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Evaluation of Hydraulic Conductivity of Non Aqueous Phase Liquids in Partially Saturated Soils

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EVALUATION OF HYDRAULIC CONDUCTIVITY OF NON AQUEOUS PHASE LIQUIDS IN PARTIALLY SATURATED SOILS

by

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ABSTRACT

EVALUATION OF HYDRAULIC CONDUCTIVITY OF NON - AQUEOUS PHASE LIQUIDS IN PARTIALLY SATURATED SOILS

Chijioke Ekeleme Akamiro
Old Dominion University, 2013
Director: Dr. Isao Ishibashi

This study seeks to investigate a problem of predicting the hydraulic conductivity of NAPLs in partially saturated soils and to relate the hydraulic conductivity to basic soil parameters that are either easy to determine or are in wide use. To evaluate hydraulic conductivity in partially saturated soils, previous researchers have focused on flow geometry, soil and chemical properties, etc. used in CHEMFLO program by Nofziger et al., (1989) and saturation equations by such authors as Van Genutchen (1980) and Brooks and Corey (1964). Among those, the soil-water characteristic curve (SWCC) is the most widely used constitutive relations for unsaturated soils (Claudia, et al. 2000). It uses matric suction to relate to fluid flow characteristics of unsaturated soils. However, the authors concluded that even the most experienced researchers have difficulties in getting a unique SWCC for a soil and that soil suction and SWCCs cannot be simply measured with great precision at the present time. Hillel (1998) stated that there is as yet no universally accepted method available to predict unsaturated hydraulic conductivity from more easily obtainable soil properties.

The approach used in this research includes the development of a new test instrumentation procedure. This study developed a new laboratory based method for solving the problem. It uses easy to obtain soil properties. The properties used are water content, NAPL content, void ratio and soil suction. The test data were used to determine

the unsaturated hydraulic conductivity of a chosen NAPL by using nonlinear regression analysis. The method could be used with both DNAPLs and LNAPLs such as gasoline.

The benefits of this study include (1) establishing previously unknown relationships between unsaturated hydraulic conductivity and basic soil properties such as water content, NAPL content, void ratio or porosity, matric suction, and soil unit weight; (2) providing a new tool for predicting the fate and transport of DNAPL or LNAPL in the vadose zone; and (3) predicting the contamination potential of NAPL/LNAPL.

This dissertation is dedicated to
my father,
Titus Ekeleme Akamiro
and
my mother,
Comfort Ahuele Akamiro.

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Ekeleme Akamiro, Nkemakolam Ekeleme Akamiro, Kelechi Adaku Akamiro, and Ikechukwu Ekeleme Akamiro.

NOMENCLATURE

A	cross-section area of soil specimen (m^2)
a	cross-section area of stand pipe (m^2)
C_g	gaseous phase NAPL concentration (mol/L)
C_l	liquid phase concentration (mol/L)
C_s	concentration of NAPL adsorbed onto the solid phase (mol/L)
D_g	gas phase diffusion coefficient (m/s)
D_l	liquid phase diffusion coefficient (m/s)
h	pressure head (KN/m^2)
h_{1w}	head difference for water at start of test (cm)
h_{2w}	head difference for water at end of test (cm)
h_{1nw}	head difference for NAPL at start of test (cm)
h_{2nw}	head difference for NAPL at end of test (cm)
h_c	CHEMFLO (Gardner, 1958) matric potential constant
i	hydraulic gradient (dimensionless)
i_{nw}	non-wetting phase hydraulic gradient (dimensionless)
i_w	wetting phase hydraulic gradient (dimensionless)
g	acceleration due to gravity (m^3/s)
h	height of soil specimen (cm)
I	identity matrix
k	intrinsic permeability of the medium (m^2)
k_{abs}	intrinsic permeability (m^2)
$k_{\text{int}\,r}$	intrinsic permeability (m^2)
k_{nw}	hydraulic conductivity of non-wetting phase (cm/s)
Pk_{TCE}	Predicted hydraulic conductivity of non-wetting phase (cm/sec)
$Pk_{TCE}(w)$	Sensitivity of water content to Pk_{TCE} (cm/sec per unit change in water content)
$Pk_{TCE}(w_n)$	Sensitivity of TCE content to Pk_{TCE} (cm/sec per unit change in TCE content)
$Pk_{TCE}(e)$	Sensitivity of void ratio to Pk_{TCE} (cm/sec per unit change in void ratio)
$Pk_{TCE}(\phi)$	Sensitivity of soil suction to Pk_{TCE} (cm/sec per unit change in soil suction)
k_d	partitioning coefficient between gaseous and solid NAPL phases (dimensionless)
k_{rw}	relative permeability to wetting phase (cm/s)
k_{rnw}	relative permeability to non wetting phase (cm/s)
k_{ro}	relative permeability to oil (NAPL) (cm/s)
k_{os}	saturated hydraulic conductivity of medium to NAPL (cm/s)
k_s	saturated hydraulic conductivity (cm/s)
k_{ws}	saturated water hydraulic conductivity (cm/s)

k_w	wetting phase coefficient of permeability (cm/s)
k_{nw}	non wetting phase coefficient of permeability (cm/s)
$k(\theta)$	unsaturated hydraulic conductivity (cm/s)
$k(h)$	CHEMFLO (Brooks & Corey, 1964) hydraulic conductivity at matric potential h (cm/s)
k_s	CHEMFLO (Brooks & Corey, 1964) saturated hydraulic conductivity (cm/s)
$k_{nw,20}$	hydraulic conductivity of non-wetting phase standardized at 20 deg. C (cm/s)
$k_{nw,T}$	hydraulic conductivity of non-wetting phase at laboratory temperature deg. C (cm/s)
L	length of soil specimen (m)
h_b	CHEMFLO (Brooks & Corey, 1964) air entry value (cm)
n	CHEMFLO (Brooks & Corey, 1964) empirical constant, dimensionless
q_{nw}	non-wetting phase flow rate (m^3/s)
S_e	normalized wetting phase (effective) saturation, (%)
S_g	gaseous phase saturation (mg/L)
S_l	liquid phase saturation (mg/L)
S_n	Saturation to NAPL (%)
S_o	Brooks-Corey-Burdine oil (NAPL) phase saturation (%)
S_w	Brooks-Corey-Burdine water phase saturation (%)
S_{or}	Brooks-Corey-Burdine relative saturation to oil (%)
S_{wr}	Brooks-Corey-Burdine relative saturation to water (%)
t	time (s)
t_1	starting time for test (minutes)
t_2	ending time for test (minutes)
q_g	gaseous phase mass flux (m/s)
q_l	liquid phase mass flux (m/s)
q_{src}	source term mass flux (m/s)
w	water content (%)
w_{TCE}	NAPL content (%)
x_1	variable representing water content (%)
x_2	variable representing NAPL content (%)
x_3	variable representing void ratio (dimensionless)
x_4	variable representing suction, (kPa)
x_5	variable representing unit weight of unsaturated soil, (kn/m^3)
x_{ij}	experimental value of independent variable at row I and column j
$x_{ij}x_{kl}$	experimental value of interaction term between x_{ij} and x_{kl}

$\vec{X}$	matrix consisting of x_i
y	variable representing unsaturated hydraulic conductivity of NAPL
y_i	variable representing unsaturated hydraulic conductivity of NAPL for each set of independent variables.
$\vec{y}$	matrix consisting of y_i
α	CHEMFLO (Van Genutchen, 1980) empirical constant
β_o	regression coefficient for intercept term (dimensionless)
β_i	regression coefficient representing each independent variable x_i (dimensionless)
$\vec{\beta}$	matrix consisting of β_i (dimensionless)
ε_i	error term for each y_i
$\vec{\varepsilon}$	matrix consisting of ε_i
ϕ	porosity (dimensionless)
$\nabla .$	divergence operator (L^{-1})
∇	gradient operator
ρ_o	NAPL density (Charbeneau, 2000) (kg/m^3)
ρ_{nw}	density of non-wetting phase (kg/m^3)
ρ_w	density of water (kg/m^3)
ρ_b	bulk density (kg/m^3)
ρ_g	density of gaseous phase (kg/m^3)
ρ_l	liquid phase density (kg/m^3)
ρ_{wet}	wet unit weight of unsaturated soil (kg/m^3)
θ	volumetric water content (m^3/m^3)
θ_r	residual water content (m^3/m^3)
θ_s	saturated water content (m^3/m^3)
ϕ	soil suction (cbar)
μ_o	dynamic viscosity of NAPL (Ns/m^2)
μ_w	dynamic viscosity of water (Ns/m^2)
μ_{20}	dynamic viscosity of NAPL at standard temperature of 20 deg. C. (Ns/m^2)
μ_T	dynamic viscosity of NAPL at laboratory temperature deg. C (Ns/m^2)
τ_g	gas phase tortuosity factor (m/m)
τ_l	liquid phase tortuosity (m/m)
λ_g	decay constant for NAPL gaseous phase (yr^{-1})
λ_l	decay constant for NAPL liquid phase (r^{-1})

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CHAPTER 1

INTRODUCTION

Determination of soil hydraulic properties in the vadose zone is important involving groundwater flow, chemical transport and contamination problems. Basic soil properties, especially the unsaturated hydraulic conductivity, are very important in providing accurate numerical solutions to flow and transport problems in the unsaturated zone. Measurement of unsaturated hydraulic conductivity is very difficult, very time-consuming, and very expensive. This problem is compounded by the expense and the large number of observations required to adequately characterize the spatial distribution due to commonly occurring field scale variability" (Yates et al., 1992). Therefore, numerical models have found increasing use in simulating the flow of fluids and chemicals, especially in the unsaturated zone. Such researchers include Mualem, 1976, 1986; van Genutchen, 1980; Arya and Paris, 1981; Saxton et al., 1985; Puckett et al., 1985; van Genutchen and Nielsen, 1985; Haverkamp and Parlange, 1986; Kool and Parker, 1988; Tyler and Wheatcraft, 1989, 1990.

Although a number of studies have been conducted on this subject, they did not address a number of important considerations (Yates et al., 1992). Those are; (a) no known study has been conducted to determine whether the predictive methods introduce a systematic bias between the predicted and measured values, (b) little information exists on the effect of using known values of the unsaturated conductivity in a procedure for estimating the soil hydraulic parameters, and (c) no information is available for calculating the values of conductivity that do not require a large amount of experimental measurements.

This study seeks to solve the above problems by providing a laboratory methodology for predicting the hydraulic conductivity of non-aqueous phase liquids (NAPLs) in partially saturated soils of the vadose zone.

In the eastern United States, the vadose zone is shallower compared to the western United States where it is deeper, anywhere from many meters to hundred of meters deep (Tindall and Kunkell, 1999). NAPLs are organic compounds with properties different from that of water. One of those properties is density. Those NAPLs that are less dense than water are called light NAPLs (LNAPLs). The NAPLs that are denser than water are known as dense NAPLs (DNAPLs). Examples of LNAPLs include gasoline, jet fuel, aviation gas, kerosene, and heating oil. Examples of DNAPLs include chloroform, carbon tetrachloride, benzyl chloride, chloroanilines, etc. LNAPLs "float" on the water table while DNAPLs sink below the water table. This makes it easier to detect LNAPLs. Table 1.1 shows a list of organic chemicals that are DNAPLs. NAPLs are immiscible organic compounds that are nearly insoluble or have low solubility in groundwater and therefore exist in the subsurface as a separate liquid phase.

DNAPLs and LNAPLs are sometimes referred to respectively as "dense" and "light" immiscible liquids. The word "immiscible" implies a separate phase from water. The separate phase can exist in equilibrium with water only after its dissolved concentration in the water has exceeded its saturation limit for the water phase at that temperature and pressure. Hence, no organic liquid is totally immiscible with water.

The word "NAPL" was originated in 1981 during studies of a hazardous waste landfill in Niagara Falls, New York where scientists and engineers discovered a complex

Table 1.1 A list of DNAPLs (Feenstra and Cherry, 1996)

Compound class	Compound
Chlorinated Solvents	Tetrachloroethylene
	Trichlorothylene
	1,1,1-Trichloroethane
	Dichloromethane
	Chloroform
	Carbon Tetrachloride
	1,2-Dichloroethane
	Chlorobenzene
	1,2-Dichlorobenzene
	1,3-Dichlorobenzene
	1,1,2-Trichloroethane
	1,2,4-Trichloobenzene
Other Halogenated Organics	Benzyl chloride
	Bromobenzene
	Bromochloromethane
	Bromodichloromethane
	Bromoform
	4-Bromophenyl phenyl ether
	Bis(2-Chloroethyl)ether
	2-Chloroethyl vinyl ether
	Bis(2-Chloroisopropyl)ether
	1-Choro-1-nitropropane
	4-Chlorophenyl phenyl ether
	1-Chloro-1-nitropropane
	4-Chlorophenyl phenyl ether
	Dibromochloromethane
	1,1-Dichloroethane
	1,2-Difluorotetrachloroethane
	1-Iodopropane
	Hexachlorobutadiene
	1,1,2,2-Tetrabromoethane
	1,1,2,2-Tetrachloroethane
	1,1,2-Trichloro-1,2,2-Trifluoroethane

Table 1.1 A list of DNAPLs (Feenstra and Cherry, 1996) (continued)

Compound class	Compound
Pesticides	Chlordane
	Chloropicrin
	1,2- Dibromo-3-chloropropane
	1,2-Dichloropropane
	1,2-Dichloropropylene
	Dichlorvos
	Disulfoton
	Ethion
	Ethylene dibromide
	Malathion
	Parathion
	-
Substituted Aromatics, Phthalates, and Miscellaneous Organics	Chloroanilines
	Chlorotoluenes
	Nitrotoluenes
	Nitrobenzene
	Benzyl butyl phthalate
	Di-n-butyl phthalate
	Diethyl phthalate
	o-Anisidine
	Phenyl ether
	Tri-o-cresol phosphate
PCB Mixtures	Aroclor 1221
	Aroclor 1232
	Aroclor 1242
	Aroclor 1248
	Aroclor 1254
Other Halogenated Organics	Pentachloroethane
	1,2,3- Trichloropropane

mixture of halogena benzenes, chlorinated solvents, and other halogenated hydrocarbons (Kolmer,1991). Almost all LNAPLs are hydrocarbon fuels. Gasoline, for example, is a complex mixture of hydrocarbons together with minute amounts of compounds that contain sulfur, oxygen, or nitrogen. There are several different hydrocarbon compounds in various proportions in any single commercial gasoline (Bland and Davidson, 1967).

For a NAPL to be regarded as a DNAPL, it must have a fluid density greater than 1.01 g/cm^3, a solubility in water of less than 2% (or about 20,000 mg/L), and a vapor pressure of less than 300 torr (1 torr = 1 mm Hg). 300 torr is about 5.8 psi. Bland and Davidson (1967) claim that compounds which are either more soluble than 2% or more volatile than 300 torr would not generally be expected to persist as DNAPL phases in the subsurface.

1.1 Chlorinated solvent usage in the USA

NAPLs enjoy very extensive daily usage. It may be said that civilization as we know it today would not be possible if it were not for the availability of (a) gasoline, fuel oil, and aviation fuel for transportation, (b) a wide variety of organic solvents such as chlorinated solvents (e.g. chloroform, carbon tetrachloride, etc) and halogenated chemicals (for example bromodichloromethane, pentachloroethane, etc.), (c) additives in motor oils, for example, bromobenzene, (d) fumigants and insecticides such as 1,3-Dichlorobenzene, (d) organics such as Trichlorobenzene used in the manufacture of chemicals, dyes, heat transfer medium, for example, 1,2,4-Trichlorobenzene, (e) organics such as chloroanilines used in the manufacture of pharmaceuticals and agricultural chemicals, (f) organics such as Aroclor 1221 used to manufacture gas-transmission turbines and hydraulic fluids, and (g) dry cleaning fluids, paint removers, grain, fruit, and soil fumigant and insecticides for vegetables, anti-knock additive in gasoline, termite control, manufacture of chemicals, in fire extinguishers, dyes, textiles, lubricants, precision equipment, capacitors, transformers, vacuum pumps, perfumes, etc.

1.2 Chlorinated solvent production in the USA

The U.S. production of chlorinated solvents began in 1906 with carbon tetrachloride (Pankow et al., 1996). This chemical became the main solvent used in North America for the first half of the last century. It replaced gasoline in the 1930s as the chemical commonly used for dry cleaning. In 1923, production of trichloroethylene (TCE) and tetrachloroethylene (PCE) began. They became the most commonly used solvents in the 1960s with the rapid expansion of the post-World War II manufacturing economy. As economic growth increased in the 1970s, so did the increased use and production of chlorinated solvents. Table 1.2 shows the 1986 U.S. production of chlorinated organic solvents (Pankow et al., 1996).

1.3 Problem of groundwater pollution

The problem of groundwater pollution is very widespread. This study involves the direct determination of the conductivity of non-aqueous phase liquid in partially saturated soil using easily determined soil properties. Chlorinated solvents are a major group of NAPLs. The most common chlorinated solvents (Merck & Co., 1989) are Perchloroethylene (PCE), Trichloroethylene (TCE), 1,1,1-Trichloroethane (TCA), and Dichloromethane (DCM). Based on their study on TCE, Mendoza and McAlary (1990) said that it is one of the most common contaminants found in groundwater. Since many other chlorinated solvents have properties similar to those of TCE, Mendoza and

McAlary (1990) argued that the general results of their study apply to many cases where volatile chlorinated solvents are accidentally released into the unsaturated zone.

More specifically, this study concentrated on the hydraulic conductivity of TCE. The method presented here can be used for any of the other DNAPLs mentioned above. With a minor adjustment, this method could also be used for the unsaturated conductivity of gasoline, which is a LNAPL. Benzene, toluene, and xylene are some of the constituents of gasoline. The National Cancer Institute has determined that benzene is a human carcinogen (Burmaster and Harris, 1982). Also, the Resource Conservation and Recovery Act of 1976 designated benzene, toluene and xylene as hazardous chemicals. For all the above reasons, it is justified to study these chemicals.

1.3.1 Documented cases of groundwater contamination by NAPLs

Documented cases include the following:

(a) The EPA reported that state agencies were unaware of more than 12,000 reported releases from underground storage tanks in the period 1970 – 1984 (Summary of State Reports on Releases from Underground Storage Tanks: EPA/600/M-86/020, August,1986).

(b) A leak in a gasoline pipeline near Los Angeles that caused contamination of a groundwater supply (William and Wilder, 1971; Mckee et al., 1972)

(c) Contamination by petroleum products in most counties in the State of Maryland (Matis, 1971).

(d) The Pennsylvania Department of Environmental Resources investigation of over 200 hydrocarbon spills from 1972 to 1974 (Osgood, 1974).

(e) Between 1950 and early 1980s, solvents used for metal cleaning and degreasing

Table 1.2 1986 U.S. production of chlorinated organic solvents (Pankow et al., 1996)

Compound	Symbol	10^6 lb	10^6 kg	Drums[c]
1,2-Dichloroethane[a]	1,2-DCA	12,940	5,871	22.9 x 10^6
1,1,1-Trichloroethane[b]	1,1,1-TCA	648	294	1,100,000
Carbon tetrachloride[a]	CTET	627	284	890,000
Methylene chloride[b]	DCM	561	255	960,000
Chloroform[a]	TCM	422	191	640,000
Tetrachloroethylene[b]	PCE	405	184	560,000
Trichloroethylene[b]	TCE	165	75	260,000

[a] American Chemical Society
[b] Halogenated Solvents Industry Alliance
[c] Based on 200 litters, or approximately 55 US gallons per drum

of equipment, electronics, and heavy machinery were released into the environment in large quantities (Coleman, 1999).

(f) The spill in Brooklyn at the site of a former refinery where 1.7 million gallons of gasoline, fuel oil, and naphtha were found under the streets of New York City Borough (Dumas, 1980).

(g) Hydrocarbon pollution beneath a refinery site in Bayonne, New Jersey (Thomas and Leis, 1981).

(h) Case study at a service station in New Jersey involving 1,200 gallons of gasoline leak (Kramer, 1982).

1.3.2 Contamination of groundwater and health hazards

Contamination of groundwater by chlorinated solvents went largely unrecognized until the late 1970s (Pankow et al., 1996). Between 1950 and the early 1980s, solvents used for metal cleaning and degreasing of equipment, electronics and heavy machinery were released into the environment in large quantities (Coleman, 1999).

While NAPLs were enjoying very wide usage across the U.S, they were causing widespread pollution of the nation's surface water and groundwater at the same time. There is evidence (Pankow et al., 1996) that excessive exposure to some NAPLs may result in liver and kidney damage.

Some of the several examples cited include:

(a) Pesticide contaminations were reported in some of the nation's rivers (Middleton and Lichtenberg, 1960).

(b) Environmental Science and Technology wrote that "After many years of apathy and indifference, private citizens, industry and government are now advocating national policies for groundwater pollution and conservation," (Environmental Science and Technology, 1972).

(c) EPA (1972) reported industrial pollution of the lower Mississippi River in Louisiana. The Federal Government responded to the pollution problem by enacting the Clean Waters Act in October, 1972 (Public Law 92-500).

(d) Kleopfer and Fairless (1972) reported the presence of numerous, industrially related organic compounds in the municipal water obtained for Evansville, Indiana from Ohio River.

(e) In July 1974, the State of Louisiana and the City of New Orleans asked EPA to undertake analytical survey of organic chemicals present in the finished water of three drinking water treatment plants in New Orleans. EPA then listed 94 organic chemicals found in finished water from the three New Orleans drinking water treatment plants in concentrations that ranged from 0.01 to 5 μg/L and also announced plans for a National Organics Reconnaissance Survey (NORS) of the water supplies of 80 of the nation's cities.

(f) In 1976, the New York State Department of Health (1978) first learned of severe groundwater contamination in Long Island due to TCE (widely used then as a septic tank cleaner by homeowners) and other chemicals.

(g) In 1977, 16 private wells were closed in Gray, Maine due to contamination with various chlorinated solvents and other compounds (Pankow et al., 1996).

(h) In December 16, 1974, President Ford signed into Law the Safe Drinking Water Act which gave the EPA Administrator the power to take such action as is needed to protect drinking water supplies (Pankow et al., 1996).

(i) Congress passed the Toxic Substances Control Act of October 11, 1976 to control the manufacture of toxic materials that are not waste products but are useful and necessary for industrial economy (Pankow et al., 1996).

(j) In 1978, Nassau-Suffolk (Long Island, New York) Regional Planning Board found that organic chemical contamination was widespread in the upper glacial aquifer (Koppleman, 1978). Thirty six wells were closed which were determined to contain up to 310 μg/L of 1,1,1-TCA, 300μg/L of TCE and other chemicals (Pankow et al., 1996).

(k) Congress passed the Resource Conservation and Recovery Act (RCRA). A major consequence of RCRA was to hold the producers of contaminants responsible for the wastes they produce from "cradle to grave." The 1986 amendments to RCRA mandated the monitoring of the groundwater and vadose zones at many underground storage tank locations (Pankow et al., 1996).

(l) Brass et al. (1977) indicated that 1,1,1-TCA, TCE, and carbon tetrachloride were present in raw waters used as drinking water in the country. Sampling from May to July, 1976 found that TCE was present in 28 out of 113 drinking waters.

(m)In May, 1978, four wells providing 80% of the drinking water to Bedford, Massachusetts, were confirmed to be contaminated with TCE at up to 500μg/L and other chemicals (Pankow et al., 1996).

(n) In January 1980, California public health officials closed 39 public wells which provide water to 400,000 people in 13 cities in the San Gabriel Valley, due to TCE contamination (Pankow et al., 1996).

(o) In June 1980, EPA (1980a) closed about 100 wells around a landfill in Jackson Township in New Jersey with concentrations of up to 3,000 μg/L of methylene chloride, and 1,000 μg/L of TCE.

(p) Petura (1981) described groundwater pollution as a "problem of immense concern" with TCE and 1,1,1-TCA which have been found in groundwater in locations such as Pennsylvania, Delaware, New Hampshire, and California.

(q) In 1981, Giger and Schaffner (1981) and Zoeteman et al. (1981) documented the presence of TCE, chloroform, and carbon tetrachloride in goundwater in Switzerland.

(r) Schwille (1981) discussed the behavior of NAPLs in subsurface systems.

1.4 Groundwater contamination sources

The sources of groundwater pollution by chlorinated solvents include the following:

(s) Leakage from underground or above ground storage tanks, drums, and buried chemical distribution pipelines,

(t) Spillage at chemical loading and off-loading sites, and during highway and train accidents.

(u) Intentional disposal into the subsurface in several ways including municipal landfills, chemical waste disposal landfills, settling ponds and lagoons.

Spills or leaks of volatile organic contaminants (voc) to the environment may result in surface or subsurface contamination. If the leak is of sufficient quantity, the voc will tend to migrate downward and outward through the unsaturated zone leaving globules, films, and small droplets of the released contaminants. The voc release or spill in the vadose zone will be distributed among three phases: the soil matrix (or solid phase), the soil moisture that is in the voids between and on the surface of the soil matrix (liquid phase), and the soil gas phase that constitutes the remaining portion of the voids between the soil assemblages (gas phase).

In the subsurface environment, contaminant transport is strongly dependent upon groundwater flow. As the water flows, the dissolved contaminants are transported with the water by advection. The immiscible organic liquid compounds will frequently exist as a separate liquid phase in the subsurface either as LNAPL or as DNAPL. The migration of the LNAPL is largely dependent upon the slope of the groundwater table while the migration of DNAPL is strongly dependent on the subsurface stratigraphy, particularly the distribution of zones of low permeability that act as barriers. As a result, the former will tend to collect in the capillary fringe or float on the groundwater table while the latter will migrate through the vadose zone downwards through the groundwater table.

Contaminants (particularly ionic and molecular constituents) will also move in response to their chemical kinetic activity. The movement is by diffusion (i.e. from areas of higher concentration to areas of lower concentration). The surface or subsurface area covered by the contaminants will depend, among many factors, on contaminant, soil, hydraulic or geologic properties of the subsurface. The transport of the contaminants may end anywhere in the subsurface above or below the groundwater table. Therefore, extraction of soil and groundwater voc by stripping may be done above the groundwater table, or below the groundwater table, or by a combination of the two in the unsaturated and saturated zones. Soil vapor extraction (SVE), therefore, typically occurs in the vadose zone.

CHAPTER 2

PREVIOUS RESEARCH FINDINGS

2.1 Introduction

Hydraulic conductivity takes a maximum value at full saturation and decreases dramatically with decreasing water content. It also varies hysteretically with matric suction. This wide variation explains why it is much more complex to model unsaturated flow problems than to model saturated flow problems. Laboratory determination of unsaturated hydraulic conductivity is a difficult task because of the large number of parameters that influence the property. The laboratory tests are also time-consuming and expensive. Several researchers have studied the problem of relative permeability of non-aqueous phase liquids and have presented their findings as described below.

2.2 Lawrence Livermore National Laboratory method

Equation 2.1 governs the transport of a single NAPL in the unsaturated zone (Lawrence Livermore National Laboratory, LLNL, 1990).

$$\frac{\partial}{\partial t}(\phi S_l C_l + \phi S_g C_g + C_s) = -\nabla \bullet |C_g q_g| - \nabla \bullet | C_l q_l | + \nabla \bullet | \rho_g \phi S_g \tau_g D_g \nabla (C_g/\rho_g)|$$

$$+ \nabla \bullet | \rho_l \phi S_l \tau_l D_l \nabla (C_l/\rho_l) - \lambda_l \phi S_l C_l - \lambda_g \phi S_g C_g - \lambda_g \phi \rho_b k_d C_l + q_{src} \tag{2.1a}$$

where,

t = time;

C = volatile NAPL concentration (mass/volume);

ϕ is effective porosity (volume of water/total volume of solid);

S is degree of saturation; subscripts l is for the aqueous phase; g for the gas phase; s is for sorption onto the solid phase; and src is for a source term;

τ is a tortuosity factor;

ρ is density;

ρ_b is bulk density;

D is the diffusion coefficient of the NAPL;

k_d is the partitioning coefficient between the aqueous phase and solid phase;

λ is the decay constant for NAPL degradation;

q is mass flux;

$\nabla\bullet$ is the divergence operator; and

∇ is the gradient operator.

The following relationships also exist:

$$C_s = \rho_b k_d C_l \tag{2.1b}$$

$$C_g = k_H C_l \tag{2.1c}$$

where k_H = is the Henry's law constant for an individual contaminant. Equation 2.1 is further explained as follows:

These three terms $\frac{\partial}{\partial t}(\phi\, S_l\, C_l + \phi\, S_g C_g + C_s)$ represent the changes in accumulated mass of volatile NAPL in the aqueous, gaseous, and solid phases, respectively. Soils with relative humidity less than 90 percent have a very high sorptive capacity because of the direct sorption of the vapor into the soil phase. This is why upper soil layers retard vapor diffusion to the surface at low humidity levels.

$-\nabla \bullet |C_g\, q_g| - \nabla \bullet |\, C_l\, q_l\, |$ terms represent the advective fluxes in the gaseous and aqueous phases. Advective transport is downward and dominates if the fluxes are high.

$+\nabla \bullet |\rho_g\, \phi S_g\, \tau_g\, D_g\, \nabla\, (C_g/\rho_g)| + \nabla \bullet |\, \rho_l\, \phi\, S_l\, \tau_l\, D_l\, \nabla\, (C_l/\rho_l)$ represents the diffusive fluxes in the gaseous and aqueous phases. Diffusion occurs by the movement of vapor from areas of higher to areas of lower concentration. As soil water content increases, gaseous diffusion and gaseous advection reduce significantly. Gaseous diffusion predominates over aqueous diffusion which is comparatively negligible. Increases in water content in the vadose zone significantly reduce both gaseous advection and gaseous diffusion.

$-\lambda_l \phi S_l C_l$, $-\lambda_g \phi S_g C_g$, and $-\lambda_g \phi \rho_B K_d C_l$ terms represent chemical or biological degradation in the three phases.

q_{src} is the source term. A source is the point of entry of a constituent of concern. It may be a primary source such as an underground or above ground tank, a secondary source such as non-aqueous phase liquid, or a residual source such as immobile NAPLs that may remain trapped behind after the passage of NAPL or after groundwater or leachate has spread it about.

2.3 Brooks and Corey (1964) method

Brooks and Corey Equations 2.2 and 2.3 can be used to model the relative permeability of non-aqueous phase liquids.

$$k_{rw} = S_e^{\{(2+3\lambda)/\lambda\}} \tag{2.2}$$

$$k_{rnw} = (1 - S_e)^2 (1 - S_e)^{\frac{2+\lambda}{\lambda}} \tag{2.3}$$

where

k_{rw} is the relative hydraulic conductivity to the wetting phase;

k_{nw} is the hydraulic conductivity of non-wetting phase;

S_e is the normalized wetting fluid (water) saturation and is defined in Equation 2.7.

λ is the pore size distribution index and has small values for soil with wide range of pore sizes and will experience a small change in water saturation with height above the capillary fringe. Larger numbers for λ indicate soil with relatively uniform pore size. For example, typical values for the Brooks and Corey λ coefficient ranges from 0.5 for aggregated clay to 2 for sandy soil, and perhaps 4.0 for very uniform materials (Pankow et al., 1996).

2.4 Van Genutchen (1980) method

Van Genutchen (1980) uses Equations 2.4 through 2.6 to determine the relative permeabilities of the wetting and non-wetting phases.

$$k_{rw} = S_e^{1/2}\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \tag{2.4}$$

$$k_r(h) = \frac{\left\{1-(\alpha h)^{n-1}\left[1+(\alpha h)^n\right]^{-m}\right\}^2}{\left[1+(\alpha h)^n\right]^{m/n}} \tag{2.5}$$

$$S_e = \frac{S_w - S_r}{S_m - S_r} \tag{2.6}$$

2.5 Parker et al., (1987) method

$$k_{rnw} = \left(1-S_e\right)^{1/2}\left(1-S_e^{1/m}\right)^{2m} \tag{2.7}$$

where,

S_e is normalized wetting fluid (water) saturation;

S_w is wetting phase (water) saturation;

S_m is maximum water saturation that can be achieved during the wetting phase;

S_r is residual wetting phase saturation;

S_{wr} is residual DNAPL saturation and is equal to $(1-S_m)$;

m is van Genutchen parameter (approximately 0.35 to 0.80);

h is hydraulic head; and

α, n are model fitting parameters.

2.6 Brooks-Corey-Burdine model

This model by Brooks-Corey-Burdine (1964) suggests that the relative permeability to oil is a function of the oil and water saturations as follows:

$$k_{ro}(S_o, S_w) = \left(\frac{S_o - S_{or}}{1 - S_{or}}\right)^2 \left(\left(\frac{S_t - S_{wr}}{1 - S_{wr}}\right)^{\varepsilon - 2} - \left(\frac{S_w - S_{wr}}{1 - S_{wr}}\right)\right)^{\varepsilon - 2} \tag{2.8a}$$

where, k_{ro} (S_o, S_w) is the relative hydraulic conductivity to oil as function of the degrees of saturation S_o of oil and S_w of water and S_t, the sum of those is defined as;

$$S_t = S_o + S_w \tag{2.8b}$$

S_{wr} is the residual (water saturation) degree of water saturation;

S_{or} is the residual (oil saturation) degree of oil saturation, and ε is given by:

$$\varepsilon = 3 + \frac{2}{\lambda} \tag{2.8c}$$

and the coefficient λ above appeared in Equations 2.2 and 2.3.

2.7 Charbeneau method

Charbeneau (2000) defined the relative permeability of NAPL as follows:

$$k_o = \frac{g\rho_o k}{\mu_o} k_{ro} = k_{os} k_{ro} \tag{2.9}$$

$$k_{os} = \frac{\rho_o \mu_w}{\rho_w \mu_o} k_{ws} \tag{2.10}$$

where

k_{os} is saturated oil (NAPL) hydraulic conductivity in the medium;

k is intrinsic hydraulic conductivity of the medium;

k_{ro} is relative hydraulic conductivity to oil (NAPL);

k_{ws} is saturated water hydraulic conductivity;

ρ_o, μ_o is density, viscosity of the NAPL phase, respectively; and

ρ_w, μ_w is density and viscosity of the water phase, respectively.

Based on his research using Equation 2.7a with $\varepsilon = 6.0$, $S_{wr} = 0.10$, and $S_{or} = 0$, Charbeneau (2000), made the following conclusions; (a) The maximum possible NAPL saturation decreases with increasing water saturation, (b) At a given NAPL saturation, the NAPL relative saturation increases with water saturation because water occupies the smallest pores, and with more water present, the NAPL is forced into lager pores which have larger permeabilities, (c) Even at irreducible water saturation, the NAPL saturation is at its maximum, and the maximum value cannot be equal to one due to increased NAPL-phase tortuosity around the water that is the wetting phase.

2.8 Hydraulic Spill Screening Model (HSSM)

This is intended for simulation of subsurface releases of LNAPLs in homogeneous soils. The model includes several modules for LNAPL flow through the vadose zone. The source is assumed at the soil surface and may be a constant flux source, a volume source, or a constant head source. It includes a soil property regression utility to estimate soil hydraulic properties using the regression equations of Rawls and Brakensiek (1985). It also has a utility for the calculation of the NAPL/water partition coefficient based on Raoult's law.

The Hydrocarbon Spill Screening Model consists of three models: KOPT for the vadose zone, OILENS for the water table, and TSGPLUME for the aquifer. The Kinematic Oily Pollutant Transport (KOPT) model simulates the flow and transport of LNAPL from at or below the ground surface to the water table. It uses capillary pressure curve parameters shown in Equation 2.7a to approximate the relative permeability of the LNAPL of interest. Comparison of results from HSSM with results from this study is inappropriate because the former simulates LNAPL transport while the latter simulates DNAPL transport.

This model uses the Brooks-Corey-Burdine model presented as Equation 2.7a to model the relative permeability for oil. In this model, the pore size distribution index, λ, and the residual water saturation, S_{wr}, are obtained by measurement of a capillary pressure curve. Capillary pressures exist at interfaces between two immiscible fluids one of which is a wetting phase and the other a non-wetting phase. In drainage case, as is the case in this study, a non-wetting phase is displacing a wetting phase. Capillary pressure is given by Equation 2.11.

$$P_c = (\rho_w - \rho_o)gh = \frac{2\gamma\cos\theta}{a}A \qquad (2.11)$$

where;

P_c is capillary pressure (N/cm^3);

ρ_w is density of water (N/cm^3);

ρ_o is density of oil or NAPL (N/cm^3);

g is acceleration due to gravity (cm/s^2);

h is pressure head (cm);

γ is interfacial tension (dynes/cm);

θ is contact angle (degrees);

a is pore radius (microns); and

A is 145 x 10^{-3} (conversion constant).

From Equation 2.10, it is seen that oil (NAPL) will only enter pores larger than the pore radius "a", while the wetting phase (water) will occupy the pores smaller than "a". A capillary pressure graph provides residual (irreducible) water saturation and residual oil (NAPL) saturation. The retention of NAPL in the vadose zone after the NAPL infiltration is represented by S_{wr} (Figure 2.1). The value of this empirical parameter depends on the saturation history of the system (Wilson et al., 1990) and decreases as water saturation increases. To use this method to evaluate the NAPL relative permeability for the soil specimen studied, the values must be known for parameters S_o, S_{or}, S_w, S_{wr}, ε, and λ during the laboratory tests. These values are not known.

2.9 CHEMFLO

Nofziger et al. (1989) developed the computer program CHEMFLO for the U.S. Environmental Protection Agency. CHEMFLO provides the user with a choice of several input systems including soil, water, and chemical systems. This model is a one-dimensional screening level model for simulating the movement of water and chemicals in unsaturated soils. Richards equation (Equation 2.12) is used to model water movement while the equation describing the movement of chemicals includes advective and dispersive transport, first-order decay in the liquid and solid phase, zero-order decay or production, and linear equilibrium adsorption. The lower boundary condition may be constant potential, constant flux, or mixed type. One of the model results may be plotted as hydraulic conductivity versus distance or time.

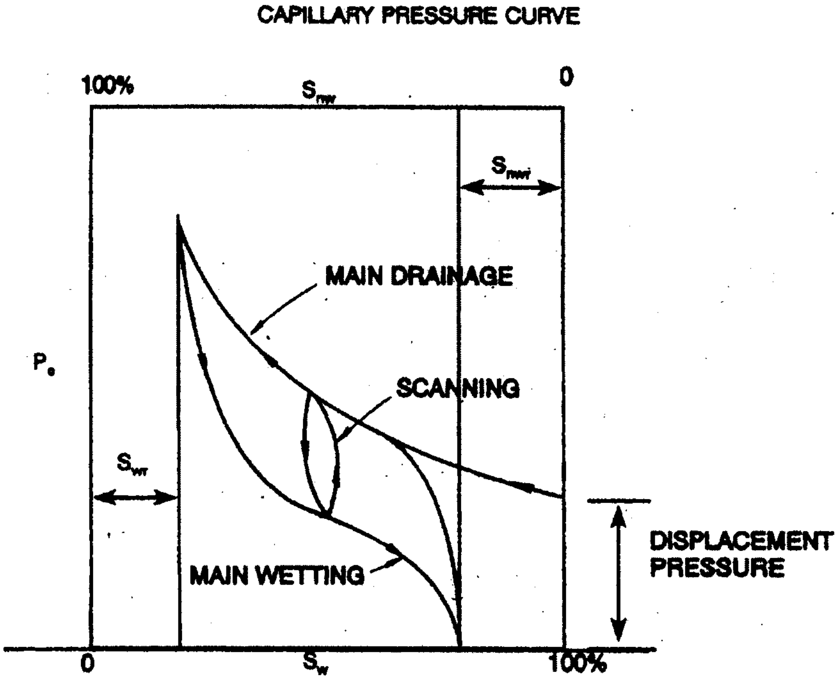

Figure 2.1 Typical capillary-saturation curve (after Pankow and Cherry, 1996).

$$\frac{\partial \theta}{\partial t} = C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left[k(h)\left(\frac{\partial h}{\partial x} - \sin(A)\right)\right] \tag{2.11}$$

Where,

$\theta = \theta(h)$ is volumetric water content;

$h = h(x,t)$ is matric potential;

x is position coordinate parallel to the direction of flow;

t is time;

A is angle between the direction of flow and the horizontal direction;

$k(h)$ is hydraulic conductivity of the soil at matric potential, h

$$C(h) = \frac{d\theta}{dh} \tag{2.12}$$

CHEMFLO code requires information on

1. Solute partitioning coefficients to solid, liquid (water), and air phases,
2. Degradation of the contaminant, i.e. the rate of degradation, m'

$$m' = -c(\alpha\theta + \beta\rho k) \tag{2.13}$$

where

c is the concentration of chemical in the water;

α is the first order degradation rate constant;

β is the first-order degradation constant in the solid phase;

ρ is the density of solid phase; and

$k = 0.693 / T_{1/2}$, where $T_{1/2}$ is the half-life of the chemical.

3. Advection and dispersion. While advection accounts for the bulk movement of the chemical with the mean flow velocity, hydrodynamic dispersion represents molecular diffusion due to natural molecular motion of dissolved chemicals and mechanical dispersion due to deviations from the mean flow velocity in the individual pores. The mass flux, J_m, of chemicals that are transported in the soil water has been expressed as

$$J_m = q\,c - \theta D \frac{\partial c}{\partial z} \tag{2.14}$$

$$D = D_o \tau + \lambda \left| \frac{q}{\theta} \right| \tag{2.15}$$

where,

q is the flow rate;

c is the solute concentration;

D is the dispersion coefficient;

z is the depth;

$\theta\, D \frac{\partial c}{\partial z}$ represents the hydrodynamic process;

D_o is the molecular diffusion coefficient;

τ is the tortuosity of the soil; and

λ is the dispersivity factor.

The CHEMFLO transport equation for chemicals in the unsaturated zone is

$$\frac{\partial}{\partial t}(\theta c + \rho S) = \frac{\partial}{\partial z}\left[\theta D\left(\frac{\partial c}{\partial z} - qc\right)\right] - \alpha\theta c - \beta\rho S \tag{2.16}$$

CHEMFLO program solves the one-dimensional equations for water and chemical movement in unsaturated soils using the above equations and the following input parameters:

Definition of soil system:

1. Name of the soil
2. Orientation from vertical of the flow system
3. Finite or semi-infinite soil system
4. Length of soil system (cm)

Definition of water system:

1. Boundary condition for water at the upper surface
2. Desired matric potential (cm) at the upper surface
3. Boundary condition for water at the lower surface
4. Desired matric potential (cm) at the lower surface
5. Uniform initial matric potential (cm) throughout the soil
6. Matric potential (cm) throughout soil before simulation
7. Maximum time to be simulated (hr)
8. Mesh size in depth (cm)
9. Mesh size in time (hr)
10. Period between graphic or tabular outputs (hr)
11. Output file name.

Definition of chemical system:

1. Boundary condition for chemical at the upper surface
2. Desired concentration of the inflowing solution $(\mu g / cm^3)$
3. Boundary condition for chemical at the lower surface

4. Uniform chemical concentration throughout the soil $(\mu g / cm^3)$.
5. Chemical concentration throughout the soil $(\mu g / cm^3)$
6. Chemical concentration before simulation $(\mu g / cm^3)$

Soil and chemical parameters:

1. Soil bulk density (g / cm^3)
2. Water soil partition coefficient of soil (cm^3 / g)
3. Diffusion coefficient of chemical in water (cm^2 / hr)
4. Dispersivity (cm)
5. First-order degradation constant, liquid $(1 / hr)$
6. First-order degradation constant, solid, $(1 / hr)$
7. Zero-order rate constant, liquid $(\mu g / cm^3 / hr)$

CHEMFLO is a highly capable program. Perhaps, however, its greatest weakness arises from the fact that its description of the soil modeled using the engineering properties of soil is not adequate.

2.10 ONESTEP

This program has the capability to estimate up to five unknown parameters in the van Genuchten soil hydraulic property model. It requires measurements of cumulative outflow with time during one-step outflow experiments. The user has the option to supplement the outflow data with measurements of equilibrium moisture contents and pressure heads.

Mualem-van Genutchen model (Mualem, 1976; van Genutchen, 1980) involves five parameters namely: effective saturation (S_e), saturated water hydraulic conductivity

(k_s), and parameters m ,n , and α for the determination of unsaturated water hydraulic conductivity, $k(\theta)$. Unsaturated water hydraulic conductivity can be determined by evaluating the five parameters in van Genutchen's (1980) model. The values for residual water content (θ_r), and parameter α , m, and n can be evaluated by a nonlinear inversion method to maximize several objective functions. This method involves:

1. Assuming soil hydraulic properties
2. Setting up experiment with initial and boundary conditions
3. Measuring α , or m, or n during the experiment
4. Solving the following Richard's equation (1931)

$$\frac{\partial\theta}{\partial x} = -\frac{\partial}{\partial x}\left[k(\psi)\frac{\partial\psi}{\partial x}\right] \tag{2.17}$$

   Where ψ is the suction head, and $k(\psi)$ is hydraulic conductivity expressed in terms of suction head.

5. Optimizing the parameters by minimizing an objective function that contains the sums of squared deviations between the observed and predicted flow variables

6. Repeating the numerical simulation several times

Kool et al. (1985a,b) used this inverse modeling approach to determine soil hydraulic properties from one-step outflow experiments. As with HSSM, this approach determines water hydraulic conductivity.

2.11 SOHYP

This is a soil parameter estimation model. It is an analytical model for calculating unsaturated hydraulic conductivity function. It is based on the soil moisture content-pressure head curve equation. The equation enables the user to derive closed-form analytical expressions for the relative hydraulic conductivity using the Burdine (1953) or Mualem (1976) equations. SOHYP is an older model of RETC computer program.

SOHYP was developed to estimate the unknown coefficients θ_r, α, and n from observed soil water retention data. It was later modified to RETC code to allow some or all of the unknowns, θ_r, θ_s, α, n, and k_s to be estimated simultaneously from measured soil water retention and or data for water hydraulic conductivity data. The Marquardt (1963) regression method was used in the optimization program.

2.12 RETC

This computer program is used to analyze the soil water retention and hydraulic conductivity functions of unsaturated soil. It uses the models of Brooks-Corey and van Genuchten to represent the soil water retention curve, and the theoretical pore-size distribution models of Mualem and Burdine to predict the unsaturated conductivity function from observed soil water retention data. The program can predict hydraulic conductivity from observed soil water retention data assuming that one observed conductivity value at any saturation value is known.

2.13 SOIL

SOIL is used to estimate soil hydraulic properties by using nonlinear least-square analysis. Input to the code includes pairs of measured water content and suction values. It offers the user choice of Brooks and Corey (1964), Brutsaert (1966), Vauclin et al.

(1979), and van Genuchten (1981) to be used to estimate the soil-water characteristic function and the unsaturated hydraulic conductivity. The unsaturated hydraulic conductivity function is estimated by the series-parallel model of Childs and Collis-George (1950) and is obtained by straight-line fitting on a log-log plot.

SOIL is used in hydrological, ecological, and agricultural studies to estimate soil hydraulic properties using a nonlinear least-squares method of analysis. The user can choose from the models developed by Brooks and Corey (1964) or van Genutchen (1981) and use the code to estimate the soil-water characteristic curve and water unsaturated hydraulic conductivity.

2.14 SWANFLOW

The Simultaneous Water, Air, and Non-aqueous Phase Flow (SWANFLOW) uses a finite-difference code to simulate a three-dimensional flow of water and an immiscible non-aqueous phase under saturated and unsaturated near-surface conditions. It is used to simulate the migration of organic chemicals and in analyzing the effects of remedial technologies at hazardous waste sites where immiscible fluids are encountered. It is also be used to evaluate the migration and clean up of fuel spills and leaks.

The input parameters are aquitard and aquifer thickness, water table depth, reference porosity, reference pressure, intrinsic permeability, hydraulic conductivity and media compressibility.

2.15 Missing area in previous research

As can be seen from the cited researches above, hydraulic conductivity has been related to matric suction ψ, saturation and capillary pressure. None has explored the relationship between hydraulic conductivity and some basic soil/liquid engineering properties such as

- Moisture content of the partially saturated soil;
- NAPL content of the partially saturated soil;
- Void ratio of the partially saturated soil;
- Suction in the partially saturated soil; and
- Density of the partially saturated soil.

Hydraulic conductivity may also be a function of

- Double layer thickness;
- pH; and
- Fluid properties ρ_w, ρ_{napl}, μ_{napl} and v_{napl}, and medium property, k, intrinsic permeability.

These fluid properties are combined in the expression for relative permeability: $K = \rho gk/\mu$. For clay soils, cation composition plays an important role on permeability. In general, higher valence cations result in thinner diffuse double layer, flocculated structure and higher permeability while low valence cations lead to thicker diffuse double layer, dispersed structure and lower permeability. The "thickness" of the double layer is expressed as:

$$t_{dl} = f\left(\frac{1}{v}\sqrt{\frac{DT}{n_o}}\right) \tag{2.18}$$

where v, D,T, and n_o, respectively, represent cation valence, dielectric constant of the medium, temperature, and electrolyte concentration (Mitchell, 1993). For heterovalent systems with constant charge, Collis-George and Bozeman (1970) showed that there is a much greater concentration of divalent than monovalent cations near the clay surface even if the concentration of monovalent cations is much greater in the bulk solution. Also, low pH often leads to flocculation. It appears justifiable, therefore, to conclude that k_{rnw} is also a function of double layer thickness and pH. However, thickness of the double layer and the medium dielectric constant and electrolyte concentration are not easy to determine. For this reason pH can be used as one of the controlling parameters to affect the double layer thickness and thus relative permeability. This study is an effort to broaden the current state of knowledge in this area.

CHAPTER 3

RESEARCH PROGRAM

3.1 Research task

This research is to study the laboratory conductivity of TCE in partially saturated sands and to relate each value of hydraulic conductivity to some basic soil parameters that are either easy to determine or are in wide use. Hydraulic conductivity is one of the most important properties governing solute transport and water flow in partially saturated soil. It has been observed that hydraulic conductivity exhibits significant spatial variability (Russo and Bouton, 1992; Byers and Stephens, 1983; Warrick and Nielsen, 1980; and Nielsen et al., 1973). Measurement of hydraulic conductivity is a difficult and time-consuming undertaking. Therefore, much research has focused on parameter estimation techniques for unsaturated hydraulic conductivity as a function of degree of saturation, θ, or soil water pressure head, (Burdine, 1953; Gardner, 1958; Brooks and Corey, 1964; Mualem, 1976; and van Genutchen, 1980). However, there is as yet no universally accepted method available to predict unsaturated hydraulic conductivity from more easily obtainable soil properties (Hillel, 1998).

The research focused on two major tasks. The first task is to experimentally determine the hydraulic conductivity in a partially saturated soil of a chosen non-aqueous phase liquid as a function of the model variables identified in Section 5.1. The second task involved the exploration of possible relationship between hydraulic conductivity and the various independent soil and liquid parameters. The first task was done by using a modified falling head test equipment. The method of regression analyses was used to further investigate the possible relationship in the second task of the study. This study recognized from the beginning that there may be no clear relationship between the hydraulic conductivity and independent variables.

Some of the model variables may produce no change in the hydraulic conductivity when all the remaining variables are held constant. They will then be replaced by another NAPL and/or soil parameter and the analyses is then repeated. The objective is to discover all β_j regression coefficients, where β_j represents the expected change in hydraulic conductivity per unit change in each model variable, when all the remaining model variables are held constant. These sensitivity analyses will be conducted for all independent variables.

3.2 Research benefits and anticipated results

3.2.1 Research benefits

The benefits of this study include promise of discovering previously unknown relationships between NAPL hydraulic conductivity and easily obtainable soil properties. This new relationship can be used to verify hydraulic conductivity values used in several currently existing computational methods provided that the verification is done for soils whose properties are fully known and are within the space containing the data used in this study. The results may lead to; 1. Availability of a new tool for predicting the fate and transport of NAPLs in the vadose zone, 2. Prediction of contamination potential of non-aqueous phase liquids, 3. The ability to compare the results with those obtained by using numerical methods such as finite element or finite difference methods, 4. Ease of use in multi-layered soils and for studying the variability of the conductivity of other NAPL liquids in unsaturated soils, and 5. Potential to reduce risk to human health and the environment. For example, this method can be used to determine whether standards for

Maximum Concentration Levels (MCLs) for drinking water set by EPA in 1987 are satisfied for any current or proposed situation according to Equations 3.1.

$$Q = k_{MCL} iAt \tag{3.1a}$$

$$MCL = \frac{mass}{volume} = \frac{mg}{Liter} \tag{3.1b}$$

$$MCL = \frac{mass}{Q} = \frac{mg}{k_{MCL} iAt} \tag{3.1c}$$

$$k_{MCL} = \frac{mg}{MCL}(iAt) \tag{3.1d}$$

where,

Q is volume of contaminant (cm^3, Liter);

k_{MCL} is the maximum contaminant effective unsaturated hydraulic conductivity;

i is hydraulic gradient;

A is cross section area (cm^2);

t is time (sec).

Conformity with US EPA Maximum Contaminant Level will require that actual contaminant effective hydraulic conductivity must not exceed k_{MCL}.

3.2.2 Anticipated results

It is anticipated that the model will discover some hitherto unknown relationship between dependent variable hydraulic conductivity of a NAPL in a partially saturated soil and independent variables NAPL , water and soil properties. The relationship may be a multiple linear or non-linear model. Interaction terms will be investigated and included if found to be significant. As previously mentioned, this researcher realizes that, there may be no relationship between hydraulic conductivity and one or more of the independent variables. In that case, this study will identify those variables that have no relationship with the conductivity of the NAPL. The model will be assessed for adequacy in predicting the fate and transport of the NAPL. It is also anticipated that the new model can be used in computer models for environmental water quality protection.

This study may have high applicability because a new instrumentation that did not exist before has been used and the soil properties used are easy to obtain. It has scalability defined here as how well the solution will work when the size of the problem is increased. Any conclusions presented are valid within the confines of the data used. The method presented in this study is scalable and so can be used in soils with multiple layers, and a mixture of chemicals.

3.3 NAPL to be studied

NAPLs of interest to this researcher include perchloroethylene (tetrachloroethylene, ethylene tetrachloride, PCE), Trichloroethylene (ethynyl trichloride, TCE), 1,1,1-trichloroethane (methyl chloroform, TCA), dichloromethane (methylene dichloride, DCM), and gasoline. The first four are DNAPLs and gasoline is a LNAPL. Pankow et al. (1996) considered the first four as the most common chlorinated solvents. In their study of groundwater contamination, Mendoza and McAlary (1989) chose to study TCE. Their rationale was also that TCE is one of the most common organic contaminants found in groundwater. They argued that since many other chlorinated solvents have properties similar to those of TCE, the general results of the study could be applied to many cases where volatile chlorinated solvents are accidentally released into the unsaturated zone. This study selected TCE as the NAPL of choice for the same reasons.

3.4 Properties of NAPLs

The hydraulic conductivity of any fluid will depend in part on its properties. The following discussion focuses on the properties of chlorinated solvents that have helped in leading to extensive contamination of groundwater. The properties are:

Volatility:

The higher the volatility of the chemical, the higher the concentration of the gaseous phase, and the lower the concentration in the aqueous and liquid phases and in the concentration adsorbed onto the soil solids. Higher volatility decreases TCE hydraulic conductivity.

Density:

When a sufficient volume of a chemical is spilled above the capillary fringe, the fluid denser than the native water will most likely penetrate deeper into the subsurface. The range of densities is from 1.2 to 1.7 g/cm^3 (Pankow et al., 1996). Frind (1982) calculated the effect of density on the vertical component of groundwater velocity, v_g by Equation 3.2.

$$v_g = \frac{-k_{zz}}{\theta_t}\left(\frac{\rho}{\rho_o} - 1\right) \tag{3.2}$$

Where,

k_{zz} is the hydraulic conductivity in the vertical direction;

θ_t is porosity;

ρ is the density of the contaminated water; and

ρ_o is the density of the native ground water.

Equation 3.1 shows that higher densities increase NAPL hydraulic conductivity.

Viscosity:

Cohen and Mercer (1993) showed that the mobility of chlorinated solvents increases with increasing density/viscosity ratios. This means that if density of a chlorinated solvent remains constant, increasing depth and temperatures will decrease viscosity and so increase hydraulic conductivity. At greater soil depths, soil temperature increases. This will reduce the viscosity and so increase the density-viscosity ratio which in turn increases the mobility of a chlorinated solvent. Increased hydraulic conductivity reduces travel time to fresh water aquifer.

Interfacial tension:

Interfacial tension causes water to rise above the phreatic surface. Capillary rise is inversely proportional to the diameter of a capillary tube. Hazen (1930) related the height of capillary rise in unsaturated soil to the effective size. He approximated the capillary rise height, h_l, in mm to be equal a constant C (that varies from 10 to 50 mm^2) divided by the product of void ratio, e, and the effective size, D_{10} (in mm), of the soil. Equation 3.3 describes the Hazen's empirical formula.

$$h_1(mm) = \frac{C}{eD_{10}} \qquad (3.3)$$

The capillary rise varies non-linearly from a minimum at 100 percent saturation to a maximum (h_l) at zero percent saturation. This is particularly important in fine grained soils with smaller D_{10} and higher capillary rises. The interfacial tension is low between water and a liquid chlorinated solvent. Therefore, it is easy for a chlorinated solvent to enter into small pore spaces and fractures. This increases the depth of penetration into the subsurface. Low interfacial tension contributes also to the low retention capacities of soils for chlorinated solvents (Pankow and Cherry, 1993).

The surface tension of chlorinated solvents plays an important role in the capillary zone. Water has a higher surface tension than chlorinated solvents. Therefore, when chlorinated solvents reach the capillary fringe, they are held up until hydrostatic head increases to the level where it is higher than the capillary retention or rise of the water. The capillary rise, h_c, (Equation 3.4) itself is inversely proportional to the liquid density and the diameter, d of the capillary tube and directly proportional to the interfacial tension.

$$h_c = \frac{4T\cos\alpha}{d\gamma_w} \tag{3.4}$$

where,

T is liquid-air surface tension;

α is contact angle;

d is diameter of capillary tube;

γ_w is unit weight of water.

Therefore, in fine grained soils where the pore throat radius is smaller, higher hydrostatic head is needed to displace capillary water. Small pore sizes require high hydrostatic heads to displace entrained water. When the pore size is small as in fine grained soils, and the liquid density is small as in LNAPLs, high interfacial tension will result in very high capillary retention. This will lead to significant lateral spreading of a LNAPL above the capillary fringe. For DNAPLs with the same small pore size, higher interfacial tension will result in a relatively smaller capillary retention and relatively smaller lateral spreading but with higher tendency to sink into the saturated zone. Surface tension affects how the surface of liquid in larger pores are shaped. Low interfacial tension between NAPL and water enables the NAPL phase to enter small pore spaces. This increases hydraulic conductivity. Interfacial tension at solid surfaces controls which fluid is the wetting phase.

Wettability is the tendency of one fluid to replace another on a surface. According to Vance (1995), the following broad rules apply.

- In soil, water is the wetting fluid with respect to solvents or air.
- Solvents are wetting fluids in air, but not when in the presence of water.
- With respect to carbonaceous soil components, solvents are the wetting fluids in the presence of air or water.

Because NAPLs are organic and form part of the carbonaceous soil components, they are the wetting fluid in the presence of air and water. Therefore, free phase chlorinated solvents have the ability to dehydrate clays, causing cracking and additional migration through initially impermeable soil layers. Bentonite pellets used to seal wells in areas contaminated with DNAPLs may not work because they may be dehydrated and so that they will not swell.

Solubility:

In general, NAPLs have low solubility in water, up to hundreds of mg/L. Solubility values such as these are low but can exceed Maximum Concentration Limits for drinking water set by EPA in 1987. Low water solubility means that when sufficient quantities of NAPLs are present, a separate NAPL phase will exist and will affect hydraulic conductivity. The persistence of NAPLs in the subsurface was very clearly illustrated by Palmer and Johnson (1989) in the following example. Consider a soil with a 35 percent porosity and containing TCE at a 25 percent residual saturation. This means that there is 0.07 m^3 or 103 kg of TCE within the soil. Assuming TCE solubility in water of 1,100 mg/L and ground water flow rate of 1.7 cm/day, it would take 15.4 years for the TCE to be removed by dissolution. If the contaminated aquifer is 2 m long, 30.8 years are necessary.

Low solubilities in water, especially when accompanied by low vapor pressures, as in the case of Tetrachloroethylene (PCE, with a solubility of 150 mg/L at 25°C and vapor pressure of 14 mm of Hg at 20°C) ensure that the losses due to dissolution and volatilization are very small. This makes chlorinated solvents very mobile in the vadose zone. Mass transport of solute across a gas-liquid interface are explained using the two-film theory. When the concentration of contaminant A in the bulk water is greater than its concentration at the air-water interface, contaminant A will diffuse from the bulk water to the air-water interface where its concentration is lower. The driving force (for stripping in the liquid phase) is the difference in the concentration levels. The reverse occurs for stripping in the gas phase. When solubility in water is high, more of the chemical will dissolve in groundwater and advective transportation will increase. Polycyclic aromatic hydrocarbons (PAHs) have melting point that are at least 80° C (for naphthalene). Therefore, they are solids at the temperatures typical in the subsurface. This can limit their migration potential in the soil. However, PAHs can become soluble and mobile when they are dissolved by petroleum hydrocarbons. Such PAH solutions are typically lighter than water. Chlorinated solvents are liquids at normal subsurface temperatures. This makes them very mobile in unsaturated and saturated soils. Table 3.1 lists properties of some Chlorinated solvents. Higher vapor pressure increases partition to the vapor phase.

NAPL/water partitioning coefficient (Octanol-water partitioning coefficient):

The octanol-water partitioning coefficient, k_{ow}, is the ratio of the concentration of an organic compound in octanol to the concentration in water (C_o/C). This coefficient gives an indication of how much of a chemical will partition into the aqueous or NAPL phase. A low value (< 10) means that the NAPL has low soil adsorption and tends to be hydrophilic. Therefore, a low value increases hydraulic conductivity.

Soil/water partitioning coefficient, k_p:

This is the ratio of the concentration of the NAPL or chemical to be adsorbed by soil or sediment (X) to the concentration in water (C), $k_p = X/C$. A low value means that there is more of the NAPL dissolved in water than adsorbed by soil and should increase hydraulic conductivity. Concentrations X and C are usually expressed in parts per billion (ppb) or micro gram per kilogram ($\mu g / kg$).

Organic/carbon partitioning coefficient, k_{oc}:

The organic carbon partition coefficient measures the ratio of the concentration of the organic chemical adsorbed to soil organic carbon to the concentration in water ($k_{oc} = C_c/C = k_p/f_{oc}$) where f_{oc} is the fraction of organic carbon in the soil. The concentration adsorbed (C_c) is also expressed in either ppb or $\mu g / kg$. Almost all of the adsorption of organic chemicals by a soil is due to the organic carbon content of the soil.

For NAPLs, partitioning to soils is low (Pankow and Cherry, 1996). Therefore, hydraulic conductivity will not be significantly retarded by low soil water and low organic carbon partitioning coefficients.

Table 3.1 Pure compound solubilities at 20 ^{0}C and Maximum Concentration Levels (MCLs) for drinking water (EPA, 1987)

Chlorinated solvent	Abbreviation	MCL (EPA) (mg/L)	Solubility (mg/L)
Tetrachloroethylene	PCE	0.005	200
1,1,1-Trichloroethane	1,1,1-TCA	0.2	720
Carbon tetrachloride	CTET	0.005	785
Trichloroethylene	TCE	0.005	1,100
Chloroform	TCM	0.1[a]	8,200
Methylene chloride	DCM	0.01[a]	20,000

[a] New York Department of Environmental Conservation Guidelines for Groundwater.

Vapor-liquid partitioning coefficient:

This is the ratio of the concentration of a compound in the vapor to the concentration in the liquid at equilibrium. It depends on vapor and atmospheric pressures, temperature, and the composition of the vapor and liquid. A low value increases hydraulic conductivity.

Degradibility:

Degradability of chlorinated solvents by either biological means or by abiotic-chemical reactions is low (Pankow and Cherry, 1996). This increases the lifetimes of these solvents. It is a fact that some NAPLs can be degraded in the subsurface under conditions favorable for degradation such as:

- **moisture**: moisture content of the medium should exceed 92% relative humidity
- **temperature**: optimum being in the range of 20° to 45°C
- **total dissolved solids**: not to exceed 40,000 mg/L and should not vary by more than a factor of 2.0 over a period of a few days.
- **pH**: 6 to 8 is considered favorable
- **nutrients**: the rule-of-thumb for TOC:N:P ratio is 20:5:1. Micronutrients such as sulfur, potassium, calcium, magnesium, iron, e.t.c. are assumed to be available to support microorganism metabolism.

For example, trichloroethane and trichloroethylene can be degraded by soil and marine bacteria; PCBs can be degraded by Pseudomonas and Flavobacterium. Also, the relationship between water content and capillary pressure is hysteretic. Effects due to biochemical processes and hysteresis will not be included in this study This study ignores the effect of contaminant degradability on hydraulic conductivity of NAPLs. TCE hydraulic conductivity increases as degradability decreases.

CHAPTER 4

LABORATORY EXPERIMENTAL METHOD

4.1 Laboratory method and setup

The research method aims to evaluate the hydraulic conductivity of key NAPLs in partially saturated sands in the laboratory. The method used is a modification of the falling head method and was developed for hydraulic conductivity testing of unsaturated soils.

The experimental setup is shown in Figures 4.1 through 4.3. The arrows in Figure 4.2 show the movement of water to equalize pressures inside and outside the porous ceramic cup. The setup consists of the following and the symbols used in those figures are described as follows:

A: tensiometer

B: 5-bar ceramic cylinder 4.0 inch OD, and 3.68 inch ID

C: Teflon cylinder, 6 inch OD, and 5-3/4 inch ID

D: ¾ inch diameter bolt

E: bottom teflon plate, 10 inches by 10 inches by 1 inch thick

F: top teflon plate, 10 inches by 10 inches by 1 inch

G: water container

H: pressure gauge

I: vacuum pump

J: burette

K: plastic tube

L, M: porous ceramic stone

N: NAPL reservoir

O: air pressure supply panel

P: water container

Q: carbon dioxide cylinder

R: flask

Porous ceramic cylinders are generally inert with very consistent and uniform pore structures. They are capable of meeting most demanding pressure differentials without leaks and are equipped with open structures that permit fluid movement from one surface to the other.

The ceramic cylinder was purchased from Soil Moisture Equipment Corporation. It is hydrophilic (water loving) with a displacement pressure of 2 bar (model No B01M1). The pores and channels have a highly charged pore surface that attracts and bonds the polar water molecules giving it the ability to fill pores by capillary action. It has a bubbling (displacement or air-entry) pressure of 38 to 45 psi, an approximate porosity of 32%, a hydraulic conductivity of 6.30×10^{-7} cm/sec, a maximum pore size of 1.1 μm, and a 4.2 ml/hr/cm^2/14.7 psi flow through a ¼-inch thick plate. The air-entry value is the pressure at which air will break through a wetted pore channel.

The Teflon cylinder surrounds the ceramic cylinder. Like the ceramic cylinder, the Teflon cylinder has "O" rings above and below it. Figure 4.4 shows operating parts of model 2100F tensiometer purchased from Soil Moisture Equipment Corporation. This model was chosen because of a long nylon tube that can extend from the tensiometer to

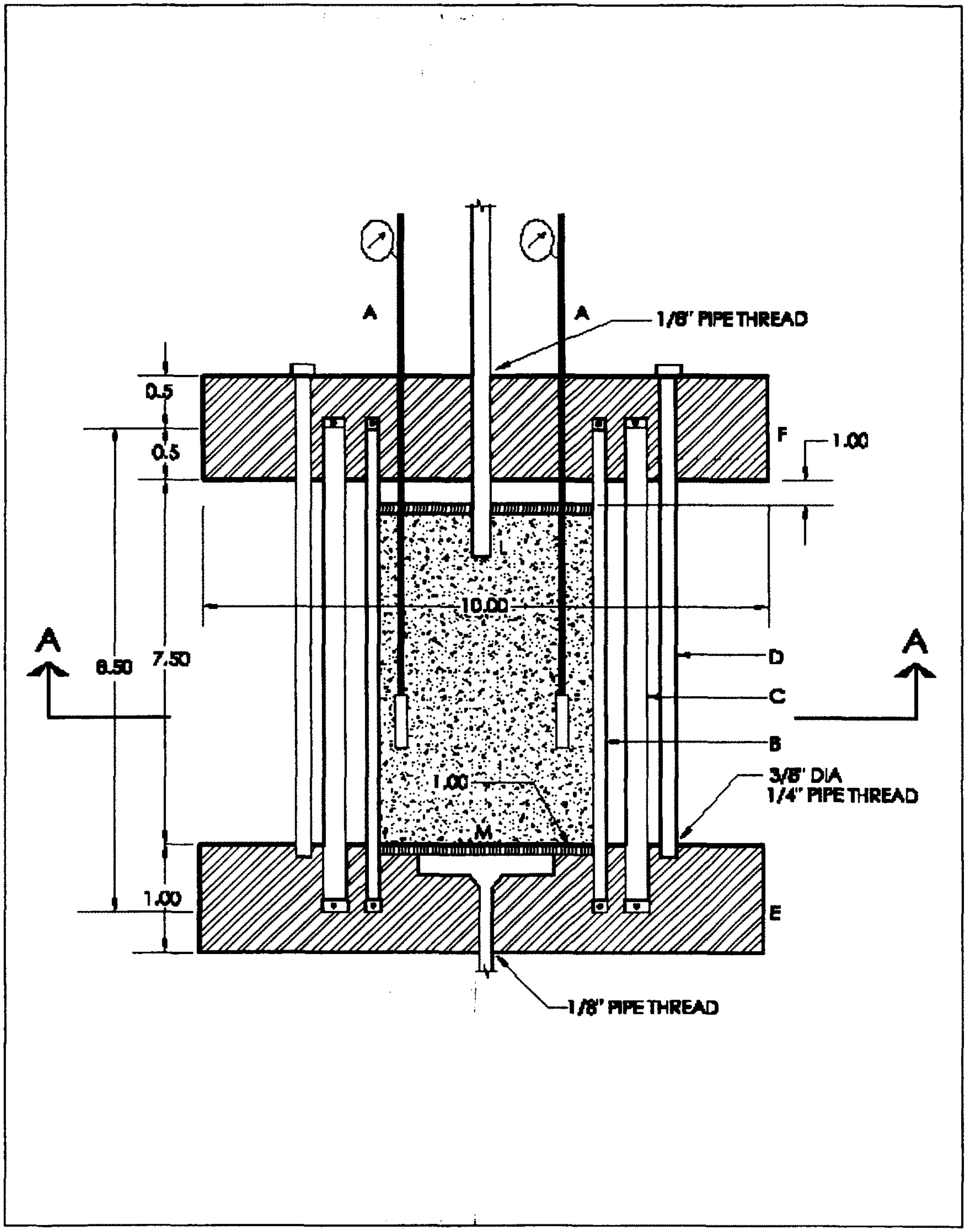

Figure 4.1 Test chamber for partially saturated soil.

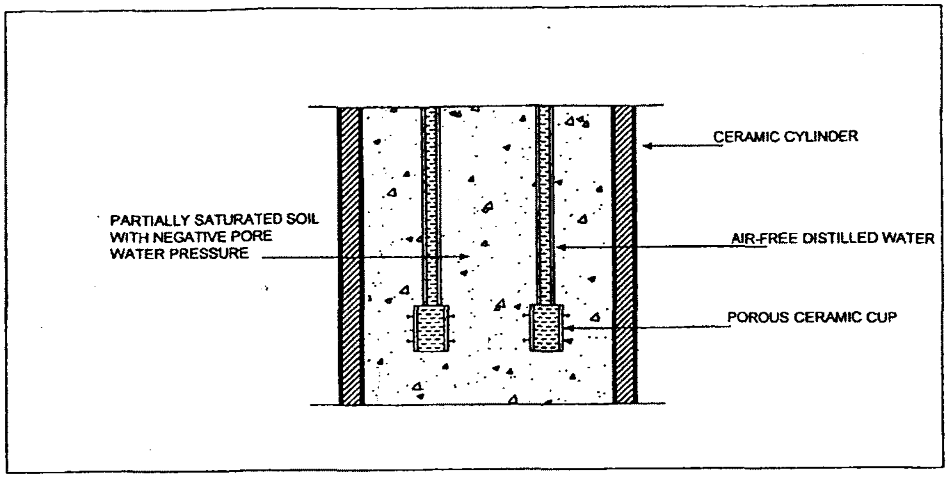

Figure 4.2 Cross-section through porous ceramic cup and ceramic cylinder

the middle of the soil specimen. Special care was taken to avoid a kink in the nylon tube. The tensiometer must be prepared as follows before the usage in conductivity tests:

1. Prepare about 0.95 liter (one-quarter gallon) of air-free water.
2. Immerse the porous ceramic cup in air-free water for at least one hour to fill the pores.
3. Fill the plastic applicator bottle with air-free water. Unscrew the service cap and squeeze the bottle to allow the water to slowly run down the inside wall of the plastic body tube as shown in Figure 4.5.
4. Remove the water vent screw and squeeze the applicator bottle to force water through the outer nylon tube, to the porous ceramic cup and back through the vent tube and out through the vent. Continue this until a clear flow of water, with no air bubbles,

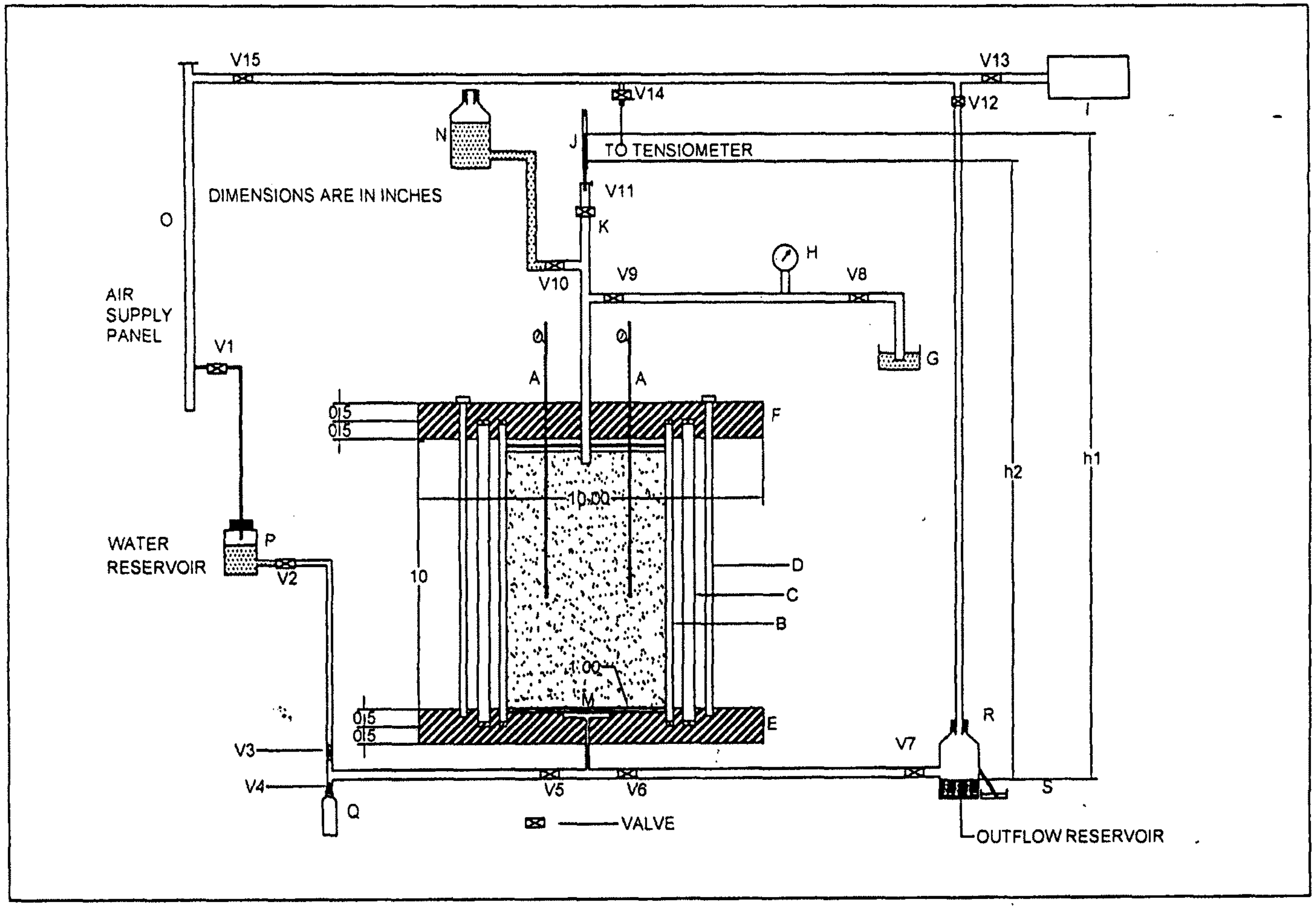

Figure 4.3 Front view of instrument setup

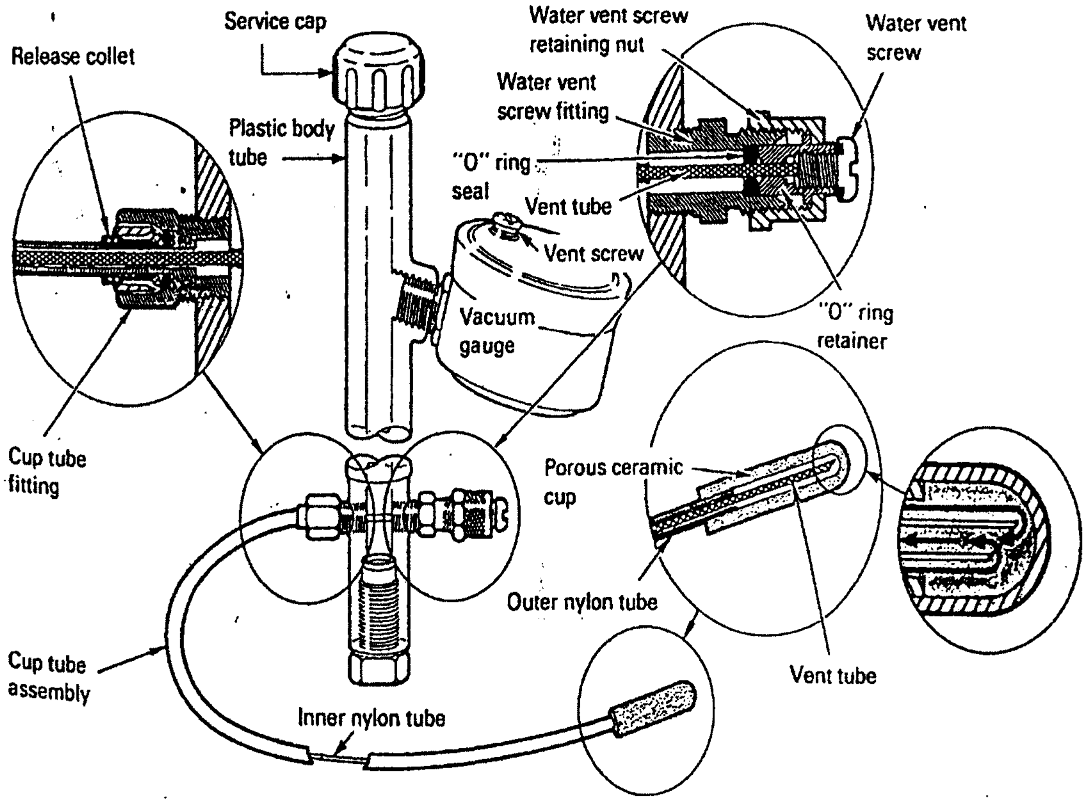

Figure 4.4 Operating parts of the 2100F tensiometer.

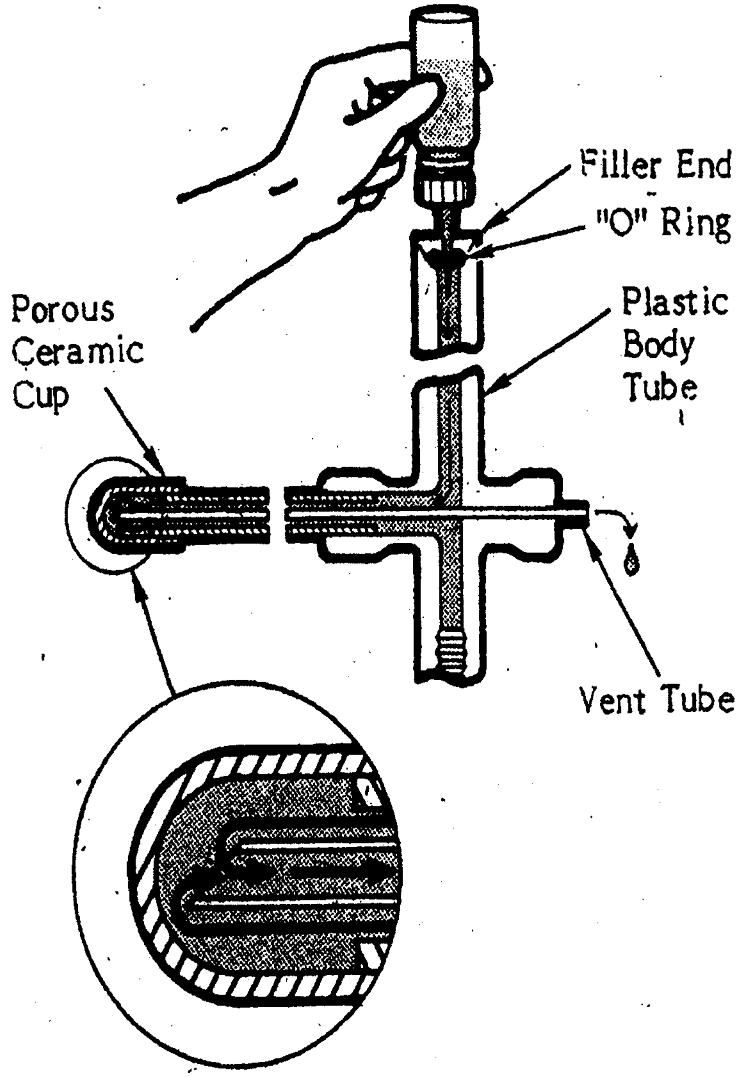

Figure 4.5 Filling the 2100F tensiometer with water.

exits from the vent tube. This purges air from the system. Replace the water vent screw.

5. Remove air from the vacuum dial gauge by applying suction from the vacuum pump. The vacuum gauge reading will be seen to rise. Stop the suction so that the gauge reading drops to zero. Add water to the inside wall of the plastic tube to keep the water level above the vacuum gauge connection. Repeat this process several times to remove as much air as possible from the vacuum gage. Make sure the gauge reading is zero before recording test pressure. This can be done by removing the vacuum gauge vent screw, inserting a small screw driver into the hole in the gauge cover and turning the screwdriver either clockwise to reduce the reading to zero or counter-clockwise to increase the reading to zero from any initial reading.
6. Loosen the water vent screw to purge water from the nylon tubes. Tighten the water vent screw.
7. If necessary, fill the plastic body tube with water.
8. Screw the service cap on snugly.
9. Use absorbent tissue or a clean cloth to remove excess moisture on the porous ceramic cup.
10. Support the tensiometer in a vertical position so that moisture is free to evaporate from the porous ceramic cup. Allow the tensiometer to remain in this position for about twenty four hours for the probe to come to equilibrium with the soil. The tensiometer operates in the range of zero to 85 centibars.

4.2 Laboratory procedure

The procedure for the laboratory test can be presented in the following sections: For the procedures described below, the open or close status of each valve is contained in Table 4.1.

4.2.1 Test setup

Oven dry a volume of soil about twice the volume of the ceramic cylinder to a constant weight. Prepare the instrumentation as shown in Figure 4.1. Make sure that (a) air-free water is available, (b) the vacuum pump, the pressure supply panel, and all valves are in good working condition, (c) the 40 gallon carbon dioxide cylinder is full, (d) the tensiometers are ready after preparation as discussed earlier, and (e) the water containers are filled with de-aired water.

4.2.2 Specimen preparation

Install the ceramic and Teflon cylinders into the bottom plate. Support the top plate in a horizontal position with a tripod or burette stand. Carefully secure the tensiometers into the top plate such that the bottom of the porous ceramic cup is about 10 cm inches below the bottom face of the top plate. In this position, the porous ceramic cups will be in the middle of the height of the soil specimen since the specimen will be filled to a height about one inch below the bottom of the top cap. Put aside the top plate with the tensiometer assembly. Pour the dry soil specimen into the ceramic cylinder with a scoop or funnel to form a uniform layer with a top at about eight three inches above the bottom porous stone. It may be necessary to incline the funnel to pour the soil, depending on the height of the top plate-tensiometer assembly above the top of the ceramic cylinder.

Table 4.1 Valve position during test.

Valve # (Fig. 4.3)	Taking initial measurements	Carbon dioxide displacement of air	Water displacement of carbon dioxide	Drainage of water	Flow NAPL from	
					Reservoir	Burette
1	C	C	O	C	C	C
2	C	C	O	C	C	C
3	C	C	O	C	C	C
4	C	O	C	C	C	C
5	C	O	O	C	C	C
6	C	C	C	O	O	O
7	C	C	C	O	O	O
8	C	O	O	C	C	C
9	C	O	O	C	C	C
10	C	C	C	C	O	C
11	C	C	C	C	C	O
12	C	C	C	O	C	C
13	C	C	O	O	C	C
14	C	C	C	C	C	C
15	C	C	O	C	C	C

C = closed, O = open.

Lower the top plate-tensiometer assembly to complete the attachment to the cylinders. Determine the length of the soil specimen and completely lower the top plate.

4.2.3 Initial measurements

The entire test set-up was placed on a balance to measure the change in mass. The initial measurements include mass of instrument set-up before and after filling with the soil specimen. The difference will give the mass of the dry soil. The mass of the initial set-up includes the combined masses of, (a) bottom plate plus attached bolts, (b) the two attached tubes, (c) Teflon cylinder, (d) ceramic cylinder, and (e) top plate plus NAPL burette and input tank. The length of the dry soil specimen is also recorded.

4.2.4 Carbon dioxide displacement of air

At this point, the soil consists of two phases, solid and air. The carbon dioxide saturation method is used to saturate the specimen. First, the air must be displaced using carbon dioxide from the carbon dioxide tank, G. Referring to Figure 4.3, the carbon dioxide flows from the tank into the specimen from the bottom and exits through the water container, G. The gauge, H, indicates the carbon dioxide pressure. The displacement of air is completed after gas bubbles stop flowing through the water container, G.

Carbon dioxide is denser than air. Carbon dioxide from the carbon dioxide cylinder is used to expel air from the dry soil within the ceramic cylinder. The expulsion of air is assumed complete after about five minutes. The vacuum pump is used to (a) complete saturating the sample with water, (b) remove air from the tensiometer dial gauge as described in step 5 of section 4.1.1 above, and (c) apply suction pressure on the soil specimen to induce negative pressure. Flow valves 1 through 15 are used as shown in Figure 4.3 to control fluid flow. The open or close status of each valve is shown in Table 4.1 during various phases of the test.

4.2.5 Water displacement of carbon dioxide

Activate the vacuum pump. Direct the air pressure from the vacuum pump through the air pressure supply panel to cause water to flow through the water reservoir and the bottom plate upwards into the sample. Water will displace the carbon dioxide. The displacement is completed when the pressure at gauge, H, is zero and no more bubbles are seen coming from water container, G. At the completion of this task, the soil is still two phases, namely solid and water. The sample is now saturated with water. The sample is allowed to remain saturated for at least one half hour for cohesionless samples.

4.2.6 Drainage of water

The next task is to create a partially saturated soil. With the valves in the positions indicated in Table 4.1, vacuum pressure is pulled through the tube in the bottom plate, E. In response to this suction pressure, the tensiometer gauges will record the negative pressure. At the completion of the drainage, the soil specimen consists of three phases, namely: solid, water, and vacuum. The vacuum phase is replaced with air by applying suction with valve v11 open and burette J is empty. Records taken are a timed record of instrument mass from which changes in mass of water, water content, and NAPL content are calculated.

4.2.7 Flow NAPL from NAPL reservoir

Record the total instrument mass. Introduce NAPL (TCE) into the NAPL reservoir N with a funnel. First, TCE is withdrawn from reservoir N into the specimen. The flow is by gravity and takes a few minutes during which the TCE being denser than water occupies the space just below the water phase. It may be necessary to open reservoir N to the atmosphere to get TCE to flow into the specimen. Reported density values for water, TCE and sand are about 1.0, 1.47 and 1.6 g/cm^3, respectively. This downward flow of TCE can be increased, if desired, by applying suction from the bottom of the sample. This flow is continued until there is an overflow of liquid through container, R into container, S. Valve closed/open position during each phase of the test is shown in Table 4.1. Record the difference in height, h_1.

4.2.8 Flow NAPL from burette

With all the valves closed except valves v11, v6 and v7, NAPL is allowed to flow from burette J through the soil specimen into erlenmeyer flask R and S. Apply suction with the vacuum pump if necessary to increase flow rate. Use a vented Erlenmeyer flask R when applying suction. Use Erlenmeyer flask with double side arms, R when flowing the NAPL. The value of mass of the entire set-up is used to compute increase in mass due to the TCE. This increase in mass is used to calculate timed values of the NAPL content, soil suction values, and density of the soil containing the soil solid, TCE, and water. The final value of the height difference, h_2 is also recorded.

4.3 Development of equation for data analyses

The rate of fluid flow, q, through the soil specimen is given in Equation 4.1 as:

$$q = -a\frac{dh}{dt} \tag{4.1}$$

where q is measured in m^3/s, a is the area of the standpipe m^2, h is the height by which the fluid in the standpipe is above the level in the outflow reservoir (m), and t is the time over which the fluid flow occurred in seconds. The hydraulic conductivity of the non-wetting phase can be obtained from Equation 4.2:

$$k_{nw} = \frac{-q_{nw}\mu_{nw}}{(\rho_{nw} - \rho_w)g} \tag{4.2}$$

where, k_{nw} is the hydraulic conductivity of the non-wetting phase, which is a function of fluid saturation, and fluid saturation is a function of capillary pressure. μ_{nw} is the dynamic viscosity of the non-wetting phase. Darcy's law states that

$$q = kiA \tag{4.3a}$$

where

q is flow rate (m^3/s);

k is coefficient of permeability (m/s);

i is hydraulic conductivity (Δ h/L); and

A is cross-sectional area of the soil specimen (m^2).

For water (wetting phase) and NAPL (non-wetting phase), Darcy's law is, respectively,

$$q_w = k_w i_w A \tag{4.3b}$$

$$q_{nw} = k_{nw} i_{nw} A \tag{4.3c}$$

The subscripts w and nw in Equations 4.3b and 4.3c represent wetting and non-wetting phases, respectively. Equation 4.3a can be written as Equation 4.4.

$$q = kiA = k\frac{h}{L}A = -a\frac{dh}{dt} \tag{4.4}$$

Rewriting Equation 4.4 for the wetting phase:

$$-aL\frac{dh}{Ah} = k_w dt \tag{4.5a}$$

And for the non-wetting phase:

$$-aL\frac{dh}{Ah} = k_{nw}\,dt \tag{4.5b}$$

The influence of fluid density and absolute (dynamic) viscosity on the coefficient of permeability is shown in Equations 4.6a and b for both wetting and non-wetting phases, respectively.

$$k_w = \frac{\rho_w g k_{\text{int}}}{\mu_w} \tag{4.6a}$$

$$k_{nw} = \frac{\rho_{nw} g k_{\text{int}}}{\mu_{nw}} \tag{4.6b}$$

In Equations 4.6a and b,

k_w, k_{nw} are wetting phase and non-wetting phase coefficients of permeability (m/s)

ρ_w , ρ_{nw} are wetting phase and non-wetting phase fluid densities (kg/m^3),

g is gravitational constant (m/sec^2),

μ_w, μ_{nw} are absolute (dynamic) viscosities of wetting phase and non-wetting phase (N-s/m^2).

k_{int} is intrinsic permeability (units of cm^2) that depends only on the characteristics of the porous medium, independent of the fluid properties. Substitute Equation 4.6a into Equation 4.5a to get Equation 4.7 for the wetting phase.

$$-\frac{aL}{A}\frac{dh}{h} = \frac{\rho_w g}{\mu_w} k_{\text{int}}\, dt \quad \ldots\ldots\ldots \tag{4.7a}$$

$$\frac{\rho_w g k_{\text{int}}}{\mu_w}\int dt = -\frac{aL_w}{A}\int \frac{dh}{h} \tag{4.7b}$$

$$\frac{\rho_w g k_{\text{int}}}{\mu_w} t\Big|_1^2 = -\frac{aL_w}{A}\ln h\Big|_1^2 \tag{4.7c}$$

$$\frac{\rho_w g k_{\text{int}}}{\mu_w}(t_2 - t_1) = -\frac{aL_w}{A}\ln(h_2 - h_1) \tag{4.7d}$$

$$\frac{\rho_w g k_{\text{int}}}{\mu_w}(t_2 - t_1) = \frac{aL_w}{A}\ln\frac{h_1}{h_2} \tag{4.7e}$$

From Equation 4.7e, the intrinsic permeability, k_{int} for the wetting phase is obtained in Equation 4.8

$$k_{\text{int},w} = \frac{a\mu_w}{A\rho_w g}\frac{L_w}{(t_2 - t_1)_w}\ln\frac{h_{1w}}{h_{2w}} \tag{4.8}$$

Similarly, by substituting Equation 4.6b into Equation 4.5b Equation 4.9 is obtained.

$$k_{\text{int},nw} = \frac{a\mu_{nw}}{A\rho_{nw}g}\frac{L_{nw}}{(t_2 - t_1)_{nw}}\ln\frac{h_{1nw}}{h_{2nw}} \tag{4.9}$$

From Equation 4.8, solve for the acceleration due to gravity for the wetting phase:

$$g = \frac{a}{A}\frac{\mu_w}{\rho_w}\frac{1}{k_{\text{int},w}}\frac{L_w}{(t_2 - t_1)_w}\ln\frac{h_{1w}}{h_{2w}} \tag{4.10a}$$

Similarly, for the non-wetting phase,

$$g = \frac{a}{A}\frac{\mu_{nw}}{\rho_{nw}}\frac{1}{k_{\text{int},nw}}\frac{L_{nw}}{(t_2 - t_1)_{nw}}\ln\frac{h_{1nw}}{h_{2nw}} \tag{4.10b}$$

From Equation 4.6a,

$$k_w = \frac{\rho_w}{\mu_w}\left[\frac{a}{A}\frac{\mu_w}{\rho_w}\frac{L_w}{(t_2 - t_1)_w}\ln\frac{h_{1w}}{h_{2w}}\right] \tag{4.11}$$

From Equation 4.6b,

$$k_{nw} = \frac{a}{A}\frac{L_{nw}}{(t_2 - t_1)_{nw}}\ln\frac{h_{1nw}}{h_{2nw}} \tag{4.12}$$

$$k_{nw,T} = \left[\frac{a}{A}\frac{\rho_{nw}}{\rho_w}\frac{L_{nw}}{(t_2 - t_1)_{nw}}\ln\frac{h_{1nw}}{h_{2nw}}\right]_T \tag{4.13}$$

where k_{nw} is the non-wetting phase coefficient of permeability, which is measured in the laboratory at a laboratory temperature of $T^{o}C$. It is customary to express the values of k_{nw} $(k_{nw,20})$ at 20°C. When the laboratory temperature is T°C at the time of testing, the k value, $(k_{nw,T})$ shall be corrected according to:

$$k_{nw,20} = k_{nw,T}\left[\frac{\mu_T}{\mu_{20}}\right] \tag{4.14}$$

The summary of data used to compute measured coefficient of hydraulic conductivity is in Appendix D.

4.4 Assumptions in experimental method

The following assumptions have been made for this model.

Source of NAPL:

The source of NAPL is from a supply bottle. The volume of NAPL available for transport through the partially saturated zone exceeds the NAPL absorption capacity of the medium. This volume is also assumed to be sufficient to form a fluid phase distinct from the water phase.

Flow direction:

Soil is assumed homogeneous. Therefore, flow is one-dimensional with no lateral spreading of NAPL. Any lateral spreading is assumed to be negligible.

Type of release:

The type of release of the NAPL is consistent with standard falling head approach but involves a four phase soil model. It is the gradual release type.

Effect of NAPL solubility:

This phase is negligible because of the low solubility of TCE in water. For NAPLs with low solubility, the component of concern is the immiscible phase.

Selected variables:

The empirical formulation combines the data from the laboratory results with the methods and tools of multiple regression analyses to discover hitherto unknown relationships between the laboratory determined values of hydraulic conductivity of the five NAPLs in partially saturated sands and several elected soil and NAPL properties. It is assumed that these soil and NAPL properties are random variables.

4.5 Parameters that affect hydraulic conductivity

It is clear from the above discussion that the hydraulic conductivity of non-aqueous phase liquids in unsaturated soils can be affected by the several factors summarized below.

Soil properties:

The following soil parameters affect relative permeability:

- θ : volumetric water content
- p_c : capillary pressure
- ρ_{nw} : density of unsaturated soil
- ϕ : porosity
- e : void ratio
- G_s : specific gravity of unsaturated soil
- θ_r : residual saturation
- k_s : saturated hydraulic conductivity
- D_{10} : effective size of soil grains
- PI : plasticity index = LL – PL

- OCR: overconsolidation ratio

NAPL fluid properties:

Several fluid properties exist that may influence hydraulic conductivity of any fluid. They include volatility, density, viscosity, interfacial tension, solubility, octanol-water partitioning coefficient, soil-water partitioning coefficient, organic carbon partitioning coefficient, vapor-liquid partitioning coefficient, degradability, and Henry's constant.

Other parameters:

Other parameters that may affect hydraulic conductivity include:

- preferential pathways
- degree of mechanical dispersion
- hysteresis of the fluid

4.6 Variables used in study

It is immediately obvious that no laboratory or field test can account for the effect of all the above variables. For this reason, only the following variables will be considered in this study. The variables considered in this study are the water content, soil NAPL content, void ratio, suction pressure, and density of the unsaturated soil. The empirical formulation of how each variable is used in the proposed model is presented in Chapter 5.

4.7 Description of soil used

Two sources of sand used are from the soil mechanics laboratories of Old Dominion University and Norfolk State University. Tables 4.2 through 4.5 present the results of the sieve analyses for both soils. Figure 4.6 plots their grain-size distribution curves. It was found that ODU sand is fine sand while NSU is coarse sand.

Table 4.2. Sieve analysis data for ODU sand.

Sieve #	Sieve size	Sieve mass Empty	Sieve mass with soil	Soil mass retained	% mass retained	Cum. Mass retained	Percent finer by weight
	(mm)	(g)	(g)	(g)	(%)	(%)	(%)
4	4.75	608.3	608.3	0.00	0	0	100
10	2	538.3	540.8	2.5	0.07	0.07	99.93
16	1.18	425.1	476.3	51.2	1.50	1.57	98.43
30	0.600	425.0	1093.2	668.2	19.52	21.09	78.91
40	0.425	393.7	810.7	417.0	12.18	33.27	66.73
60	0.250	399.2	2358.0	1958.8	57.22	90.49	9.51
100	0.150	355.0	580.7	225.7	6.59	97.08	2.92
200	0.075	342.1	436.0	93.9	2.74	99.82	0.10
Pan	-	491.0	496.7	5.7	0.17	100	0.0

Table 4.3. Sieve analysis data for NSU sand.

Sieve #	Sieve size	Sieve mass Empty	Sieve mass with soil	Soil mass retained	% mass retained	Cum. Mass retained	Cum. % passing
	(mm)	(g)	(g)	(g)	(%)	(%)	(%)
4	4.75	608.1	608.1	0.00	0.00	0.00	100
10	2	538.1	538.1	0.00	0.00	0.0	100
16	1.18	426.4	426.4	0.00	0.00	0.00	100
30	0.600	424.8	2445.3	2020.5	76.30	76.30	23.70
40	0.425	394.1	960.0	565.9	21.37	97.67	2.33
60	0.250	398.5	457.2	58.7	2.22	99.89	0.11
100	0.150	354.7	358.2	3.5	0.13	100.00	0.00
200	0.075	342.2	342.2	0.0	0.00	100.00	0.00
Pan	-	491.0	491.0	0.0	0.00	100.00	0.0

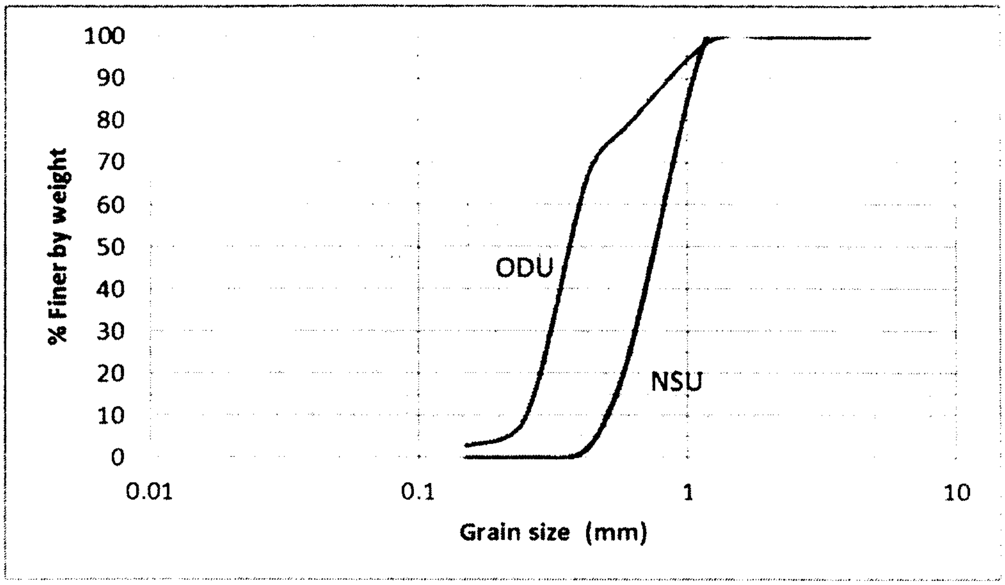

Figure 4.6 Grain size distribution for ODU and NSU sand.

Table 4.4 Summary of sieve analyses.

Sand	Retained, (%)		Finer, (%)	
	R_4	R_{200}	F_4	F_{200}
ODU	0	99.82	100	0
NSU	0	100	100	0

Table 4.5 Summary of soil sizes.

Sand	d_{10} (mm)	d_{30} (mm)	d_{60} (mm)	C_u $=(d_{60}/d_{10})$	C_g $=\left(d_{30}^2/d_{10}d_{60}\right)$	USCS Classification
ODU	0.26	0.31	0.4	1.54	0.92	SP
NSU	0.49	0.65	0.82	1.64	1.03	SP

CHAPTER 5

GLM - LINEAR SYSTEM MODELING

5.1 Proposed model

The objective of this analysis is to investigate and build a relationship between the experimental test results of hydraulic conductivity and the basic soil and NAPL properties. The system will be modeled using the generalized system modeling (GLM) approach. The research generated system data of the type shown in the following:

$$\begin{array}{ccccc} k_{nw1} & w_{11} & w_{n12} & e_{13} & \phi_{14} \\ k_{nw2} & w_{21} & w_{n22} & e_{23} & \phi_{24} \\ . & . & . & . & . \\ . & . & . & . & . \\ k_{nwn} & w_{n1} & w_{nn2} & x_{n3} & \phi_{n4} \end{array} \tag{5.1}$$

where k_{nw_i} represents the unsaturated (effective) hydraulic conductivity of the non-wetting phase and is the response variable, and the symbol w_{ij} , w_{nij} , e_{ij} , and ϕ_{ij}, represent, respectively, the water content, NAPL content, void ratio, and soil suction; subscript i=1, 2, ..., n represent the number of experiments performed and j=1,2,3, 4 represent the four independent variables. Appendix C contains laboratory data generated from the laboratory tests.

The unsaturated hydraulic conductivity, k_{nw}, also known as the effective hydraulic conductivity, (k_{eff}, cm/sec) is the one measured during the experiment for the non-wetting phase of the partially saturated soil. The relative conductivity, k_{rnw}, is then defined in Equation 5.2 below.

$$k_{rnw} = \frac{k_{eff}}{k_{abs}} \tag{5.2}$$

where,

k_{rnw} is the relative hydraulic conductivity of the non-wetting phase (dimensionless);

k_{abs} is the absolute (saturated) hydraulic conductivity of the non-wetting phase (cm/sec);

The value of n has to be greater than k + 1 since the degree of freedom, n - (k+1), must be positive where k is the total number of independent variables.

5.2 Linear model

Initially, it was unknown whether the relationship is linear or nonlinear. To explore the nature of the relationship, it is necessary to build a model for prediction of k_{nw}. That model may be linear or nonlinear. The unknown relationship, if linear, may be expressed by Equation 5.3.

$$k_{nw} = f(w, w_n\ e, \phi) \tag{5.3}$$

In Equation 5.3, w is (water content of partially saturated soil before the addition of NAPL (%)); w_n is (NAPL content (%)); e is (void ratio); ϕ is (soil suction in centibar).

The task of building the generalized linear model may be divided into the following:

(1) perform multiple linear regression analyses with all possible multicollinearity on independent variables and build a relationship among the response variable, k_{nw}, and the variables shown in Equation 5-3.

(2) perform normality check on the laboratory test data set.

(3) use both the generalized linear model (GLM) and stepwise methods of analyses

(4) compare the results from the GLM and stepwise methods to find out the "effective regressors".

The resulting model will be useful in predicting hydraulic conductivity of the NAPL in any partially saturated soil provided that no extrapolations will be made beyond the range of values used in the laboratory tests for the selected independent variables. Linear models may take several forms. Linear models can take the alternative forms shown in Equations 5.4 through 5.7.

$$k_{nw_i} = \beta_o + \beta_1 w_{11} + \beta_2 w_{n21} + \ldots\ldots\ldots\ldots\ldots + \beta_k \, \phi_{k1} + \varepsilon_i \tag{5.4}$$

$$k_{nw_i} = \beta_o + \beta_1 w_{11} + \beta_2 {w_{n21}}^2 + \ldots\ldots\ldots\ldots\ldots + \beta_k \, \phi_{k1}^2 + \varepsilon_i \tag{5.5}$$

$$k_{nw_i} = \beta_o + \beta_1 \ln w_{11} + \beta_2 \ln w_{n21} + \ldots\ldots\ldots\ldots\ldots + \beta_k \ln \phi_{ki} + \varepsilon_i \tag{5.6}$$

$$k_{nw_i} = \sum_{i=0}^{k} \beta_i f_i \left(w_{11}, w_{n21} \;, \ldots\ldots\ldots\ldots, \; \phi_{ki} \right) + \varepsilon_i \tag{5.7}$$

The intercept on the regression plot is β_o. The parameters β_j where j = 0, 1, 2, 3, 4, are the regression coefficients. Each coefficient other than β_o represents the expected change in hydraulic conductivity k_{nw} per unit change in each independent variable when all the remaining regressors are held constant. The term, ε_i in Equations 5.4 through 5.7 is random error term.

The proposed initial model may also be expressed as:

$$\vec{k}_{nw} = \vec{\alpha}\vec{\beta} + \vec{\varepsilon} \tag{5.8}$$

The parameters in Equation 5.8 are described by Equations 5.9 through 5.12

$$\vec{k}_{nw} = \begin{bmatrix} k_{nw1} \\ k_{nw2} \\ . \\ . \\ k_{nwn} \end{bmatrix} \tag{5.9}$$

$$\vec{\alpha} = \begin{bmatrix} 1 & w_{11} & w_{n21} & e_{31} & \phi_{41} \\ 1 & w_{12} & w_{n22} & e_{32} & \phi_{42} \\ . & . & . & . & . \\ . & . & . & . & . \\ 1 & w_{1n} & w_{n2n} & e_{3n} & \phi_{4n} \end{bmatrix} \tag{5.10}$$

$$\vec{\beta} = \begin{bmatrix} \beta_o \\ \beta_1 \\ . \\ . \\ \beta_k \end{bmatrix} \tag{5.11}$$

$$\vec{\varepsilon} = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ . \\ . \\ \varepsilon_n \end{bmatrix} \tag{5.12}$$

The matrix of random error terms, $\vec{\varepsilon}$, is assumed to be normally distributed with mean zero and variance , $\sigma^2 \vec{I}$. The identity matrix, $\vec{I}$ is defined as the n x n square matrix of size n with unit value on the diagonal and zeros elsewhere i.e $\vec{\varepsilon} \sim \mathrm{N}\left(0, \frac{\sigma^2}{\sqrt{n}} \vec{I}\right)$. ε is random error term ≥ 0 and $\varepsilon \sim NID(\mu, \sigma^2)$ with a mean = 1.0 and variance = σ^2.

5.3 Linear model assumptions

A linear model assumes normal distribution for the matrix of residuals $\vec{\varepsilon}$ in Equation 5.12. Four assumptions are used to justify the use of linear regression models. If any one of them is violated, the predictions from the model become inefficient or misleading.

Linearity:

This means that the model is linear in the partial regression coefficients, β_i where i = 1, 2, ... , n. Equation 5.8 predicts the expected value of the response variable k_{nwi} and may be re-written by Equation 5.13.

$$E(k_{nw_i}) = \beta_o + \beta_{1i} w_{1i} + \beta_{2i} w_{n2i} + \ldots + \beta_{ki} \rho_{wet\ ki} \tag{5.13}$$

Equation 5.13 implies that the expected value of the error terms in Equation 5.9, $E(\vec{\varepsilon}_i) = 0$, where i = 1, 2, ... , n and that the relationship between each pair of dependent and independent variables in Equation 5.1 is linear. If linearity is valid, a plot of predicted versus observed values of the response variable will be a 45° diagonal line around which the points will be symmetrically distributed. Also, if linearity is valid, a plot of residuals versus predicted response variable will show points symmetrically distributed around a horizontal line.

Constant variance (homoscedasticity):

The model also assumes that the variance of the error terms is constant for all k_{nwi} values according to Equation 5.14.

$$Var(k_{nw_i}) = \sigma^2 = Var(\varepsilon_i) \tag{5.14}$$

Homoscedasticity can be checked by plotting residuals versus predicted values of the dependent variable. Heteroscedasticity may be caused by violation of the linearity and or independence assumptions.

Independence of error terms (uncorrelation):

The assumption of uncorrelation states that the covariance is zero between any pairs of k_{nw_i}, k_{nw_j} or ε_i and ε_j. That is

$$Cov(k_{nwi}, k_{nwj}) = 0 = Cov(\varepsilon_i, \varepsilon_j) \tag{5.15}$$

where i ≠ j, and i, j = 1, ..., n. The residuals are approximately constant, not getting larger. This is basis to conclude that there is independence of the error terms. Correlation may be due to miss-specified model or violation of the linearity assumption. Residual autocorrelation may be detected by autocorrelation plot of the residuals.

Normality test:

Finally, in a linear model, it is assumed that k_{nw_i} and ε_i are normally distributed as follows, i.e., k_{nw} ~ N(E(k_{nw}), σ^2) and $\varepsilon \sim N(0, \sigma^2)$. It is therefore clear that the estimated errors (residuals) play important roles in assessing the model assumptions. In matrix form, these assumptions are:

$$E(\vec{\varepsilon}) = \begin{bmatrix} E(\varepsilon_1) \\ E(\varepsilon_2) \\ . \\ . \\ E(\varepsilon_n) \end{bmatrix} = \begin{bmatrix} 0 \\ 0. \\ . \\ . \\ 0 \end{bmatrix} = \vec{0} \tag{5.16}$$

$$D(\vec{\varepsilon}) = \begin{bmatrix} \sigma^2 & 0 & 0 & 0 & 0 \\ 0 & \sigma^2 & 0 & 0 & 0 \\ 0 & 0 & \sigma^2 & 0 & 0 \\ 0 & 0 & 0 & \sigma^2 & 0 \\ 0 & 0 & 0 & 0 & \sigma^2 \end{bmatrix} = \begin{bmatrix} Var(\sigma_1) & Cov(\varepsilon_1\varepsilon_2) & . & . & Cov(\varepsilon_1\varepsilon_{2n}) \\ Cov(\varepsilon_2,\varepsilon_1) & Var(\sigma_2) & . & . & Cov(\varepsilon_2,\varepsilon_n) \\ . & . & Var(\varepsilon_i) & . & . \\ . & . & . & Var(\varepsilon_i) & . \\ Cov(\varepsilon_n,\varepsilon_1) & Cov(\varepsilon_n,\varepsilon_2) & . & . & Var(\sigma_n) \end{bmatrix} \tag{5.17}$$

Where, $D(\vec{\varepsilon})$, is the dispersion (or the variance covariance matrix) of the vector $\underline{\varepsilon}$ and $\operatorname{cov}(\varepsilon_i,\varepsilon_j)$ is the covariance (measure of linear association between) of ε_i and ε_j; $i \neq j$. Deviations from normality may be due to, (a) the distributions of the independent or the dependent variables are significantly not normal, (b) violation of the linearity assumption, (c) or both.

The common tests for normality are Kolmogorov-Smirnov, Cramer-Von Mises, Anderson-Darling, and Shapiro-Wilk tests. Tests for normality were performed using the Shapiro-Wilk statistic since the number of independent normally distributed variables is less than 2000. The null hypothesis is that the data values are a random sample from a normally and independently distributed population (H_o : var ~ NID (μ,σ^2)). A decision has to be made to reject the null hypothesis of normality by comparing the probability that is associated with a test statistic with the Shapiro-wilk *p*-value shown in Table 5.1 as Pr<W. The last column in Tables 5.1 and 5.2 uses the symbols ND (normally distributed) and N (not normally distributed). The alternate hypothesis is (H_a : var ~ not NID (μ,σ^2)). If the *p*-value is less than the chosen level of significance such as 0.05 for 95% confidence, then the null hypothesis is rejected leading to a conclusion that the data does not come from a normal distribution. The smaller the *p*-value, the stronger the evidence for rejecting the null hypothesis.

The Shapiro-Wilk *p*-values in Tables 5.1 and 5.2 are much less than the level of significance α = 0.05. In Tables 5.1 and 5.2, NN in the last columns means the distribution is not normal. Therefore, the normality tests for a linear model failed at the α-level of 0.05. With 95% confidence, it is concluded that, for a linear model, there is insufficient evidence to conclude that most of the data are from a normal distribution. Therefore, the null hypothesis that the sample consisting of the data (w, w_n, e, ϕ,) are a random sample from a normally distributed population is rejected and the conclusion is that the data are not from a normally distributed population. Because all four assumptions have to be satisfied, a linear model cannot be used.

Based on the results of linear regression analyses, it was decided that nonlinear regression analyses will be more appropriate for modeling the independent variable. This decision will be checked in the following chapter.

Table 5.1 Sample output from linear regression analysis by Stepwise selection method showing non-normal distribution of the variables

Var	N	Mean	SD	CV (%)	Tests for location						Shapiro-Wilk		
					Stud T	Pr> $\lvert t\rvert$	Sign M	Pr $\geq \lvert M\rvert$	Signed rank S	Pr $\lvert S\rvert$	Sh-W	Pr<W (*p*-value)	ND
k_{nw}	41	0.0010	0.00059	57.65	11.105	0.0001	20.5	<0.0001	430.5	<0.0001	0.8618	<0.0001	N
w	41	9.9482	6.2004	62.33	10.273	<0.0001	20.5	<0.0001	430.5	<0.0001	0.8526	<0.0001	N
w_n	41	12.4791	5.5733	44.66	14.3373	<0.0001	20.5	<0.0001	430.5	<0.0001	0.9428	0.0393	N
e	41	0.8313	0.0536	6.44	99.3103	<0.0001	20.5	<0.0001	430.5	<0.0001	0.9355	0.0221	N
ϕ	41	15.7927	16.6782	105.61	6.0632	<0.0001	20.5	<0.0001	430.5	<0.0001	0.5517	<0.0001	N

Table 5.2 Sample output from linear regression analysis by all possible selection method showing non-normal distribution of the variables

Var	N	Mean	SD	CV (%)	Tests for location							Shapiro-Wilk	
					Stud-T	Pr> $\lvert t\rvert$	Sign M	Pr $\geq \lvert M\rvert$	Signed rank S	Pr $\lvert S\rvert$	Sh-W	Pr<W (p-value)	NN
k_{nw}	41	0.0085	0.02740	322.35	1.986	0.0539	20.5	<0.0001	430.5	<0.0001	0.3216	<0.0001	NN
w	41	11.827	7.52136	63.59	10.0687	<0.0001	20.5	<0.0001	430.5	<0.0001	0.8174	<0.0001	NN
w_n	41	10.979	6.01666	54.80	11.6840	<0.0001	20.5	<0.0001	430.5	<0.0001	0.9553	<0.0001	NN
e	41	0.80946	0.08847	10.93	56.4850	<0.0001	20.5	<0.0001	430.5	<0.0001	0.8456	0.0001	NN
ϕ	41	15.8476	16.5722	104.57	6.2313	<0.0001	20.5	<0.0001	430.5	<0.0001	0.5428	<0.0001	NN

CHAPTER 6

GLM - NONLINEAR REGRESSION MODEL

6.1 Model definition

In section 3.1, it was mentioned that this research will focus on two major tasks: the experimental determination of the hydraulic conductivity in a partially saturated soil of a chosen non-aqueous liquid and the exploration of possible relationship between hydraulic conductivity and each independent x_i in Equation 6.1. This Chapter explores the possible relationships between hydraulic conductivity and the various independent soil and liquid parameters. Chapter 5 showed that a linear regression model cannot explain the relationship of water content, NAPL content, void ratio and soil suction to unsaturated hydraulic conductivity. Therefore, a NLIN exponential relationship of the form shown in Equation 6.1 is proposed.

$$k_{nw} = A\left\{e^{(b_1x_1+b_2x_2+b_3x_3+b_4x_4)}\right\}+\varepsilon \tag{6.1}$$

k_{nw} is the unsaturated hydraulic conductivity of the NAPL (cm/sec);

A is initial value of k_{nw} when each independent variable, $x_i = 0$;

b_i are shape gradients that represent the relative change in k_{nw} associated with a change in x_i, when all other $x_j\ (\neq x_i)$ are constant.

6.2 Outlier analyses

Examination of the measured experiment data indicated possible outliers. Extreme outliers may have significant influence on the hydraulic conductivity to be predicted. Table 6.1 shows the results of the outlier analysis and Figure 6.1 shows a box and whiskers plot of TCE effective unsaturated hydraulic conductivity (cm/sec).

Table 6.1 Outlier analyses on dependent variables Mk_{nw}

	Mk_{nw}
Q1	0.000698
Q3	0.001086
IQR	0.000388
Q1-3*IQR	0.000301
Q3+3*IQR	-0.000466
Coefficient of variation	57.6589
Standard deviation	0.000591
Number of observations	41

Outliers are problematic because they may cause (a) distortion of predicted values, (b) inflation of error sums of squares (SSE), expressed in Equation 6.2, and (c) conclusions to be skewed.

$$SSE = \sum \left(k_{nwi} - \hat{k}_{nwi} \right)^2 \tag{6.2}$$

where, $\hat{k}_{nwi}$ is the predicted value of k_{nwi} and the error sum of squares is a measure of how much variability in k_{nw} is unexplained by the model.

With reference to Table 6.1, Q1, Q3, and IQR, respectively, represent the first quartile, the third quartile, and the interquartile range. The first quartile, Q1 is the median for the first half of the data (= 25%) and the third quartile, Q3 is the median for the second half of the data (= 75%) and IQR = Q3-Q1. Extreme outliers are points that situate in more than three interquartile ranges from the smallest point in the first quartile or from the largest point in the third quartile.

Of the 41 total observations of k_{nw}, the following 4 were extreme outliers: 0.0000258 from test number 27; 0.0000384 from test number 34; 0.0000943 from test number 36; and 0.003287 from test number 43. The regression analyses was run on the remaining data.

6.3 Trial models

With the outliers screened out, several models were tried to obtain a valid model representation of k_{nw} relationship to water content, w, NAPL content w_n, void ratio, e and soil suction, ϕ. For each trial model, the SAS iterative nonlinear regression

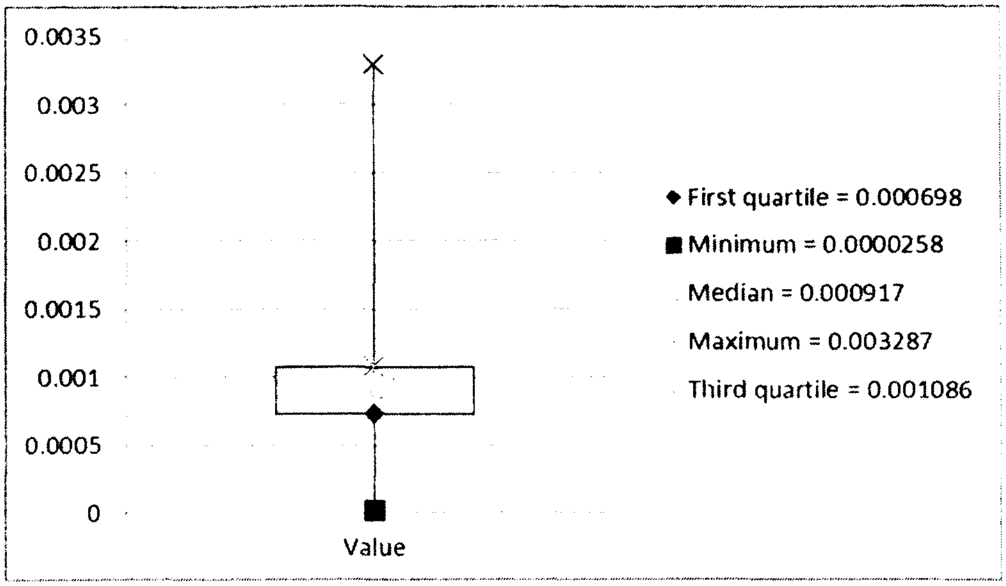

Figure 6.1 Box and Whiskers plot of measured TCE unsaturated hydraulic conductivity (cm/sec.)

procedure, NLIN, was used with the Levenberg-Marquardt method for a faster convergence.

The Levenberg-Marquardt method is a combination of the gradient descent method and the Gauss-Newton methods of solving nonlinear least squares problems. In the former method, the sum of the squared errors is reduced by updating the coefficients in the direction of the greatest minimization. In the later, the sum of squared errors is reduced by assuming the least squares function is locally quadratic, and finding the minimum of the quadratic. The former is used at a large distance from the minimum while the latter is used as the solution approaches the minimum to achieve rapid convergence (Lourakis, 2005; Madsen et al., 2004; and Marquardt, 1963).

Nonlinear regression analysis searches for parameters that make a trial model to fit the measured data as closely as possible. Results from each model were checked against the assumptions of nonlinear regression discussed in Section 6.6

6.4 Fitting model

To obtain the proposed model, over one hundred possible candidate models were investigated using the PROC NLIN SAS procedure. The validation criteria used were maximum F-value, minimum root-mean-square-error, maximum coefficient of determination and a plot of measured versus predicted values of k_{nw} conductivity. Convergence was achieved with Equation 6.3. Figure 6.2 plots the measured and predicted hydraulic conductivity values. The model of Equation 6.3 has an F-value of 68.60, an R^2 value of 93.5% and a root mean square error of 0.000792327 cm/sec. Thus, the model accounts for over 93% of the variability in the measured data.

$$Pk_{TCE} = \frac{e^3}{(1+e)} \left(\begin{array}{l} 4.7042\left(\dfrac{e(1+e)}{\rho_w G_s (1+w+w_n)} \right) \quad + \\ 0.000447 \log\left(\dfrac{\rho_w G_s (1+w+w_n)}{(1+e)} \right) * \\ \exp\left(\dfrac{-2.5263}{w} - 0.0228 w_n - 0.3046 e + 0.0193 \phi \right) \end{array} \right) \frac{w_n}{w} \tag{6.3}$$

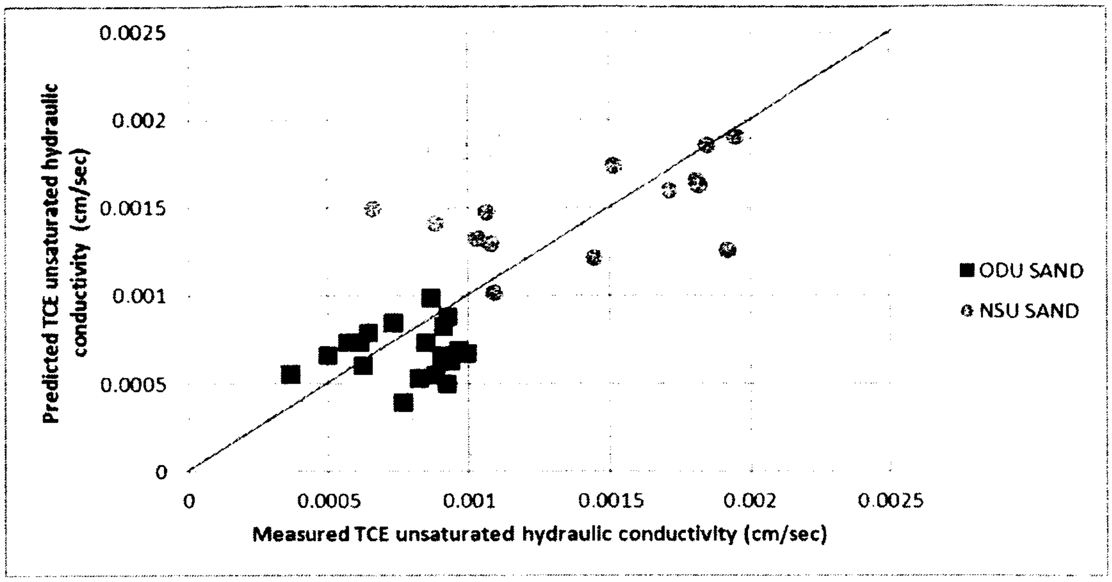

Figure 6.2 Measured vs. predicted TCE conductivity (cm/sec.) from the final model.

6.5 Checking the assumptions of nonlinear regression

6.5.1 Independence of observations

Each independent variable $w, w_n, e, \varphi,$ is nonrandom and measured in the experiments independent of the others with negligible error. However, any random variation in each one is negligible compared to the range in which it is measured.

6.5.2 Measurement error in independent variables

Laboratory tests were performed with extreme care and attention to detail to minimize procedural errors. While it is true that there are some random errors introduced in the measurements, it is also true that the independent variables were measured with usually acceptable laboratory errors.

6.5.3 Normal distribution of dependent variable

Referring to the Central Limit Theorem, Montgomery and Runger (1999) wrote that "in many cases of practical interest, if sample size n ≥ 30, the normal approximation will be satisfactory regardless of the shape of the population. Even if n is less than 30, the central limit theorem is valid if the population distribution is not severely non-normal". A larger sample size is always desirable but such would be more expensive and may not guarantee improved accuracy. Table 6.2 computes data used to plot Figure 6.3 providing evidence that the assumption of normal distribution via the Central Limit Theorem was valid for the non-linear regression model. The symbols used in Table 6.2 are explained below.

x(j) are observations arranged in ascending order, $j = 1, 2, 3, \ldots\ldots\ldots, 41$ observations

(j-0.5)/n is cumulative frequency of Mk_{TCE}

ϕ (j) is the cumulative normal probability and

Table 6.3 is a summary of the laboratory test data and includes the measured (Mk_{TCE}) and predicted (Pk_{TCE}) hydraulic conductivity of TCE in the SP (poorly graded) unsaturated sand.

The last column (e_t) in Table 6.3 is the difference between measured and predicted hydraulic conductivities.

Table 6.2 Data used to generate normal probability plot for residuals.

j	$x(j) = Mk_{TCE}$	$J = \frac{j-0.5}{41}$	$\phi(z_j)$	J	$x(j) = Mk_{TCE}$	$J = \frac{j-0.5}{41}$	$\phi(z_j)$
1	0.0000384	0.012195	-2.24	22	0.000919	0.52439	0.09
2	0.0000943	0.036585	-1.78	23	0.000923	0.54878	0.16
3	0.0000258	0.060976	-1.54	24	0.000923	0.573171	0.16
4	0.000361	0.085366	-1.36	25	0.000927	0.597561	0.22
5	0.000498	0.109756	-1.21	26	0.000935	0.621951	0.29
6	0.000572	0.134146	-1.09	27	0.000964	0.646341	0.35
7	0.000616	0.158537	-0.98	28	0.000997	0.670732	0.42
8	0.000625	0.182927	-0.89	29	0.001032	0.695122	0.49
9	0.000646	0.207317	-0.8	30	0.001065	0.719512	0.56
10	0.000662	0.231707	-0.71	31	0.001079	0.743902	0.64
11	0.000734	0.256098	-0.63	32	0.001093	0.768293	0.71
12	0.000767	0.280488	-0.56	33	0.001447	0.792683	0.8
13	0.000822	0.304878	-0.49	34	0.001516	0.817073	0.89
14	0.000846	0.329268	-0.42	35	0.001713	0.841463	0.99
15	0.000868	0.353659	-0.35	36	0.001813	0.865854	1.09
16	0.000883	0.378049	-0.29	37	0.00182	0.890244	1.21
17	0.000884	0.402439	-0.22	38	0.001849	0.914634	1.37
18	0.000903	0.426829	-0.16	39	0.001919	0.939024	1.54
19	0.000912	0.45122	-0.1	40	0.001947	0.963415	1.79
20	0.000916	0.47561	0.03	41	0.003287	0.987805	2.25
21	0.000917	0.5	0.03				

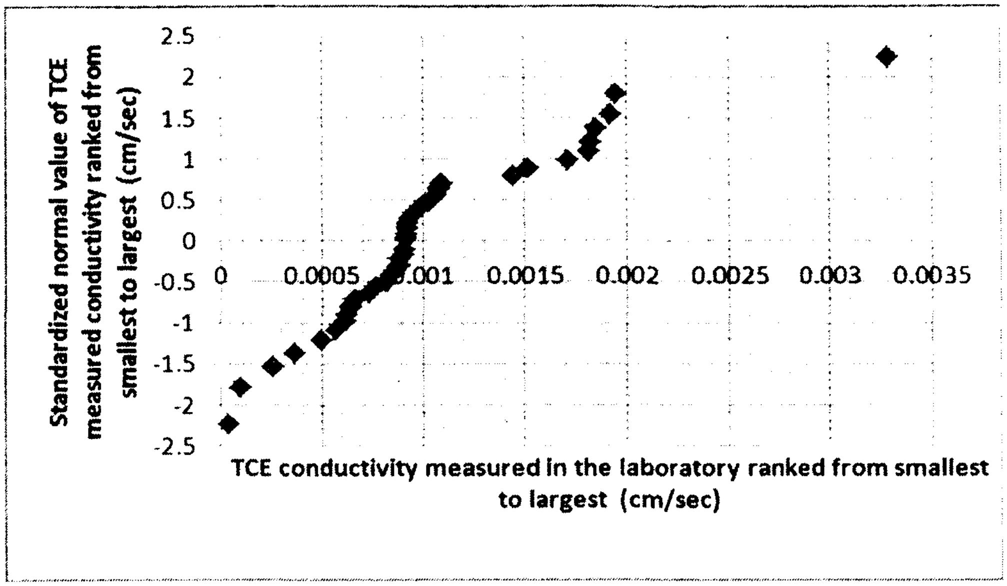

Figure 6.3 Normal probability plot obtained from standardized normal distribution for TCE measured hydraulic conductivity.

6.5.4 Homoscedasticity of dependent variable

If the errors are normal and independent with mean zero and common variance, then the least squares estimators for the parameters will achieve minimum variance in the class of all unbiased estimators (Myers, 1990). This assumption is based on the fact that when the error variance σ^2 is constant, the variability in k_{nw} at any values of x_i is the same.

6.5.5 Root-mean-square error

The residuals are defined as $e_i = (Mk_{TCE} - Pk_{TCE})_i$ where i = 1, 2, . . . , 37. The cumulative normal probability plot, Figure 6.3 and the residuals plots, Figures 6.4

through 6.7 indicate satisfactory performance of the model with a variance of zero, and a root-mean-square error (RMSE) of 0.000295325 cm/sec that is about one half of the standard deviation of 0.000591. Plotted points in Figures 6.4 through 6.7 are concentrated in regions of higher variable sensitivity indicating that data collection for the soil tested should, in general, be concentrated in these regions namely: zero to 15% for water content, 5% to 18% for NAPL content, 0.7 to 0.9 for void ratio, and 4% to 16% for soil suction. The plots also show that the random errors are centered around zero consistent with the least squares requirement, $\sum_{i=1}^{n=37} e_i = 0$. The RMSE was determined from Equation 6.4.

$$RMSE(k_{TCE}) = \sqrt{\frac{\sum_{i=1}^{n} e_i^2}{n}} \tag{6.4}$$

where

$i = 1, 2, \ldots\ldots, 37.$

6.6 Convergence criteria

The convergence criteria for the Marquardt method uses the Bates and Watts (1981) relative offset convergence measure, R, given in equation 6.10 to determine convergence,

$$R = \sqrt{\frac{r'X(X'X)^{-1}X'r}{LOSS}} < c \tag{6.5}$$

Table 6.3 Summary of laboratory test data and hydraulic conductivity of TCE in unsaturated sand.

Test #	w (%)	w_n (%)	e	ϕ (cbar)	ρ_{wet} (kg/m^3)	Mk_{TCE} (cm/sec)	Pk_{TCE} (cm/sec)	e_t (cm/sec)
1	28.475	9.1286	0.9232	12	1879.6	0.001919	0.001257762	0.000661238
8	25.339	2.5729	0.8348	7	1847.39	0.000997	0.000674007	0.000322993
9	4.6161	28.62	0.8019	10	1959.5	0.000884	0.000550918	0.000333082
10	6.7711	15.614	0.8737	78	1730.9	0.000734	0.000845200	-0.00011120
15	3.4901	7.7799	0.9868	66	1503.5	0.000662	0.001493279	-0.00083128
16	3.6221	7.9295	0.972	7	1510.3	0.000883	0.001409863	-0.00052686
17	5.6558	10.239	0.8216	34	1698.7	0.000964	0.000692714	0.000271286
18	0.6934	12.134	0.8504	68	1633.7	0.001947	0.001907911	0.000039089
19	2.6403	15.747	0.7615	10	1798.1	0.000923	0.000499419	0.000423581
20	1.6625	14.238	0.7245	11	1916.5	0.000767	0.00039216	0.00037484
21	3.8902	8.3451	0.7042	13	1918.6	0.001093	0.001018789	0.000074211
22	1.8714	6.154	0.8061	6	1555.8	0.001032	0.001326749	-0.00029475
23	12.764	5.9545	0.7656	11	1736.6	0.000822	0.000527106	0.000294894
24	6.9098	14.747	0.7927	13	1728	0.001713	0.001597202	0.000115798
25	6.2322	22.835	0.7774	6	1924.6	0.001813	0.001650332	0.000162668
26	11.459	27.057	0.8586	11.5	1698.7	0.001849	0.001858649	-9.649E-06
28	9.3601	11.127	0.7842	8	1803.1	0.000361	0.000553001	-0.000192
29	10.353	4.8086	0.8332	5	1689.4	0.000572	0.000732043	-0.00016004
30	9.2079	11.72	0.8495	8	1680.2	0.000646	0.000788352	-0.00014235
31	8.7084	7.2407	0.8278	6	1643.7	0.000616	0.000735246	-0.00011925
32	9.966	13.126	0.8163	14	1800.8	0.000903	0.000638563	0.000264437
33	9.9615	6.6625	0.7979	14	1670.2	0.000923	0.000634953	0.000288047

Table 6.3 Summary of laboratory test data and hydraulic conductivity of TCE in unsaturated sand (Continued)

Test #	w $(\%)$	w_n $(\%)$	e	ϕ $(cbar)$	ρ_{wet} (kg/m^3)	Mk_{TCE} $(cm/\sec)$	Pk_{TCE} $(cm/\sec)$	e_i $(cm/\sec)$
35	10.983	14.326	0.8736	29	1764.5	0.000912	0.00082877	0.00008323
37	8.0504	13.627	0.8119	6.5	1791.6	0.000935	0.000629676	0.000305324
38	11.451	8.5719	0.8127	12	1720.9	0.000917	0.000657842	0.000259158
39	11.429	5.1211	0.8092	12.5	1713	0.000919	0.000650821	0.000268179
40	9.1792	11.28	0.8145	10	1800	0.000916	0.000633578	0.000282422
41	9.2195	7.935	0.8225	10	1706.6	0.001447	0.001215644	0.000231356
42	10.367	11.73	0.8727	13	1745.9	0.00182	0.001626035	0.000193965
44	8.0362	13.745	0.8765	10	1677.3	0.000927	0.000882126	0.000044874
45	8.1726	13.745	0.8765	10	1677.3	0.000927	0.000988555	-0.00012056
46	7.931	11.675	0.8965	8.5	1620.8	0.000868	0.000731798	0.000114202
47	12.043	12.364	0.8404	9	1742.3	0.000846	0.001739423	-0.00022342
48	12.068	18.017	0.8441	22	1859.5	0.001516	0.000606235	0.000018765
49	9.8633	17.701	0.818	5	1911	0.000625	0.000661799	-0.0001638
50	14.052	13.709	0.8242	7	1798.1	0.000498	0.00147136	-0.00040636
51	13.839	18.147	0.8486	11.5	1868.1	0.001065	0.001296536	-0.00021754
Sum of residuals, $\sum(e_i)$								0.00190858

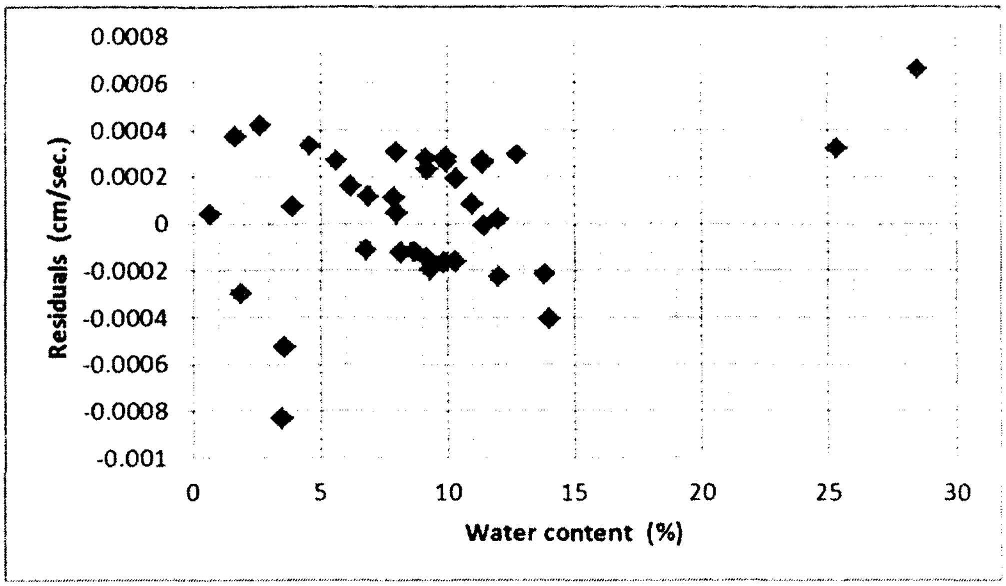

Figure 6.4 Plot of residuals versus water content.

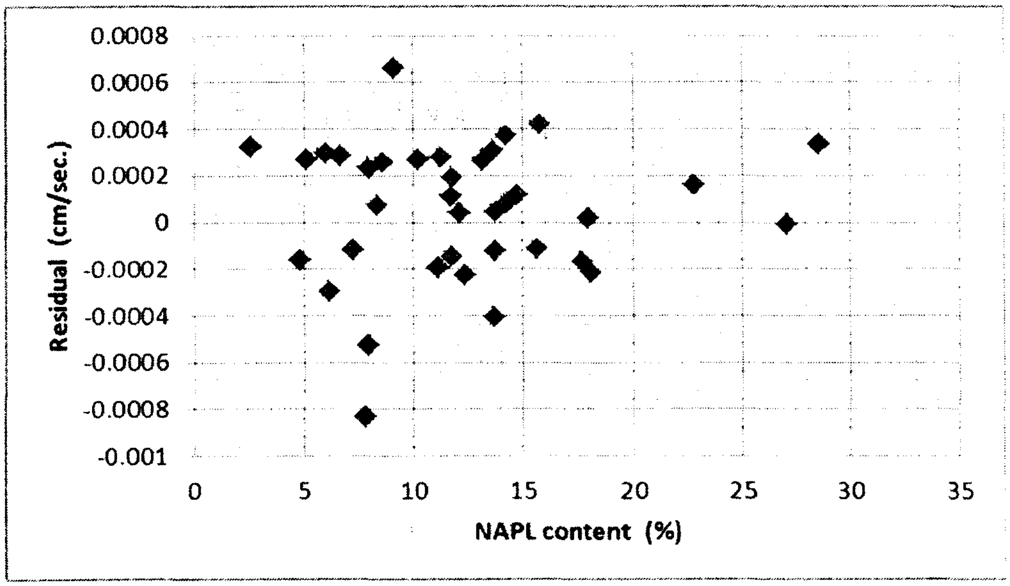

Figure 6.5 Plot of residuals versus TCE content.

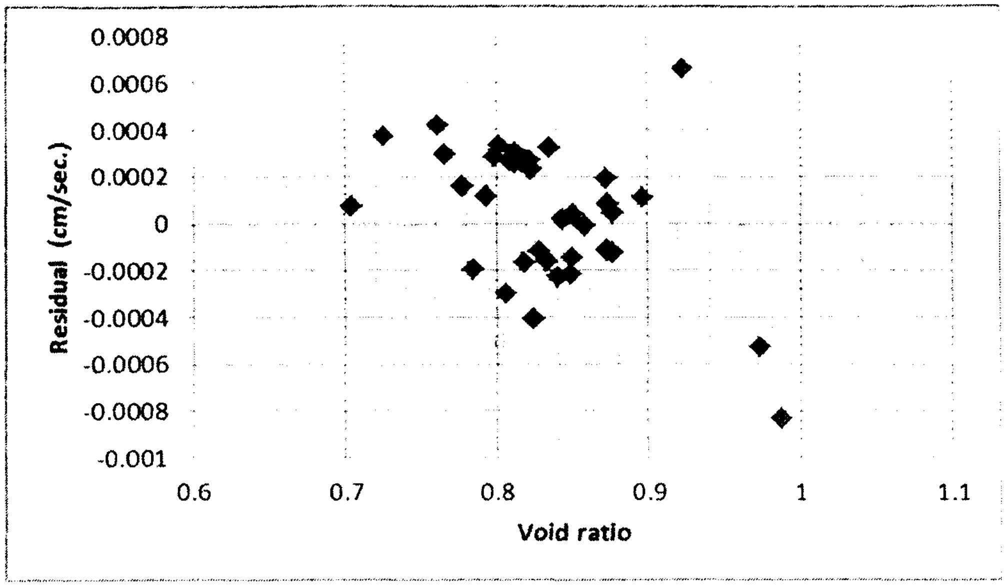

Figure 6.6 Plot of residuals versus void ratio.

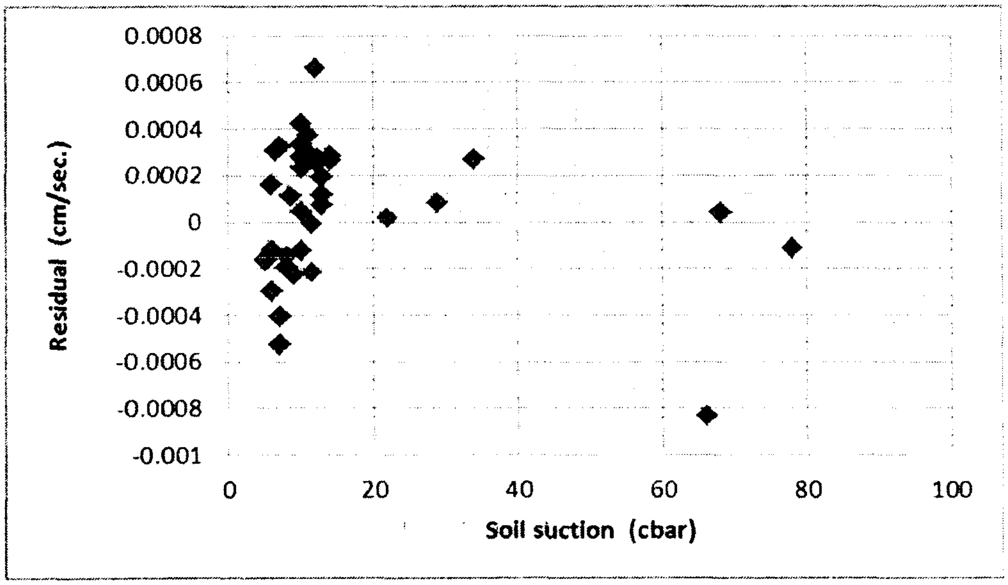

Figure 6.7 Plot of residuals versus soil suction.

where

r is residual vector;

X is Jacobian matrix;

r', X' are transpose of matrix r, or X;

LOSS is the sum of squared errors (SSE); and

c = 10^{-5} (by default).

From Appendix Table B1, R = 4.491E-6. Convergence criteria is satisfied when R is less than 10^{-5}. When the calculated SSE becomes smaller than the value assigned to SINGULAR threshold for minimization (default value of c = 10^{-5}), convergence criteria is assumed. The Prospective Parameter Change (PPC) measure is the maximum relative change in the parameters for the next iteration. PPC(b3) = 0.000199 means that parameter b3 has the largest PPC value of the coefficients b1 to b4 in the last iterative stage, and would change by 0.000199 if PROC NLIN were to go an additional iteration step, yet it was unnecessary due to convergence of the model.

In summary, the final nonlinear model describing the relationships among k_{nw} and the independent variables can be estimated by Equation 6.3.

6.7 Applicability of proposed model

The proposed model may be useful in the following applications.

6.7.1 Environmental water quality studies

The previous models use various degrees of saturation and other parameters as shown in Equations 2.3 through 2.8 and in Table 7.7. The Akamiro model uses soil and liquid engineering properties. A combination of these models provides additional research capabilities that can be used in environmental water quality studies. For example, the depth of penetration, D, of a NAPL spill through the vadose zone has been expressed as (Pastrovich et al., 1979)

$$D = \frac{V}{AR_s} \tag{6.6}$$

where

D = depth of penetration, (m);

V = volume of soil (m^3);

A = area of the release, (m^2);

R_s = retention capacity, (L/m^3).

The retention capacity is defined as the average volume of solvent which is retained per unit volume of the aquifer, regardless of whether certain release lenses within the overall region are accessible to the DNAPL or not (Pankow and Cherry, 1996). The retention capacity for unsaturated sandy porous medium is in the range of 3 to 30 (L/m^3) (Mercer and Cohen, 1990). Equation 6.6 can be related to model Equation 6.3 to obtain Equation 6.7.

$$D = Pk_{TCE}\, t \tag{6.7}$$

where t is time in seconds. Correspondingly, the retention capacity can then be related to the soil and liquid properties by Equation 6.8.

$$R_s = \frac{V}{APk_{TCE}t} \tag{6.8}$$

Pankow and Cherry (1996) wrote that "Unfortunately, it will never be possible to predict precisely the extent or rate of DNAPL migration." Findings from this research would probably facilitate such prediction.

6.7.2 Capability to model light non-aqueous phase liquids (LNAPL)

The instrumentation developed in this study can also be employed to model the unsaturated hydraulic conductivity of LNAPLs. This can be done by allowing LNAPL to enter the test chamber from the opening in the bottom plate instead of entry from the opening in the top plate as was done for DNAPLs due to due to the density difference between LNAPLs and DNAPLs.

CHAPTER 7

SENSITIVITY ANALYSES

7.1 Sensitivity of TCE to liquid and soil properties

Regression analysis reproduced the system relationship between the dependent variable, Pk_{TCE}, and the independent variables; water content, w, NAPL content, w_n, void ratio, e, and soil suction, ϕ in SP (poorly graded) sand. Equation 6.3 is the model obtained from the regression analyses. This model equation can be then used for prediction purposes. Sensitivity analysis was used to determine the sensitivity (amount of contribution to TCE conductivity) of each of the four independent variables to the dependent variable. In sensitivity analyses, the model Equation 6.3 is used to discover the responses, $Pk_{TCE}(w)$, $Pk_{TCE}(w_n)$, $Pk_{tce}(e)$, and $Pk_{TCE}(\phi)$. $Pk_{TCE}(w)$ is the response of the dependent variable as water content changes from its minimum to its maximum test values while the other independent variables were held constant at their mean test values. The other responses are defined similarly.

This chapter developed the discrete (relative) sensitivity and normalized discrete sensitivity analysis of each independent variable to TCE hydraulic conductivity. In discrete sensitivity analyses, each independent variables is changed from its minimum value to its maximum test value. In normalized sensitivity analyses, each independent variable is normalized so that it varies from zero to 100% and so uses the same units for each independent variable.

7.2 Discrete sensitivity analysis

Tables 7.1 through 7.5 summarize the data used in the discrete sensitivity analyses of water content, w, NAPL content, w_n, void ratio, e, and soil suction, φ, respectively to Pk_{TCE}. Contaminant transport mechanisms in the subsurface include advection, hydrodynamic dispersion and diffusion (Lagrega et al., 1994). Factors that facilitate or inhibit DNAPL penetration through the vadose zone are shown in Table 7.1. Relative to water, the high density and low viscosity enable NAPLs to move faster through the medium. Sensitivities discussed below show how the resultant vertical movement changes as each contributing parameter changes over its range.

Table 7.1 Factors that affect DNAPL transport through the vadose zone[a]

Factor	Facilitates	Inhibits
Permeability	High	Low
Geological structure	Angled beddings in sandy aquifers, fractures, fine-grained.	Horizontal beddings in sandy aquifers, silt, clay.
Interfacial tension	Low	High
Viscosity	Low	High
Volume released	High	Low
Duration of release	High	Low

[a] (Lagrega et al., 1994).

7.3 Discrete sensitivity to water content

Water is the wetting phase in the presence of NAPL and air. Therefore, it preferentially wets the soil solid particles. NAPL is the wetting phase relative to air and occupies the void space between the aqueous phase and gaseous (air) phase. Increase in water content reduces the void space available for flow of NAPL. Mathematically, this can be seen from Equation 4.16. Therefore, the increase in water content will reduce the

Table 7.2 Discrete sensitivity of TCE conductivity to water content[a]

w (%)	Predicted TCE hydraulic conductivity by Equation 6.3 (cm/sec)
0.69	0.010738109
1	0.007388784
2	0.003661692
3	0.002419711
4	0.001799000
5	0.001426791
6	0.001178828
7	0.00100186
8	0.00086926
9	0.000766235
10	0.000683911
11	0.000616641
12	0.000560658
13	0.000513356
14	0.000472873
16	0.000437845
17	0.000407247
18	0.000380297
19	0.000356385
20	0.00033503
21	0.000315849
22	0.00029853
23	0.000282819
24	0.000268505
25	0.000255413
26	0.000243396
27	0.00023233
28	0.000222108
28.5	0.000212641

[a] $w_n(\%) = 10.97883$, e = 0.80945, and ϕ(cbar) = 15.84756.

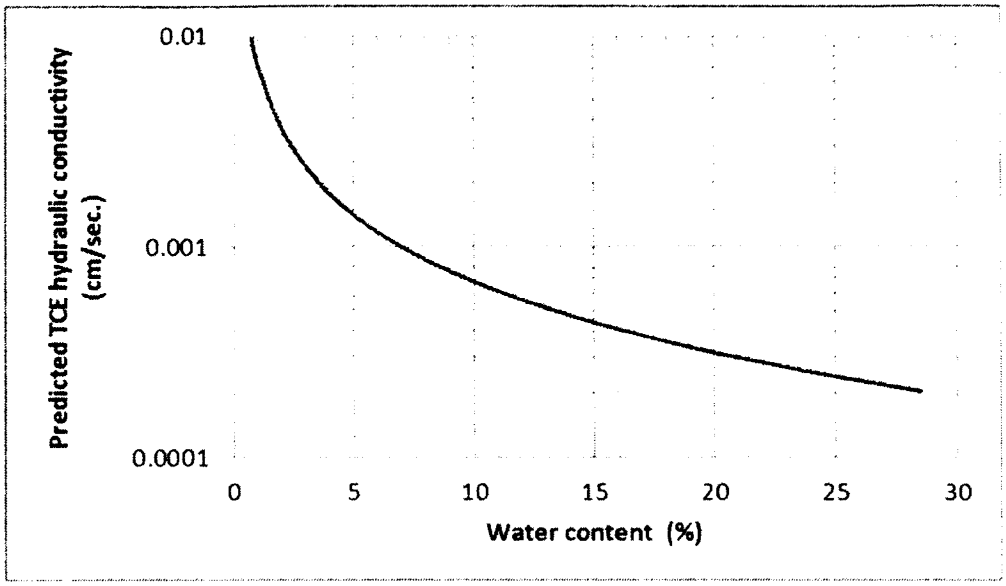

Figure 7.1 Discrete sensitivity of TCE conductivity (cm/sec) to water content

effective conductivity of TCE as shown in Table 7.2.

Table 7.2 is obtained by varying the water content while keeping the other parameters constant at their average values measured in the laboratory. Water content is changed from its minimum to its maximum laboratory test values with 1% step increases. Figure 7.1 illustrates the response, $Pk_{TCE}(w)$, of Water content sensitivity to TCE conductivity. $Pk_{TCE}(w)$ decreases more rapidly below about 10% than above 10%. This is probably due to the fact that the soil is in its driest condition below 10% water content.

7.4 Discrete sensitivity to NAPL content

Increase in NAPL content will naturally increase its unsaturated hydraulic conductivity when other independent variables are kept constant as shown in Table 7.3 and in Figure 7.2. The response, $Pk_{TCE}(w_n)$ shown in Figure 7.2 describes a more rapid sensitivity below 10% NAPL content. It confirms the expectation that

$Pk_{TCE}(w_n)$ increases as w_n increases. However, at higher TCE content, the rate of increase in TCE permeability decreases.

Table 7.3 Discrete sensitivity of TCE conductivity to TCE content[a]

w_n (%)	Predicted TCE hydraulic conductivity by using Equation 6.3 (cm/sec)
2.6	0.00014473
3	0.000166415
4	0.000219971
5	0.000272610
6	0.000324356
7	0.000375231
8	0.000425256
9	0.000474454
10	0.000522844
11	0.000570446
12	0.000617279
13	0.000663362
14	0.000708713
15	0.000753348
16	0.000797285
17	0.00084054
18	0.000883128
19	0.000925066
20	0.000966367
21	0.001007046
22	0.001047118
23	0.001086595
24	0.001125491
25	0.001163818
26	0.001201589
27	0.001238816
28	0.00127551
28.6	0.001293662

[a] $w(\%)=11.82713$, $e = 0.809451$, and $\phi\,(\text{cbar}) = 15.84756$.

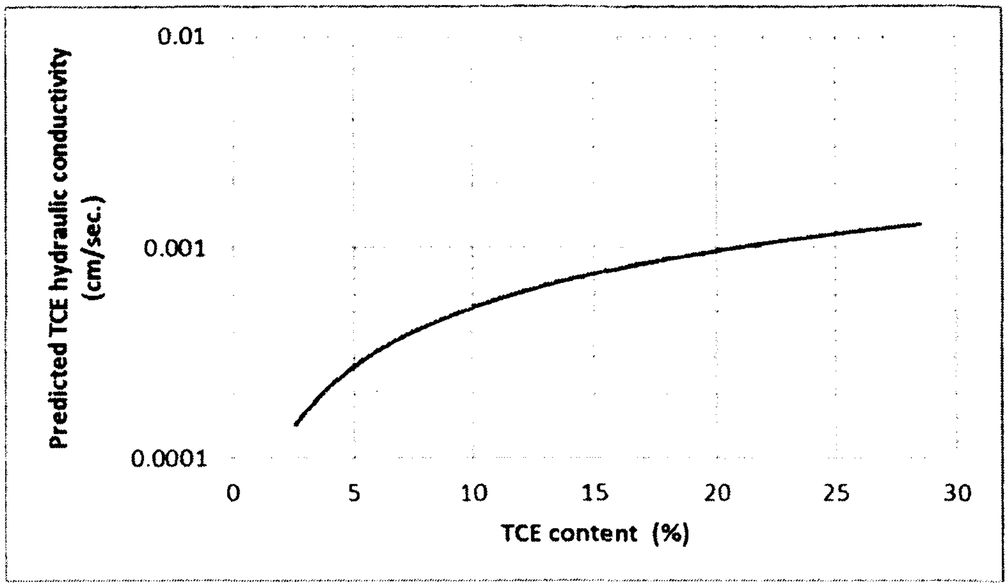

Figure 7.2 Discrete sensitivity of TCE conductivity to TCE content (cm/sec)

7.5 Discrete sensitivity to void ratio

The calculated the void ratio sensitivity is shown in Table 7.4 and plotted in Figures 7.3. Figure 7.4 shows Pk_{TCE} increasing from about 0.00032 cm/sec to 0.00126 cm/sec as void ratio increases linearly from 0.7 to 0.987 while the other independent variables are held constant at the average of their measured values. It is expected that $Pk_{TCE}(e)$ increases as void ratio increases. Figure 7.3 confirms this expectation. Mitchell (1993) found a similar linear relationship between void ratio and hydraulic conductivity for several sandy soils.

Table 7.4 Discrete sensitivity of TCE conductivity to void ratio[a]

e	Predicted TCE hydraulic conductivity by using Equation 6.3 (cm/sec)
0.70	0.000318513
0.72	0.000356504
0.74	0.000397797
0.76	0.000442577
0.78	0.000491036
0.80	0.000543369
0.82	0.000599778
0.84	0.000660468
0.86	0.000725652
0.88	0.000795546
0.9	0.000870372
0.92	0.000950356
0.94	0.001035729
0.96	0.00112673
0.98	0.001223599
0.987	0.001258935

[a] $w(\%) = 11.82713$, $w_n(\%) = 10.97883$, and $\phi(\text{cbar}) = 15.84756$.

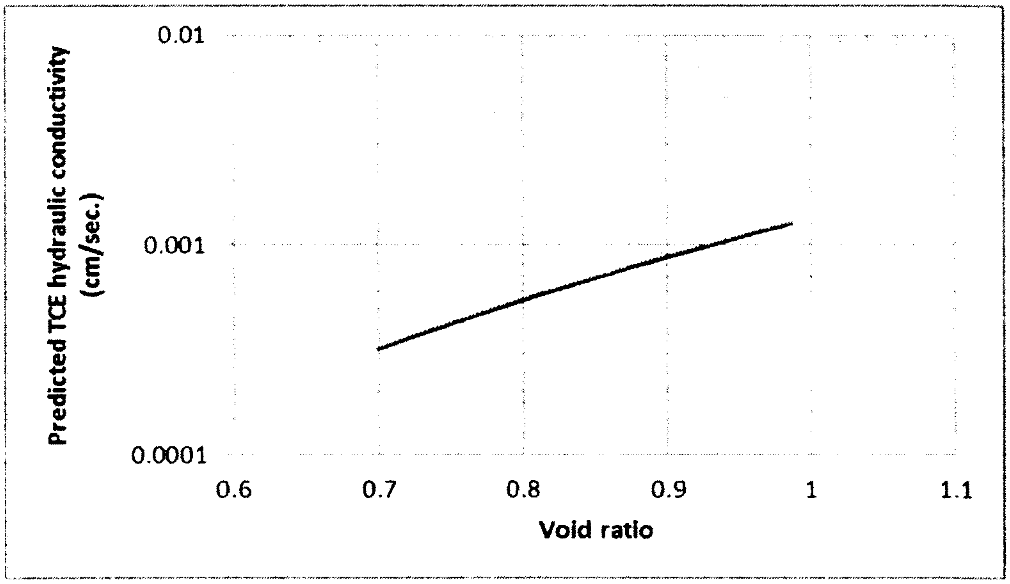

Figure 7.3 Discrete sensitivity of TCE conductivity (cm/sec) to void ratio

7.6 Discrete sensitivity of soil suction

Calculated discrete sensitivity data are presented in Table 7.5. Figure 7.4 shows that increasing the suction pressure will increase the NAPL conductivity from 0.000286 cm/sec to 0.000448 cm/sec when soil suction increased from 2 cbar to 74 cbar while the other independent

Table 7.5 Discrete sensitivity of TCE conductivity to soil suction[a]

φ (cbar)	Predicted TCE hydraulic conductivity by using Equation 6.3 (cm/sec)
2	0.000286376
4	0.000290157
6	0.000293975
8	0.000297831
10	0.000301724
12	0.000305656
14	0.000309626
16	0.000313635
18	0.000317682
20	0.000321768
22	0.000325894
24	0.000330059
26	0.000334264
28	0.000338509
30	0.000342795
32	0.000347121
34	0.000351488
36	0.000355895
38	0.000360345
40	0.000364835
42	0.000369368
44	0.000373943
46	0.000378560
48	0.000383219
50	0.000387922
52	0.000392668
54	0.000397457
56	0.000402290
58	0.000407166
60	0.000412087
62	0.000417053
64	0.000422063
66	0.000427118
68	0.000432219
70	0.000437365
72	0.000442556
74	0.000447794

[a] $w(\%) = 11.82713$, $w_n(\%) = 10.97883$, $e = 0.809451$.

variables were held constant at the average of their measured values. Figure 7.4 shows that log $Pk_{TCE}(\phi)$ has a linear relationship with soil suction and will increase proportionately with soil suction in the range of soil suction values tested.

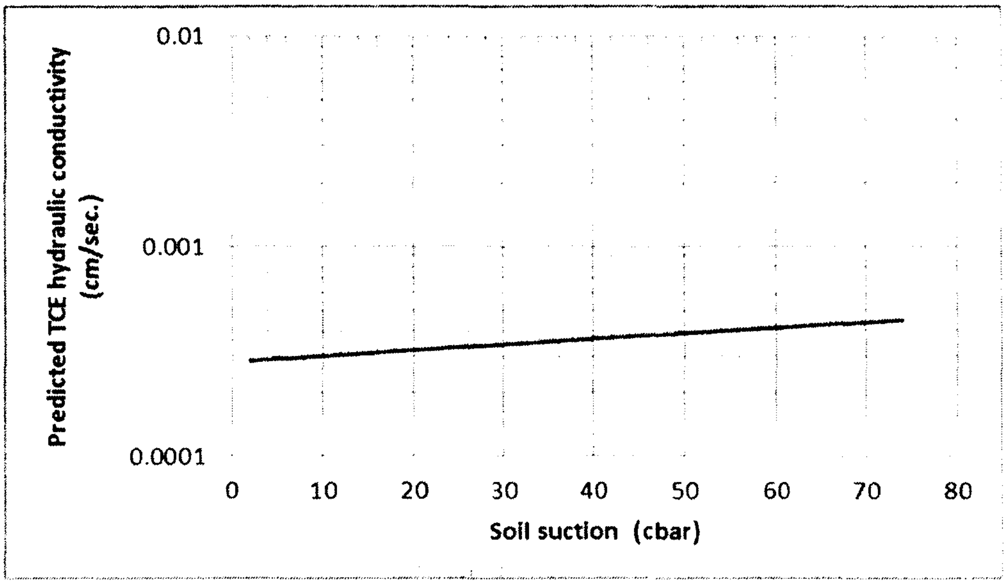

Figure 7.4 Discrete sensitivity of TCE conductivity (cm/sec) to soil suction

7.7 Results from discrete sensitivity analyses

Table 7.6 summarizes aggregated results from discrete sensitivity analyses of the independent parameters to TCE hydraulic conductivity. The last column shows the magnitude of the change in Pk_{TCE} per unit change in each independent variable. This column is obtained by dividing the values in the column for "total change in variable" by the corresponding value in the column for "total change in Pk_{TCE}. Based on this, it was concluded that, of the four independent variables studied, one unit change in void ratio produced the maximum positive change in Pk_{TCE} whereas one unit change in water content produced the maximum negative change. Therefore, based on total absolute change (Table 7.6) water content is the most sensitive of the four variables.

Table 7.6 Summary of results from discrete sensitivity analyses.

Independent variable	Change in variable		Change in Pk_{TCE} (cm/sec)		Total change in variable	Total change in Pk_{TCE} (cm/sec)
	from	to	From	to		
w (%)	0.69	28.5	0.0107381	0.0002126	27.81	-0.0105255
w_n (%)	2.6	28.6	0.00014473	0.0012937	26.0	0.00114893
e	0.7	0.987	0.00031851	0.0012589	0.287	0.00094042
ϕ (cbar)	2	74	0.000286376	0.0004478	72	0.00016142

7.8 Normalized discrete sensitivity analyses

The range from the minimum value to the maximum value for each independent variable in Table 7.6 is different due to the range and the units used for the variables. It is beneficial to develop sensitivity analyses for which the range and units are the same for each independent variable. Such analyses was done by using relative parameters as defined in Equations 7.1 through 7.4 performing normalized discrete sensitivity analyses using the relative parameters and the Pk_{TCE} data from Tables 7.2 to 7.5.

$$w_{relative}(\%)=\frac{w-w_{\min}}{w_{\max}-w_{\min}} \tag{7.1}$$

$$w_{nrelative}(\%)=\frac{w_n-w_{n\min}}{w_{\max}-w_{n\min}} \tag{7.2}$$

$$e_{relative}(\%)=\frac{e-e_{\min}}{e_{\max}-e_{\min}} \tag{7.3}$$

$$\varphi_{relative}(\%)=\frac{\varphi-\varphi_{\min}}{\varphi_{\max}-\varphi_{\min}} \tag{7.4}$$

The data for relative soil and liquid properties used in Equations 7.1 through 7.4 represent the independent variables and discrete sensitivities listed respectively in Table 6.3, and Tables 7.1 through 7.4. The normalized discrete sensitivity values of TCE unsaturated hydraulic conductivity are plotted in Figure 7.5.

7.9 Summary of normalized sensitivity analyses

The normalized discrete sensitivity analyses show that log Pk_{TCE} has (a) a nonlinear decline as water content increases, (b) a nonlinear increase as NAPL content increases, (c) a linear increase as void ratio or soil suction increases as shown in Figures 7.5. The discrete and normalized discrete sensitivity analyses are consistent in the conclusion that water content is the most sensitive of the four parameters based on absolute contribution to TCE conductivity.

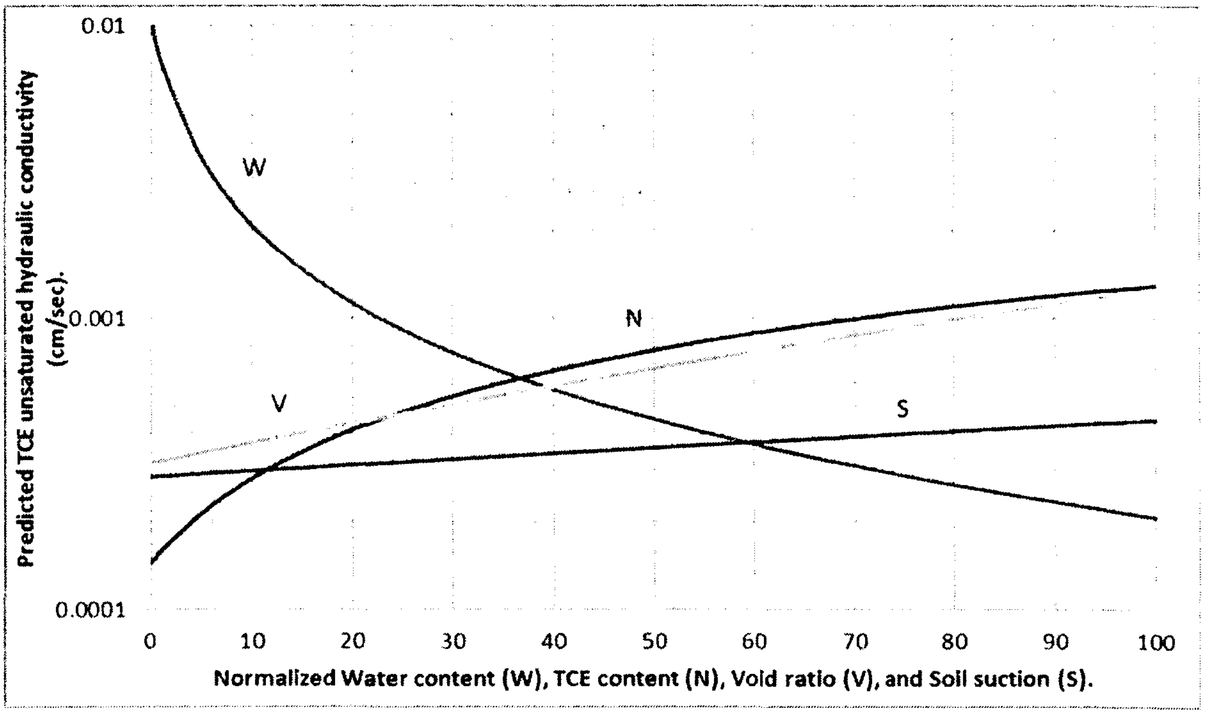

Figure 7.5 Normalized discrete sensitivity of TCE conductivity to water content, (W), TCE content (N), void ratio, (V), and soil suction (S)

7.10 Issues with previous models

A review of Chapter II showed that the other researchers' models for estimating Pk_{TCE} are expressed in terms of parameters λ, ε, m, n , and various degrees of saturation such as effective saturation, S_e; water saturation, S_w; oil saturation, S_o;

maximum saturation, S_m; residual water saturation, S_{wr}; and residual oil saturation, S_{ro}. The following observations are made on those models;

1. One problem with those models is with the various forms of degrees of saturation. It makes it almost impossible to obtain hydraulic conductivity values from one single test since many saturation parameters are involved. Many tests are needed and possibly sources of errors would equally increase. As the sources of error increase, the accuracy of the model estimates would become questionable.

2. Except for the degree of water saturation, all the other degrees of saturation mentioned above are not commonly utilized parameters by geotechnical engineers. Model Equation 6.3 eliminates the above problems because the input variables can be obtained from one single test and are commonly used in geotechnical engineering profession.

7.11 Comparison of TCE hydraulic conductivity models

It must be emphasized that conclusions are solely based on the laboratory data used in this study. Therefore, comparisons with any other models are appropriate only if those models use the data consistent with those upon which conclusions from this study have been based upon. Also, results from this study can be compared to results from previous studies as long as the data from previous studies are within the same data categories shown in Table 7.7. Sections 7.11.1 to 7.11.4 are used to compare the research model with previous models.

7.11.1 Introduction to comparison of models

The following equations are used for comparisons.

Brooks and Corey, (1964):

$$k_{rnw} = (1 - S_e)^2 (1 - S_e)^{\frac{2+\lambda}{\lambda}} \tag{2.3}$$

Parker et al, (1987):

$$k_{rnw} = (1 - S_e)^{1/2} \left(1 - S_e^{\,1/m}\right)^{2m} \tag{2.5}$$

$$S_e = \frac{S_w - S_r}{S_m - S_r} \tag{2.6}$$

Brooks-Corey-Burdine model (1964):

$$k_{ro}(S_o, S_w) = \left(\frac{S_o - S_{or}}{1 - S_{or}}\right)^2 \left(\left(\frac{S_t - S_{wr}}{1 - S_{wr}}\right)^{\varepsilon-2} - \left(\frac{S_w - S_{wr}}{1 - S_{wr}}\right)\right)^{\varepsilon-2} \tag{2.8a}$$

$$\mathrm{S_t} = S_o + S_w \tag{2.8b}$$

$$\varepsilon = 3 + \frac{2}{\lambda} \tag{2.8c}$$

7.11.2 Conductivity values by previous models

Based on information in cited literatures, the values used for parameters S_w, S_r, λ, m, n, S_o, S_{or}, S_{wr}, and ε in the previous models are summarized in Table 7.8. The uncertainty as to what values to use in the model equations is of concern and may be an unacceptable risk to some users. This is a major difficulty to using any one of these models. Mark et al., (http://info.ngwa.org/gwol/pdf/031977527.pdf) acknowledge that the many different methods of determining residual NAPL saturation have led to a wide range in literature and perceived values for residual NAPL saturation.

Table 7.7 Comparison of variables used in referenced Pk_{TCE} models.

Model	w	w_n	e	θ	ρ_{wet}	s_e	s_w	s_r	s_m	s_O	S_{or}	S_{wr}	K_{os}	K_{ro}	K_{ws}	λ	m	N	Other	Eq. #
Brooks and Corey (BC) (1964)						x										x				2.3 2.5
Brooks-Corey-Burdine (BCB) (1964)							X			x	x	x								2.8
Charbeneeur (2000)													x	x	x				G, ρ_o, μ ,	2.10 2.11
Hoffmann-Riem et. al., 1989)						x													θ,θ_r,θ	2.2
Van Genutchen (VG) (1980)						x	X	x	x								x	X	α,h	2.5 2.6
Akamiro (2012)	x	x	x	x	x															6.3

The values in Table 7.8 are the minimum and maximum in the literatures. Both Brooks and Corey and Parker et al., conductivity values from Equations 2.3 and 2.5, respectively, depend on values of parameter S_e and m. The author concluded that the respective conductivity values will vary from minimum to maximum by using minimum and maximum parameter values in all possible combinations. In Tables 7.9 through 7.18, most probable combinations of those maximum and minimum values are used to compute conductivity values for each model.

The computed effective conductivity values in Tables 7.9 through 7.18 are for the Brooks and Corey (BC), Parker et al., (PA), and Brooks-Corey-Burdine (BCB) models alongside Akamiro's values. The values for S_w and S_o are the values of degrees of saturation to water and TCE, respectively, obtained from the experimental research during this research.

Table 7.19 consists of the average of the hydraulic conductivity values from λ Tables 7.9 and 7.10 for the BC model, the average values from Tables 7.11 to 7.14 for the PA model, and the average values from Tables 7.15 to 7.18 for the BCB model. Figure 7.6 is a plot of the values from Table 7.19.

7.11.3 Further comparison with brooks and corey model

In the Brooks and Corey research, they reported the pore-size distribution (psd) index, λ, values for the soils in their experimental study. The psd index is the negative of the slope of the log-log plot of the effective saturation, S_e, as a function of the capillary pressure head, P_c/γ. The research they conducted was based on observation of a large number of experimental data on soils of unspecified sample size with their λ values.

In Tables 7.21 through 7.23, TCE effective hydraulic conductivity values have been computed using the Brooks and Corey λ values with $S_r = 0.001$. Those are summarized in Tables 7.24 and plotted in Figure 7.8. Similarly, the computed TCE effective hydraulic conductivity values are computed with $S_r = 0.1$, shown in Tables 7.25 through 7.28 and plotted in Figure 7.9.

From Figures 7.8 and 7.9, it is revealed again that λ is a sensitive parameter to TCE effective hydraulic conductivity and the computed values agree with Akamiro model values in some cases. Thus, in this model, selection of parameters is very critical practice in evaluating TCE conductivity.

Table 7.8 Values for model parameters used in Tables 7.10 to 7.19

Model parameter	Minimum value	Maximum value	Comment	Source
S_r	0.001	0.1	S_r = 0.001 is used in Tables 7.9, 7.11 and 7.12. S_r = 0.1 is used in Tables 7.10, 7.13, 7.14.	http://en.wikipedia .org/iki/water_con tent
S_{or}	0.002	0.18	S_{or} = 0.002 is used in Tables 7.15, and 7.16. S_{or} = 0.18 is used in Tables 7.17 and 7.18.	Poulsenand Kueper, 1992.
S_{wr}	0.08	0.17	S_{wr} = 0.08 is used in Tables 7.15, and 7.17. S_{wr} = 0.17 is used in Tables 7.16, and 7.18	Guarnaccia et al., 1997.
λ	2	2	λ = 2 is used in Tables 7.9, 7.10, 7.15, 7.16, 7.17, and 7.18.	Pankow and Cherry, 1996.
m	0.35	0.80	m = 0.35 is used in Table 7.11, and 7.13. m = 0.80 is used in Table 7.12, and 7.14.	Pankow and Cherry, 1996.
S_m	1.0	1.0	S_m = 1.0 is used in calculating S_e in Tables 7.9 through 7.14.	Pankow and Cherry, 1996.

Table 7.9 TCE conductivity by Brooks and Corey (1964) model with S_r = 0.001.

Test #	S_w	S_r	S_e	λ	$\frac{2+\lambda}{\lambda}$	$k_{rnw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.8173	0.001	0.817117	2	2	0.00111864	0.001257762
8	0.8042	0.001	0.804004	2	2	0.00147567	0.000674007
9	0.1525	0.001	0.151652	2	2	0.51796078	0.000550918
10	0.2054	0.001	0.204605	2	2	0.40025087	0.000845200
15	0.0944	0.001	0.093493	2	2	0.67527971	0.001493279
16	0.0994	0.001	0.098498	2	2	0.66048935	0.001409863
17	0.1838	0.001	0.182983	2	2	0.44557869	0.000692714
18	0.0217	0.001	0.020721	2	2	0.91965781	0.001907911
19	0.0925	0.001	0.091592	2	2	0.68096467	0.000499419
20	0.063	0.001	0.062062	2	2	0.77392061	0.00039216
21	0.4384	0.001	0.437838	2	2	0.09987262	0.001018789
22	0.2327	0.001	0.231932	2	2	0.3480157	0.001326749
23	0.2141	0.001	0.213313	2	2	0.38300743	0.000527106
24	0.1822	0.001	0.181381	2	2	0.44908285	0.001597202
25	0.3051	0.001	0.304404	2	2	0.23411395	0.001650332
26	0.3187	0.001	0.318018	2	2	0.21631747	0.001858649
28	0.3318	0.001	0.331131	2	2	0.20015384	0.000553001
29	0.2894	0.001	0.288689	2	2	0.25599935	0.000732043
30	0.2809	0.001	0.28018	2	2	0.26846965	0.000788352
31	0.326	0.001	0.325325	2	2	0.20719422	0.000735246
32	0.0333	0.001	0.032332	2	2	0.87680884	0.000638563
33	0.3478	0.001	0.347147	2	2	0.1816608	0.000634953
35	0.3357	0.001	0.335035	2	2	0.19552174	0.00082877
37	0.9203	0.001	0.92022	2	2	4.0511E-05	0.000629676
38	0.2648	0.001	0.264064	2	2	0.2933324	0.000657842
39	0.3762	0.001	0.375576	2	2	0.15202658	0.000650821
40	0.3771	0.001	0.376476	2	2	0.15115112	0.000633578
41	0.3009	0.001	0.3002	2	2	0.23982544	0.001215644
42	0.2993	0.001	0.298599	2	2	0.2420285	0.001626035
44	0.3175	0.001	0.316817	2	2	0.21784554	0.000882126
45	0.3048	0.001	0.304104	2	2	0.2345185	0.000988555
46	0.2448	0.001	0.244044	2	2	0.32657728	0.000731798
47	0.2434	0.001	0.242643	2	2	0.32900568	0.001739423
48	0.252	0.001	0.251251	2	2	0.31430004	0.000606235
49	0.381	0.001	0.38038	2	2	0.14740107	0.000661799
50	0.3939	0.001	0.393293	2	2	0.13549248	0.00147136
51	0.3195	0.001	0.318819	2	2	0.21530324	0.001296536

Table 7.10 TCE conductivity by Brooks and Corey (1964) model with $S_r = 0.1$

Test #	S_w	S_r	S_e	λ	$\frac{2+\lambda}{\lambda}$	$k_{rnw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.8173	0.1	0.797	2	2	0.00169818	0.001257762
8	0.8042	0.1	0.782444	2	2	0.00224017	0.000674007
9	0.1525	0.1	0.058333	2	2	0.78630093	0.000550918
10	0.2054	0.1	0.117111	2	2	0.60760901	0.000845200
15	0.0944	0.1	-0.00622	2	2	1.02512215	0.001493279
16	0.0994	0.1	-0.00067	2	2	1.00266933	0.001409863
17	0.1838	0.1	0.093111	2	2	0.67641982	0.000692714
18	0.0217	0.1	-0.087	2	2	1.3961053	0.001907911
19	0.0925	0.1	-0.00833	2	2	1.03375232	0.000499419
20	0.063	0.1	-0.04111	2	2	1.17486597	0.00039216
21	0.4384	0.1	0.376	2	2	0.15161367	0.001018789
22	0.2327	0.1	0.147444	2	2	0.52831234	0.001326749
23	0.2141	0.1	0.126778	2	2	0.58143225	0.000527106
24	0.1822	0.1	0.091333	2	2	0.68173939	0.001597202
25	0.3051	0.1	0.227889	2	2	0.35540146	0.001650332
26	0.3187	0.1	0.243	2	2	0.32838516	0.001858649
28	0.3318	0.1	0.257556	2	2	0.30384763	0.000553001
29	0.2894	0.1	0.210444	2	2	0.38862504	0.000732043
30	0.2809	0.1	0.201	2	2	0.40755584	0.000788352
31	0.326	0.1	0.251111	2	2	0.31453541	0.000735246
32	0.0333	0.1	-0.07411	2	2	1.33105756	0.000638563
33	0.3478	0.1	0.275333	2	2	0.27577389	0.000634953
35	0.3357	0.1	0.261889	2	2	0.29681577	0.00082877
37	0.9203	0.1	0.911444	2	2	6.1498E-05	0.000629676
38	0.2648	0.1	0.183111	2	2	0.44529924	0.000657842
39	0.3762	0.1	0.306889	2	2	0.23078705	0.000650821
40	0.3771	0.1	0.307889	2	2	0.22945804	0.000633578
41	0.3009	0.1	0.223222	2	2	0.36407191	0.001215644
42	0.2993	0.1	0.221444	2	2	0.36741631	0.001626035
44	0.3175	0.1	0.241667	2	2	0.33070487	0.000882126
45	0.3048	0.1	0.227556	2	2	0.35601559	0.000988555
46	0.2448	0.1	0.160889	2	2	0.49576731	0.000731798
47	0.2434	0.1	0.159333	2	2	0.49945379	0.001739423
48	0.252	0.1	0.168889	2	2	0.47712959	0.000606235
49	0.381	0.1	0.312222	2	2	0.22376521	0.000661799
50	0.3939	0.1	0.326556	2	2	0.20568712	0.00147136
51	0.3195	0.1	0.243889	2	2	0.32684548	0.001296536

Table 7.11 TCE conductivity by Parker et al. (1987) model with $S_r = 0.001$, $m = 0.35$ and Akamiro model.

Test #	S_w	S_r	S_e	$(1 - S_e)^{0.5}$	m	$(1 - S_e^{1/m})^{2m}$	$k_{rnw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.8173	0.001	0.817117	0.42764808	0.35	0.56149806	0.24012357	0.001257762
8	0.8042	0.001	0.804004	0.44271435	0.35	0.5840443	0.25856479	0.000674007
9	0.1525	0.001	0.151652	0.92105828	0.35	0.9968014	0.91811218	0.000550918
10	0.2054	0.001	0.204605	0.89184942	0.35	0.99246666	0.88513082	0.000845200
15	0.0944	0.001	0.093493	0.95210635	0.35	2.124095	2.02236434	0.001493279
16	0.0994	0.001	0.098498	0.94947433	0.35	1.40492634	1.33394149	0.001409863
17	0.1838	0.001	0.182983	0.90388994	0.35	0.99452719	0.89894312	0.000692714
18	0.0217	0.001	0.020721	0.98958541	0.35	6.37962363	6.31318246	0.001907911
19	0.0925	0.001	0.091592	0.95310462	0.35	2.30345719	2.19543568	0.000499419
20	0.063	0.001	0.062062	0.96847196	0.35	4.23218386	4.0987514	0.00039216
21	0.4384	0.001	0.437838	0.74977474	0.35	0.93291107	0.69947316	0.001018789
22	0.2327	0.001	0.231932	0.87639493	0.35	0.98921427	0.86694237	0.001326749
23	0.2141	0.001	0.213313	0.8869536	0.35	0.99151214	0.87942526	0.000527106
24	0.1822	0.001	0.181381	0.90477545	0.35	0.9946631	0.89994676	0.001597202
25	0.3051	0.001	0.304404	0.83402374	0.35	0.97647942	0.81440702	0.001650332
26	0.3187	0.001	0.318018	0.82582200	0.35	0.97332935	0.8037968	0.001858649
28	0.3318	0.001	0.331131	0.81784404	0.35	0.97004409	0.79334478	0.000553001
29	0.2894	0.001	0.288689	0.84339274	0.35	0.97979959	0.82635586	0.000732043
30	0.2809	0.001	0.28018	0.84842196	0.35	0.98146116	0.8326932	0.000788352
31	0.326	0.001	0.325325	0.82138583	0.35	0.97152965	0.79800068	0.000735246
32	0.0333	0.001	0.032332	0.98370101	0.35	5.59220311	5.50105582	0.000638563
33	0.8173	0.001	0.817117	0.42764808	0.35	0.56149806	0.24012357	0.000634953
35	0.3357	0.001	0.335035	0.81545384	0.35	0.96901701	0.79018864	0.00082877
37	0.9203	0.001	0.92022	0.28245315	0.35	0.3370031	0.09518759	0.000629676
38	0.2648	0.001	0.264064	0.85786709	0.35	0.98435767	0.84444804	0.000657842
39	0.3762	0.001	0.375576	0.79020531	0.35	0.95694668	0.75618435	0.000650821
40	0.3771	0.001	0.376476	0.78963506	0.35	0.95664811	0.75540289	0.000633578
41	0.3009	0.001	0.3002	0.83654038	0.35	0.97740023	0.81763475	0.001215644
42	0.2993	0.001	0.298599	0.83749711	0.35	0.97774468	0.81885834	0.001626035
44	0.3175	0.001	0.316817	0.82654896	0.35	0.97361783	0.8047428	0.000882126
45	0.3048	0.001	0.304104	0.83420375	0.35	0.976546	0.81463833	0.000988555
46	0.2448	0.001	0.244044	0.86945728	0.35	0.9875212	0.85860749	0.000731798
47	0.2434	0.001	0.242643	0.87026281	0.35	0.98772539	0.85958067	0.001739423
48	0.252	0.001	0.251251	0.86530269	0.35	0.98643596	0.85356569	0.000606235
49	0.381	0.001	0.38038	0.78715921	0.35	0.95533844	0.75200345	0.000661799
50	0.3939	0.001	0.393293	0.7789138	0.35	0.95081976	0.74060663	0.00147136
51	0.3195	0.001	0.318819	0.82533701	0.35	0.97313589	0.80316507	0.001296536

Table 7.12 TCE conductivity by Parker et al. (1987) model with $S_r = 0.001$, $m = 0.8$ and Akamiro model.

Test #	S_w	S_r	S_e	$(1-S_e)^{0.5}$	m	$\left(1-S_e^{1/m}\right)^{2m}$	$k_{rnw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.8173	0.001	0.817117	0.42764808	0.8	0.09070966	0.03879181	0.001257762
8	0.8042	0.001	0.804004	0.44271435	0.8	0.1010363	0.04473022	0.000674007
9	0.1525	0.001	0.151652	0.92105828	0.8	0.85293655	0.78560427	0.000550918
10	0.2054	0.001	0.204605	0.89184942	0.8	0.78909157	0.70375086	0.000845200
15	0.0944	0.001	0.093493	0.95210635	0.8	2.124095	2.02236434	0.001493279
16	0.0994	0.001	0.098498	0.94947433	0.8	1.40492634	1.33394149	0.001409863
17	0.1838	0.001	0.182983	0.90388994	0.8	0.81550512	0.73712687	0.000692714
18	0.0217	0.001	0.020721	0.98958541	0.8	6.37962363	6.31318246	0.001907911
19	0.0925	0.001	0.091592	0.95310462	0.8	2.30345719	2.19543568	0.000499419
20	0.063	0.001	0.062062	0.96847196	0.8	4.23218386	4.0987514	0.00039216
21	0.4384	0.001	0.437838	0.74977474	0.8	0.49436515	0.37066251	0.001018789
22	0.2327	0.001	0.231932	0.87639493	0.8	0.75519233	0.66184673	0.001326749
23	0.2141	0.001	0.213313	0.8869536	0.8	0.77834422	0.69035521	0.000527106
24	0.1822	0.001	0.181381	0.90477545	0.8	0.81744462	0.73960383	0.001597202
25	0.3051	0.001	0.304404	0.83402374	0.8	0.66357441	0.55343681	0.001650332
26	0.3187	0.001	0.318018	0.825822	0.8	0.64622361	0.53366567	0.001858649
28	0.3318	0.001	0.331131	0.81784404	0.8	0.62950019	0.51483298	0.000553001
29	0.2894	0.001	0.288689	0.84339274	0.8	0.68357368	0.57652108	0.000732043
30	0.2809	0.001	0.28018	0.84842196	0.8	0.69438056	0.58912772	0.000788352
31	0.3260	0.001	0.325325	0.82138583	0.8	0.63690498	0.52314472	0.000735246
32	0.0333	0.001	0.032332	0.98370101	0.8	5.59220311	5.50105582	0.000638563
33	0.8173	0.001	0.817117	0.42764808	0.8	0.09070966	0.03879181	0.000634953
35	0.3357	0.001	0.335035	0.81545384	0.8	0.62452117	0.50926818	0.00082877
37	0.9203	0.001	0.92022	0.28245315	0.8	0.02460229	0.00694899	0.000629676
38	0.2648	0.001	0.264064	0.85786709	0.8	0.71479499	0.6131991	0.000657842
39	0.3762	0.001	0.375576	0.79020531	0.8	0.57289008	0.45270078	0.000650821
40	0.3771	0.001	0.376476	0.78963506	0.8	0.57174555	0.45147033	0.000633578
41	0.3009	0.001	0.3002	0.83654038	0.8	0.66892852	0.55958571	0.001215644
42	0.2993	0.001	0.298599	0.83749711	0.8	0.6709675	0.56193334	0.001626035
44	0.3175	0.001	0.316817	0.82654896	0.8	0.64775519	0.53540138	0.000882126
45	0.3048	0.001	0.304104	0.83420375	0.8	0.66395693	0.55387536	0.000988555
46	0.2448	0.001	0.244044	0.86945728	0.8	0.7400217	0.64341725	0.000731798
47	0.2434	0.001	0.242643	0.87026281	0.8	0.74178087	0.6455443	0.001739423
48	0.252	0.001	0.251251	0.86530269	0.8	0.73095983	0.63250151	0.000606235
49	0.381	0.001	0.38038	0.78715921	0.8	0.566788	0.44615239	0.000661799
50	0.3939	0.001	0.393293	0.7789138	0.8	0.55041652	0.42872702	0.00147136
51	0.3195	0.001	0.318819	0.82533701	0.8	0.64520251	0.53250951	0.001296536

Table 7.13 TCE conductivity by Parker et al. (1987) model with $S_r = 0.1$, $m = 0.35$ and Akamiro model.

Test #	S_w	S_r	S_e	$(1-S_e)^{0.5}$	m	$\left(1-S_e^{1/m}\right)^{2m}$	$k_{rnw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.8173	0.1	0.797	0.45055521	0.35	0.59566315	0.26837914	0.001257762
8	0.8042	0.1	0.782444	0.46642851	0.35	0.6189173	0.28868067	0.000674007
9	0.1525	0.1	0.058333	0.97039511	0.35	0.99979147	0.97019275	0.000550918
10	0.2054	0.1	0.117111	0.93962167	0.35	0.99847211	0.93818603	0.000845200
15	0.0944	0.1	-0.00622	1.00310629	0.35	2.124095	2.13069305	0.001493279
16	0.0994	0.1	-0.00067	1.00033328	0.35	1.40492634	1.40539457	0.001409863
17	0.1838	0.1	0.093111	0.95230714	0.35	0.99920666	0.95155163	0.000692714
18	0.0217	0.1	-0.087	1.04259292	0.35	6.37962363	6.65135044	0.001907911
19	0.0925	0.1	-0.00833	1.00415802	0.35	2.30345719	2.31303501	0.000499419
20	0.063	0.1	-0.04111	1.02034852	0.35	4.23218386	4.31830256	0.00039216
21	0.4384	0.1	0.376	0.78993671	0.35	0.9568062	0.75581633	0.001018789
22	0.2327	0.1	0.147444	0.92333935	0.35	0.99704862	0.92061422	0.001326749
23	0.2141	0.1	0.126778	0.9344636	0.35	0.99808335	0.93267256	0.000527106
24	0.1822	0.1	0.091333	0.95324009	0.35	0.99924918	0.95252437	0.001597202
25	0.3051	0.1	0.227889	0.87869853	0.35	0.98974398	0.86968659	0.001650332
26	0.3187	0.1	0.243	0.87005747	0.35	0.98767353	0.85933273	0.001858649
28	0.3318	0.1	0.257556	0.86165216	0.35	0.98543759	0.84910443	0.000553001
29	0.2894	0.1	0.210444	0.88856939	0.35	0.9918348	0.88131404	0.000732043
30	0.2809	0.1	0.201	0.893868	0.35	0.99284026	0.88746814	0.000788352
31	0.326	0.1	0.251111	0.86538367	0.35	0.98645763	0.85366432	0.000735246
32	0.0333	0.1	-0.07411	1.03639332	0.35	5.59220311	5.79572194	0.000638563
33	0.8173	0.1	0.797	0.45055521	0.35	0.59566315	0.26837914	0.000634953
35	0.3357	0.1	0.261889	0.85913393	0.35	0.98472422	0.84600999	0.00082877
37	0.9203	0.1	0.911444	0.29758285	0.35	0.36041902	0.10725452	0.000629676
38	0.2648	0.1	0.183111	0.90381906	0.35	0.99451622	0.89886272	0.000657842
39	0.3762	0.1	0.306889	0.83253295	0.35	0.97592387	0.81248877	0.000650821
40	0.3771	0.1	0.307889	0.83193216	0.35	0.97569784	0.81171441	0.000633578
41	0.3009	0.1	0.223222	0.88134997	0.35	0.99033393	0.87283078	0.001215644
42	0.2993	0.1	0.221444	0.88235795	0.35	0.9905527	0.87402205	0.001626035
44	0.3175	0.1	0.241667	0.87082337	0.35	0.98786629	0.86025705	0.000882126
45	0.3048	0.1	0.227556	0.87888819	0.35	0.98978688	0.869912	0.000988555
46	0.2448	0.1	0.160889	0.91603008	0.35	0.99621224	0.91256038	0.000731798
47	0.2434	0.1	0.159333	0.91687876	0.35	0.99631602	0.913501	0.001739423
48	0.252	0.1	0.168889	0.91165296	0.35	0.99564839	0.9076858	0.000606235
49	0.381	0.1	0.312222	0.82932369	0.35	0.97470229	0.8083437	0.000661799
50	0.3939	0.1	0.326556	0.82063661	0.35	0.97121901	0.79701788	0.00147136
51	0.3195	0.1	0.243889	0.8695465	0.35	0.98754391	0.85871535	0.001296536

Table 7.14 TCE conductivity by Parket et al. (1987) model with $S_r = 0.1$, $m = 0.8$ and Akamiro model

Test #	S_w	S_r	S_e	$(1-S_e)^{0.5}$	m	$(1-S_e^{1/m})^{2m}$	$k_{mw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.8173	0.1	0.797	0.45055521	0.8	0.10670356	0.04807584	0.001257762
8	0.8042	0.1	0.782444	0.46642851	0.8	0.11880589	0.05541445	0.000674007
9	0.1525	0.1	0.058333	0.97039511	0.8	0.95452736	0.92626868	0.000550918
10	0.2054	0.1	0.117111	0.93962167	0.8	0.89265956	0.83876227	0.000845200
15	0.0944	0.1	-0.00622	1.00310629	0.8	2.124095	2.13069305	0.001493279
16	0.0994	0.1	-0.00067	1.00033328	0.8	1.40492634	1.40539457	0.001409863
17	0.1838	0.1	0.093111	0.95230714	0.8	0.918984	0.87515502	0.000692714
18	0.0217	0.1	-0.087	1.04259292	0.8	6.37962363	6.65135044	0.001907911
19	0.0925	0.1	-0.00833	1.00415802	0.8	2.30345719	2.31303501	0.000499419
20	0.063	0.1	-0.04111	1.02034852	0.8	4.23218386	4.31830256	0.00039216
21	0.4384	0.1	0.376	0.78993671	0.8	0.57235086	0.45212095	0.001018789
22	0.2327	0.1	0.147444	0.92333935	0.8	0.85787148	0.79210649	0.001326749
23	0.2141	0.1	0.126778	0.9344636	0.8	0.88173681	0.82395095	0.000527106
24	0.1822	0.1	0.091333	0.95324009	0.8	0.92088299	0.87782258	0.001597202
25	0.3051	0.1	0.227889	0.87869853	0.8	0.76023826	0.66802024	0.001650332
26	0.3187	0.1	0.243	0.87005747	0.8	0.74133237	0.64500177	0.001858649
28	0.3318	0.1	0.257556	0.86165216	0.8	0.72301441	0.62298693	0.000553001
29	0.2894	0.1	0.210444	0.88856939	0.8	0.7818909	0.69476432	0.000732043
30	0.2809	0.1	0.201	0.893868	0.8	0.7935229	0.70930473	0.000788352
31	0.326	0.1	0.251111	0.86538367	0.8	0.73113626	0.63271338	0.000735246
32	0.0333	0.1	-0.07411	1.03639332	0.8	5.59220311	5.79572194	0.000638563
33	0.8173	0.1	0.797	0.45055521	0.8	0.10670356	0.04807584	0.000634953
35	0.0333	0.1	-0.07411	1.03639332	0.8	5.59220311	5.79572194	0.00082877
37	0.3357	0.1	0.261889	0.85913393	0.8	0.71754374	0.61646617	0.000629676
38	0.9203	0.1	0.911444	0.29758285	0.8	0.02901933	0.00863565	0.000657842
39	0.2648	0.1	0.183111	0.90381906	0.8	0.81534985	0.73692874	0.000650821
40	0.3762	0.1	0.306889	0.83253295	0.8	0.66040929	0.54981249	0.000633578
41	0.3771	0.1	0.307889	0.83193216	0.8	0.65913513	0.54835571	0.001215644
42	0.3009	0.1	0.223222	0.88134997	0.8	0.76605026	0.67515838	0.001626035
44	0.2993	0.1	0.221444	0.88235795	0.8	0.76826076	0.67788099	0.000882126
45	0.3175	0.1	0.241667	0.87082337	0.8	0.74300543	0.64702649	0.000988555
46	0.3048	0.1	0.227556	0.87888819	0.8	0.76065385	0.66852968	0.000731798
47	0.2448	0.1	0.160889	0.91603008	0.8	0.84202024	0.77131587	0.001739423
48	0.2434	0.1	0.159333	0.91687876	0.8	0.84386608	0.77372289	0.000606235
49	0.252	0.1	0.168889	0.91165296	0.8	0.83248175	0.75893445	0.000661799
50	0.381	0.1	0.312222	0.82932369	0.8	0.65361254	0.54205636	0.00147136
51	0.3939	0.1	0.326556	0.82063661	0.8	0.63533596	0.52137995	0.001296536

Table 7.15 TCE conductivity by Brooks-Corey-Burdine (1964) with S_{or} =0.002, S_{wr} = 0.08 and Akamiro model

Test #	S_o	S_w	S_{or}	S_{wr}	S_t	λ	ε	$k_{rnw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.156	0.8173	0.002	0.08	0.9733	2	4	0.008777022	0.001257762
8	0.0559	0.8042	0.002	0.08	0.8601	2	4	0.002613431	0.000674007
9	0.6478	0.1525	0.002	0.08	0.8003	2	4	0.07028375	0.000550918
10	0.3244	0.2054	0.002	0.08	0.5298	2	4	0.000150052	0.000845200
15	0.1554	0.0944	0.002	0.08	0.2498	2	4	1.26651E-06	0.001493279
16	0.1492	0.0994	0.002	0.08	0.2486	2	4	3.88911E-07	0.001409863
17	0.2279	0.1838	0.002	0.08	0.4117	2	4	5.75347E-07	0.000692714
18	0.2695	0.0217	0.002	0.08	0.2912	2	4	0.000830577	0.001907911
19	0.3839	0.0925	0.002	0.08	0.4764	2	4	0.002523981	0.000499419
20	0.0598	0.063	0.002	0.08	0.1228	2	4	4.38092E-09	0.00039216
21	0.0542	0.4384	0.002	0.08	0.4926	2	4	0.005262173	0.001018789
22	0.2103	0.2327	0.002	0.08	0.443	2	4	5.34095E-08	0.001326749
23	0.5148	0.2141	0.002	0.08	0.7289	2	4	0.011230778	0.000527106
24	0.2549	0.1822	0.002	0.08	0.4371	2	4	8.31099E-06	0.001597202
25	0.1941	0.3051	0.002	0.08	0.4992	2	4	1.69855E-05	0.001650332
26	0.2595	0.3187	0.002	0.08	0.5782	2	4	4.01735E-06	0.001858649
28	0.1239	0.3318	0.002	0.08	0.4557	2	4	0.000496188	0.000553001
29	0.1545	0.2894	0.002	0.08	0.4439	2	4	9.25043E-05	0.000732043
30	0.0843	0.2809	0.002	0.08	0.3652	2	4	0.000580153	0.000788352
31	0.281	0.326	0.002	0.08	0.607	2	4	7.50051E-06	0.000735246
32	0.0574	0.0333	0.002	0.08	0.0907	2	4	1.51058E-06	0.000638563
33	0.322	0.3478	0.002	0.08	0.6698	2	4	9.60853E-06	0.000634953
35	0.2687	0.3357	0.002	0.08	0.6044	2	4	9.94125E-06	0.00082877
37	0.1792	0.9203	0.002	0.08	1.0995	2	4	0.054588031	0.000629676
38	0.3048	0.2648	0.002	0.08	0.5696	2	4	1.08912E-05	0.000657842
39	0.1212	0.3762	0.002	0.08	0.4974	2	4	0.000880256	0.000650821
40	0.1051	0.3771	0.002	0.08	0.4822	2	4	0.001290619	0.000633578
41	0.2966	0.3009	0.002	0.08	0.5975	2	4	1.08068E-07	0.001215644
42	0.1616	0.2993	0.002	0.08	0.4609	2	4	8.53454E-05	0.001626035
44	0.2531	0.3175	0.002	0.08	0.5706	2	4	2.86161E-06	0.000882126
45	0.377	0.3048	0.002	0.08	0.6818	2	4	0.000176307	0.000988555
46	0.2054	0.2448	0.002	0.08	0.4502	2	4	4.61719E-07	0.000731798
47	0.1419	0.2434	0.002	0.08	0.3853	2	4	4.7108E-05	0.001739423
48	0.2648	0.252	0.002	0.08	0.5168	2	4	2.43345E-07	0.000606235
49	0.3551	0.381	0.002	0.08	0.7361	2	4	2.21652E-05	0.000661799
50	0.4036	0.3939	0.002	0.08	0.7975	2	4	6.73625E-06	0.00147136
51	0.2882	0.3195	0.002	0.08	0.6077	2	4	4.63913E-06	0.001296536

Table 7.16 TCE conductivity by Brooks-Corey-Burdine (1964) with S_{or} = 0.002, S_{wr} = 0.08 and Akamiro model

Test #	S_o	S_w	S_{or}	S_{wr}	S_t	λ	ε	$k_{rnw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.156	0.8173	0.002	0.17	0.9733	2	4	0.010797608	0.001257762
8	0.0559	0.8042	0.002	0.17	0.8601	2	4	0.002979100	0.000674007
9	0.6478	0.1525	0.002	0.17	0.8003	2	4	0.088012105	0.000550918
10	0.3244	0.2054	0.002	0.17	0.5298	2	4	0.000300029	0.000845200
15	0.1554	0.0944	0.002	0.17	0.2498	2	4	3.76049E-05	0.001493279
16	0.1492	0.0994	0.002	0.17	0.2486	2	4	2.20147E-05	0.001409863
17	0.2279	0.1838	0.002	0.17	0.4117	2	4	9.07508E-06	0.000692714
18	0.2695	0.0217	0.002	0.17	0.2912	2	4	0.002465992	0.001907911
19	0.3839	0.0925	0.002	0.17	0.4764	2	4	0.004496259	0.000499419
20	0.0598	0.063	0.002	0.17	0.1228	2	4	1.79544E-07	0.00039216
21	0.0542	0.4384	0.002	0.17	0.4926	2	4	0.004399991	0.001018789
22	0.2103	0.2327	0.002	0.17	0.443	2	4	5.36815E-07	0.001326749
23	0.5148	0.2141	0.002	0.17	0.7289	2	4	0.014547069	0.000527106
24	0.2549	0.1822	0.002	0.17	0.4371	2	4	4.19016E-05	0.001597202
25	0.1941	0.3051	0.002	0.17	0.4992	2	4	3.6858E-07	0.001650332
26	0.2595	0.3187	0.002	0.17	0.5782	2	4	1.38409E-05	0.001858649
28	0.1239	0.3318	0.002	0.17	0.4557	2	4	0.000253661	0.000553001
29	0.1545	0.2894	0.002	0.17	0.4439	2	4	2.2325E-05	0.000732043
30	0.0843	0.2809	0.002	0.17	0.3652	2	4	0.000237946	0.000788352
31	0.281	0.326	0.002	0.17	0.607	2	4	1.61974E-05	0.000735246
32	0.0574	0.0333	0.002	0.17	0.0907	2	4	1.76201E-05	0.000638563
33	0.322	0.3478	0.002	0.17	0.6698	2	4	1.4716E-05	0.000634953
35	0.2687	0.3357	0.002	0.17	0.6044	2	4	2.48684E-05	0.00082877
37	0.1792	0.9203	0.002	0.17	1.0995	2	4	0.067610057	0.000629676
38	0.3048	0.2648	0.002	0.17	0.5696	2	4	2.22063E-05	0.000657842
39	0.1212	0.3762	0.002	0.17	0.4974	2	4	0.000562677	0.000650821
40	0.1051	0.3771	0.002	0.17	0.4822	2	4	0.000866946	0.000633578
41	0.2966	0.3009	0.002	0.17	0.5975	2	4	2.14837E-07	0.001215644
42	0.1616	0.2993	0.002	0.17	0.4609	2	4	2.06633E-05	0.001626035
44	0.2531	0.3175	0.002	0.17	0.5706	2	4	1.27066E-05	0.000882126
45	0.377	0.3048	0.002	0.17	0.6818	2	4	0.000248315	0.000988555
46	0.2054	0.2448	0.002	0.17	0.4502	2	4	8.8632E-07	0.000731798
47	0.1419	0.2434	0.002	0.17	0.3853	2	4	4.62544E-06	0.001739423
48	0.2648	0.252	0.002	0.17	0.5168	2	4	9.44839E-07	0.000606235
49	0.3551	0.381	0.002	0.17	0.7361	2	4	2.99772E-05	0.000661799
50	0.4036	0.3939	0.002	0.17	0.7975	2	4	8.60517E-06	0.00147136
51	0.2882	0.3195	0.002	0.17	0.6077	2	4	9.44224E-06	0.001296536

Table 7.17 TCE conductivity by Brooks-Corey-Burdine (1964) with $S_{or} = 0.002$, $S_{wr} = 0.17$ and Akamiro model

Test #	S_o	S_w	S_{or}	S_{wr}	S_t	λ	ε	$k_{rnw}(BCB)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.156	0.8173	0.18	0.08	0.9733	2	4	0.013001114	0.001257762
8	0.0559	0.8042	0.18	0.08	0.8601	2	4	0.003871189	0.000674007
9	0.6478	0.1525	0.18	0.08	0.8003	2	4	0.104109007	0.000550918
10	0.3244	0.2054	0.18	0.08	0.5298	2	4	0.000222267	0.000845200
15	0.1554	0.0944	0.18	0.08	0.2498	2	4	1.87603E-06	0.001493279
16	0.1492	0.0994	0.18	0.08	0.2486	2	4	5.76081E-07	0.001409863
17	0.2279	0.1838	0.18	0.08	0.4117	2	4	8.52242E-07	0.000692714
18	0.2695	0.0217	0.18	0.08	0.2912	2	4	0.001230306	0.001907911
19	0.3839	0.0925	0.18	0.08	0.4764	2	4	0.00373869	0.000499419
20	0.0598	0.063	0.18	0.08	0.1228	2	4	6.48931E-09	0.00039216
21	0.0542	0.4384	0.18	0.08	0.4926	2	4	0.007794683	0.001018789
22	0.2103	0.2327	0.18	0.08	0.443	2	4	7.91137E-08	0.001326749
23	0.5148	0.2141	0.18	0.08	0.7289	2	4	0.016635781	0.000527106
24	0.2549	0.1822	0.18	0.08	0.4371	2	4	1.23108E-05	0.001597202
25	0.1941	0.3051	0.18	0.08	0.4992	2	4	2.51601E-05	0.001650332
26	0.2595	0.3187	0.18	0.08	0.5782	2	4	5.95077E-06	0.001858649
28	0.1239	0.3318	0.18	0.08	0.4557	2	4	0.000734988	0.000553001
29	0.1545	0.2894	0.18	0.08	0.4439	2	4	0.000137024	0.000732043
30	0.0843	0.2809	0.18	0.08	0.3652	2	4	0.000859362	0.000788352
31	0.281	0.326	0.18	0.08	0.607	2	4	1.11103E-05	0.000735246
32	0.0574	0.0333	0.18	0.08	0.0907	2	4	2.23757E-06	0.000638563
33	0.322	0.3478	0.18	0.08	0.6698	2	4	1.42328E-05	0.000634953
35	0.2687	0.3357	0.18	0.08	0.6044	2	4	1.47257E-05	0.00082877
37	0.1792	0.9203	0.18	0.08	1.0995	2	4	0.080859455	0.000629676
38	0.3048	0.2648	0.18	0.08	0.5696	2	4	1.61328E-05	0.000657842
39	0.1212	0.3762	0.18	0.08	0.4974	2	4	0.001303895	0.000650821
40	0.1051	0.3771	0.18	0.08	0.4822	2	4	0.001911752	0.000633578
41	0.2966	0.3009	0.18	0.08	0.5975	2	4	1.60078E-07	0.001215644
42	0.1616	0.2993	0.18	0.08	0.4609	2	4	0.000126419	0.001626035
44	0.2531	0.3175	0.18	0.08	0.5706	2	4	4.2388E-06	0.000882126
45	0.377	0.3048	0.18	0.08	0.6818	2	4	0.000261157	0.000988555
46	0.2054	0.2448	0.18	0.08	0.4502	2	4	6.83929E-07	0.000731798
47	0.1419	0.2434	0.18	0.08	0.3853	2	4	6.97795E-05	0.001739423
48	0.2648	0.252	0.18	0.08	0.5168	2	4	3.60459E-07	0.000606235
49	0.3551	0.381	0.18	0.08	0.7361	2	4	3.28325E-05	0.000661799
50	0.4036	0.3939	0.18	0.08	0.7975	2	4	9.97818E-06	0.00147136
51	0.2882	0.3195	0.18	0.08	0.6077	2	4	6.87179E-06	0.001296536

Table 7.18 TCE conductivity by Brooks-Corey-Burdine (1964) with $S_{or} = 0.18$, $S_{wr} = 0.08$ and Akamiro model

Test #	S_o	S_w	S_{or}	S_{wr}	S_t	λ	ε	$k_{rmw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.156	0.8173	0.18	0.17	0.9733	2	4	0.015994141	0.001257762
8	0.0559	0.8042	0.18	0.17	0.8601	2	4	0.004412843	0.000674007
9	0.6478	0.1525	0.18	0.17	0.8003	2	4	0.130369435	0.000550918
10	0.3244	0.2054	0.18	0.17	0.5298	2	4	0.000444423	0.000845200
15	0.1554	0.0944	0.18	0.17	0.2498	2	4	5.57028E-05	0.001493279
16	0.1492	0.0994	0.18	0.17	0.2486	2	4	3.26097E-05	0.001409863
17	0.2279	0.1838	0.18	0.17	0.4117	2	4	1.34426E-05	0.000692714
18	0.2695	0.0217	0.18	0.17	0.2912	2	4	0.003652793	0.001907911
19	0.3839	0.0925	0.18	0.17	0.4764	2	4	0.006660161	0.000499419
20	0.0598	0.063	0.18	0.17	0.1228	2	4	2.65952E-07	0.00039216
21	0.0542	0.4384	0.18	0.17	0.4926	2	4	0.006517562	0.001018789
22	0.2103	0.2327	0.18	0.17	0.443	2	4	7.95166E-07	0.001326749
23	0.5148	0.2141	0.18	0.17	0.7289	2	4	0.021548095	0.000527106
24	0.2549	0.1822	0.18	0.17	0.4371	2	4	6.20675E-05	0.001597202
25	0.1941	0.3051	0.18	0.17	0.4992	2	4	5.45965E-07	0.001650332
26	0.2595	0.3187	0.18	0.17	0.5782	2	4	2.0502E-05	0.001858649
28	0.1239	0.3318	0.18	0.17	0.4557	2	4	0.00037574	0.000553001
29	0.1545	0.2894	0.18	0.17	0.4439	2	4	3.30693E-05	0.000732043
30	0.0843	0.2809	0.18	0.17	0.3652	2	4	0.000352462	0.000788352
31	0.281	0.326	0.18	0.17	0.607	2	4	2.39927E-05	0.000735246
32	0.0574	0.0333	0.18	0.17	0.0907	2	4	2.61001E-05	0.000638563
33	0.322	0.3478	0.18	0.17	0.6698	2	4	2.17983E-05	0.000634953
35	0.2687	0.3357	0.18	0.17	0.6044	2	4	3.68367E-05	0.00082877
37	0.1792	0.9203	0.18	0.17	1.0995	2	4	0.100148553	0.000629676
38	0.3048	0.2648	0.18	0.17	0.5696	2	4	3.28934E-05	0.000657842
39	0.1212	0.3762	0.18	0.17	0.4974	2	4	0.000833475	0.000650821
40	0.1051	0.3771	0.18	0.17	0.4822	2	4	0.001284179	0.000633578
41	0.2966	0.3009	0.18	0.17	0.5975	2	4	3.1823E-07	0.001215644
42	0.1616	0.2993	0.18	0.17	0.4609	2	4	3.06079E-05	0.001626035
44	0.2531	0.3175	0.18	0.17	0.5706	2	4	1.88219E-05	0.000882126
45	0.377	0.3048	0.18	0.17	0.6818	2	4	0.000367821	0.000988555
46	0.2054	0.2448	0.18	0.17	0.4502	2	4	1.31288E-06	0.000731798
47	0.1419	0.2434	0.18	0.17	0.3853	2	4	6.85151E-06	0.001739423
48	0.2648	0.252	0.18	0.17	0.5168	2	4	1.39956E-06	0.000606235
49	0.3551	0.381	0.18	0.17	0.7361	2	4	4.44043E-05	0.000661799
50	0.4036	0.3939	0.18	0.17	0.7975	2	4	1.27466E-05	0.00147136
51	0.2882	0.3195	0.18	0.17	0.6077	2	4	1.39865E-05	0.001296536

Table 7.19 Akamiro model and summary of average of hydraulic conductivity values for all models

Test #	$k_{rnw}(BC)$	$k_{rnw}(vG)$	$k_{rnw}(BCB)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.00140841	0.14884259	0.012142471	0.001257762
8	0.00185792	0.161847533	0.003469141	0.000674007
9	0.652130855	0.90004447	0.098193574	0.000550918
10	0.50392994	0.841457495	0.000279193	0.000845200
15	0.85020093	2.076528695	2.41126E-05	0.001493279
16	0.83157934	1.36966803	1.38973E-05	0.001409863
17	0.560999255	0.86569416	5.98632E-06	0.000692714
18	1.157881555	6.48226645	0.002044917	0.001907911
19	0.857358495	2.254235345	0.004354773	0.000499419
20	0.97439329	4.20852698	1.14092E-07	0.00039216
21	0.125743145	0.569518238	0.005993602	0.001018789
22	0.43816402	0.810377453	3.66126E-07	0.001326749
23	0.48221984	0.831600995	0.015990431	0.000527106
24	0.56541112	0.867474385	3.11477E-05	0.001597202
25	0.294757705	0.726387665	1.0765E-05	0.001650332
26	0.272351315	0.710449243	1.10778E-05	0.001858649
28	0.252000735	0.69506728	0.000465144	0.000553001
29	0.322312195	0.744738825	7.12307E-05	0.000732043
30	0.338012745	0.754648448	0.000507481	0.000788352
31	0.260864815	0.701880775	1.47002E-05	0.000735246
32	1.1039332	5.64838888	1.18671E-05	0.000638563
33	0.228717345	0.14884259	1.50889E-05	0.000634953
35	0.246168755	1.985297188	2.1593E-05	0.00082877
37	5.10045E-05	0.206464318	0.075801524	0.000629676
38	0.36931582	0.591286378	2.05309E-05	0.000657842
39	0.191406815	0.68957566	0.000895076	0.000650821
40	0.19030458	0.64210003	0.001338374	0.000633578
41	0.301948675	0.699601738	2.00303E-07	0.001215644
42	0.304722405	0.732493028	6.57589E-05	0.001626035
44	0.274275205	0.719570555	9.65723E-06	0.000882126
45	0.295267045	0.721363045	0.0002634	0.000988555
46	0.411172295	0.7707787	8.36212E-07	0.000731798
47	0.414229735	0.79748546	3.20911E-05	0.001739423
48	0.395714815	0.791868973	7.37051E-07	0.000606235
49	0.18558314	0.691358498	3.23448E-05	0.000661799
50	0.1705898	0.627101973	9.51655E-06	0.00147136
51	0.27107436	0.67894247	8.73492E-06	0.001296536

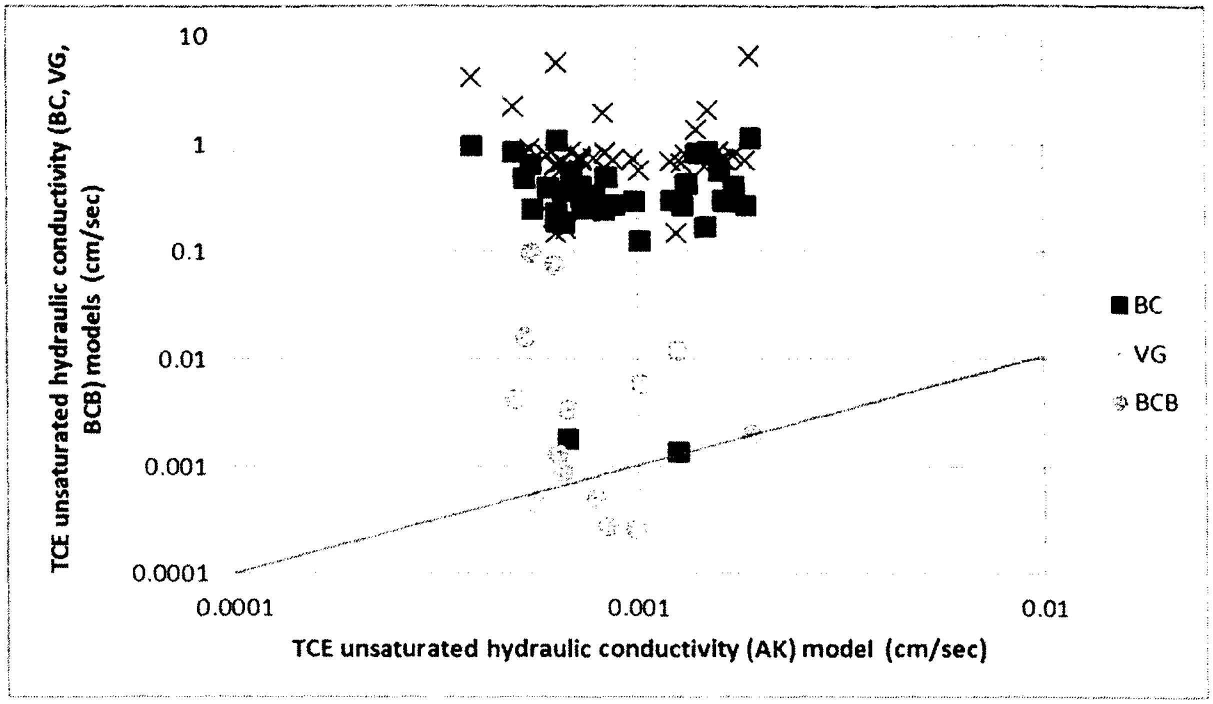

Figure 7.6 Comparison plot of TCE unsaturated hydraulic conductivity by Brooks and Corey (BC), Parker et al., (PA), and Brooks-Corey-Burdine (BCB) models with Akamiro model.

7.12 Discussion of parameters in models

The pore-size distribution index (psd) index, λ, in the BC model is the negative of the slope of the log-log plot of effective saturation, S_e, as a function of capillary pressure head, P_c / γ. Brooks and Corey (1964) determined S_r as the value of S_w from a plot of capillary pressure head vs S_w at which the curve appears to approach a vertical asymptote. The research they conducted was based on observation of a large number of experimental data of unspecified sample size.

They studied five unconsolidated media consisting of volcanic sand, fine sand, glass beads, Touchet silt loam, and fragmented fox hill sandstone and two consolidated sandstone cores. These soils were not classified according to the USCS or AASHTO criteria.

In Tables 7.21 through 7.23, TCE effective hydraulic conductivity values have been computed using the Brooks and Corey model and the values of λ in Table 7.20. For Figure 7.21, residual saturation value of Sr = 0.001 and pore size distribution index, λ = 2.29 have been used. Table 7.22 used residual saturation value of Sr = 0.001 and pore size distribution index, λ = 3.7. Table 7.23 used residual saturation value of Sr = 0.001 and pore size distribution index, λ = 7.3. The computed TCE hydraulic conductivity values from Tables 7.21 through 7.23 are tabulated in Table 7.24 and plotted in Figure 7.7.

Similarly the TCE hydraulic conductivities are computed in Tables 7.25 through Table 7.27 by using the Brooks and Corey model and the values of λ in Table 7.20. For Figure 7.25, residual saturation value of Sr = 0.1 and pore size distribution index, λ = 2.29 have been used. Table 7.26 used residual saturation value of Sr = 0.1 and pore size distribution index, λ = 3.7. Table 7.27 used residual saturation value of Sr = 0.1 and pore size distribution index, λ = 7.3. The computed TCE hydraulic conductivity values from Tables 7.25 through 7.27 are tabulated in Table 7.28 and plotted in Figure 7.8.

A study of Figures 7.7 and 7.8 shows the effect of the residual saturation. In Figure 7.7, plotted for S_r = 0.001, the one-to-one correlation line with some of the computed values agrees much more than a similar line drawn in Figure 7.8 for S_r = 0.1. From Equation 2.6, residual saturation affects the value of effective saturation and the value of effective saturation affects the values computed by the Brooks and Corey (1964) model.

Table 7.20 Description of soils studied by Brooks and Corey, 1964.

	Soil description	λ value
1	Volcanic sand. This material comes from a wind-blown deposit along Crab Creek in Washington State, It consists of dark-colored aggregates which can be broken down into finer particles by pressure. It is not known to what degree these aggregates are themselves permeable, but they undoubtedly have some permeability. At any rate, this sand has a degree of structure and has both primary and secondary porosity.	2.29
2	Fine sand. This sand was supplied by the Hanford Laboratories of General Electric Company at Richmond, Washington, and apparently contains some volcanic minerals. It contains a wide range of particle sizes, ranging down to silt size. Most o fthe particles are angular and not as rounded as most river bed sands.	3.7
3	Glass beads: The beads were purchased from the Minnesota Mining and Manufacturing Company and designated as size 130-5005. This material is an example of media having a very narrow range of pore sizes. It is not much different in this respect, however, from many clean river bed sands.	7.3

Table 7.21 TCE conductivity by Brooks and Corey (1964) model $S_r = 0.001, \lambda = 2.29$

Test #	S_w	S_r	S_e	λ	$\frac{2+\lambda}{\lambda}$	$k_{rnw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.8173	0.001	0.817117	2.29	1.87336245	0.00138717	0.001257762
8	0.8042	0.001	0.804004	2.29	1.87336245	0.00181391	0.000674007
9	0.1525	0.001	0.151652	2.29	1.87336245	0.52886163	0.000550918
10	0.2054	0.001	0.204605	2.29	1.87336245	0.41202371	0.000845200
15	0.0944	0.001	0.093493	2.29	1.87336245	0.68372608	0.001493279
16	0.0994	0.001	0.098498	2.29	1.87336245	0.66921976	0.001409863
17	0.1838	0.001	0.182983	2.29	1.87336245	0.4571295	0.000692714
18	0.0217	0.001	0.020721	2.29	1.87336245	0.9220996	0.001907911
19	0.0925	0.001	0.091592	2.29	1.87336245	0.68929917	0.000499419
20	0.063	0.001	0.062062	2.29	1.87336245	0.78022563	0.00039216
21	0.4384	0.001	0.437838	2.29	1.87336245	0.10742945	0.001018789
22	0.2327	0.001	0.231932	2.29	1.87336245	0.35984174	0.001326749
23	0.2141	0.001	0.213313	2.29	1.87336245	0.39482315	0.000527106
24	0.1822	0.001	0.181381	2.29	1.87336245	0.46061026	0.001597202
25	0.3051	0.001	0.304404	2.29	1.87336245	0.24512683	0.001650332
26	0.3187	0.001	0.318018	2.29	1.87336245	0.22706082	0.001858649
28	0.3318	0.001	0.331131	2.29	1.87336245	0.21061162	0.000553001
29	0.2894	0.001	0.288689	2.29	1.87336245	0.26728443	0.000732043
30	0.2809	0.001	0.28018	2.29	1.87336245	0.27988268	0.000788352
31	0.326	0.001	0.325325	2.29	1.87336245	0.21778136	0.000735246
32	0.0333	0.001	0.032332	2.29	1.87336245	0.88046585	0.000638563
33	0.3478	0.001	0.347147	2.29	1.87336245	0.19173993	0.000634953
35	0.3357	0.001	0.335035	2.29	1.87336245	0.20589006	0.00082877
37	0.9203	0.001	0.92022	2.29	1.87336245	5.58E-05	0.000629676
38	0.2648	0.001	0.264064	2.29	1.87336245	0.30494611	0.000657842
39	0.3762	0.001	0.375576	2.29	1.87336245	0.16136876	0.000650821
40	0.3771	0.001	0.376476	2.29	1.87336245	0.16046884	0.000633578
41	0.3009	0.001	0.3002	2.29	1.87336245	0.25091544	0.001215644
42	0.2993	0.001	0.298599	2.29	1.87336245	0.25314708	0.001626035
44	0.3175	0.001	0.316817	2.29	1.87336245	0.22861382	0.000882126
45	0.3048	0.001	0.304104	2.29	1.87336245	0.24553698	0.000988555
46	0.2448	0.001	0.244044	2.29	1.87336245	0.33835522	0.000731798
47	0.2434	0.001	0.242643	2.29	1.87336245	0.34079125	0.001739423
48	0.252	0.001	0.251251	2.29	1.87336245	0.32603048	0.000606235
49	0.381	0.001	0.38038	2.29	1.87336245	0.15661213	0.000661799
50	0.3939	0.001	0.393293	2.29	1.87336245	0.14434383	0.00147136
51	0.3195	0.001	0.318819	2.29	1.87336245	0.22602984	0.001296536

Table 7.22 TCE conductivity by Brooks and Corey (1964) model $S_r = 0.001, \lambda = 3.7$

Test #	S_w	S_r	S_e	λ	$\frac{2+\lambda}{\lambda}$	$k_{rnw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.8173	0.001	0.817117	3.7	1.54054054	0.00244171	0.001257762
8	0.8042	0.001	0.804004	3.7	1.54054054	0.00312013	0.000674007
9	0.1525	0.001	0.151652	3.7	1.54054054	0.55861697	0.000550918
10	0.2054	0.001	0.204605	3.7	1.54054054	0.44464185	0.000845200
15	0.0944	0.001	0.093493	3.7	1.54054054	0.70643146	0.001493279
16	0.0994	0.001	0.098498	3.7	1.54054054	0.69271869	0.001409863
17	0.1838	0.001	0.182983	3.7	1.54054054	0.48893447	0.000692714
18	0.0217	0.001	0.020721	3.7	1.54054054	0.92854793	0.001907911
19	0.0925	0.001	0.091592	3.7	1.54054054	0.71169302	0.000499419
20	0.063	0.001	0.062062	3.7	1.54054054	0.79704214	0.00039216
21	0.4384	0.001	0.437838	3.7	1.54054054	0.13012924	0.001018789
22	0.2327	0.001	0.231932	3.7	1.54054054	0.39287376	0.001326749
23	0.2141	0.001	0.213313	3.7	1.54054054	0.42764367	0.000527106
24	0.1822	0.001	0.181381	3.7	1.54054054	0.4923364	0.001597202
25	0.3051	0.001	0.304404	3.7	1.54054054	0.27660367	0.001650332
26	0.3187	0.001	0.318018	3.7	1.54054054	0.25790883	0.001858649
28	0.3318	0.001	0.331131	3.7	1.54054054	0.24077571	0.000553001
29	0.2894	0.001	0.288689	3.7	1.54054054	0.29937217	0.000732043
30	0.2809	0.001	0.28018	3.7	1.54054054	0.3122447	0.000788352
31	0.326	0.001	0.325325	3.7	1.54054054	0.24825718	0.000735246
32	0.0333	0.001	0.032332	3.7	1.54054054	0.89014988	0.000638563
33	0.3478	0.001	0.347147	3.7	1.54054054	0.2209765	0.000634953
35	0.3357	0.001	0.335035	3.7	1.54054054	0.23583695	0.00082877
37	0.9203	0.001	0.92022	3.7	1.54054054	0.00012945	0.000629676
38	0.2648	0.001	0.264064	3.7	1.54054054	0.33770824	0.000657842
39	0.3762	0.001	0.375576	3.7	1.54054054	0.18875055	0.000650821
40	0.3771	0.001	0.376476	3.7	1.54054054	0.18778815	0.000633578
41	0.3009	0.001	0.3002	3.7	1.54054054	0.28256834	0.001215644
42	0.2993	0.001	0.298599	3.7	1.54054054	0.28486468	0.001626035
44	0.3175	0.001	0.316817	3.7	1.54054054	0.25952078	0.000882126
45	0.3048	0.001	0.304104	3.7	1.54054054	0.2770267	0.000988555
46	0.2448	0.001	0.244044	3.7	1.54054054	0.37137435	0.000731798
47	0.2434	0.001	0.242643	3.7	1.54054054	0.37381761	0.001739423
48	0.252	0.001	0.251251	3.7	1.54054054	0.35898963	0.000606235
49	0.381	0.001	0.38038	3.7	1.54054054	0.18365836	0.000661799
50	0.3939	0.001	0.393293	3.7	1.54054054	0.17046202	0.00147136
51	0.3195	0.001	0.318819	3.7	1.54054054	0.2568382	0.001296536

Table 7.23 TCE conductivity by Brooks and Corey (1964) model $S_r = 0.001, \lambda = 7.3$

Test #	S_w	S_r	S_e	λ	$\frac{2+\lambda}{\lambda}$	$k_{rnw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.8173	0.001	0.817117	7.3	1.2739726	0.00384039	0.001257762
8	0.8042	0.001	0.804004	7.3	1.2739726	0.00481767	0.000674007
9	0.1525	0.001	0.151652	7.3	1.2739726	0.58365196	0.000550918
10	0.2054	0.001	0.204605	7.3	1.2739726	0.47261957	0.000845200
15	0.0944	0.001	0.093493	7.3	1.2739726	0.72515956	0.001493279
16	0.0994	0.001	0.098498	7.3	1.2739726	0.71213348	0.001409863
17	0.1838	0.001	0.182983	7.3	1.2739726	0.51599683	0.000692714
18	0.0217	0.001	0.020721	7.3	1.2739726	0.93374512	0.001907911
19	0.0925	0.001	0.091592	7.3	1.2739726	0.73015256	0.000499419
20	0.063	0.001	0.062062	7.3	1.2739726	0.81077206	0.00039216
21	0.4384	0.001	0.437838	7.3	1.2739726	0.15172382	0.001018789
22	0.2327	0.001	0.231932	7.3	1.2739726	0.42150409	0.001326749
23	0.2141	0.001	0.213313	7.3	1.2739726	0.45588778	0.000527106
24	0.1822	0.001	0.181381	7.3	1.2739726	0.51931587	0.001597202
25	0.3051	0.001	0.304404	7.3	1.2739726	0.30470569	0.001650332
26	0.3187	0.001	0.318018	7.3	1.2739726	0.28561238	0.001858649
28	0.3318	0.001	0.331131	7.3	1.2739726	0.26802244	0.000553001
29	0.2894	0.001	0.288689	7.3	1.2739726	0.32782914	0.000732043
30	0.2809	0.001	0.28018	7.3	1.2739726	0.3408432	0.000788352
31	0.326	0.001	0.325325	7.3	1.2739726	0.27571461	0.000735246
32	0.0333	0.001	0.032332	7.3	1.2739726	0.89798291	0.000638563
33	0.3478	0.001	0.347147	7.3	1.2739726	0.24757705	0.000634953
35	0.3357	0.001	0.335035	7.3	1.2739726	0.26293476	0.00082877
37	0.9203	0.001	0.92022	7.3	1.2739726	0.000254	0.000629676
38	0.2648	0.001	0.264064	7.3	1.2739726	0.3664695	0.000657842
39	0.3762	0.001	0.375576	7.3	1.2739726	0.21399653	0.000650821
40	0.3771	0.001	0.376476	7.3	1.2739726	0.21298736	0.000633578
41	0.3009	0.001	0.3002	7.3	1.2739726	0.31077675	0.001215644
42	0.2993	0.001	0.298599	7.3	1.2739726	0.31311146	0.001626035
44	0.3175	0.001	0.316817	7.3	1.2739726	0.28726269	0.000882126
45	0.3048	0.001	0.304104	7.3	1.2739726	0.30513658	0.000988555
46	0.2448	0.001	0.244044	7.3	1.2739726	0.40012975	0.000731798
47	0.2434	0.001	0.242643	7.3	1.2739726	0.4025634	0.001739423
48	0.252	0.001	0.251251	7.3	1.2739726	0.38777505	0.000606235
49	0.381	0.001	0.38038	7.3	1.2739726	0.20865244	0.000661799
50	0.3939	0.001	0.393293	7.3	1.2739726	0.19475047	0.00147136
51	0.3195	0.001	0.318819	7.3	1.2739726	0.28451584	0.001296536

Table 7.24 Summary of TCE conductivity by Brooks and Corey (1964) model $S_r = .001$

Test #	$Pk_{TCE}(\lambda = 2.29)$ (cm/sec)	$Pk_{TCE}(\lambda = 3.7)$ (cm/sec)	$Pk_{TCE}(\lambda = 7.3)$ (cm/sec)	$Pk_{TCE}(\lambda = 2.0)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.00138717	0.00244171	0.00384039	0.00384039	0.001257762
8	0.00181391	0.00312013	0.00481767	0.00481767	0.000674007
9	0.52886163	0.55861697	0.58365196	0.58365196	0.000550918
10	0.41202371	0.44464185	0.47261957	0.47261957	0.000845200
15	0.68372608	0.70643146	0.72515956	0.72515956	0.001493279
16	0.66921976	0.69271869	0.71213348	0.71213348	0.001409863
17	0.4571295	0.48893447	0.51599683	0.51599683	0.000692714
18	0.9220996	0.92854793	0.93374512	0.93374512	0.001907911
19	0.68929917	0.71169302	0.73015256	0.73015256	0.000499419
20	0.78022563	0.79704214	0.81077206	0.81077206	0.00039216
21	0.10742945	0.13012924	0.15172382	0.15172382	0.001018789
22	0.35984174	0.39287376	0.42150409	0.42150409	0.001326749
23	0.39482315	0.42764367	0.45588778	0.45588778	0.000527106
24	0.46061026	0.4923364	0.51931587	0.51931587	0.001597202
25	0.24512683	0.27660367	0.30470569	0.30470569	0.001650332
26	0.22706082	0.25790883	0.28561238	0.28561238	0.001858649
28	0.21061162	0.24077571	0.26802244	0.26802244	0.000553001
29	0.26728443	0.29937217	0.32782914	0.32782914	0.000732043
30	0.27988268	0.3122447	0.3408432	0.3408432	0.000788352
31	0.21778136	0.24825718	0.27571461	0.27571461	0.000735246
32	0.88046585	0.89014988	0.89798291	0.89798291	0.000638563
33	0.19173993	0.2209765	0.24757705	0.24757705	0.000634953
35	0.20589006	0.23583695	0.26293476	0.26293476	0.00082877
37	5.58E-05	0.00012945	0.000254	0.000254	0.000629676
38	0.30494611	0.33770824	0.3664695	0.3664695	0.000657842
39	0.16136876	0.18875055	0.21399653	0.21399653	0.000650821
40	0.16046884	0.18778815	0.21298736	0.21298736	0.000633578
41	0.25091544	0.28256834	0.31077675	0.31077675	0.001215644
42	0.25314708	0.28486468	0.31311146	0.31311146	0.001626035
44	0.22861382	0.25952078	0.28726269	0.28726269	0.000882126
45	0.24553698	0.2770267	0.30513658	0.30513658	0.000988555
46	0.33835522	0.37137435	0.40012975	0.40012975	0.000731798
47	0.34079125	0.37381761	0.4025634	0.4025634	0.001739423
48	0.32603048	0.35898963	0.38777505	0.38777505	0.000606235
49	0.15661213	0.18365836	0.20865244	0.20865244	0.000661799
50	0.14434383	0.17046202	0.19475047	0.19475047	0.00147136
51	0.22602984	0.2568382	0.28451584	0.28451584	0.001296536

Table 7.25 TCE conductivity by Brooks and Corey (1964) model $S_r = 0.1, \lambda = 2.29$

Test #	S_w	S_r	S_e	λ	$\frac{2+\lambda}{\lambda}$	$k_{mw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.8173	0.1	0.797	2.29	1.87336245	0.00207817	0.001257762
8	0.8042	0.1	0.782444	2.29	1.87336245	0.0027175	0.000674007
9	0.1525	0.1	0.058333	2.29	1.87336245	0.79230863	0.000550918
10	0.2054	0.1	0.117111	2.29	1.87336245	0.61726909	0.000845200
15	0.0944	0.1	-0.00622	2.29	1.87336245	1.02431721	0.001493279
16	0.0994	0.1	-0.00067	2.29	1.87336245	1.00258472	0.001409863
17	0.1838	0.1	0.093111	2.29	1.87336245	0.68484387	0.000692714
18	0.0217	0.1	-0.087	2.29	1.87336245	1.38143405	0.001907911
19	0.0925	0.1	-0.00833	2.29	1.87336245	1.03266648	0.000499419
20	0.063	0.1	-0.04111	2.29	1.87336245	1.16888703	0.00039216
21	0.4384	0.1	0.376	2.29	1.87336245	0.16094433	0.001018789
22	0.2327	0.1	0.147444	2.29	1.87336245	0.53909321	0.001326749
23	0.2141	0.1	0.126778	2.29	1.87336245	0.59150025	0.000527106
24	0.1822	0.1	0.091333	2.29	1.87336245	0.69005853	0.001597202
25	0.3051	0.1	0.227889	2.29	1.87336245	0.36723424	0.001650332
26	0.3187	0.1	0.243	2.29	1.87336245	0.34016883	0.001858649
28	0.3318	0.1	0.257556	2.29	1.87336245	0.31552563	0.000553001
29	0.2894	0.1	0.210444	2.29	1.87336245	0.40042942	0.000732043
30	0.2809	0.1	0.201	2.29	1.87336245	0.41930337	0.000788352
31	0.326	0.1	0.251111	2.29	1.87336245	0.32626691	0.000735246
32	0.0333	0.1	-0.07411	2.29	1.87336245	1.31906088	0.000638563
33	0.3478	0.1	0.275333	2.29	1.87336245	0.28725321	0.000634953
35	0.3357	0.1	0.261889	2.29	1.87336245	0.30845209	0.00082877
37	0.9203	0.1	0.911444	2.29	1.87336245	8.3596E-05	0.000629676
38	0.2648	0.1	0.183111	2.29	1.87336245	0.45685188	0.000657842
39	0.3762	0.1	0.306889	2.29	1.87336245	0.24175295	0.000650821
40	0.3771	0.1	0.307889	2.29	1.87336245	0.24040474	0.000633578
41	0.3009	0.1	0.223222	2.29	1.87336245	0.3759064	0.001215644
42	0.2993	0.1	0.221444	2.29	1.87336245	0.3792497	0.001626035
44	0.3175	0.1	0.241667	2.29	1.87336245	0.34249545	0.000882126
45	0.3048	0.1	0.227556	2.29	1.87336245	0.36784871	0.000988555
46	0.2448	0.1	0.160889	2.29	1.87336245	0.5069034	0.000731798
47	0.2434	0.1	0.159333	2.29	1.87336245	0.51055292	0.001739423
48	0.252	0.1	0.168889	2.29	1.87336245	0.48843922	0.000606235
49	0.381	0.1	0.312222	2.29	1.87336245	0.23462686	0.000661799
50	0.3939	0.1	0.326556	2.29	1.87336245	0.21624722	0.00147136
51	0.3195	0.1	0.243889	2.29	1.87336245	0.33862428	0.001296536

Table 7.26 TCE conductivity by Brooks and Corey (1964) model $S_r = 0.1, \lambda = 3.7$

Test #	S_w	S_r	S_e	λ	$\frac{2+\lambda}{\lambda}$	$k_{rnw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.8173	0.1	0.797	3.7	1.54054054	0.00353315	0.001257762
8	0.8042	0.1	0.782444	3.7	1.54054054	0.00451482	0.000674007
9	0.1525	0.1	0.058333	3.7	1.54054054	0.80831748	0.000550918
10	0.2054	0.1	0.117111	3.7	1.54054054	0.64339574	0.000845200
15	0.0944	0.1	-0.00622	3.7	1.54054054	1.02220471	0.001493279
16	0.0994	0.1	-0.00067	3.7	1.54054054	1.00236236	0.001409863
17	0.1838	0.1	0.093111	3.7	1.54054054	0.70748706	0.000692714
18	0.0217	0.1	-0.087	3.7	1.54054054	1.34360673	0.001907911
19	0.0925	0.1	-0.00833	3.7	1.54054054	1.02981816	0.000499419
20	0.063	0.1	-0.04111	3.7	1.54054054	1.15331815	0.00039216
21	0.4384	0.1	0.376	3.7	1.54054054	0.18829671	0.001018789
22	0.2327	0.1	0.147444	3.7	1.54054054	0.56848744	0.001326749
23	0.2141	0.1	0.126778	3.7	1.54054054	0.61879941	0.000527106
24	0.1822	0.1	0.091333	3.7	1.54054054	0.71240964	0.001597202
25	0.3051	0.1	0.227889	3.7	1.54054054	0.40024488	0.001650332
26	0.3187	0.1	0.243	3.7	1.54054054	0.37319349	0.001858649
28	0.3318	0.1	0.257556	3.7	1.54054054	0.3484019	0.000553001
29	0.2894	0.1	0.210444	3.7	1.54054054	0.43319084	0.000732043
30	0.2809	0.1	0.201	3.7	1.54054054	0.45181737	0.000788352
31	0.326	0.1	0.251111	3.7	1.54054054	0.35922758	0.000735246
32	0.0333	0.1	-0.07411	3.7	1.54054054	1.28804484	0.000638563
33	0.3478	0.1	0.275333	3.7	1.54054054	0.31975248	0.000634953
35	0.3357	0.1	0.261889	3.7	1.54054054	0.34125552	0.00082877
37	0.9203	0.1	0.911444	3.7	1.54054054	0.00018732	0.000629676
38	0.2648	0.1	0.183111	3.7	1.54054054	0.48866305	0.000657842
39	0.3762	0.1	0.306889	3.7	1.54054054	0.27312162	0.000650821
40	0.3771	0.1	0.307889	3.7	1.54054054	0.27172902	0.000633578
41	0.3009	0.1	0.223222	3.7	1.54054054	0.40887574	0.001215644
42	0.2993	0.1	0.221444	3.7	1.54054054	0.41219854	0.001626035
44	0.3175	0.1	0.241667	3.7	1.54054054	0.37552597	0.000882126
45	0.3048	0.1	0.227556	3.7	1.54054054	0.400857	0.000988555
46	0.2448	0.1	0.160889	3.7	1.54054054	0.53737784	0.000731798
47	0.2434	0.1	0.159333	3.7	1.54054054	0.54091323	0.001739423
48	0.252	0.1	0.168889	3.7	1.54054054	0.51945717	0.000606235
49	0.381	0.1	0.312222	3.7	1.54054054	0.26575323	0.000661799
50	0.3939	0.1	0.326556	3.7	1.54054054	0.24665815	0.00147136
51	0.3195	0.1	0.243889	3.7	1.54054054	0.37164429	0.001296536

Table 7.27 TCE conductivity by Brooks and Corey (1964) model $S_r = 0.1, \lambda = 7.3$

Test #	S_w	S_r	S_e	λ	$\frac{2+\lambda}{\lambda}$	$k_{mw}(BC)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.8173	0.1	0.797	7.3	1.2739726	1.2739726	0.001257762
8	0.8042	0.1	0.782444	7.3	1.2739726	1.2739726	0.000674007
9	0.1525	0.1	0.058333	7.3	1.2739726	1.2739726	0.000550918
10	0.2054	0.1	0.117111	7.3	1.2739726	1.2739726	0.000845200
15	0.0944	0.1	-0.00622	7.3	1.2739726	1.2739726	0.001493279
16	0.0994	0.1	-0.00067	7.3	1.2739726	1.2739726	0.001409863
17	0.1838	0.1	0.093111	7.3	1.2739726	1.2739726	0.000692714
18	0.0217	0.1	-0.087	7.3	1.2739726	1.2739726	0.001907911
19	0.0925	0.1	-0.00833	7.3	1.2739726	1.2739726	0.000499419
20	0.063	0.1	-0.04111	7.3	1.2739726	1.2739726	0.00039216
21	0.4384	0.1	0.376	7.3	1.2739726	1.2739726	0.001018789
22	0.2327	0.1	0.147444	7.3	1.2739726	1.2739726	0.001326749
23	0.2141	0.1	0.126778	7.3	1.2739726	1.2739726	0.000527106
24	0.1822	0.1	0.091333	7.3	1.2739726	1.2739726	0.001597202
25	0.3051	0.1	0.227889	7.3	1.2739726	1.2739726	0.001650332
26	0.3187	0.1	0.243	7.3	1.2739726	1.2739726	0.001858649
28	0.3318	0.1	0.257556	7.3	1.2739726	1.2739726	0.000553001
29	0.2894	0.1	0.210444	7.3	1.2739726	1.2739726	0.000732043
30	0.2809	0.1	0.201	7.3	1.2739726	1.2739726	0.000788352
31	0.326	0.1	0.251111	7.3	1.2739726	1.2739726	0.000735246
32	0.0333	0.1	-0.07411	7.3	1.2739726	1.2739726	0.000638563
33	0.3478	0.1	0.275333	7.3	1.2739726	1.2739726	0.000634953
35	0.3357	0.1	0.261889	7.3	1.2739726	1.2739726	0.00082877
37	0.9203	0.1	0.911444	7.3	1.2739726	1.2739726	0.000629676
38	0.2648	0.1	0.183111	7.3	1.2739726	1.2739726	0.000657842
39	0.3762	0.1	0.306889	7.3	1.2739726	1.2739726	0.000650821
40	0.3771	0.1	0.307889	7.3	1.2739726	1.2739726	0.000633578
41	0.3009	0.1	0.223222	7.3	1.2739726	1.2739726	0.001215644
42	0.2993	0.1	0.221444	7.3	1.2739726	1.2739726	0.001626035
44	0.3175	0.1	0.241667	7.3	1.2739726	1.2739726	0.000882126
45	0.3048	0.1	0.227556	7.3	1.2739726	1.2739726	0.000988555
46	0.2448	0.1	0.160889	7.3	1.2739726	1.2739726	0.000731798
47	0.2434	0.1	0.159333	7.3	1.2739726	1.2739726	0.001739423
48	0.252	0.1	0.168889	7.3	1.2739726	1.2739726	0.000606235
49	0.381	0.1	0.312222	7.3	1.2739726	1.2739726	0.000661799
50	0.3939	0.1	0.326556	7.3	1.2739726	1.2739726	0.00147136
51	0.3195	0.1	0.243889	7.3	1.2739726	1.2739726	0.001296536

Table 7.28 Summary of TCE conductivity by Brooks and Corey (1964) model $S_r = 0.1$

Test #	$Pk_{TCE}(\lambda = 2.29)$ (cm/sec)	$Pk_{TCE}(\lambda = 3.7)$ (cm/sec)	$Pk_{TCE}(\lambda = 7.3)$ (cm/sec)	$Pk_{TCE}(\lambda = 2.0)$ (cm/sec)	Pk_{TCE} (cm/sec)
1	0.00207817	0.00353315	1.2739726	0.00169818	0.001257762
8	0.0027175	0.00451482	1.2739726	0.00224017	0.000674007
9	0.79230863	0.80831748	1.2739726	0.78630093	0.000550918
10	0.61726909	0.64339574	1.2739726	0.60760901	0.000845200
15	1.02431721	1.02220471	1.2739726	1.02512215	0.001493279
16	1.00258472	1.00236236	1.2739726	1.00266933	0.001409863
17	0.68484387	0.70748706	1.2739726	0.67641982	0.000692714
18	1.38143405	1.34360673	1.2739726	1.3961053	0.001907911
19	1.03266648	1.02981816	1.2739726	1.03375232	0.000499419
20	1.16888703	1.15331815	1.2739726	1.17486597	0.00039216
21	0.16094433	0.18829671	1.2739726	0.15161367	0.001018789
22	0.53909321	0.56848744	1.2739726	0.52831234	0.001326749
23	0.59150025	0.61879941	1.2739726	0.58143225	0.000527106
24	0.69005853	0.71240964	1.2739726	0.68173939	0.001597202
25	0.36723424	0.40024488	1.2739726	0.35540146	0.001650332
26	0.34016883	0.37319349	1.2739726	0.32838516	0.001858649
28	0.31552563	0.3484019	1.2739726	0.30384763	0.000553001
29	0.40042942	0.43319084	1.2739726	0.38862504	0.000732043
30	0.41930337	0.45181737	1.2739726	0.40755584	0.000788352
31	0.32626691	0.35922758	1.2739726	0.31453541	0.000735246
32	1.31906088	1.28804484	1.2739726	1.33105756	0.000638563
33	0.28725321	0.31975248	1.2739726	0.27577389	0.000634953
35	0.30845209	0.34125552	1.2739726	0.29681577	0.00082877
37	8.3596E-05	0.00018732	1.2739726	6.1498E-05	0.000629676
38	0.45685188	0.48866305	1.2739726	0.44529924	0.000657842
39	0.24175295	0.27312162	1.2739726	0.23078705	0.000650821
40	0.24040474	0.27172902	1.2739726	0.22945804	0.000633578
41	0.3759064	0.40887574	1.2739726	0.36407191	0.001215644
42	0.3792497	0.41219854	1.2739726	0.36741631	0.001626035
44	0.34249545	0.37552597	1.2739726	0.33070487	0.000882126
45	0.36784871	0.400857	1.2739726	0.35601559	0.000988555
46	0.5069034	0.53737784	1.2739726	0.49576731	0.000731798
47	0.51055292	0.54091323	1.2739726	0.49945379	0.001739423
48	0.48843922	0.51945717	1.2739726	0.47712959	0.000606235
49	0.23462686	0.26575323	1.2739726	0.22376521	0.000661799
50	0.21624722	0.24665815	1.2739726	0.20568712	0.00147136
51	0.33862428	0.37164429	1.2739726	0.32684548	0.001296536

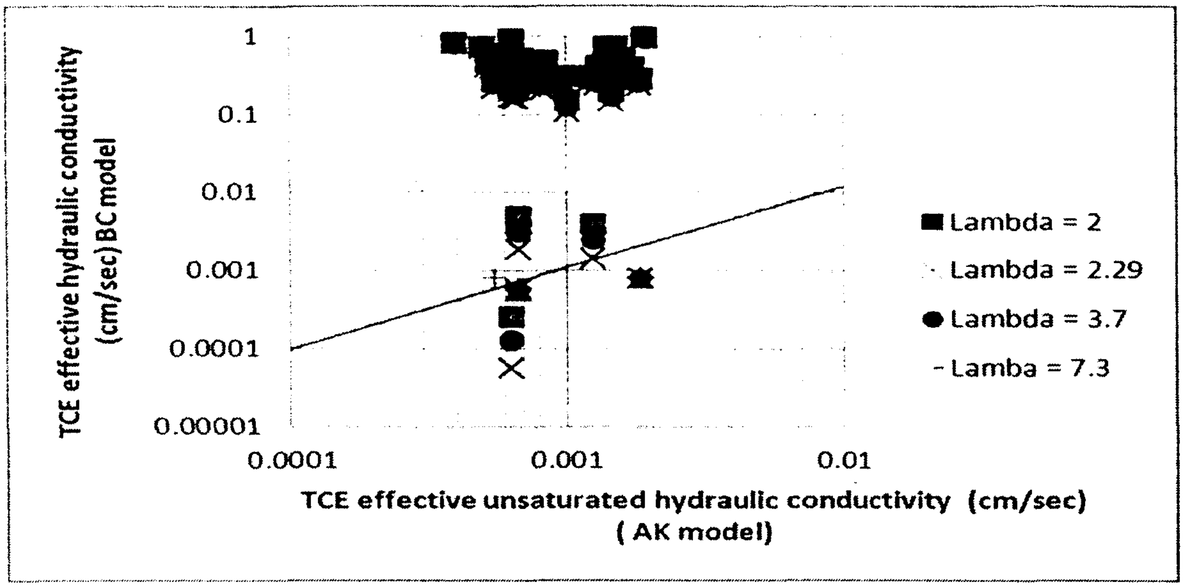

Figure 7.7 TCE effective hydraulic conductivity by Brooks and Corey and Akamiro models using $S_r = 0.001$

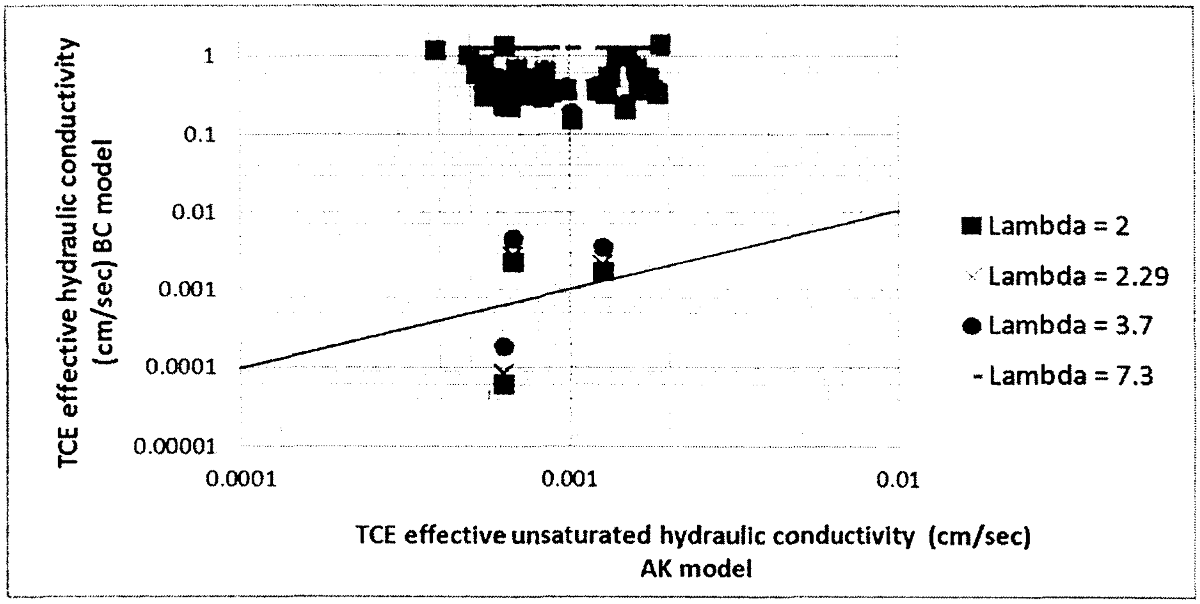

Figure 7.8 TCE effective hydraulic conductivity by Brooks and Corey and Akamiro models using $S_r = 0.1$

7.13 Conclusion from model comparisons

Figure 7.6 shows that the BCB model plots rather closely to the AK model while the BC and VG models plot the furthest. Therefore the BCB model is consistent with the AK model. It is concluded that the existing previous models may be good, however, the parameters obtained from literatures may not be accurate enough to compute the conductivity. Accurate usage of these models requires experimentally determined parameter values, which involve additional cost for equipment, labor and other direct or indirect costs.

CHAPTER 8

SUMMARY AND CONCLUSIONS

8.1 Summary

Chapter 1 reviewed the production, uses and sources of groundwater pollution in the USA. It was pointed out that the measurement of permeability in unsaturated soils is very difficult, very time consuming, and very expensive.

Chapter 2 was a review of previous research findings. These current methods depend on saturations and coefficients, some of which depend on other coefficients such as Equations 2.4 and 2.5 (Brooks and Corey 1966); Equations 2.6 to 2.8 (Van Genutchen, 1980); and Equation 2.9 (Brooks-Corey-Burdine). None of the current methods explored the relationship between unsaturated (effective) hydraulic permeability of a contaminant and basic easy to determine soil and engineering properties such as moisture content, contaminant content, void ratio, suction, and wet unit weight. This study is an effort to produce new knowledge in this area to relate NAPL contaminant conductivity in unsaturated soil to these soil and liquid engineering properties.

Chapter 3 discussed the research tasks, research benefits and anticipated results. It also discussed NAPL fluid properties.

Chapter 4 discussed the newly designed laboratory instrumentation and the derivation of

Equation 4.17 which is used to compute the measured TCE unsaturated conductivity, Mk_{TCE}.

Chapter 5 explored the validity of using a linear model subset of generalized linear model for fitting the dependent variable to the independent variables. It concluded that the relationship is nonlinear.

The new model was presented in Chapter 6. The assumptions of nonlinear regression analysis were verified. Chapter 7 discussed the discrete and normalized discrete sensitivity analyses.

The research task was to develop a model for predicting unsaturated hydraulic conductivity of an immiscible liquid such as dense non-aqueous phase liquid, DNAPL, using independent variables of soil and liquid engineering properties such as water content, NAPL content, void ration, and soil suction. To solve this problem, the following tasks were completed:

1. A new test instrumentation was developed. This test instrumentation was successfully used for a considerably very long period of testing time.

2. A new empirical model was developed and used to determine the unsaturated (effective) hydraulic conductivity of NAPL of choice for over fifty laboratory tests.

3. A nonlinear regression model was developed using the nonlinear regression model, NLIN, and the Marquardt iterative method. The convergence criteria

based on the Bates and Watts relative offset convergence measure was met. The assumptions for this model were checked and confirmed.

4. Sensitivity analyses were completed and the results were consistent with expected outcome.

8.2 Conclusions

From this research, the following conclusions are obtained:

1. The newly developed laboratory instrumentation performed satisfactorily. it is hereby recommended for hydraulic conductivity tests for both light and dense NAPLs and other immiscible liquids in any soil medium. The Akamiro model may be used as input to current numerical procedures such as CHEMFLO, etc. Such use may discover any possible bias of the other models in Table 7.7

2. Water content has the highest sensitivity and the other independent variables can be ranked in order of decreasing sensitivity as follows: TCE content, void ratio and soil suction.

3. Figure 7.5 showed that below 36% normalized value, water content produced the greatest sensitivity to TCE hydraulic conductivity and above 36%, TCE content and void ratio produced about the same sensitivity with TCE content contribution being slightly higher. Based on this, the independent variables can be ranked in decreasing order of greatest contribution to TCE conductivity as follows: water content, TCE content, void ratio, and soil suction, (b) water content showed the greatest decreasing contribution to TCE conductivity.

4. Accurate usage of previous models requires experimentally determined parameter values. This, however, involves additional cost for equipment, labor and other direct or indirect costs.

5. In the opinion of this researcher, the model may be applicable for fine gravels as well. It is applicable for fine gravels because soil with grain size from 2.00 mm to 4.75 mm is classified as sand by USCS and gravel by AASHTO. It is not applicable to silt or clay by reason of differences in particle size and shape, structure, surface charge, specific surface, interactive forces, plasticity, shear resistance and volume change.

6. The following recommendations are made for further studies:

   (i) Study be extended to include other soil types and soil

   (ii) Study can be conducted for mixtures of different types of contaminants,

   (iii) Improvement on test procedure could be achieved, which includes automation of data acquisition.

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APPENDIX A

Sample NLIN regression analyses computer code

```
/* SAS code for the analysis of NAPL lab data */


/* This is a program developed for analyzing the data
from laboratory tests conducted on unsaturated soil
to model the hydraulic conductivity (Y) of an NAPL.
The independent variables are as follows.
1. X1 = water content (%)
2. X2 = NAPL content (%)
3. X3 = void ratio
4. X4 = soil suction (millibars)
5. X5 = wet unit weight of unsaturated soil
containing air, water and NAPL (Kg per
cubic meter)*/


OPTIONS  OBS=MAX;
OPTIONS  PS = 60;
data napl;
INPUT test Y  X1  X2  X3  X4  X5 YL YU SR;
DATALINES;
1   0.001919  28.4751 9.1286  0.9232  12  1879.6  .        0.001919  5.0413
8   0.000997  25.339  2.5729  0.8348  7   1847.39 0.000997  .        14.3755
9   0.000884  4.6161  28.620  0.8019  10  1959.5  0.000884  .        0.2355
10  0.000734  6.7711  15.614  0.8737  78  1730.9  0.000734  .        0.4367
15  0.000662  3.4901  7.7799  0.9868  66  1503.5  0.000662  .        0.6481
16  0.000883  3.6221  7.9295  0.9720  7   1510.3  0.000883  .        0.6670
```

17	0.000964	5.6558	10.239	0.8216	34	1698.7	0.000964	.	0.8065
18	0.001947	0.6934	12.134	0.8504	68	1633.7	.	0.001947	0.0780
19	0.000923	2.6403	15.747	0.7615	10	1798.1	0.000923	.	0.2448
20	0.000767	1.6625	14.238	0.7245	11	1916.5	0.000767	.	1.0544
21	0.001093	3.8902	8.3451	0.7042	13	1918.6	0.001093	.	4.3996
22	0.001032	1.8714	6.1540	0.8061	6	1555.8	0.001032	.	1.0544
23	0.000822	12.764	5.9545	0.7656	11	1736.6	0.000822	.	4.3996
24	0.001713	11.000	28.000	0.7927	13	1728.0	.	0.001713	1.1066
25	0.001813	6.2322	22.835	0.7774	6	1924.6	.	0.001813	0.4158
26	0.001849	11.459	27.057	0.8486	11.5	1698.7	.	0.001849	0.7147
27	.	19.197	17.826	0.8486	10	1714.5	0.000258	.	1.5727
28	0.000361	9.399	21.500	0.7842	8	1803.1	0.000361	.	1.2282
29	0.000572	10.353	4.8086	0.8332	5	1689.4	0.000572	.	2.6788
30	0.000646	9.2079	11.720	0.8495	8	1680.2	0.000646	.	1.8728
31	0.000616	8.7084	7.2407	0.8278	6	1643.7	0.000616	.	3.3318
32	0.000903	9.966	13.126	0.8163	14	1800.9	0.000903	.	1.1601
33	0.000923	9.9615	6.6625	0.7979	14	1670.2	0.000923	.	5.8124
34	.	10.657	14.404	0.8180	10	1836.7	.	.	1.0802
35	0.000912	10.983	14.326	0.8736	29	1764.5	0.000912	.	1.2490
36	.	27.983	8.3657	0.8119	17	2003.2	.	.	5.1366
37	0.000935	8.0504	13.627	0.8119	6.5	1791.6	0.000935	.	0.8687
38	0.000917	11.451	8.5719	0.8127	12	1720.9	0.000917	.	3.1115
39	0.000919	11.429	5.1211	0.8092	12.5	1713	0.000919	.	3.5892
40	0.000916	9.1792	11.280	0.8145	10	1800.9	0.000916	.	1.0418
41	0.001447	9.2195	7.9350	0.8225	10	1706.6	0.001447	.	1.8520

```
42  0.001820  10.367  11.730  0.8727  13   1745.9    .    0.001820 1.2540
 43    .      9.7078  16.107  0.8504  12   1836      .    0.003287 0.8084
44  0.000927  8.0362  13.745  0.8765  10   1677.3  0.000927    .    1.1919
45  0.000868  8.1726  11.675  0.8965  8.5  1620.8  0.000868    .    1.7157
46  0.000846  7.931   12.364  0.8404  9    1742.3  0.000846    .    0.9517
47  0.001516  12.043  18.017  0.8441  22   1859.5  0.001516    .    1.0730
48  0.000625  12.068  17.701  0.8180  5    1911    0.000625    .    0.9760
49  0.000498  9.8633  13.709  0.8242  7    1798.1  0.000498    .    1.1087
50  0.001065  14.052  18.147  0.8486  11.5 1868.1  0.001065    .    1.3419
51  0.001079  13.839  13.213  0.8339  14   1881    0.001079    .    1.3591
                              RUN;
                               ;


PROC NLIN data = napl maxiter = 5000 method = marquardt;
        PARMS a1 = 0.00006 to 10 by 0.5
              b1 = -0.00000002 to 1 by 0.05
              b2 = 0.0000002 to 0.05 by 0.0025
              b3 = 0.1 to 5 by 0.245
              b4 = -0.00001 to -0.01 by 0.0005
              b5 = 0.003 to 0.005  by  0.0005
              v = 0 to 0.001 by 0.0001;

        a = a1*b1*b2*b4*b5;
```

```
j = x3**3/(1+x3);

c = (b1*x1+b2*x2+b3*x3+b4*x4+b5*x5);

IF 0 LE Y LE 0.001 THEN d = 0.0;

ELSE IF Y GT 0.001 THEN d = j*log(x5)*exp(c);

model Y = v + SR*(a1*(x2+x1*x2+x2*x2)/(x1*x4*x5*x5))+d*(1/SR);

OUTPUT OUT = napl  predicted=pred  p=yhat student R=resid l95m=lower
u95m=upper;

run;

proc print data = napl;

run;

quit;

proc plot data = napl;

plot pred*Y;

run;

proc plot data = napl;

plot pred*(x1 x2 x3 x4 x5);
```

```
run;

proc univariate data = napl;
var Y;
run;

proc univariate data = napl;
var YL;
run;

proc univariate data = napl;
var YU;
run;
```

APPENDIX B

Summary of output from NLIN computer code

```
                         The NLIN Procedure
                                   Dependent Variable Y
                                    Method: Marquardt

                                     Iterative Phase
                                                                   Sum of
          Iter      b1        b2        b3        b4        p         m     Squares

       0  -0.00010   0.0499   0.8000  -0.00010   5.5000  0.000010  6.591E-6
       1   -2.4398  -0.0415   3.1767  -0.00216   4.9752  0.000035   4.27E-6
       2   -2.2044  -0.0308   3.1053   0.0151    4.7220  0.000033   3.64E-6
       3   -2.3173  -0.0238   2.9328   0.0140    4.6637  0.000033  3.308E-6
       4   -2.3123  -0.0216   2.7942   0.0131    4.6690  0.000036  3.295E-6
       5   -2.3051  -0.0211   2.6437   0.0130    4.6721  0.000040  3.289E-6
       6   -2.3141  -0.0211   2.4705   0.0133    4.6739  0.000046  3.283E-6

^G Get Help      ^O WriteOut      ^R Read File      ^Y Prev Page      ^K Cut Text      ^C Cur Pos
 ^X Exit          ^J Justify       ^W Where Is       ^V Next Page      ^U UnCut Text    ^T To Spell
                5  -2.3051  -0.0211   2.6437   0.0130   4.6721  0.000040  3.289E-6
       6   -2.3141  -0.0211   2.4705   0.0133    4.6739  0.000046  3.283E-6
       7   -2.3294  -0.0212   2.2701   0.0137    4.6753  0.000054  3.277E-6
       8   -2.3483  -0.0215   2.0403   0.0142    4.6768  0.000065   3.27E-6
       9   -2.3698  -0.0218   1.7819   0.0148    4.6786  0.000080  3.264E-6
      10   -2.3931  -0.0220   1.4991   0.0154    4.6808  0.000100  3.259E-6
      11   -2.4174  -0.0223   1.2007   0.0161    4.6835  0.000128  3.253E-6
      12   -2.4414  -0.0225   0.8995   0.0167    4.6865  0.000164  3.247E-6
      13   -2.4637  -0.0227   0.6121   0.0174    4.6899  0.000208  3.241E-6
      14   -2.4831  -0.0228   0.3551   0.0179    4.6932  0.000257  3.236E-6
      15   -2.4985  -0.0229   0.1417   0.0184    4.6963  0.000308  3.231E-6
      16   -2.5098  -0.0229  -0.0222   0.0187    4.6990  0.000354  3.228E-6
      17   -2.5259  -0.0230  -0.2167   0.0192    4.7020  0.000413  3.228E-6
      18   -2.5262  -0.0229  -0.2784   0.0193    4.7034  0.000438  3.227E-6
      19   -2.5265  -0.0229  -0.2966   0.0193    4.7039  0.000444  3.227E-6
```

```
              20    -2.5263    -0.0228    -0.3020    0.0193    4.7041   0.000446   3.227E-6
              21    -2.5263    -0.0228    -0.3038    0.0193    4.7041   0.000447   3.227E-6
              22    -2.5263    -0.0228    -0.3044    0.0193    4.7042   0.000447   3.227E-6
              23    -2.5263    -0.0228    -0.3046    0.0193    4.7042   0.000447   3.227E-6
NOTE: Missing values were generated as a result of performing an operation on missing values.    Each place is given by ($
                              of times) AT (statement)/(line):(column).


                                                  4 AT 8/85:23


                                         NOTE: Convergence criterion met.


                                                  Estimation Summary

                                              Method              Marquardt
                                                Iterations             23
                                               Subiterations            22
                                            Average Subiterations    0.956522
                                                  R               4.491E-6
                                               PPC(b3)            0.000199
                                               RPC(b3)            0.000634
                                                Object            1.93E-10

     ^G Get Help       ^O WriteOut       ^R Read File      ^Y Prev Page      ^K Cut Text       ^C Cur Pos
                                   RPC(b3)          0.000634
                                                Object            1.93E-10
                                               Objective          3.227E-6
                                              Observations Read          41
                                              Observations Used          37
                                             Observations Missing         4
     ^L                                 The SAS System          13:14 Tuesday, August 21, 2$
```

```
                              The NLIN Procedure

                  NOTE: An intercept was not specified for this model.

                                  Sum of       Mean              Approx
     Source              DF      Squares      Square    F Value    Pr > F

     Model                6     0.000043     7.141E-6     68.60    <.0001
               Error                 31     3.227E-6   1.041E-7
                  Uncorrected Total        37    0.000046


                                                        Approx
   Parameter     Estimate    Std Error   Approximate 95% Confidence Limits

                 b1          -2.5263      0.7596    -4.0756    -0.9770
                 b2          -0.0228      0.0177    -0.0589     0.0132
                 b3          -0.3046      3.1413    -6.7113     6.1021
                 b4           0.0193      0.0180    -0.0173     0.0560
                 p            4.7042      0.3864     3.9161     5.4922
               m            0.000447     0.00114   -0.00188    0.00278


                            Approximate Correlation Matrix
                b1            b2            b3            b4            p             m

b1     1.0000000     0.3258377     0.4385611    -0.9363609    -0.0191590    -0.4455852
b2     0.3258377     1.0000000     0.0984725    -0.1898725     0.1214479    -0.2322504
b3     0.4385611     0.0984725     1.0000000    -0.5179358    -0.1405111    -0.9880832
b4    -0.9363609    -0.1898725    -0.5179358     1.0000000     0.0516668     0.4929809
p     -0.0191590     0.1214479    -0.1405111     0.0516668     1.0000000     0.0966319
```

```
^G Get Help      ^O WriteOut      ^R Read File      ^Y Prev Page      ^K Cut Text      ^C Cur Pos
     b4      -0.9363609    -0.1898725    -0.5179358     1.0000000     0.0516668     0.4929809
          p      -0.0191590     0.1214479    -0.1405111     0.0516668     1.0000000     0.0966319
          m      -0.4455852    -0.2322504    -0.9880832     0.4929809     0.0966319     1.0000000
^L                                        The SAS System                13:14 Tuesday, August 21, 2$

 Obs test  Y      X1      X2     X3    X4     X5      YL      YU      SR        pred        lower        upper        res$

  1   1 .001919 28.4751  9.1286 0.9232 12.0 1879.60 .       .001919  5.0413 .001257762 .001012970 .001502555 0.0006612$
  2   8 .000997 25.3390  2.5729 0.8348  7.0 1847.39 .000997 .       14.3755 .000674007 .000561097 .000786918 0.0003229$
  3   9 .000884  4.6161 28.6200 0.8019 10.0 1959.50 .000884 .        0.2355 .000550918 .000458627 .000643209 0.0003330$
  4  10 .000734  6.7711 15.6140 0.8737 78.0 1730.90 .000734 .        0.4367 .000845200 .000703611 .000986789 -.0001112$
  5  15 .000662  3.4901  7.7799 0.9868 66.0 1503.50 .000662 .        0.6481 .001493279 .001243123 .001743436 -.0008312$
  6  16 .000883  3.6221  7.9295 0.9720  7.0 1510.30 .000883 .        0.6670 .001409863 .001173681 .001646046 -.0005268$
  7  17 .000964  5.6558 10.2390 0.8216 34.0 1698.70 .000964 .        0.8065 .000692714 .000576670 .000808759 0.0002712$
  8  18 .001947  0.6934 12.1340 0.8504 68.0 1633.70 .       .001947  0.0780 .001907911 .001252682 .002563140 0.0000390$
  9  19 .000923  2.6403 15.7470 0.7615 10.0 1798.10 .000923 .        0.2448 .000499419 .000415756 .000583083 0.0004235$
 10  20 .000767  1.6625 14.2380 0.7245 11.0 1916.50 .000767 .        1.0544 .000392160 .000326465 .000457856 0.0003748$
 11  21 .001093  3.8902  8.3451 0.7042 13.0 1918.60 .001093 .        4.3996 .001018789 .000471761 .001565816 0.0000742$
 12  22 .001032  1.8714  6.1540 0.8061  6.0 1555.80 .001032 .        1.0544 .001326749 .000810328 .001843170 -.0002947$
 13  23 .000822 12.7640  5.9545 0.7656 11.0 1736.60 .000822 .        4.3996 .000527106 .000438804 .000615407 0.0002948$
 14  24 .001713 11.0000 28.0000 0.7927 13.0 1728.00 .       .001713  1.1066 .001597202 .001177309 .002017095 0.0001157$
 15  25 .001813  6.2322 22.8350 0.7774  6.0 1924.60 .       .001813  0.4158 .001650332 .001196681 .002103983 0.0001626$
 16  26 .001849 11.4590 27.0570 0.8486 11.5 1698.70 .       .001849  0.7147 .001858649 .001407979 .002309320 -.0000096$
          17  27 .      19.1970 17.8260 0.8486 10.0 1714.50 .000258 .        1.5727 .          .          .          .        $
 18  28 .000361  9.3990 21.5000 0.7842  8.0 1803.10 .000361 .        1.2282 .000553001 .000460362 .000645641 -.0001920$
 19  29 .000572 10.3530  4.8086 0.8332  5.0 1689.40 .000572 .        2.6788 .000732043 .000609410 .000854676 -.0001600$
 20  30 .000646  9.2079 11.7200 0.8495  8.0 1680.20 .000646 .        1.8728 .000788352 .000656286 .000920418 -.0001423$
 21  31 .000616  8.7084  7.2407 0.8278  6.0 1643.70 .000616 .        3.3318 .000735246 .000612076 .000858415 -.0001192$
 22  32 .000903  9.9660 13.1260 0.8163 14.0 1800.90 .000903 .        1.1601 .000638563 .000531590 .000745537 0.0002644$
 23  33 .000923  9.9615  6.6625 0.7979 14.0 1670.20 .000923 .        5.8124 .000634953 .000528585 .000741322 0.0002880$
          24  34 .      10.6570 14.4040 0.8180 10.0 1836.70 .       .        1.0802 .          .          .          .        $
 25  35 .000912 10.9830 14.3260 0.8736 29.0 1764.50 .000912 .        1.2490 .000828770 .000689933 .000967607 0.0000832$
```

```
        26  36  .      27.9830  8.3657 0.8119 17.0 2003.20 .      .       5.1366 .        .          .          .         $
   27  37  .000935  8.0504 13.6270 0.8119  6.5 1791.60 .000935 .       0.8687 .000629676 .000524192 .000735160 0.0003053$
   28  38  .000917 11.4510  8.5719 0.8127 12.0 1720.90 .000917 .       3.1115 .000657842 .000547639 .000768045 0.0002591$
   29  39  .000919 11.4290  5.1211 0.8092 12.5 1713.00 .000919 .       3.5892 .000650821 .000541795 .000759848 0.0002681$
   30  40  .000916  9.1792 11.2800 0.8145 10.0 1800.90 .000916 .       1.0418 .000633578 .000527440 .000739715 0.0002824$
   31  41  .001447  9.2195  7.9350 0.8225 10.0 1706.60 .001447 .       1.8520 .001215644 .000965609 .001465679 0.0002313$
   32  42  .001820 10.3670 11.7300 0.8727 13.0 1745.90 .      .001820  1.2540 .001626035 .001251023 .002001047 0.0001939$
  31  41  .001447  9.2195  7.9350 0.8225 10.0 1706.60 .001447 .       1.8520 .001215644 .000965609 .001465679 0.0002313$
   32  42  .001820 10.3670 11.7300 0.8727 13.0 1745.90 .      .001820  1.2540 .001626035 .001251023 .002001047 0.0001939$
        33  43  .       9.7078 16.1070 0.8504 12.0 1836.00 .     .003287  0.8084 .        .          .          .         $
   34  44  .000927  8.0362 13.7450 0.8765 10.0 1677.30 .000927 .       1.1919 .000882126 .000734351 .001029901 0.0000448$
   35  45  .000868  8.1726 11.6750 0.8965  8.5 1620.80 .000868 .       1.7157 .000988555 .000822951 .001154159 -.0001205$
   36  46  .000846  7.9310 12.3640 0.8404  9.0 1742.30 .000846 .       0.9517 .000731798 .000609206 .000854390 0.0001142$
   37  47  .001516 12.0430 18.0170 0.8441 22.0 1859.50 .001516 .       1.0730 .001739423 .001272704 .002206141 -.0002234$
   38  48  .000625 12.0680 17.7010 0.8180  5.0 1911.00 .000625 .       0.9760 .000606235 .000504677 .000707792 0.0000187$
   39  49  .000498  9.8633 13.7090 0.8242  7.0 1798.10 .000498 .       1.1087 .000661799 .000550934 .000772665 -.0001637$
   40  50  .001065 14.0520 18.1470 0.8486 11.5 1868.10 .001065 .       1.3419 .001471360 .001235030 .001707690 -.0004063$
   41  51  .001079 13.8390 13.2130 0.8339 14.0 1881.00 .001079 .       1.3591 .001296536 .001057913 .001535159 -.0002175$
       ^L                                The SAS System                13:14 Tuesday, August 21, 2$

                                                The UNIVARIATE Procedure
                                                     Variable:  Y

                                                        Moments

                            N                         37    Sum Weights              37
                            Mean              0.00103549    Sum Observations   0.038313
                            Std Deviation     0.00042164    Variance           1.77779E-7
                            Skewness          0.98901258    Kurtosis           0.09038056
                            Uncorrected SS    0.00004607    Corrected SS       6.40006E-6
                            Coeff Variation   40.7189257    Std Error Mean     0.00006932
```

```
                    Basic Statistical Measures

              Location                  Variability

    Mean     0.001035     Std Deviation          0.0004216
    Median   0.000919     Variance              1.77779E-7
    Mode     0.000923     Range                    0.00159
                          Interquartile Range    0.0002570


                    Tests for Location: Mu0=0

            Test          -Statistic-    -----p Value------
Test          -Statistic-    -----p Value------

         Student's t    t  14.93842    Pr > |t|    <.0001
         Sign           M      18.5    Pr >= |M|   <.0001
         Signed Rank    S     351.5    Pr >= |S|   <.0001


                    Quantiles (Definition 5)

                    Quantile      Estimate

                    100% Max      0.001947
                    99%           0.001947
                    95%           0.001919
                    90%           0.001820
                    75% Q3        0.001079
                    50% Median    0.000919
                    25% Q1        0.000822
                    10%           0.000616
                    5%            0.000498
```

```
                        1%          0.000361
                        0% Min         0.000361


                         Extreme Observations

                ------Lowest------      ------Highest-----

                   Value     Obs          Value     Obs

                0.000361      18       0.001813      15
                0.000498      39       0.001820      32
                0.000572      19       0.001849      16
^L                   The SAS System              13:14 Tuesday, August 21, 2$

                        The UNIVARIATE Procedure
                              Variable:  Y

                Variable:  Y

                         Extreme Observations

                ------Lowest------      ------Highest-----

                   Value     Obs          Value     Obs

                0.000616      21       0.001919       1
                0.000625      38       0.001947       8


                            Missing Values

                           -----Percent Of-----
```

Missing Value	Count	All Obs	Missing Obs
.	4	9.76	100.00

APPENDIX C

Summary of output from NLIN computer code

Table C1 Summary of laboratory data from research

TST#	a/A	μ_w	G_s	μ_{TCE}	ρ_{TCE}	ρ_w	w	w_n
1	0.013259694	0.000891	2.65	0.00057	1460	1000	28.4751	9.128632
8	0.013259694	0.000891	2.65	0.00057	1460	1000	25.33399	2.572984
9	0.013259694	0.000891	2.65	0.00057	1460	1000	4.616132	28.62002
10	0.013259694	0.000891	2.65	0.00057	1460	1000	6.771097	15.61395
15	0.013259694	0.000891	2.65	0.00057	1460	1000	3.490063	7.779932
16	0.013259694	0.000891	2.65	0.00057	1460	1000	3.622124	7.929515
17	0.013259694	0.000891	2.65	0.00057	1460	1000	5.655778	10.23891
18	0.013259694	0.000891	2.65	0.00057	1460	1000	0.693413	12.13472
19	0.013259694	0.000891	2.65	0.00057	1460	1000	2.640264	15.74729
20	0.013259694	0.000891	2.65	0.00057	1460	1000	1.662473	14.23754
21	0.013259694	0.000891	2.65	0.00057	1460	1000	3.890211	8.34512
22	0.013259694	0.000891	2.65	0.00057	1460	1000	1.871401	6.154031
23	0.013259694	0.000891	2.65	0.00057	1460	1000	12.76392	5.95453
24	0.013259694	0.000891	2.65	0.00057	1460	1000	6.909789	14.74728
25	0.013259694	0.000891	2.65	0.00057	1460	1000	6.23216	22.8354
26	0.013259694	0.000891	2.65	0.00057	1460	1000	11.45935	27.05681
27	0.013259694	0.000891	2.67	0.00057	1460	1000	19.19687	17.82566
28	0.013259694	0.000891	2.67	0.00057	1460	1000	9.360076	11.12703
29	0.013259694	0.000891	2.67	0.00057	1460	1000	10.35329	4.80864
30	0.013259694	0.000891	2.67	0.00057	1460	1000	9.207921	11.72029

Table C2 Summary laboratory data from research (Continued)

TST#	e	L	$(t_2 - t_1)$	θ	h_1	h_2	$\ln(h_1/h_2)$	ρ_{wet}	k_{TCE}	R
1	0.9233	0.193675	60	12	1.0192	0.6509	0.448417	1879.6	0.0019193	1.0087037
8	0.8348	0.19685	60	7	0.7906	0.6287	0.229138	1847.39	0.0009968	0.9999834
9	0.8019	0.19685	90	10	0.8461	0.6239	0.304647	1959.5	0.0008835	0.9999816
10	0.8737	0.1905	120	78	0.8461	0.5969	0.348888	1730.9	0.0007344	1.0000051
15	0.9868	0.195263	120	66	1.1652	0.8573	0.30686	1503.5	0.0006621	0.9871118
16	0.972	0.192266	150	7	1.3557	0.8065	0.519369	1510.3	0.0008827	0.9925484
17	0.8216	0.188913	120	34	1.3557	0.8541	0.462025	1698.7	0.0009644	0.9925210
18	0.8504	0.192266	60	68	1.3557	0.8573	0.458285	1633.7	0.0019472	0.9890662
19	0.7615	0.192266	120	10	1.3557	0.8779	0.434541	1798.1	0.0009232	0.9905022
20	0.724512	0.192266	150	11	1.364772	0.869124	0.451257	1916.5	0.0007670	0.9292965
21	0.704163	0.192266	120	13	1.361246	0.813846	0.514385	1918.6	0.0010928	0.9096617
22	0.80605	0.193675	115	6	1.26524	0.796927	0.462254	1555.8	0.0010323	1.0187986
23	0.7656	0.1905	150	11	1.3938	0.8557	0.487869	1736.6	0.0008216	1.0260582
24	0.7927	0.193675	75	13	1.2986	0.7874	0.500306	1728	0.0017131	1.0407151
25	0.7774	0.193675	65	6	1.3589	0.8588	0.458895	1924.6	0.0018130	0.9998557
26	0.8486	0.193675	70	11.5	1.3637	0.8239	0.503908	1698.7	0.0018487	1.1689251
27	0.8486	0.1905	420	10	1.3653	0.889	0.429032	1714.5	0.0002580	1.1543109
28	0.9233	0.193675	300	8	1.3653	0.889	0.429032	1803.1	0.0003612	1.0087037
29	0.8348	0.19685	180	5	1.3653	0.889	0.429032	1689.4	0.0005720	0.9999834
30	0.8019	0.19685	180	8	1.3589	0.8827	0.431445	1680.2	0.0006458	0.9999816

Table C3 Summary of laboratory data from research (Continued)

TST#	a/A	μ_w	G_s	μ_{TCE}	ρ_{TCE}	ρ_w	w	w_n
31	0.013259694	0.000891	2.67	0.00057	1460	1000	8.708415	7.2407
32	0.013259694	0.000891	2.67	0.00057	1460	1000	9.96597	13.12591
33	0.013259694	0.000891	2.67	0.00057	1460	1000	9.961501	6.6625
34	0.013259694	0.000891	2.67	0.00057	1460	1000	10.65693	14.40389
35	0.013259694	0.000891	2.67	0.00057	1460	1000	10.98295	14.32631
36	0.013259694	0.000891	2.67	0.00057	1460	1000	27.98254	8.36566
37	0.013259694	0.000891	2.67	0.00057	1460	1000	8.0504	13.62748
38	0.013259694	0.000891	2.67	0.00057	1460	1000	11.451	8.57187
39	0.013259694	0.000891	2.67	0.00057	1460	1000	11.429	5.12108
40	0.013259694	0.000891	2.67	0.00057	1460	1000	9.1792	11.27963
41	0.013259694	0.000891	2.67	0.00057	1460	1000	9.2195	7.93497
42	0.013259694	0.000891	2.67	0.00057	1460	1000	10.376	11.72925
43	0.013259694	0.000891	2.67	0.00057	1460	1000	9.7078	16.10694
44	0.013259694	0.000891	2.67	0.00057	1460	1000	8.0362	13.7451
45	0.013259694	0.000891	2.67	0.00057	1460	1000	8.1726	11.67525
46	0.013259694	0.000891	2.67	0.00057	1460	1000	7.931	12.36433
47	0.013259694	0.000891	2.67	0.00057	1460	1000	12.043	18.01567
48	0.013259694	0.000891	2.67	0.00057	1460	1000	12.068	17.701
49	0.013259694	0.000891	2.68	0.00057	1460	1000	9.8633	13.7085
50	0.013259694	0.000891	2.68	0.00057	1460	1000	14.052	18.147
51	0.013259694	0.000891	2.68	0.00057	1460	1000	13.839	13.213

Table C4 Summary of laboratory data from research (Continued)

TST#	e	L	$(t_2 - t_1)$	θ	h_1	h_2	$\ln(h_1/h_2)$	ρ_{wet}	M k_{TCE}	R
31	0.8278	0.20161	180	6	1.3462	0.889	0.414944	1643.7	0.0006163	1.0304513
32	0.8163	0.18891	120	14	1.3557	0.8795	0.43272	1800.9	0.0009033	1.0047627
33	0.7979	0.1905	120	14	1.3684	0.8827	0.438412	1670.2	0.0009228	1.0369676
34	0.818	0.187325	1440	10	1.3684	1.0954	0.222523	1836.7	0.0000384	1.0000010
35	0.8736	0.185738	120	29	1.3764	0.8827	0.444241	1764.5	0.0009117	1.0120358
36	0.8119	0.185738	300	17	1.3748	1.2256	0.114878	2003.2	0.0000943	1.0030028
37	0.8119	0.1857	120	6.5	1.3843	0.8779	0.455417	1791.6	0.0009345	1.0008007
38	0.8127	0.1857	120	12	1.37	0.8763	0.446858	1720.9	0.0009169	1.0272915
39	0.8092	0.1857	120	12.5	1.3716	0.8763	0.448025	1713	0.0009193	1.0041068
40	0.8145	0.1842	120	10	1.3716	0.8747	0.449852	1800.9	0.0009156	0.9842453
41	0.8225	0.1842	75	10	1.3716	0.8795	0.44438	1706.6	0.0014472	1.0057055
42	0.8727	0.18098	60	13	1.3811	0.8763	0.454927	1745.9	0.0018195	0.9971443
43	0.8504	0.18256	33	12	1.3716	0.8763	0.448025	1836	0.0032865	0.9887910
44	0.8765	0.18415	118	10	1.3716	0.8763	0.448025	1677.3	0.0009271	1.0330767
45	0.8965	0.18415	126	8.5	1.3716	0.8763	0.448025	1620.8	0.0008682	1.0410204
46	0.8404	0.18098	125	9	1.3716	0.8827	0.440748	1742.3	0.0008461	1.0016705
47	0.8441	0.18336	73	22	1.3716	0.87	0.45524	1859.5	0.0015162	1.0126746
48	0.818	0.18733	178	5	1.3716	0.8763	0.448025	1911	0.0006252	0.9973042
49	0.8242	0.18733	224	7	1.3716	0.8763	0.448025	1798.1	0.0004968	1.0096431
50	0.8486	0.18098	101	11.5	1.3716	0.8763	0.448025	1868.1	0.0010645	1.0259351
51	0.8339	0.18415	103	14	1.3716	0.87	0.45524	1881	0.0010792	0.9870789
31	0.8278	0.20161	180	6	1.3462	0.889	0.414944	1643.7	0.0006163	1.0304513

APPENDIX D

Data from Laboratory tests

Table D1. Laboratory data from test #1

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
1	0.193675	1.928	2.65	0.000727547	0.352	0.000352	18.25726	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.591	0.000591	30.65353	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.656	0.000656	34.0249	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.611	0.000611	31.69087	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.613	0.000613	31.79461	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.624	0.000624	32.36515	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.601	0.000601	31.1722	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.581	0.000581	30.13485	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.572	0.000572	29.66805	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.559	0.000559	28.99378	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.544	0.000544	28.21577	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.527	0.000527	27.33402	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.516	0.000516	26.76349	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.588	0.000588	30.49793	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.549	0.000549	28.4751	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.549	0.000549	28.4751	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.549	0.000549	28.4751	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.549	0.000549	28.4751	0	0	1460	0	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.549	0.000549	28.4751	0.21	10.89212	1460	0.000144	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.549	0.000549	28.4751	0.165	8.558091	1460	0.000113	0.09366	0.001334
1	0.193675	1.928	2.65	0.000727547	0.549	0.000549	28.4751	0.153	7.935685	1460	0.000105	0.09366	0.001334

Table D1. Laboratory data from test #1 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	Sn	$Sn-2$	Avg Sn
1	0.001399	0.000319723	0.000672	0.923271	0.480053	1629.421	52.40253	0	47.59747	n	n	n
1	0.001399	8.07233E-05	0.000672	0.923271	0.480053	1800.224	87.98266	0	12.01734	n	n	n
1	0.001399	1.57233E-05	0.000672	0.923271	0.480053	1846.677	97.65926	0	2.34074	n	n	n
1	0.001399	6.07233E-05	0.000672	0.923271	0.480053	1814.517	90.96007	0	9.039927	n	n	n
1	0.001399	5.87233E-05	0.000672	0.923271	0.480053	1815.946	91.25781	0	8.742185	n	n	n
1	0.001399	4.77233E-05	0.000672	0.923271	0.480053	1823.808	92.89539	0	7.104606	n	n	n
1	0.001399	7.07233E-05	0.000672	0.923271	0.480053	1807.37	89.47136	0	10.52864	n	n	n
1	0.001399	9.07233E-05	0.000672	0.923271	0.480053	1793.077	86.49395	0	13.50605	n	n	n
1	0.001399	9.97233E-05	0.000672	0.923271	0.480053	1786.645	85.15411	0	14.84589	n	n	n
1	0.001399	0.000112723	0.000672	0.923271	0.480053	1777.355	83.21879	0	16.78121	n	n	n
1	0.001399	0.000127723	0.000672	0.923271	0.480053	1766.635	80.98573	0	19.01427	n	n	n
1	0.001399	0.000144723	0.000672	0.923271	0.480053	1754.486	78.45492	0	21.54508	n	n	n
1	0.001399	0.000155723	0.000672	0.923271	0.480053	1746.624	76.81734	0	23.18266	n	n	n
1	0.001399	8.37233E-05	0.000672	0.923271	0.480053	1798.08	87.53604	0	12.46396	n	n	n
1	0.001399	0.000122723	0.000672	0.923271	0.480053	1770.208	81.73008	0	18.26992	n	n	n
1	0.001399	0.000122723	0.000672	0.923271	0.480053	1770.208	81.73008	0	18.26992	n	n	n
1	0.001399	0.000122723	0.000672	0.923271	0.480053	1770.208	81.73008	0	18.26992	n	n	n
1	0.001399	0.000122723	0.000672	0.923271	0.480053	1770.208	81.73008	0	18.26992	n	n	n
1	0.001399	-2.11123E-05	0.000672	0.923271	0.480053	1920.286	81.73008	21.41293	-3.143009	12	-	12
1	0.001399	9.7096E-06	0.000672	0.923271	0.480053	1888.127	81.73008	16.82444	1.445476	12	-	12
1	0.001399	1.79288E-05	0.000672	0.923271	0.480053	1879.551	81.73008	15.60085	2.669071	12	-	12

Table D8. Laboratory data from test #8

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{ait+solids}$
8	0.1969	2.021	2.65	0.0007626	0.538	0.0005	26.62	0	0	1460	0	0.0937	0.0014
8	0.1969	2.021	2.65	0.0007626	0.545	0.0005	26.967	0	0	1460	0	0.0937	0.0014
8	0.1969	2.021	2.65	0.0007626	0.53	0.0005	26.225	0	0	1460	0	0.0937	0.0014
8	0.1969	2.021	2.65	0.0007626	0.52	0.0005	25.73	0	0	1460	0	0.0937	0.0014
8	0.1969	2.021	2.65	0.0007626	0.473	0.0005	23.404	0	0	1460	0	0.0937	0.0014
8	0.1969	2.021	2.65	0.0007626	0.461	0.0005	22.81	0	0	1460	0	0.0937	0.0014
8	0.1969	2.021	2.65	0.0007626	0.44	0.0004	21.771	0	0	1460	0	0.0937	0.0014
8	0.1969	2.021	2.65	0.0007626	0.44	0.0004	21.771	0	0	1460	0	0.0937	0.0014
8	0.1969	2.021	2.65	0.0007626	0.46	0.0005	22.761	0	0	1460	0	0.0937	0.0014
8	0.1969	2.021	2.65	0.0007626	0.512	0.0005	25.334	0.052	2.573	1460	3.56164E-05	0.0937	0.0014

Table D8. Laboratory data from test #8(continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
8	0.0014	0.000593	0.0006	0.8348	0.455	1828.8	84.508	0	15.492	n	n	n
8	0.0014	0.000593	0.0006	0.8348	0.455	1833.8	85.607	0	14.393	n	n	n
8	0.0014	0.000593	0.0006	0.8348	0.455	1823.1	83.251	0	16.749	n	n	n
8	0.0014	0.000593	0.0006	0.8348	0.455	1815.9	81.68	0	18.32	n	n	n
8	0.0014	0.000593	0.0006	0.8348	0.455	1782.4	74.298	0	25.702	n	n	n
8	0.0014	0.000593	0.0006	0.8348	0.455	1773.8	72.413	0	27.587	n	n	n
8	0.0014	0.00593	0.0006	0.8348	0.455	1758.8	69.114	0	30.886	n	n	n
8	0.0014	0.000593	0.0006	0.8348	0.455	1758.8	69.114	0	30.866	n	n	n
8	0.0014	0.000593	0.0006	0.8348	0.455	1773.1	72.256	0	27.744	7	7	7
8	0.0014	0.000593	0.0006	0.8348	0.455	1847.4	80.424	5.5945	13.982	7	7	7

Table D9. Laboratory data from test #9

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
9	0.1969	0.598	2.65	2.058	29.057	0	0	1460	0	2.65	0.0008	0.09366	0.001356
9	0.1969	0.538	2.65	2.058	26.142	0	0	1460	0	2.65	0.0008	0.09366	0.001356
9	0.1969	0.504	2.65	2.058	24.49	0	0	1460	0	2.65	0.0008	0.09366	0.001356
9	0.1969	0.611	2.65	2.058	29.689	0	0	1460	0	2.65	0.0008	0.09366	0.001356
9	0.1969	0.488	2.65	2.058	23.712	0	0	1460	0	2.65	0.0008	0.09366	0.001356
9	0.1969	0.246	2.65	2.058	11.953	0	0	1460	0	2.65	0.0008	0.09366	0.001356
9	0.1969	0.117	2.65	2.058	5.6851	0	0	1460	0	2.65	0.0008	0.09366	0.001356
9	0.1969	0.095	2.65	2.058	4.6161	0	0	1460	0	2.65	0.0008	0.09366	0.001356
9	0.1969	0.095	2.65	2.058	4.6161	0	0	1460	0	2.65	0.0008	0.09366	0.001356
9	0.1969	0.095	2.65	2.058	4.6161	0	0	1460	0	2.65	0.0008	0.09366	0.001356
9	0.1969	0.095	2.65	2.058	4.6161	0.589	28.62	1460	0.0004	2.65	0.0008	0.09366	0.001356

Table D9. Laboratory data from test #9 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
9	0.001399	2E-05	0.0006	0.8019	0.445	1898	96.02616	0	3.973843	n	n	n
9	0.001399	8E-05	0.0006	0.8019	0.445	1855.1	86.39143	0	13.60857	n	n	n
9	0.001399	0.0001	0.0006	0.8019	0.445	1830.8	80.93174	0	19.06826	n	n	n
9	0.001399	1E-05	0.0006	0.8019	0.445	1907.3	98.11368	0	1.886318	n	n	n
9	0.001399	0.0001	0.0006	0.8019	0.445	1819.4	78.36248	0	21.63752	n	n	n
9	0.001399	0.0004	0.0006	0.8019	0.445	1646.5	39.5024	0	60.4976	n	n	n
9	0.001399	0.0005	0.0006	0.8019	0.445	1554.3	18.78773	0	81.21227	n	n	n
9	0.001399	0.0005	0.0006	0.8019	0.445	1538.6	15.25499	0	84.74501	n	n	n
9	0.001399	0.0005	0.0006	0.8019	0.445	1538.6	15.25499	0	84.74501	4	2	3
9	0.001399	0.0005	0.0006	0.8019	0.445	1538.6	15.25499	0	84.74501	41	2	n
9	0.001399	0.0001	0.0006	0.8019	0.445	1959.5	15.25499	64.78147	19.96354	10	2	10

Table D10. Laboratory data from test #10

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
10	0.1905	1.979	2.65	0.000747	0.036	4E-05	1.8191	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.319	0.0003	16.119	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.56	0.0006	28.297	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.536	0.0005	27.084	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.53	0.0005	26.781	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.529	0.0005	26.731	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.526	0.0005	26.579	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.526	0.0005	26.579	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.525	0.0005	26.529	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.518	0.0005	26.175	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.52	0.0005	26.276	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.52	0.0005	26.276	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.43	0.0004	21.728	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.422	0.0004	21.324	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.422	0.0004	21.324	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.422	0.0004	21.324	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.422	0.0004	21.324	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.151	0.0002	7.6301	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.146	0.0001	7.3775	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.139	0.0001	7.0237	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.134	0.0001	6.7711	0	0	1460	0	0.0937	0.0013
10	0.1905	1.979	2.65	0.000747	0.134	0.0001	6.7711	0.309	15.614	1460	0.0002	0.0937	0.0013

Table D10. Laboratory data from test #10 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
10	0.001399	0.0006	0.0007	0.8737	0.4663	1440	5.5174	0	94.48257			
10	0.001399	0.0003	0.0007	0.8737	0.4663	1642.3	48.891	0	51.10946			
10	0.001399	9E-05	0.0007	0.8737	0.4663	1814.5	85.827	0	14.17335			
10	0.001399	0.0001	0.0007	0.8737	0.4663	1797.4	82.148	0	17.85164			
10	0.001399	0.0001	0.0007	0.8737	0.4663	1793.1	81.229	0	18.77121			
10	0.001399	0.0001	0.0007	0.8737	0.4663	1792.4	81.076	0	18.92447			
10	0.001399	0.0001	0.0007	0.8737	0.4663	1790.2	80.616	0	19.38426			
10	0.001399	0.0001	0.0007	0.8737	0.4663	1790.2	80.616	0	19.38426			
10	0.001399	0.0001	0.0007	0.8737	0.4663	1789.5	80.462	0	19.53752			
10	0.001399	0.0001	0.0007	0.8737	0.4663	1784.5	79.39	0	20.61035			
10	0.001399	0.0001	0.0007	0.8737	0.4663	1785.9	79.696	0	20.30383			
10	0.001399	0.0001	0.0007	0.8737	0.4663	1785.9	79.696	0	20.30383			
10	0.001399	0.0002	0.0007	0.8737	0.4663	1721.6	65.903	0	34.0974			
10	0.001399	0.0002	0.0007	0.8737	0.4663	1715.9	64.677	0	35.32349			
10	0.001399	0.0002	0.0007	0.8737	0.4663	1715.9	64.677	0	35.32349			
10	0.001399	0.0002	0.0007	0.8737	0.4663	1715.9	64.677	0	35.32349			
10	0.001399	0.0002	0.0007	0.8737	0.4663	1715.9	64.677	0	35.32349	58	52	55
10	0.001399	0.0005	0.0007	0.8737	0.4663	1522.2	23.143	0	76.85746	66	60	63
10	0.001399	0.0005	0.0007	0.8737	0.4663	1518.6	22.376	0	77.62377	78	74	76
10	0.001399	0.0005	0.0007	0.8737	0.4663	1513.6	21.303	0	78.6966	80	78	79
10	0.001399	0.0005	0.0007	0.8737	0.4663	1510.1	20.537	0	79.46291	82	80	81
10	0.001399	0.0003	0.0007	0.8737	0.4663	1730.9	20.537	32.437	47.02598	78	7	78

Table D15. Laboratory data from test #15

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
15	0.1953	2.063	2.65	0.000778	0.038	4E-05	1.842	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.236	0.0002	11.44	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.398	0.0004	19.292	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.526	0.0005	25.497	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.536	0.0005	25.982	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.537	0.0005	26.03	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.54	0.0005	26.175	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.542	0.0005	26.272	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.53	0.0005	25.691	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.546	0.0005	26.466	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.549	0.0005	26.612	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.552	0.0006	26.757	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.546	0.0005	26.466	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.094	9E-05	4.5565	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.078	8E-05	3.7809	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.031	3E-05	1.5027	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.033	3E-05	1.5996	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.071	7E-05	3.4416	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.072	7E-05	3.4901	0	0	1460	0	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.072	7E-05	3.4901	0.058	2.8114	1460	4E-05	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.072	7E-05	3.4901	0.148	7.174	1460	0.0001	0.0937	0.0013446
15	0.1953	2.063	2.65	0.000778	0.072	7E-05	3.4901	0.173	8.3858	1460	0.0001	0.0937	0.0013446

Table D15. Laboratory data from test #15 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
15	0.001399	0.0006	0.0006	0.7894	0.4412	1519.6	6.23	0	93.77004			
15	0.001399	0.0006	0.0008	1.0457	0.5112	1454.5	29.21	0	70.79048			
15	0.001399	0.0006	0.001	1.2553	0.5566	1412.2	41.033	0	58.9672			
15	0.001399	0.0006	0.0011	1.421	0.5869	1384	47.907	0	52.09279			
15	0.001399	0.0006	0.0011	1.434	0.5891	1382	48.377	0	51.62262			
15	0.001399	0.0006	0.0011	1.4352	0.5894	1381.8	48.424	0	51.57607			
15	0.001399	0.0006	0.0011	1.4391	0.59	1381.2	48.563	0	51.43692			
15	0.001399	0.0006	0.0011	1.4417	0.5905	1380.8	48.655	0	51.34457			
15	0.001399	0.0006	0.0011	1.4262	0.5878	1383.2	48.096	0	51.90369			
15	0.001399	0.0006	0.0011	1.4469	0.5913	1380	48.839	0	51.16086			
15	0.001399	0.0006	0.0011	1.4508	0.592	1379.4	48.976	0	51.02394			
15	0.001399	0.0006	0.0011	1.4547	0.5926	1378.8	49.112	0	50.88775			
15	0.001399	0.0006	0.0011	1.4469	0.5913	1380	48.839	0	51.16086			
15	0.001399	0.0006	0.0007	0.8619	0.4629	1499.4	14.115	0	85.88495			
15	0.001399	0.0006	0.0006	0.8412	0.4569	1505	12.001	0	87.99918			
15	0.001399	0.0006	0.0006	0.7804	0.4383	1522.2	5.1413	0	94.85866	2	60	60
15	0.001399	0.0006	0.0006	0.783	0.4391	1521.5	5.4549	0	94.54506	4	68	68
15	0.001399	0.0006	0.0006	0.8321	0.4542	1507.5	11.043	0	88.95725	8	71	71
15	0.001399	0.0006	0.0006	0.8334	0.4546	1507.1	11.181	0	88.81911	8	72	72
15	0.001399	0.0006	0.0007	0.8848	0.4695	1505.8	10.531	5.8106	83.65818	8	70	70
15	0.001399	0.0006	0.0007	0.9646	0.491	1504	9.6602	13.601	76.73904	8	68	68
15	0.001399	0.0006	0.0008	0.9868	0.4967	1503.5	9.4433	15.541	75.01562	8	66	66

Table D16. Laboratory data from test #16

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
16	0.1923	2.043	2.67	0.000765	0.008	8E-06	0.3916	0	0	1460	0	0.0937	0.001324
16	0.1923	2.043	2.67	0.000765	0.559	0.0006	27.362	0	0	1460	0	0.0937	0.001324
16	0.1923	2.043	2.67	0.000765	0.56	0.0006	27.411	0	0	1460	0	0.0937	0.001324
16	0.1923	2.043	2.67	0.000765	0.54	0.0005	26.432	0	0	1460	0	0.0937	0.001324
16	0.1923	2.043	2.67	0.000765	0.561	0.0006	27.46	0	0	1460	0	0.0937	0.001324
16	0.1923	2.043	2.67	0.000765	0.561	0.0006	27.46	0	0	1460	0	0.0937	0.001324
16	0.1923	2.043	2.67	0.000765	0.192	0.0002	9.3979	0	0	1460	0	0.0937	0.001324
16	0.1923	2.043	2.67	0.000765	0.188	0.0002	9.2022	0	0	1460	0	0.0937	0.001324
16	0.1923	2.043	2.67	0.000765	0.078	8E-05	3.8179	0	0	1460	0	0.0937	0.001324
16	0.1923	2.043	2.67	0.000765	0.087	9E-05	4.2584	0	0	1460	0	0.0937	0.001324
16	0.1923	2.043	2.67	0.000765	0.085	9E-05	4.1605	0	0	1460	0	0.0937	0.001324
16	0.1923	2.043	2.67	0.000765	0.074	7E-05	3.6221	0	0	1460	0	0.0937	0.001324
16	0.1923	2.043	2.67	0.000765	0.074	7E-05	3.6221	0.003	0.1468	1460	2E-06	0.0937	0.001324
16	0.1923	2.043	2.67	0.000765	0.074	7E-05	3.6221	0.036	1.7621	1460	2E-05	0.0937	0.001324
16	0.1923	2.043	2.67	0.000765	0.074	7E-05	3.6221	0.162	7.9295	1460	0.0001	0.0937	0.001324

Table D16. Laboratory data from test #16 (continued)

Test #	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
16	0.001332	0.0006	0.0006	0.7408	0.4255	1539.8	1.4114	0	98.58859			
16	0.001883	0.0006	0.0011	1.4609	0.5936	1381.9	50.009	0	49.99143			
16	0.001884	0.0006	0.0011	1.4622	0.5939	1381.7	50.053	0	49.94675			
16	0.001864	0.0006	0.0011	1.436	0.5895	1385.7	49.144	0	50.85586			
16	0.001885	0.0006	0.0011	1.4635	0.5941	1381.4	50.098	0	49.90215			
16	0.001885	0.0006	0.0011	1.4635	0.5941	1381.4	50.098	0	49.90215			
16	0.001516	0.0006	0.0008	0.9812	0.4953	1474.3	25.572	0	74.42757			
16	0.001512	0.0006	0.0007	0.976	0.4939	1475.6	25.174	0	74.82621			
16	0.001402	0.0006	0.0006	0.8322	0.4542	1512.9	12.249	0	87.75142			
16	0.001411	0.0006	0.0006	0.844	0.4577	1509.6	13.471	0	86.52851			
16	0.001409	0.0006	0.0006	0.8414	0.4569	1510.3	13.203	0	86.79732			
16	0.001398	0.0006	0.0006	0.827	0.4527	1514.3	11.694	0	88.3061			
16	0.001400	0.0006	0.0006	0.8297	0.4535	1514.3	11.656	0.3237	88.02029			
16	0.001423	0.0006	0.0007	0.8592	0.4621	1513.4	11.255	3.7504	84.99428	5	8	6.5
16	0.001509	0.0006	0.0007	0.972	0.4929	1510.3	9.9493	14.918	75.13216	6	8	7

Table D17. Laboratory data from test #17

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
17	0.1889	2.051	2.67	0.000768	0.119	0.0001	5.802	0	0	1460	0	0.0937	0.00130
17	0.1889	2.051	2.67	0.000768	0.476	0.0005	23.208	0	0	1460	0	0.0937	0.00130
17	0.1889	2.051	2.67	0.000768	0.573	0.0006	27.938	0	0	1460	0	0.0937	0.00130
17	0.1889	2.051	2.67	0.000768	0.589	0.0006	28.718	0	0	1460	0	0.0937	0.00130
17	0.1889	2.051	2.67	0.000768	0.594	0.0006	28.961	0	0	1460	0	0.0937	0.00130
17	0.1889	2.051	2.67	0.000768	0.605	0.0006	29.498	0	0	1460	0	0.0937	0.00130
17	0.1889	2.051	2.67	0.000768	0.606	0.0006	29.547	0	0	1460	0	0.0937	0.00130
17	0.1889	2.051	2.67	0.000768	0.605	0.0006	29.498	0	0	1460	0	0.0937	0.00130
17	0.1889	2.051	2.67	0.000768	0.167	0.0002	8.1424	0	0	1460	0	0.0937	0.00130
17	0.1889	2.051	2.67	0.000768	0.116	0.0001	5.6558	0	0	1460	0	0.0937	0.00130
17	0.1889	2.051	2.67	0.000768	0.116	0.0001	5.6558	0	0	1460	0	0.0937	0.00130
17	0.1889	2.051	2.67	0.000768	0.116	0.0001	5.6558	0.21	10.239	1460	0.0001	0.0937	0.00130

Table D17. Laboratory data from test #17 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
17	0.00140	0.0005	0.0006	0.8216	0.451	1550.8	18.856	0	81.1442			
17	0.00140	0.0002	0.0006	0.8216	0.451	1805.9	75.423	0	24.57681			
17	0.00140	6E-05	0.0006	0.8216	0.451	1875.3	90.793	0	9.206964			
17	0.00140	4E-05	0.0006	0.8216	0.451	1886.7	93.328	0	6.671731			
17	0.00140	4E-05	0.0006	0.8216	0.451	1890.3	94.121	0	5.87947			
17	0.00140	3E-05	0.0006	0.8216	0.451	1898.1	95.864	0	4.136498			
17	0.00140	3E-05	0.0006	0.8216	0.451	1898.8	96.022	0	3.978045			
17	0.00140	3E-05	0.0006	0.8216	0.451	1898.1	95.864	0	4.136498			
17	0.00140	0.0005	0.0006	0.8216	0.451	1585.1	26.461	0	73.5385	1	15	15
17	0.00140	0.0005	0.0006	0.8216	0.451	1548.7	18.38	0	81.61956	2	37	37
17	0.00140	0.0005	0.0006	0.8216	0.451	1548.7	18.38	0	81.61956	2	38	38
17	0.00140	0.0004	0.0006	0.8216	0.451	1698.7	18.38	22.791	58.82851	2	34	34

Table D18. Laboratory data from test #18

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
18	0.0004	0.0006	2.76	0.4596	1600.1	34.21	0	65.79021				18	0.0004
18	0.0001	0.0006	2.67	0.4596	1818.1	81.637	0	18.36299				18	0.0001
18	0.0001	0.0006	2.67	0.4596	1830.2	84.28	0	15.71951				18	0.0001
18	9E-05	0.0006	2.67	0.4596	1835.2	85.369	0	14.63101				18	9E-05
18	9E-05	0.0006	2.67	0.4596	1838.8	86.146	0	13.85352				18	9E-05
18	9E-05	0.0006	2.67	0.4596	1837.4	85.835	0	14.16452				18	9E-05
18	1E-04	0.0006	2.67	0.4596	1834.5	85.213	0	14.78651				18	1E-04
18	0.0006	0.0006	2.67	0.4596	1465.8	4.976	0	95.02403				18	0.0006
18	0.0006	0.0006	2.67	0.4596	1444.3	0.311	0	99.689				18	0.0006
18	0.0006	0.0006	2.67	0.4596	1444.3	0.311	0	99.689				18	0.0006
18	0.0006	0.0006	2.67	0.4596	1444.3	0.311	0	99.689				18	0.0006
18	0.0006	0.0006	2.67	0.4596	1452.2	2.0215	0	97.97851				18	0.0006
18	0.0006	0.0006	2.67	0.4596	1452.9	2.177	0	97.82301				18	0.0006
18	0.0006	0.0006	2.67	0.4596	1470.8	2.177	2.6627	95.16036				18	0.0006
18	0.0006	0.0006	2.67	0.4596	1470.8	2.177	2.6627	95.16036				18	0.0006
18	0.0006	0.0006	2.67	0.4596	1471.5	2.177	2.7692	95.05385				18	0.0006
18	0.0006	0.0006	2.67	0.4596	1488.6	2.177	5.3253	92.4977	3	70	70	18	0.0006
18	0.0005	0.0006	2.67	0.4596	1603.7	2.177	22.473	75.3502	4	68	68	18	0.0005
18	0.0004	0.0006	2.67	0.4596	1646.6	2.177	28.863	68.95983				18	0.0004
18	0.0005	0.0006	2.67	0.4596	1633.7	2.177	26.946	70.87694	4	68	68	18	0.0005

Table D18. Laboratory data from test#18 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	E	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
18	0.00140	0.0004	0.0006	0.8504	0.4596	1600.1	34.21	0	65.79021			
18	0.00140	0.0001	0.0006	0.8504	0.4596	1818.1	81.637	0	18.36299			
18	0.00140	0.0001	0.0006	0.8504	0.4596	1830.2	84.28	0	15.71951			
18	0.00140	9E-05	0.0006	0.8504	0.4596	1835.2	85.369	0	14.63101			
18	0.00140	9E-05	0.0006	0.8504	0.4596	1838.8	86.146	0	13.85352			
18	0.00140	9E-05	0.0006	0.8504	0.4596	1837.4	85.835	0	14.16452			
18	0.00140	1E-04	0.0006	0.8504	0.4596	1834.5	85.213	0	14.78651			
18	0.00140	0.0006	0.0006	0.8504	0.4596	1465.8	4.976	0	95.02403			
18	0.00140	0.0006	0.0006	0.8504	0.4596	1444.3	0.311	0	99.689			
18	0.00140	0.0006	0.0006	0.8504	0.4596	1444.3	0.311	0	99.689			
18	0.00140	0.0006	0.0006	0.8504	0.4596	1444.3	0.311	0	99.689			
18	0.00140	0.0006	0.0006	0.8504	0.4596	1452.2	2.0215	0	97.97851			
18	0.00140	0.0006	0.0006	0.8504	0.4596	1452.9	2.177	0	97.82301			
18	0.00140	0.0006	0.0006	0.8504	0.4596	1470.8	2.177	2.6627	95.16036			
18	0.00140	0.0006	0.0006	0.8504	0.4596	1470.8	2.177	2.6627	95.16036			
18	0.00140	0.0006	0.0006	0.8504	0.4596	1471.5	2.177	2.7692	95.05385			
18	0.00140	0.0006	0.0006	0.8504	0.4596	1488.6	2.177	5.3253	92.4977	3	70	70
18	0.00140	0.0005	0.0006	0.8504	0.4596	1603.7	2.177	22.473	75.3502	4	68	68
18	0.00140	0.0004	0.0006	0.8504	0.4596	1646.6	2.177	28.863	68.95983	-	-	-
18	0.00140	0.0005	0.0006	0.8504	0.4596	1633.7	2.177	26.946	70.87694	4	68	68

Table D19. Laboratory data from test #19

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
19	0.1923	2.121	2.67	0.000794	0.295	0.0003	13.909	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.52	0.0005	24.517	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.522	0.0005	24.611	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.526	0.0005	24.8	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.528	0.0005	24.894	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.53	0.0005	24.988	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.532	0.0005	25.083	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.534	0.0005	25.177	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.534	0.0005	25.177	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.534	0.0005	25.177	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.505	0.0005	23.81	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.144	0.0001	6.7893	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.035	4E-05	1.6502	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.066	7E-05	3.1117	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.056	6E-05	2.6403	0	0	1460	0	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.056	6E-05	2.6403	0.001	0.0471	1460	7E-07	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.056	6E-05	2.6403	0.329	15.512	1460	0.0002	0.0937	0.00132
19	0.1923	2.121	2.67	0.000794	0.056	6E-05	2.6403	0.339	15.983	1460	0.0002	0.0937	0.00132

Table D19. Laboratory data from test #19 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	E	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
19	0.00140	0.0003	0.0006	0.7615	0.4323	1726.6	48.769	0	51.23068			
19	0.00140	8E-05	0.0006	0.7615	0.4323	1887.4	85.966	0	14.03374			
19	0.00140	8E-05	0.0006	0.7615	0.4323	1888.8	86.297	0	13.7031			
19	0.00140	8E-05	0.0006	0.7615	0.4323	1891.7	86.958	0	13.04182			
19	0.00140	8E-05	0.0006	0.7615	0.4323	1893.1	87.289	0	12.71118			
19	0.00140	7E-05	0.0006	0.7615	0.4323	1894.6	87.619	0	12.38054			
19	0.00140	7E-05	0.0006	0.7615	0.4323	1896	87.95	0	12.0499			
19	0.00140	7E-05	0.0006	0.7615	0.4323	1897.4	88.281	0	11.71926			
19	0.00140	7E-05	0.0006	0.7615	0.4323	1897.4	88.281	0	11.71926			
19	0.00140	7E-05	0.0006	0.7615	0.4323	1897.4	88.281	0	11.71926			
19	0.00140	1E-04	0.0006	0.7615	0.4323	1876.7	83.486	0	16.51353			
19	0.00140	0.0005	0.0006	0.7615	0.4323	1618.7	23.806	0	76.19396			
19	0.00140	0.0006	0.0006	0.7615	0.4323	1540.8	5.7862	0	94.21381			
19	0.00140	0.0005	0.0006	0.7615	0.4323	1563	10.911	0	89.0889	10	14	12
19	0.00140	0.0005	0.0006	0.7615	0.4323	1555.8	9.2579	0	90.74209	10	11	10.5
19	0.00140	0.0005	0.0006	0.7615	0.4323	1556.5	9.2579	0.1132	90.62886	10	11	10.5
19	0.00140	0.0003	0.0006	0.7615	0.4323	1790.9	9.2579	37.254	53.48854	10	10	10
19	0.00140	0.0003	0.0006	0.7615	0.4323	1798.1	9.2579	38.386	52.35621	10	10	10

Table D22. Laboratory data from test #22

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
22	0.1937	2.084	2.67	0.000781	0.336	0.0003	16.123	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.46	0.0005	22.073	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.469	0.0005	22.505	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.474	0.0005	22.745	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.478	0.0005	22.937	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.479	0.0005	22.985	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.14	0.0001	6.7179	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.128	0.0001	6.142	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.12	0.0001	5.7582	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.08	8E-05	3.8388	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.055	6E-05	2.6392	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.048	5E-05	2.3033	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.045	5E-05	2.1593	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.045	5E-05	2.1593	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.039	4E-05	1.8714	0	0	1460	0	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.039	4E-05	1.8714	0.059	2.8311	1460	4E-05	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.039	4E-05	1.8714	0.129	6.19	1460	9E-05	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.039	4E-05	1.8714	0.271	13.004	1460	0.0002	0.0937	0.00133
22	0.1937	2.084	2.67	0.000781	0.039	4E-05	1.8714	0.054	2.5912	1460	4E-05	0.0937	0.00133

Table D22. Laboratory data from test #22 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	E	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
22	0.00140	0.0003	0.0006	0.7927	0.4422	1729.5	54.303	0	45.69663			
22	0.00140	0.0002	0.0006	0.7927	0.4422	1818.1	74.344	0	25.6561			
22	0.00140	0.0001	0.0006	0.7927	0.4422	1824.5	75.798	0	24.20154			
22	0.00140	0.0001	0.0006	0.7927	0.4422	1828.1	76.607	0	23.39346			
22	0.00140	0.0001	0.0006	0.7927	0.4422	1831	77.253	0	22.74699			
22	0.00140	0.0001	0.0006	0.7927	0.4422	1831.7	77.415	0	22.58537			
22	0.00140	0.0005	0.0006	0.7927	0.4422	1589.4	22.626	0	77.3736			
22	0.00140	0.0005	0.0006	0.7927	0.4422	1580.8	20.687	0	79.313			
22	0.00140	0.0005	0.0006	0.7927	0.4422	1575.1	19.394	0	80.60594			
22	0.00140	0.0005	0.0006	0.7927	0.4422	1546.5	12.929	0	87.07063			
22	0.00140	0.0006	0.0006	0.7927	0.4422	1528.7	8.8889	0	91.11106			
22	0.00140	0.0006	0.0006	0.7927	0.4422	1523.7	7.7576	0	92.24238			
22	0.00140	0.0006	0.0006	0.7927	0.4422	1521.5	7.2728	0	92.72723			
22	0.00140	0.0006	0.0006	0.7927	0.4422	1521.5	7.2728	0	92.72723			
22	0.00140	0.0006	0.0006	0.7927	0.4422	1517.2	6.3031	0	93.69693			
22	0.00140	0.0005	0.0006	0.7927	0.4422	1559.4	6.3031	6.5311	87.16583			
22	0.00140	0.0005	0.0006	0.7927	0.4422	1609.4	6.3031	14.28	79.41706			
22	0.00140	0.0004	0.0006	0.7927	0.4422	1710.9	6.3031	29.999	63.69813			
22	0.00140	0.0005	0.0006	0.7927	0.4422	1555.8	6.3031	5.9776	87.71931			

Table D23. Laboratory data from test #23

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
23	0.1905	2.116	2.67	0.000793	0.516	0.0005	24.386	0	0	1460	0	0.09366	0.00131
23	0.1905	2.116	2.67	0.000793	0.517	0.0005	24.433	0	0	1460	0	0.09366	0.00131
23	0.1905	2.116	2.67	0.000793	0.517	0.0005	24.433	0	0	1460	0	0.09366	0.00131
23	0.1905	2.116	2.67	0.000793	0.517	0.0005	24.433	0	0	1460	0	0.09366	0.00131
23	0.1905	2.116	2.67	0.000793	0.517	0.0005	24.433	0	0	1460	0	0.09366	0.00131
23	0.1905	2.116	2.67	0.000793	0.495	0.0005	23.393	0	0	1460	0	0.09366	0.00131
23	0.1905	2.116	2.67	0.000793	0.592	0.0006	27.977	0	0	1460	0	0.09366	0.00131
23	0.1905	2.116	2.67	0.000793	0.592	0.0006	27.977	0	0	1460	0	0.09366	0.00131
23	0.1905	2.116	2.67	0.000793	0.266	0.0003	12.571	0	0	1460	0	0.09366	0.00131
23	0.1905	2.116	2.67	0.000793	0.266	0.0003	12.571	0.204	9.6408	1460	0.0001	0.09366	0.00131
23	0.1905	2.116	2.67	0.000793	0.266	0.0003	12.571	0.048	2.2684	1460	3E-05	0.09366	0.00131

Table D23. Laboratory data from test #23 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
23	0.00140	9.08E-05	6.07E-04	0.7656	0.4336	1881	85.042	0	1.50E+01			
23	0.00140	8.98E-05	6.07E-04	0.7656	0.4336	1881.7	85.207	0	1.48E+01			
23	0.00140	8.98E-05	6.07E-04	0.7656	0.4336	1881.7	85.207	0	1.48E+01			
23	0.00140	8.98E-05	6.07E-04	0.7656	0.4336	1881.7	85.207	0	1.48E+01			
23	0.00140	8.98E-05	6.07E-04	0.7656	0.4336	1881.7	85.207	0	1.48E+01			
23	0.00140	1.12E-04	6.07E-04	0.7656	0.4336	1866	81.581	0	1.84E+01			
23	0.00140	1.48E-05	6.07E-04	0.7656	0.4336	1935.3	97.567	0	2.43E+00			
23	0.00140	1.48E-05	6.07E-04	0.7656	0.4336	1935.3	97.567	0	2.43E+00			
23	0.00140	3.41E-04	6.07E-04	0.7656	0.4336	1702.3	43.839	0	5.62E+01	9	7	8
23	0.00140	2.01E-04	6.07E-04	0.7656	0.4336	1848.1	43.839	23.028	3.31E+01	12	12	12
23	0.00140	3.08E-04	6.07E-04	0.7656	0.4336	1736.6	43.839	5.4184	5.07E+01	12	10	11

Table D24. Laboratory data from test #24

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
24	0.1937	2.084	2.67	0.000781	0.18	0.0002	8.6372	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.388	0.0004	18.618	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.508	0.0005	24.376	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.537	0.0005	25.768	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.541	0.0005	25.96	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.533	0.0005	25.576	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.302	0.0003	14.491	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.252	0.0003	12.092	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.226	0.0002	10.845	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.207	0.0002	9.9328	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.196	0.0002	9.405	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.18	0.0002	8.6372	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.145	0.0001	6.9578	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.145	0.0001	6.9578	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.144	0.0001	6.9098	0	0	1460	0	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.144	0.0001	6.9098	0.386	18.522	1460	0.0003	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.144	0.0001	6.9098	0.346	16.603	1460	0.0002	0.0937	0.0013
24	0.1937	2.084	2.67	0.000781	0.144	0.0001	6.9098	0.19	9.1171	1460	0.0001	0.0937	0.0013

Table D24. Laboratory data from test #24 (continued)

Tes t#	V_{TOTAL}	V_{air}	V_{voids}	E	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
24	0.0014	0.0004	0.0006	0.7927	0.4422	1618	29.091	0	70.909			
24	0.0014	0.0002	0.0006	0.7927	0.4422	1766.6	62.707	0	37.293			
24	0.0014	0.0001	0.0006	0.7927	0.4422	1852.4	82.102	0	17.898			
24	0.0014	8E-05	0.0006	0.7927	0.4422	1873.1	86.788	0	13.212			
24	0.0014	8E-05	0.0006	0.7927	0.4422	1876	87.435	0	12.565			
24	0.0014	9E-05	0.0006	0.7927	0.4422	1870.3	86.142	0	13.858			
24	0.0014	0.0003	0.0006	0.7927	0.4422	1705.2	48.808	0	51.192			
24	0.0014	0.0004	0.0006	0.7927	0.4422	1669.4	40.728	0	59.272			
24	0.0014	0.0004	0.0006	0.7927	0.4422	1650.9	36.525	0	63.475			
24	0.0014	0.0004	0.0006	0.7927	0.4422	1637.3	33.455	0	66.545			
24	0.0014	0.0004	0.0006	0.7927	0.4422	1629.4	31.677	0	68.323			
24	0.0014	0.0004	0.0006	0.7927	0.4422	1618	29.091	0	70.909			
24	0.0014	0.0005	0.0006	0.7927	0.4422	1593	23.434	0	76.566			
24	0.0014	0.0005	0.0006	0.7927	0.4422	1593	23.434	0	76.566			
24	0.0014	0.0005	0.0006	0.7927	0.4422	1592.3	23.273	0	76.727			
24	0.0014	0.0002	0.0006	0.7927	0.4422	1868.1	23.273	42.729	33.998	11	12	11.5
24	0.0014	0.0002	0.0006	0.7927	0.4422	1839.5	23.273	38.301	38.426	12	12	12
24	0.0014	0.0003	0.0006	0.7927	0.4422	1728	23.273	21.032	55.695	13	13	13

Table D25. Laboratory data from test #25

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
25	0.1937	2.102	2.67	0.000787	0.245	0.0002	11.656	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.42	0.0004	19.981	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.438	0.0004	20.837	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.5	0.0005	23.787	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.502	0.0005	23.882	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.512	0.0005	24.358	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.534	0.0005	25.404	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.533	0.0005	25.357	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.533	0.0005	25.357	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.533	0.0005	25.357	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.496	0.0005	23.597	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.249	0.0002	11.846	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.161	0.0002	7.6594	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.138	0.0001	6.5652	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.131	0.0001	6.2322	0	0	1460	0	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.131	0.0001	6.2322	0.464	22.074	1460	0.0003	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.131	0.0001	6.2322	0.516	24.548	1460	0.0004	0.0937	0.0013
25	0.1937	2.102	2.67	0.000787	0.131	0.0001	6.2322	0.46	21.884	1460	0.0003	0.0937	0.0013

Table D25. Laboratory data from test #25 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	E	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
25	0.0014	0.0004	0.0006	0.7774	0.4374	1677.3	40.032	0	59.968			
25	0.0014	0.0002	0.0006	0.7774	0.4374	1802.4	68.627	0	31.373			
25	0.0014	0.0002	0.0006	0.7774	0.4374	1815.2	71.568	0	28.432			
25	0.0014	0.0001	0.0006	0.7774	0.4374	1859.5	81.699	0	18.301			
25	0.0014	0.0001	0.0006	0.7774	0.4374	1861	82.026	0	17.974			
25	0.0014	0.0001	0.0006	0.7774	0.4374	1868.1	83.66	0	16.34			
25	0.0014	8E-05	0.0006	0.7774	0.4374	1883.8	87.254	0	12.746			
25	0.0014	8E-05	0.0006	0.7774	0.4374	1883.1	87.091	0	12.909			
25	0.0014	8E-05	0.0006	0.7774	0.4374	1883.1	87.091	0	12.909			
25	0.0014	8E-05	0.0006	0.7774	0.4374	1883.1	87.091	0	12.909			
25	0.0014	0.0001	0.0006	0.7774	0.4374	1856.7	81.045	0	18.955			
25	0.0014	0.0004	0.0006	0.7774	0.4374	1680.2	40.686	0	59.314			
25	0.0014	0.0005	0.0006	0.7774	0.4374	1617.3	26.307	0	73.693			
25	0.0014	0.0005	0.0006	0.7774	0.4374	1600.8	22.549	0	77.451			
25	0.0014	0.0005	0.0006	0.7774	0.4374	1595.8	21.405	0	78.595			
25	0.0014	0.0002	0.0006	0.7774	0.4374	1927.4	21.405	51.929	26.666	25	26	25.5
25	0.0014	0.0001	0.0006	0.7774	0.4374	1964.6	21.405	57.749	20.846	5	5	5
25	0.0014	0.0002	0.0006	0.7774	0.4374	1924.6	21.405	51.481	27.114	4	8	6

Table D26. Laboratory data from test #26

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
26	0.1937	2.021	2.67	0.000757	0.04	4E-05	1.9792	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.066	7E-05	3.2657	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.097	1E-04	4.7996	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.126	0.0001	6.2345	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.164	0.0002	8.1148	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.195	0.0002	9.6487	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.256	0.0003	12.667	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.424	0.0004	20.98	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.483	0.0005	23.899	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.492	0.0005	24.344	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.493	0.0005	24.394	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.493	0.0005	24.394	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.241	0.0002	11.925	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.154	0.0002	7.62	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.117	0.0001	5.7892	0	0	1460	0	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.117	0.0001	5.7892	0.263	13.013	1460	0.0002	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.117	0.0001	5.7892	0.293	14.498	1460	0.0002	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.117	0.0001	5.7892	0.31	15.339	1460	0.0002	0.0937	0.0013
26	0.1937	2.021	2.67	0.000757	0.117	0.0001	5.7892	0.239	11.826	1460	0.0002	0.0937	0.0013

Table D26. Laboratory data from test #26 (continued)

Tes t#	V_{TOTAL}	V_{air}	V_{voids}	E	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
26	0.0014	0.0006	0.0006	0.8486	0.4591	1472.9	6.2272	0	93.77278			
26	0.0014	0.0006	0.0006	0.8486	0.4591	1491.5	10.275	0	89.72509			
26	0.0014	0.0005	0.0006	0.8486	0.4591	1513.6	15.101	0	84.899			
26	0.0014	0.0005	0.0006	0.8486	0.4591	1534.4	19.616	0	80.38427			
26	0.0014	0.0005	0.0006	0.8486	0.4591	1561.5	25.532	0	74.46841			
26	0.0014	0.0004	0.0006	0.8486	0.4591	1583.7	30.358	0	69.64232			
26	0.0014	0.0004	0.0006	0.8486	0.4591	1627.3	39.854	0	60.14582			
26	0.0014	0.0002	0.0006	0.8486	0.4591	1747.3	66.008	0	33.99151			
26	0.0014	0.0002	0.0006	0.8486	0.4591	1789.5	75.194	0	24.80637			
26	0.0014	0.0002	0.0006	0.8486	0.4591	1795.9	76.595	0	23.40524			
26	0.0014	0.0001	0.0006	0.8486	0.4591	1796.7	76.75	0	23.24956			
26	0.0014	0.0001	0.0006	0.8486	0.4591	1796.7	76.75	0	23.24956			
26	0.0014	0.0004	0.0006	0.8486	0.4591	1616.6	37.519	0	62.48102			
26	0.0014	0.0005	0.0006	0.8486	0.4591	1554.4	23.975	0	76.02522			
26	0.0014	0.0005	0.0006	0.8486	0.4591	1527.9	18.215	0	81.78539			
26	0.0014	0.0003	0.0006	0.8486	0.4591	1715.9	18.215	28.044	53.7416	10	8	9
26	0.0014	0.0003	0.0006	0.8486	0.4591	1737.3	18.215	31.243	50.54268	11	10	10.5
26	0.0014	0.0003	0.0006	0.8486	0.4591	1749.5	18.215	33.055	48.72997	12	10	11
26	0.0014	0.0004	0.0006	0.8486	0.4591	1698.7	18.215	25.485	56.30073	13	10	11.5

Table D27. Laboratory data from test #27

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
27	0.1905	2.021	2.67	0.000756929	0.005	0.000005	0.247402	0	0	1460	0	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.068	0.000068	3.364671	0	0	1460	0	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.196	0.000196	9.698169	0	0	1460	0	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.336	0.000336	16.62543	0	0	1460	0	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.481	0.000481	23.8001	0	0	1460	0	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.604	0.000604	29.88619	0	0	1460	0	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.619	0.000619	30.6284	0	0	1460	0	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.604	0.000604	29.88619	0	0	1460	0	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.373	0.000373	18.45621	0	0	1460	0	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.355	0.000355	17.56556	0	0	1460	0	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.265	0.000265	13.11232	0	0	1460	0	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.216	0.000216	10.68778	0	0	1460	0	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.196	0.000196	9.698169	0	0	1460	0	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.196	0.000196	9.698169	0.014	0.692726	1460	9.59E-06	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.196	0.000196	9.698169	0.233	11.52895	1460	0.00016	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.196	0.000196	9.698169	0.185	9.153884	1460	0.000127	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.196	0.000196	9.698169	0.176	8.70856	1460	0.000121	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.196	0.000196	9.698169	0.161	7.966353	1460	0.00011	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.196	0.000196	9.698169	0.182	9.005443	1460	0.000125	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.196	0.000196	9.698169	0.182	9.005443	1460	0.000125	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.196	0.000196	9.698169	0.182	9.005443	1460	0.000125	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.196	0.000196	9.698169	0.182	9.005443	1460	0.000125	0.09366	0.001312
27	0.1905	2.021	2.67	0.000756929	0.196	0.000196	9.698169	0.182	9.005443	1460	0.000125	0.09366	0.001312

Table D27. Laboratory data from test #27 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
27	0.001399	0.000637	0.000642	0.848616	0.459055	1447.897	0.778402	0	99.2216			
27	0.001399	0.000574	0.000642	0.848616	0.459055	1492.921	10.58627	0	89.41373			
27	0.001399	0.000446	0.000642	0.848616	0.459055	1584.397	30.51336	0	69.48664			
27	0.001399	0.000306	0.000642	0.848616	0.459055	1684.449	52.30861	0	47.69139			
27	0.001399	0.000161	0.000642	0.848616	0.459055	1788.075	74.88227	0	25.11773			
27	0.001399	3.83E-05	0.000642	0.848616	0.459055	1875.978	94.03096	0	5.96904			
27	0.001399	2.33E-05	0.000642	0.848616	0.459055	1886.697	96.36617	0	3.633834			
27	0.001399	3.83E-05	0.000642	0.848616	0.459055	1875.978	94.03096	0	5.96904			
27	0.001399	0.000269	0.000642	0.848616	0.459055	1710.892	58.06879	0	41.93121			
27	0.001399	0.000287	0.000642	0.848616	0.459055	1698.028	55.26654	0	44.73346			
27	0.001399	0.000377	0.000642	0.848616	0.459055	1633.708	41.25531	0	58.74469			
27	0.001399	0.000426	0.000642	0.848616	0.459055	1598.69	33.62697	0	66.37303			
27	0.001399	0.000446	0.000642	0.848616	0.459055	1584.397	30.51336	0	69.48664			
27	0.001399	0.000437	0.000642	0.848616	0.459055	1594.402	30.51336	1.492826	67.99382			
27	0.001399	0.000287	0.000642	0.848616	0.459055	1750.912	30.51336	24.84489	44.64176	12	26	19
27	0.001399	0.00032	0.000642	0.848616	0.459055	1716.609	30.51336	19.72663	49.76002	12	20	16
27	0.001399	0.000326	0.000642	0.848616	0.459055	1710.177	30.51336	18.76695	50.71969	10	17	13.5
27	0.001399	0.000336	0.000642	0.848616	0.459055	1699.457	30.51336	17.1675	52.31915	10	12	11
27	0.001399	0.000322	0.000642	0.848616	0.459055	1714.465	30.51336	19.40673	50.07991	10	12	11
27	0.001399	0.000322	0.000642	0.848616	0.459055	1714.465	30.51336	19.40673	50.07991	10	10	10
27	0.001399	0.000322	0.000642	0.848616	0.459055	1714.465	30.51336	19.40673	50.07991	10	10	10
27	0.001399	0.000322	0.000642	0.848616	0.459055	1714.465	30.51336	19.40673	50.07991	10	10	10
27	0.001399	0.000322	0.000642	0.848616	0.459055	1714.465	30.51336	19.40673	50.07991	10	10	10

Table D28. Laboratory data from test #28

Te st#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
28	0.1905	2.094	2.67	0.000784	0.005	5E-06	0.2388	0	0	1460	0	0.0937	0.0013
28	0.1905	2.094	2.67	0.000784	0.068	7E-05	3.2474	0	0	1460	0	0.0937	0.0013
28	0.1905	2.094	2.67	0.000784	0.196	0.0002	9.3601	0	0	1460	0	0.0937	0.0013
28	0.1905	2.094	2.67	0.000784	0.336	0.0003	16.046	0	0	1460	0	0.0937	0.0013
28	0.1905	2.094	2.67	0.000784	0.481	0.0005	22.97	0	0	1460	0	0.0937	0.0013
28	0.1905	2.094	2.67	0.000784	0.604	0.0006	28.844	0	0	1460	0	0.0937	0.0013
28	0.1905	2.094	2.67	0.000784	0.619	0.0006	29.561	0	0	1460	0	0.0937	0.0013
28	0.1905	2.094	2.67	0.000784	0.604	0.0006	28.844	0	0	1460	0	0.0937	0.0013
28	0.1905	2.094	2.67	0.000784	0.373	0.0004	17.813	0	0	1460	0	0.0937	0.0013
28	0.1905	2.094	2.67	0.000784	0.355	0.0004	16.953	0	0	1460	0	0.0937	0.0013
28	0.1905	2.094	2.67	0.000784	0.265	0.0003	12.655	0	0	1460	0	0.0937	0.0013
28	0.1905	2.094	2.67	0.000784	0.216	0.0002	10.315	0	0	1460	0	0.0937	0.0013
28	0.1905	2.094	2.67	0.000784	0.196	0.0002	9.3601	0	0	1460	0	0.0937	0.0013
28	0.1905	2.094	2.67	0.000784	0.196	0.0002	9.3601	0.014	0.6686	1460	1E-05	0.0937	0.0013
28	0.1905	2.094	2.67	0.000784	0.196	0.0002	9.3601	0.233	11.127	1460	0.0002	0.0937	0.0013

Table D28. Laboratory data from test #28 (continued)

Tes t#	V_{TOTAL}	V_{air}	V_{voids}	E	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
28	0.0014	0.0006	0.0006	0.7842	0.4395	1500.1	0.813	0	99.187			
28	0.0014	0.0005	0.0006	0.7842	0.4395	1545.1	11.057	0	88.943			
28	0.0014	0.0004	0.0006	0.7842	0.4395	1636.6	31.87	0	68.13			
28	0.0014	0.0003	0.0006	0.7842	0.4395	1736.6	54.634	0	45.366			
28	0.0014	0.0001	0.0006	0.7842	0.4395	1840.2	78.211	0	21.789			
28	0.0014	1E-05	0.0006	0.7842	0.4395	1928.1	98.211	0	1.7887			
28	0.0014	-4E-06	0.0006	0.7842	0.4395	1938.9	100.65	0	-0.65			
28	0.0014	1E-05	0.0006	0.7842	0.4395	1928.1	98.211	0	1.7887			
28	0.0014	0.0002	0.0006	0.7842	0.4395	1763.1	60.65	0	39.35			
28	0.0014	0.0003	0.0006	0.7842	0.4395	1750.2	57.724	0	42.276			
28	0.0014	0.0004	0.0006	0.7842	0.4395	1685.9	43.089	0	56.911			
28	0.0014	0.0004	0.0006	0.7842	0.4395	1650.9	35.122	0	64.878	7	7	7
28	0.0014	0.0004	0.0006	0.7842	0.4395	1636.6	31.87	0	68.13	8	8	8
28	0.0014	0.0004	0.0006	0.7842	0.4395	1646.6	31.87	1.5592	66.571	10	10	10
28	0.0014	0.0003	0.0006	0.7842	0.4395	1803.1	31.87	25.949	42.181	8	8	8

Table D29. Laboratory data from test #29

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
29	0.180975	2.038	2.67	0.000763296	0.277	0.000277	13.59176	0	0	1460	0	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.29	0.00029	14.22964	0	0	1460	0	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.47	0.00047	23.06183	0	0	1460	0	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.494	0.000494	24.23945	0	0	1460	0	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.499	0.000499	24.48479	0	0	1460	0	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.503	0.000503	24.68106	0	0	1460	0	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.508	0.000508	24.9264	0	0	1460	0	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.501	0.000501	24.58292	0	0	1460	0	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.499	0.000499	24.48479	0	0	1460	0	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.529	0.000529	25.95682	0	0	1460	0	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.35	0.00035	17.1737	0	0	1460	0	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.257	0.000257	12.6104	0	0	1460	0	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.225	0.000225	11.04024	0	0	1460	0	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.211	0.000211	10.35329	0	0	1460	0	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.211	0.000211	10.35329	0.008	0.392542	1460	5.48E-06	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.211	0.000211	10.35329	0.058	2.845927	1460	3.97E-05	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.211	0.000211	10.35329	0.095	4.661433	1460	6.51E-05	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.211	0.000211	10.35329	0.084	4.121688	1460	5.75E-05	0.09366	0.001246
29	0.180975	2.038	2.67	0.000763296	0.211	0.000211	10.35329	0.115	5.642787	1460	7.88E-05	0.09366	0.001246

Table D29. Laboratory data from test #29 (continued)

Tes t#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-$	$Sn-1$	$Sn-2$	Avg Sn
29	0.001399	0.000359	0.000636	0.833195	0.454504	1654.434	43.5552	0	56.445			
29	0.001399	0.000346	0.000636	0.833195	0.454504	1663.724	45.59931	0	54.401			
29	0.001399	0.000166	0.000636	0.833195	0.454504	1792.363	73.90232	0	26.098			
29	0.001399	0.000142	0.000636	0.833195	0.454504	1809.514	77.67606	0	22.324			
29	0.001399	0.000137	0.000636	0.833195	0.454504	1813.088	78.46225	0	21.538			
29	0.001399	0.000133	0.000636	0.833195	0.454504	1815.946	79.09121	0	20.909			
29	0.001399	0.000128	0.000636	0.833195	0.454504	1819.52	79.87741	0	20.123			
29	0.001399	0.000135	0.000636	0.833195	0.454504	1814.517	78.77673	0	21.223			
29	0.001399	0.000137	0.000636	0.833195	0.454504	1813.088	78.46225	0	21.538			
29	0.001399	0.000107	0.000636	0.833195	0.454504	1834.527	83.17942	0	16.821			
29	0.001399	0.000286	0.000636	0.833195	0.454504	1706.604	55.03365	0	44.966			
29	0.001399	0.000379	0.000636	0.833195	0.454504	1640.14	40.41042	0	59.59			
29	0.001399	0.000411	0.000636	0.833195	0.454504	1617.271	35.37877	0	64.621			
29	0.001399	0.000425	0.000636	0.833195	0.454504	1607.266	33.17743	0	66.823			
29	0.001399	0.000419	0.000636	0.833195	0.454504	1612.983	33.17743	0.8616	65.961	4	4	4
29	0.001399	0.000385	0.000636	0.833195	0.454504	1648.716	33.17743	6.2465	60.576	4	4	4
29	0.001399	0.00036	0.000636	0.833195	0.454504	1675.159	33.17743	10.231	56.591	4	4	4
29	0.001399	0.000367	0.000636	0.833195	0.454504	1667.297	33.17743	9.0466	57.776	4	4	4
29	0.001399	0.000346	0.000636	0.833195	0.454504	1689.452	33.17743	12.385	54.437	5	5	5

Table D30. Laboratory data from test #30

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
30	0.2032	2.02	2.67	0.000756554	0.324	0.000324	16.0396	0	0	1460	0	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.582	0.000582	28.81188	0	0	1460	0	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.585	0.000585	28.9604	0	0	1460	0	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.587	0.000587	29.05941	0	0	1460	0	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.589	0.000589	29.15842	0	0	1460	0	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.588	0.000588	29.10891	0	0	1460	0	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.574	0.000574	28.41584	0	0	1460	0	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.567	0.000567	28.06931	0	0	1460	0	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.552	0.000552	27.32673	0	0	1460	0	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.241	0.000241	11.93069	0	0	1460	0	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.215	0.000215	10.64356	0	0	1460	0	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.185	0.000185	9.158416	0	0	1460	0	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.186	0.000186	9.207921	0	0	1460	0	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.186	0.000186	9.207921	0.153	7.574257	1460	0.000105	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.186	0.000186	9.207921	0.215	10.64356	1460	0.000147	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.186	0.000186	9.207921	0.245	12.12871	1460	0.000168	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.186	0.000186	9.207921	0.189	9.356436	1460	0.000129	0.09366	0.001399
29	0.2032	2.02	2.67	0.000756554	0.186	0.000186	9.207921	0.145	7.178218	1460	9.93E-05	0.09366	0.001399

Table D30. Laboratory data from test #30 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
30	0.001399	0.000319	0.000643	0.849531	0.459322	1675.159	50.41106	0	49.589			
30	0.001399	6.07E-05	0.000643	0.849531	0.459322	1859.54	90.55319	0	9.4468			
30	0.001399	5.77E-05	0.000643	0.849531	0.459322	1861.684	91.01996	0	8.98			
30	0.001399	5.57E-05	0.000643	0.849531	0.459322	1863.114	91.33114	0	8.6689			
30	0.001399	5.37E-05	0.000643	0.849531	0.459322	1864.543	91.64232	0	8.3577			
30	0.001399	5.47E-05	0.000643	0.849531	0.459322	1863.828	91.48673	0	8.5133			
30	0.001399	6.87E-05	0.000643	0.849531	0.459322	1853.823	89.30848	0	10.692			
30	0.001399	7.57E-05	0.000643	0.849531	0.459322	1848.821	88.21935	0	11.781			
30	0.001399	9.07E-05	0.000643	0.849531	0.459322	1838.101	85.8855	0	14.114			
30	0.001399	0.000402	0.000643	0.849531	0.459322	1615.842	37.49711	0	62.503			
30	0.001399	0.000428	0.000643	0.849531	0.459322	1597.261	33.45178	0	66.548			
30	0.001399	0.000458	0.000643	0.849531	0.459322	1575.821	28.78409	0	71.216			
30	0.001399	0.000457	0.000643	0.849531	0.459322	1576.536	28.93968	0	71.06	16	20	18
30	0.001399	0.000352	0.000643	0.849531	0.459322	1685.879	28.93968	16.305	54.755	10	12	11
30	0.001399	0.000309	0.000643	0.849531	0.459322	1730.187	28.93968	22.912	48.148	9	10	9.5
30	0.001399	0.000289	0.000643	0.849531	0.459322	1751.627	28.93968	26.109	44.951	9	9	9
30	0.001399	0.000327	0.000643	0.849531	0.459322	1711.606	28.93968	20.141	50.919	9	9	9
30	0.001399	0.000357	0.000643	0.849531	0.459322	1680.161	28.93968	15.452	55.608	8	8	8

Table D31. Laboratory data from test #31

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
31	0.2016	2.044	2.67	0.000766	0.028	3E-05	1.3699	0	0	1460	0	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.128	0.0001	6.2622	0	0	1460	0	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.382	0.0004	18.689	0	0	1460	0	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.564	0.0006	27.593	0	0	1460	0	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.569	0.0006	27.838	0	0	1460	0	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.575	0.0006	28.131	0	0	1460	0	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.427	0.0004	20.89	0	0	1460	0	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.287	0.0003	14.041	0	0	1460	0	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.283	0.0003	13.845	0	0	1460	0	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.224	0.0002	10.959	0	0	1460	0	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.222	0.0002	10.861	0	0	1460	0	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.189	0.0002	9.2466	0	0	1460	0	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.189	0.0002	9.2466	0	0	1460	0	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.178	0.0002	8.7084	0	0	1460	0	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.178	0.0002	8.7084	0.137	6.7025	1460	9E-05	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.178	0.0002	8.7084	0.564	27.593	1460	0.0004	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.178	0.0002	8.7084	0.177	8.6595	1460	0.0001	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.178	0.0002	8.7084	0.13	6.3601	1460	9E-05	0.0937	0.00139
31	0.2016	2.044	2.67	0.000766	0.178	0.0002	8.7084	0.078	3.816	1460	5E-05	0.0937	0.00139

Table D31. Laboratory data from test #31 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
31	0.00140	0.0006	0.0006	0.8278	0.4529	1480.8	4.4183	0	95.5817			
31	0.00140	0.0005	0.0006	0.8278	0.4529	1552.2	20.198	0	79.80204			
31	0.00140	0.0003	0.0006	0.8278	0.4529	1733.8	60.278	0	39.72172			
31	0.00140	7E-05	0.0006	0.8278	0.4529	1863.8	88.997	0	11.00274			
31	0.00140	6E-05	0.0006	0.8278	0.4529	1867.4	89.786	0	10.21376			
31	0.00140	6E-05	0.0006	0.8278	0.4529	1871.7	90.733	0	9.26698			
31	0.00140	0.0002	0.0006	0.8278	0.4529	1765.9	67.379	0	32.62087			
31	0.00140	0.0003	0.0006	0.8278	0.4529	1665.9	45.288	0	54.71239			
31	0.00140	0.0004	0.0006	0.8278	0.4529	1663	44.656	0	55.34357			
31	0.00140	0.0004	0.0006	0.8278	0.4529	1620.8	35.346	0	64.65357			
31	0.00140	0.0004	0.0006	0.8278	0.4529	1619.4	35.031	0	64.96916			
31	0.00140	0.0004	0.0006	0.8278	0.4529	1595.8	29.824	0	70.17645			
31	0.00140	0.0004	0.0006	0.8278	0.4529	1595.8	29.824	0	70.17645			
31	0.00140	0.0005	0.0006	0.8278	0.4529	1588	28.088	0	71.91221	10	12	11
31	0.00140	0.0004	0.0006	0.8278	0.4529	1685.9	28.088	14.807	57.10528	10	6	8
31	0.00140	7E-05	0.0006	0.8278	0.4529	1991	28.088	60.957	10.95519	10	6	8
31	0.00140	0.0003	0.0006	0.8278	0.4529	1714.5	28.088	19.13	52.78208	10	6	8
31	0.00140	0.0004	0.0006	0.8278	0.4529	1680.9	28.088	14.05	57.86183	10	6	8
31	0.00140	0.0004	0.0006	0.8278	0.4529	1643.7	28.088	8.4302	63.48199	9.5	6	7.75

Table D32. Laboratory data from test #32

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
32	0.1889	2.057	2.67	0.00077	0.58	0.0006	28.196	0	0	1460	0	0.0937	0.00130
32	0.1889	2.057	2.67	0.00077	0.585	0.0006	28.439	0	0	1460	0	0.0937	0.00130
32	0.1889	2.057	2.67	0.00077	0.574	0.0006	27.905	0	0	1460	0	0.0937	0.00130
32	0.1889	2.057	2.67	0.00077	0.545	0.0005	26.495	0	0	1460	0	0.0937	0.00130
32	0.1889	2.057	2.67	0.00077	0.37	0.0004	17.987	0	0	1460	0	0.0937	0.00130
32	0.1889	2.057	2.67	0.00077	0.262	0.0003	12.737	0	0	1460	0	0.0937	0.00130
32	0.1889	2.057	2.67	0.00077	0.23	0.0002	11.181	0	0	1460	0	0.0937	0.00130
32	0.1889	2.057	2.67	0.00077	0.205	0.0002	9.966	0	0	1460	0	0.0937	0.00130
32	0.1889	2.057	2.67	0.00077	0.205	0.0002	9.966	0.001	0.0486	1460	7E-07	0.0937	0.00130
32	0.1889	2.057	2.67	0.00077	0.205	0.0002	9.966	0.229	11.133	1460	0.0002	0.0937	0.00130
32	0.1889	2.057	2.67	0.00077	0.205	0.0002	9.966	0.323	15.702	1460	0.0002	0.0937	0.00130
32	0.1889	2.057	2.67	0.00077	0.205	0.0002	9.966	0.258	12.543	1460	0.0002	0.0937	0.00130

Table D32. Laboratory data from test #32 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
32	0.00140	5E-05	0.0006	0.8163	0.4494	1884.6	92.231	0	7.7694			
32	0.00140	4E-05	0.0006	0.8163	0.4494	1888.1	93.026	0	6.9743			
32	0.00140	5E-05	0.0006	0.8163	0.4494	1880.3	91.276	0	8.7235			
32	0.00140	8E-05	0.0006	0.8163	0.4494	1859.5	86.665	0	13.335			
32	0.00140	0.0003	0.0006	0.8163	0.4494	1734.5	58.837	0	41.163			
32	0.00140	0.0004	0.0006	0.8163	0.4494	1657.3	41.663	0	58.337			
32	0.00140	0.0004	0.0006	0.8163	0.4494	1634.4	36.574	0	63.426			
32	0.00140	0.0004	0.0006	0.8163	0.4494	1616.6	32.599	0	67.401			
32	0.00140	0.0004	0.0006	0.8163	0.4494	1617.3	32.599	0.1089	67.292	12	13	12.5
32	0.00140	0.0003	0.0006	0.8163	0.4494	1780.2	32.599	24.942	42.459	12	12	12
32	0.00140	0.0002	0.0006	0.8163	0.4494	1847.4	32.599	35.18	32.221	14	14	14
32	0.00140	0.0002	0.0006	0.8163	0.4494	1800.9	32.599	28.1	39.301	14	14	14

Table D33. Laboratory data from test #33

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{ait+solids}$
33	0.1905	2.078	2.67	0.0007783	0.185	0.0002	8.9028	0	0	1460	0	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.579	0.0006	27.863	0	0	1460	0	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.579	0.0006	27.863	0	0	1460	0	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.579	0.0006	27.863	0	0	1460	0	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.578	0.0006	27.815	0	0	1460	0	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.571	0.0006	27.478	0	0	1460	0	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.564	0.0006	27.141	0	0	1460	0	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.558	0.0006	26.853	0	0	1460	0	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.455	0.0005	21.896	0	0	1460	0	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.305	0.0003	14.678	0	0	1460	0	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.301	0.0003	14.485	0	0	1460	0	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.246	0.0002	11.838	0	0	1460	0	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.223	0.0002	10.731	0	0	1460	0	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.207	0.0002	9.9615	0	0	1460	0	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.207	0.0002	9.9615	0.094	4.5236	1460	6.43836E-05	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.207	0.0002	9.9615	0.12	5.7748	1460	8.21918E-05	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.207	0.0002	9.9615	0.127	6.1116	1460	8.69863E-05	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.207	0.0002	9.9615	0.106	5.1011	1460	7.26027E-05	0.0937	0.00131
33	0.1905	2.078	2.67	0.0007783	0.207	0.0002	9.9615	0.052	2.5024	1460	3.56164E-05	0.0937	0.00131

Table D33. Laboratory data from test#33 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
33	0.00140	0.0004	0.0006	0.7979	0.4438	1617.3	29.791	0	70.209			
33	0.00140	4E-05	0.0006	0.7979	0.4438	1898.8	93.238	0	6.7623			
33	0.00140	4E-05	0.0006	0.7979	0.4438	1898.8	93.238	0	6.7623			
33	0.00140	4E-05	0.0006	0.7979	0.4438	1898.8	93.238	0	6.7623			
33	0.00140	4E-05	0.0006	0.7979	0.4438	1898.1	93.077	0	6.9233			
33	0.00140	5E-05	0.0006	0.7979	0.4438	1893.1	91.949	0	8.0505			
33	0.00140	6E-05	0.0006	0.7979	0.4438	1888.1	90.822	0	9.1778			
33	0.00140	6E-05	0.0006	0.7979	0.4438	1883.8	89.856	0	10.144			
33	0.00140	0.0002	0.0006	0.7979	0.4438	1810.2	73.27	0	26.73			
33	0.00140	0.0003	0.0006	0.7979	0.4438	1703	49.115	0	50.885			
33	0.00140	0.0003	0.0006	0.7979	0.4438	1700.2	48.471	0	51.529			
33	0.00140	0.0004	0.0006	0.7979	0.4438	1660.9	39.614	0	60.386			
33	0.00140	0.0004	0.0006	0.7979	0.4438	1644.4	35.91	0	64.09			
33	0.00140	0.0004	0.0006	0.7979	0.4438	1633	33.334	0	66.666			
33	0.00140	0.0003	0.0006	0.7979	0.4438	1700.2	33.334	10.368	56.298	10	12	11
33	0.00140	0.0003	0.0006	0.7979	0.4438	1718.8	33.334	13.236	53.431	14	10	12
33	0.00140	0.0003	0.0006	0.7979	0.4438	1723.8	33.334	14.008	52.659	14	10	12
33	0.00140	0.0003	0.0006	0.7979	0.4438	1708.7	33.334	11.691	54.975	16	12	14
33	0.00140	0.0004	0.0006	0.7979	0.4438	1670.2	33.334	5.7354	60.931	16	12	14

Table D34. Laboratory data from test #34

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
34	0.1873	2.055	2.67	0.00077	0.494	0.0005	24.039	0	0	1460	0	0.0937	0.00129
34	0.1873	2.055	2.67	0.00077	0.573	0.0006	27.883	0	0	1460	0	0.0937	0.00129
34	0.1873	2.055	2.67	0.00077	0.576	0.0006	28.029	0	0	1460	0	0.0937	0.00129
34	0.1873	2.055	2.67	0.00077	0.582	0.0006	28.321	0	0	1460	0	0.0937	0.00129
34	0.1873	2.055	2.67	0.00077	0.516	0.0005	25.109	0	0	1460	0	0.0937	0.00129
34	0.1873	2.055	2.67	0.00077	0.321	0.0003	15.62	0	0	1460	0	0.0937	0.00129
34	0.1873	2.055	2.67	0.00077	0.247	0.0002	12.019	0	0	1460	0	0.0937	0.00129
34	0.1873	2.055	2.67	0.00077	0.219	0.0002	10.657	0	0	1460	0	0.0937	0.00129
34	0.1873	2.055	2.67	0.00077	0.219	0.0002	10.657	0	0	1460	0	0.0937	0.00129
34	0.1873	2.055	2.67	0.00077	0.219	0.0002	10.657	0.318	15.474	1460	0.0002	0.0937	0.00129
34	0.1873	2.055	2.67	0.00077	0.219	0.0002	10.657	0.308	14.988	1460	0.0002	0.0937	0.00129
34	0.1873	2.055	2.67	0.00077	0.219	0.0002	10.657	0.299	14.55	1460	0.0002	0.0937	0.00129
34	0.1873	2.055	2.67	0.00077	0.219	0.0002	10.657	0.296	14.404	1460	0.0002	0.0937	0.00129

Table D34. Laboratory data from test #34 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
34	0.00140	0.0001	0.0006	0.818	0.45	1821.7	78.462	0	21.538			
34	0.00140	6E-05	0.0006	0.818	0.45	1878.1	91.009	0	8.9909			
34	0.00140	5E-05	0.0006	0.818	0.45	1880.3	91.486	0	8.5144			
34	0.00140	5E-05	0.0006	0.818	0.45	1884.6	92.439	0	7.5615			
34	0.00140	0.0001	0.0006	0.818	0.45	1837.4	81.956	0	18.044			
34	0.00140	0.0003	0.0006	0.818	0.45	1698	50.984	0	49.016			
34	0.00140	0.0004	0.0006	0.818	0.45	1645.1	39.231	0	60.769			
34	0.00140	0.0004	0.0006	0.818	0.45	1625.1	34.784	0	65.216			
34	0.00140	0.0004	0.0006	0.818	0.45	1625.1	34.784	0	65.216			
34	0.00140	0.0002	0.0006	0.818	0.45	1852.4	34.784	34.594	30.622	12	9	10.5
34	0.00140	0.0002	0.0006	0.818	0.45	1845.2	34.784	33.506	31.71	12	9	10.5
34	0.00140	0.0002	0.0006	0.818	0.45	1838.8	34.784	32.527	32.689	12	8	10
34	0.00140	0.0002	0.0006	0.818	0.45	1836.7	34.784	32.201	33.015	12	8	10

Table D35. Laboratory data from test #35

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
35	0.1857	1.994	2.67	0.000747	0.137	0.0001	6.8706	0	0	1460	0	0.0937	0.00128
35	0.1857	1.994	2.67	0.000747	0.342	0.0003	17.151	0	0	1460	0	0.0937	0.00128
35	0.1857	1.994	2.67	0.000747	0.536	0.0005	26.881	0	0	1460	0	0.0937	0.00128
35	0.1857	1.994	2.67	0.000747	0.542	0.0005	27.182	0	0	1460	0	0.0937	0.00128
35	0.1857	1.994	2.67	0.000747	0.219	0.0002	10.983	0	0	1460	0	0.0937	0.00128
35	0.1857	1.994	2.67	0.000747	0.161	0.0002	8.0742	0	0	1460	0	0.0937	0.00128
35	0.1857	1.994	2.67	0.000747	0.156	0.0002	7.8235	0	0	1460	0	0.0937	0.00128
35	0.1857	1.994	2.67	0.000747	0.13	0.0001	6.5196	0	0	1460	0	0.0937	0.00128
35	0.1857	1.994	2.67	0.000747	0.428	0.0004	21.464	0	0	1460	0	0.0937	0.00128
35	0.1857	1.994	2.67	0.000747	0.219	0.0002	10.983	0.286	14.343	1460	0.0002	0.0937	0.00128
35	0.1857	1.994	2.67	0.000747	0.219	0.0002	10.983	0.315	15.797	1460	0.0002	0.0937	0.00128
35	0.1857	1.994	2.67	0.000747	0.219	0.0002	10.983	0.256	12.839	1460	0.0002	0.0937	0.00128

Table D35. Laboratory data from test #35 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat - w$	$Sat - N$	$Sat - A$	$Sn - 1$	$Sn - 2$	$Avg\ Sn$
35	0.00140	0.0005	0.0007	0.8736	0.4663	1522.9	20.998	0	79.002			
35	0.00140	0.0003	0.0007	0.8736	0.4663	1669.4	52.417	0	47.583			
35	0.00140	0.0001	0.0007	0.8736	0.4663	1808.1	82.151	0	17.849			
35	0.00140	0.0001	0.0007	0.8736	0.4663	1812.4	83.071	0	16.929			
35	0.00140	0.0004	0.0007	0.8736	0.4663	1581.5	33.566	0	66.434			
35	0.00140	0.0005	0.0007	0.8736	0.4663	1540.1	24.676	0	75.324			
35	0.00140	0.0005	0.0007	0.8736	0.4663	1536.5	23.91	0	76.09			
35	0.00140	0.0005	0.0007	0.8736	0.4663	1517.9	19.925	0	80.075			
35	0.00140	0.0002	0.0007	0.8736	0.4663	1730.9	65.598	0	34.402			
35	0.00140	0.0002	0.0007	0.8736	0.4663	1785.9	33.566	30.024	36.411	43	38	40.5
35	0.00140	0.0002	0.0007	0.8736	0.4663	1806.7	33.566	33.068	33.366	34	29	31.5
35	0.00140	0.0003	0.0007	0.8736	0.4663	1764.5	33.566	26.874	39.56	29	10	29

Table D36. Laboratory data from test #36

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{ait+solids}$
36	0.1857	2.062	2.67	0.000772	0.562	0.0006	27.255	0	0	1460	0	0.0937	0.00128
36	0.1857	2.062	2.67	0.000772	0.566	0.0006	27.449	0	0	1460	0	0.0937	0.00128
36	0.1857	2.062	2.67	0.000772	0.592	0.0006	28.71	0	0	1460	0	0.0937	0.00128
36	0.1857	2.062	2.67	0.000772	0.602	0.0006	29.195	0	0	1460	0	0.0937	0.00128
36	0.1857	2.062	2.67	0.000772	0.599	0.0006	29.049	0	0	1460	0	0.0937	0.00128
36	0.1857	2.062	2.67	0.000772	0.598	0.0006	29.001	0	0	1460	0	0.0937	0.00128
36	0.1857	2.062	2.67	0.000772	0.599	0.0006	29.049	0	0	1460	0	0.0937	0.00128
36	0.1857	2.062	2.67	0.000772	0.583	0.0006	28.274	0	0	1460	0	0.0937	0.00128
36	0.1857	2.062	2.67	0.000772	0.577	0.0006	27.983	0	0	1460	0	0.0937	0.00128
36	0.1857	2.062	2.67	0.000772	0.577	0.0006	27.983	0.181	8.7779	1460	0.0001	0.0937	0.00128
36	0.1857	2.062	2.67	0.000772	0.577	0.0006	27.983	0.164	7.9534	1460	0.0001	0.0937	0.00128

Table D36. Laboratory data from test #36 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
36	0.00140	6E-05	0.0006	0.8119	0.4481	1875.3	89.635	0	10.365			
36	0.00140	6E-05	0.0006	0.8119	0.4481	1878.1	90.273	0	9.7268			
36	0.00140	3E-05	0.0006	0.8119	0.4481	1896.7	94.42	0	5.58			
36	0.00140	2E-05	0.0006	0.8119	0.4481	1903.8	96.015	0	3.9851			
36	0.00140	3E-05	0.0006	0.8119	0.4481	1901.7	95.536	0	4.4635			
36	0.00140	3E-05	0.0006	0.8119	0.4481	1901	95.377	0	4.623			
36	0.00140	3E-05	0.0006	0.8119	0.4481	1901.7	95.536	0	4.4635			
36	0.00140	4E-05	0.0006	0.8119	0.4481	1890.3	92.985	0	7.0154			
36	0.00140	5E-05	0.0006	0.8119	0.4481	1886	92.028	0	7.9724	18	18	17
36	0.00140	-7E-05	0.0006	0.8119	0.4481	2015.3	92.028	19.773	-11.8	18	18	17
36	0.00140	-6E-05	0.0006	0.8119	0.4481	2003.2	92.028	17.916	-9.943	16	16	17

Table D37. Laboratory data from test #37

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
37	0.1857	2.062	2.67	0.000772	0.034	3E-05	1.6489	0	0	1460	0	0.0937	0.00128
37	0.1857	2.062	2.67	0.000772	0.174	0.0002	8.4384	0	0	1460	0	0.0937	0.00128
37	0.1857	2.062	2.67	0.000772	0.267	0.0003	12.949	0	0	1460	0	0.0937	0.00128
37	0.1857	2.062	2.67	0.000772	0.272	0.0003	13.191	0	0	1460	0	0.0937	0.00128
37	0.1857	2.062	2.67	0.000772	0.273	0.0003	13.24	0	0	1460	0	0.0937	0.00128
37	0.1857	2.062	2.67	0.000772	0.432	0.0004	20.951	0	0	1460	0	0.0937	0.00128
37	0.1857	2.062	2.67	0.000772	0.271	0.0003	13.143	0	0	1460	0	0.0937	0.00128
37	0.1857	2.062	2.67	0.000772	0.193	0.0002	9.3598	0	0	1460	0	0.0937	0.00128
37	0.1857	2.062	2.67	0.000772	0.213	0.0002	10.33	0	0	1460	0	0.0937	0.00128
37	0.1857	2.062	2.67	0.000772	0.166	0.0002	8.0504	0.181	8.7779	1460	0.0001	0.0937	0.00128
37	0.1857	2.062	2.67	0.000772	0.166	0.0002	8.0504	0.325	15.761	1460	0.0002	0.0937	0.00128
37	0.1857	2.062	2.67	0.000772	0.166	0.0002	8.0504	0.27	13.094	1460	0.0002	0.0937	0.00128
37	0.1857	2.062	2.67	0.000772	0.166	0.0002	8.0504	0.458	22.211	1460	0.0003	0.0937	0.00128
37	0.1857	2.062	2.67	0.000772	0.166	0.0002	8.0504	0.348	16.877	1460	0.0002	0.0937	0.00128
37	0.1857	2.062	2.67	0.000772	0.166	0.0002	8.0504	0.279	13.531	1460	0.0002	0.0937	0.00128

Table D37. Laboratory data from test #37 (continued)

Tes t#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
37	0.00140	0.0006	0.0006	0.8119	0.4481	1497.9	5.4228	0	94.57723			
37	0.00140	0.0005	0.0006	0.8119	0.4481	1598	27.752	0	72.24818			
37	0.00140	0.0004	0.0006	0.8119	0.4481	1664.4	42.585	0	57.4153			
37	0.00140	0.0004	0.0006	0.8119	0.4481	1668	43.382	0	56.61784			
37	0.00140	0.0004	0.0006	0.8119	0.4481	1668.7	43.542	0	56.45835			
37	0.00140	0.0002	0.0006	0.8119	0.4481	1782.4	68.901	0	31.09892			
37	0.00140	0.0004	0.0006	0.8119	0.4481	1667.3	43.223	0	56.77733			
37	0.00140	0.0004	0.0006	0.8119	0.4481	1611.6	30.782	0	69.2178			
37	0.00140	0.0004	0.0006	0.8119	0.4481	1625.8	33.972	0	66.02794			
37	0.00140	0.0003	0.0006	0.8119	0.4481	1721.6	26.476	19.773	53.75133	40	45	42.5
37	0.00140	0.0002	0.0006	0.8119	0.4481	1824.5	26.476	35.504	38.02049	24	12	36
37	0.00140	0.0003	0.0006	0.8119	0.4481	1785.2	26.476	29.495	44.0288	12	8	10
37	0.00140	0.0001	0.0006	0.8119	0.4481	1919.6	26.476	50.033	23.49131	10	5	7.5
37	0.00140	0.0002	0.0006	0.8119	0.4481	1841	26.476	38.016	35.50793	10	4	7
37	0.00140	0.0003	0.0006	0.8119	0.4481	1791.6	26.476	30.479	43.04562	9	4	6.5

Table D38. Laboratory data from test #38

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{ait+solids}$
38	0.1857	2.061	2.67	0.000772	0.124	0.0001	6.0165	0	0	1460	0	0.0937	0.00128
38	0.1857	2.061	2.67	0.000772	0.418	0.0004	20.281	0	0	1460	0	0.0937	0.00128
38	0.1857	2.061	2.67	0.000772	0.567	0.0006	27.511	0	0	1460	0	0.0937	0.00128
38	0.1857	2.061	2.67	0.000772	0.571	0.0006	27.705	0	0	1460	0	0.0937	0.00128
38	0.1857	2.061	2.67	0.000772	0.581	0.0006	28.19	0	0	1460	0	0.0937	0.00128
38	0.1857	2.061	2.67	0.000772	0.457	0.0005	22.174	0	0	1460	0	0.0937	0.00128
38	0.1857	2.061	2.67	0.000772	0.389	0.0004	18.874	0	0	1460	0	0.0937	0.00128
38	0.1857	2.061	2.67	0.000772	0.236	0.0002	11.451	0	0	1460	0	0.0937	0.00128
38	0.1857	2.061	2.67	0.000772	0.236	0.0002	11.451	0	0	1460	0	0.0937	0.00128
38	0.1857	2.061	2.67	0.000772	0.236	0.0002	11.451	0.101	4.9005	1460	7E-05	0.0937	0.00128
38	0.1857	2.061	2.67	0.000772	0.236	0.0002	11.451	0.151	7.3265	1460	0.0001	0.0937	0.00128
38	0.1857	2.061	2.67	0.000772	0.236	0.0002	11.451	0.175	8.491	1460	0.0001	0.0937	0.00128
38	0.1857	2.061	2.67	0.000772	0.236	0.0002	11.451	0.176	8.5395	1460	0.0001	0.0937	0.00128
38	0.1857	2.061	2.67	0.000772	0.236	0.0002	11.451	0.179	8.6851	1460	0.0001	0.0937	0.00128
38	0.1857	2.061	2.67	0.000772	0.236	0.0002	11.451	0.111	5.3857	1460	8E-05	0.0937	0.00128

Table D38. Laboratory data from test #38 (continued)

Tes t#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
38	0.00140	0.0005	0.0006	0.8127	0.4483	1561.5	19.765	0	80.23465			
38	0.00140	0.0002	0.0006	0.8127	0.4483	1771.6	66.628	0	33.37163			
38	0.00140	6E-05	0.0006	0.8127	0.4483	1878.1	90.379	0	9.621321			
38	0.00140	6E-05	0.0006	0.8127	0.4483	1881	91.016	0	8.983729			
38	0.00140	5E-05	0.0006	0.8127	0.4483	1888.1	92.61	0	7.389748			
38	0.00140	0.0002	0.0006	0.8127	0.4483	1799.5	72.845	0	27.1551			
38	0.00140	0.0002	0.0006	0.8127	0.4483	1750.9	62.006	0	37.99417			
38	0.00140	0.0004	0.0006	0.8127	0.4483	1641.6	37.618	0	62.38207			
38	0.00140	0.0004	0.0006	0.8127	0.4483	1641.6	37.618	0	62.38207			
38	0.00140	0.0003	0.0006	0.8127	0.4483	1713.8	37.618	11.027	51.35522	15	10	12.5
38	0.00140	0.0003	0.0006	0.8127	0.4483	1749.5	37.618	16.486	45.89638	14	10	12
38	0.00140	0.0003	0.0006	0.8127	0.4483	1766.6	37.618	19.106	43.27614	14	10	12
38	0.00140	0.0003	0.0006	0.8127	0.4483	1767.3	37.618	19.215	43.16696	14	10	12
38	0.00140	0.0003	0.0006	0.8127	0.4483	1769.5	37.618	19.543	42.83943	14	10	12
38	0.00140	0.0003	0.0006	0.8127	0.4483	1720.9	37.618	12.119	50.26345	14	10	12

Table D39. Laboratory data from test #39

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{ait+solids}$
39	0.1857	2.065	2.67	0.000773	0.058	6E-05	2.8087	0	0	1460	0	0.0937	0.00128
39	0.1857	2.065	2.67	0.000773	0.316	0.0003	15.303	0	0	1460	0	0.0937	0.00128
39	0.1857	2.065	2.67	0.000773	0.403	0.0004	19.516	0	0	1460	0	0.0937	0.00128
39	0.1857	2.065	2.67	0.000773	0.575	0.0006	27.845	0	0	1460	0	0.0937	0.00128
39	0.1857	2.065	2.67	0.000773	0.577	0.0006	27.942	0	0	1460	0	0.0937	0.00128
39	0.1857	2.065	2.67	0.000773	0.586	0.0006	28.378	0	0	1460	0	0.0937	0.00128
39	0.1857	2.065	2.67	0.000773	0.338	0.0003	16.368	0	0	1460	0	0.0937	0.00128
39	0.1857	2.065	2.67	0.000773	0.278	0.0003	13.462	0	0	1460	0	0.0937	0.00128
39	0.1857	2.065	2.67	0.000773	0.251	0.0003	12.155	0	0	1460	0	0.0937	0.00128
39	0.1857	2.065	2.67	0.000773	0.253	0.0003	12.252	0	0	1460	0	0.0937	0.00128
39	0.1857	2.065	2.67	0.000773	0.236	0.0002	11.429	0.09	4.3584	1460	6E-05	0.0937	0.00128
39	0.1857	2.065	2.67	0.000773	0.236	0.0002	11.429	0.115	5.569	1460	8E-05	0.0937	0.00128
39	0.1857	2.065	2.67	0.000773	0.236	0.0002	11.429	0.122	5.908	1460	8E-05	0.0937	0.00128
39	0.1857	2.065	2.67	0.000773	0.236	0.0002	11.429	0.096	4.6489	1460	7E-05	0.0937	0.00128

Table D39. Laboratory data from test #39 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
39	0.00140	0.0006	0.0006	0.8092	0.4473	1517.2	9.2672	0	90.733			
39	0.00140	0.0003	0.0006	0.8092	0.4473	1701.6	50.49	0	49.51			
39	0.00140	0.0002	0.0006	0.8092	0.4473	1763.8	64.391	0	35.609			
39	0.00140	5E-05	0.0006	0.8092	0.4473	1886.7	91.873	0	8.1267			
39	0.00140	5E-05	0.0006	0.8092	0.4473	1888.1	92.193	0	7.8072			
39	0.00140	4E-05	0.0006	0.8092	0.4473	1894.6	93.631	0	6.3692			
39	0.00140	0.0003	0.0006	0.8092	0.4473	1717.3	54.005	0	45.995			
39	0.00140	0.0003	0.0006	0.8092	0.4473	1674.4	44.419	0	55.581			
39	0.00140	0.0004	0.0006	0.8092	0.4473	1655.1	40.105	0	59.895			
39	0.00140	0.0004	0.0006	0.8092	0.4473	1656.6	40.424	0	59.576			
39	0.00140	0.0003	0.0006	0.8092	0.4473	1708.7	37.708	9.8494	52.443	15	14	14.5
39	0.00140	0.0003	0.0006	0.8092	0.4473	1726.6	37.708	12.585	49.707	14	14	14
39	0.00140	0.0003	0.0006	0.8092	0.4473	1731.6	37.708	13.351	48.941	14	14	14
39	0.00140	0.0003	0.0006	0.8092	0.4473	1713	37.708	10.506	51.786	12	13	12.5

Table D40. Laboratory data from test #40

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
40	0.1842	2.059	2.67	0.000771	0.038	4E-05	1.8456	0	0	1460	0	0.0937	0.00127
40	0.1842	2.059	2.67	0.000771	0.078	8E-05	3.7882	0	0	1460	0	0.0937	0.00127
40	0.1842	2.059	2.67	0.000771	0.397	0.0004	19.281	0	0	1460	0	0.0937	0.00127
40	0.1842	2.059	2.67	0.000771	0.565	0.0006	27.441	0	0	1460	0	0.0937	0.00127
40	0.1842	2.059	2.67	0.000771	0.57	0.0006	27.683	0	0	1460	0	0.0937	0.00127
40	0.1842	2.059	2.67	0.000771	0.238	0.0002	11.559	0	0	1460	0	0.0937	0.00127
40	0.1842	2.059	2.67	0.000771	0.175	0.0002	8.4993	0	0	1460	0	0.0937	0.00127
40	0.1842	2.059	2.67	0.000771	0.204	0.0002	9.9077	0	0	1460	0	0.0937	0.00127
40	0.1842	2.059	2.67	0.000771	0.189	0.0002	9.1792	0	0	1460	0	0.0937	0.00127
40	0.1842	2.059	2.67	0.000771	0.189	0.0002	9.1792	0.2	9.7135	1460	0.0001	0.0937	0.00127
40	0.1842	2.059	2.67	0.000771	0.189	0.0002	9.1792	0.214	10.393	1460	0.0001	0.0937	0.00127
40	0.1842	2.059	2.67	0.000771	0.189	0.0002	9.1792	0.243	11.802	1460	0.0002	0.0937	0.00127
40	0.1842	2.059	2.67	0.000771	0.189	0.0002	9.1792	0.272	13.21	1460	0.0002	0.0937	0.00127

Table D40. Laboratory data from test #40 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
40	0.00140	0.0006	0.0006	0.8145	0.4489	1498.6	6.0499	0	93.95			
40	0.00140	0.0006	0.0006	0.8145	0.4489	1527.2	12.418	0	87.582			
40	0.00140	0.0002	0.0006	0.8145	0.4489	1755.2	63.206	0	36.794			
40	0.00140	6E-05	0.0006	0.8145	0.4489	1875.3	89.952	0	10.048			
40	0.00140	6E-05	0.0006	0.8145	0.4489	1878.8	90.749	0	9.2515			
40	0.00140	0.0004	0.0006	0.8145	0.4489	1641.6	37.891	0	62.109			
40	0.00140	0.0005	0.0006	0.8145	0.4489	1596.5	27.861	0	72.139			
40	0.00140	0.0004	0.0006	0.8145	0.4489	1617.3	32.478	0	67.522			
40	0.00140	0.0004	0.0006	0.8145	0.4489	1606.6	30.09	0	69.91			
40	0.00140	0.0003	0.0006	0.8145	0.4489	1749.5	30.09	21.809	48.1	10	10	10
40	0.00140	0.0003	0.0006	0.8145	0.4489	1759.5	30.09	23.336	46.574	10	10	10
40	0.00140	0.0003	0.0006	0.8145	0.4489	1780.2	30.09	26.498	43.411	10	10	10
40	0.00140	0.0003	0.0006	0.8145	0.4489	1800.9	30.09	29.661	40.249	10	10	10

Table D41. Laboratory data from test #41

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
41	0.18098	2.05	2.67	0.000768	0.063	6E-05	3.0732	0	0	1460	0	0.0937	0.00125
41	0.1842	2.05	2.67	0.000768	0.341	0.0003	16.634	0	0	1460	0	0.0937	0.00127
41	0.1842	2.05	2.67	0.000768	0.551	0.0006	26.878	0	0	1460	0	0.0937	0.00127
41	0.1842	2.05	2.67	0.000768	0.323	0.0003	15.756	0	0	1460	0	0.0937	0.00127
41	0.1842	2.05	2.67	0.000768	0.263	0.0003	12.829	0	0	1460	0	0.0937	0.00127
41	0.1842	2.05	2.67	0.000768	0.221	0.0002	10.78	0	0	1460	0	0.0937	0.00127
41	0.1842	2.05	2.67	0.000768	0.224	0.0002	10.927	0	0	1460	0	0.0937	0.00127
41	0.1842	2.05	2.67	0.000768	0.204	0.0002	9.9512	0.017	0.8293	1460	1E-05	0.0937	0.00127
41	0.1842	2.05	2.67	0.000768	0.189	0.0002	9.2195	0.048	2.3415	1460	3E-05	0.0937	0.00127
41	0.1842	2.05	2.67	0.000768	0.189	0.0002	9.2195	0.076	3.7073	1460	5E-05	0.0937	0.00127
41	0.1842	2.05	2.67	0.000768	0.189	0.0002	9.2195	0.098	4.7805	1460	7E-05	0.0937	0.00127
41	0.1842	2.05	2.67	0.000768	0.189	0.0002	9.2195	0.153	7.4634	1460	0.0001	0.0937	0.00127
41	0.1842	2.05	2.67	0.000768	0.189	0.0002	9.2195	0.186	9.0732	1460	0.0001	0.0937	0.00127
41	0.1842	2.05	2.67	0.000768	0.189	0.0002	9.2195	0.149	7.2683	1460	0.0001	0.0937	0.00127

Table D41. Laboratory data from test #41 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
41	0.00140	0.00057	0.0006	0.8225	0.4513	1510.1	9.9766	0	90.023			
41	0.00140	0.00029	0.0006	0.8225	0.4513	1708.7	54	0	46			
41	0.00140	0.00008	0.0006	0.8225	0.4513	1858.8	87.255	0	12.745			
41	0.00140	0.00031	0.0006	0.8225	0.4513	1695.9	51.15	0	48.85			
41	0.00140	0.00037	0.0006	0.8225	0.4513	1653	41.648	0	58.352			
41	0.00140	0.00041	0.0006	0.8225	0.4513	1623	34.997	0	65.003			
41	0.00140	0.00041	0.0006	0.8225	0.4513	1625.1	35.472	0	64.528			
41	0.00140	0.00042	0.0006	0.8225	0.4513	1623	32.305	1.8439	65.851	9	9	9
41	0.00140	0.00041	0.0006	0.8225	0.4513	1634.4	29.93	5.2063	64.864	10	10	10
41	0.00140	0.00039	0.0006	0.8225	0.4513	1654.4	29.93	8.2433	61.827	7	7	7
41	0.00140	0.00038	0.0006	0.8225	0.4513	1670.2	29.93	10.63	59.441	8	8	8
41	0.00140	0.00034	0.0006	0.8225	0.4513	1709.5	29.93	16.595	53.475	8	8	8
41	0.00140	0.00032	0.0006	0.8225	0.4513	1733	29.93	20.174	49.896	10	10	10
41	0.00140	0.00034	0.0006	0.8225	0.4513	1706.6	29.93	16.161	53.909	10	10	10

Table D42. Laboratory data from test #42

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{ait+solids}$
42	0.18098	1.995	2.67	0.000747	0.177	0.0002	8.8722	0	0	1460	0	0.0937	0.00125
42	0.18098	1.995	2.67	0.000747	0.338	0.0003	16.942	0	0	1460	0	0.0937	0.00125
42	0.18098	1.995	2.67	0.000747	523	0.523	26216	0	0	1460	0	0.0937	0.00125
42	0.18098	1.995	2.67	0.000747	0.526	0.0005	26.366	0	0	1460	0	0.0937	0.00125
42	0.18098	1.995	2.67	0.000747	0.501	0.0005	25.113	0	0	1460	0	0.0937	0.00125
42	0.18098	1.995	2.67	0.000747	0.48	0.0005	24.06	0	0	1460	0	0.0937	0.00125
42	0.18098	1.995	2.67	0.000747	0.4	0.0004	20.05	0	0	1460	0	0.0937	0.00125
42	0.18098	1.995	2.67	0.000747	0.288	0.0003	14.436	0	0	1460	0	0.0937	0.00125
42	0.18098	1.995	2.67	0.000747	0.242	0.0002	12.13	0	0	1460	0	0.0937	0.00125
42	0.18098	1.995	2.67	0.000747	0.207	0.0002	10.376	0	0	1460	0	0.0937	0.00125
42	0.18098	1.995	2.67	0.000747	0.207	0.0002	10.376	0.203	10.175	1460	0.0001	0.0937	0.00125
42	0.18098	1.995	2.67	0.000747	0.207	0.0002	10.376	0.213	10.677	1460	0.0001	0.0937	0.00125
42	0.18098	1.995	2.67	0.000747	0.207	0.0002	10.376	0.279	13.985	1460	0.0002	0.0937	0.00125
42	0.18098	1.995	2.67	0.000747	0.207	0.0002	10.376	0.241	12.08	1460	0.0002	0.0937	0.0012

Table D42. Laboratory data from test #42 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
42	0.00140	0.0005	0.0007	0.8727	0.466	1552.2	27.144	0	72.856			
42	0.00140	0.0003	0.0007	0.8727	0.466	1667.3	51.834	0	48.166			
42	0.00140	-0.522	0.0007	0.8727	0.466	375192	80205	0	-80105			
42	0.00140	0.0001	0.0007	0.8727	0.466	1801.7	80.665	0	19.335			
42	0.00140	0.0002	0.0007	0.8727	0.466	1783.8	76.831	0	23.169			
42	0.00140	0.0002	0.0007	0.8727	0.466	1768.8	73.611	0	26.389			
42	0.00140	0.0003	0.0007	0.8727	0.466	1711.6	61.342	0	38.658			
42	0.00140	0.0004	0.0007	0.8727	0.466	1631.6	44.166	0	55.834			
42	0.00140	0.0004	0.0007	0.8727	0.466	1598.7	37.112	0	62.888			
42	0.00140	0.0004	0.0007	0.8727	0.466	1573.7	31.745	0	68.255			
42	0.00140	0.0003	0.0007	0.8727	0.466	1718.8	31.745	21.323	46.933	10	6	8
42	0.00140	0.0003	0.0007	0.8727	0.466	1725.9	31.745	22.373	45.882	8	4	6
42	0.00140	0.0003	0.0007	0.8727	0.466	1773.1	31.745	29.306	38.95	12	10	11
42	0.00140	0.0003	0.0007	0.8727	0.466	1745.9	31.745	25.314	42.941	14	12	13

Table D43. Laboratory data from test #43

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{ait+solids}$
43	0.18256	2.019	2.67	0.000756	0.251	0.0003	12.432	0	0	1460	0	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.308	0.0003	15.255	0	0	1460	0	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.535	0.0005	26.498	0	0	1460	0	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.538	0.0005	26.647	0	0	1460	0	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.557	0.0006	27.588	0	0	1460	0	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.566	0.0006	28.034	0	0	1460	0	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.396	0.0004	19.614	0	0	1460	0	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.281	0.0003	13.918	0	0	1460	0	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.254	0.0003	12.58	0	0	1460	0	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.239	0.0002	11.838	0	0	1460	0	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.196	0.0002	9.7078	0	0	1460	0	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.196	0.0002	9.7078	0.217	10.748	1460	0.0001	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.196	0.0002	9.7078	0.141	6.9837	1460	1E-04	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.196	0.0002	9.7078	0.143	7.0827	1460	1E-04	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.196	0.0002	9.7078	0.453	22.437	1460	0.0003	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.196	0.0002	9.7078	0.459	22.734	1460	0.0003	0.0937	0.00126
43	0.18256	2.019	2.67	0.000756	0.196	0.0002	9.7078	0.354	17.533	1460	0.0002	0.0937	0.00126

Table D43. Laboratory data from test #43 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
43	0.00140	0.0004	0.0006	0.8504	0.4596	1622.3	39.03	0	60.97			
43	0.00140	0.0003	0.0006	0.8504	0.4596	1663	47.894	0	52.106			
43	0.00140	0.0001	0.0006	0.8504	0.4596	1825.2	83.192	0	16.808			
43	0.00140	0.0001	0.0006	0.8504	0.4596	1827.4	83.658	0	16.342			
43	0.00140	9E-05	0.0006	0.8504	0.4596	1841	86.613	0	13.387			
43	0.00140	8E-05	0.0006	0.8504	0.4596	1847.4	88.012	0	11.988			
43	0.00140	0.0002	0.0006	0.8504	0.4596	1725.9	61.578	0	38.422			
43	0.00140	0.0004	0.0006	0.8504	0.4596	1643.7	43.695	0	56.305			
43	0.00140	0.0004	0.0006	0.8504	0.4596	1624.4	39.497	0	60.503			
43	0.00140	0.0004	0.0006	0.8504	0.4596	1613.7	37.164	0	62.836			
43	0.00140	0.0004	0.0006	0.8504	0.4596	1583	30.478	0	69.522			
43	0.00140	0.0003	0.0006	0.8504	0.4596	1738	30.478	23.112	46.41			
43	0.00140	0.0004	0.0006	0.8504	0.4596	1683.7	30.478	15.017	54.505	32	40	36
43	0.00140	0.0003	0.0006	0.8504	0.4596	1685.2	30.478	15.23	54.292	42	49	45.5
43	0.00140	0.0001	0.0006	0.8504	0.4596	1906.7	30.478	48.247	21.275	12	9	10.5
43	0.00140	0.0001	0.0006	0.8504	0.4596	1911	30.478	48.886	20.636	12	12	12
43	0.00140	0.0002	0.0006	0.8504	0.4596	1836	30.478	37.703	31.819	12	12	12

Table D44. Laboratory data from test #44

Te st#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
44	0.18415	1.991	2.67	0.000746	0.079	8E-05	3.9679	0	0	1460	0	0.0937	0.00127
44	0.18415	1.991	2.67	0.000746	0.317	0.0003	15.922	0	0	1460	0	0.0937	0.00127
44	0.18415	1.991	2.67	0.000746	0.535	0.0005	26.871	0	0	1460	0	0.0937	0.00127
44	0.18415	1.991	2.67	0.000746	0.549	0.0005	27.574	0	0	1460	0	0.0937	0.00127
44	0.18415	1.991	2.67	0.000746	0.551	0.0006	27.675	0	0	1460	0	0.0937	0.00127
44	0.18415	1.991	2.67	0.000746	0.27	0.0003	13.561	0	0	1460	0	0.0937	0.00127
44	0.18415	1.991	2.67	0.000746	0.186	0.0002	9.342	0	0	1460	0	0.0937	0.00127
44	0.18415	1.991	2.67	0.000746	0.159	0.0002	7.9859	0	0	1460	0	0.0937	0.00127
44	0.18415	1.991	2.67	0.000746	0.16	0.0002	8.0362	0	0	1460	0	0.0937	0.00127
44	0.18415	1.991	2.67	0.000746	0.16	0.0002	8.0362	0.097	4.8719	1460	7E-05	0.0937	0.00127
44	0.18415	1.991	2.67	0.000746	0.16	0.0002	8.0362	0.305	15.319	1460	0.0002	0.0937	0.00127
44	0.18415	1.991	2.67	0.000746	0.16	0.0002	8.0362	0.32	16.072	1460	0.0002	0.0937	0.00127
44	0.18415	1.991	2.67	0.000746	0.16	0.0002	8.0362	0.196	9.8443	1460	0.0001	0.0937	0.00127

Table D44. Laboratory data from test #44 (continued)

Tes t#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
44	0.00140	0.0006	0.0007	0.8765	0.4671	1479.3	12.087	0	87.913			
44	0.00140	0.0003	0.0007	0.8765	0.4671	1649.4	48.502	0	51.498			
44	0.00140	0.0001	0.0007	0.8765	0.4671	1805.2	81.857	0	18.143			
44	0.00140	0.0001	0.0007	0.8765	0.4671	1815.2	83.999	0	16.001			
44	0.00140	0.0001	0.0007	0.8765	0.4671	1816.7	84.305	0	15.695			
44	0.00140	0.0004	0.0007	0.8765	0.4671	1615.8	41.311	0	58.689			
44	0.00140	0.0005	0.0007	0.8765	0.4671	1555.8	28.459	0	71.541			
44	0.00140	0.0005	0.0007	0.8765	0.4671	1536.5	24.328	0	75.672			
44	0.00140	0.0005	0.0007	0.8765	0.4671	1537.2	24.481	0	75.519			
44	0.00140	0.0004	0.0007	0.8765	0.4671	1606.6	24.481	10.165	65.354	12	11	11.5
44	0.00140	0.0003	0.0007	0.8765	0.4671	1755.2	24.481	31.963	43.556	10	9	9.5
44	0.00140	0.0003	0.0007	0.8765	0.4671	1765.9	24.481	33.535	41.984	10	9	9.5
44	0.00140	0.0004	0.0007	0.8765	0.4671	1677.3	24.481	20.54	54.979	10	10	10

Table D45. Laboratory data from test #45

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
45	0.18415	1.97	2.67	0.000738	0.164	0.0002	8.3249	0	0	1460	0	0.0937	0.00127
45	0.18415	1.97	2.67	0.000738	0.335	0.0003	17.005	0	0	1460	0	0.0937	0.00127
45	0.18415	1.97	2.67	0.000738	0.52	0.0005	26.396	0	0	1460	0	0.0937	0.00127
45	0.18415	1.97	2.67	0.000738	0.573	0.0006	29.086	0	0	1460	0	0.0937	0.00127
45	0.18415	1.97	2.67	0.000738	0.582	0.0006	29.543	0	0	1460	0	0.0937	0.00127
45	0.18415	1.97	2.67	0.000738	0.291	0.0003	14.772	0	0	1460	0	0.0937	0.00127
45	0.18415	1.97	2.67	0.000738	0.226	0.0002	11.472	0	0	1460	0	0.0937	0.00127
45	0.18415	1.97	2.67	0.000738	0.178	0.0002	9.0355	0	0	1460	0	0.0937	0.00127
45	0.18415	1.97	2.67	0.000738	0.161	0.0002	8.1726	0	0	1460	0	0.0937	0.00127
45	0.18415	1.97	2.67	0.000738	0.161	0.0002	8.1726	0.172	8.731	1460	0.0001	0.0937	0.00127
45	0.18415	1.97	2.67	0.000738	0.161	0.0002	8.1726	0.249	12.64	1460	0.0002	0.0937	0.00127
45	0.18415	1.97	2.67	0.000738	0.161	0.0002	8.1726	0.284	14.416	1460	0.0002	0.0937	0.00127
45	0.18415	1.97	2.67	0.000738	0.161	0.0002	8.1726	0.278	14.112	1460	0.0002	0.0937	0.00127
45	0.18415	1.97	2.67	0.000738	0.161	0.0002	8.1726	0.221	11.218	1460	0.0002	0.0937	0.00127
45	0.18415	1.97	2.67	0.000738	0.161	0.0002	8.1726	0.137	6.9543	1460	9E-05	0.0937	0.00127

Table D45. Laboratory data from test #45 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
45	0.00140	0.0005	0.0007	0.8965	0.4727	1525.1	24.794	0	75.206			
45	0.00140	0.0003	0.0007	0.8965	0.4727	1647.3	50.647	0	49.353			
45	0.00140	0.0001	0.0007	0.8965	0.4727	1779.5	78.616	0	21.384			
45	0.00140	9E-05	0.0007	0.8965	0.4727	1817.4	86.629	0	13.371			
45	0.00140	8E-05	0.0007	0.8965	0.4727	1823.8	87.989	0	12.011			
45	0.00140	0.0004	0.0007	0.8965	0.4727	1615.8	43.995	0	56.005			
45	0.00140	0.0004	0.0007	0.8965	0.4727	1569.4	34.168	0	65.832			
45	0.00140	0.0005	0.0007	0.8965	0.4727	1535.1	26.911	0	73.089			
45	0.00140	0.0005	0.0007	0.8965	0.4727	1522.9	24.341	0	75.659			
45	0.00140	0.0004	0.0007	0.8965	0.4727	1645.9	24.341	17.811	57.848	9	5	7
45	0.00140	0.0003	0.0007	0.8965	0.4727	1700.9	24.341	25.784	49.875	9	6	7.5
45	0.00140	0.0003	0.0007	0.8965	0.4727	1725.9	24.341	29.409	46.251	10	7	8.5
45	0.00140	0.0003	0.0007	0.8965	0.4727	1721.6	24.341	28.787	46.872	10	7	8.5
45	0.00140	0.0003	0.0007	0.8965	0.4727	1680.9	24.341	22.885	52.774	10	7	8.5
45	0.00140	0.0004	0.0007	0.8965	0.4727	1620.8	24.341	14.187	61.473	10	7	8.5

Table D46. Laboratory data from test #46

Te st#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
46	0.18098	2.03	2.67	0.00076	0.187	0.0002	9.2118	0	0	1460	0	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.294	0.0003	14.483	0	0	1460	0	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.577	0.0006	28.424	0	0	1460	0	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.602	0.0006	29.655	0	0	1460	0	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.611	0.0006	30.099	0	0	1460	0	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.608	0.0006	29.951	0	0	1460	0	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.475	0.0005	23.399	0	0	1460	0	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.364	0.0004	17.931	0	0	1460	0	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.315	0.0003	15.517	0	0	1460	0	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.299	0.0003	14.729	0	0	1460	0	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.283	0.0003	13.941	0	0	1460	0	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.282	0.0003	13.892	0	0	1460	0	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.282	0.0003	13.892	0.266	13.103	1460	0.0002	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.161	0.0002	7.931	0.252	12.414	1460	0.0002	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.161	0.0002	7.931	0.254	12.512	1460	0.0002	0.0937	0.00125
46	0.18098	2.03	2.67	0.00076	0.161	0.0002	7.931	0.247	12.167	1460	0.0002	0.0937	0.00125

Table D46. Laboratory data from test #46 (continued)

Tes t#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat - w$	$Sat - N$	$Sat - A$	$Sn - 1$	$Sn - 2$	Avg Sn
46	0.00140	0.0005	0.0006	0.8404	0.4566	1584.4	29.266	0	70.734			
46	0.00140	0.0003	0.0006	0.8404	0.4566	1660.9	46.011	0	53.989			
46	0.00140	6E-05	0.0006	0.8404	0.4566	1863.1	90.301	0	9.6985			
46	0.00140	4E-05	0.0006	0.8404	0.4566	1881	94.214	0	5.786			
46	0.00140	3E-05	0.0006	0.8404	0.4566	1887.4	95.623	0	4.3775			
46	0.00140	3E-05	0.0006	0.8404	0.4566	1885.3	95.153	0	4.847			
46	0.00140	0.0002	0.0006	0.8404	0.4566	1790.2	74.338	0	25.662			
46	0.00140	0.0003	0.0006	0.8404	0.4566	1710.9	56.967	0	43.033			
46	0.00140	0.0003	0.0006	0.8404	0.4566	1675.9	49.298	0	50.702			
46	0.00140	0.0003	0.0006	0.8404	0.4566	1664.4	46.794	0	53.206			
46	0.00140	0.0004	0.0006	0.8404	0.4566	1653	44.29	0	55.71			
46	0.00140	0.0004	0.0006	0.8404	0.4566	1652.3	44.133	0	55.867	54	52	53
46	0.00140	0.0002	0.0006	0.8404	0.4566	1842.4	44.133	28.513	27.353	14	14	14
46	0.00140	0.0003	0.0006	0.8404	0.4566	1745.9	25.197	27.013	47.791	9	8	8.5
46	0.00140	0.0003	0.0006	0.8404	0.4566	1747.3	25.197	27.227	47.576	9	9	9
46	0.00140	0.0003	0.0006	0.8404	0.4566	1742.3	25.197	26.477	48.327	9	9	9

Table D47. Laboratory data from test #47

est #	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
47	0.18336	2.026	2.67	0.000759	0.298	0.0003	14.709	0	0	1460	0	0.0937	0.00126
47	0.18336	2.026	2.67	0.000759	0.574	0.0006	28.332	0	0	1460	0	0.0937	0.00126
47	0.18336	2.026	2.67	0.000759	0.602	0.0006	29.714	0	0	1460	0	0.0937	0.00126
47	0.18336	2.026	2.67	0.000759	0.606	0.0006	29.911	0	0	1460	0	0.0937	0.00126
47	0.18336	2.026	2.67	0.000759	0.52	0.0005	25.666	0	0	1460	0	0.0937	0.00126
47	0.18336	2.026	2.67	0.000759	0.367	0.0004	18.115	0	0	1460	0	0.0937	0.00126
47	0.18336	2.026	2.67	0.000759	0.337	0.0003	16.634	0	0	1460	0	0.0937	0.00126
47	0.18336	2.026	2.67	0.000759	0.315	0.0003	15.548	0	0	1460	0	0.0937	0.00126
47	0.18336	2.026	2.67	0.000759	0.242	0.0002	11.945	0	0	1460	0	0.0937	0.00126
47	0.18336	2.026	2.67	0.000759	0.303	0.0003	14.956	0	0	1460	0	0.0937	0.00126
47	0.18336	2.026	2.67	0.000759	0.232	0.0002	11.451	0	0	1460	0	0.0937	0.00126
47	0.18336	2.026	2.67	0.000759	0.244	0.0002	12.043	0	0	1460	0	0.0937	0.00126
47	0.18336	2.026	2.67	0.000759	0.244	0.0002	12.043	0.38	18.756	1460	0.0003	0.0937	0.00126
47	0.18336	2.026	2.67	0.000759	0.244	0.0002	12.043	0.383	18.904	1460	0.0003	0.0937	0.00126
47	0.18336	2.026	2.67	0.000759	0.244	0.0002	12.043	0.332	16.387	1460	0.0002	0.0937	0.00126

Table D47. Laboratory data from test #47 (continued)

Tes t#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat - w$	$Sat - N$	$Sat - A$	$Sn - 1$	$Sn - 2$	$Avg\ Sn$
47	0.00140	0.0003	0.0006	0.8441	0.4577	1660.9	46.528	0	53.472			
47	0.00140	7E-05	0.0006	0.8441	0.4577	1858.1	89.622	0	10.378			
47	0.00140	4E-05	0.0006	0.8441	0.4577	1878.1	93.994	0	6.0064			
47	0.00140	3E-05	0.0006	0.8441	0.4577	1881	94.618	0	5.3818			
47	0.00140	0.0001	0.0006	0.8441	0.4577	1819.5	81.191	0	18.809			
47	0.00140	0.0003	0.0006	0.8441	0.4577	1710.2	57.302	0	42.698			
47	0.00140	0.0003	0.0006	0.8441	0.4577	1688.7	52.618	0	47.382			
47	0.00140	0.0003	0.0006	0.8441	0.4577	1673	49.183	0	50.817			
47	0.00140	0.0004	0.0006	0.8441	0.4577	1620.8	37.785	0	62.215			
47	0.00140	0.0003	0.0006	0.8441	0.4577	1664.4	47.309	0	52.691			
47	0.00140	0.0004	0.0006	0.8441	0.4577	1613.7	36.223	0	63.777			
47	0.00140	0.0004	0.0006	0.8441	0.4577	1622.3	38.097	0	61.903			
47	0.00140	0.0001	0.0006	0.8441	0.4577	1893.8	38.097	40.638	21.265	17	18	17.5
47	0.00140	0.0001	0.0006	0.8441	0.4577	1896	38.097	40.959	20.944	18	18	18
47	0.00140	0.0002	0.0006	0.8441	0.4577	1859.5	38.097	35.505	26.398	22	22	22

Table D48. Laboratory data from test #48

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
48	0.18733	2.055	2.67	0.00077	0.007	7E-06	0.3406	0	0	1460	0	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.078	8E-05	3.7956	0	0	1460	0	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.304	0.0003	14.793	0	0	1460	0	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.514	0.0005	25.012	0	0	1460	0	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.561	0.0006	27.299	0	0	1460	0	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.566	0.0006	27.543	0	0	1460	0	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.571	0.0006	27.786	0	0	1460	0	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.355	0.0004	17.275	0	0	1460	0	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.307	0.0003	14.939	0	0	1460	0	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.274	0.0003	13.333	0	0	1460	0	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.265	0.0003	12.895	0	0	1460	0	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.248	0.0002	12.068	0	0	1460	0	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.248	0.0002	12.068	0.052	2.5304	1460	4E-05	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.248	0.0002	12.068	0.114	5.5474	1460	8E-05	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.248	0.0002	12.068	0.357	17.372	1460	0.0002	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.248	0.0002	12.068	0.362	17.616	1460	0.0002	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.248	0.0002	12.068	0.365	17.762	1460	0.0003	0.0937	0.00129
48	0.18733	2.055	2.67	0.00077	0.248	0.0002	12.068	0.371	18.054	1460	0.0003	0.0937	0.00129

Table D48. Laboratory data from test #48 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat - w$	$Sat - N$	$Sat - A$	$Sn - 1$	$Sn - 2$	Avg Sn
48	0.00140	0.0006	0.0006	0.818	0.45	1473.6	1.1118	0	98.888			
48	0.00140	0.0006	0.0006	0.818	0.45	1524.4	12.389	0	87.611			
48	0.00140	0.0003	0.0006	0.818	0.45	1685.9	48.284	0	51.716			
48	0.00140	0.0001	0.0006	0.818	0.45	1836	81.638	0	18.362			
48	0.00140	7E-05	0.0006	0.818	0.45	1869.5	89.103	0	10.897			
48	0.00140	6E-05	0.0006	0.818	0.45	1873.1	89.897	0	10.103			
48	0.00140	6E-05	0.0006	0.818	0.45	1876.7	90.691	0	9.3086			
48	0.00140	0.0003	0.0006	0.818	0.45	1722.3	56.384	0	43.616			
48	0.00140	0.0003	0.0006	0.818	0.45	1688	48.761	0	51.239			
48	0.00140	0.0004	0.0006	0.818	0.45	1664.4	43.519	0	56.481			
48	0.00140	0.0004	0.0006	0.818	0.45	1658	42.09	0	57.91			
48	0.00140	0.0004	0.0006	0.818	0.45	1645.9	39.39	0	60.61			
48	0.00140	0.0003	0.0006	0.818	0.45	1683	39.39	5.6569	54.953	44	44	44
48	0.00140	0.0003	0.0006	0.818	0.45	1727.3	39.39	12.402	48.209	45	42	43.5
48	0.00140	0.0001	0.0006	0.818	0.45	1901	39.39	38.837	21.773	20	13	16.5
48	0.00140	0.0001	0.0006	0.818	0.45	1904.6	39.39	39.381	21.229	9	4	6.5
48	0.00140	0.0001	0.0006	0.818	0.45	1906.7	39.39	39.707	20.903	4	1	2.5
48	0.00140	0.0001	0.0006	0.818	0.45	1911	39.39	40.36	20.25	6	4	5

Table D49. Laboratory data from test #49

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
49	0.18733	2.048	2.67	0.000767	0.544	0.0005	26.563	0	0	1460	0	0.0937	0.00129
49	0.18733	2.048	2.67	0.000767	0.571	0.0006	27.881	0	0	1460	0	0.0937	0.00129
49	0.18733	2.048	2.67	0.000767	0.57	0.0006	27.832	0	0	1460	0	0.0937	0.00129
49	0.18733	2.048	2.67	0.000767	0.372	0.0004	18.164	0	0	1460	0	0.0937	0.00129
49	0.18733	2.048	2.67	0.000767	0.316	0.0003	15.43	0	0	1460	0	0.0937	0.00129
49	0.18733	2.048	2.67	0.000767	0.294	0.0003	14.355	0	0	1460	0	0.0937	0.00129
49	0.18733	2.048	2.67	0.000767	0.28	0.0003	13.672	0	0	1460	0	0.0937	0.00129
49	0.18733	2.048	2.67	0.000767	0.264	0.0003	12.891	0	0	1460	0	0.0937	0.00129
49	0.18733	2.048	2.67	0.000767	0.196	0.0002	9.5703	0	0	1460	0	0.0937	0.00129
49	0.18733	2.048	2.67	0.000767	0.202	0.0002	9.8633	0	0	1460	0	0.0937	0.00129
49	0.18733	2.048	2.67	0.000767	0.202	0.0002	9.8633	0	0	1460	0	0.0937	0.00129
49	0.18733	2.048	2.67	0.000767	0.202	0.0002	9.8633	0.274	13.379	1460	0.0002	0.0937	0.00129
49	0.18733	2.048	2.67	0.000767	0.202	0.0002	9.8633	0.295	14.404	1460	0.0002	0.0937	0.00129
49	0.18733	2.048	2.67	0.000767	0.202	0.0002	9.8633	0.288	14.063	1460	0.0002	0.0937	0.00129
49	0.18733	2.048	2.67	0.000767	0.202	0.0002	9.8633	0.266	12.988	1460	0.0002	0.0937	0.00129

Table D49. Laboratory data from test #49 (continued)

Tes t#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
49	0.00140	9E-05	0.0006	0.8242	0.4518	1852.4	86.045	0	13.955			
49	0.00140	6E-05	0.0006	0.8242	0.4518	1871.7	90.315	0	9.6847			
49	0.00140	6E-05	0.0006	0.8242	0.4518	1871	90.157	0	9.8428			
49	0.00140	0.0003	0.0006	0.8242	0.4518	1729.5	58.839	0	41.161			
49	0.00140	0.0003	0.0006	0.8242	0.4518	1689.5	49.982	0	50.018			
49	0.00140	0.0003	0.0006	0.8242	0.4518	1673.7	46.502	0	53.498			
49	0.00140	0.0004	0.0006	0.8242	0.4518	1663.7	44.288	0	55.712			
49	0.00140	0.0004	0.0006	0.8242	0.4518	1652.3	41.757	0	58.243			
49	0.00140	0.0004	0.0006	0.8242	0.4518	1603.7	31.001	0	68.999			
49	0.00140	0.0004	0.0006	0.8242	0.4518	1608	31.95	0	68.05			
49	0.00140	0.0004	0.0006	0.8242	0.4518	1608	31.95	0	68.05			
49	0.00140	0.0002	0.0006	0.8242	0.4518	1803.8	31.95	29.684	38.366	26	36	31
49	0.00140	0.0002	0.0006	0.8242	0.4518	1818.8	31.95	31.959	36.09	4	8	6
49	0.00140	0.0002	0.0006	0.8242	0.4518	1813.8	31.95	31.201	36.849	7	7	7
49	0.00140	0.0002	0.0006	0.8242	0.4518	1798.1	31.95	28.817	39.232	7	7	7

Table D50. Laboratory data from test #50

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{air+solids}$
50	0.18098	2.021	2.67	0.000757	0.431	0.0004	21.326	0	0	1460	0	0.0937	0.00125
50	0.18098	2.021	2.67	0.000757	0.596	0.0006	29.49	0	0	1460	0	0.0937	0.00125
50	0.18098	2.021	2.67	0.000757	0.609	0.0006	30.134	0	0	1460	0	0.0937	0.00125
50	0.18098	2.021	2.67	0.000757	0.609	0.0006	30.134	0	0	1460	0	0.0937	0.00125
50	0.18098	2.021	2.67	0.000757	0.37	0.0004	18.308	0	0	1460	0	0.0937	0.00125
50	0.18098	2.021	2.67	0.000757	0.329	0.0003	16.279	0	0	1460	0	0.0937	0.00125
50	0.18098	2.021	2.67	0.000757	0.307	0.0003	15.19	0	0	1460	0	0.0937	0.00125
50	0.18098	2.021	2.67	0.000757	0.284	0.0003	14.052	0	0	1460	0	0.0937	0.00125
50	0.18098	2.021	2.67	0.000757	0.284	0.0003	14.052	0.376	18.605	1460	0.0003	0.0937	0.00125
50	0.18098	2.021	2.67	0.000757	0.284	0.0003	14.052	0.378	18.704	1460	0.0003	0.0937	0.00125
50	0.18098	2.021	2.67	0.000757	0.284	0.0003	14.052	0.404	19.99	1460	0.0003	0.0937	0.00125
50	0.18098	2.021	2.67	0.000757	0.284	0.0003	14.052	0.309	15.289	1460	0.0002	0.0937	0.00125

Table D50. Laboratory data from test #50 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	$Avg\ Sn$
50	0.00140	0.00021	0.0006	0.8486	0.4591	1752.3	67.098	0	32.902			
50	0.00140	0.00005	0.0006	0.8486	0.4591	1870.3	92.786	0	7.2145			
50	0.00140	0.00003	0.0006	0.8486	0.4591	1879.6	94.809	0	5.1906			
50	0.00140	0.00003	0.0006	0.8486	0.4591	1879.6	94.809	0	5.1906			
50	0.00140	0.00027	0.0006	0.8486	0.4591	1708.7	57.602	0	42.398			
50	0.00140	0.00031	0.0006	0.8486	0.4591	1679.4	51.219	0	48.781			
50	0.00140	0.00034	0.0006	0.8486	0.4591	1663.7	47.794	0	52.206			
50	0.00140	0.00036	0.0006	0.8486	0.4591	1647.3	44.213	0	55.787			
50	0.00140	0.00010	0.0006	0.8486	0.4591	1916	44.213	40.093	15.694	34	32	33
50	0.00140	0.00010	0.0006	0.8486	0.4591	1917.4	44.213	40.306	15.48	17	15	16
50	0.00140	0.00008	0.0006	0.8486	0.4591	1936	44.213	43.079	12.708	12	10	11
50	0.00140	0.00015	0.0006	0.8486	0.4591	1868.1	44.213	32.949	22.838	13	10	11.5

Table D51. Laboratory data from test #51

Test#	H_s	M_s	G_S	V_s	ΔM_w	V_w	w	ΔM_n	w_n	ρ_n	V_n	$SoilD$	$V_{ait+solids}$
51	0.18415	2.045	2.67	0.000763	0.205	0.0002	10.024	0	0	1460	0	0.0937	0.00127
51	0.18415	2.045	2.67	0.000763	0.574	0.0006	28.068	0	0	1460	0	0.0937	0.00127
51	0.18415	2.045	2.67	0.000763	0.601	0.0006	29.389	0	0	1460	0	0.0937	0.00127
51	0.18415	2.045	2.67	0.000763	0.502	0.0005	24.548	0	0	1460	0	0.0937	0.00127
51	0.18415	2.045	2.67	0.000763	0.366	0.0004	17.897	0	0	1460	0	0.0937	0.00127
51	0.18415	2.045	2.67	0.000763	0.299	0.0003	14.621	0	0	1460	0	0.0937	0.00127
51	0.18415	2.045	2.67	0.000763	0.286	0.0003	13.985	0	0	1460	0	0.0937	0.00127
51	0.18415	2.045	2.67	0.000763	0.283	0.0003	13.839	0	0	1460	0	0.0937	0.00127
51	0.18415	2.045	2.67	0.000763	0.283	0.0003	13.839	0.287	14.034	1460	0.0002	0.0937	0.00127
51	0.18415	2.045	2.67	0.000763	0.283	0.0003	13.839	0.323	15.795	1460	0.0002	0.0937	0.00127
51	0.18415	2.045	2.67	0.000763	0.283	0.0003	13.839	0.361	17.653	1460	0.0002	0.0937	0.00127
51	0.18415	2.045	2.67	0.000763	0.283	0.0003	13.839	0.363	17.751	1460	0.0002	0.0937	0.00127
51	0.18415	2.045	2.67	0.000763	0.283	0.0003	13.839	0.364	17.8	1460	0.0002	0.0937	0.00127
51	0.18415	2.045	2.67	0.000763	0.283	0.0003	13.839	0.304	14.866	1460	0.0002	0.0937	0.00127

Table D51. Laboratory data from test#51 (continued)

Test#	V_{TOTAL}	V_{air}	V_{voids}	e	n	ρ_{wet}	$Sat-w$	$Sat-N$	$Sat-A$	$Sn-1$	$Sn-2$	Avg Sn
51	0.00140	0.0004	0.0006	0.8338	0.4547	1608	32.222	0	67.778			
51	0.00140	6E-05	0.0006	0.8338	0.4547	1871.7	90.222	0	9.7783			
51	0.00140	4E-05	0.0006	0.8338	0.4547	1891	94.466	0	5.5344			
51	0.00140	0.0001	0.0006	0.8338	0.4547	1820.2	78.905	0	21.095			
51	0.00140	0.0003	0.0006	0.8338	0.4547	1723	57.528	0	42.472			
51	0.00140	0.0003	0.0006	0.8338	0.4547	1675.2	46.997	0	53.003			
51	0.00140	0.0004	0.0006	0.8338	0.4547	1665.9	44.954	0	55.046			
51	0.00140	0.0004	0.0006	0.8338	0.4547	1663.7	44.482	0	55.518			
51	0.00140	0.0002	0.0006	0.8338	0.4547	1868.8	44.482	30.898	24.62	54	53	53.5
51	0.00140	0.0001	0.0006	0.8338	0.4547	1894.6	44.482	34.774	20.744	36	34	35
51	0.00140	0.0001	0.0006	0.8338	0.4547	1921.7	44.482	38.865	16.653	26	24	25
51	0.00140	0.0001	0.0006	0.8338	0.4547	1923.1	44.482	39.08	16.438	18	16	17
51	0.00140	0.0001	0.0006	0.8338	0.4547	1923.9	44.482	39.187	16.33	15	13	14
51	0.00140	0.0001	0.0006	0.8338	0.4547	1881	44.482	32.728	22.79	14	14	14

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Chijioke Ekeleme Akamiro was born in Nigeria on November 16, 1949 to Mr. Titus Ekeleme Akamiro and Mrs. Comfort Ahuele Akamiro. He attended Colliery Secondary Technical School, Enugu, Nigeria and the former College of Technology, now Institute of Management and Technology, Enugu, Nigeria. He holds an Ordinary National Diploma in Mechanical Engineering (1973) from Institute of Management and Technology, Enugu, Nigeria.

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He was elected to the Petroleum Engineering honor Society at West Virginia University. He was funded by the National Science Foundation in the amount of $150,000.00 for the establishment of a Soils Mechanics Laboratory at Norfolk State University, Norfolk, Virginia. He has written an unpublished textbook on Statics.

Chijioke is currently the Program Leader for the Building Construction Technology Program at Norfolk State University and holds the rank of Assistant Professor. Chijioke worked in the oilfields of Nigeria first as a Wireline Specialist with Camco (Nigeria) Limited, as a Directional Drilling Engineer with Sante Fe Petroleum Development Company, and as an oilfield Production Supervisor at Nigeria Agip Oil Company, all at Port Harcourt, Nigeria.

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