DETERMINING THE RELATIVE EFFECTS OF VOLUMETRIC WATER CONTENT AND DRY DENSITY ON THE DIELECTRIC CONSTANT OF SOILS

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

DETERMINING THE RELATIVE EFFECTS OF
VOLUMETRIC WATER CONTENT AND DRY DENSITY
ON THE DIELECTRIC CONSTANT OF SOILS

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a candidate for the degree of master of Civil and Environmental Engineering,

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ABSTRACT

Non destructive subsurface investigation using electromagnetic (EM) waves is a growing technique in geotechnical engineering (Mohamed 2006). The ability to "see" under the Earth's surface without having to excavate is important since the soil remains intact and undisturbed.

When there is a discontinuity in dielectric constants, a portion of the EM energy is reflected and the remainder is refracted into the next material. The reflected EM wave indicates detection of an object, a change in material, or a void or crack in the subsurface.

The composition of a soil-water system (i.e. how much water or air is in the soil) will control the reflection and refraction of an EM wave traveling through the soil-water system. Pure water at 20 degrees Celsius has a dielectric of around 80 and air at one atmosphere pressure and 20 degrees Celsius has a dielectric of 1, thus relative volume of water in the soil is hypothesized to have a greater effect than the dry unit weight on the dielectric constant of the soil-water system.

The overall project goal is to better understand the dielectric constant of soil (including the soil-water system) in order to improve subsurface detection methods. Predictive models for dielectric constant of a soil as a function of the EM wave frequency transmitted to the soil as well as a multitude of soil properties, including but not limited to soil water content and dry unit weight (also referred to as dry density), are to be investigated.

It is hypothesized that effects of volumetric water content will dominate the effects of dry density on the dielectric constant of a soil water system. The relative influence of these soil properties on the resulting dielectric constant is to be evaluated through dielectric constant testing in this study.

Through an extensive series of testing, volumetric water content was found to have up to 525 times more impact on the dielectric constant than dry density, but typical results show this quantifiable difference is more reasonably between 7 and 15 times greater effect for volumetric water content than dry density on the dielectric constant of sand.

Table of Contents

List of Tables

List of Figures

1. Introduction

Non destructive subsurface investigation using electromagnetic (EM) waves is a growing technique in geotechnical engineering (Mohamed 2006). The ability to "see" under the Earth's surface without having to excavate is important since the soil remains intact and undisturbed.

1.1 Background

There are many applications of non destructive testing for civil engineers. One widely used technique is ground penetrating radar, or GPR. GPR uses transmitting and receiving antennas or only one containing both functions. The transmitting antenna radiates short pulses of the high-frequency (usually polarized) radio waves into the ground. When the wave hits a buried object or a boundary with a different dielectric constant, the receiving antenna records a variation in the reflected return signal. The dielectric constant of the soil-water system is a key parameter, because it controls the velocity of the EM wave. When there is a discontinuity in dielectric constants, a portion of the EM energy is reflected and the remainder is refracted into the next material. The reflected EM wave indicates detection of an object, a change in material, or a void or crack in the subsurface. The composition of a soil-water system (i.e. how much water or air is in the soil) will control the reflection and refraction of an EM wave traveling through the soil-water system. Pure water at 20 degrees Celsius has a dielectric of around 80 and air at one atmosphere pressure and 20 degrees Celsius has a dielectric of 1, thus relative volume of water in the soil is hypothesized to have a greater effect than the dry unit weight of the soil on the dielectric constant of the soil-water system. The reflection and refraction of an EM wave in a soil-water system can also be transferred to military applications, where the detection of Improvised Explosive Devices (IED) and mines is a very timely issue.

Two parameters commonly used in predictive models for dielectric constant of a soil-water system are the soil water content and dry unit weight. These two properties were chosen for investigation to determine if one has a greater effect on dielectric constant than the other. Solid quartz particles, the primary components of a quartz sand, have a dielectric constant of 4 ± 2 (Bottom 1972). Density alone should do little to affect the dielectric constant of the sand because density primarily only affects the pores, or voids between solid particles, of a sand. Density when used in this paper refers to the bulk dry density of a soil-water system, or weight of solids divided by volume. Sands at maximum density have the least amount of voids between solid particles, with more voids being created between particles the less dense the sand becomes. Whether these voids are filled with air or solid particles, the dielectric of those pores can only range from 1 if the sand is at the minimum density and pores are completely filled with air to a maximum of 6 if there are no pores in the sand. The introduction of water with a dielectric of 80 should have a much greater effect on the variance in dielectric constant for the specimen.

1.2 Objective

The overall project goal is to better understand the dielectric constant of soil (including the soil-water system) in order to improve subsurface detection methods involving EM waves. Predictive models for dielectric constant of a soil as a function of the EM wave frequency transmitted to the soil as well as a multitude of soil properties, including but not limited to soil water content and dry unit weight (also referred to as dry density), are to be investigated. It is hypothesized that effects of volumetric water content of a soil will dominate the effects of soil dry density on the dielectric constant of a soil water system. The relative influence of these soil properties on the resulting dielectric constant is to be evaluated through dielectric constant testing in this study.

1.3 Scope

In order to evaluate the hypothesis, dielectric constant was measured over a range of dry densities and moisture conditions for quartz sands. One hundred and twenty measurements were performed on specimens ranging from air dry to near saturation. Relative densities of the specimens ranged from zero to one hundred percent (void ratios of 1.18 to 0.46). The results of the one hundred and twenty measurements were used to evaluate the validity of the hypothesis.

1.4 Layout of Thesis

The literature review (Chapter 2) covers the effects of the soil parameters of interest, volumetric water content and dry density, on the dielectric constant of a soil-water system. A background on RF waves and how they can be used for measuring dielectric constant is also provided.

The materials and methods chapter (3) includes how the background of knowledge on RF waves and their use for dielectric testing is put into practice with two dielectric testing devices. The characteristics of the soils used for dielectric constant measurements are also described in Chapter 3.

Results of the dielectric constant measurements are presented in Chapter 4. A discussion of the results and their implications with respect to the hypothesis is included in this chapter.

Practical implications of the findings from this study are presented in Chapter 5. Recommendations for future work are presented in Chapter 6.

2. Literature Review

This chapter includes a background on radio frequency (RF) and EM waves. The use of these waves for testing purposes is explained, as well as how they are used to measure the dielectric constant of a soil-water system. Some practical uses for RF waves and the dielectric constant in civil engineering applications are then explained. Furthermore, several empirical models to predict the dielectric constant are described and analyzed for areas that could be improved to yield more accurate prediction of the dielectric constant of soils.

2.1 Background

Radio frequency (RF) waves fall in the general frequency range of 1 MHz to 10 GHz. One Hz is equal to one cycle, or wave, per second. Radio waves are actually on the low end of frequency of the electromagnetic spectrum. Visible light falls between 10^{14} and 10^{15} Hz, while X-rays and radiation are a few orders of magnitude higher. The full electromagnetic spectrum is shown in Figure 2.1. RF waves can have wavelengths that vary from about 1 millimeter to 300 meters. The wavelength is the length of one wave, from crest to crest, or trough to trough (Equation 2.1).

$$\lambda = C / f \tag{2.1}$$

In this equation, λ = EM wave length [m] , C = speed of light, a constant, [3.0 X 10^8 m/s] , and f = frequency of the waves [s^{-1} or Hz].

The larger the length of an RF wave, the further it can penetrate into a medium before being attenuated. The relative penetration depths for RF waves into a soil-water system are shown in Table 2.1 and plotted in Figure 2.2. Waves with higher frequency and therefore smaller wavelength may not be able to penetrate the soil-water system for the purposes of dielectric constant testing.

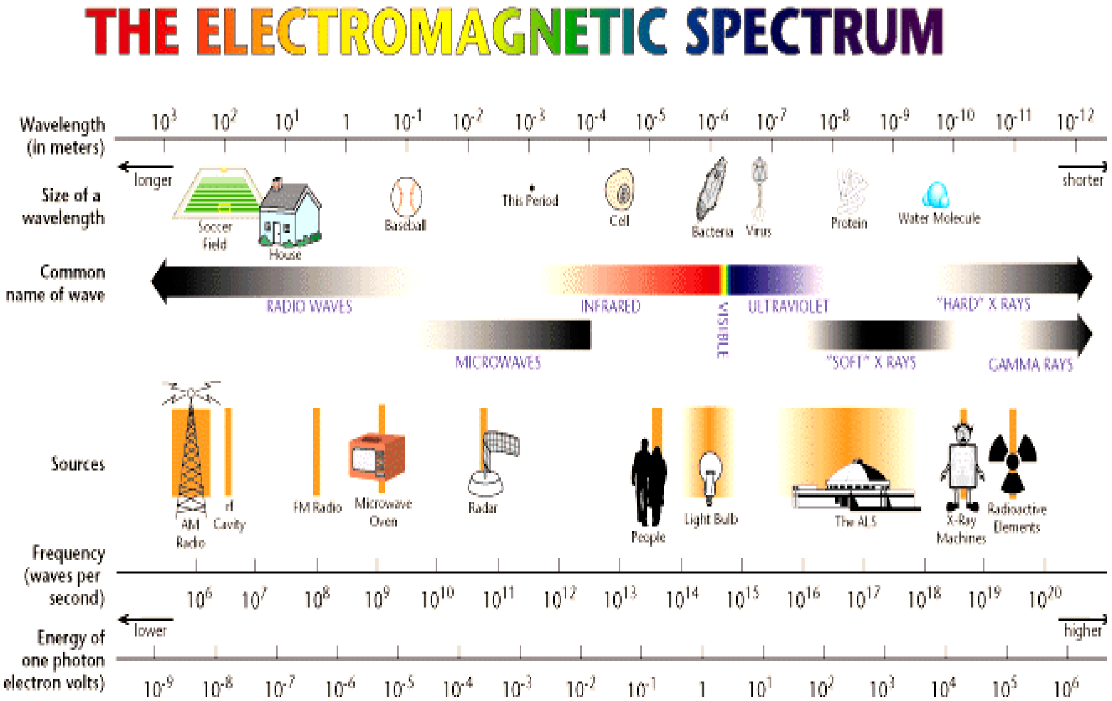

Figure 2.1 Frequency and Wavelength of Waves in the Electromagnetic Spectrum (Berkeley Lab 2011)

Table 2.1 Relative Penetration Depth of RF Wave vs Frequency and Wavelength (Golio 2008)

Frequency, f	Wavelength, λ (m)	Penetration Depth (m)
1 MHz	300	≈ 200
100 MHz	3.0	≈ 50
300 MHz	1.0	≈ 15
900 MHz	0.33	≈ 0.5
1 GHz	0.15	≈ 0.3

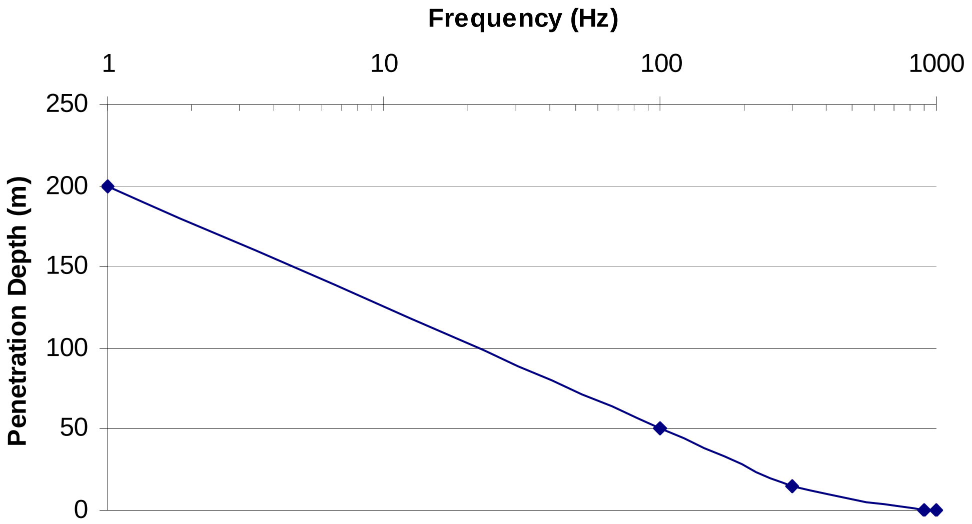

Figure 2.2 Plot of Relative Penetration Depth of RF Wave vs Frequency (Golio 2008)

The dielectric of the soil-water system can be found by determining the velocity [L/T] of the RF waves as they pass through the system. The velocity of an RF wave through a medium is equal to the speed of light, c, divided by the square root of the dielectric constant of that medium (Tyco 2011). (Equation 2.2)

$$V_{RF} = c / (\varepsilon^{1/2}) \qquad (2.2)$$

Where V_{RF} is the velocity of the RF wave, c is the speed of light, (3.0×10^8 meters/second), and ε is the dielectric constant of the media through which the wave travels. Knowledge of the velocity of an RF wave through a soil-water system allows determination of the dielectric constant of that system.

The dielectric constant of a material is the ratio of its permittivity, or ability of the material to hold charge or be polarized by an electric field, to the permittivity of a vacuum. Therefore, the dielectric constant is often referred to as the relative permittivity (IEEE 1997). Since the dielectric constant is just a ratio of two similar quantities, it is dimensionless. Given its definition the dielectric constant of a vacuum is 1 (Jackson

1998). Any material is able to polarize more than a vacuum, so the dielectric constant of a material is always greater than 1. Materials with low dielectric constants have a low ability to polarize and hold charge and are therefore good insulators. Materials that have high dielectric constants are good at holding charge and are ideal capacitors (IEEE 1997).

Water has a dielectric constant of 80 and air has a dielectric constant of 1. In terms of a soil and the pore space, the portion of these pores, or voids, occupied by water may have a greater effect on the dielectric constant of the soil-water system as a whole.

Mitchell (1993) gives an equation for the dielectric constant of the pore medium in a soil as:

$$\varepsilon = (1 / K)^{2} * (2 n_0 e^2 v^2 / \varepsilon_0 k T) \qquad (2.3)$$

where 1/K is the thickness of the layer of water bound to the soil (often called the electrical double-layer for clays), n_0 is the electrolyte concentration of the pore medium, e is the electronic charge (1.602×10^{-23} J K^{-1}), v is the valence of the medium in the pores of the soil-water system, ε_0 is the permittivity of vacuum (8.8542×10^{-12} C^2 J^{-1} m^{-1}), k is the Boltzmann constant (the gas constant per molecule equal to 1.38×10^{-23} J K^{-1}) and T is the temperature in degrees Kelvin.

There are clearly numerous variables related to charge and concentration of the pore medium that play a role in the dielectric constant of the soil-water system, and because water has a higher dielectric constant than air and therefore more affinity for charge (IEEE 1997), it is likely that the amount of water will have a dominant effect on the dielectric constant of the soil-water system.

2.2 Civil Engineering Applications

Non destructive testing methods, including RF waves are used in many civil engineering applications to characterize the subsurface or perform quality control on materials (Lord et al. 1980). For example, in testing the integrity of concrete piles or grout, it would not be sensible to cut into the concrete to examine for cracks, voids, etc. RF waves can be transmitted into the concrete to locate voids. The contents of the void, typically air/or water, have different dielectric constants than the concrete resulting in a dielectric discontinuity which causes portions of a transmitted RF signal to be reflected and refracted (Liu 1998).

Ground Penetrating Radar (GPR) is another example of the use of RF waves in civil engineering. GPR utilizes a short burst of radio-frequency energy radiated into the subsurface to non-destructively detect discontinuities in the subsurface (Kurtz 1995). Discontinuities can be cavities, voids, transitions between soil and rock, filled areas, the groundwater table or buried objects (Dolphin 1997).

2.3 Dielectric Constant versus Volumetric Water Content

Knowledge of the dielectric constant of a soil-water system allows for increased accuracy and precision of the location of subsurface anomalies, their size and shape, and what those anomalies might be. In the late 1970's and early 1980's the dielectric constant of a soil-water system was not a practical measurement. Selig and Manusukhani (1975) and Okrasinski et al. (1978) found that the dielectric constant was strongly dependent on the volumetric moisture content of soil and that dielectric constant increased with an increase in volumetric water content, but there was still limited data available to adequately characterize this behavior.. Due to the lack of data and uncertainty of measurement techniques, simple empirical models were developed to predict the dielectric constant of a soil-water system using physical soil properties that were easily measured such as the volumetric water content, the grain size (texture) of a soil or the soil dry density.

2.3.1 Topp, Annan and Davis Model

Topp et al. used the volumetric water content to estimate the dielectric constant of a soil-water system. Volumetric water content (θ_v) is equal to the volume of water (V_W) in the soil-water system divided by the total volume (V_T) of the system. The Topp, Annan and Davis model is an empirical technique to estimate dielectric content for soil-water systems. The model was initiated based on dielectric constant measurements on glass beads to represent solid soil particles to simplify his geometry. The Topp, Annan and Davis model predicted the dielectric constant based on the volumetric water content in a given matrix of glass beads. The empirical expression Topp et al. developed to estimate the dielectric constant based on volumetric water content is:

$$\varepsilon = 3.33 + 32.8\,\theta + 116\,\theta^2 - 70.9\,\theta^3 \qquad (2.4)$$

Where ε is the dielectric constant of the matrix of glass bead-water system and θ is the volumetric water content of the glass bead-water system. Topp et al. then estimated the dielectric for sands by substituting his estimation of dielectric constant for solid sand quartz particles for the dielectric number used to represent the glass beads. This resulted in a new empirical expression to estimate the dielectric constant for sands:

$$\varepsilon = 3.03 + 9.3\,\theta + 146\,\theta^2 - 76\,\theta^3 \qquad (2.5)$$

Because of the increasing complexity of soil particles with the additions of silts and clays, and Topp, Annan and Davis's estimation of soil particles as perfect spheres, it was deemed that only sand could be represented by the equation for glass beads with a simple dielectric substitution. Particles of silt and clay are not typically spherical and therefore there are no equations in the Topp et al. model to predict the dielectric constant for soils other than sands. The curves of dielectric constant versus volumetric water content for the glass bead and sand expressions are shown in Figure 2.3.

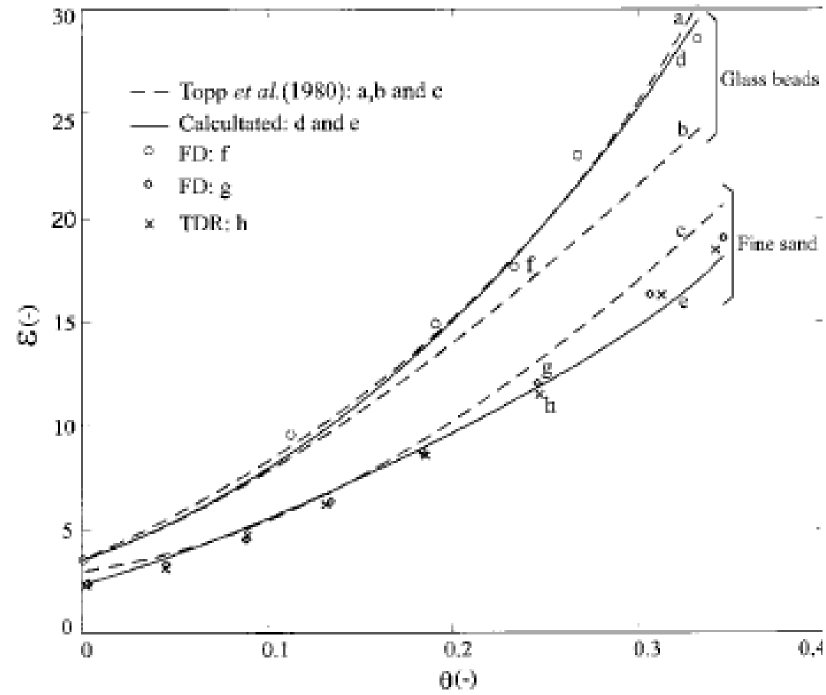

Figure 2.3 Dielectric Constant vs Volumetric Water Content for Topp et al. (1980) Glass Bead and Sand Equations. (Hilhorst 2000)

Topp et al. give the earliest dielectric estimation model, using the assumption of sand particles as spherical glass beads. Topp, Annan and Davis's model agrees with the limited data interpreted by Selig and Manusukhani (1975) and Okrasinski et al (1978) that dielectric constant increases with an increase in volumetric water content. Volumetric water content can be correlated to the dielectric constant of a soil-water system, but what about the effect of dry density on the dielectric constant of the soil water system?

2.4 Dielectric Constant versus Porosity (Dry Density)

The simple glass bead model for sand particles was used for another empirical prediction of the dielectric constant, this time using the soil property of porosity. A soil's porosity, n, is equal to the volume of voids (V_V) in the soil matrix divided by the total volume (V_T) of the system. Porosity can range from zero to one. The dry density of a soil is inversely related to the porosity of the soil (Equation 2.6); the more pore space in a soil the lower the dry density (Buckman 1960).

$$\gamma_d = G_S \gamma_w \; [\, 1 + (n / (1 - n)) \,] \qquad (2.6)$$

Where γ_d is the dry density of the soil, G_S is the specific gravity of the soil, γ_w is the unit weight of water [equal to 62.4 lb/ft^3 or 1.0 g/cm^3] and n is the porosity of the soil. As porosity increases, dry unit weight decreases, and vice versa.

2.4.1 Kaya Model

Kaya (2001) used a mixture rule for the dielectric constant of a soil-water system to predict the dielectric constant of sand, fine glass beads and coarse glass beads over a range of porosities. Kaya's empirical equation is:

$$\varepsilon = \varepsilon_{water}\, n + \varepsilon_{soil}\, (1 - n) \qquad (2.7)$$

Where n is the porosity of the mixture and ε_{soil} is the dielectric constant of the soil and ε_{water} is the dielectric constant of the pore water. As Kaya further analyzed the soil-water system it was noted that some of the pore water is adsorbed by soil particles resulting in a decrease in the dielectric constant of the pore water but an increase in the dielectric constant of the soil. Considering this fact, the dielectric constant of a soil-water system can be written as:

$$\varepsilon = (\varepsilon_{water} - d\,\varepsilon_1)\,(\varepsilon_{soil} + d\,\varepsilon_2)\,(1 - n) \tag{2.8}$$

In this modified form, $d\,\varepsilon_1$ and $d\,\varepsilon_2$ are constants based on soil properties that affect the bound water in the soil-water system as previously shown in Equation 2.3 by Mitchell. The curves of dielectric constant versus porosity for fine and coarse glass beads and sand are shown in Figure 2.4.

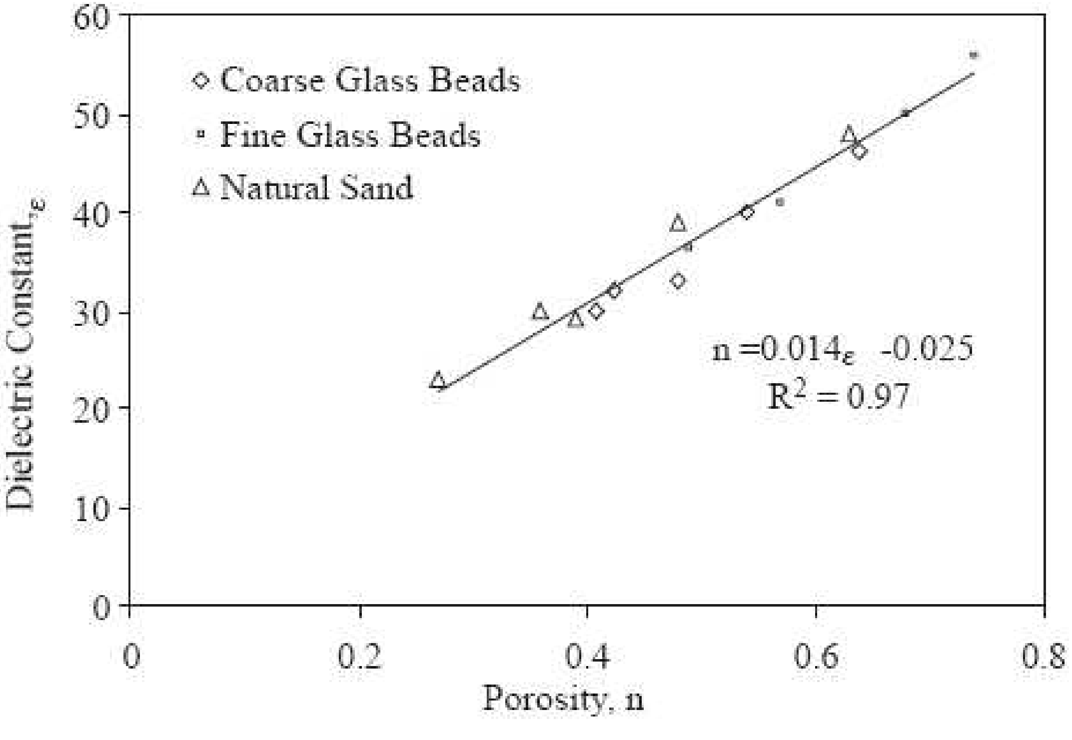

Figure 2.4 Dielectric Constant vs Porosity for Kaya (2001)
Empirical Prediction Equations for Simple Mixtures

Kaya (2001) showed that the dielectric constant increases for an increase in the porosity of the soil-water system; i.e. a decrease in the dry density of the soil-water system yields an increase in dielectric constant. This is for the case of saturated soil-water systems as an increase in porosity, i.e. a decrease in dry density means that there is more water in the system, and therefore a higher dielectric constant. This effect is better explained with a soil phase diagram as shown in Figure 2.5.

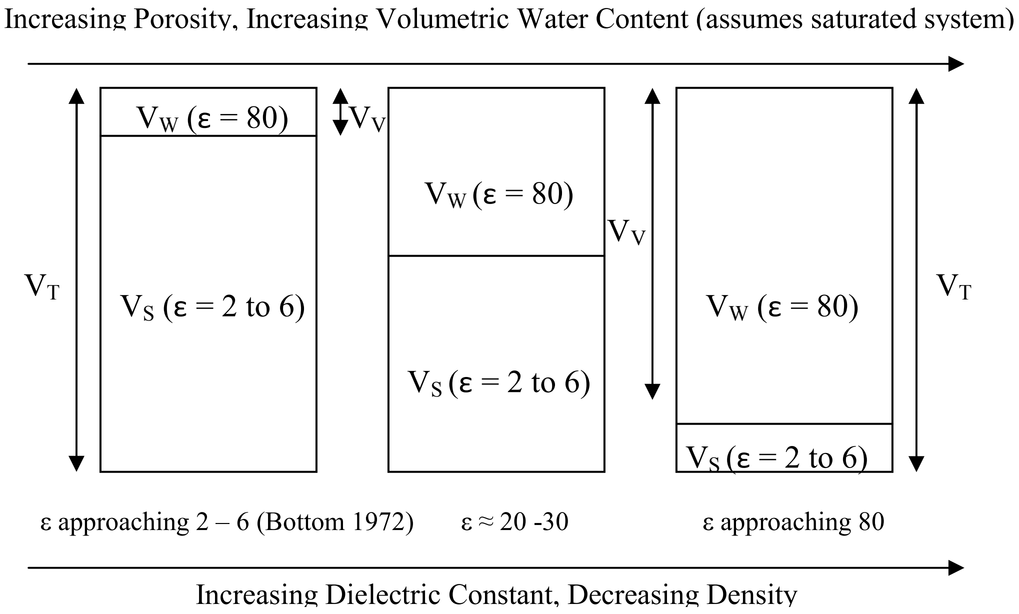

Figure 2.5 Soil Phase Diagram for Increasing Dielectric Constant with Increasing Porosity for Saturated Sand

For saturated soils, the volume of voids is fully comprised of water. Thus, when the porosity of the soil increases, the volume of water in the soil increases as well. This increase in the volume of water causes an increase in the dielectric constant. Kaya shows this increase in dielectric constant with increasing porosity in his model, and supports the model with previous test results from Arulanandan (1991) related to porosity and dielectric constant.

Kaya used research results from Arulanandan (1991) to compare to his model predictions. Arulanandan tested a wide range of soil types for dielectric constant. Results from Arulanandan’s series of testing (1991) are presented in Table 2.2.

Table 2.2 Dielectric Constants of Soils at Various Porosities (Arulanandan 1991) at 50 MHz Measured Horizontally, ε_{horz}, and Vertically, ε_{ver}, Through Soil Sample

Soil Type	**Porosity,**	ε_{ver}	ε_{horz}	ε_{avrg}
Snow cal (Kaolinite + Illite)	0.56	34.0	43.2	40.1
	0.55	32.8	42.7	39.4
	0.52	31.4	40.1	37.2
	0.50	30.4	35.3	33.7
	0.47	29.5	38.0	35.2
	0.44	28.7	33.7	32.0
	0.42	27.5	33.1	31.2
	0.65	42.9	47.4	45.9
	0.61	41.0	45.2	43.8
Snow cal (Kaolinite + 5% Montmorillonite by dry mass)	0.58	37.5	42.7	41.0
	0.54	35.6	39.9	38.5
	0.51	33.7	38.1	36.6
	0.47	31.2	36.5	34.7
	0.44	28.9	35.0	33.0
	0.42	25.4	33.9	31.1
	0.54	39.8	40.3	40.1
	0.52	36.7	39.8	38.8
Yolo loam	0.49	34.3	38.3	37.0
	0.47	33.5	37.4	36.1
	0.56	38.8	41.1	40.3
	0.55	34.7	41.0	38.9
Marysville red soil	0.52	33.9	40.1	38.0
	0.51	33.0	39.7	37.5
	0.86	60.0	70.6	67.1
	0.85	55.0	69.0	64.3
Snow cal (Kaolinite + 30% Montmorillonite by dry mass)	0.82	54.0	67.3	62.9
	0.74	49.0	57.5	54.7
	0.68	43.2	57.2	52.5
	0.45	28.3	33.0	31.4
	0.54	33.0	40.6	38.1
Illite kaolin MP	0.52	30.9	40.2	37.1
	0.51	30.0	37.3	34.9
	0.32	23.2	24.5	24.1
Sand	0.34	24.0	25.5	25.0
	0.36	25.0	29.0	27.7
	0.40	28.0	30.0	29.3
	0.40	27.5	29.6	28.9
	0.44	30.5	32.3	31.7
	0.51	30.4	37.1	34.9
Natural soils	0.52	34.0	38.0	36.7
	0.52	34.0	39.7	37.8
	0.56	33.4	42.7	39.6
	0.76	50.0	57.5	55.0

In Arulanandan's (1991) testing, RF waves were sent through the soil samples horizontally and vertically to measure the dielectric constant. For comparison to the empirical model, Kaya calculated an average dielectric constant from both the horizontal and vertical results (Equation 2.9).

$$\varepsilon_{avrg} = (\varepsilon_{ver} + 2\,\varepsilon_{horz}) / 3 \qquad (2.9)$$

More weight was placed on the horizontally measured dielectric constant for the averaging because the porosity was determined to be distributed more uniformly throughout the specimen in the horizontal direction than in the vertical direction during testing. The results from Table 2.2 are plotted with porosity in decimal form on the x-axis and Kaya's (2001) calculated average dielectric constant from Arulanandan's (1991) results on the y-axis in Figure 2.6.

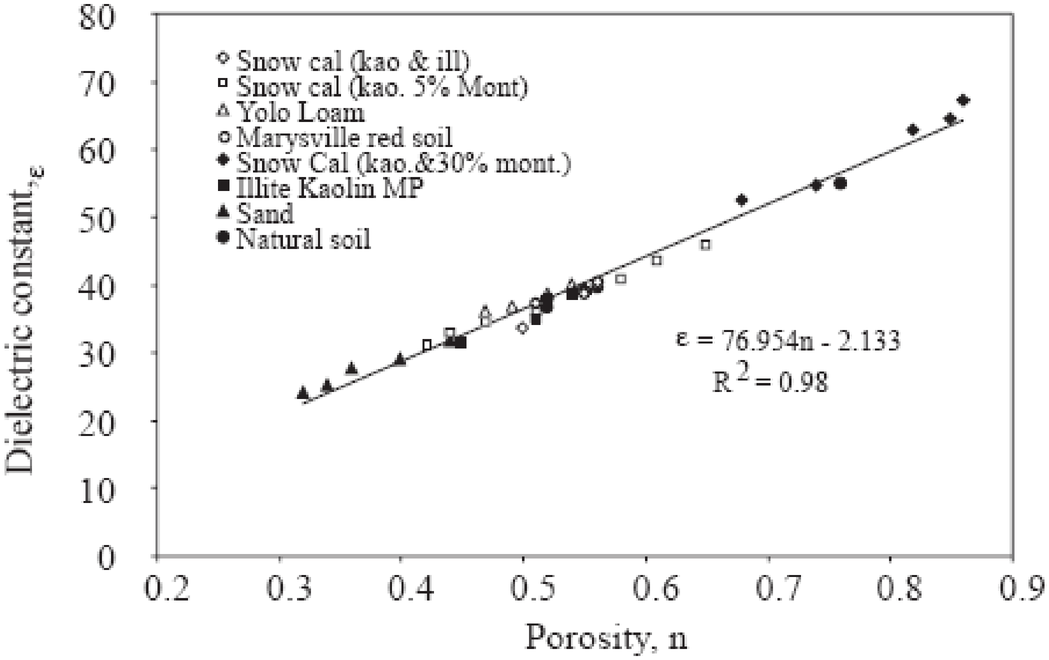

Figure 2.6 Dielectric Constant of Soils at Different Porosities (Kaya 2001)

The results from Kaya's empirical model (2001) compared to Arulanandan's measurements (1991) of multiple soil types are compared in Figure 2.7.

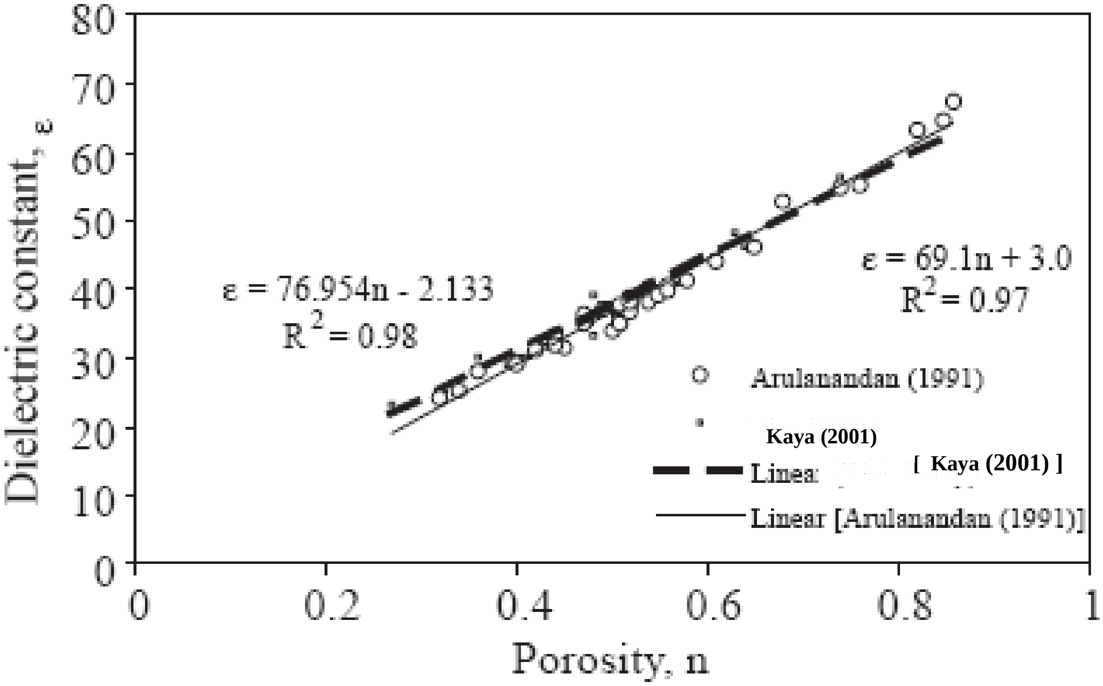

Figure 2.7 Comparison of Dielectric Constant of Soils of Kaya (2001) and Arulanandan (1991) vs the Porosity of the Soil Mixture

Results from both Arulanandan and Kaya conclude that dielectric constant increases with an increase in soil porosity for saturated soils. Given the inverse relationship between porosity and soil dry density, a decrease in soil dry density for saturated soils will yield an increase in the dielectric constant of that soil-water system.

Martinez and Byrnes (2001) take the relationship between density and dielectric constant one step further, and make a prediction for the dielectric constant of unsaturated soils versus dry density as well. The predictive model created by Martinez and Byrnes actually includes varying degrees of saturation and soil porosity, and predicts the expected dielectric constant based on these two soil parameters. This predictive model can be seen in Figure 2.8.

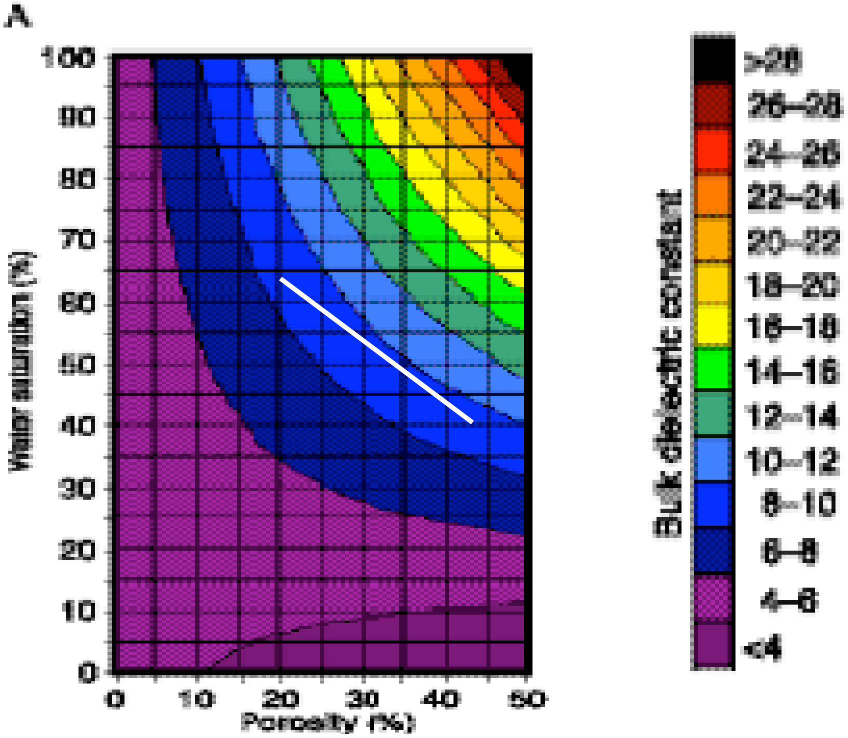

Figure 2.8. Martinez and Byrnes (2001) Dielectric Constant Prediction Model for Quartz Sand with Varying Degree of Saturation and Porosity

In agreeance with Kaya's results, Martinez and Byrnes (2001) predict an increase in the dielectric condtant with an increase in soil porosity for a fully saturated quartz sand. But what is interesting to note though, is that for low degrees of saturation Martinez and Byrnes believe the dielectric constant will actually decrease with an increase in porosity. This is because the majority of the void space is filled with air, which has a dielectrric constant of 1; lower than a quartz sand particle of 2 to 6 (Bottom 1972).

2.5 Analysis

Both water content and density appear to have an effect on the dielectric constant of a soil water mixture. An increase in volumetric water content gives an increase in dielectric constant and conversely, an increase in density should produce a decrease in dielectric constant for saturated soils. But for non saturated soils this relationship between density and dielectric constant appears to be reversed. The effects of water content and density on the dielectric constant have never been directly compared through measured dielectric constant test results. Will an increase in both density and volumetric water content of a soil-water system truly not change the dielectric constant of the soil-water system (as shown by the white line in Figure 2.8), or will this produce an increase or a decrease in the dielectric constant? Which soil parameter, density or water content, has more influence on the dielectric constant? And if one of these parameters has greater influence on the dielectric constant, can these effects be quantified? These are questions that will all be attempted to be answered with the dielectric testing procedure in this study.

2.6 Summary

Radio frequency waves can be used to measure the dielectric constant of a soil-water system. In early research Selig and Manusukhani (1975), Okrasinski et al (1978), and Topp (1980) concluded that an increase in volumetric water content will produce an increase in the dielectric constant of a soil water system. Arulanandan (1991) and Kaya (2001) found that increasing porosity increases the dielectric constant of a soil-water system for fully saturated soils. Due to the inverse relationship between porosity and density, this means that an increase in the density of the soil will yield a decrease in the dielectric constant of that soil when saturated. However when near dry, with little water in the pore space, an increase in the density of the soil actually increases the dielectric constant. The relative effect of these two soil parameters, volumetric water content and dry density, on the dielectric constant of a soil-water system will be investigated through dielectric constant measurements on soil specimens.

3. Materials and Methods

This chapter introduces the soils used in dielectric constant measurements and gives the characteristic properties of these soils. The methods and devices used for testing these soils for dielectric constant are explained.

3.1 Soils

Two soils were chosen to perform dielectric testing on, a silica sand and a silt. The sand was chosen because it is mineralogically simple and the dielectric results can easily be compared with Topp's (1980) research which included sand particles. The silt, or loess, was chosen to be able to compare results to the more complex predictive models. Geotechnical characterization of these soils was performed to quantify the parameters for each soil to be used in the dielectric models. The soils used and their sources are listed in Table 3.1.

Table 3.1 Soils Used in Dielectric Testing

Soil	**Source**	**Contact**
Silica Sand	U.S. Silica	Stephanie Wood
Loess	Missouri River (dredged)	Dr.Erik Loehr (thesis by Bozok 2008)

3.2 Lab Characterization Testing

All characterization tests were performed using applicable standards. These standards were developed by the American Society for Testing and Materials (ASTM) who develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems and services. This includes soil testing standards, and the tests used for characterizing the soils that were tested for dielectric constant are listed in Table 3.2.

Table 3.2 Standardized Test Procedures Used in Soil Characterization

Parameter Desired	**Test Procedure**
Atterberg Limits	ASTM D4318
Water Content	ASTM D2216
Standard Proctor Compaction	ASTM D698
Specific Gravity	ASTM D854
Grain Size Analysis	ASTM D422

3.2.1 Characterization Testing Results

The results from the geotechnical characterization of the soils are presented in Table 3.3 and Figures 3.1 – 3.4. Table 3.3 is a summary of the results from tests based on standards ASTM D4318, ASTM D698, ASTM D854, ASTM D422. The standard test for obtaining soil water content, ASTM D2216, is included in all of the other tests except for Grain Size Analysis. The soil classifications are based on particle size.

Table 3.3 Soil Atterberg Limits, Grain Sizes, Proctor Results and Classification

Soil	Atterberg Limits			USCS Particle Size			Specific Gravity, Gs	Standard Proctor Compaction		Classification	
				> 74 µm	3 µm-74 µm	< 3 µm		Optimum Water Content	Maximum Dry Density (pcf)	USCS	USDA Textural
	LL	PL	PI	% Sand	% Silt	% Clay					
Silica Sand	-	-	-	100	0	0	2.65	-	-	SP	sand
Loess	19	14	6	88	9	3	2.64	11	116	SM	sand

SP – Poorly Graded Sand (Uniformly Graded)
SM – Silty Sand

Figure 3.1 is the soil plasticity chart, which is created by plotting the liquid limit (LL) of the soil obtained from the Atterberg Limits test, against the plasticity index (PI) of the soil, which is equal to the liquid limit of the soil minus the plastic limit (PL) of the soil. This is shown in Equation 3.1

$$PI = LL - PL \tag{3.1}$$

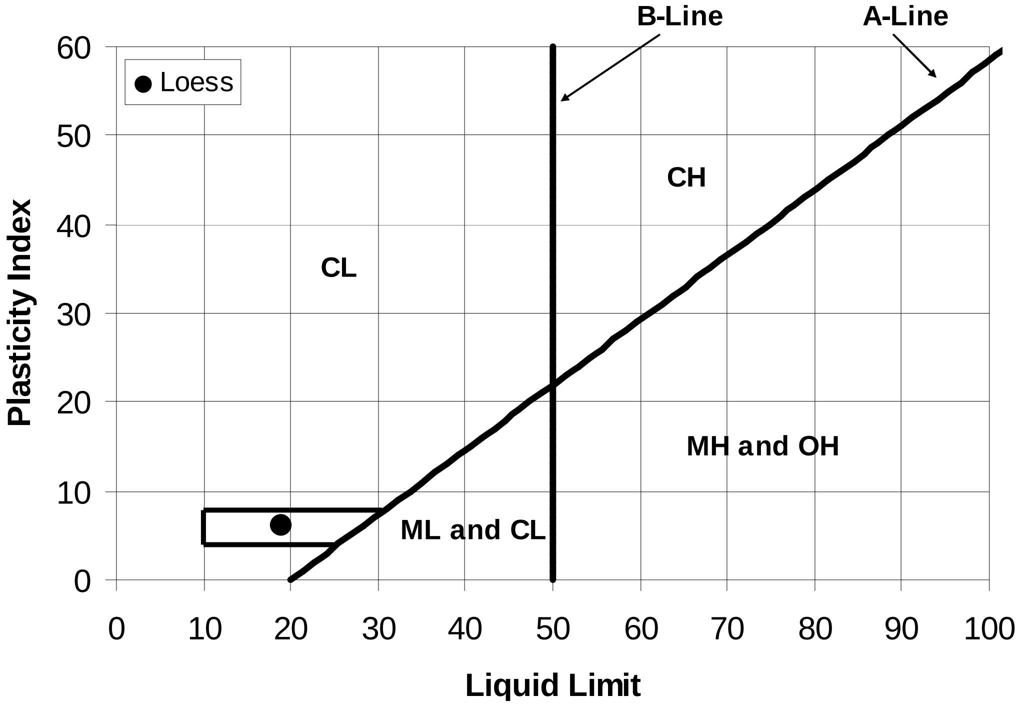

Figure 3.1 Soil Plasticity Chart for Loess Sample

Typically soils that plot above the A-Line are clays and below the A-Line are silts. The B-Line divides high plasticity soils from low plasticity soils. The boxed region, which the loess used for dielectric testing falls into, does not follow these typical rules and can either be classified as a silty sand (SM), clayey sand (SC), low plasticity silt (ML), or low plasticity clays (CL) based on the results from the grain size analysis. The loess classifies as a silty sand (SM) based on the plasticity chart and the grain size analysis. Figure 3.2 is the USDA textural triangle which plots percent sand, silt and clay on three separate axes, and is another method for classifying soils.

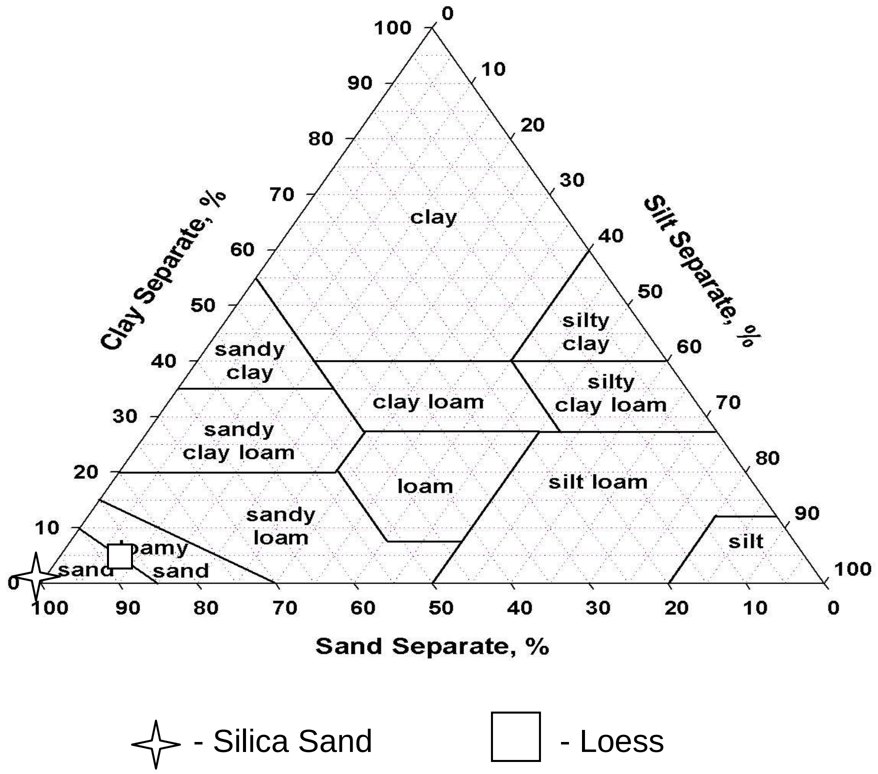

Figure 3.2 USDA Textural Triangle Chart for Sand and Loess Samples

Based on the USDA textural triangle, the loess and sand samples used in dielectric constant testing both classify as sands. Figure 3.3 is a plot of the results from the grain size analysis, in which a percent of soil by weight that passes through a specific size opening in a sieve is plotted against the opening sizes (mm) in the multiple sieves that were used to sort and separate the soil.

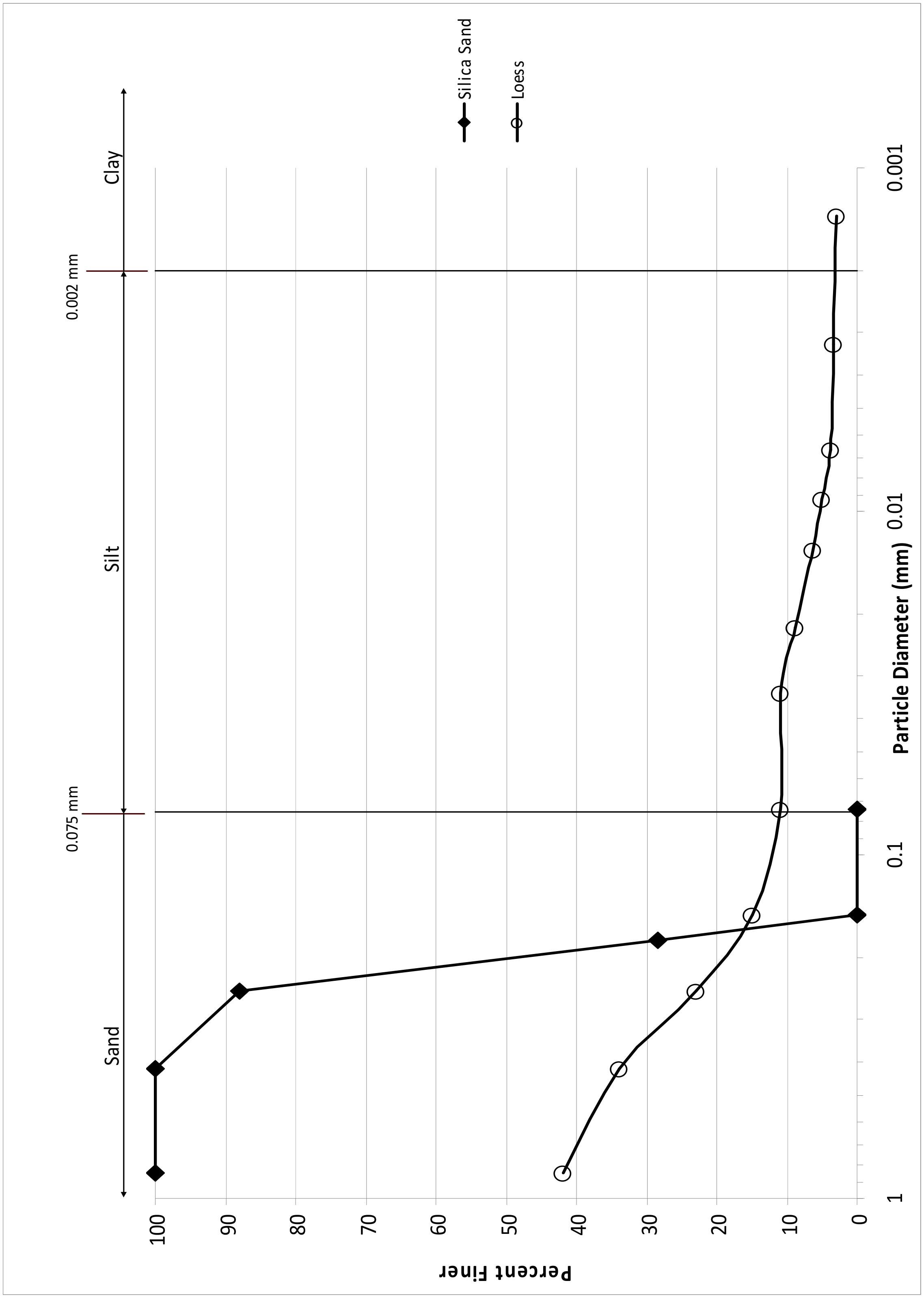

Figure 3.3 Grain Size Distribution for Sand (SP) and Loess (SM) Samples

The Standard Proctor Compaction test, ASTM D698, is a test method to determine the maximum dry density of a soil and the optimum water content at which the soil can be compacted using a specified energy. This is performed by compacting a soil with an estimated water content into a mold with a known volume and weight. Then the soil in the mold is weighed and the density of the soil is determined. Finally, the true water content of the soil is measured by ASTM D2216 and the dry density can be calculated. This is repeated as many times as necessary with varying water contents to develop a curve that peaks and ultimately drops off. The results for the Standard Proctor Compaction test of the loess are displayed in Table 3.4 and Figure 3.4.

Table 3.4 Standard Proctor Compaction Test Results for Loess Samples at Five Varying Water Contents

Sample	Water Content (%)	Dry Unit Weight (g/cm^3)
1	3.05	104.8
2	7.04	114.9
3	14.22	112.9
4	19.3	103.1
5	11.94	115.2

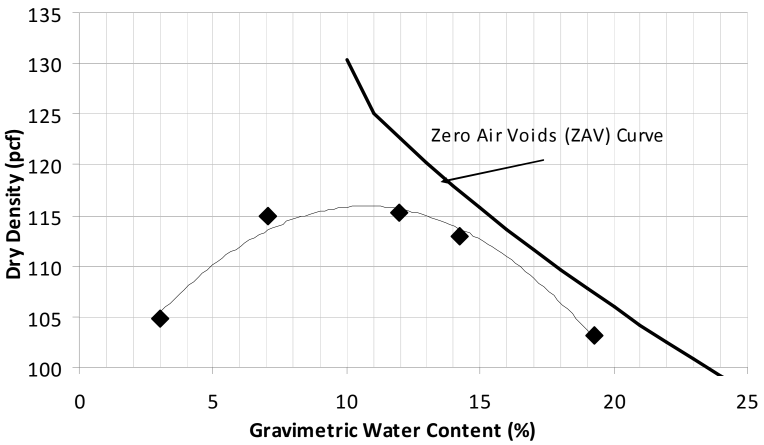

Figure 3.4 Standard Proctor Compaction Curve for Loess
(Maximum Dry Density = 116 pcf, Optimum Water Content = 11%)

3.2.2 Characterization Summary

The sand used for testing classifies as a poorly graded sand (SP) because all of the particles are approximately 0.2 millimeters in diameter. The loess has a low plasticity of 6 and is classified as a silty sand (SM) because it falls in the boxed zone connected to the A-line on the plasticity chart and has greater than 12% of its particles passing the 0.075 millimeter sieve (fines).

3.3 Dielectric Constant Tests

Two methods were used for dielectric constant testing of the soils. These methods are frequency domain and time domain reflectometry, or TDR. The frequency domain testing is performed using a network analyzer, and the TDR testing is performed using parallel plate transverse electromagnetic (TEM) cell.

3.3.1 Network Analyzer

An Agilent Series network analyzer is connected to a dielectric probe that when contacted to a surface gives a readout of dielectric constant vs. frequency for that surface, over a range of frequencies input by the user. While performing the network analyzer tests on sand, a ceramic dish as opposed to a metal tin is used to contain the sand as to minimize the effect of the container on the measured dielectric constant. Tests are performed on wet (saturated) and dry sand samples as well as samples ranging in density from loosely packed to maximum density.

The loosest compaction state was achieved by allowing the sand to fall through air with the smallest drop height possible and in a circular motion to fill the ceramic container. The densest compaction state was achieved by filling the ceramic container with sand, placing a static weight (approximately 5 lbs) on top of the sand, and placing the container on a vibrating table for two minutes. This method reduces the air voids in the sample and results in a dense state for the sand. The state of zero water was achieved by oven drying all of the sand samples at 110 degrees Celsius for a minimum of 16 hours. Saturation for the sand used in testing was found to be around 25 percent gravimetric water content and this state was achieved by adding an amount of water equal to 25 percent of the weight of dry sand.

The dielectric constant results from the clean quartz sand were compared to determine the relative effect of volumetric water content and soil dry density on the dielectric constant of the soil. Advantages of the network analyzer testing are the quickness and ease in which the tests can be performed and repeated. Thirty to forty dielectric tests can be performed per hour on the network analyzer. A disadvantage of the network analyzer is the precision of the results. For a given soil sample at a constant water content and density, the readout of dielectric constant could vary by as much as 12 percent from test to test at a given frequency. This variance was measured as twenty dielectric measurements were taken on the exact same sand specimen in very short succession (5 minutes total elapsed time). The sand was prepared similar to the wet specimens as the water content was close to saturation, but not compacted to any specific density. The density was still maintained constant between tests as the water content was assumed to, because the tests were taken in such quick succession without allowing for water evaporation. The results from this variance testing are presented in Table 3.5.

Table 3.5 Results from Network Analyzer Variance Testing

Test	ε		Test	ε		Test	ε		Test	ε
1	31.2		6	28.4		11	31.2		16	29.9
2	26.6		7	27.0		12	24.6		17	22.3
3	24.0		8	23.2		13	25.6		18	29.1
4	23.2		9	26.6		14	24.4		19	20.2
5	25.7		10	30.6		15	29.1		20	29.3

The average measured dielectric constant was 26.6 and the standard deviation and coefficient of variation for these tests was 3.2 and 0.1 respectively. Therefore it was calculated that any test result could be within 3 of an actual value. The 12% difference between tests was calculated as 3 / 26.6 and was reasoned to be a good estimation of the variance of the network analyzer testing device.

The variability is a result of human error in that the ceramic dish had to be held steady in contact with the dielectric probe for five seconds for a dielectric reading. Small movements caused wide variance in results. Typically erroneous results (values greater than three standard deviations, approximately 9, from the measured dielectric constants) were discarded and tests were re-performed but even values that were kept still varied from other tests under the same conditions slightly. The variance of results is why as many trials as possible were performed for each set of conditions and the average values of dielectric constant were taken at the input frequencies. The network analyzer setup is shown in Figure 3.5

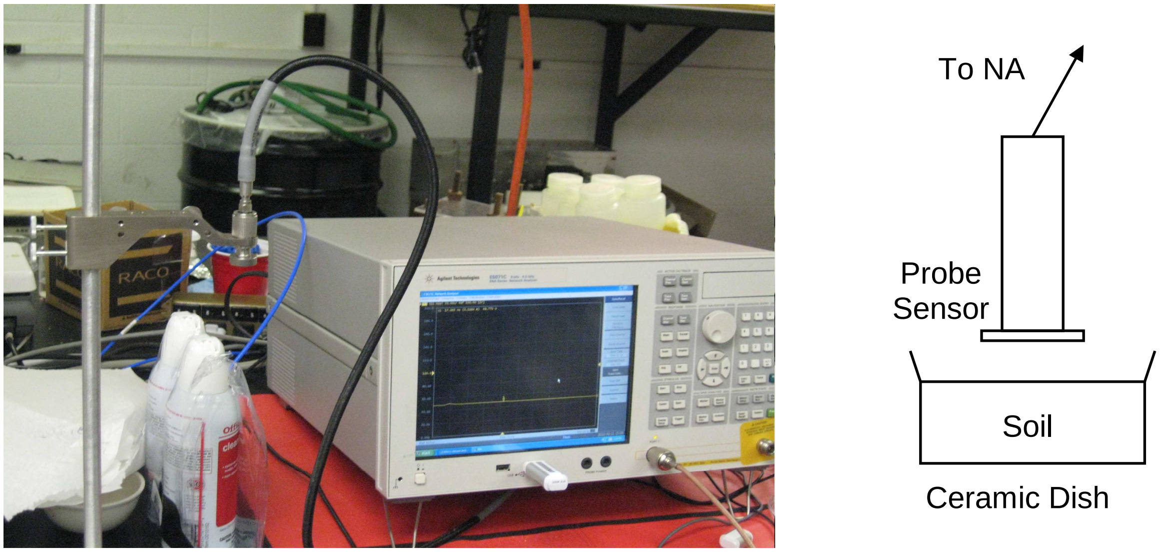

Figure 3.5 Network Analyzer and Test Set Up

3.3.2 TEM Cell

The TEM cell is based on the TDR principle in which a signal is sent through a soil sample by a digital serial analyzer and recorded at the other end of the soil sample in a digital storage oscilloscope. Both devices for testing in this study were Tektronix models. The digital serial analyzer produces a plot of impedance in Ohms on the y-axis versus time on the x-axis. The impedance of the input and output lead wires is a known, and thus the impedance change as the signal travels through the soil can be calculated. The impedance and the travel time of the EM signal through the soil are used to calculate the dielectric constant of the soil. The cell used could contain a soil sample 5 inches by 8 inches with a thickness of 3/8 of an inch. The total (wet) density of the soil was found by measuring the weight of the sample in the cell and dividing by the cell volume. More water contents were used in TEM cell testing than in network analyzer testing. While two conditions, wet and dry were chosen for the sand testing in the network analyzer, five water contents were chosen for the loess and sand in equal increments to perform dielectric constant testing in the TEM Cell. Advantages of the TEM cell are that the results are much more precise than the network analyzer, with multiple tests of the same conditions yielding results within 3 percent of one another as opposed to 12 percent with the network analyzer. The TEM cell tests, however, were more time consuming in comparison to the network analyzer. When the TEM cell is fully calibrated and operational, six to ten tests can be performed per hour. This is because the cell needed to be cleaned between tests, and the input and output wires had to be handled with great care during and between tests, as the digital serial analyzer and digital storage oscilloscope are sensitive to static electric shock. Another problem with the TEM Cell was that the soil sample was not contained fully by a constant material on all sides. On the top and bottom of the cell, the soil sample is contained by parallel aluminum plates, whereas on the edges of the cell the soil sample is contained by plastic (Plexiglass ®). The aluminum and plastic have different dielectric constants, and this variance in dielectric produces fringing field effects on the EM (RF) signal as it passes through the cell. Therefore while the TEM measurements were precise in comparison to one another, each of the tests may have been affected by the fringe fields in the same magnitude and manner deviating the measured dielectric constant from the "true" value. A photograph and schematic of the TEM cell can be seen in Figure 3.6.

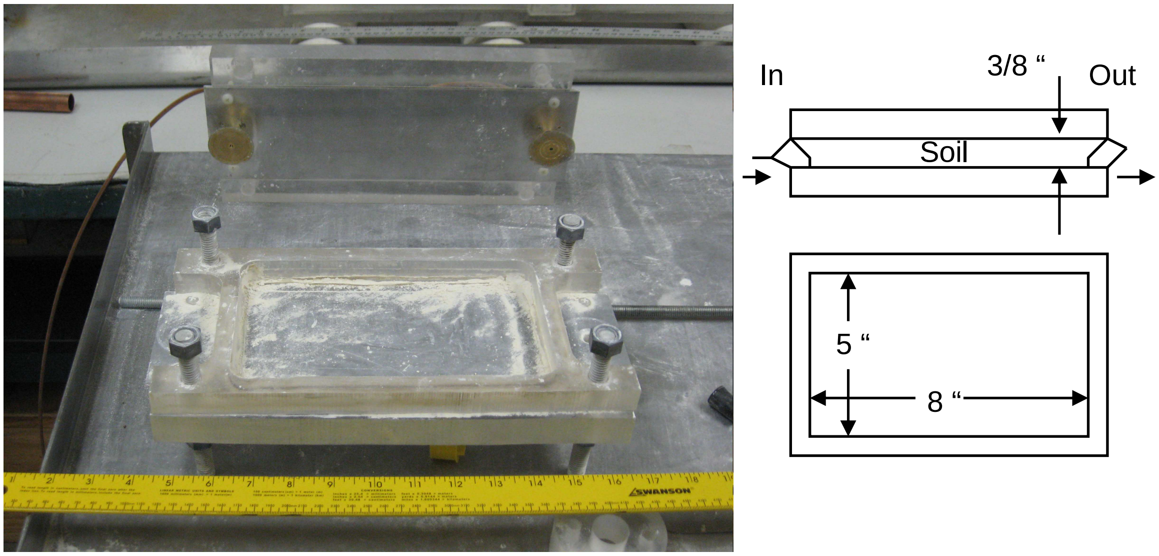

Figure 3.6 TEM Cell and Dimensions

3.4 Summary

A poorly graded, clean fine quartz sand (SP) and a loess (classifies as silty sand, SM) are used for dielectric constant testing. These soils are tested in the network analyzer and TEM cell to determine the effects of water content on the dielectric constant relative to the effects of dry density on the dielectric constant.

4. Results and Discussion

The relative effect of two soil parameters, volumetric water content and dry density, on the dielectric constant of a soil-water system is investigated through dielectric constant measurements on specimens of quartz sand using a network analyzer device. Loess specimens were also tested, in addition to the use of a TEM Cell device to measure the dielectric constant of both the quartz sand and loess, but this chapter focuses on the results from the quartz sand tested for dielectric constant using the network analyzer device. The results from the TEM Cell device testing to measure dielectric constant for loess and sand are in Appendix A.

4.1 Network Analyzer Results

The comparison of the effect of dry density and water content on the dielectric constant of sand was performed using the network analyzer data. Four conditions of the sand were chosen to be able to isolate the effects of volumetric water content from those of dry density on the dielectric constant and quantify the relative importance of each factor in the dielectric measurement. The sand was tested under conditions of loose dry sand, loose wet sand, dense dry sand and dense wet sand.

The results for the four groups of tests are shown in Tables 4.1 through 4.4. The symbols to identify each test are W or D for the first character to indicate wet or dry, and L or D for the second character to indicate loose or dense.

While tests are characterized as loose or dense they are better sorted and titled by average relative density, D_R, with Low D_R from 0 to 30%, Medium D_R between 30% and 70% relative density, and High D_R indicating a relative density greater than 70%.

Table 4.1 Measured Dielectric Constant (Network Analyzer Probe) for Wet Quartz Sand at Low Relative Density ($D_{R\ AVG}$ = 22%)

Sample	Dry Density (g/cm^3)	Void Ratio	Relative Density (%)	Gravimetric Water Content	Volumetric Water Content (%)	Degree of Saturation (%)	Dielectric Constant at 1 GHz	Weight of Water in Sample (g)
WL1	1.39	0.91	38.2	0.241	33.5	70.5	11.1	50.3
WL2	1.26	1.10	10.7	0.232	29.2	55.7	23.1	38.0
WL3	1.25	1.12	8.4	0.240	30.0	56.8	24.8	45.0
WL4	1.26	1.11	9.8	0.242	30.4	57.8	18.8	38.0
WL5	1.39	0.90	38.8	0.242	33.7	71.2	17.6	50.6
WL6	1.23	1.16	2.5	0.241	29.6	55.0	18.4	42.9
WL7	1.31	1.02	22.8	0.237	31.1	61.7	18.7	46.6
WL8	1.33	0.99	26.9	0.242	32.3	65.0	19.6	43.6
WL9	1.33	0.99	26.3	0.242	32.2	64.8	27.4	51.6
WL10	1.40	0.90	39.4	0.238	33.3	70.5	21.7	43.3
WL11	1.41	0.88	42.0	0.234	33.0	70.6	22.5	42.9
WL12	1.31	1.03	21.1	0.239	31.3	61.7	19.0	45.3
WL13	1.22	1.18	0.5	0.239	29.1	53.9	16.2	46.6
WL14	1.34	0.97	29.0	0.232	31.1	63.2	15.5	48.3
WL15	1.23	1.15	3.6	0.221	27.1	50.6	15.2	38.0
WL16	1.23	1.16	2.7	0.229	28.0	52.2	16.8	40.7
WL17	1.26	1.10	10.8	0.216	27.2	52.0	18.0	39.5
WL18	1.24	1.14	5.1	0.222	27.4	51.4	15.0	34.3
WL19	1.27	1.08	13.4	0.212	26.9	51.8	18.4	36.4
WL20	1.26	1.10	10.8	0.215	27.0	51.6	20.0	39.2
WL21	1.26	1.11	9.9	0.218	27.4	52.1	15.5	41.1
WL22	1.27	1.09	12.5	0.210	26.6	51.0	14.5	45.2
WL23	1.36	0.96	31.2	0.219	29.6	60.7	22.3	40.0
WL24	1.38	0.92	35.8	0.221	30.4	63.4	23.2	51.7
WL25	1.41	0.88	41.6	0.214	30.1	64.4	18.8	42.2
WL26	1.37	0.93	34.7	0.220	30.2	62.8	21.9	40.8
WL27	1.39	0.91	38.2	0.214	29.7	62.5	13.8	37.1
WL28	1.41	0.87	42.6	0.216	30.6	65.5	22.9	44.3
WL29	1.28	1.07	14.7	0.217	27.7	53.5	14.1	37.4
WL30	1.39	0.91	37.4	0.225	31.2	65.4	20.5	49.9
AVG	**1.31**	**1.02**	**22.0**	**0.228**	**29.9**	**59.6**	**18.8**	**43.0**
STD	**0.07**	**0.10**	**14.4**	**0.011**	**2.1**	**6.8**	**3.7**	**4.9**
COV	**0.05**	**0.10**	**0.7**	**0.050**	**0.1**	**0.1**	**0.2**	**0.1**
Min	**1.22**	**0.87**	**0.5**	**0.210**	**26.6**	**50.6**	**11.1**	**34.3**
Max	**1.41**	**1.18**	**42.6**	**0.242**	**33.7**	**71.2**	**27.4**	**51.7**

Table 4.2 Measured Dielectric Constant (Network Analyzer Probe) for Wet Quartz Sand at Medium Relative Density ($D_{R\ AVG}$ = 55%)

Sample	Dry Density (g/cm^3)	Void Ratio	Relative Density (%)	Gravimetric Water Content	Volumetric Water Content (%)	Degree of Saturation (%)	Dielectric Constant at 1 GHz	Weight of Water in Sample (g)
WD1	1.56	0.69	67.5	0.234	36.6	89.2	23.4	60.3
WD2	1.54	0.73	63.1	0.246	37.8	89.8	23.8	60.4
WD3	1.57	0.69	67.7	0.231	36.1	88.2	25.7	61.4
WD4	1.44	0.85	46.4	0.230	33.0	72.0	23.2	52.8
WD5	1.58	0.68	70.0	0.235	37.2	92.2	22.0	59.5
WD6	1.35	0.96	30.7	0.232	31.4	64.1	23.9	50.2
WD7	1.44	0.84	47.3	0.244	35.2	77.1	30.9	56.3
WD8	1.44	0.84	47.6	0.221	31.9	70.0	23.3	51.0
WD9	1.40	0.89	40.5	0.242	33.9	72.2	27.8	54.3
WD10	1.52	0.74	61.4	0.220	33.6	79.2	25.4	53.8
WD11	1.44	0.84	46.8	0.223	32.1	70.1	28.4	51.3
WD12	1.40	0.89	39.8	0.219	30.7	65.0	27.0	49.1
WD13	1.38	0.92	36.1	0.213	29.4	61.3	23.2	47.0
WD14	1.36	0.94	32.7	0.212	28.9	59.5	26.6	46.2
WD15	1.41	0.88	41.7	0.219	30.8	65.9	30.6	49.3
WD16	1.50	0.77	57.6	0.219	32.8	75.8	29.9	52.5
WD17	1.44	0.84	47.3	0.231	33.3	72.9	22.3	53.3
WD18	1.48	0.79	54.3	0.230	34.0	77.2	29.1	54.5
WD19	1.40	0.90	39.4	0.222	31.0	65.5	31.2	49.5
WD20	1.46	0.81	50.7	0.224	32.7	72.7	26.6	52.3
WD21	1.56	0.69	67.5	0.221	34.6	84.5	24.0	55.4
WD22	1.51	0.75	59.0	0.211	31.9	74.2	23.2	51.1
WD23	1.50	0.77	57.6	0.214	32.2	74.2	25.7	51.5
WD24	1.60	0.66	72.5	0.224	35.9	90.4	31.2	57.4
WD25	1.60	0.65	73.0	0.211	33.9	85.7	24.6	54.2
WD26	1.51	0.75	59.8	0.223	33.7	78.7	25.6	53.9
WD27	1.61	0.64	74.8	0.227	36.6	93.7	24.4	58.6
WD28	1.57	0.69	68.7	0.227	35.7	87.7	29.1	57.1
WD29	1.57	0.69	67.6	0.210	32.8	80.1	20.2	52.5
WD30	1.56	0.70	66.3	0.211	32.9	79.8	29.3	52.6
AVG	**1.49**	**0.78**	**55.2**	**0.224**	**33.4**	**77.0**	**26.1**	**53.6**
STD	**0.08**	**0.09**	**13.1**	**0.010**	**2.3**	**9.7**	**3.1**	**3.9**
COV	**0.05**	**0.12**	**0.2**	**0.044**	**0.1**	**0.1**	**0.1**	**0.1**
Min	**1.35**	**0.64**	**30.7**	**0.210**	**28.9**	**59.5**	**20.2**	**46.2**
Max	**1.61**	**0.96**	**74.8**	**0.246**	**37.8**	**93.7**	**31.2**	**61.4**

Table 4.3 Measured Dielectric Constant (Network Analyzer Probe) for Dry Quartz Sand at Medium Relative Density ($D_{R\ AVG}$ = 62%)

Sample	Dry Density (g/cm^3)	Void Ratio	Relative Density (%)	Gravimetric Water Content	Volumetric Water Content (%)	Degree of Saturation (%)	Dielectric Constant at 1 GHz	Weight of Water in Sample (g)
DL1	1.78	0.49	96.2	0.0003	0.048	0.15	2.5	0.081
DL2	1.69	0.57	85.0	0.0000	0.000	0.00	2.4	0.000
DL3	1.60	0.65	73.3	0.0005	0.077	0.20	2.4	0.147
DL4	1.53	0.74	61.7	0.0009	0.131	0.31	2.5	0.236
DL5	1.46	0.82	49.9	0.0004	0.061	0.14	2.5	0.104
DL6	1.58	0.67	70.2	0.0006	0.099	0.25	2.3	0.189
DL7	1.58	0.67	70.2	0.0007	0.117	0.29	2.5	0.152
DL8	1.62	0.64	74.9	0.0011	0.177	0.45	2.5	0.142
DL9	1.37	0.93	34.7	0.0000	0.000	0.00	2.5	0.000
DL10	1.46	0.82	50.7	0.0002	0.030	0.07	2.4	0.048
DL11	1.53	0.74	61.8	0.0000	0.000	0.00	2.4	0.000
DL12	1.64	0.62	78.3	0.0008	0.127	0.33	2.5	0.190
DL13	1.51	0.75	59.1	0.0003	0.039	0.09	2.4	0.063
DL14	1.50	0.76	58.0	0.0003	0.043	0.10	2.6	0.073
DL15	1.61	0.65	73.5	0.0001	0.023	0.06	2.5	0.032
DL16	1.57	0.68	68.9	0.0003	0.055	0.13	2.4	0.115
DL17	1.50	0.76	57.7	0.0009	0.140	0.32	2.5	0.196
DL18	1.47	0.81	51.8	0.0009	0.139	0.31	2.4	0.263
DL19	1.52	0.75	59.9	0.0002	0.036	0.08	2.4	0.051
DL20	1.55	0.71	65.4	0.0003	0.040	0.10	2.4	0.056
DL21	1.49	0.78	55.0	0.0000	0.000	0.00	2.5	0.000
DL22	1.51	0.76	58.5	0.0000	0.000	0.00	2.3	0.000
DL23	1.44	0.84	47.6	0.0004	0.052	0.11	2.4	0.078
DL24	1.39	0.91	38.1	0.0000	0.000	0.00	2.5	0.000
DL25	1.60	0.66	72.1	0.0000	0.000	0.00	2.4	0.000
DL26	1.46	0.81	50.8	0.0016	0.230	0.51	2.6	0.414
DL27	1.57	0.69	67.7	0.0000	0.000	0.00	2.2	0.000
DL28	1.58	0.67	70.2	0.0002	0.028	0.07	2.4	0.042
DL29	1.48	0.79	54.7	0.0002	0.033	0.08	2.4	0.040
DL30	1.48	0.80	53.5	0.0005	0.079	0.18	2.5	0.103
AVG	**1.54**	**0.73**	**62.3**	**0.0004**	**0.060**	**0.14**	**2.4**	**0.094**
STD	**0.09**	**0.09**	**13.2**	**0.0004**	**0.060**	**0.14**	**0.1**	**0.098**
COV	**0.06**	**0.13**	**0.2**	**1.0113**	**1.000**	**0.99**	**0.0**	**1.041**
Min	**1.37**	**0.49**	**34.7**	**0.0000**	**0.000**	**0.00**	**2.2**	**0.000**
Max	**1.78**	**0.93**	**96.2**	**0.0016**	**0.230**	**0.51**	**2.6**	**0.414**

Table 4.4 Measured Dielectric Constant (Network Analyzer Probe) for Dry Quartz Sand at High Relative Density ($D_{R\ AVG}$ = 94%)

Sample	Dry Density (g/cm^3)	Void Ratio	Relative Density (%)	Gravimetric Water Content	Volumetric Water Content (%)	Degree of Saturation (%)	Dielectric Constant at 1 GHz	Weight of Water in Sample (g)
DD1	1.79	0.48	96.7	0.0002	0.043	0.13	2.5	0.064
DD2	1.74	0.52	91.8	0.0000	0.000	0.00	2.5	0.000
DD3	1.70	0.56	86.3	0.0000	0.000	0.00	2.5	0.000
DD4	1.73	0.53	89.8	0.0001	0.024	0.07	2.6	0.035
DD5	1.72	0.54	88.3	0.0000	0.000	0.00	2.6	0.000
DD6	1.78	0.49	96.5	0.0000	0.000	0.00	2.7	0.000
DD7	1.72	0.54	88.5	0.0000	0.000	0.00	2.6	0.000
DD8	1.81	0.46	99.3	0.0000	0.000	0.00	2.7	0.000
DD9	1.76	0.50	93.9	0.0000	0.000	0.00	2.7	0.000
DD10	1.76	0.50	93.9	0.0000	0.000	0.00	2.7	0.000
DD11	1.79	0.48	96.6	0.0004	0.072	0.22	2.7	0.108
DD12	1.77	0.49	95.3	0.0013	0.223	0.68	2.6	0.335
DD13	1.78	0.49	96.1	0.0000	0.000	0.00	2.7	0.000
DD14	1.75	0.52	92.2	0.0000	0.000	0.00	2.7	0.000
DD15	1.76	0.50	93.9	0.0000	0.000	0.00	2.7	0.000
DD16	1.80	0.47	98.4	0.0002	0.039	0.12	2.7	0.061
DD17	1.80	0.47	98.3	0.0003	0.051	0.16	2.7	0.077
DD18	1.80	0.48	97.8	0.0000	0.000	0.00	2.7	0.000
DD19	1.81	0.46	99.7	0.0000	0.000	0.00	2.5	0.000
DD20	1.72	0.54	88.7	0.0000	0.000	0.00	2.6	0.000
DD21	1.76	0.50	94.2	0.0000	0.000	0.00	2.6	0.000
DD22	1.70	0.56	86.2	0.0000	0.000	0.00	2.6	0.000
DD23	1.80	0.47	98.7	0.0001	0.026	0.08	2.6	0.038
DD24	1.74	0.53	90.7	0.0000	0.000	0.00	2.6	0.000
DD25	1.80	0.47	98.7	0.0002	0.044	0.14	2.6	0.066
DD26	1.79	0.48	97.3	0.0003	0.048	0.15	2.6	0.072
DD27	1.74	0.52	91.2	0.0005	0.080	0.23	2.5	0.116
DD28	1.79	0.48	96.8	0.0003	0.060	0.18	2.5	0.093
DD29	1.72	0.55	88.2	0.0004	0.065	0.18	2.6	0.098
DD30	1.74	0.53	90.8	0.0007	0.128	0.37	2.6	0.192
AVG	**1.76**	**0.50**	**93.8**	**0.0002**	**0.030**	**0.09**	**2.6**	**0.045**
STD	**0.03**	**0.03**	**4.2**	**0.0003**	**0.049**	**0.15**	**0.1**	**0.074**
COV	**0.02**	**0.06**	**0.0**	**1.6347**	**1.632**	**1.63**	**0.0**	**1.631**
Min	**1.70**	**0.46**	**86.2**	**0.0000**	**0.000**	**0.00**	**2.5**	**0.000**
Max	**1.81**	**0.56**	**99.7**	**0.0013**	**0.223**	**0.68**	**2.7**	**0.335**

Some individual test results fall outside the relative density used to categorize each group of tests, because the average values from all thirty trials at each test were used to classify each test group as low, medium or high relative density.

A statistical analysis of all of the results was performed to determine the average, standard deviation, and coefficient of variation for the variables of concern, namely dry density, volumetric water content and dielectric constant, at each condition of testing. A summary of the statistical results is shown in Table 4.5.

Table 4.5 Summary of Statistical Analysis for Network Analyzer Sand Testing (Each value is an average of thirty tests performed at each condition)

Test	**Parameter**		
	Dry Density (gm/cm^3) [AVG,STD,COV**] (Min, Max)**	**Volumetric Water Content (%) [AVG,**STD,COV**] (Min, Max)**	**Dielectric Constant [AVG,**STD,COV**] (Min, Max)**
Wet Dense	**[1.49**, 0.08, 0.05**]** **(1.35, 1.61)**	**[33.4**, 2.3, 0.07**]** **(28.9, 37.8)**	**[26.1**, 3.1, 0.12**]** **(20.2, 31.2)**
Wet Loose	**[1.31**, 0.07, 0.05**]** **(1.22, 1.41)**	**[29.9**, 2.1, 0.07**]** **(26.6, 50.6)**	**[18.8**, 3.7, 0.20**]** **(11.1, 27.4)**
Dry Dense	**[1.76**, 0.03, 0.02**]** **(1.70, 1.81)**	**[0.030**, 0.049, 1.63**]** **(0.000, 0.223)**	**[2.6**, 0.1, 0.03**]** **(2.5, 2.7)**
Dry Loose	**[1.54**, 0.09, 0.06**]** **(1.37, 1.78)**	**[0.060**, 0.060, 1.00**]** **(0.000, 0.230)**	**[2.4**, 0.1, 0.04**]** **(2.2, 2.6)**

4.2 Network Analyzer Discussion

The first point that can be made when looking at the data in Table 4.5 is that the tests that were characterized as Wet Dense actually have an average dry density that is slightly less than the average dry density for tests that were characterized as Dry Loose.

The relative density of each specimen may be a better way to analyze the effects of dry density versus the effects of water content. The relative density, D_R, of each specimen is calculated as the maximum void ratio for all of the specimens tested minus the actual void ratio of the specimen of interest divided by the difference in the maximum and minimum of the void ratios of all of the specimens tested (Equation 4.1).

$$D_R = (e_{max} – e_0) / (e_{max} - e_{min}) \qquad (4.1)$$

The value obtained from Equation 4.1 will be in decimal form and can be multiplied by 100 to achieve a percentage relative density.

The void ratio, e_0, term used in the relative density equation is equivalent to the specific gravity, Gs of the soil (taken as 2.65 for sands) multiplied by the unit weight of water (1.0 g/cm^3) and divided by the dry unit weight of the specimen, γ_d (g/cm^3), all subtracted by 1 (Equation 4.2).

$$e_0 = [2.65 * (1.0 / \gamma_d)] - 1 \qquad (4.2)$$

The average values of these quantities and other important quantities related to the water content of the soil, including: degree of saturation, S_R, of the specimen and weight of water in the specimen, W_W can be seen in Tables 4.1 through 4.4 for each test set, and are summarized for reference in Table 4.6. The equations used to determine the degree of saturation and the weight of water for each specimen are 4.3 and 4.4, respectively.

$$S_R = w * Gs / e_0 \qquad (4.3)$$

$$W_W = w * \gamma_d * V_T \qquad (4.4)$$

The symbol V_T represents the total volume of the specimen tested. The values of the parameters presented in Table 4.6 may play a more pertinent role in quantifying the effects of water content and dry density on the dielectric constant of a soil-water system since the names of the test sets and average dry densities from these sets presented in Table 4.5 are somewhat misleading. To clear up this case, the data sets will be labeled simply as condition 1 through condition 4 and presented with the average values of void ratio, relative density, degree of saturation, and weight of water in the specimen, along with the average dry unit weight, volumetric water content and dielectric constant from Table 4.5. Thirty tests were performed at each condition, and the values presented are an average of the thirty values from the tests on the sand specimens.

Table 4.6 Averageof Dry Density, Void Ratio, Relative Density, Volumetric Water Content, Degree of Saturation, Weight of Water in Specimen, and Measured Dielectric Constant for Network Analyzer Sand Testing (Each value is an average of thirty tests performed at each condition)

Condition	Dry Density (g/cm^3)	Void Ratio	Relative Density	Volumetric Water Content (%)	Degree of Saturation (%)	Dielectric Constant at 1 GHz	Weight of Water in Sample (g)
1	1.49	0.78	0.55	33.41	76.96	26.06	53.64
2	1.31	1.02	0.22	29.91	59.64	18.84	43.02
3	1.76	0.50	0.94	0.03	0.09	2.61	0.05
4	1.54	0.73	0.62	0.06	0.14	2.44	0.09

4.2.1 Test Condition Observations

The conditions (Table 4.6) were compared to each other and the difference between the average values was calculated. The results from these differences in average values gives a way to compare the change in dielectric constant between test conditions versus each parameter to quantify the effects of each parameter on the measured dielectric constant. The difference in average values between test conditions is shown in Table 4.7.

Table 4.7 Difference in Average Values of Dry Density, Void Ratio, Relative Density, Volumetric Water Content, Degree of Saturation, Weight of Water in Sample, and Measured Dielectric Constant for Network Analyzer Sand Testing

Conditions Compared	Dry Density (g/cm^3)	Void Ratio	Relative Density	Volumetric Water Content (%)	Degree of Saturation	Dielectric Constant at 1 GHz	Weight of Water in Sample (g)
1-2	0.18	0.24	0.33	3.50	17.32	7.21	10.62
2-3	0.45	0.52	0.72	29.88	59.55	16.23	42.98
3-4	0.23	0.23	0.32	0.03	0.05	0.17	0.05
1-3	0.27	0.28	0.39	33.38	76.87	23.45	53.59
1-4	0.04	0.05	0.07	33.35	76.82	23.61	53.55
2-4	0.22	0.29	0.40	29.85	59.50	16.40	42.93

The values in Table 4.7 are plotted to show the effect of an increase or decrease in a given parameter on the measured dielectric constant. Figures 4.1 and 4.2 show change in average value in dry density and volumetric water content between test conditions, respectively, versus change in average measured dielectric constant between test conditions. The figures for void ratio and relative density are similar to that of dry density (Figure 4.1), and can be found in Appendix B. In addition, the figures for weight of water in the sample and degree of saturation are similar to that of volumetric water content (Figure 4.2) and can also be found in Appendix B.

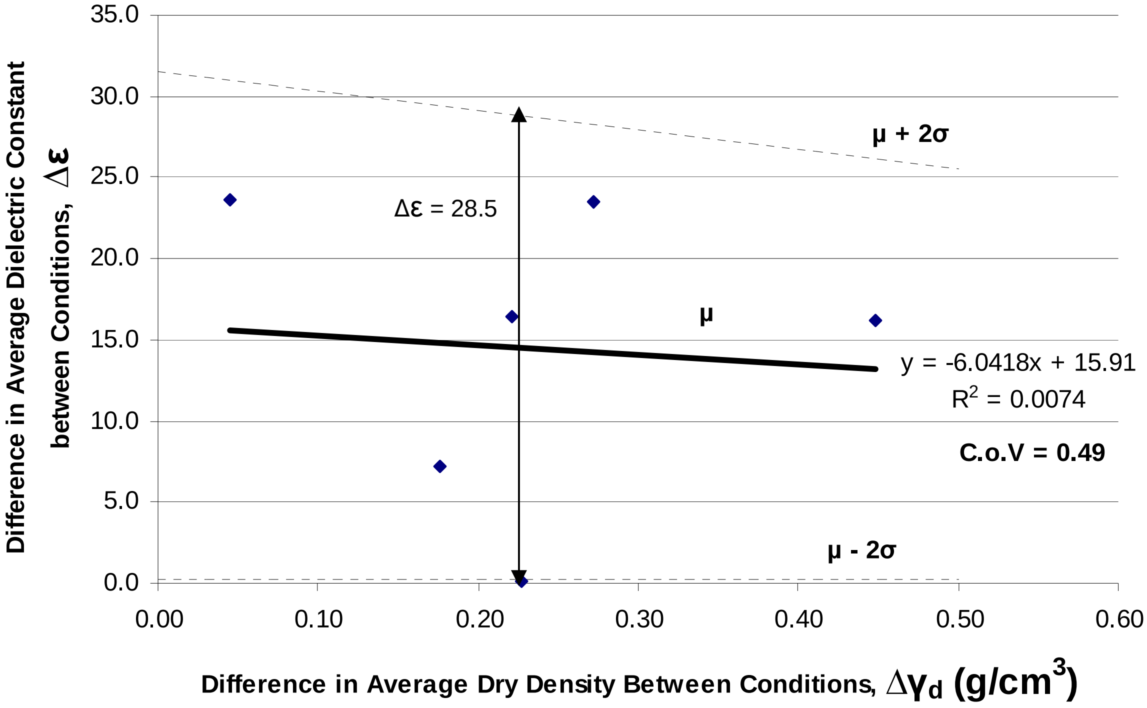

Figure 4.1 The Effect of the Difference in Average Dry Density for Test Conditions on the Difference in Measured Dielectric Constants for those Test Conditions

An observation that can be made from Figure 4.1 is that there is no specific trend between difference in dry density of a test specimen and the difference in measured dielectric constant for that specimen. Between two test conditions there is a 0.04 g/cm^3 (2.6%) difference in dry density and a difference in measured dielectric constant of nearly 24 (90.6%). Percent difference between conditions calculated as the difference in the values between test conditions divided by the larger value. Two other test conditions have a difference in dry density of 0.23 g/cm^3 (12.5%) and a negligible change in measured dielectric constant. In addition, the differences in dry density between two sets of two test conditions is approximately the same, 0.23 g/cm^3, but for one of those sets the difference in measured dielectric constant between the two conditions is greater than 16 and for the other set is practically zero. Figure 4.1 shows that for a given increase or decrease in dry density, there is no reasonable approach to estimate the difference in expected measured dielectric constant for these data. Figure 4.2 for volumetric water content, however, displays a far more evident trend.

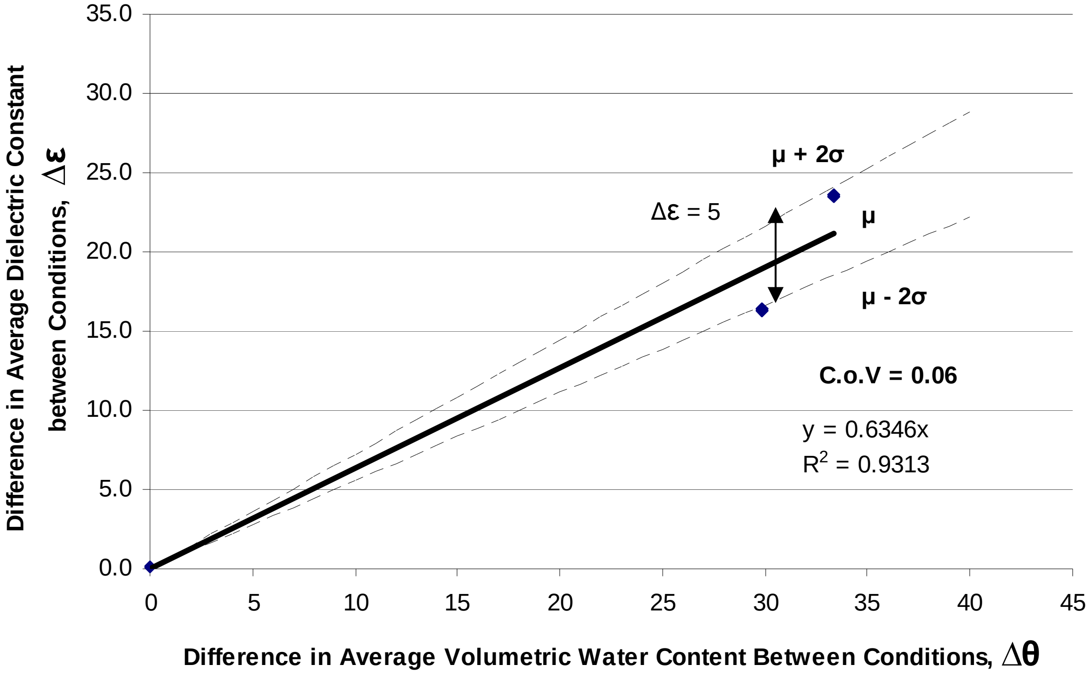

Figure 4.2 The Effect of the Difference in Average Volumetric Water Content for Test Conditions on the Difference in Measured Dielectric Constants for those Test Conditions

As the difference in average volumetric water content between tests increases, the difference in the measured dielectric constant between those tests increases. This trend gives a method to estimate the dielectric constant of a specimen based on the volumetric water content of that specimen and similar test results on other specimens. When looking at the coefficients of variation, c.o.v., from Figures 4.1 and 4.2, the likelihood of predicting the dielectric constant based on differences in volumetric water content and dry density can be compared. Coefficient of variation in figures labeled as C.o.V. but presented in text in proper manner with all lowercase letters. The coefficient of variation represents the dispersion of a value from the mean value. Coefficient of variation is equal to the standard deviation of a data set divided by the mean value of that data set. A small c.o.v. means that the majority of the points are close to the mean value and a large c.o.v. indicates that some points are far from the mean value. The coefficients of variation were calculated by assuming that the largest range of points around the mean trendline represents four full standard deviations, or two standard deviation above the mean value and two standard deviation below the mean value. The coefficient of variation is then calculated by dividing the standard deviation by the mean value for the data set. The estimated coefficient of variation was assumed constant for the data set and was used to plot plus and minus two standard deviations from the mean. These lines are also displayed in Figures 4.1 and 4.2. Figures 4.1 and 4.2 have coefficients of variation of 0.49 and 0.06, respectively. Thus the dispersion of the data is larger when based on the dry density than the volumetric water content. This indicates a better relationship between volumetric water content on a predicted dielectric constant than for dry density, but does not show anything about the impact of one of the variables versus another. In order to determine the relative impact of dry density and volumetric water content of the dielectric constant of a sand specimen, individual test results were investigated.

4.2.2 Sorting of Individual Test Results

The data from all 120 tests using the network analyzer device (Tables 4.1 through 4.4) were plotted to evaluate the relative effect of dry density and volumetric water content on the dielectric constant of sand. In order to determine the relative difference between the dry unit weight and the volumetric water content, the data were sorted separately based on these two variables. The relative density is used to sort the individual tests in terms of dry unit weight, because the relative density inherently compares all of the data as opposed to just presenting a number for dry unit weight that has no basis in terms of the other tests. For example, a dry density of 1.22 g/cm^3 versus a dry density of 1.81 g/cm^3 does not do justice to how far apart these two specimens were in the range of densities tested, but their relative densities of 0% and 100%, respectively, make this difference much more evident. These are the values of zero and one hundred percent relative density because the void ratios from these tests are the maximum and minimum void ratio values that were used in the relative density equation (4.1).

The data were sorted with respect to relative density by Low D_R, Medium D_R and High D_R. Low D_R indicates a relative density from 0 to 30%, Medium D_R indicates a relative density between 30 and 70%, and High D_R indicates a relative density greater than 70%. The data were also sorted separately with respect to volumetric water content. For this grouping, two sets were formed. One set is labeled dry and includes test specimens with volumetric water contents below 10 percent. The other set is labeled wet and includes test specimens with volumetric water content greater than 10 percent. The data sorted by relative density are plotted in terms of all of the variables influenced by water content against the resulting measured dielectric constant. These variables are volumetric water content (Figure 4.3), gravimetric water content (Figure 4.4), degree of saturation (Figure 4.5) and weight of water in the specimen (Figure 4.6). The data sorted by volumetric water content are plotted in terms of all of the variables influenced by the density of the specimen against the measured dielectric constant. These variables are dry unit weight (Figure 4.7), void ratio (Figure 4.8) and relative density (Figure 4.9).

The data sorted by relative density are plotted against all of the variables influenced by water, and the data sorted by volumetric water content are plotted against all of the variables influenced by dry density to try to quantify the relative impact of these two variables on the dielectric constant. Figures 4.3 through 4.9 are presented in this section, they are analyzed in section 4.2.3 Analysis of Individual Test Results.

The mean trendline of each data set, as well as plus and minus two standard deviations based on a constant coefficient of variation are plotted in Figures 4.3 through 4.9, and the coefficient of variation displayed was calculated assuming the largest range of the data around the trendline represents four total standard deviations.

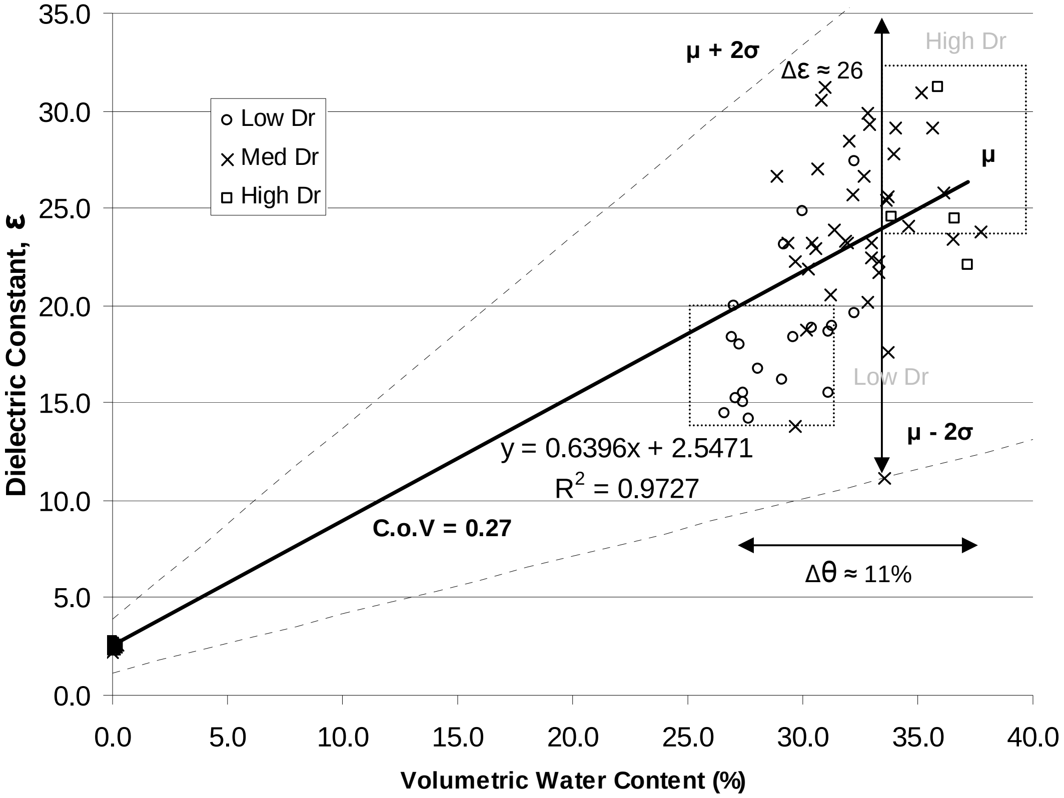

Figure 4.3 Volumetric Water Content versus Dielectric Constant for 120 Individual Tests in Network Analyzer Sorted by Relative Density

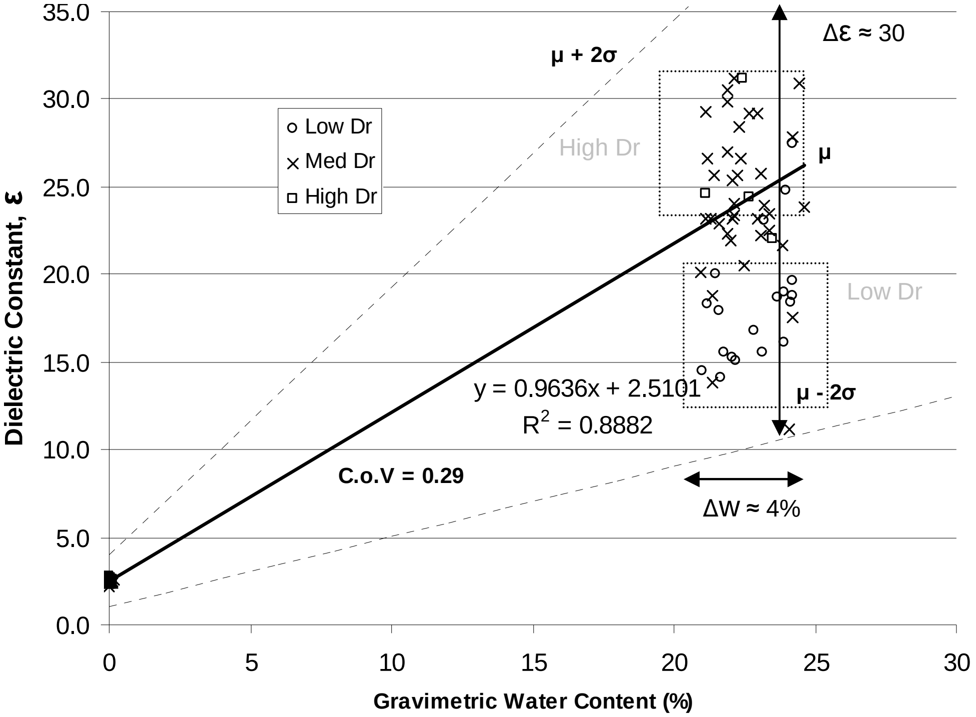

Figure 4.4 Gravimetric Water Content versus Dielectric Constant for 120 Individual Tests in Network Analyzer Sorted by Relative Density

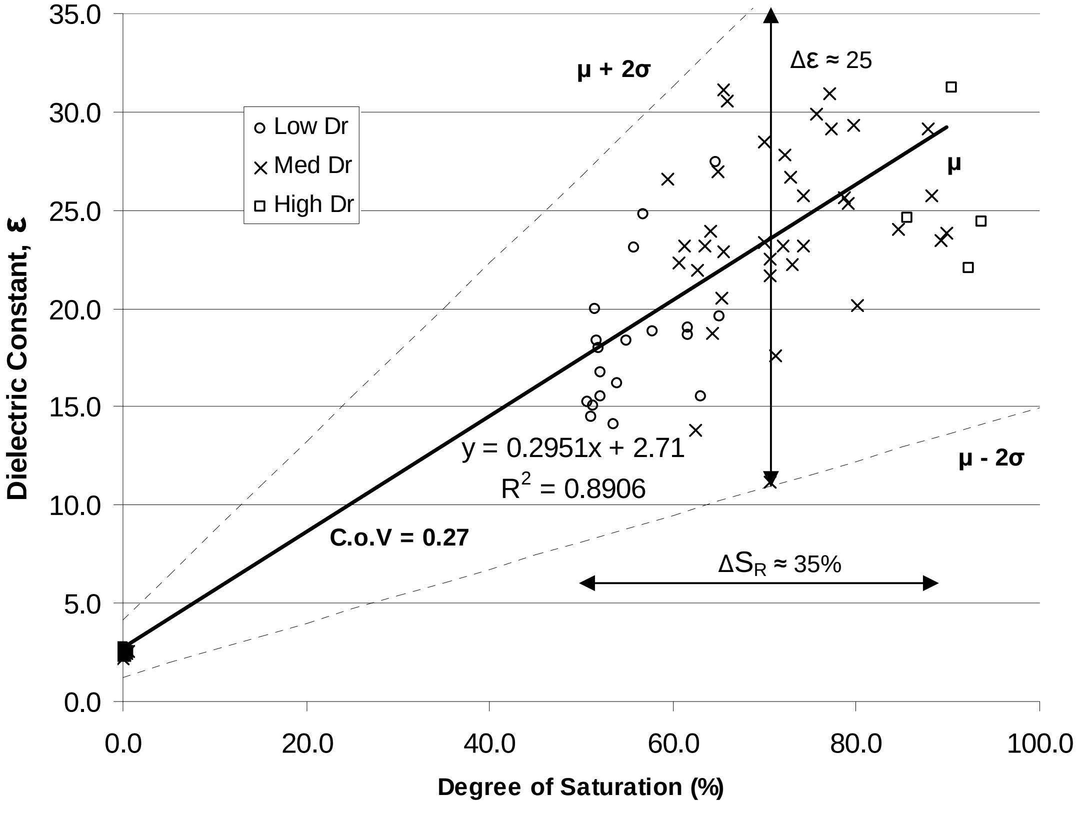

Figure 4.5 Degree of Saturation versus Dielectric Constant for 120 Individual Tests in Network Analyzer Sorted by Relative Density

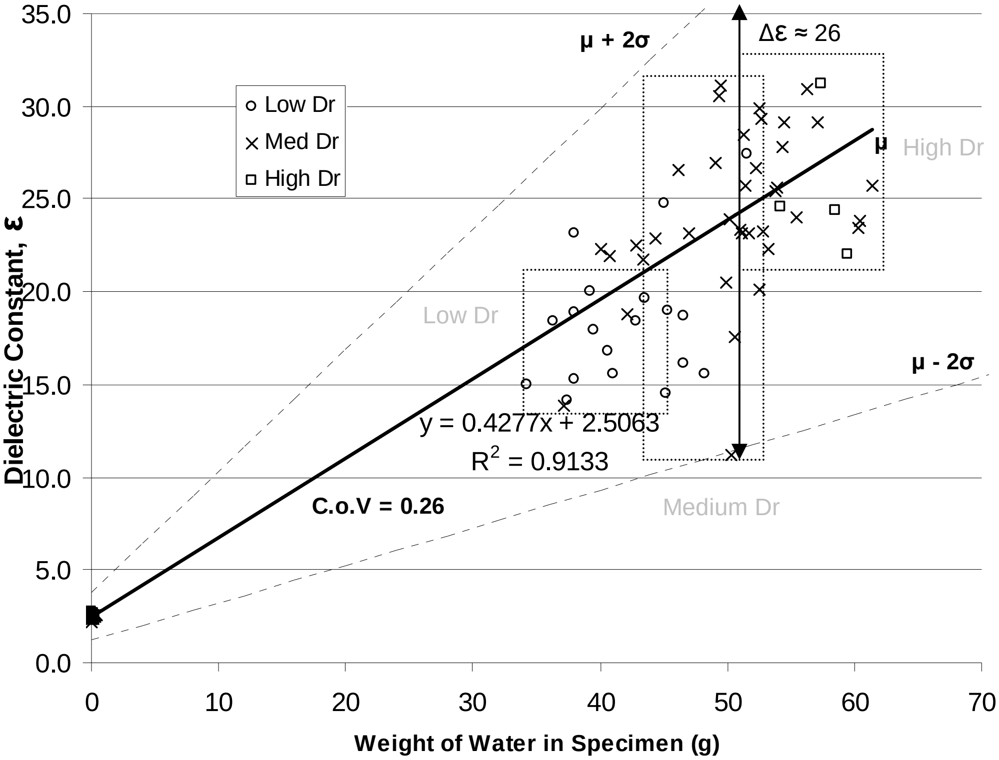

Figure 4.6 Weight of Water in Sand Specimen versus Dielectric Constant for 120 Individual Tests in Network Analyzer Sorted by Relative Density

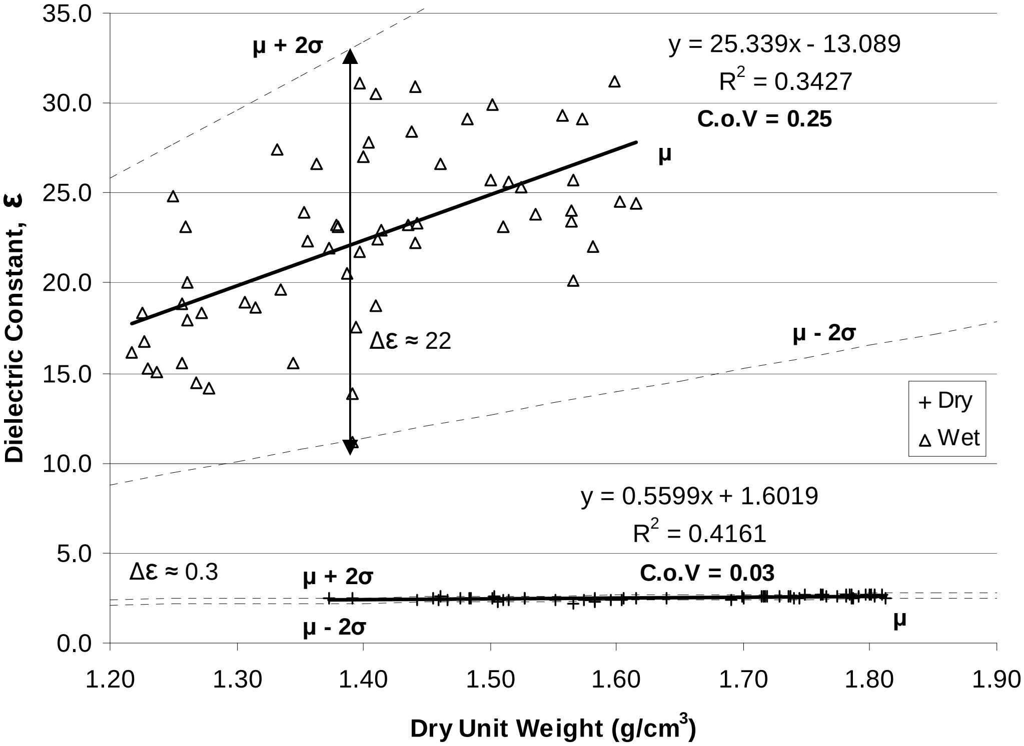

Figure 4.7 Dry Unit Weight versus Dielectric Constant for 120 Individual Tests in Network Analyzer Sorted by Volumetric Water Content

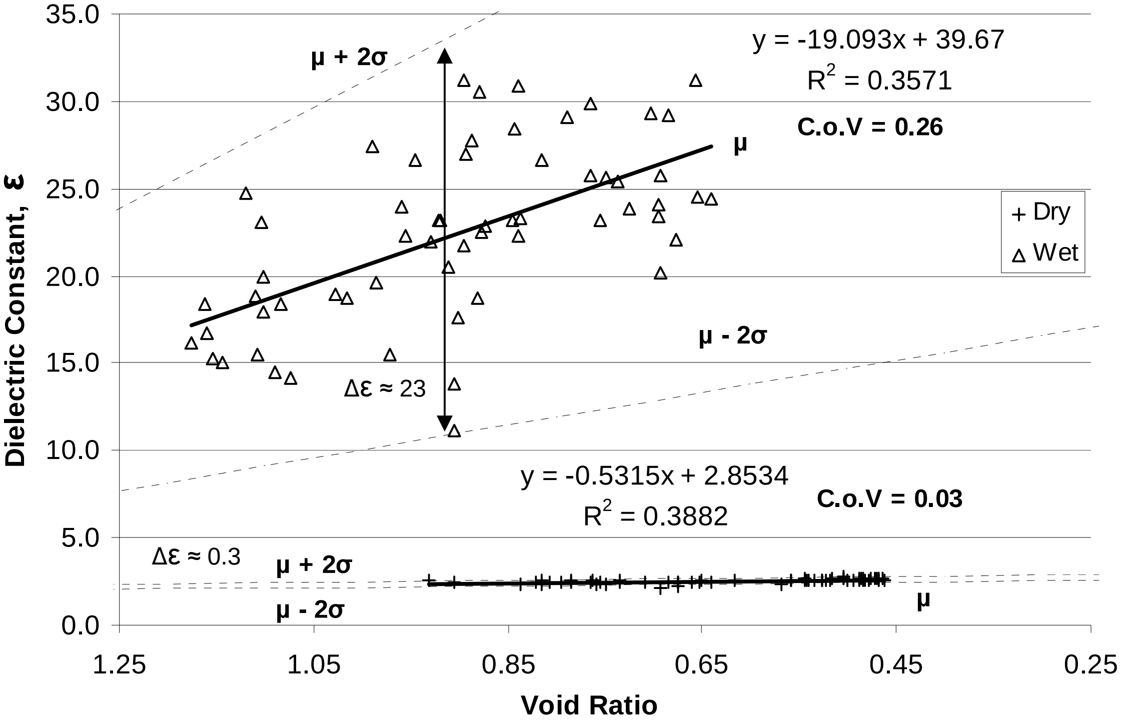

Figure 4.8 Void Ratio versus Dielectric Constant for 120 Individual Tests in Network Analyzer Sorted by Volumetric Water Content

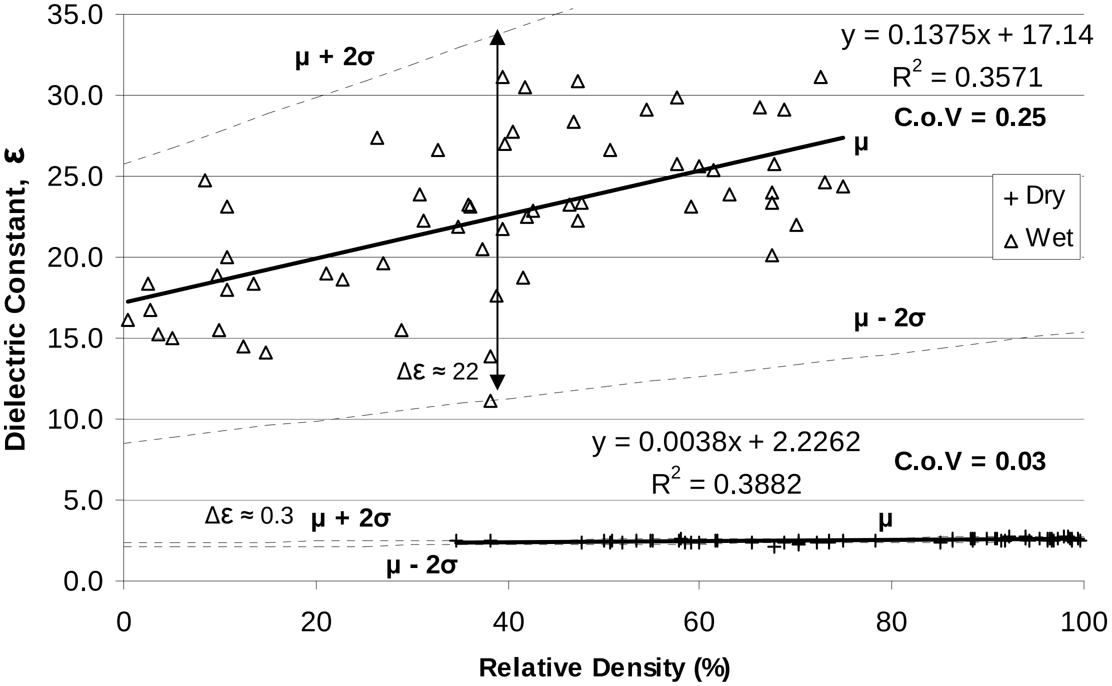

Figure 4.9 Relative Density versus Dielectric Constant for 120 Individual Tests in Network Analyzer Sorted by Volumetric Water Content

4.2.3 Analysis of Individual Test Results

Figures 4.3 through 4.6 show a general trend that with an increase in water content, there is an increase in the dielectric constant. The large cluster of points near a volumetric water content of zero have an approximate dielectric constant of 2.6. This is expected based on the dielectric of solid quartz particles. As water is added to the sample the dielectric constant increases to 32. This trend occurs regardless of the relative density of the specimens. This is best illustrated in Figure 4.5 for degree of saturation. Figure 4.5 has a larger percent spread of the wet samples on the x-axis than Figures 4.3 and 4.4; a spread of 35% versus 11% and 4% respectively. The trend is continually increasing dielectric constant with an increase in degree of saturation for this full span. What can be drawn from the closely spaced cluster of wet specimens in Figures 4.3 and 4.4 is that the Low D_R specimens generally lie below the mean trendline of the data set and the High D_R specimens generally lie above the mean trendline of the data set. Essentially this means the lower relative density specimens have a lower dielectric constant than the higher relative density specimens. This would tend to contradict previous research in that the specimens with low relative density (similar to porosity as shown by Arulanandan 1991 and Kaya 2001) should have more voids and more water in the specimen when saturated, therefore a higher dielectric constant. Figures 4.3 and 4.4 would therefore suggest that the relative density of the specimen does affect the dielectric constant in that an increase in relative density displays an increase in dielectric constant. Figure 4.6 settles this issue though, as it illustrates that in the 120 tests performed, the low D_R specimens have less water in them than the medium D_R specimens and even less water still than the high D_R specimens. This explains why the dielectric for the low D_R

specimens is typically lower than the high D_R specimens, because there was less water in the specimen during testing. This is better shown with another soil phase diagram (Figure 4.10).

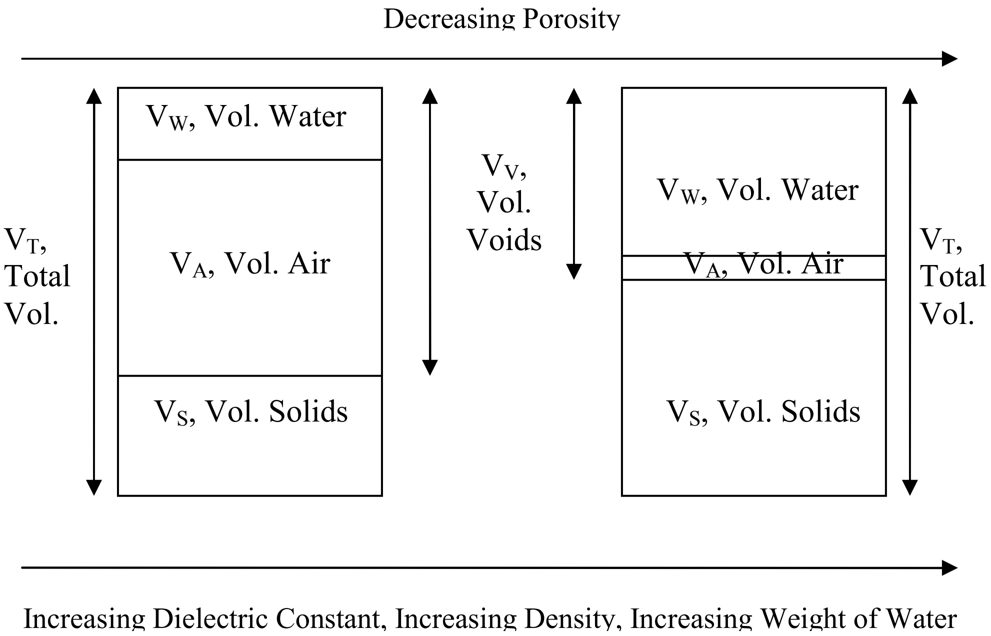

Figure 4.10 Soil Phase Diagram for Increasing Density, Increasing Weight of Water, and Increasing Dielectric Constant

Because the soil samples are not fully saturated, the porosity can decrease and the amount of water in the specimen can actually increase. The high relative density specimens have more water in the smaller total overall void space. The lower relative density specimens have larger void space that is partially occupied by air ($\varepsilon = 1$), which does not significantly affect the dielectric constant as much as water ($\varepsilon = 80$). There is less water in the low relative density specimens even though the porosity is higher than the high relative density specimens. For fully-saturated sands this would not be the case as the higher porosity specimens would have more water and a higher measured dielectric as shown by Kaya (2001) and Arulanandan (1991). The Martinez and Byrnes (2001) model for non-saturated sands more accurately describes the behavior shown in the network analyzer dielectric constant tests.

Based on Figures 4.3 through 4.6, water content has a significant effect on dielectric constant, with increasing volumetric water content producing a higher measured dielectric constant. Figures 4.7 through 4.9 must be analyzed to determine to what extent dry density affects the dielectric constant of a sand specimen.

Figures 4.7 through 4.9 confirm that the volumetric water content affects the dielectric constant in that all of the points in the dry set of specimens have lower measured dielectric constants than the points in the wet set of specimens. The trend of increasing dielectric constant with increasing volumetric water content is demonstrated in all seven Figures (4.3 – 4.9). It should be noted that the values of the x-axis for Figure 4.8 are in decreasing order because a higher void ratio actually indicates a lower dry unit weight. Thus, plotting void ratio in deceasing order is the same as plotting dry unit weight and relative density in increasing order.

What can also be interpreted from Figures 4.7 through 4.9 is that there is no trend of increasing dielectric constant with increasing dry unit weight for the dry specimens. There is no definable in the dielectric constant with an increase in dry unit weight from 1.35 to 1.8 g/cm^3 (84.3 pcf to 112 pcf) (Figure 4.7) and an increase in relative density from 35 to 99% (Figure 4.9). There are no sporadic points that could indicate a jump in dielectric constant in any direction either, as the coefficient of variation is 0.03 for the entire data set of dry test specimens in both Figures 4.7 and 4.9. This is better explained in Table 4.8 with the slopes of the best fit trendlines of Figures 4.7, 4.8 and 4.9.

Table 4.8 Slope of Trendlines for Dry Specimens for Dielectric Constant plotted against Dry Unit Weight, Void Ratio and Relative Density

Figure	Independent Parameter	Slope of Best Fit Line for Dry Tests
4.7	Dry Unit Weight	0.5599
4.8	Void Ratio	0.5315
4.9	Relative Density	0.0038

The slopes are all within 0.56 of zero, indicating a negligible change in dielectric constant with a change in parameters related to density. Figure 4.9 conveys this point the best, with a slope of only 0.0038.

A further look into the results from the wet specimens alone should reinforce the point that density has little effect on the dielectric constant and water has a much greater effect. Figure 4.11 is a 3D surface plot including the three principle variables of concern: dielectric constant, dry unit weight and volumetric water content. Data from the wet specimens only are plotted in Figure 4.10.

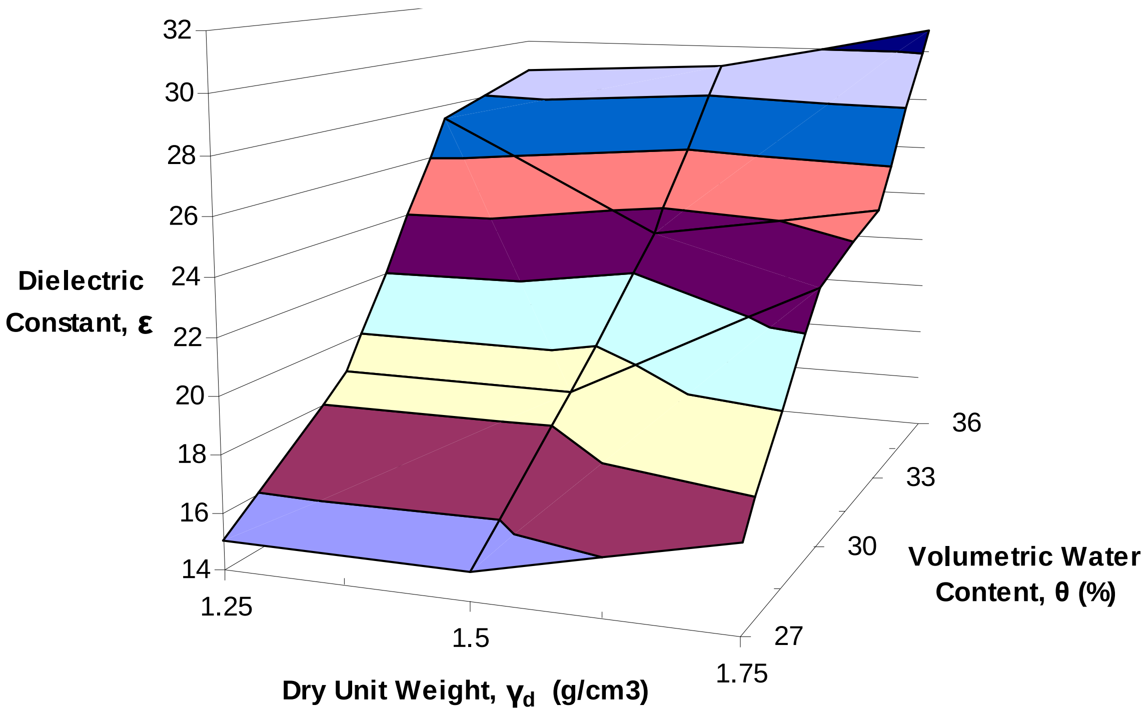

Figure 4.11 3D Surface Plot of Dry Unit Weight versus Volumetric Water Content versus Dielectric Constant for Wet Quartz Sand Test Specimens

Figure 4.11 displays the full range of dry unit weights and volumetric water contents that were present during testing. The figure illustrates that the degree of change of dielectric constant with respect to volumetric water content is much higher than for changes in the dry unit weight. At each dry unit weight interval, the dielectric constant continually increases with an increase in volumetric water content. This is not the case for the dielectric constant at each volumetric water content interval. For a volumetric water content of 33 the dielectric constant actually drops with increasing dry unit weight. Across the full range of dry unit weights tested, the dielectric constant changes from 15 to 18 for volumetric water contents near 27%, from 18 to 22 for volumetric water contents near 30%, from 27 to 24 for volumetric water contents near 33% and from 29 to 31 for volumetric water contents near 36%. Across the full range of volumetric water contents tested, the dielectric constant changes from 15 to 29 for dry unit weights near 1.25 g/cm^3, from 15 to 30 for dry unit weights near 1.5 g/cm^3 and from 18 to 31 for dry unit weights near 1.75 g/cm^3. These results are summarized in Table 4.9.

Table 4.9 Dielectric Constant Results from 3D Surface Plot of Dry Unit Weight versus Volumetric Water Content versus Dielectric Constant for Wet Quartz Sand Test Specimens

	Volumetric Water Content (%)				
	27	30	33	36	
1.25 g/cm^3	15	18	27	29	**Δ14**
1.50 g/cm^3	15			30	**Δ15**
1.75 g/cm^3	18	22	24	31	**Δ13**
	Δ3	**Δ4**	**Δ3**	**Δ2**	

Based on the 3D surface plot for the wet sand specimens it can be estimated that the volumetric water content has at least 13/4 = 3.25 and up to 15/2 = 7.5 times greater impact on the dielectric constant than dry unit weight. These numbers were taken from the smallest and largest difference in measured dielectric constant for varying volumetric water content and dry unit weight, or 15 and 13, and 4 and 2 respectively.

The dominant effect of volumetric water content on dielectric constant is evident from Figures 4.3 through 4.9. Figure 4.11 further illustrates the effect of volumetric water content on the dielectric constant of sand and also begins to estimate the extent of which water content affects the dielectric constant of sand relative to dry unit weight. Investigating smaller sample sizes of individual tests at similar conditions can help to quantify the magnitude of the effect on volumetric water content versus dry unit weight on the dielectric constant.

4.2.4 Analysis of Smaller Sample Size with Similar Conditions

To quantify the effect of water versus the effect of dry density on the dielectric constant, the influence of volumetric water content and dry unit weight was investigated separately and compared. The effects of water and dry density on the measured dielectric constant of an individual specimen are attempted to be isolated one at a time using this technique. In order to do this, individual samples with the same void ratio (within 0.02) or relative density (within 1%) and varying volumetric water contents were analyzed together. Specimens with the same volumetric water content (within 2%), degree of saturation (within .01%), or weight of water (within 1 g) in the specimen and varying densities were analyzed in the same manner. This way the effects of each parameter, volumetric water content and dry unit weight, can be examined individually and compared to determine which has a more significant effect.

Figure 4.12 is a compilation of all of the test specimens that have a relative density of $57.5\% \leq D_R \leq 59.5\%$. There are six specimens that fall in this category, and they are plotted versus volumetric water content on the x-axis and dielectric constant on the y-axis. Figure 4.13 includes all of the specimens that have a void ratio of $0.88 \leq e_0 \leq 0.92$. There are five specimens that fit this description, and they are also plotted versus volumetric water content on the x-axis and dielectric constant on the y-axis.

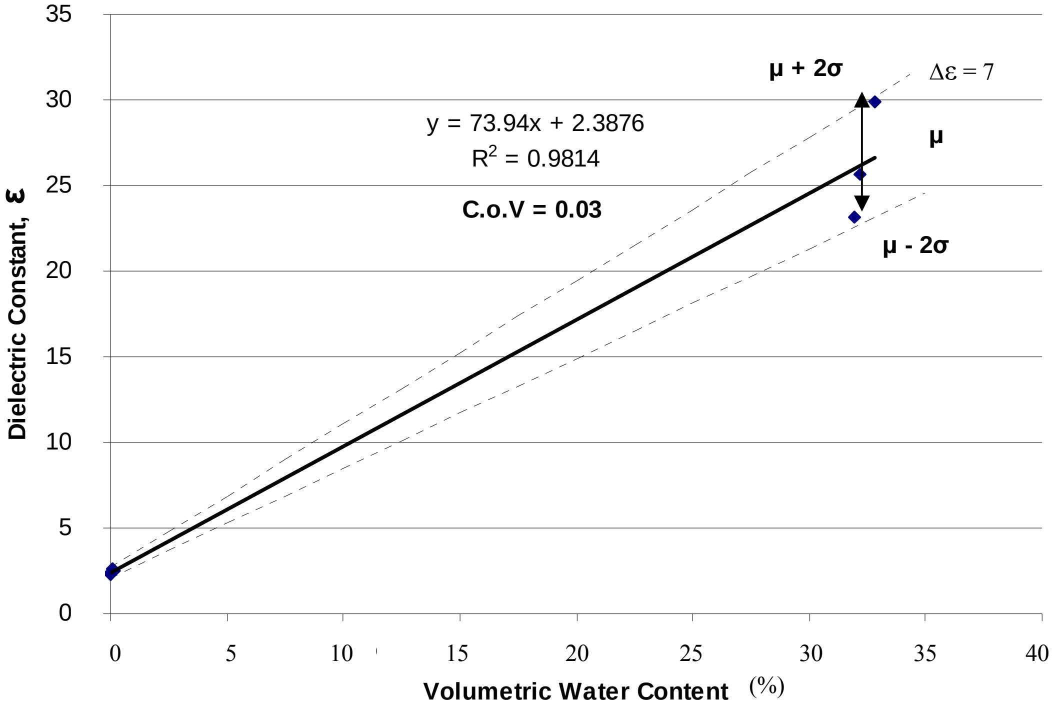

Figure 4.12 Volumetric Water Content versus Dielectric Constant for Sand Specimens with a Relative Density, D_R = 58.5% (n=6)

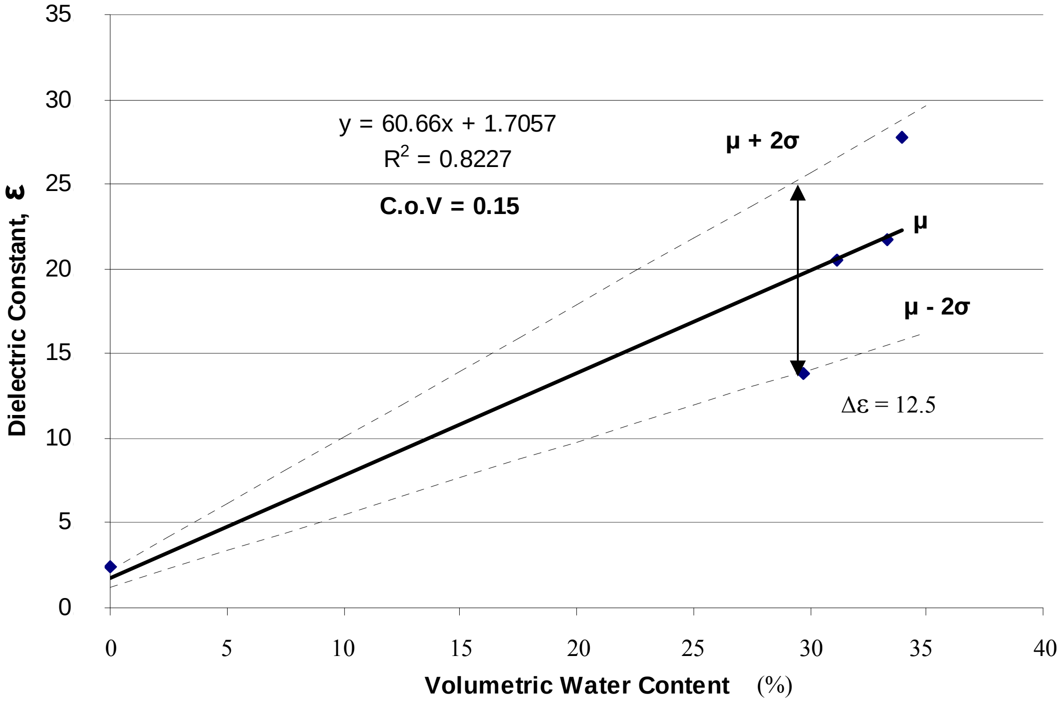

Figure 4.13 Volumetric Water Content versus Dielectric Constant for Sand Specimens with a Void Ratio, e_0 = 0.90 (n=5)

The next set of figures will be from test specimens that have the same volumetric water content, degree of saturation, or weight of water in the specimen and varying densities. Figure 4.14 is comprised of all of the test specimens that have a volumetric water content of 30% ≤ θ ≤ 34%. There are 12 specimens that fall in this category, and they are plotted with relative density on the x-axis versus dielectric constant on the y-axis. Figure 4.15 is made up from all of the specimens that have a degree of saturation of .09% ≤ S_R ≤ 0.11%. There are 20 specimens that fit this description, and they are also plotted with relative density on the x-axis versus dielectric constant on the y-axis. Finally, Figure 4.16 is a compilation of all of the tests specimens that have a weight of water of 51 g ≤ W_W ≤ 53 g. There are seven specimens that match this description and they too are plotted with relative density on the x-axis versus dielectric constant on the y-axis.

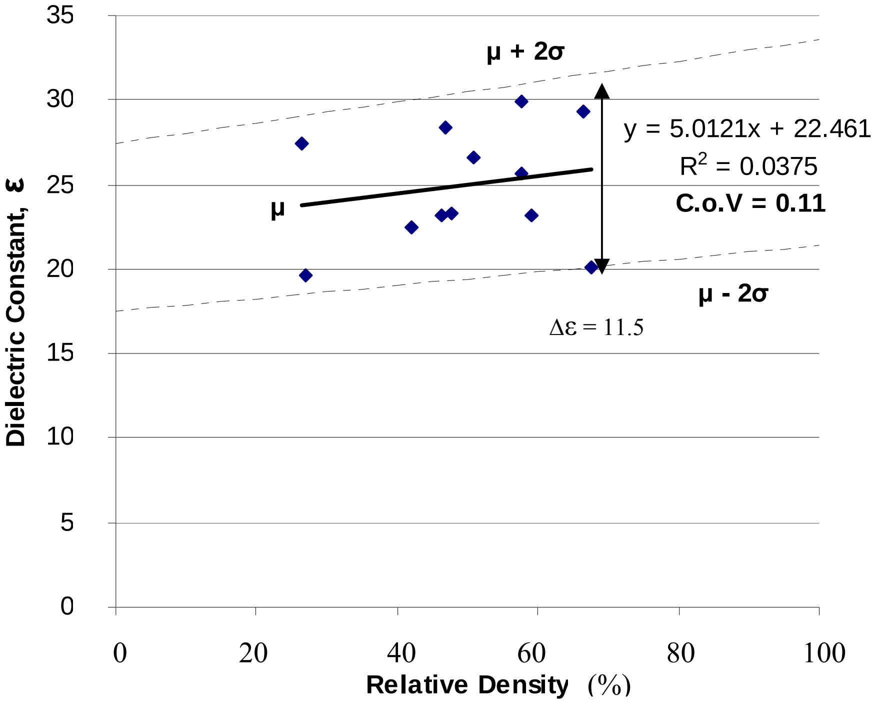

Figure 4.14 Relative Density versus Dielectric Constant for Sand Specimens with a Volumetric Water Content, θ = 32% (n=12)

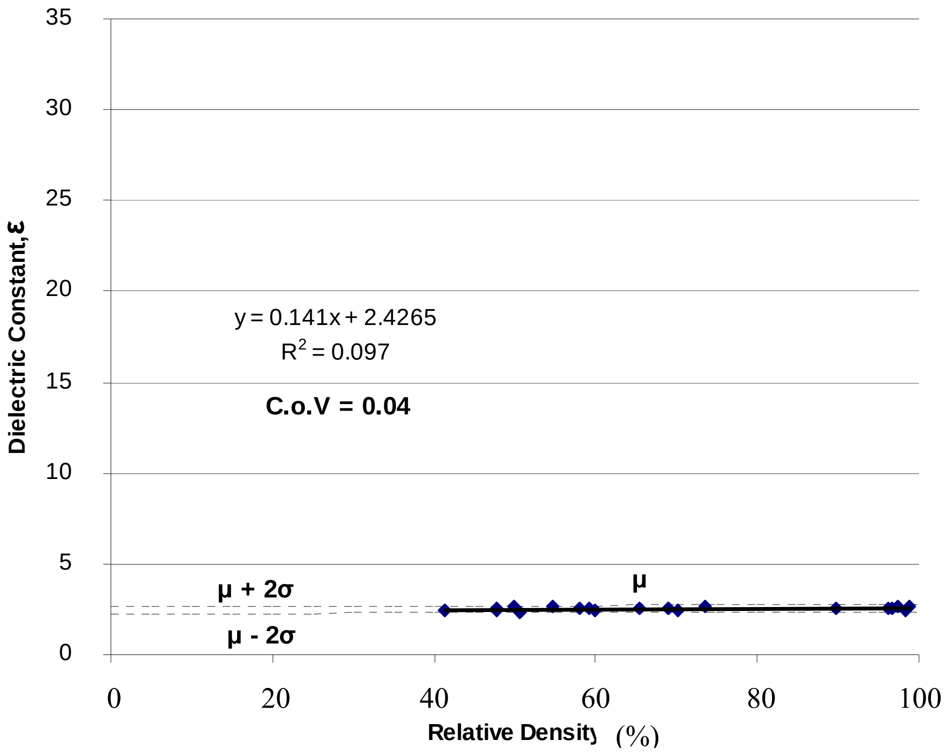

Figure 4.15 Relative Density versus Dielectric Constant for Sand Specimens with a Degree of Saturation, $S_R = 0.10\%$ (n=20)

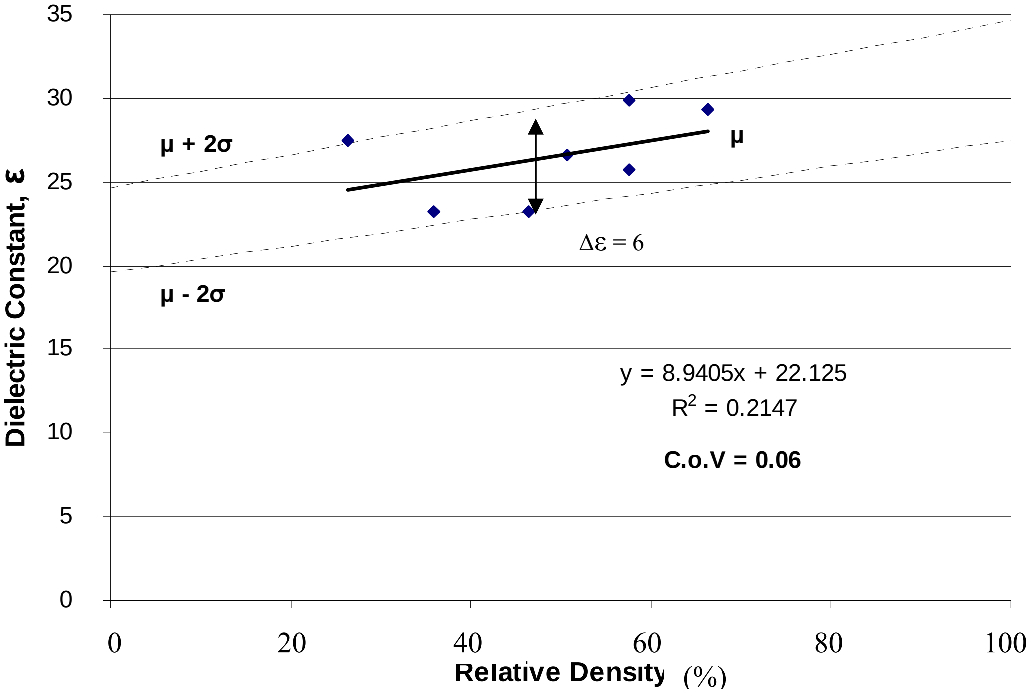

Figure 4.16 Relative Density versus Dielectric Constant for Sand Specimens with a Weight of Water in the Specimen, $W_W = 52$ g (n=7)

Because the parameters on the x-axis, volumetric water content and relative density, are both plotted in percent, and percentages are on scales of 0 to 100, the slopes of the graphs can be compared directly. The larger the slope, the more the dielectric constant is affected by changes in the given parameter. Comparison of one slope to another can be used to quantify how much a parameter affects the dielectric constant. The data in each figure were fitted with a linear best-fit line. Regression coefficients (R^2) were also calculated. The parameters for Figures 4.11 through 4.15 are presented in Table 4.10 along with the statistical analysis results.

Table 4.10 Results from Analysis of Smaller Sample Sizes (n) with Similar Conditions

Fig. No.	**Parameters**	**Constant**	**n**	**Eqn.**	**R^2**	**C.o.V**	**Slope, m**
4.11	ε vs θ	$D_R = 58.5\%$	6	y = 73.94x + 2.3876	0.981	0.03	73.94
4.12	ε vs θ	$e_0 = 0.90$	5	y = 60.66x + 1.7057	0.823	0.15	60.66
4.13	ε vs D_R	$\theta = 32\%$	12	y = 5.0121x + 22.461	0.040	0.11	5.01
4.14	ε vs D_R	$S_R = 0.10\%$	20	y = 0.141x + 2.4265	0.097	0.04	0.14
4.15	ε vs D_R	$W_W = 52$ g	7	y = 8.9405x + 22.125	0.215	0.06	8.94

For consistent dry unit weight and varying volumetric water content, the slope in Figure 4.12 for test specimens with a relative density of 58.5% is 73.9, and in Figure 4.13 for the test specimens with a void ratio of 0.90 the slope is 60.7. For consistent volumetric water content and varying relative density, the slope in Figure 4.14 for test specimens with a volumetric water content of 32% is 5.0, in Figure 4.15 for test specimens with a degree of saturation of 0.10% (dry) the slope is 0.141 and in Figure 4.16 for test specimens with a weight of water of 52 g the slope is 8.9.

Using these slopes, the effect of the volumetric water content on the dielectric constant versus the effect of dry density can be quantified. The results from this analysis can be seen in Table 4.11. The ratio of the slopes of the figures with varying water content divided by the slopes of the figures with varying density (as shown in the last column of Table 4.11) quantifies the relative magnitude of the effect of water content versus dry density on the dielectric constant.

Table 4.11 Results from Slope Comparisons of Smaller Sample Sizes with Similar Conditions [(1) = figure in column 1, (2) = figure in column 2, (3) = slope of figure listed in column 1, (4) = slope of figure listed in column 2]

Figure with Varying Water Content (1)	Figure with Varying Density (2)	Slope from (1) = (3)	Slope from (2) = (4)	Ratio of Effects = (3)/(4)
Figure 4.11	Figure 4.13	73.9	5.0	15
	Figure 4.14	73.9	0.141	524
	Figure 4.15	73.9	8.9	8
Figure 4.12	Figure 4.13	60.7	5.0	12
	Figure 4.14	60.7	0.141	430
	Figure 4.15	60.7	8.9	7

Effects of volumetric water content on the dielectric constant can be up to 525 times greater than the effects of density on the dielectric constant (Table 4.11). The coefficients of variation of the figures the slopes were taken from are all less than 0.15 (Table 4.10). The factors of 525 and 430 times greater effect of volumetric water content than dry density on the dielectric constant may be debated, but in general, the results indicate that volumetric water content has between 7 and 15 times greater effect on the dielectric constant and sand specimens than dry density. These numbers are slightly larger but fairly consistent with the results from the 3D surface plot (Figure 4.11) and Table 4.9.

4.3 Summary

The first step of analyzing Figures 4.1 and 4.2 and Tables 4.1 through 4.7 presented that volumetric water content had a strong relationship with dielectric constant. However, in regards to dry density, the relative impact of one variable over another could not be estimated.

Upon analysis of Figures 4.3 through 4.9 and Table 4.8 the dominant effect of volumetric water content on dielectric constant was evident. The trend of increasing dielectric constant with increasing volumetric water content was demonstrated in all seven Figures (4.3 – 4.9). Figure 4.11 and Table 4.9 illustrated the effect of volumetric water content on the dielectric constant of sand and also began to estimate the extent of which water content affects the dielectric constant of sand relative to dry unit weight. The initial estimates suggested water is three to seven times more influential on the dielectric constant of sands relative to the impact of dry density.

Analysis of smaller sample sizes with similar conditions in Figures 4.12 through 4.16 and Tables 4.10 and 4.11 clarified the quantity of the effects of volumetric water content versus dry density on the dielectric constant of sand. Volumetric water content was found to have up to 525 times more impact on the dielectric constant than dry density, but typical results show this quantifiable difference is more reasonably between 7 and 15 times.

5. Conclusions

Dielectric testing of sand samples was performed on sand specimens. The purpose of these tests was to confirm or refute the hypothesis that the effects of volumetric water content on the dielectric constant of a soil-water system dominate the effects of dry density on the dielectric constant of a soil-water system.

5.1 Summary

Thirty tests to measure dielectric constant of sand samples at four different conditions were performed in the network analyzer. The sand samples were prepared at varying states of water content, from air dry to generally saturated, and at varying densities, with values in test specimen density ranging from 1.22 to 1.81 g/cm^3. The dielectric constant measurement results were used to determine the relative influence of water content and dry density on the dielectric constant of a quartz sand-water system.

5.2 Conclusions

Volumetric water content was found to have up to 525 times more impact on the dielectric constant than dry density, but typical results show this quantifiable difference is more reasonably between 7 and 15 times greater effect for volumetric water content than dry density on the dielectric constant of sand. These results confirm the hypothesis that the effects of volumetric water content on the dielectric constant of a soil-water system dominate the effects of dry density on the dielectric constant of a soil-water system.

Some limitations to these results are a small sample size and the network analyzer sensitivity. Only 120 total tests were performed, thirty at each condition. An increased number of tests would lead to more accuracy in determination of trends and in quantification of the effects of soil parameters on the dielectric constant. The network analyzer had variance in results from test to test. This variance was estimated as presented by the variance testing results in Chapter 3. The variance was found to be as much as a value of 3 in dielectric constant between subsequent tests. Given that the quantifiable difference in the effect of volumetric water content is 7 to 15 times greater than dry density, this network analyzer sensitivity would not change the findings of this study, but is still a limitation to the test results.

5.3 Practical Implications

A greater knowledge of the dielectric constant of the soil-water system in the ground will give a greater knowledge of the expected response of a RF signal into the ground. As far as dielectric measurements are concerned, this study has shown that the volumetric water content and its variation due to changes in temperature, humidity and other external factors is a more important piece of information than dry density and how the dry density of an in-situ soil changes over time. Therefore, knowing the volumetric water content as opposed to the dry density of a soil will yield a higher accuracy in detecting an object, a change in material, or a void or crack in the subsurface, because the change in the reflected signal from the detection of one of these objects due to a change in water content will more easily be realized than dielectric changes based on density differences.

In addition, the water content of a soil is one of the most rapidly changing variables in the field. Water content can fluctuate from hour to hour, even minute to minute as water flows through a soil medium. The density however remains relatively constant for a soil over a long period of time. Because the dielectric constant changes with a change in water content, the dielectric constant for a soil at a given site may vary rapidly over time. Knowing the water content of the soil at the time of interest is a necessity if the dielectric constant of that soil is to be measured or determined.

This knowledge of water content and how it can change for a given site may save valuable time and money in determining which tests must be performed on soil samples for dielectric constant measurements. Water content should be considered a paramount piece of information, with dry density secondary, perhaps unneeded, for determining dielectric constant of a soil-water system.

6. Recommendations

The following are recommendations for further work based on the findings of this study, and ideas that were generated from preliminary results during testing.

6.1 Further Work on TEM Cell and Network Analyzer

The TEM cell results as shown in Appendix A should be analyzed to determine if they too agree with the hypothesis as did the network analyzer results. This will also give insight into different soil types (as opposed to solely clean quartz sand) and if volumetric water content is a dominating factor over dry density for other soil types.

Kaolinite should be tested to determine if the hypothesis holds true for a clay material. The loess will start to give an idea about other soil types, but a clay should be added to testing as the loess still classifies as a silty sand.

Kaolinite and loess should both be tested in the network analyzer to further investigate the influence of density and water content on the dielectric constant. In addition, all testing performed in the network analyzer should be regulated so that the probe makes the same contact pressure with the soil tested for dielectric constant. This could be performed with a fulcrum device that uses the same static weight to lift the sample towards the probe, a hydraulic piston with a uniform pressure between each test that lifts the soil sample towards the probe, or some other means. The reproducibility of a testing procedure would reduce the variance in results and some sources of error in the network analyzer testing.

6.2 Coaxial Cell

Tests of all three soil types should be performed in a coaxial cell. This coaxial cell shape would remove or reduce the fringing field effects encountered in the TEM Cell tests (Pelletier et al. 2011).

6.3 Soil

A more active clay than kaolinite should be used to cover the broad range of soils found in nature. Activity of a soil is the plasticity index, PI, divided by the percent of clay-sized particles present. High activity soils indicate that large volume change (swelling) takes place when wetted and large shrinkage takes place when dried. Soils with high activity also are typically chemically reactive. This could be an illite or a smectite, and the use of either of these in testing would allow for tests at much higher water content.

6.4 Soil Suction

Preliminary work on dielectric constant versus soil suction indicates a relationship is present (Cook 1998). The soil suction, or negative pressure of the water inside the pores of soil takes into account numerous soil variables. These variables include, but are not limited to: soil grain size, density, volumetric water content, pore water chemistry and soil mineral constituents. Further analysis of the suction of soil may yield a correlation with dielectric constant for soil-water systems.

Soil suction data could eliminate the need for direct comparison of results and the argument of the relative effect of one soil parameter over another. If all of the parameters that affect dielectric constant are lumped together into one measurement, then a dielectric prediction based on that single measurement could be the most accurate method to estimate the dielectric constant of a soil-water system.

This is an idea that was generated from preliminary results of this study, and in turn preliminary testing was performed to determine the relevance of suction to dielectric constant. The results from the preliminary testing can be seen in Appendix C in Figures C.1, C.2 and C.3.

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Appendix A

TEM Cell Results

Table A.1 Results from TEM Cell Testing on 17% Volumetric Water Content Silica Sand

TEM Cell Testing				Left				Center				Right			
Sample	Weight (g)	Volume (cm^3)	Density (g/cm^3)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)
17v_1	709.8	480	1.48	30.3	59.3	55.7	14.2	20.9	58.9	54.0	14.9	30.3	74.1	68.5	14.8
17v_2	696.5	480	1.45	19.9	45.8	42.6	14.3	10.9	54.0	48.4	15.1	11.0	41.9	38.1	14.0
17v_3	687.8	480	1.43	10.9	28.7	26.5	14.3	15.7	56.9	51.6	14.8	10.9	24.6	22.8	15.6
17v_4	614	480	1.28	15.5	45.9	42.2	13.9	19.7	62.7	57.3	14.5	20.8	50.7	46.9	14.4
17v_5	644.9	480	1.34	30.7	58.1	54.7	14.4	21.0	50.1	46.4	14.6	32.7	58.3	55.3	13.2
AVG			**1.40**				**14.2**				**14.8**				**14.4**
STD			**0.08**				**0.2**				**0.2**				**0.9**
COV			**0.06**				**0.0**				**0.0**				**0.1**

Room Temperature 77

Room Humidity 43%

Overall Averages				
w % (grav)	**STD**	**COV**		**Volumetric Water Content**
14.5	**0.5**	**0.03**		**17.7**

Table A.2 Results from TEM Cell Testing on 27% Volumetric Water Content Silica Sand

TEM Cell Testing				Left				Center				Right			
Sample	Weight (g)	Volume (cm^3)	Density (g/cm^3)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)
27v_1	738.1	480	1.54	52.3	95.7	88.0	21.6	30.9	72.6	65.4	21.0	30.6	69.8	62.8	21.9
27v_2	736.6	480	1.53	30.2	86.8	76.7	21.7	30.2	74.6	66.6	22.0	30.9	77.7	69.3	22.0
27v_3	744.2	480	1.55	30.0	77.9	69.4	21.5	30.6	81.8	72.7	21.8	30.8	78.6	69.8	22.7
27v_4	739.5	480	1.54	30.9	114.3	99.7	21.2	31.2	71.0	64.0	21.4	30.7	75.5	67.4	22.1
27v_5	761.1	480	1.59	30.0	72.0	64.5	21.8	30.8	83.2	73.9	21.7	30.1	87.5	77.3	21.5
AVG			**1.55**				**21.6**				**21.6**				**22.0**
STD			**0.02**				**0.2**				**0.4**				**0.4**
COV			**0.01**				**0.0**				**0.0**				**0.0**

Room Temperature	77
Room Humidity	43%

Overall Averages				
w % (grav)	**STD**	**COV**		**Volumetric Water Content**
21.7	**0.4**	**0.02**		**27.7**

Table A.3 Results from TEM Cell Testing on 2% Volumetric Water Content Loess

TEM Cell Testing				Left				Center				Right			
Sample	Weight (g)	Volume (cm^3)	Density (g/cm^3)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)
2%_1	664.8	480	1.39	30.3	49.5	49.2	1.6	20.9	42.9	42.5	1.9	30.3	55.7	55.2	2.0
2%_2	633.3	480	1.32	19.9	40.5	40.2	1.5	10.9	22.8	22.6	1.7	11.0	36.3	35.9	1.6
2%_3	633.2	480	1.32	11.0	29.2	28.9	1.7	15.8	34.5	34.2	1.6	10.9	27.7	27.4	1.8
2%_4	636.2	480	1.33	15.6	29.0	28.8	1.5	19.7	46.9	46.4	1.9	20.8	34.8	34.6	1.4
2%_5	616.5	460	1.34	30.7	51.8	51.5	1.4	21.0	49.4	48.9	1.8	32.7	59.2	58.8	1.5
AVG			**1.34**				**1.5**				**1.8**				**1.7**
STD			**0.03**				**0.1**				**0.1**				**0.2**
COV			**0.02**				**0.1**				**0.1**				**0.1**

Room Temperature	77
Room Humidity	43%

Overall Averages				
w % (grav)	**STD**	**COV**		**Volumetric Water Content**
1.7	**0.2**	**0.11**		**2.2**

Table A.4 Results from TEM Cell Testing on 6% Volumetric Water Content Loess

TEM Cell Testing				**Left**				**Center**				**Right**			
Sample	Weight (g)	Volume (cm^3)	Density (g/cm^3)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)
6%_1	623.8	480	1.30	52.6	83.2	81.7	5.2	31.1	54.4	53.2	5.4	30.8	52.4	51.3	5.4
6%_2	608.5	480	1.27	30.3	43.7	43.1	4.7	30.4	56.0	54.7	5.3	30.0	48.8	47.9	5.0
6%_3	582	480	1.21	30.1	50.5	49.5	5.2	30.7	48.2	47.3	5.4	30.9	56.0	54.8	5.0
6%_4	528.9	450	1.18	31.5	63.6	62.1	4.9	31.4	51.7	50.7	5.2	30.7	61.6	60.1	5.1
6%_5	551.7	480	1.15	30.3	46.6	45.8	5.2	30.9	57.9	56.6	5.1	30.2	49.0	48.1	5.0
AVG			**1.22**				**5.0**				**5.3**				**5.1**
STD			**0.06**				**0.2**				**0.2**				**0.1**
COV			**0.05**				**0.0**				**0.0**				**0.0**

Room Temperature	77
Room Humidity	43%

Overall Averages				
w % (grav)	**STD**	**COV**		**Volumetric Water Content**
5.1	**0.2**	**0.04**		**6.0**

Table A.5 Results from TEM Cell Testing on 17% Volumetric Water Content Loess

TEM Cell Testing				**Left**				**Center**				**Right**			
Sample	Weight (g)	Volume (cm^3)	Density (g/cm^3)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)
17%_1	878.3	480	1.83	30.3	72.4	68.4	10.5	20.9	83.2	77.2	10.7	30.3	103.3	96.3	10.6
17%_2	865.8	480	1.80	19.9	90.6	84.1	10.1	10.9	43.7	40.7	10.1	11.0	38.8	36.2	10.3
17%_3	1002.2	480	2.09	11.0	35.7	33.4	10.3	15.7	65.5	60.9	10.2	10.9	62.9	58.0	10.4
17%_4	826.8	480	1.72	15.6	50.5	47.3	10.1	31.5	77.4	73.2	10.1	20.8	126.2	116.2	10.5
17%_5	852.4	480	1.78	30.7	108.7	101.4	10.3	20.9	82.6	77.0	10.0	32.7	113.1	105.6	10.3
AVG			**1.84**				**10.3**				**10.2**				**10.4**
STD			**0.14**				**0.2**				**0.3**				**0.1**
COV			**0.08**				**0.0**				**0.0**				**0.0**

Room Temperature	77
Room Humidity	43%

Overall Averages				
w % (grav)	**STD**	**COV**		**Volumetric Water Content**
10.3	**0.2**	**0.02**		**17.2**

Table A.6 Results from TEM Cell Testing on 30% Volumetric Water Content Loess

TEM Cell Testing				**Left**				**Center**				**Right**			
Sample	Weight (g)	Volume (cm^3)	Density (g/cm^3)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)
30%_1	907.7	480	1.89	30.3	63.5	58.4	18.1	20.9	50.4	45.8	18.5	30.3	70.6	64.4	18.2
30%_2	915.3	480	1.91	19.9	49.4	44.9	18.0	10.9	39.0	34.6	18.6	11.0	47.0	41.4	18.4
30%_3	936.5	480	1.95	11.0	40.9	36.3	18.2	15.8	49.2	44.1	18.0	10.9	33.0	29.6	18.2
30%_4	937	480	1.95	15.6	71.2	62.7	18.0	19.7	82.0	72.4	18.2	20.8	56.2	50.8	18.0
30%_5	929	480	1.94	30.7	75.3	68.5	18.0	21.0	44.6	40.9	18.6	32.7	74.2	67.8	18.2
AVG			**1.93**				**18.1**				**18.4**				**18.2**
STD			**0.03**				**0.1**				**0.2**				**0.2**
COV			**0.01**				**0.0**				**0.0**				**0.0**

Room Temperature	77
Room Humidity	43%

Overall Averages				
w % (grav)	**STD**	**COV**		**Volumetric Water Content**
18.2	**0.2**	**0.01**		**29.7**

Table A.7 Results from TEM Cell Testing on 33% Volumetric Water Content Loess

TEM Cell Testing				**Left**				**Center**				**Right**			
Sample	Weight (g)	Volume (cm^3)	Density (g/cm^3)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)	Tin Wt (g)	Wet Wt (g)	Dry Wt (g)	Gravimetric Water Content (%)
33%_1	884.7	480	1.84	52.4	66.8	64.3	21.0	31.0	52.9	49.1	21.0	30.8	54.8	50.6	21.2
33%_2	915.2	480	1.91	30.2	45.0	42.4	21.3	30.3	52.6	48.7	21.2	31.0	62.6	57.0	21.5
33%_3	921.1	480	1.92	30.1	58.4	53.5	20.9	30.7	50.5	47.1	20.7	30.0	61.9	56.3	21.3
33%_4	926.6	480	1.93	31.0	61.2	56.0	20.8	31.3	65.2	59.3	21.1	30.7	57.6	53.0	20.6
33%_5	888.8	480	1.85	30.0	58.7	53.8	20.6	30.8	69.5	62.8	20.9	30.2	73.6	66.1	20.9
AVG			**1.89**				**20.9**				**21.0**				**21.1**
STD			**0.04**				**0.3**				**0.2**				**0.4**
COV			**0.02**				**0.0**				**0.0**				**0.0**

Room Temperature 77

Room Humidity 43%

Overall Averages				
w % (grav)	**STD**	**COV**		**Volumetric Water Content**
21.0	**0.3**	**0.01**		**32.8**

Appendix B

Additional Network Analyzer Results

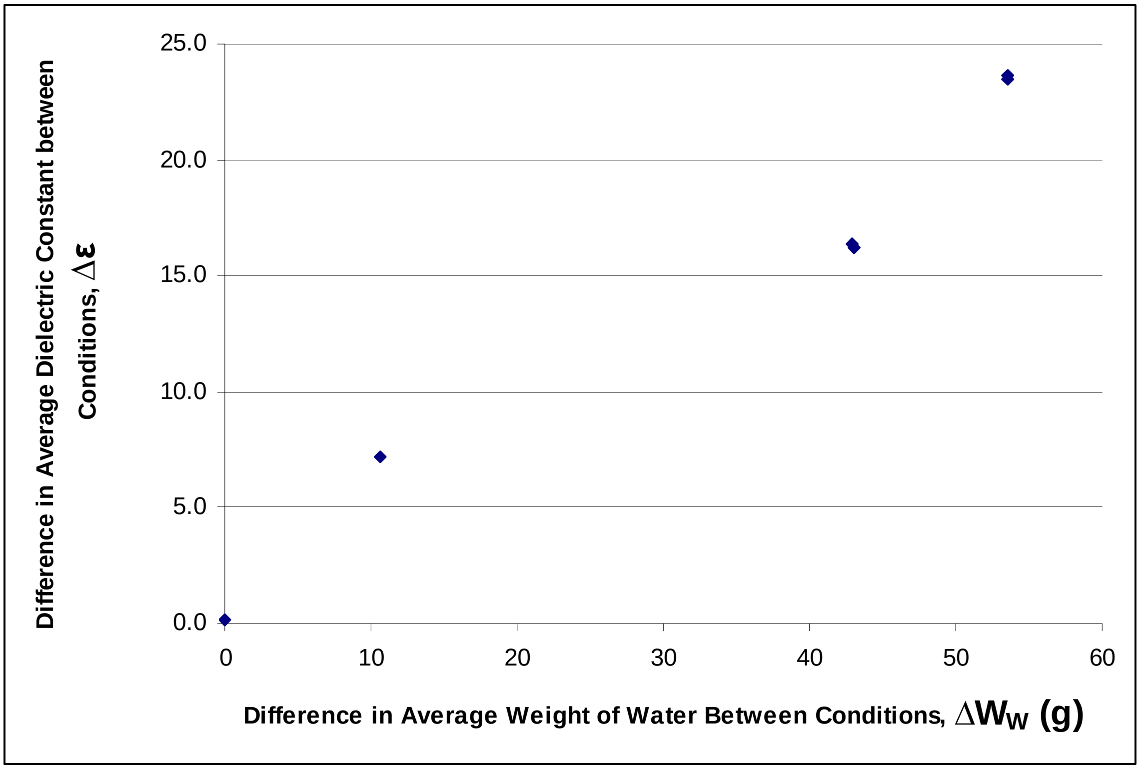

Figure B.1 The Effect of the Difference in Average Weight of Water for Test Conditions on the Difference in Measured Dielectric Constants for those Test Conditions

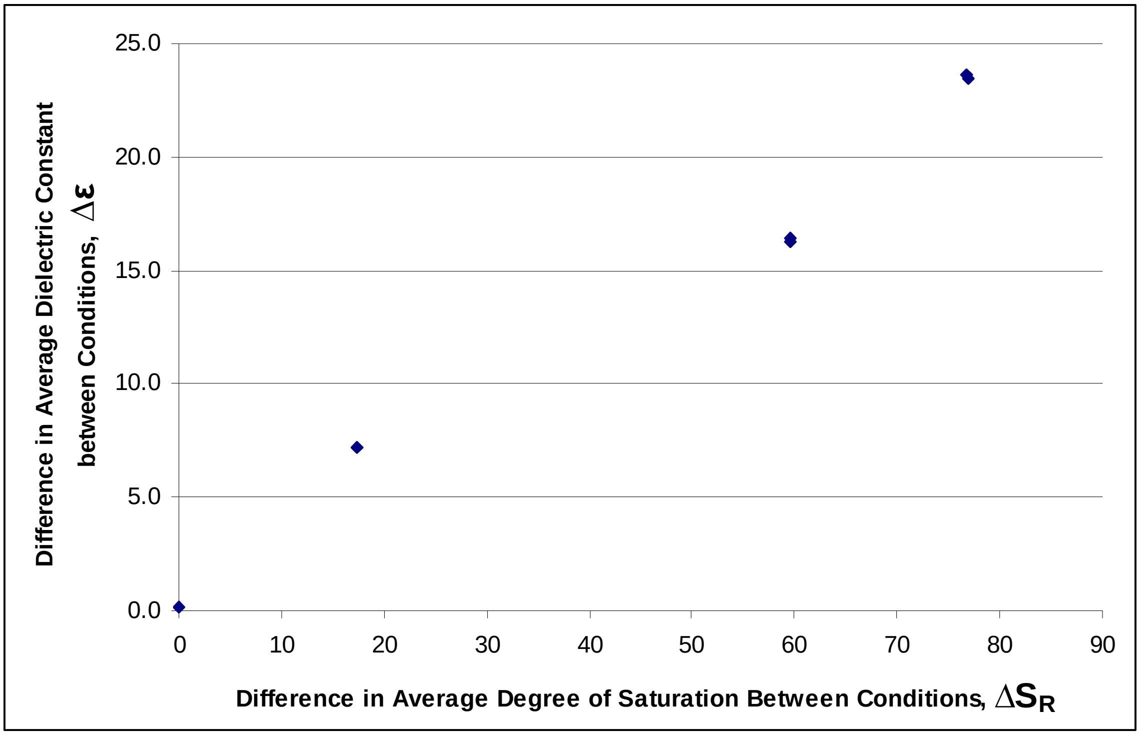

Figure B.2 The Effect of the Difference in Average Degree of Saturation for Test Conditions on the Difference in Measured Dielectric Constants for those Test Conditions

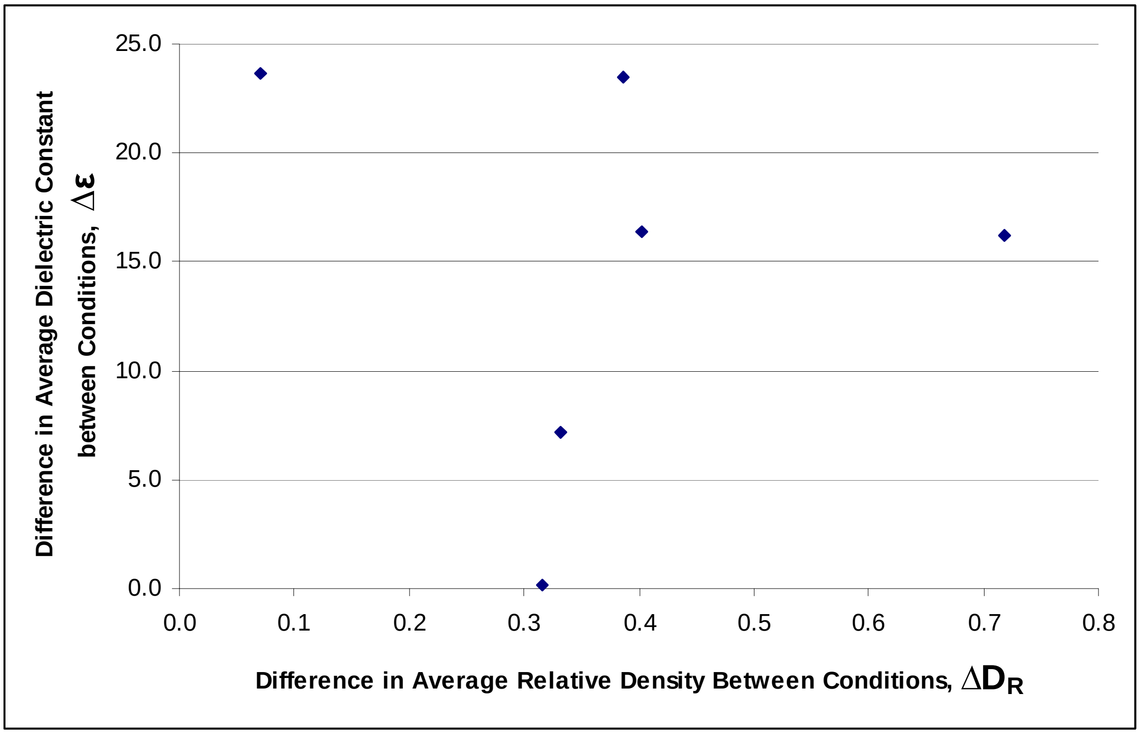

Figure B.3 The Effect of the Difference in Average Relative Density for Test Conditions on the Difference in Measured Dielectric Constants for those Test Conditions

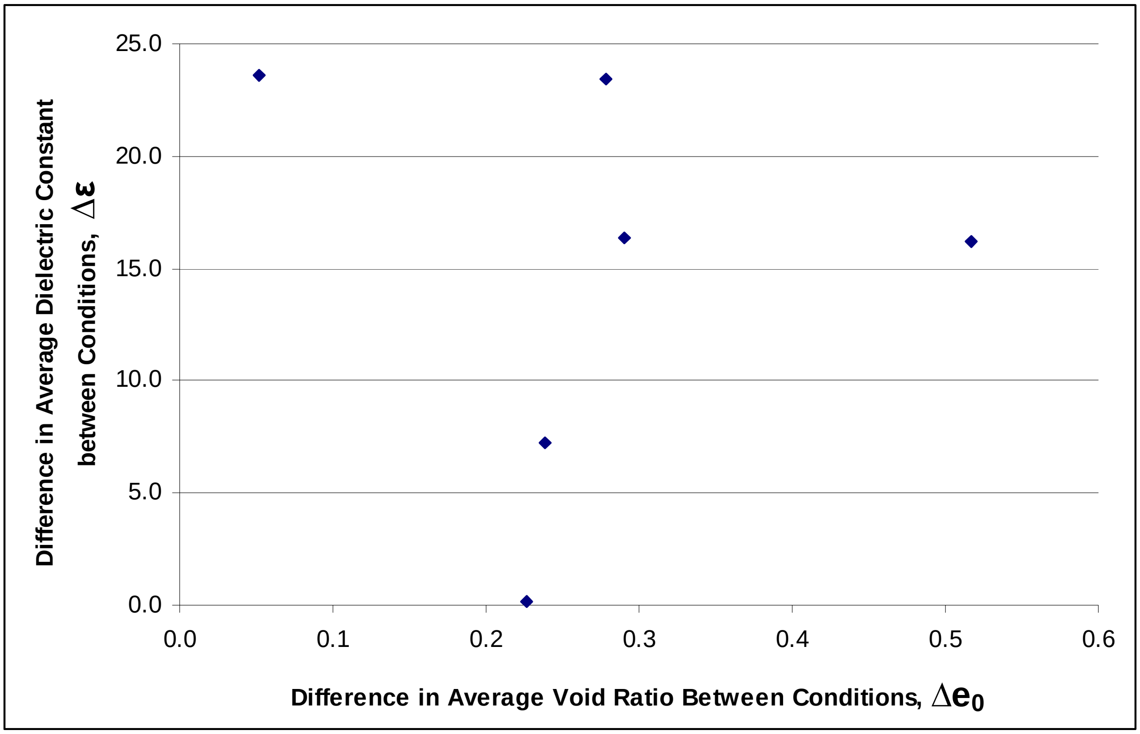

Figure B.4 The Effect of the Difference in Average Void Ratio for Test Conditions on the Difference in Measured Dielectric Constants for those Test Conditions

Appendix C

Preliminary Matric Suction Testing

Dielectric values for multiple soil samples at various soil suction values were obtained to compare to laboratory results. This can be seen in Figure C.1.

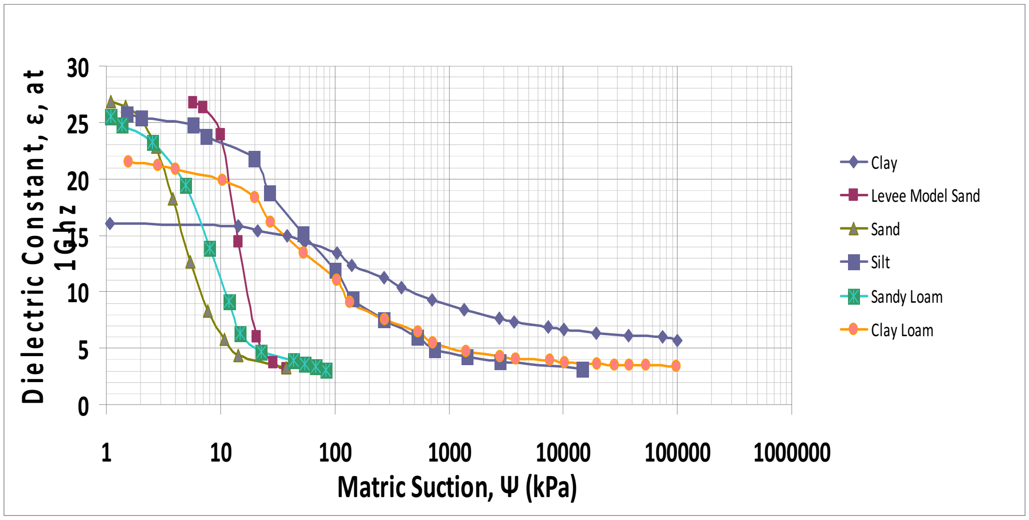

Figure C.1 Matric Suction vs Dielectric Constant for Various Soil Types

Then a Soil Water Characteristic Curve (SWCC) was created for the sand used in the network analyzer and TEM Cell testing. This can be seen in Figure C.2.

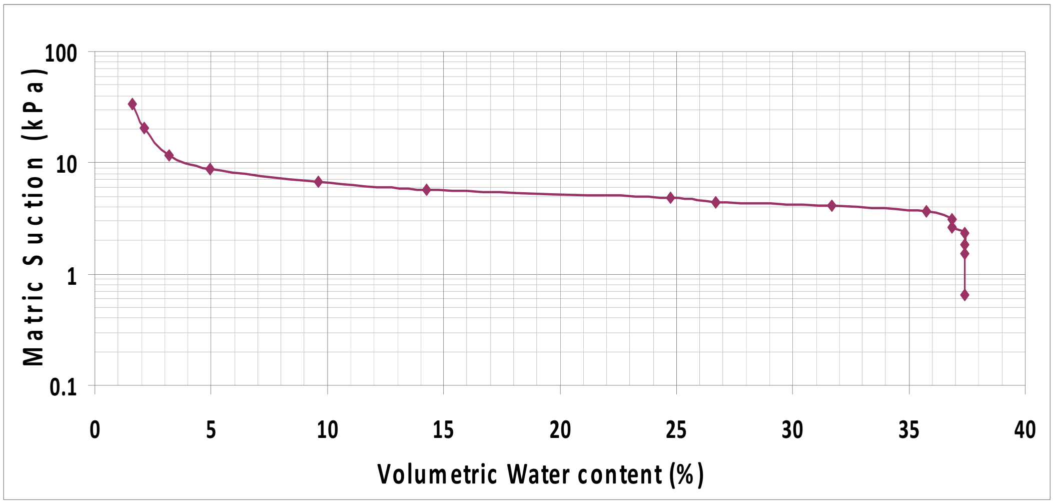

Figure C.2 Soil Water Characteristic Curve for Sand Tested in Laboratory

The results from the network analyzer for volumetric water content versus dielectric constant were used with the SWCC to directly relate suction to dielectric constant for the sand tested in the laboratory. The results are as displayed in Figure C.3 and are shown compared to the expected results (Cook 1998) for dielectric constant versus suction.

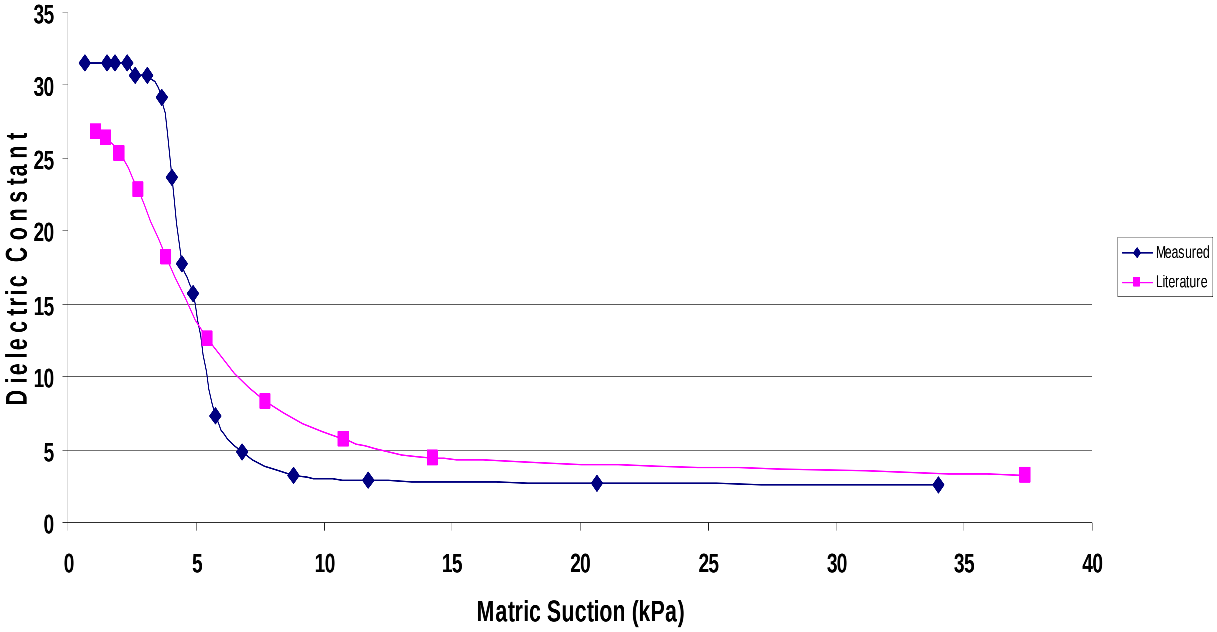

Figure C.3 Comparison of Expected Results vs Measured Results for Suction vs Dielectric Constant of Sand

Figure C.3 shows that testing for suction may be heading in the right direction and allow for better calibration of empirical models for all types of soils.