

(II) Soil Conditions at Equilibrium:

Applied Suction	Applied Suction	Initial Water Level Reading			Final Water Level Reading			Water Absorbed at Each Tube	Total Water Absorbed at Each Pressure	Total Water Absorbed [1]	Initial Wt. of SSD CS	Final Wt. of SSD CS	Water Adsorbed by / Released from CS [2]	Wt. of Water at Equilibrium	Gravimetric Water Content at Equilibrium
(kPa)	(psf)	Left Column (mm)	Right Column (mm)	Average (mm)	Left Column (mm)	Right Column (mm)	Average (mm)	(mm)	(mm)	(g)	(g)	(g)	(g)	(g)	(%)
900	18,797	197	197	197	110.5	110.5	110.5	86.5	173	11.1				21.3	17.38
400	8,354	185	185	185	160.5	160.5	160.5	24.5	49	14.2				24.4	19.93
100	2,089	198	198	198	170	170	170	28	56	17.8	144.72	144.70	0.02	28.0	22.85
10	209	170	170	170	125.5	125.5	125.5	44.5	89	23.4				33.7	27.49
2	42	125.5	125.5	125.5	82.5	82.5	82.5	43	86	28.9				39.2	31.97

Applied Suction (kPa)	Applied Suction (psf)	Initial Dial Reading (x 0.0001 in)	Dial Reading at Equilibrium (x 0.0001 in)	Change of Sample Height [3] (in)	Height of Sample at Equilibrium (in)	Estimated Diameter of Sample (in)	Volume of Sample at Equilibrium (in^3)	Volumetric Water Content at Equilibrium (%)	Dry Density at Equilibrium (pcf)	Degree of Saturation at Equilibrium (%)
900	18,797		2769	0.017	1.012	2.420	4.654	27.88	100.1	66.60
400	8,354		2864	0.026	1.021	2.440	4.776	31.17	97.6	71.89
100	2,089	2600	2980	0.038	1.033	2.470	4.950	34.48	94.1	76.04
10	209		3193	0.059	1.054	2.498	5.167	39.73	90.2	83.40
2	42		3259	0.066	1.061	2.498	5.199	45.92	89.6	95.74

(III) Final Soil Conditions:

Wt. of Wet Sample + Pan (g)	Wt. of Pan (g)	Wt. of Wet Sample (g)	Final Wt. of Water (g)	Final Gravimetric Water Content (%)
175.0	13.3	161.7	39.2	31.96

Notes: (1) Calibrated factor of water in the volume tubes: 1 grams of water = 15.653 mm of water in the volume tube

(2) Negative value means water adsorbed by SSD CS, positive value means water released from SSD CS

(3) Negative value means sample height decreases, positive value means sample height increases

APPENDIX E.2

WATER CONTENT AND SWELL POTENTIAL RELATIONSHIP

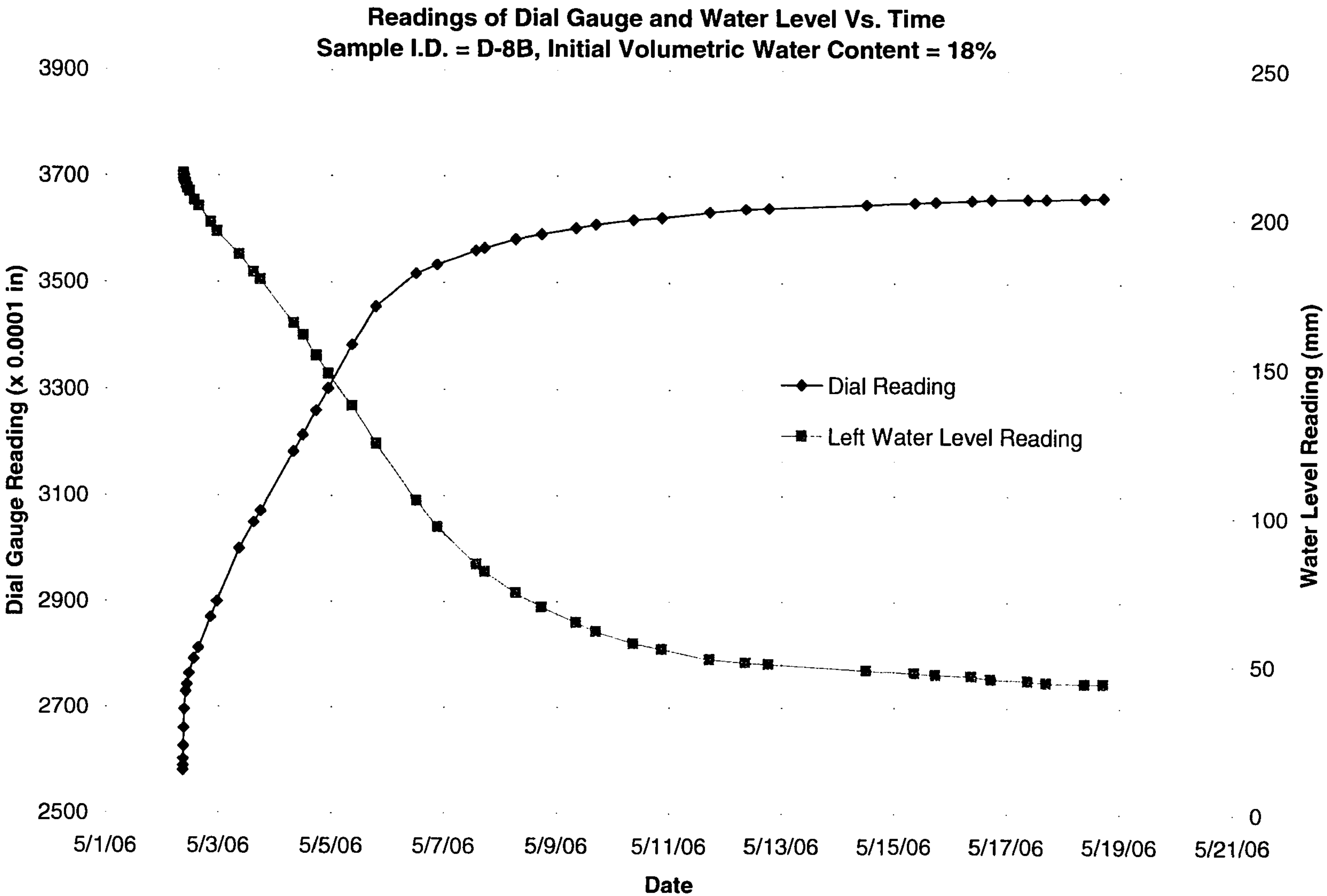
SWELL POTENTIAL VS. WATER CONTENT TEST DATA SHEET

Sample Source:	Russell Project	**Sample I.D.:**	D-8B
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	5/2/2006	**Time of Completion:**	5/18/2006

Steel Ring:		***Overburden:***		***End of the Test:***	
Ring I.D.	R1	Applied Overburden Pressure (kPa)	0	Wt. of Sat. Sample + Ring + CS (g)	567.64
Wt. of Ring (g)	253.04	Pressure from Equipment Weight (kPa)	6.30	Pan I.D.	DC-24
Ring Diameter (in)	2.498	Friction from Equipment (kPa)	2.8	Wt. of Pan (g)	13.26
Ring Height (in)	1.215	Total Overburden *Pressure* (kPa)	9.10	Wt. of Sat. Sample + Pan (g)	182.74
Spacer Height (in)	0.197			Wt. of Dry Sample + Pan (g)	140.15
Ceramic Stone (CS):		***Beginning of the Test:***		***Notes:***	
I.D. / Rating	15 bar	Wt. of Wet Sample + Ring (g)	395.61		
Initial Wt. of SSD CS (g)	144.68	Height of Sample (in)	1.018		
Final Wt. of SSD CS (g)	144.66				

Applied Suction (kPa)	Date/Clock Time	Elapsed Time (min)	Dial Gauage Reading (x 0.0001 in)	Water Level Reading Left Column (mm)	Water Level Reading Right Column (mm)
4	5/2/2006 8:47	σ'_{token}	2580		
	5/2/2006 8:48	σ_i'	2580		
	5/2/2006 8:55	0	2580	215	215
	5/2/2006 8:56	1	2589	214.5	214.5
	5/2/2006 8:59	2	2602	214	214
	5/2/2006 9:03	4	2627	214	214
	5/2/2006 9:12	8	2661	213.5	213.5
	5/2/2006 9:23	15	2695	213	213
	5/2/2006 9:58	30	2729	211.5	211.5
	5/2/2006 10:30	60	2742	210	210
	5/2/2006 11:36	120	2763	209	209
	5/2/2006 13:35	240	2791	206	206
	5/2/2006 15:32	480	2812	204	204
	5/2/2006 20:39	960	2870	198.5	198.5
	5/2/2006 23:18		2900	195.5	195.5
	5/3/2006 8:40		2999	188	188
	5/3/2006 14:54		3049	182	182
	5/3/2006 17:45		3071	179.5	179.5
	5/4/2006 7:59		3183	165	165
	5/4/2006 11:53		3213	161	161
	5/4/2006 17:28		3259	154	154
	5/4/2006 22:26		3302	148	148

Applied Suction (kPa)	Date/Clock Time	Elapsed Time (min)	Dial Gauage Reading (x 0.0001 in)	Water Level Reading	
				Left Column (mm)	Right Column (mm)
4	5/5/2006 8:41		3383	137	137
	5/5/2006 18:59		3455	124.5	124.5
	5/6/2006 12:08		3517	105.5	105.5
	5/6/2006 21:04		3534	96.5	95.5
	5/7/2006 13:41		3561	84	84
	5/7/2006 17:16		3566	81.5	81.5
	5/8/2006 6:35		3582	74.5	74.5
	5/8/2006 17:30		3591	69.5	69.5
	5/9/2006 8:08		3602	64.5	64.5
	5/9/2006 16:46		3609	61.5	61.5
	5/10/2006 8:40		3618	57.5	57.5
	5/10/2006 20:53		3622	55.5	55.5
	5/11/2006 17:19		3632	52	52
	5/12/2006 8:40		3638	51	51
	5/12/2006 18:22		3640	50.5	50.5
	5/14/2006 12:07		3648	48.5	48.5
	5/15/2006 8:42		3651	47.5	47.5
	5/15/2006 17:34		3653	47	47
	5/16/2006 8:46		3656	46.5	46.5
	5/16/2006 17:06		3658	45.5	45.5
	5/17/2006 8:41		3659	45	45
	5/17/2006 16:34		3660	44.5	44.5
	5/18/2006 8:53		3661	44	44
	5/18/2006 16:49		3662	44	44


Readings of Dial Gauge and Water Level Vs. Time
Sample I.D. = D-8B, Initial Volumetric Water Content = 18%
Dial Gauge Reading (x 0.0001 in)
3900
3700
3500
3300
3100
2900
2700
2500
Water Level Reading (mm)
250
200
150
100
50
0
Dial Reading
Left Water Level Reading
5/1/06
5/3/06
5/5/06
5/7/06
5/9/06
5/11/06
5/13/06
5/15/06
5/17/06
5/19/06
5/21/06
Date

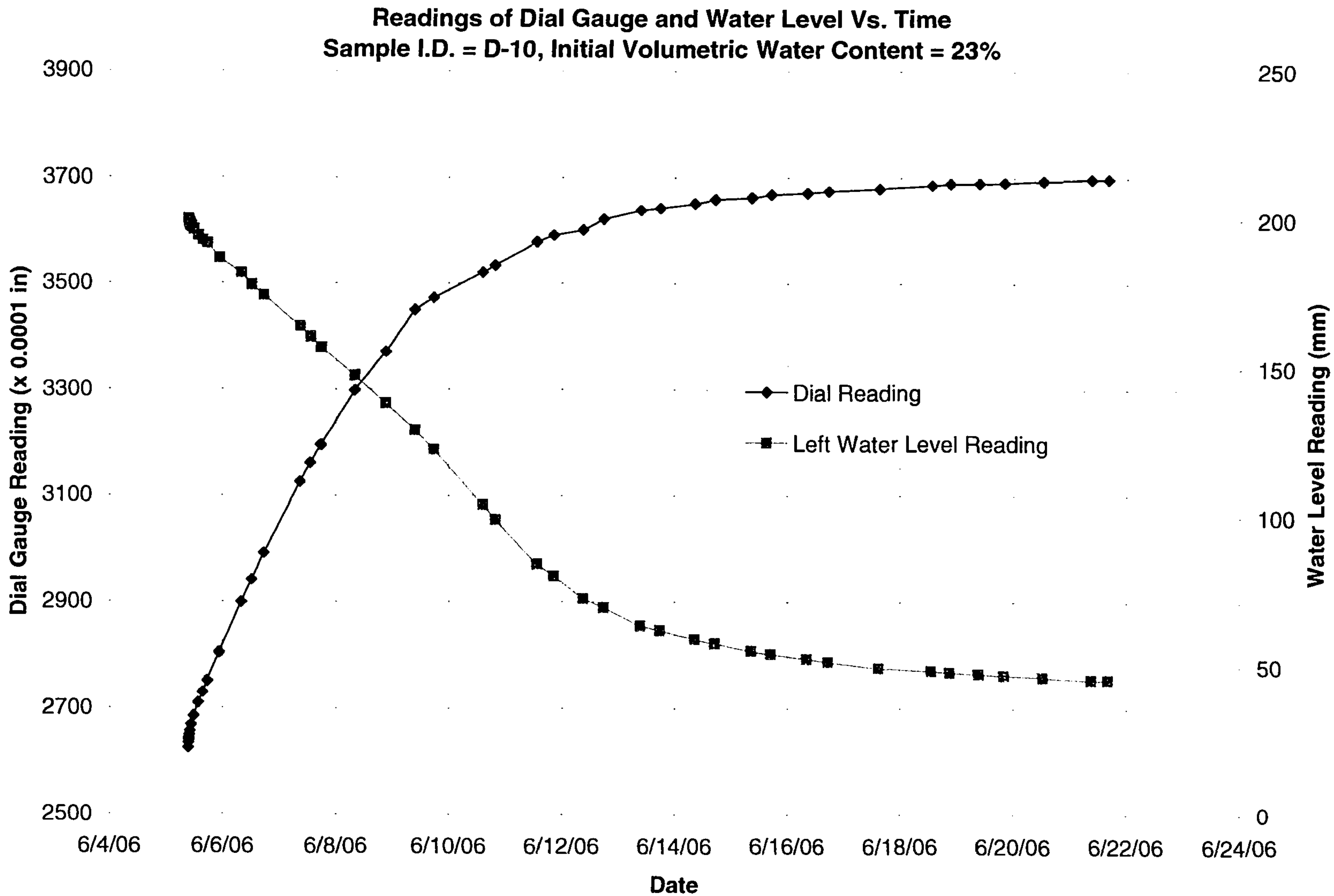
SWELL POTENTIAL VS. WATER CONTENT TEST DATA SHEET

Sample Source:	Russell Project	**Sample I.D.:**	D-10
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	6/5/2006	**Time of Completion:**	6/21/2006

Steel Ring:		***Overburden:***		***End of the Test:***	
Ring I.D.	R1	Applied Overburden Pressure (kPa)	0	Wt. of Sat. Sample + Ring + CS (g)	565.35
Wt. of Ring (g)	253.04	Pressure from Equipment Weight (kPa)	6.30	Pan I.D.	KD-4
Ring Diameter (in)	2.498	Friction from Equipment (kPa)	2.80	Wt. of Pan (g)	15.38
Ring Height (in)	1.215	Total Overburden Pressure (kPa)	9.10	Wt. of Sat. Sample + Pan (g)	182.72
Spacer Height (in)	0.197			Wt. of Dry Sample + Pan (g)	143.36
Ceramic Stone (CS):		***Beginning of the Test:***		***Notes:***	
I.D. / Rating	15 bar	Wt. of Wet Sample + Ring (g)	399.91		
Initial Wt. of SSD CS (g)	144.65	Height of Sample (in)	1.018		
Final Wt. of SSD CS (g)	144.58				

Applied Suction (kPa)	Date/Clock Time	Elapsed Time (min)	Dial Gauage Reading (x 0.0001 in)	Water Level Reading Left Column (mm)	Water Level Reading Right Column (mm)
4	6/5/2006 9:15	σ'_{token}	2625		
	6/5/2006 9:20	σ_i'	2625		
	6/5/2006 9:21	0	2625	200	200
	6/5/2006 9:25	1	2635	199.5	199.5
	6/5/2006 9:32	2	2641	199	199
	6/5/2006 9:36	4	2643	199	199
	6/5/2006 9:50	8	2649	198.5	198.5
	6/5/2006 10:03	15	2656	198	198
	6/5/2006 10:35	30	2668	197.5	197.5
	6/5/2006 11:37	60	2685	196.5	196.5
	6/5/2006 13:34	120	2710	194.5	194.5
	6/5/2006 15:26	240	2730	193	193
	6/5/2006 17:26	480	2751	192	192
	6/5/2006 22:37	960	2805	187	187
	6/6/2006 7:53		2899	182	182
	6/6/2006 12:17		2941	178	178
	6/6/2006 17:26		2991	174.5	174.5
	6/7/2006 8:55		3125	164	164
	6/7/2006 13:14		3161	160.5	160.5
	6/7/2006 17:38		3195	157	157
	6/8/2006 7:55		3298	147.5	147.5
	6/8/2006 21:02		3371	138	138
	6/9/2006 9:34		3450	129	129
	6/9/2006 17:35		3473	122.5	122.5
	6/10/2006 14:30		3521	104	104

Applied Suction (kPa)	Date/Clock Time	Elapsed Time (min)	Dial Gauage Reading (x 0.0001 in)	Water Level Reading Left Column (mm)	Right Column (mm)
4	6/10/2006 19:50		3535	99	99
	6/11/2006 13:27		3578	84	84
	6/11/2006 20:28		3591	80	80
	6/12/2006 8:59		3601	72.5	72.5
	6/12/2006 17:47		3621	69.5	69.5
	6/13/2006 9:31		3638	63.5	63.5
	6/13/2006 17:49		3642	62	62
	6/14/2006 8:41		3651	59	59
	6/14/2006 17:20		3658	57.5	57.5
	6/15/2006 8:50		3662	55	55
	6/15/2006 16:57		3668	54	54
	6/16/2006 8:17		3671	52.5	52.5
	6/16/2006 17:23		3675	51.5	51.5
	6/17/2006 14:54		3680	49.5	49.5
	6/18/2006 13:21		3686	48.5	48.5
	6/18/2006 21:14		3689	48	48
	6/19/2006 9:23		3690	47.5	47.5
	6/19/2006 19:58		3691	47	47
	6/20/2006 12:27		3695	46.5	46.5
	6/21/2006 9:00		3698	45.5	45.5
	6/21/2006 16:14		3698	45.5	45.5


Readings of Dial Gauge and Water Level Vs. Time
Sample I.D. = D-10, Initial Volumetric Water Content = 23%
3900
3700
3500
3300
3100
2900
2700
2500
Dial Gauge Reading (x 0.0001 in)
250
200
150
100
50
0
Water Level Reading (mm)
Dial Reading
Left Water Level Reading
6/4/06
6/6/06
6/8/06
6/10/06
6/12/06
6/14/06
6/16/06
6/18/06
6/20/06
6/22/06
6/24/06
Date

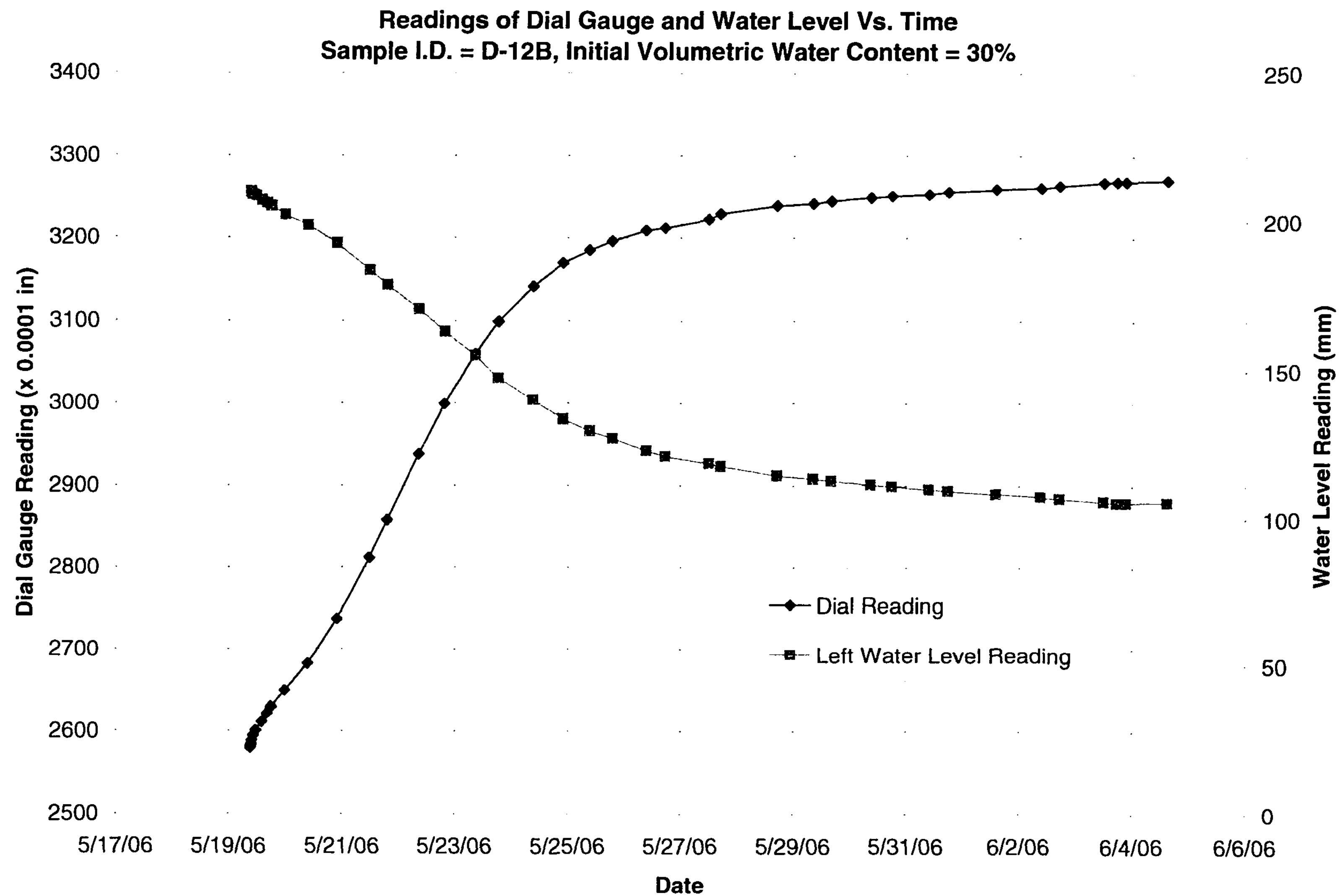
SWELL POTENTIAL VS. WATER CONTENT TEST DATA SHEET

Sample Source:	Russell Project	**Sample I.D.:**	D-12B
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	5/19/2006	**Time of Completion:**	6/4/2006

Steel Ring:		***Overburden:***		***End of the Test:***	
Ring I.D.	R1	Applied Overburden Pressure (kPa)	0	Wt. of Sat. Sample + Ring + CS (g)	563.15
Wt. of Ring (g)	253.04	Pressure from Equipment Weight (kPa)	6.30	Pan I.D.	KD29
Ring Diameter (in)	2.498	Friction from Equipment (kPa)	2.8	Wt. of Pan (g)	15.81
Ring Height (in)	1.215	Total Overburden Pressure (kPa)	9.10	Wt. of Sat. Sample + Pan (g)	181.23
Spacer Height (in)	0.197			Wt. of Dry Sample + Pan (g)	143.76
Ceramic Stone (CS):		***Beginning of the Test:***		***Notes:***	
I.D. / Rating	15 bar	Wt. of Wet Sample + Ring (g)	405.42		
Initial Wt. of SSD CS (g)	144.68	Height of Sample (in)	1.018		
Final Wt. of SSD CS (g)	144.55				

Applied Suction (kPa)	Date/Clock Time	Elapsed Time (min)	Dial Gauage Reading (x 0.0001 in)	Water Level Reading Left Column (mm)	Water Level Reading Right Column (mm)
4	5/19/2006 9:11	σ'_{token}	2576		
	5/19/2006 9:12	σ_i'	2576		
	5/19/2006 9:14	0	2580	210	210
	5/19/2006 9:15	1	2581	210	210
	5/19/2006 9:17	2	2582	210	210
	5/19/2006 9:25	4	2583	209.5	209.5
	5/19/2006 9:33	8	2585	209.5	209.5
	5/19/2006 9:52	15	2589	209	209
	5/19/2006 10:25	30	2595	209	209
	5/19/2006 11:30	60	2601	208.5	208.5
	5/19/2006 14:00	120	2611	207	207
	5/19/2006 16:04	240	2621	206	206
	5/19/2006 17:54	480	2629	205	205
	5/19/2006 23:42	960	2649	202	202
	5/20/2006 9:23		2681	198.5	198.5
	5/20/2006 21:49		2737	192.5	192.5
	5/21/2006 11:38		2812	183.5	183.5
	5/21/2006 19:13		2858	178.5	178.5
	5/22/2006 8:35		2938	170.5	170.5
	5/22/2006 19:33		2999	163	163
	5/23/2006 8:35		3060	155	155
	5/23/2006 18:19		3099	147.5	147.5
	5/24/2006 9:04		3141	140	140
	5/24/2006 21:42		3169	133.5	133.5
	5/25/2006 9:12		3185	129.5	129.5

Applied Suction (kPa)	Date/Clock Time	Elapsed Time (min)	Dial Gauage Reading (x 0.0001 in)	Water Level Reading	
				Left Column (mm)	Right Column (mm)
4	5/25/2006 18:47		3196	127	127
	5/26/2006 9:10		3209	123	123
	5/26/2006 17:19		3212	121	121
	5/27/2006 11:57		3222	118.5	118.5
	5/27/2006 17:02		3229	117.5	117.5
	5/28/2006 16:54		3239	114.5	114.5
	5/29/2006 8:21		3242	113.5	113.5
	5/29/2006 16:03		3245	113	113
	5/30/2006 8:56		3249	111.5	111.5
	5/30/2006 17:53		3251	111	111
	5/31/2006 9:39		3253	110	110
	5/31/2006 17:49		3256	109.5	109.5
	6/1/2006 13:58		3259	108.5	108.5
	6/2/2006 9:03		3261	107.5	107.5
	6/2/2006 17:05		3264	107	107
	6/3/2006 11:51		3268	106	106
	6/3/2006 17:28		3269	105.5	105.5
	6/3/2006 21:20		3269	105.5	105.5
	6/4/2006 14:50		3270	105.5	105.5



Readings of Dial Gauge and Water Level Vs. Time
Sample I.D. = D-12B, Initial Volumetric Water Content = 30%
3400
3300
3200
3100
3000
2900
2800
2700
2600
2500
Dial Gauge Reading (x 0.0001 in)
250
200
150
100
50
0
Water Level Reading (mm)
5/17/06
5/19/06
5/21/06
5/23/06
5/25/06
5/27/06
5/29/06
5/31/06
6/2/06
6/4/06
6/6/06
Date
Dial Reading
Left Water Level Reading

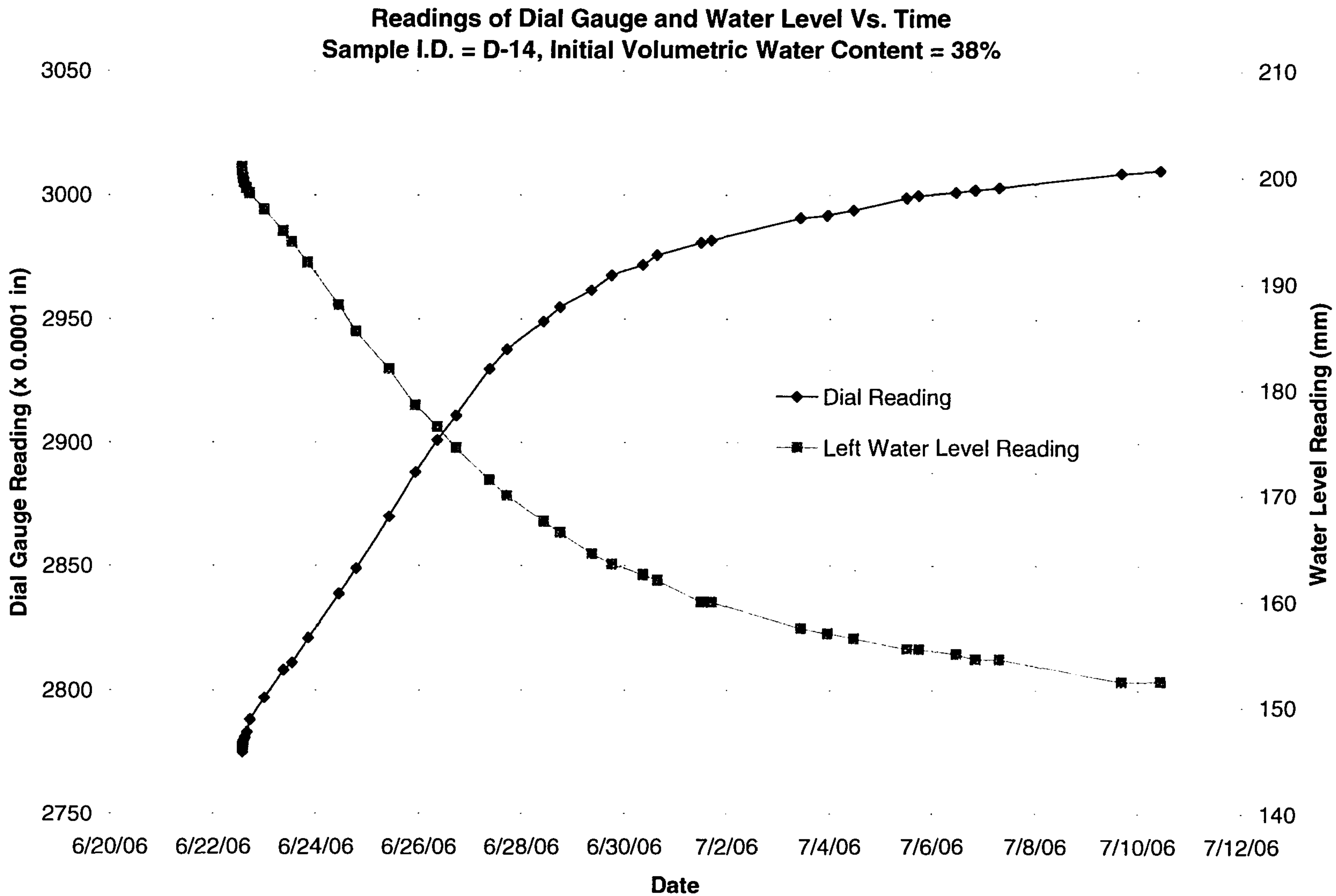
SWELL POTENTIAL VS. WATER CONTENT TEST DATA SHEET

Sample Source:	Russell Project	**Sample I.D.:**	D-14
Soil Type:	Claystone	**Geological Formation:**	Denver Formation
Solution Type:	DI Water	**Room Temperature:**	74 Degrees F.
Time of Beginning:	6/22/2006	**Time of Completion:**	7/10/2006

Steel Ring:		***Overburden:***		***End of the Test:***	
Ring I.D.	R1	Applied Overburden Pressure (kPa)	0	Wt. of Sat. Sample + Ring + CS (g)	561.63
Wt. of Ring (g)	253.04	Pressure from Equipment Weight (kPa)	6.30	Pan I.D.	KD-17
Ring Diameter (in)	2.498	Friction from Equipment (kPa)	2.80	Wt. of Pan (g)	15.71
Ring Height (in)	1.215	Total Overburden Pressure (kPa)	9.10	Wt. of Sat. Sample + Pan (g)	179.34
Spacer Height (in)	0.197			Wt. of Dry Sample + Pan (g)	143.22
Ceramic Stone (CS):		***Beginning of the Test:***		***Notes:***	
I.D. / Rating	15 bar	Wt. of Wet Sample + Ring (g)	411.55		
Initial Wt. of SSD CS (g)	144.7	Height of Sample (in)	1.018		
Final Wt. of SSD CS (g)	144.63				

Applied Suction (kPa)	Date/Clock Time	Elapsed Time (min)	Dial Gauage Reading (x 0.0001 in)	Water Level Reading Left Column (mm)	Water Level Reading Right Column (mm)
4	6/22/2006 13:44	σ'_{token}	2761		
	6/22/2006 13:44	σ_i'	2761		
	6/22/2006 13:48	0	2775	201	201
	6/22/2006 13:49	1	2776	201	201
	6/22/2006 13:53	2	2777	201	201
	6/22/2006 13:57	4	2778	201	201
	6/22/2006 14:05	8	2779	200.5	200.5
	6/22/2006 14:22	15	2780	200	200
	6/22/2006 14:50	30	2781	199.5	199.5
	6/22/2006 15:51	60	2783	199	199
	6/22/2006 17:32	120	2788	198.5	198.5
	6/22/2006 23:58	240	2797	197	197
	6/23/2006 8:55	480	2808	195	195
	6/23/2006 13:02	960	2811	194	194
	6/23/2006 20:26		2821	192	192
	6/24/2006 10:36		2839	188	188
	6/24/2006 18:39		2849	185.5	185.5
	6/25/2006 10:13		2870	182	182
	6/25/2006 22:35		2888	178.5	178.5
	6/26/2006 8:38		2901	176.5	176.5
	6/26/2006 17:25		2911	174.5	174.5
	6/27/2006 9:11		2930	171.5	171.5
	6/27/2006 17:17		2938	170	170
	6/28/2006 10:12		2949	167.5	167.5
	6/28/2006 17:55		2955	166.5	166.5

Applied Suction (kPa)	Date/Clock Time	Elapsed Time (min)	Dial Gauage Reading (x 0.0001 in)	Water Level Reading	
				Left Column (mm)	Right Column (mm)
4	6/29/2006 8:50		2962	164.5	164.5
	6/29/2006 18:11		2968	163.5	163.5
	6/30/2006 8:43		2972	162.5	162.5
	6/30/2006 15:32		2976	162	162
	7/1/2006 12:03		2981	160	160
	7/1/2006 16:54		2982	160	160
	7/3/2006 10:14		2991	157.5	157.5
	7/3/2006 22:43		2992	157	157
	7/4/2006 11:02		2994	156.5	156.5
	7/5/2006 12:04		2999	155.5	155.5
	7/5/2006 17:40		3000	155.5	155.5
	7/6/2006 11:08		3001	155	155
	7/6/2006 20:03		3002	154.5	154.5
	7/7/2006 7:10		3003	154.5	154.5
	7/9/2006 16:17		3009	152.5	152.5
	7/10/2006 10:25		3010	152.5	152.5


Readings of Dial Gauge and Water Level Vs. Time
Sample I.D. = D-14, Initial Volumetric Water Content = 38%
Dial Gauge Reading (x 0.0001 in)
3050
3000
2950
2900
2850
2800
2750
Water Level Reading (mm)
210
200
190
180
170
160
150
140
Dial Reading
Left Water Level Reading
6/20/06
6/22/06
6/24/06
6/26/06
6/28/06
6/30/06
7/2/06
7/4/06
7/6/06
7/8/06
7/10/06
7/12/06
Date