SOIL MOISTURE DETERMINATION BY FREQUENCY AND TIME DOMAIN TECHNIQUES

A Thesis Presented to

The Faculty of the Russ College of Engineering and Technology

Ohio University

In Partial Fulfillment

of the Requirement for the Degree

of

Master of Science

by

Chad L. Antle

March, 1997

ACKNOWLEDGEMENT

I would like to thank Dr. G. F. Mitchell, Dr. S. Sargand, Mr. Issam Koury, Mr. Terry Masada, and last, and most importantly, my parents, for the support, patience, and encouragement that made this endeavor possible.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Scope

The scope of this thesis will be limited to examining and calibrating a new 100 MHz Frequency Domain (FD) probe for soil moisture and complex permittivity determination. The probe has been designed specifically for use in a full size mobile cone penetrometer (CPT) system. This thesis will also include a examination of Time Domain Reflectrometry (TDR) techniques to determine soil moisture.

The moisture content of soils plays an important role in geotechnical and geo-environmental engineering and science. The moisture content of soils is one parameter that characterizes how soils might physically act. Along with the structural make up of the soil, the moisture content is the most important factor when viewing soils from the engineering aspect. Obtaining the optimum moisture content during compaction of soils is imperative to builders of roads, landfills, and foundations. In many cases knowing the correct moisture content is the difference between success and failure. For example, if the moisture content is estimated too high or too low during the compaction efforts for the clay liner of a landfill, the desired permeability might not be met. During the construction of subbases and foundations, the moisture content controls the extent to which the soil can be compacted. With most environmental remediation efforts being below the earth's surface, the moisture content of the soil can be an important parameter in the design of the remediation project. Determining the moisture content in the vadose zone and other zones of the ground can indicate how contaminants in the soil might continue to migrate or how well they can be remediated.

1.2 Traditional Methods

Determining the moisture content of soils was first accomplished by gravimetric methods. Soil samples are placed in an oven and dried for 12 to 16 hours. Differences in weight from before and after the drying process allow for the moisture content to be calculated by Equation 1.1

$$\omega = \frac{W_w}{W_s} x100\% \qquad \textbf{Eqn. 1.1}$$

Where ω = moisture content of the soil by mass, (%).

W_W = mass of the water, grams (slugs)

W_S = mass of the solids, grams (slugs)

The conversion of the gravimetric moisture content to the volumetric water content is accomplished by taking into account the specific weight of soil and water. This relationship is given in Equation 1.2

$$\Theta = \frac{\sigma_d}{\sigma_w}\omega \qquad \textbf{Eqn. 1.2}$$

Where Θ = volumetric water content, cm^3/cm^3, (in^3/in^3)

σ_d = bulk density of the soil, gm/cm^3, $(slug/in^3)$

σ_w = specific weight of water, gm/cm^3, (slug/in^3)

At the present time, the gravimetric method is considered the standard for soil moisture measurement.

Obtaining the moisture content of insitu soils is most commonly done by using nuclear or gravimetric methods. Both take time and a certain amount of training or certification. With the advent of TDR and FD moisture content determination methods, moisture contents of soils can be found almost instantaneously. With both methods being new to the field there is a need for comparison and evaluation of both types of technology as to ascertain which method is best suited for the civil engineer and his or her work.

1.3 Defining TDR

Time Domain Reflectrometry (TDR) is a technology that was originally developed to find shorts or breaks in electrical wire. Its workings can be paralleled to common radar. An electromagnetic waveform is transmitted through a cable to a probe. When the wave reaches the end of the probe it is reflected and recorded on an oscilloscope. The velocity of the waveform is affected by the surrounding material and its dielectric constant. The dielectric constant of a material is the ratio of the dielectric permittivity to the permittivity of free space (a vacuum). The dielectric constant can be represented as the material's ability to insulate.

1.4 Defining FD

Frequency Domain (FD) technology, which has been used since the mid 1930's, is based on an oscillating current. The first uses of FD technology were to study radio signals being attenuated as they traversed the ground. Use of FD technology for soil moisture determination was also identified around that time period. It has not been until recently, the late 1980's, that a probe was developed for practical use. The modern FD probe - soil moisture system can be envisioned as a capacitor. The probe forms two opposing metal plates with the soil being the dielectric medium. The oscillating current is then driven through the system, it follows the idea of voltage equals current multiplied by the capacitance (V = IC), were the capacitance comes from the soil. The oscillating current is attenuated by the capacitance of the soil matrix. The amount of capacitance or attenuation can then be related to the dielectric constant and moisture of the soil.

1.5 TDR/FD - Soil Moisture Relationship

Attaining soil moisture with TDR or FD methods is based on the difference in electrical properties between soil, water, and air. With the dielectric constant of deionized water being a value of eighty (80), and with most soils falling between three (3) and five (5), and air equalling one (1), there is a distinct difference between the three materials allowing for a soil-air-water mixing model to be applied.

When the "distinct" difference between the dielectric constants of the two materials becomes not so distinct, the data from the TDR and FD systems become unpredictable. As an example, if the soil-air-water mixture was a matrix of a sand, air, and a slight alkaline water the difference between the dielectric constant of the water and the soil becomes smaller. This makes determining the water content difficult.

Another mechanism that can cause difficulty in measuring soil moisture via TDR and FD methods are fine grained soils. Unlike coarse grained soils, fine grained soils such as clays and fine silts have large cohesive forces on the microscopic scale. These forces cause water molecules to bond to the individual soil particles, changing the dielectric constant of the soil to a value that is dependent on the amount of water that is bonded. The change in dielectric constant causes the once large difference in the soil and water's dielectric to become smaller and increase the difficulty in determining the water content using TDR or FD Methods.

1.6 Objective

The objectives of this research were as follows:

- Calibrate the 100 MHz Frequency Domain Soil Moisture/Resistivity probe for several different soil types.
- Determine the factors that influence the frequency domain calibration procedure
- Contrast and compare Time Domain Reflectometry soil moisture measuring techniques to Frequency Domain techniques.
- Determine the range of TDR use for clayey coarse sand.

CHAPTER 2

LITERATURE REVIEW

2.1 Time Domain Reflectrometry

Much of the literature that has been published at the time this document was written was about calibration and experimental use of Time Domain Reflectrometery (TDR). The number of articles and publications dealing with TDR are numerous and have been helpful in understanding the entire concept of TDR and its possible uses. Many of the articles are two prong, one side dealing with determination of dielectric constants of soil, and the second dealing with the calibration of TDR for specific soils. The foremost published research dealing with TDR probes and their calibration is by Clarke G. Topp.

In 1980, Clarke G. Topp introduce a TDR method for the determination of water content in soil. In the article, titled *Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines,* (Topp, 1980) Topp describes the first experimentation with a coaxial cable TDR probe and water content of soil. The document is cited by many researchers as the foundation of their research. Of the many conclusions that are within the article, one of the most important is the that measured dielectric constant can be assumed to be approximately equal to the real part of the complex dielectric constant. This means that the imaginary part can be neglected; i.e. the electrical losses are small enough to be ignored. Another important conclusion by Topp was the soil texture, density, and salt content are almost independent of the dielectric constant while using a system that operated between 20 MHz and 1GHz. His research included materials ranging from sandy loam to clay, vermiculite, and two different diameters of glass beads. The wide range of materials allowed the average as well as the extremes of pore sizes to be tested. His tests resulted in the development of an empirical equation that is now an accepted standard for TDR and soil moisture determination. At one time it was considered an "universal" equation for all soils. Today with continued research, the equation has begun to show its dependence on soil and particle types. He did note that the specific surface of the material did play an important role when relating the dielectric constant to the soil moisture content. A higher specific surface area caused a higher dielectric constant at a higher water content, and a lower dielectric constant at a lower water content. In the end result, Topp's work laid the foundation for new and quick methods for determining soil moisture.

An article that complements and provides validity to Topp's work is an article by M. Ansoult, W. DeBacker, and M. Declercq; *Statistical Relationship Between Apparent Dielectric Constant and Water Content in Porous Media,* (Ansoult, et. al.1985). The researchers constructed a statistical environment that simulated soil with three phases present; soil, water, and air. The probability of the three phases being present were based on the porosity of the material. An important trait of the model was it could take into account the importance of bonded water. However, the amount of bonded water had to be known. Another conclusion of the research was at a given water content, an increase in porosity would reduce the apparent dielectric constant (K) since the amount of air (K= 1) would increase, and the soil (K=4) amount will decrease. The statistical evaluation of the relationship between the dielectric constant and water content proved the theoretical accuracy and validity of Topp's research. It also raised questions about soil texture and bulk density that should be researched in further investigations.

After the large number of articles and experimentation validating the work of Topp and his colleagues, a new wave of research started to appear, experimentation in application. Research in the application of TDR probes has ranged from highway and geotechnical (van Schelt, 1994) aligned projects to environmental remediation projects (Kaya, 1994). In an article, titled *The Effective use of TDR in Geotechnical Engineering,* (Kaya. 1994), the use of TDR probes in the process of finding the optimum moisture content during compaction was researched. The system used a soil sample in standard compaction mold creating a coaxial type of setup. A rod was inserted into the sample, and the moisture content was determined using TDR. The same type of coaxial TDR system was also described for use in a slip spoon soil sampler. The researcher also discussed a system of imbedded TDR probes in embankments or earthen dam structures to monitor the moisture content. This type of setup could be useful in several situations such as identifying potential failures in a structure.

There has also been another angle of research that aims itself at determining other various properties of the soil using the TDR probes. Uses of TDR probes such as finding subsurface lateral flow of water (Logsdon, 1994), the unfrozen/frozen interface in soils

(Baker, 1982), water balances (Van Wesenbeek, 1988), and soil salinity (Malicki, 1994) are just a few examples of what has been published.

Malicki's research published under *Determining Soil Salinity from Simultaneous Readings of its Electrical Conductivity and Permittivity using TDR,* (Malicki, 1994), looked at salinity in the soil and how TDR in conjunction with the electrical conductivity could be used to determine salinity. The soils used for the research were as follows: Winzerboden loamy sand, Buchberg silt, Abist silt loam, river bed sand, and purified quartz sand. Five different salinities or conductivities were reached by moistening the soils with a KCl solution. A TDR probe was used to measure the bulk permittivity and bulk conductivity of the different soil-KCl mixtures. The TDR probes were used due to their non-destructive element. The tests led the researchers to many conclusions about the relationship between soil moisture, bulk permittivity (dielectric constant), and bulk conductivity. Of these, one of the most important is the salinity of the soil can be determined as a moisture independent variable. The importance of this comes from looking at the relationship from the other side. The moisture content of soils is independent of soil salinity.

Several mixing models that have been presented in past publications were tested against results from experimentation. The mixing models are either semi - empirical or theoretical equations. Semi - empirical models have resulted from physical testing of the soils, such as with Topp's well known equation (Topp,1980). Whereas theoretical equations are constructed to take into account parameters that influence the dielectric constant of the soil water air matrix, theoretical mixing models such as Roth's three part mixing model (Roth, 1987) and Birchak's four part mixing model (Birchak, 1987) take into consideration the physical characteristics of the soil matrix. Other mixing models such as Dirksen and Dasberg's (Dirksen and Dasberg, 1994) take into account soil and water volumes as well as the relaxation of particles at high frequencies.

In research, titled *Calibration of TDR for Application in Mining, Grains, and Fruit Storage and Handling,* (Zegelin, *1994),* researcher Steven Zegelin used TDR probes to examine and validate the use of several different mixing models that were implemented on coal, fruits, and wheat. The materials used in the research, coal, fruit, and wheat, are atypical of the materials that have been previously tested. However, the application of these materials and their related industry have a positive future with TDR. The materials tested also represent valid information to those dealing with soils. The texture of the materials can be closely related to other soils such as clay and organically dominated soils.

The results of the physical testing revealed that the fruits, apricots, sultanas, and wheat closely follow the linear relationship of the mixing models. In comparison, the coal and nickel ore do not follow the linearity of the theoretical models. The non - linearity of the coal and nickel ore can be explained by possible swelling of the material but more likely explained by the bound or trapped water within the material and electrical conductivity that the material possess.

2.2 Frequency Domain Probes

As was briefly discussed in the introduction to this thesis, both frequency and time domain technologies have been used as early as the 1900's in the frame work of electrical engineering. Most of the recent work in FD technology, from the mid eighties to the present, has been researched by the Europeans. Probes have varied from concept to their actual physical design. Operating frequencies have ranged from radio frequencies to around 150 MHz. Various physical designs of probes range from hand held probes to the highly robust CPT probe. The procedures have also differed; some papers relate the frequency directly to the soil moisture content, while others have related the frequency to the dielectric constant and the dielectric constant to the soil moisture. The end result, what ever shape or method, is a very applicable technology to measure soil moisture.

Many of the early papers investigated the properties of soils at high frequencies, and not the use of frequency domain technology to determine the water content of the soil. However, the advent of a soil moisture probe using frequency domain technology could not have been possible without the important previous research reviewed here.

The first documented use of frequency domain (FD) technology to relate soil moisture, *The Electrical Properties of Soil for Alternating Currents at Radio Frequencies*, (Smith - Rose, 1933) was by British researcher R. L. Smith-Rose. In 1933 Smith-Rose investigated the electrical properties of soil being influenced by an alternating current at radio frequencies. His work centered around determining the electrical properties of soil and how they affected the transmission of radio waves from transmitting towers to receiving towers. His work took into consideration that moisture contents of soils have a bearing on the amount of conductivity and capacitance of the surrounding soil. The results of his research showed the conductivity of the soil begins to become constant with higher and higher moisture contents. He also concluded that with higher frequencies the conductivity became greater at lower moisture contents. The research became one of the first to assign dielectric constant values to dry and moist soil at radio frequencies. The article puts into perspective the relationship between soil moisture and FD technology.

An article published in 1987 by Ernest Selig, titled *Relationship of Soil Moisture to the Dielectric Property* (Selig, 1987), reviewed articles that researched the relationship between soil moisture and frequency response. It is one of the first articles to look at the topic from more of an engineering side than soil science. In this article, Selig examined the literature that covered the theoretical aspects of the relationship between soil moisture and dielectric constant to the design and field tests of soil moisture probes. He dealt specifically with frequency domain theory and probes. He also compared this technology to resistance methods to determine water content.

Selig (1987)examined several probe designs that operated in ranges from 800 kHz to just above 1 GHz. Most of the probes encountered operated in the range of 10 to 30 MHz. The probes were tested on materials that included a wide variety of soils, concrete, and highway materials. Conclusions from his investigation highlighted several important facts. At high frequencies, (1 GHz) the soil-moisture relationship is independent of compaction. Moist soils act as an electrical network of parallel - series combinations of resistors and capacitors. This indicated that the apparent conductance or capacitance of a soil will vary with the frequency used. Based on this idea and the fact that physiochemical properties of the pore water, distribution of solid, liquid, and air phases, and structure and void ratio of solid phase, the relationship between the composite dielectric constant and the moisture of soil per unit volume will be nonlinear. Looking at properties of soil at ultra high and microwave frequencies was researched by Hoekstra and Delaney in 1974. Under a paper, titled *Dielectric Properties of Soils at UHF and Microwave Frequencies (Hoekstra, 1974)*, they determined how soil particles would react to frequencies that range from 10 MHz to 2600 MHz. This range includes the CPT probe and TDR probe that currently exist. The purpose of their research was to determine the main parameters effecting the dielectric constant. The research looked specifically at both parts, real and imaginary, of the complex dielectric constant of a soil and how they behaved when subjected to different frequencies. The results showed that in the range of 100 MHz to 1000 MHz the dielectric losses were the smallest and the real part of the dielectric constant was dominant when determining the overall dielectric constant. This is an important conclusion because it allows the dielectric constant to be related solely to the frequency. They also believed that the Maxwell Wagner dispersions did not have an effect at the higher frequencies.

In the mid 1960's an article, titled *In situ measurement of moisture in soil and similar substances by 'fringe' capacitance (*Thomas, 1965), was published. The development of a soil moisture probe operating at 30 MHz was researched. The probe was used for laboratory and in situ testing. Thomas defined his fringe capacitance probe as a device to collect data from the soil lying around a particular area or fringe of the probe. His tests included laboratory tests on clay, clean sand, and sand-clay-peat mix. With the use of distilled water, the probe was tested from a volumetric water content range of 0.1 to 21.1 percent. Tests were also conducted using NaCl to test the probe's resistance to higher conductances. Along with the other tests, the probe was also tested against a variety of materials to determine the relationship between the capacitance response and the permitivities of the materials. A second set of tests were conducted on in situ soils by Thomas (1965). Nearly forty tests were performed on five different soil types that ranged from 3.8 to 48.9 % volumetric water content. Bulk densities, gravimetric moisture contents, and capacitance measurements were taken on all test. The results of the tests show a positive and increasing relationship between the capacitance of the soil and the moisture content. A linear trend of the relationship was shown for moisture contents from 0.0 to 10.0 %. A linear function of the logarithm of the capacitance was shown from around 5 to 45% volumetric moisture content.

An article, titled *Soil Moisture Measurement by an Improved Capacitance Technique, Part I & II,* 1987 (Bell, et. al. 1987), researched an improved technique of using capacitance to determine soil moisture. The technique used a 150 MHz current and use of the then recent advances in electronic technology that created a more stable and sensitive probe. The article looked at testing four different soils: Chalk overlain by topsoil, medium fine sand, sandy clay, and fine chalky silt overlain by poorly graded fine gravel. All soils were set up using a lysoimeter to control the moisture content of the soils. The researcher used gravimetric and neutron methods to standardize and compare results to the capacitance probe. The data from the experimentation are analyzed by using linear regressions and comparing the R^2 values. The values ranged from 0.74 to 0.96, which indicated a good linear relationship. The difference in the slopes and R^2 values indicated to the researchers that soil type and fabric played an important role for the calibration of the probe. The comparison of the frequency domain probe to the neutron moisture probe indicated good reliability. Of all of the literature reviewed on FD technology, this research is the closest relating to this thesis and complements it nicely.

A 20 MHz FD probe was developed and tested by Dirksen and Hilhorst (Dirksen and Hilhorst, 1994) in the mid 1990's. The probe design is similar to the two and three prong TDR probes that exist. They tested the probe in several different soil types, including fine sand, sandy-silt, silty-sand, clayey-silt, and pure clay. The types of materials they used covered a wide array of specific surface sizes and bulk densities. The probe that was developed uses an ASIC circuit to make the relationship between the frequency and the dielectric constant. Without being able to review (due to it not being published) the results of how the frequency at 20 MHz compares to the dielectric constant or to the moisture content, it is hard to compare the 20 MHz FD probe and the probe researched for my thesis. The results of their testing were compared to Topp's "universal" equation. Their research for sandy soils indicated results that closely paralleled Topp's equation. The results for the experiments using clayey soils were not as good as they were for the sandy soils. The clayey soils indicated a steeper slope than encountered in Topp's work. The overall results also indicated as the specific surface area increased so did the FD function of complex permittivity and volumetric water content (ε (θ)). The steeper relationships yielded results indicating the FD probe is more sensitive to changes in water content in these soils. The research did give notice to the fact that at different frequencies separate calibrations would have to be performed to account for how the soil particles would behave. The researchers also noted that the laboratory experiments for calibration must replicate in situ conditions, i.e. bulk density, in order for the calibration to be correct.

Another area of interest to this thesis was the theoretical ideas and relationships that existed between TDR, FD, soils, and soil moisture content. Many factors are known to influence dielectric constant and soil moisture readings from FD and TDR probes. Factors such as bound water, soil matrix, specific surface area, and soil type are considered to affect the soil moisture measurements the most. A number of articles have looked at parameters that effect the readings and try to account for them. Of these papers, a majority of them use mixing models to examine the affecting parameters. In *Influence of Matrix on TDR Soil Moisture Readings and its Elimination,* Malicki,(1994), examined bulk density and porosity of soils and how they influence dielectric constant readings with TDR. He determined the soil matrix factors have to be taken into account when looking at the conversion of the dielectric-moisture content relationship to other soil properties. His research used several different types of soils ranging from organic soils, inorganic soils, forest litter, and wood bark and sawdust. A total of 894 quadruplet (894/4) readings of dielectric constant, moisture content, particle density, and bulk density were taken from 62 samples. The data were divided into subsets of triplets between moisture content, bulk density, and dielectric constant and were analyzed to give a correction factor for the bulk density of the material. The end result of the experimentation was to define that the soil matrix does have a significant effect on TDR readings. He found the deviations in the bulk density of the tested soils can result in 0.40 to 1.4 percent change in volumetric soil moisture readings. He also predicted higher errors should be expected with very moist soils with low densities and smaller errors are associated with dry soils of high densities.

CHAPTER 3

EXPERIMENTAL SETUP AND PROCEDURE

3.1 Introduction

Numerous laboratory tests were conducted on several types of soils in order to calibrate and verify the use of the frequency domain probe as a way to measure soil moisture. TDR probes and gravimetric methods were also employed for comparison and validation.

3.2 Description and Preparation of Soils

Several types of soils and soil mixtures were used in this research, all originating from southeast Ohio. The *Soil Survey of Athens County, Ohio*,(United States Soil Conservation Service, 1985) was implemented in defining the soils. The soils and soil mixtures are listed in Table 3.1. The first soil defined is an Upshur clay, a silty clay loam - silt loam mixture. The soil is characterized by a dark red to brown color with a moderately slow permeability. Upshur soil is also characterized by high shrink-swell potential. The gradation curve can be seen in Figure 3.1.

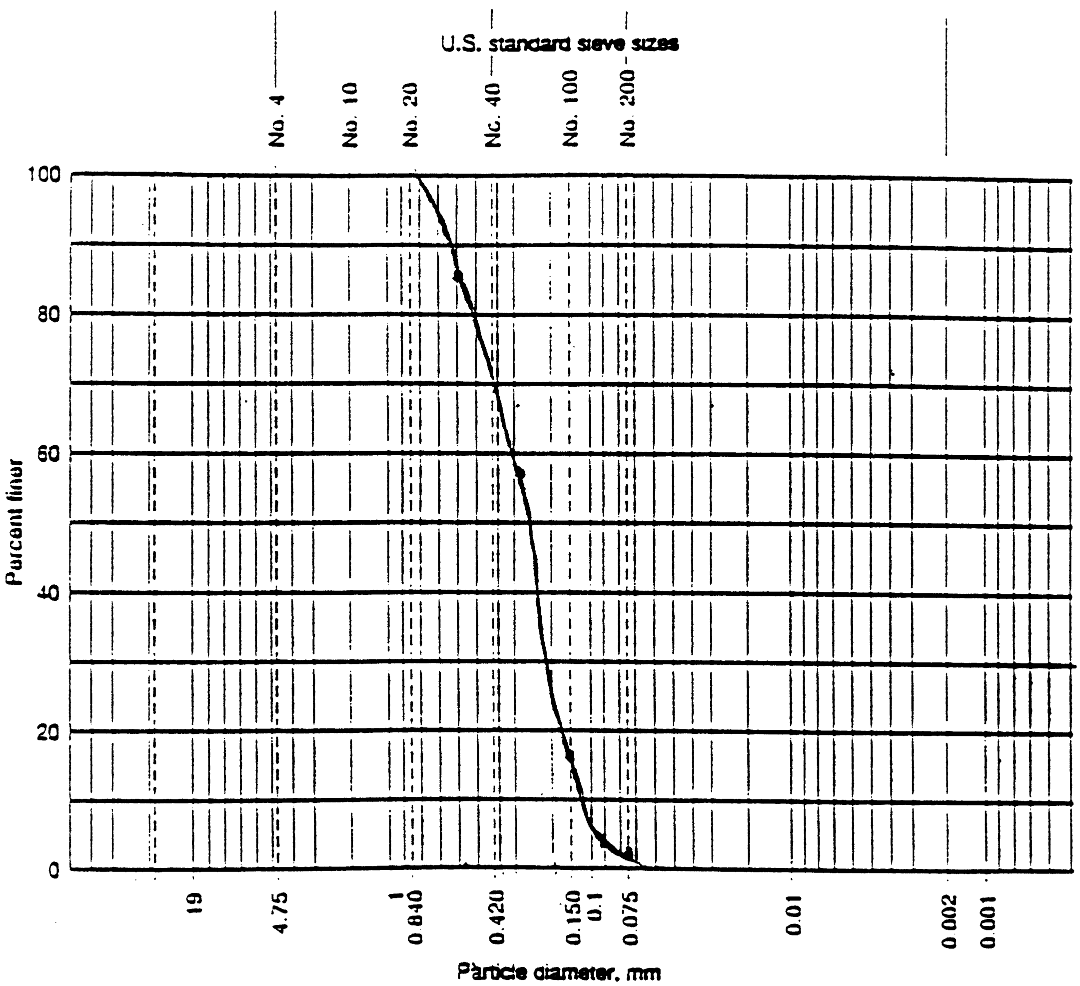
The second soil is defined as a Guernsey clay complex which has a yellowish brown color. It too consists of silty clay loam with moderate permeability. The soil is not as vulnerable to shrinkage and swelling as the Upshur clay. Both types of clays are prone to slip and slope failure. The gradation curve for the Guernsey clay is depicted in Figure 3.2.

TABLE 3.1 SOIL TYPES

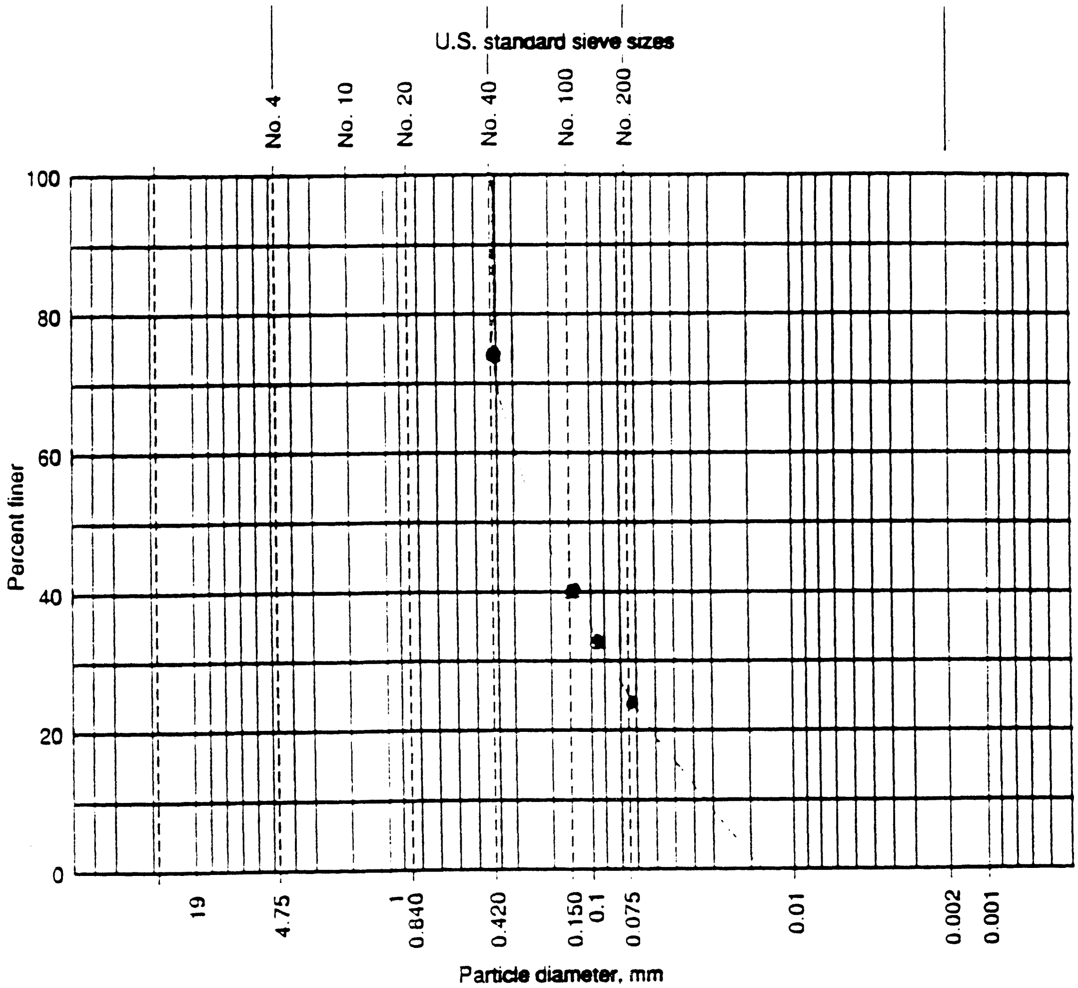
Soil Name	Soil Type - Classification
Upshur clay	Clay - high swell, low permeability
Guernsey clay	Clay - medium swell, low permeability
Hocking River coarse sand	alluvium sand
Lake Erie fine sand	laucstrine sand
Hocking River silt	fine silt
Silty coarse sand	35 % Hocking River Silt, 65 % Coarse Sand
Clayey fine sand	35 % Guernsey Clay, 65 % Fine Sand
Clayey coarse sand	35 % Guernsey Clay, 65 % Coarse Sand

The sands used for the procedure are a fine grained sand and a coarse grained sand. The grain size distributions can be seen in Figures 3..3 and 3.4, respectively. The large grained sand was obtained from the Hocking River in Athens County, Ohio, and is a typical flood plain alluvium. The fine grained sand is a typical beach or lacustrine sand from the Great Lakes area.

The silt is from the Hocking River, Athens County, Ohio, and is a typical river silt. The gradation curve for the silt material can be found in Figure 3..5.



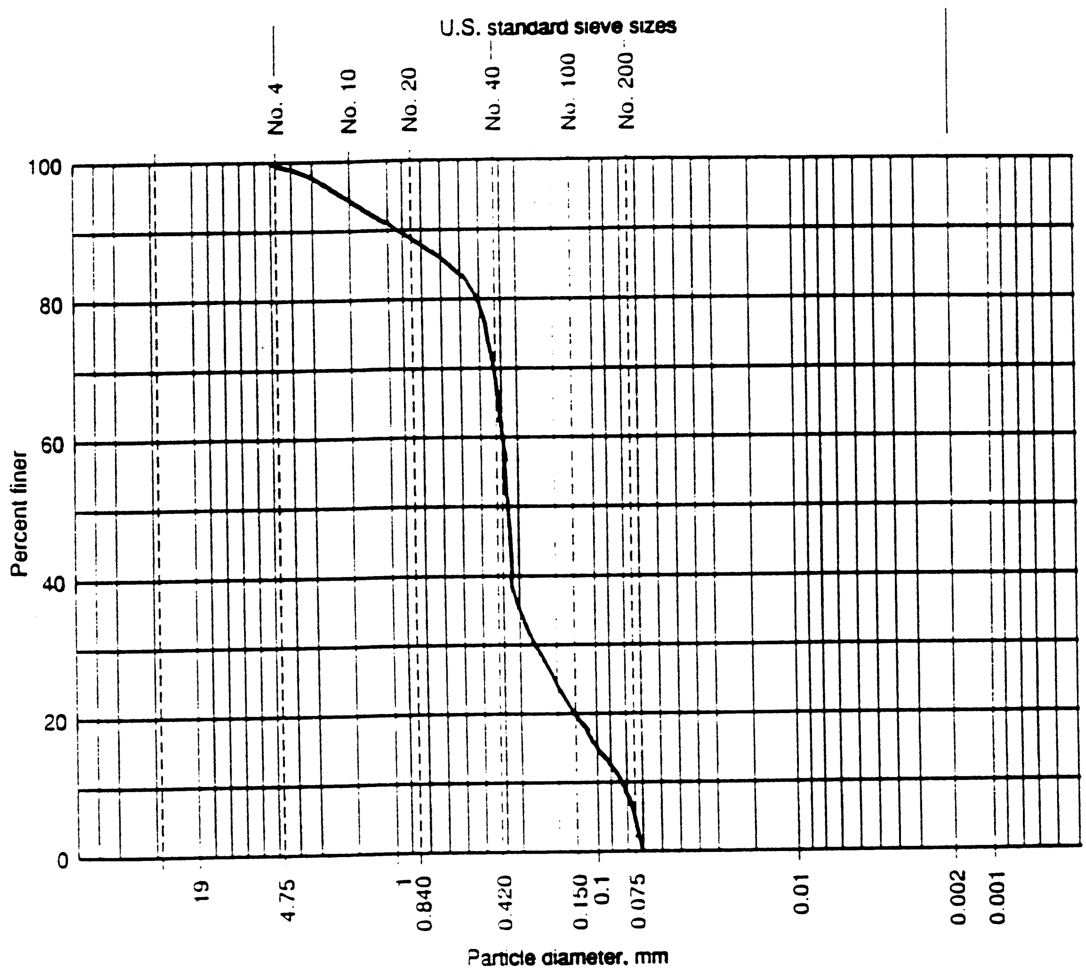
Upshur Grain Size Distribution
Figure 3.1



Gurnsey Grain Size Distribution

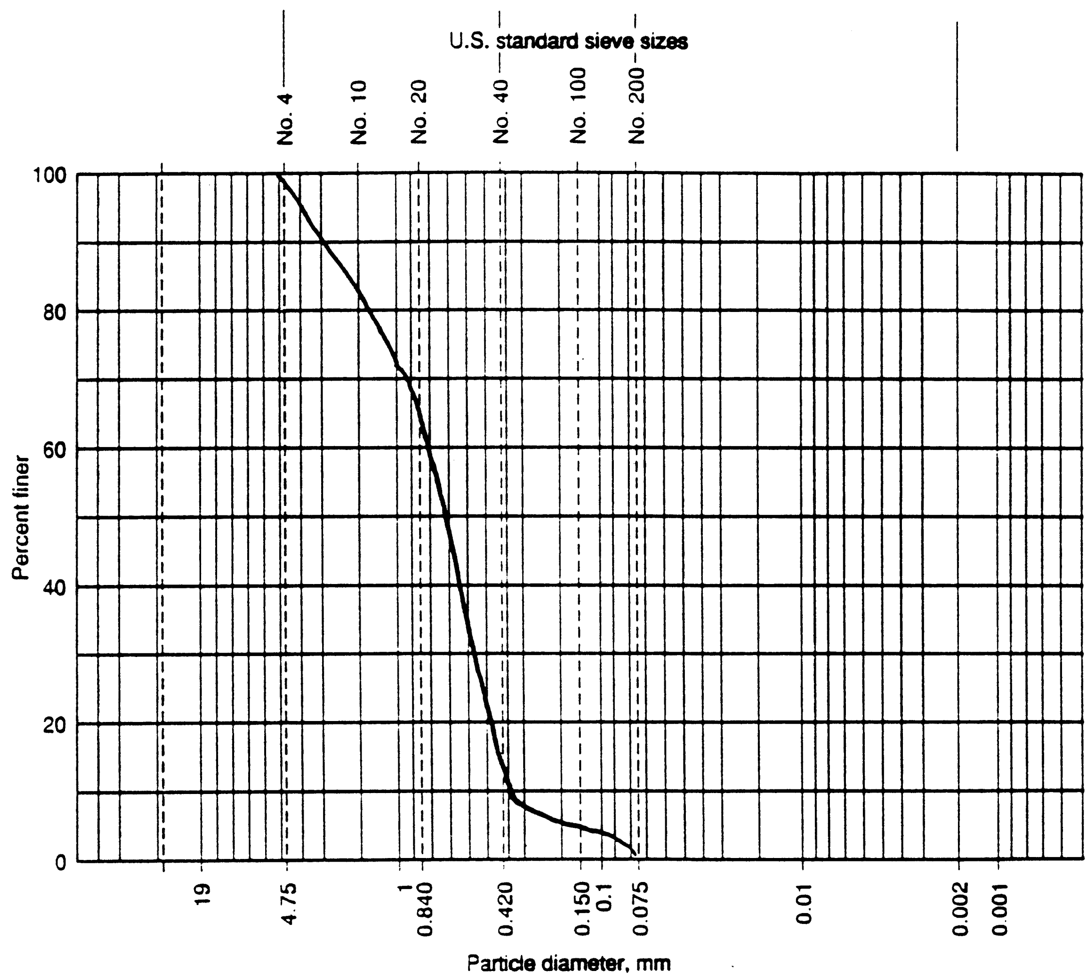
Figure 3.2

The mixtures for the silty sand (Figure 3.6) and clayey coarse sand (Figure 3.7) were created by combining the coarse river bed sand with the Hocking River silt and Gurnsey clay, respectively. The clayey fine sand (Figure 3.8) was created by mixing the fine grained sand with the Gurnsey clay. The mixtures were modeled after typical silt/clay and silt/sand percentages that are naturally found.



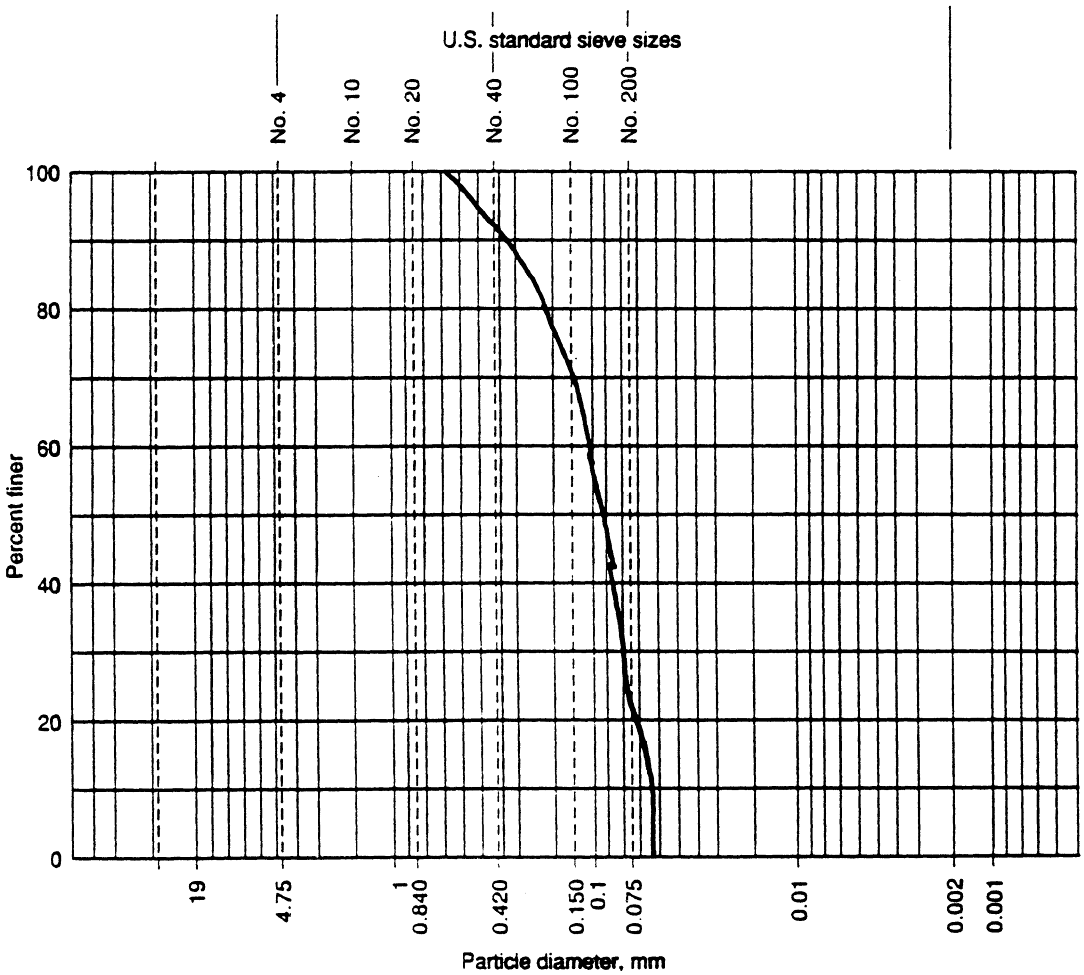
Fine Sand Grain Size Distribution

Figure 3.3



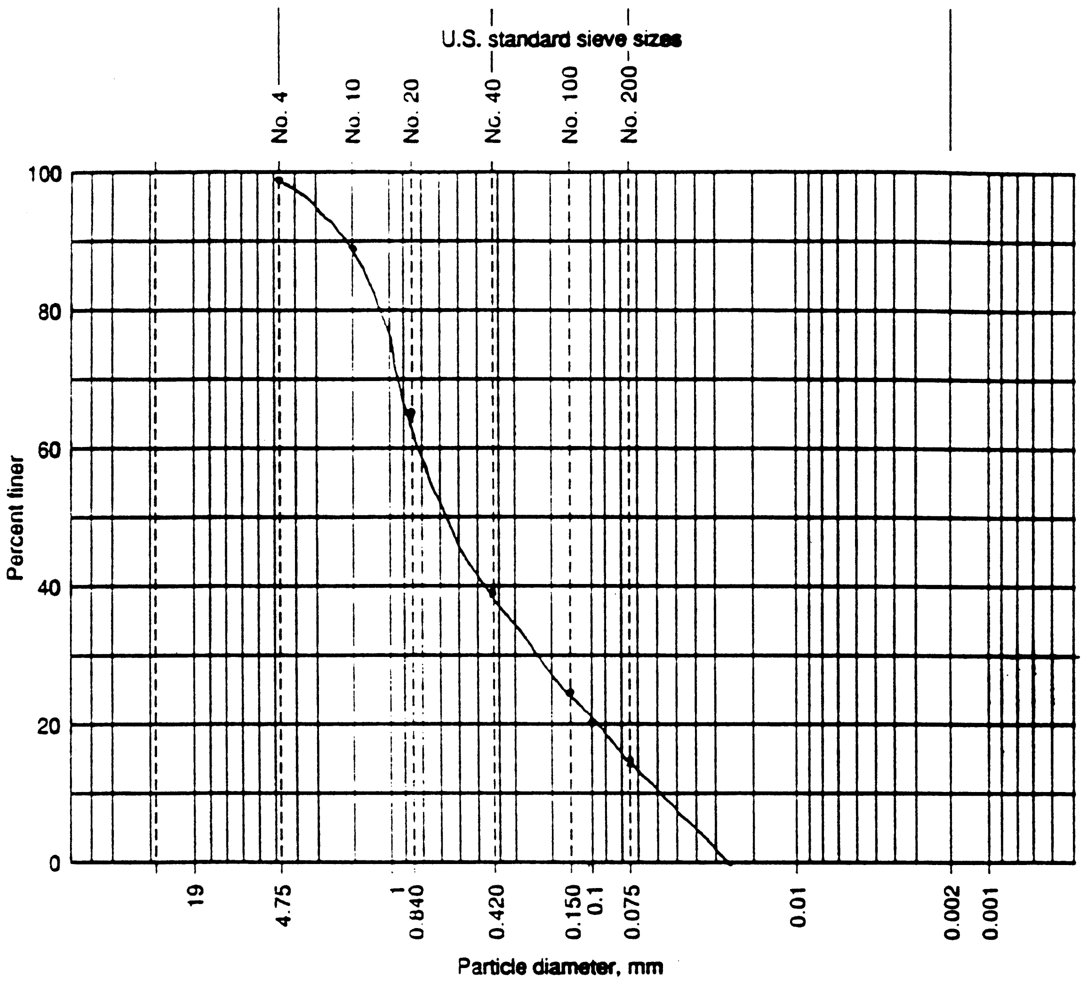
Coarse Sand Grain Size Distribution

Figure 3.4



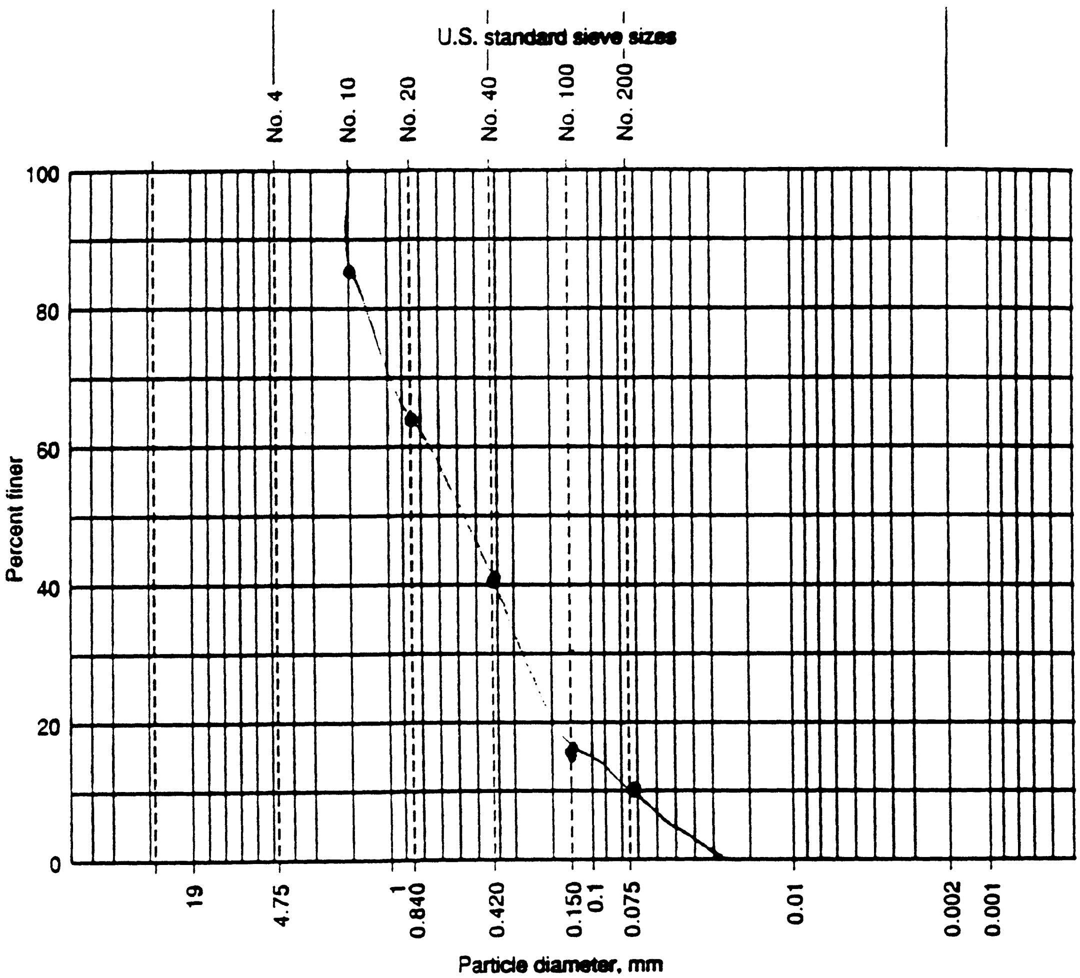
Hocking River Silt Grain Size Distribution

Figure 3.5



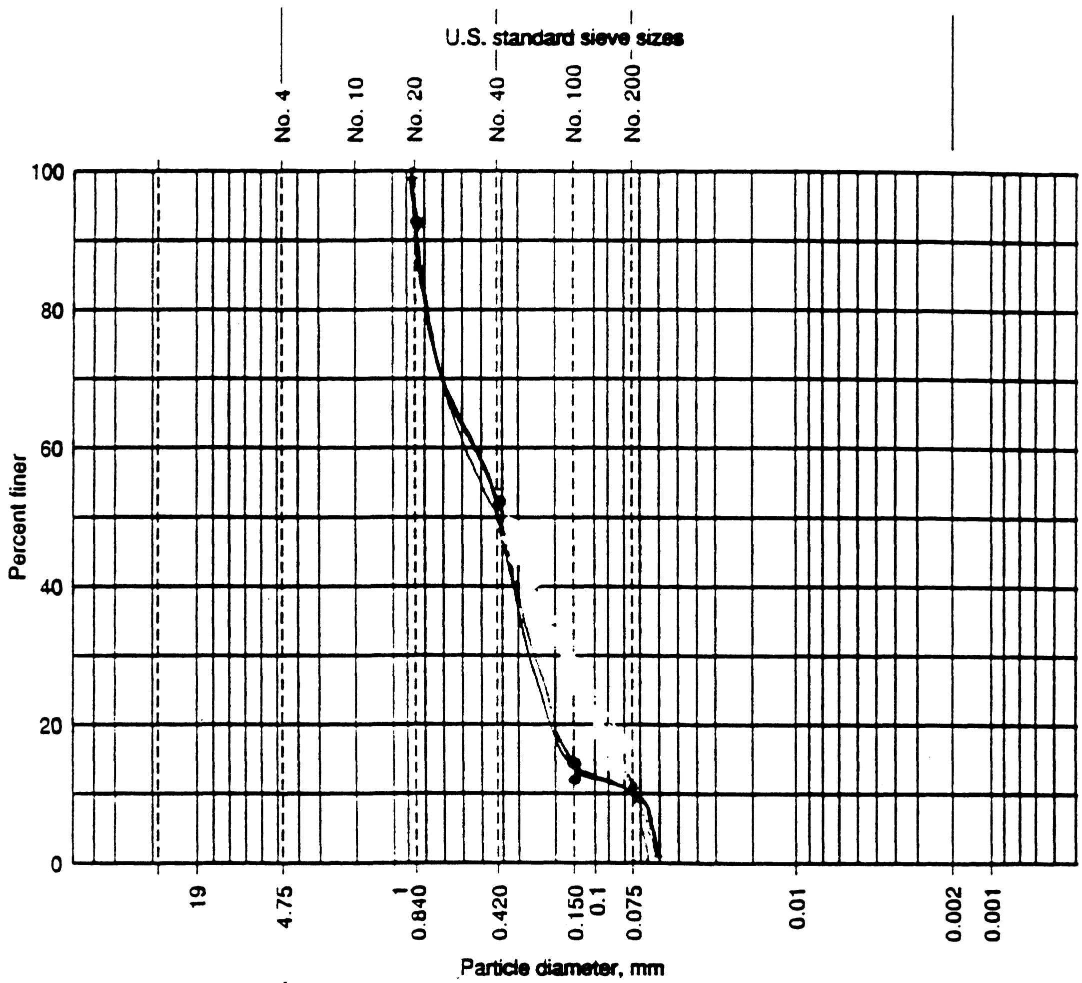
Silty Sand Grain Size Distribution

Figure 3.6



Clayey Coarse Sand Grain Size Distribution

Figure 3.7



Clayey Fine Sand Grain Size Distribution

Figure 3.8

3.3 Experimental Equipment

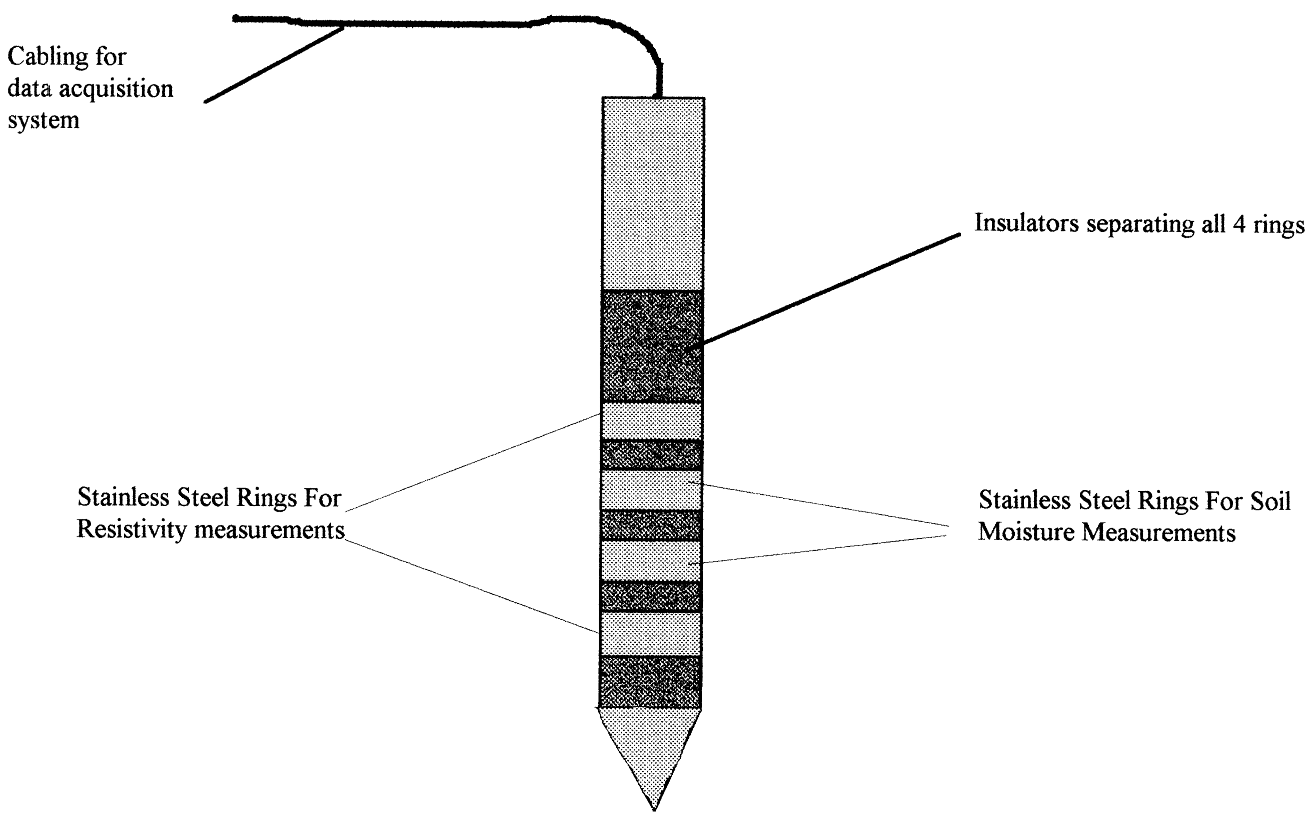
The equipment that was used in the procedure is listed in Table 3.2

TABLE 3.2 EXPERIMENTAL EQUIPMENT

ARA Frequency Domain Probe, Applied Research Associates, Inc
Tektronix Frequency Counter/Generator -TM530B
TDR Probe
Tektronix Oscilloscope with printer - 1502B
FD Probe Interface Module, Applied Research Associates, Inc
SoilTest Stainless Steel Moisture Cups
Blue M Electric Soil Drying Oven
Fluke Digital Multi Meter, Model 75
Hobart Mixer, Model # 120

A description of the equipment is as follows.

The frequency domain probe (commonly referred to by its trade name, SM/R (soil moisture/resistivity) probe) is cylindrically shaped and is approximately 20 inches long and 1.75 inches in diameter. The probe is pictured in Figure 3.9.



Schematic of Frequency Domain Probe

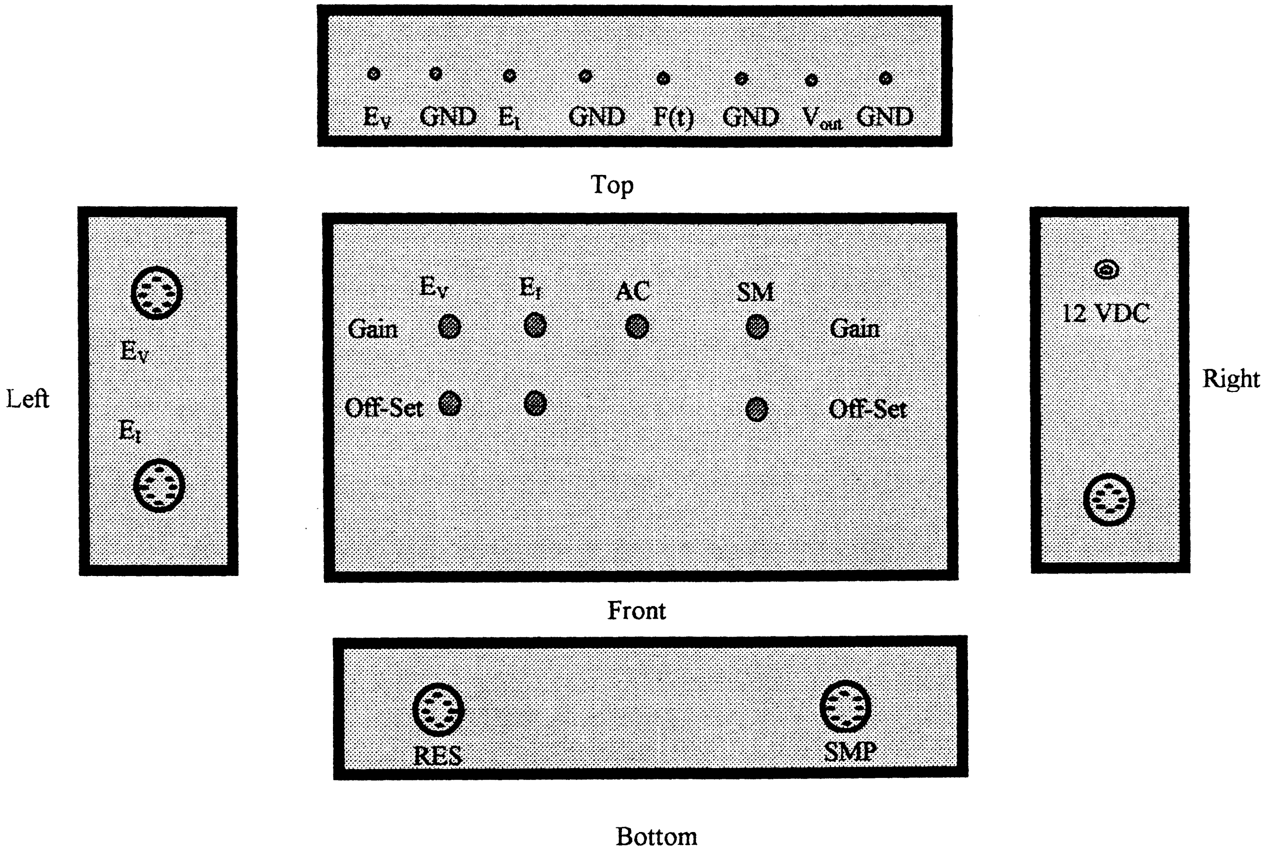
Figure 3.9

The two most inner steel rings on the probe are used when determining the soil moisture while the outer rings are used for resistivity measurements. The operating range for the soil moisture probe range is approximately from 90 to 100 MHz. Operating range for the resistivity measurements is from 10 ohms to 100 kilo - ohms. The shape of the probe was designed to be used with a full size cone penetrometer test system (CPT).

The FD probe interface module converts the frequency response from the FD probe to a voltage that the acquisition system can read. The interface module has an operating range from zero to four volts. Both the probe and the interface module were constructed by Applied Research Associates (ARA) and ANATECH. The FD probe interface module is pictured in Figure 3.10

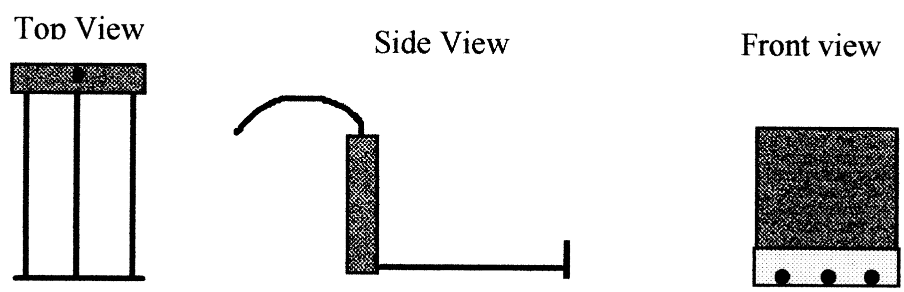
The frequency counter is a Tektronics model TM503B and can measure frequencies from 0 to 30 MHz..

In contrast to the Frequency Domain probe, the Time Domain probe consist of three stainless steel rods that are connected to a series of wires allowing a signal to be sent and reflected back through them. The rods are mounted parallel to each other and connect to a PC board which serves as a wiring harness. The center rod is connected to the coaxial cable's center lead. The outside leads are connected to the two outside rods of the probe. The TDR probes can be seen in Figure 3.11



SM/R InterFace Module

Figure 3.10



TDR Soil Moisture Probes

Figure 3.11

The oscilloscope used in the tests is a Tektronics Cable Tester Model 1502B with printer module. The oscilloscope enables the transmitted and reflected signal through the probe to be graphically interpreted.

The test containers were of three types. Two of the containers were used in one part for the FD procedure, while the other container was used for the TDR procedure. The larger containers had a volume of approximately 50 liters, and were approximately 40 cm in diameter and 50 cm tall. The smaller container had a volume of 2.5 liters, and was approximately 30 cm long, 20 cm wide, and 7cm deep.

3.4.0 Procedure

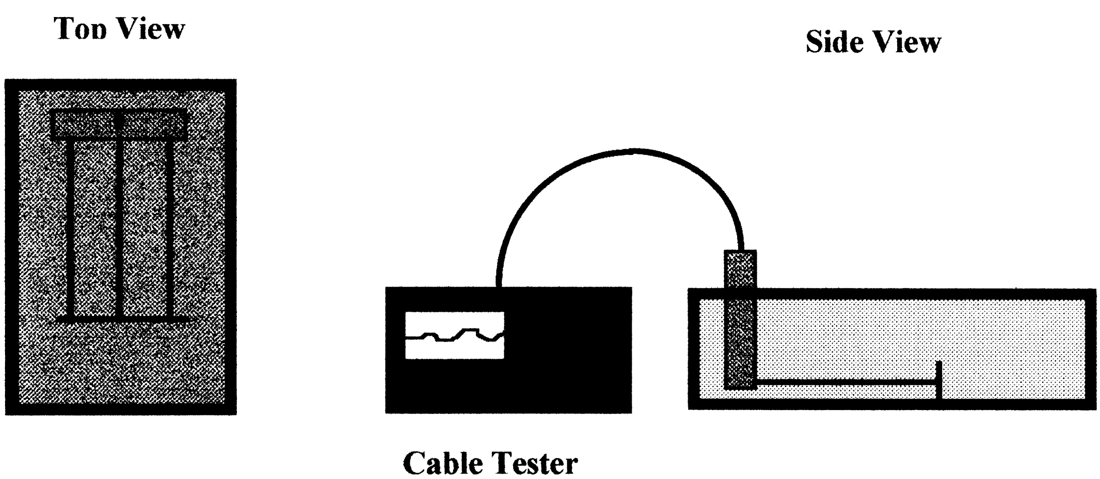
Since an evaluation of TDR was partially accomplished through the literature, the procedure here included the testing and measurement set up for the FD probe and a limited set of TDR tests. The problem of determining the percentage at which clay of a sand-clay mixture impedes the determination of TDR moisture content is considered first.

3.4.1 TDR Procedure

An arrangement of ten different samples that ranged from ten to seventy-five percent clay, by mass, were used. Referring to Figure 3.12, the experimental setup is diagrammed. The arrangement consisted of a non - conducting plastic container with matching lid that holds two to four kilograms of soil, approximately two to four inches deep. The size and depth of the container allowed the TDR probe to be completely encased by the soil - water matrix. Complete circumvential contact of the soil to the three circular rods of the probe was a necessity.

The Gurnsey clay was mixed with a coarse grained sand to create ten different sand-clay percentages. Ten, twenty-five, thirty-five, forty-five, fifty-five, sixty-five, seventy-five and eighty-five percent by mass clay mixtures were created to cover a range from clayey sand to sandy clay.

After calibration of the probe, the test commenced. Measurements with the TDR system were taken for zero percent water content to approximately saturation. Water was added to the soil to obtain predetermined moisture content by mass. The water was mixed with the soil until equally distributed throughout the test container. The TDR probe was placed into the soil, making sure the soil completely surrounded the probe's individual rods. The cover of the container was placed on and the sample left to equalize for twenty four hours. After equalization occurred, the TDR probe was connected to the cable tester and a measurement was taken in the form of a hard copy graph. After taking the measurement, a small sample of the soil that was in the direct vicinity of the probe's rods was removed and used for a gravimetric moisture content determination. The procedure was followed for all ten tests.



TDR Experimental Setup

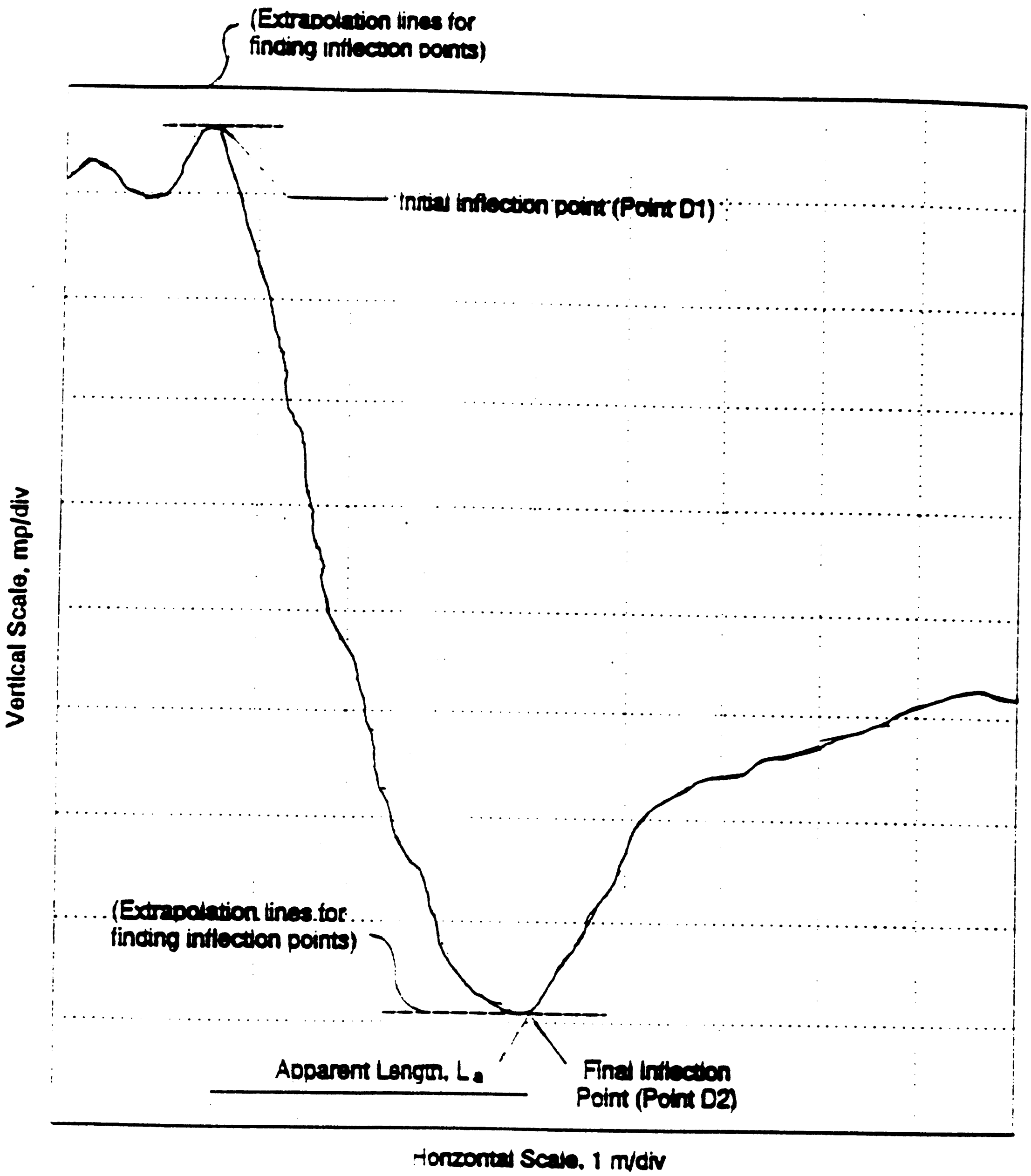
Figure 3.12

3.4.2 Calibration of TDR Probes

In order to obtain correct and accurate results the probes were put through a sequence of tests to verify operation. The calibration procedure was taken from the U.S. Department of Transportation's *LTPP Seasonal Monitoring Program: Instrumentation Installation and Data Collection Guidelines, 1994*. The procedure for calibration follows.

Three checks were performed on the probe, a check in air, distilled water, and one with the probe being shorted out. All checks on the probe were done using the cable tester and accompanied printer.

The first check was accomplished by shorting the probe; this allowed the beginning of the probe to be found on the oscilloscope. The probe end can be found on the trace by identifying the first inflection point. The trace is the visual description of the signal. The trace can be seen on either the screen of the cable tester or the printed trace. The point of inflection was found by moving the cursor across the screen, which corresponded to going down the length of the wire that connects the probe to the cable tester. A typical trace and probe end can be seen in Figure 3.13. The inflection point is typically identified as a sharp concave shaped "jump" in the signal. The probe end can be estimated by knowing the length of the cable that is between the probe and the cable tester. Finding the end of the probe allows for the amount of electrical attenuation in the signal to be determined. The value was used for the other calibration procedures as well as for the actual experimental procedure.



Typical TDR Signal

Figure 3.13

The second calibration was done by holding the probe in the air. The cable tester's cursor was moved to the first inflection point encountered after the probe end. The trace of the signal is then printed.

The third step of calibration was done by submerging the probe into a five gallon bucket of distilled water at room temperature. The probe was placed parallel to the bottom of the container. At least six inches of water was above and below the probe is needed. The cursor was positioned at the center of the first inflection point encountered, as was done with the second calibration check. A printed copy of the trace was then made.

After determining the point where the probe begins and the point where the first inflection point occurs for water and air, the apparent lengths for each can be found. This was done by subtracting the inflection point's value from the probe end's value. The dielectric constant was determined after finding the apparent length. The dielectric constants for air and water must be checked against their actual values, one and eighty, respectively. Using equation 3.1, the dielectric constant can be determined.

$$K = \left[\left(\frac{L_a}{L} \right) V_p \right]^2 \qquad \textbf{Eqn. 3.1}$$

where **K** = dielectric constant, unitless

L_a = apparent length of probe, meters

L = probe length, 0.203m

V_p =phase velocity setting on cable tester; ratio of the actual propagation velocity to the speed of light.

If the values from the calibration checks are not approximately equal to the given values, the probe can not be used.

3.4.3 Calibration of FD Probe

Use of the frequency domain Soil Moisture/ Resistivity (SM/R) probe in the laboratory calls for the use of a multimeter, frequency counter-generator, calibration jig, SM/R interface module, and the four ring SM/R probe. To calibrate the probe a number of tests need to be conducted. The frequency generator/counter was first connected to the interface module. The high signal of the frequency counter was connected to the binding post labeled F(t) on the back of the module. The low signal of the frequency counter was connected to the adjacent binding post labeled GND. A multimeter was then connected to the V_{out} and GND binding posts located on the same side of the F(t) binding post. With the SM/R probe disconnected from the interface module, a 10 kHz TTL (Transistor to Transistor Logic) signal was applied to the F(t) binding post. The V_{out} signal should read 4.000Vdc +/- 1.0%. If not, the trim pot labeled GAIN should be adjusted until the voltage is within range. A 26.50 kHz Transistor - Transistor Logic (TTL) signal was then applied to the F(t) binding post. The V_{out} should read 0.000 volts (DC) +/-1.00%. If the reading was not 0.000, then the OFS(offset) trim pot was adjusted until V_{out} is near 0.000. The process of adjusting the GAIN and OFS trim pots for TTL signals between 19.0 and 26.50 kHz may have to be done several times until the V_{out} voltages are within the acceptable range.

3.4.4 FD Probe Calibration Against Ionic Conductivity

The probe was put through a number of tests to determine its ability to measure soil moisture and the probe's resistance to salinity within the soil's pore water.

The first calibration procedure for the SM/R probe was to test the probe's resiliency against the ionic conductivity of the soil matrix. The probe's resiliency was measured by how much the increased ionic conductivity attenuated the probe's frequency response. The procedure was accomplished by using a simple homogenous material and slowly increasing the ionic conductivity of the material. The four trials were run using deionized water and fine and coarse grained sands as the test materials. The deionized water was considered a simple homogenous material, keeping the relationship between ionic conductivity and frequency attenuation simple. The procedure used the large test containers filled with 30.0 liters of deionized water. The probe was placed and centered in the container and supported by the top frame of the container. Frequencies and voltages were recorded from the frequency counter and the multimeter. The SM/R probe was removed from the water and dried off. After removing the probe, a conductivity meter was placed in the solution to the depth of the two inside rings. A conductivity measurement was taken and recorded. At this point a predetermined amount of NaCl was added to the water and stirred for approximately 1/2 hour or until the NaCl was completely dissolved. The use of a bench scale laboratory magnetic mixer was employed to assure a homogenous salt-water solution. Increasing amounts of NaCl were added to the solution, while measurements were continued with the probe and the conductivity meter.

The second part of the procedure was to test the probe resiliency to ionic conductivity using a soil as the base material. The procedure used the same basic idea as the previous test with water. Two separate tests were conducted using a conductivity of 2 mS/cm and 20 mS/cm, respectively. The tests differed because successive salt concentrations could not be added without the soil reaching saturation first. In order to maintain adequate separation of moisture contents, the NaCl solution was added to the soil at ranges from 5% moisture content to saturation at 5% intervals. The salt concentrations were held constant as the water content was increased. Once saturation was reached, the soil was then dried and the procedure was restarted with the next higher NaCl solution. It was also taken into account that the soil would have salt within its pores and attached to the outside of the actual soil particles when adding the next set of solutions to the soil.

3.4.5 Soil Moisture Test - FD probes

The testing and calibration of the Soil Moisture/Resistivity probe for soil moisture was done by using the described soils and materials under *Experimental Materials* in Chapter 3. The procedure of the test closely resembled the initial FD testing previously described.

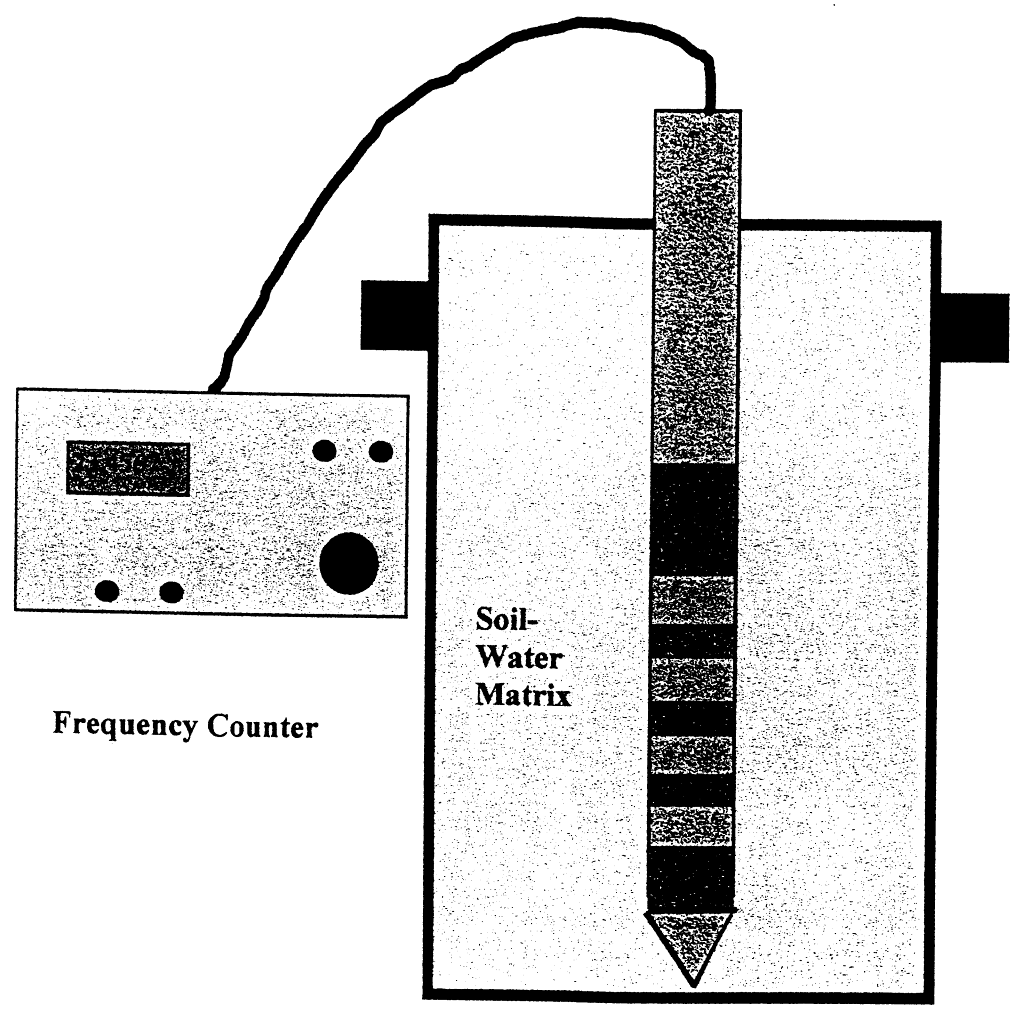
The first step in testing and calibrating the SM/R probe for specific soils was to prepare the individual soil samples. The volume of soil used was approximately 50 liter amounts. The natural soils were completely dried and then put through a sieving procedure to obtain the soil type wanted and also to remove impurities such as rocks and organics. The procedure also allowed the soils to be characterized by grain size. After the soil was broken down to its grain size and sieved, the soil was placed into the 50 liter container. The two inner rings of the probe must have an approximate four to six inch diameter sphere of soil surrounding them in order to achieve good results. The 50 liter test container gave approximately a six inch radius around the probe's two inner rings. The frequency response was measured for the prescribed materials that ranged in moisture content from 0.00 % to saturation.

The soil for each test was mixed with deionized water. The mixing process was as follows. Water, at a predetermined amount, was added slowly to the soil. Mixing of the soil and the water began immediately after the water was added to the soil. Mixing of the soil was found to be done best by using the researcher's hands. To improve the mixing, latex gloves were worn. This was done in order to not allow the researcher's hands to pick up any of the water and/or soil. Achieving the most complete and homogenous mixture was necessary in order to avoid errors in measuring the soil moisture content. Having a heterogeneous mix not only discredits the calibration of the probe but makes gravimetric or volumetric moisture interpretation much more difficult.

After mixing of the soil and water was completed, the soil was added to the test container in five lifts. A compaction effort was done to each lift. After the probe was pushed through the soil in the test container another compaction to the entire soil matrix was performed The initial compaction of the lifts is done by using a standard procter hammer.

Twelve blows were impacted on each lift. The final compaction effort was accomplished by using the same standard procter hammer; however, twenty four blows were impacted on the test soil. A separate test of compaction was also performed to look at the influence that over-consolidation might have on the probe's frequency response. The soil was placed and compacted in separate lifts as before; however, once the probe was inserted into the soil, a weight of approximately 180 pounds was placed upon the soil to model overconsolidation.

Once the probe was placed in the soil, frequency and voltage readings that correspond to the added moisture content could be recorded. The experimental set up is diagrammed in Figure 3.14



SM/R FD Experimental Setup

Figure 3.14

Soil samples were taken to verify the assumed moisture content. The samples were obtained by first removing the soil from one side of the probe to the depth of the two inner rings. Soil samples were then collected from the entire area adjacent to the inner rings. The samples were collected for gravimetric moisture content analysis. The samples were weighed and then placed into a laboratory oven at approximately 87 degrees F. The gravimetric moisture content was determined as described in ASTM method D2216.

In addition to using the gravimetric samples as a way to correlate the frequency response of the probe, a TDR probe was placed within the soil matrix to obtain the soil moisture by Time Domain Reflectometry. After removing the SM/R probe from the soil and taking the soil samples, the TDR probe was placed in the direct area of where the inner rings of the SM/R probe were located. Soil was then placed and re - compacted over the TDR probe to insure complete encapsulation of the probe by the soil. Readings were then taken with the oscilloscope and a hard copy graph of the TDR trace was printed.

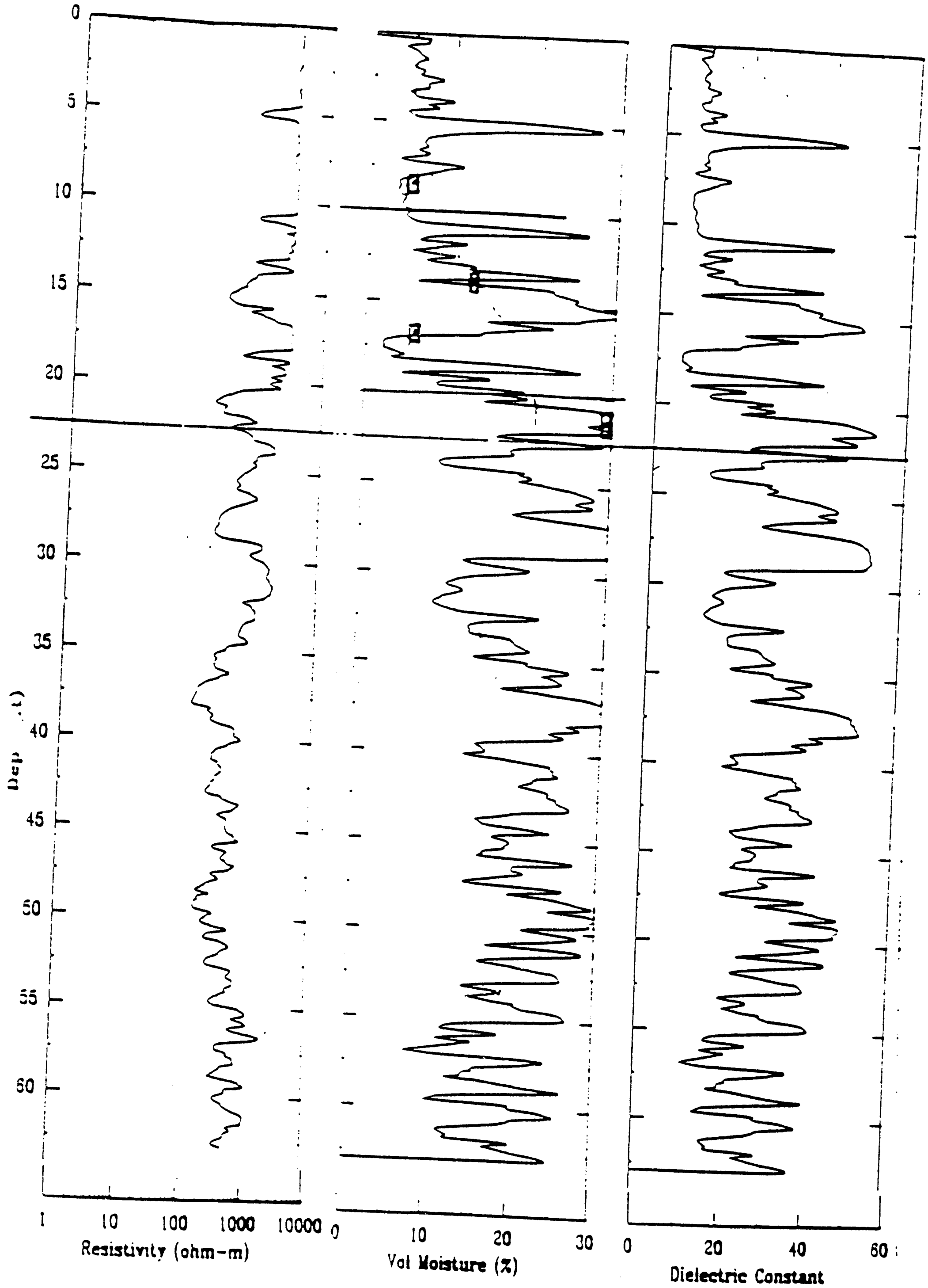
3.4.6 Field CPT - SM/R Probe Procedure

The extension of the evaluation SM/R probe under in situ conditions was not feasible using a full size cone penetrometer vehicle. However, the probe configuration was designed to be used for both bench scale and CPT type experimentation and investigation. In situ procedures could be designed to provide further verification of the probe's readings as well as shed light on how other factors such as bulk density and porosity might affect the probe's frequency response.

The procedure for the field testing could be started with preparing the probe so it could be used with the CPT system. The SM/R probe would be connected to the wiring system that is threaded through the push rods and is then connected to the interface module, multimeter, and frequency counter. (The SM/R probe was designed to connect in series to the peizocone and/or any other type of cones that are pushed. The SM/R probe can also be pushed by itself.)

After the connections have been made to the data acquisition equipment, the probe could be lowered and pushed into the ground at a rate of approximately 1 cm/sec. The push rate allows for the probe's readings to be correlated with depths at which the readings were recorded. The push would be stopped after reaching the water table. The probe would then be removed from the soil. The first push of the probe would allowed for the soil moisture profile to be examined for a wide range of moistures. A location is needed that has a variance in moisture contents so a correlation between the frequency response and the soil moisture would have sufficient data to be analyzed. After locating a soil moisture profile that was adequate for the procedure, the CPT would be moved approximately 1 foot from the previous test hole. The new position would be used as the actual test hole for the procedure. The SM/R probe would then be pushed into the soil at a rate of 1 cm/sec and stopped every one-half to one feet to record data from the data acquisition equipment. As the probe is pushed through the soil, frequency response data would be taken at the above intervals and in between those intervals as time allowed.

After the frequency response/depth data push are completed, the CPT would be moved approximately one foot away from the test hole to collect soil samples. Soil samples would be taken by use of a spit spoon sampler that was designed to be used with the CPT system. The soil sampler can collect samples that are approximately 30 inches long. The sampler would be pushed from the ground surface to the final depth of the previous push. The samples are removed from the sampler, numbered and placed inside air tight containers. After determining the soil moisture content of the samples by gravimetric methods, correlation with the frequency response could be determined and analyzed. A typical set of field test data can be seen in Figure 3.15.



Typical data from SM/R and CPT, (ARA, 1996)

Figure 3.15

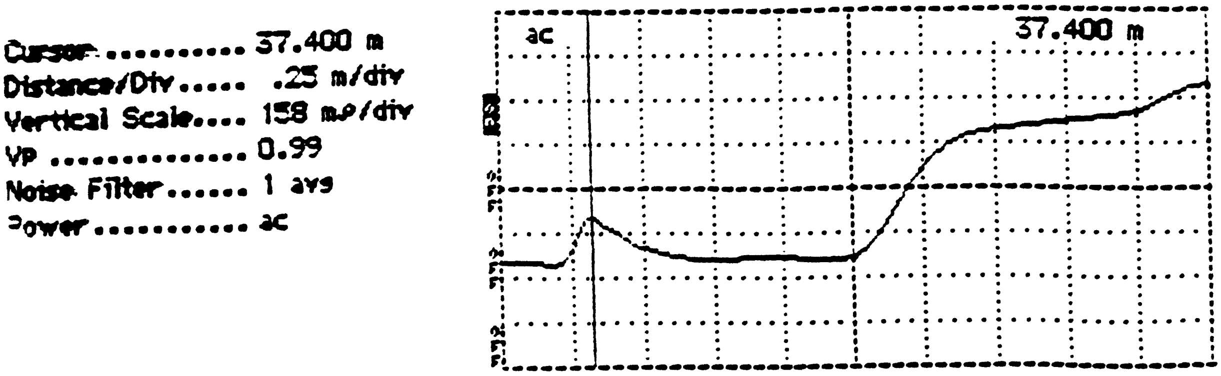
3.5 Data Reduction

Reduction of the data obtained from the TDR and FD probes was necessary to determine moisture contents or dielectric constants of soils. The methods employed here for TDR and FD techniques are quite different.

3.5.1 TDR Data Reduction

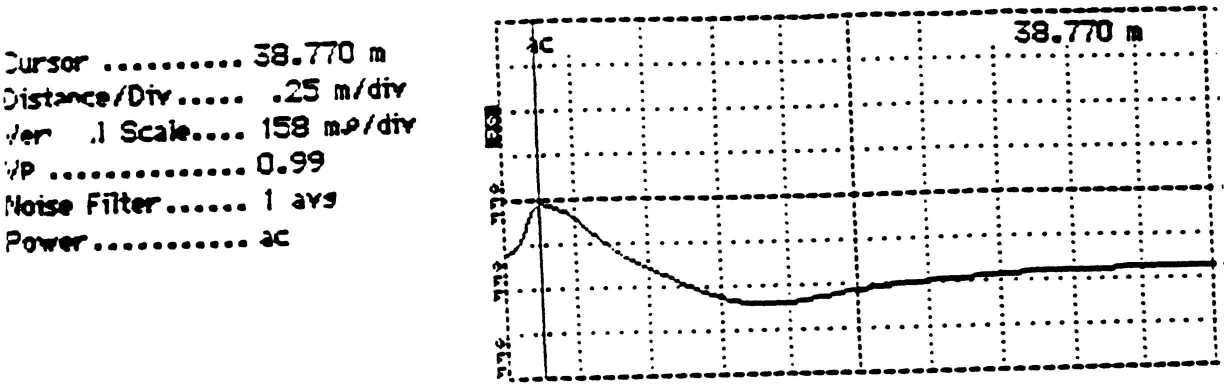
The trace or signal from the cable tester (which is seen on the cable tester's screen or from a print out) is often called the trace. The first peak or inflection denotes the beginning of the probe, as explained in the calibration procedure. The second inflection point represents the point at which the signal is reflected off the end of the probe. The difference in distance between these two points, the apparent length, allows for the dielectric constant and moisture content to be determined. The apparent length changes as the conductance of the material surrounding the probe's rods changes.

Determination of the second inflection point on the trace of the return signal can sometimes be complicated by the shape and slopes of the trace. This, of course, is directly related to the type of material that surrounds the probe. An example of traces from sand and clay can be seen in Figures 3.16 and 3.17. There is a quite noticeable difference on how the two traces behave. The clay tends to not inflect as fast as the sand.



Typical Sand TDR Trace

Figure 3.16



Typical Clay TDR Trace

Figure 3.17

There are different methods of trying to identify the second inflection point. There are primarily four different methods to determine the inflection point; Method of Tangents, Method of Peaks, Method of Diverging Lines, Alternate Method of Tangents.

The Method of Tangents determines the initial inflection point by locating the intersection of horizontal and negatively sloped tangents at the trace's local maximum value. The second inflection point is located at the intersection of the horizontal and positively sloped tangents to the trace's local minimum value.

The Method of Peaks accomplishes finding the initial inflection point by locating the intersection of the tangents drawn on either side of the local maximum. The final inflection point is located at the intersection of the tangents drawn on both sides of the local minimum.

The Method of Diverging Lines finds the initial inflection point where the trace diverges from the local maximum's positively sloped tangent. The second inflection point is determined by where the trace diverges from the local minimum's negatively sloped tangent.

The Alternate Method of Tangents determines the initial inflection point by determining the point of intersection of the horizontal and positively sloped tangents at the trace's local maximum value. The final inflection point is located at the point where the horizontal and negatively sloped tangents and the trace's local minimum value intersect.

After attaining the apparent length and dielectric constant, the moisture content of the soil can then be determined. In order to change the dielectric constant values into moisture contents, an universal equation was developed after exhaustive research by Canadian researcher Clarke G. Topp (1980). The equation relates the dielectric constant of the material to moisture content, by volume, based on a regression type analysis. The equation is as follows:

$$\Theta = (-0.053+0.0293K -0.00055K^2+ 0.0000043K^3)*100 \qquad \text{Eqn. 3.2}$$

Where Θ = volumetric water content, in percent

K = dielectric constant, unitless

3.5.2 FD Data Reduction

The data collected from the SM/R probe is in the form of a frequency response. The relationship between soil moisture can be made either by using the frequency response or a voltage. The frequency response can be converted to a voltage by way of the Interface Module. The true moisture contents that were determined gravimetrically were correlated with either a voltage or a frequency. Another alternative that existed was making a dielectric constant to frequency correlation, and then making a correlation between the dielectric constant and the moisture content, as can be seen in Figures 3.18 and 3.19. Many authors of previous research that have dealt with soil moisture have chosen the latter path. However, if the probe is going to be used specifically for soil moisture determination there is no need to make this intermediate jump from frequency response to dielectric constant.

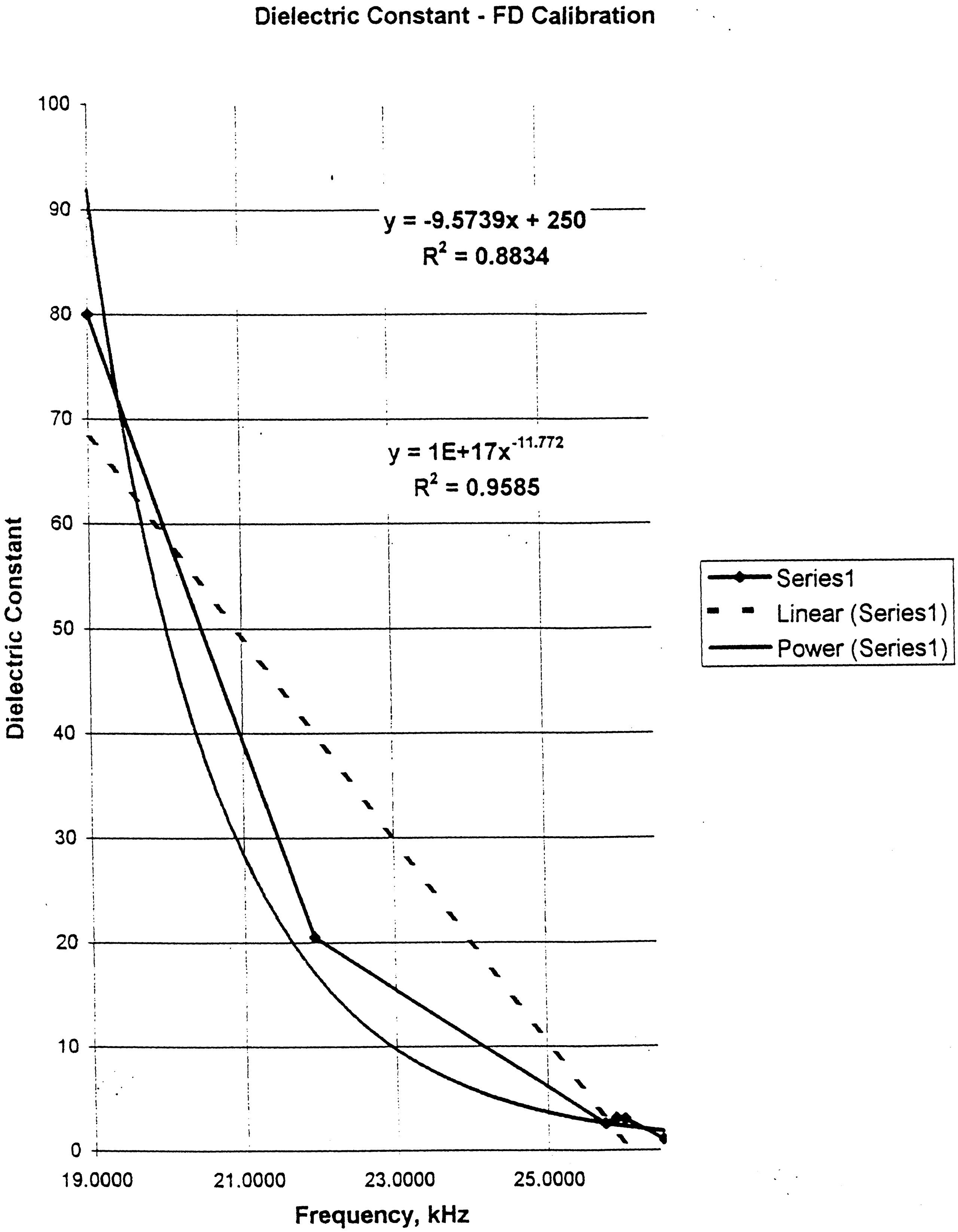
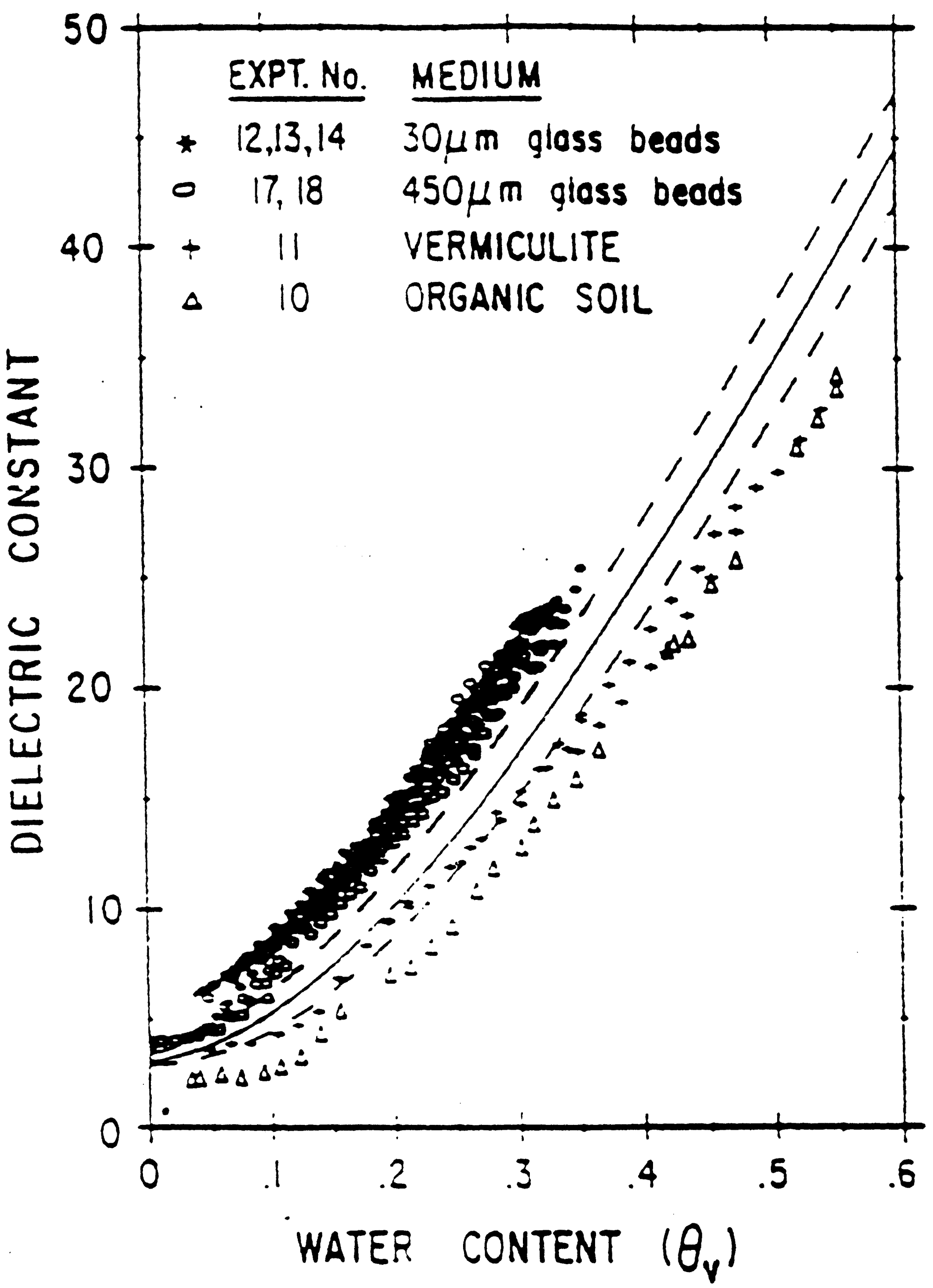

Dielectric Constant - FD Calibration
100
90
80
70
60
50
40
30
20
10
0
19.0000
21.0000
23.0000
25.0000
Dielectric Constant
Frequency, kHz
y = -9.5739x + 250
R² = 0.8834
y = 1E+17x^-11.772
R² = 0.9585
Series1
Linear (Series1)
Power (Series1)

Figure 3.18


EXPT. No.
MEDIUM
12,13,14
30µm glass beads
17, 18
450µm glass beads
11
VERMICULITE
10
ORGANIC SOIL
DIELECTRIC CONSTANT
WATER CONTENT (θv)
0
10
20
30
40
50
0
.1
.2
.3
.4
.5
.6

CHAPTER 4

TIME AND FREQUENCY DOMAIN THEORY

Measuring soil moisture using frequency or time domain techniques is a process that uses electric alternating current theory. The probes themselves operate under the same general theory; it is only the form of data that varies.

4.1 Dielectric Properties of Materials

From alternating current theory, when dealing with a dielectric substance that has considerable conductance it is convenient to describe the permittivity of the substance complexly. For dielectric substances that fall into this category, the complex permittivity is defined as:

$$\varepsilon = \varepsilon_1 - j\varepsilon_2 \qquad \textbf{Eqn. 4.1}$$

or

$$\varepsilon = \varepsilon_1(1 - j\tan\delta) \qquad \textbf{Eqn. 4.2}$$

where $\delta = \varepsilon_2 / \varepsilon_1$ **Eqn. 4. 3** where ε = complex permittivity, farads/m

ε_1 = real part of permittivity, farads/m

ε_2 = imaginary part of permittivity, farads/m

tan δ = loss tangent of ratio between vectors of imaginary and real parts of permittivity

The imaginary part of the permittivity represents the energy absorption by the material. Energy is absorbed by ionic conductivity and dielectric losses.

$$\varepsilon_2 = \varepsilon_{2d} + \frac{\sigma}{\varepsilon_0 \omega} \qquad \textbf{Eqn. 4.4}$$

where ε_{2d} = dielectric losses, farads/m

σ = ionic conductivity, Siemens /m

ω = angular frequency, hertz

ε_0 = permittivity of free space, 8.85×10^{-12} farads/m

As seen from Equation 4.4, the dependency of the imaginary part of the materials permittivity is based not only on the dielectric losses but the frequency (ω) of the alternating current (A.C.) being used.

In some cases it is more convenient to measure the permittivity of a soil by modeling it as a capacitor. The permittivity is measured by the complex impedance, *Z*, of the capacitor. The relationship between the complex impedance and the complex permittivity is given in Equation 4.5.

$$Z = \frac{1}{G + j\omega C} = \frac{1}{j\omega \varepsilon \varepsilon_0 \alpha} \qquad \textbf{Eqn. 4.5}$$

Where **Z** = complex impedance

G = inductance, farads^{-1}

C = capacitance, farads

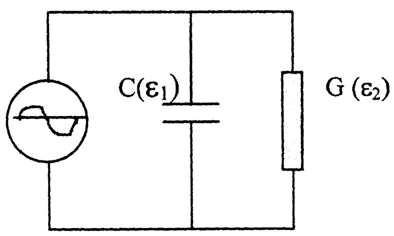
ω = angular frequency, hertz

ε = complex permittivity, farads/m

ε_0 = permittivity of free space

α = electrode geometry constant

The relationship is diagrammed in Figure 4.1.

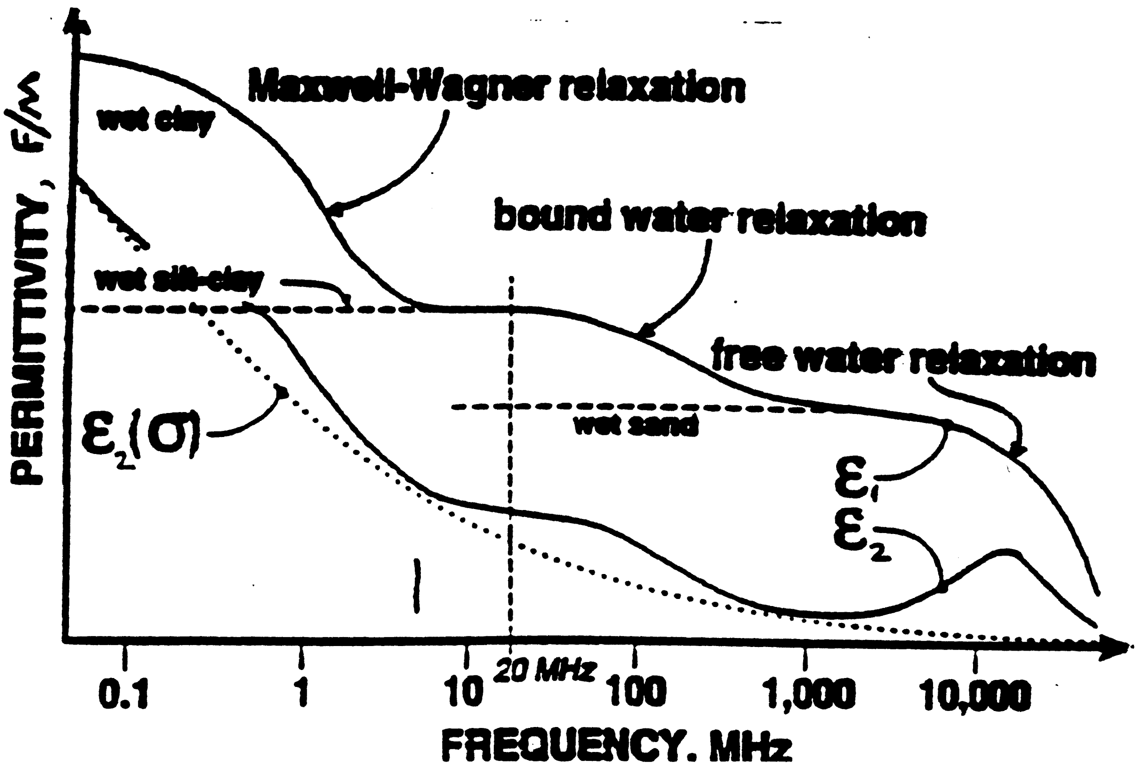


Electrical relationship between complex impedance and complex permittivity

Figure 4.1

When exposed to an A.C. current, molecules of a substance, in this case water, will try to reorientate themselves either to the positive or negative poles of the current. As the poles change back from positive or negative, the molecules will also try to change back The reorientation process happens rapidly, although, it is not instantaneous. When the frequency of the current alternates too fast for the molecules to follow, the particles will "relax" and no longer move. At the "relaxation" frequency, the imaginary part of the complex permittivity is much smaller than the real part. This is because the ionic conductivity becomes much smaller relative to the dielectric losses. Referring to Figure 4..2, the relationships between frequency, ionic conductivity, and the real and imaginary parts of the complex permittivity can be observed. As can be seen from the Figure 4.2, in the range of 1 GHz the effect of the imaginary part of the complex permittivity is at a minimum. It is in this range that losses from the ionic conductivity and dielectric losses have the least impact on permittivity measurements. Minimizing the losses allows for a sensor that uses either frequency or time domain techniques to determine a permittivity or dielectric constant that is independent of the ionic conductivity.

The importance of minimizing these losses is important when trying to develope a soil moisture sensor that operates independently of soil type. The ionic conductivity losses are affected by the soil characteristics such as specific surface area, density, and mineral content. It has been stated by several researchers that the best operating frequency for soil moisture determination is around 1 GHz. Falling back from this value increases the variability that the soil's characteristics affect the soil moisture measurements. It is obvious from Figure 4.2 that choosing the correct operating frequency range will have an impact on calibration and the overall use of the probe.



Complex Permittivity - Frequency Relationship (Hilhorst and Dirksen, 1994)

Figure 4. 2

4.2 TDR Theory

As was stated previously, TDR technology uses a probe and a voltage source (the cable tester) to determine the dielectric constant of the surrounding material. The cable tester generates an alternating current signal at approximately 1 GHz. The signal travels the length of the cable until it reaches the probe. Until this point the signal is shielded by a coaxial cable, which allow no losses to occur except for the resistance of the cable itself. Once the signal has reached the beginning of the probe the journey continues to the end of the probe. The time taken for the signal to travel this distance is directly related to the real part of the complex permittivity, ε_1. The relationship is given in Equation 4.6

$$\varepsilon_1 = \left(\frac{c\, t_{refl}}{2l} \right)^2 \qquad \textbf{Eqn. 4.6}$$

Where c = propagation velocity of signal, m/s

t_{refl} = travel time, seconds

l =length of rod, m

Once arriving at the end of the probe, the signal is reflected and travels back to the beginning of the probe. The imaginary part of the complex permittivity, ε_2 is related to the ratio of the amplitude of the transmitted and reflected signals, as given in Equation 4.7

$$\varepsilon_2 = \frac{\sqrt{\varepsilon_1}}{120\pi l} \ln \frac{u_{trans}}{u_{refl}} \qquad \textbf{Eqn. 4.7}$$

Where u_{trans} = amplitude of signal transmission, m/s

u_{refl} = amplitude of reflected signal transmission, m/s

l =length of rod, m

ε_1 = real part of permittivity

ε_2 = imaginary part of permittivity

The difference between the actual and reflected signal is due to attenuation of the signal by the surrounding material. If the probe is used in air the difference will be quite small. Whereas if the probe is used in water, the difference will be large. The difference in the signal that is sent and received is displayed as a trace on the screen of the cable tester. As was stated in Chapter 3, section 3.7, TDR Data Reduction, the difference seen on the TDR trace is called the apparent length. Using Equation 3.1, the dielectric constant of the material can be calculated. The dielectric constant of a material is related to the material's permittivity by :

$$\varepsilon = K\varepsilon_0 \qquad \textbf{Eqn. 4.8}$$

Where **K** = dielectric constant, unitless

ε = complex permittivity, farads/m

ε_0 = permittivity of free space, 8.85 x 10^{-12} farads /m

After attaining the dielectric constant of the material, two options are available to determine the soil moisture content. One option is to use Topp's universal equation to calculate the moisture content. The other option is to calibrate the TDR probe for the specific soil and develop a soil specific soil moisture equation.

4.3 Frequency Domain Theory

The theory behind the frequency domain system is basically the same as the TDR, to use the attenuation of an electrical signal to determine the soil moisture content. However, the process in which this is accomplished is based in the frequency and not the time domain. The capacitance of the soil is used to determine the soil's dielectric constant or complex permittivity. The capacitance of a dielectric material is defined as :

$$C = \alpha \varepsilon_0 K \qquad \textbf{Eqn. 4.9}$$

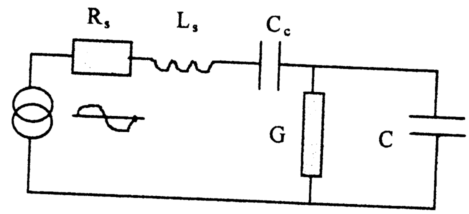
where **C** = capacitance, farads

K = dielectric constant

α = electrode geometry constant

ε_0 = permittivity of free space, 8.85×10^{-12} farad/m

The FD probe forms a capacitor through the two inner steel rings of the probe and the soil. The general model for this capacitor is give in Figure 4.3



General Model for FD Probes

Figure 4.3

Where $\mathbf{R_s}$ = series resistance

$\mathbf{L_s}$ = total self inductance for the rings and wiring

$\mathbf{C_c}$ = coupling capacitor

G, C = inductance and capacitance that are encountered around the length of the rings.

If a known current, *I*, develops a voltage, *u*, across *Z* ($u = iZ$) the amplitude and phase of the complex voltage relative to the applied voltage can be measured. The real and imaginary parts of the permittivity or impedance can be calculated using Equations 4.5, 4.10, 4.11

$$Z = \frac{1}{G + j\omega C} = \frac{1}{j\omega \varepsilon \varepsilon_0 \alpha} \qquad \textbf{Eqn. 4.5}$$

$$\varepsilon_1 = \frac{C}{\alpha \varepsilon_0} \qquad \textbf{Eqn. 4.10}$$

Where ε_1 = real part of permittivity, farads/m

α = electrode geometry constant

ε_o = permittivity of free space, farad/m

C = capacitance, farads

$$\varepsilon_2 = \frac{G}{\omega \varepsilon_0 \alpha} \qquad \textbf{Eqn. 4.11}$$

Where ε_2 = imaginary part of permittivity, farad/m

α = electrode geometry constant

ε_o = permittivity of free space, farad/m

G = inductance, farads^{-1}

ω = angular frequency, hertz

The frequency response of the probe as it is subjected to different materials or dielectrics will behave according to Equation 4.12

$$F = \frac{1}{2\pi\sqrt{LC}} \qquad \textbf{Eqn. 4.12}$$

Where **F** = frequency response, kHz

L = inductance, $farads^{-1}$

C = capacitance, farads

As the capacitance of the soil increases, i.e., with increasing water content, the frequency response will decrease. As was stated before, it is the measurement of the difference in the sent and received frequencies that allow for the complex permittivity to be determined.

4.4 Soil - Water / Complex Permittivity Mixing Models

Examining the behavior of soil particles as they interact with water can answer many questions on the data received from using TDR or FD tests. It is important to understand how the water acts and interacts with all types of soil at all moisture levels. There are several mixing models that have been proposed by past researchers that try to describe the soil - water - air interaction. These models are useful in understanding the processes, but have little use to the engineer wanting soil moisture data to design a foundation or solving an environmental remediation problem.

The interaction of water and air within a sand matrix is the least complicated to examine. The discrete phases of solid, liquid, and gas are maintained. The mixing model creates a complex permittivity of the soil-water-air matrix to be equal to the relative volumetric percentages of its constituents. As an example, if a sand has a porosity of 0.30, 70 % of the volume is made up entirely of the sand particles. The other 30% of the total volume is divided by the air and the water that is contained in the voids. If the soil is dry, the complex permittivity of the soil - air matrix will be close to the value of the soil particles. This is caused by the low permittivity value and volume of air. On the other hand, the complex permittivity of a saturated sand will be a combination of the soil particle's complex permittivity, around 3.0, and the complex permittivity of the water, around 81.0. At saturation the complex permitivity of the soil matrix would be around 26.0.

A mixing model presented by Baker, (1989) is given in Equation 4.13

$$K = \left((1-\Phi)K_s^{\alpha} + \Theta K_{fw}^{\alpha} + \left(\Phi - \Theta K_g^{\alpha}\right)\right)^{\frac{1}{\alpha}} \qquad \textbf{Eqn. 4.13}$$

Where **K** = complex dielectric constant of soil matrix, unitless

Φ = porosity, unitless

Θ = volumetric moisture content, cm^3/cm^3

$\mathbf{K_s}$ = complex dielectric constant, solid phase

$\mathbf{K_{fw}}$ = complex dielectric constant, free water

$\mathbf{K_g}$ = complex dielectric constant, gas phase

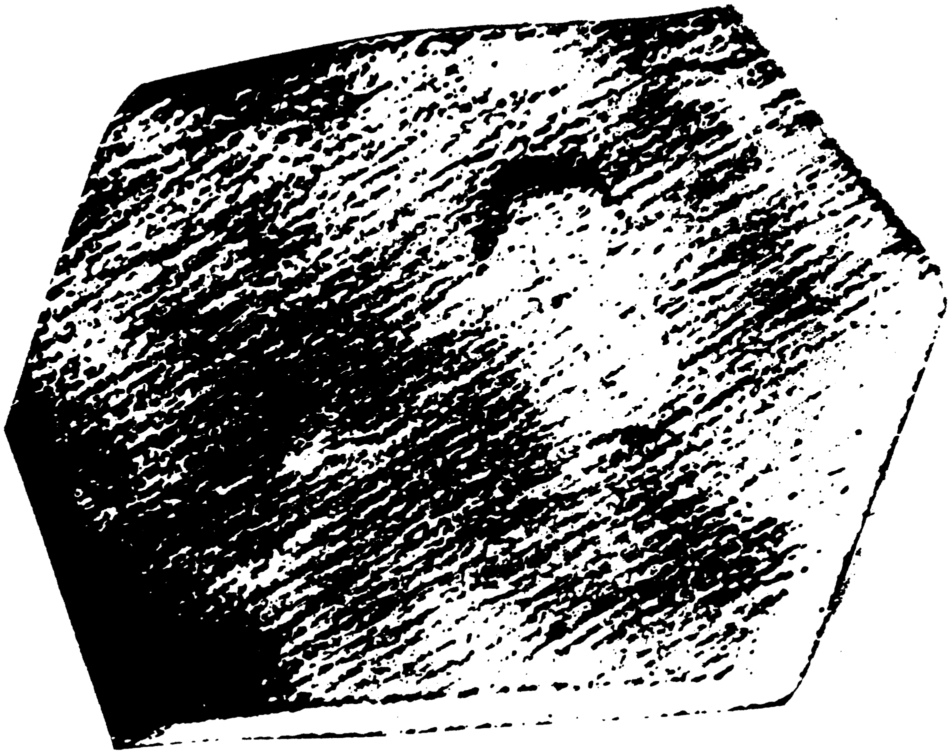
α = geometric orientation coefficient

Depending on the surface area and particle size of the sand the mixing model may not hold true. In most cases, the sand particles will have a static electrical charge on them that allows them to attract water molecules to their particles' surface. The validity of the previously presented mixing model is dependent on the degree of attraction or adhesion that the sand particles create. As the water content increases in the coarser materials, the adhesion plays a less important role, and does not need to be taken into account.

The relatively simple mixing model presented in Equation 4.13, for sandy soils can not be used with the more cohesive fine grained soils such as silts and clays. Silty sand and clayey sand mixtures must also be described by a different relationship.

The problem as mentioned before with fine grained soils is they have a tendency to become quite cohesive on the microscopic scale. Referring to Chapter 3 from the first edition of Lambe and Whitman's Soil Mechanics I, (1969) a better understanding of the cohesive forces that develop in clay particles can be obtained. The clays used for testing have the most tendency to be cohesive as compared to the silts and other clay/silt sand mixtures. However, it is not to say the problem still does not exists with more coarse grained soils. The mixing model presented can be used to describe all of the fine grained soils, but only the clay will be looked at here.

The Gurnsey and Upshur clays used are from the kaolinite family. The kaolinite family represents a group of minerals that are platy in structure and have the formation as seen in Figure 4.4. They consist of one silica molecule stacked on top of a Gibbsite molecule, forming a sheet like structure. The silica molecule is a tetrahedral and has one silicon atom nestled among four oxygen atoms.



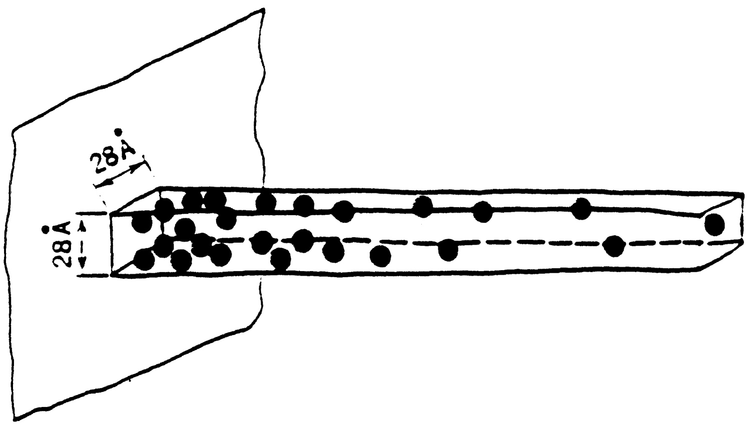
Kaolinite Particle, (Lambe and Whitman, 1969)

Figure 4.4

Gibbsite is a molecule that has four oxygen atoms that surround a central aluminum atom creating a tetrahedral form. Individual sheets of kaolinite are stacked upon each other to form an intricate crystalline structure. They are often referred to as two layered sheets. The "stacks" of kaolinite lattices are held in place by hydrogen bonding and secondary valence forces.

Often the atomical structure of the tetrahedral can change due to isomorphous substitution; one type of atom (aluminum (+4)) is interchanged for another type of atom (silicon (+3)). The exchange can have effects on the lattice structure and cause a positive or net negative charge (for the case above) to occur. When adding water to the soil particles, the atoms that commonly interact in isomorphous substitution; (sodium, calcium) are hydrated and become enlarged with a shell of water now surrounding them. The increase in size no longer permits the atoms to be within the lattice structure. With the size increase, the hydrated atoms move away from the mineral surface to a distance that is at an equilibrium between the two forces that are acting on them; (1) thermal energies moving them outward, (2) the attracting negative charge that the mineral surface has.

As the hydrated atoms move out from the mineral surface, the concentration of the hydrated atom decreases. This distance from the mineral surface to the point of equilibrium is defined as the double diffused layer. The double layer for Kaolinite can be seen in Figure 4.5.



Diffused Double Layer of Kaolinite, (Lambe and Whitman, 1969)

Figure 4.5

Depending on which atom is isomorphously substituted, the diffused double layer can be of different thickness. The water molecules are also attracted to the mineral surface by the overall charge of the water, stray electrical charges, hydrogen bonding, and van der Waals forces.

The mixing model for the fine grained materials takes into consideration the effect of "bound" water, water that has been attracted to the soil particles by the above description. The mixing model consists of the complex permittivity for the water, air, soil, and bound water. With the cohesion of water to the soil particles, the mixing model is no longer a discrete three part relationship. The mixing model used for clays deals with the air, soil, and unbound water, exactly as was done with the coarse grained soils mixing model. However, the mixing model used for the clays must take into account the bound water.

A mixing model presented by Birchak, (1974) is given in Equation 4.14

$$K = \left((1-\Phi)K^{\alpha}{}_{s} + (\Phi-\Theta)K_{g}^{\alpha} + (\Theta-\Theta_{bw})K_{fw}^{\alpha} + \Theta_{bw}K_{bw}^{\alpha}\right)^{\frac{1}{\alpha}} \qquad \textbf{Eqn. 4.14}$$

Where **K** = complex dielectric constant of soil matrix

Φ = porosity

Θ = volumetric moisture content, cm^3/cm^3

Θ_{bw} = volumetric moisture content of bound water, cm^3/cm^3

$\mathbf{K_s}$ = complex dielectric constant, solid phase

$\mathbf{K_{fw}}$ = complex dielectric constant, free water

$\mathbf{K_{bw}}$ = complex dielectric constant, bound water

$\mathbf{K_g}$ = complex dielectric constant, gas phase

α = geometric orientation coefficient

As can be seen in the equation, the mixing model is a four part relationship. The complicated part of the model is measuring the volume of bound and free water within the soil. The bound water can be calculated by gravimetric methods. If a sample is dried at above 100 degrees centigrade, the total water, including the bound water, that is contained within the soil will be driven off. This can be compared to a normally (oven temperature at 88-90 degrees) dried gravimetric sample and the difference between bound and free water calculated. With this known, an adjustment to the complex permittiviy can be made. This of course is unnecessary when doing calibration with the frequency domain system because the relationship between the frequency response and the water content is all that is needed.

CHAPTER 5

DATA ANALYSIS

5.1 Data Interpretation

The data collected from the frequency domain probe consists of a frequency response measurement and a correlating moisture content. The relationship between the frequency and moisture content is different for each soil type that was tested.

5.2 Fine and Coarse Sands

The results of the tests for the fine and coarse sands are located in Tables 5.1 and 5.2, respectively. The graphical results can be seen in Figures 5.1 and 5.2

TABLE 5. 1 FINE SAND

Frequency Response, kHz	Gravimetric Moisture Content %
25.9852	0.00
23.0500	5.10
24.4870	10.10
24.6218	11.00
22.1605	18.00

TABLE 5.2 COARSE SAND

Frequency Response, kHz	Gravimetric Moisture Content %
25.8731	0.00
25.3540	5.20
24.2118	7.20
23.3564	11.00
23.1925	12.10

Analyzing the results of the coarse and fine sands indicates how the soils responded to the oscillating electrical current. One would expect that the sand - water mixture would give the best results by maintaining discreteness in the three part mixing model of water-soil-air. However, with the sands being so porous, true and accurate water contents were hard to determine by gravimetric methods. The most accurate points of data are from completely dry and saturated conditions. TDR volumetric water contents were used to create a second set of calibration curves in order to compensate for the effect of drainage and porosity of the sands. The results of the analysis are in Figures 5.3 and 5.4 The results of these tests show a relationship that is very similar to the results using moisture contents determined from gravimetric methods. It has been well documented that Topp's Equation (Topp,1980) and TDR are considerably more reliable for coarse grained materials than for fine grained soils. This suggests that the FD probe is equally reliable as TDR in coarse grained soils.

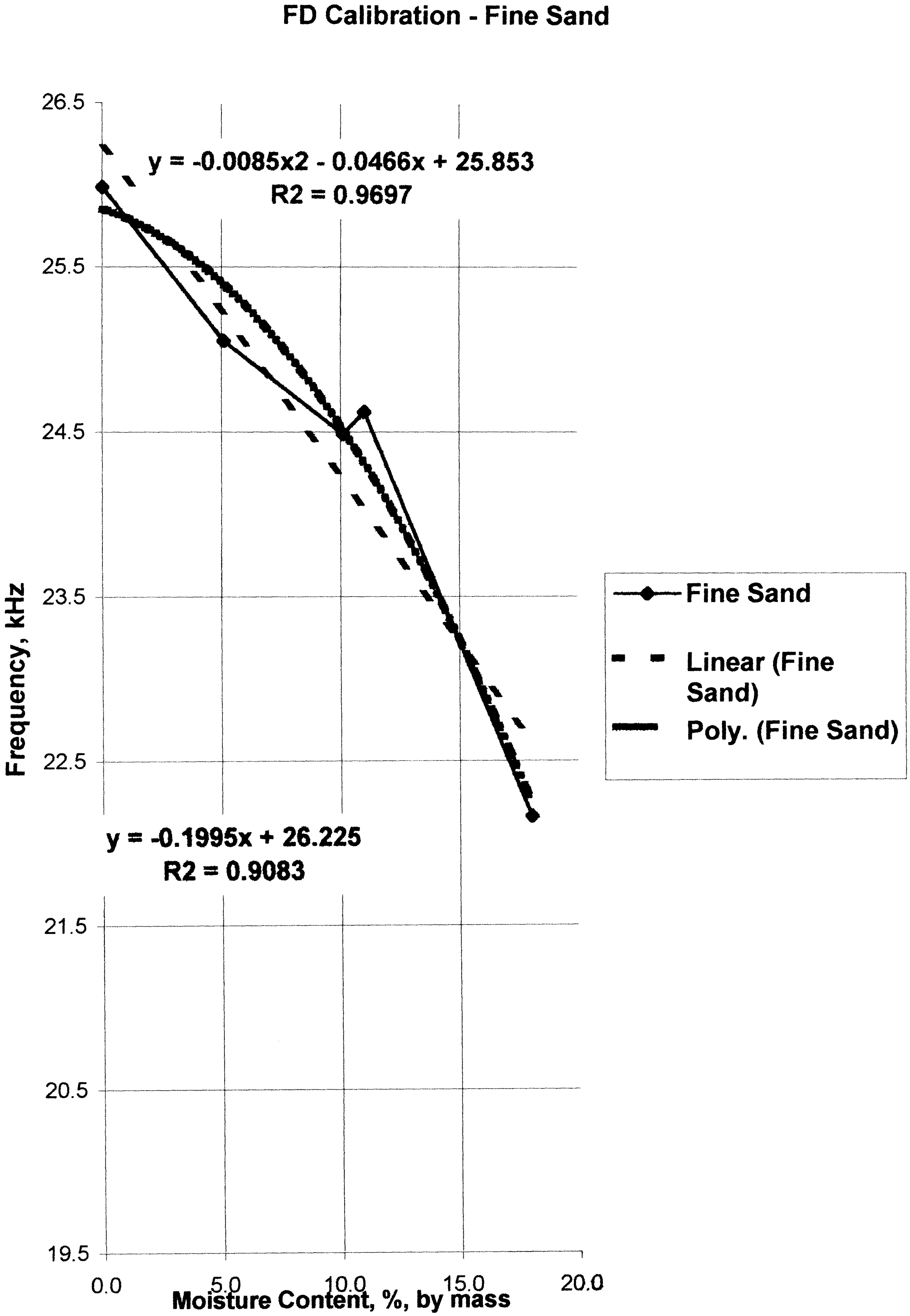

FD Calibration - Fine Sand
y = -0.0085x2 - 0.0466x + 25.853
R2 = 0.9697
y = -0.1995x + 26.225
R2 = 0.9083
Frequency, kHz
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0.0
5.0
10.0
15.0
20.0
Moisture Content, %, by mass
Fine Sand
Linear (Fine Sand)
Poly. (Fine Sand)

Figure 5.1

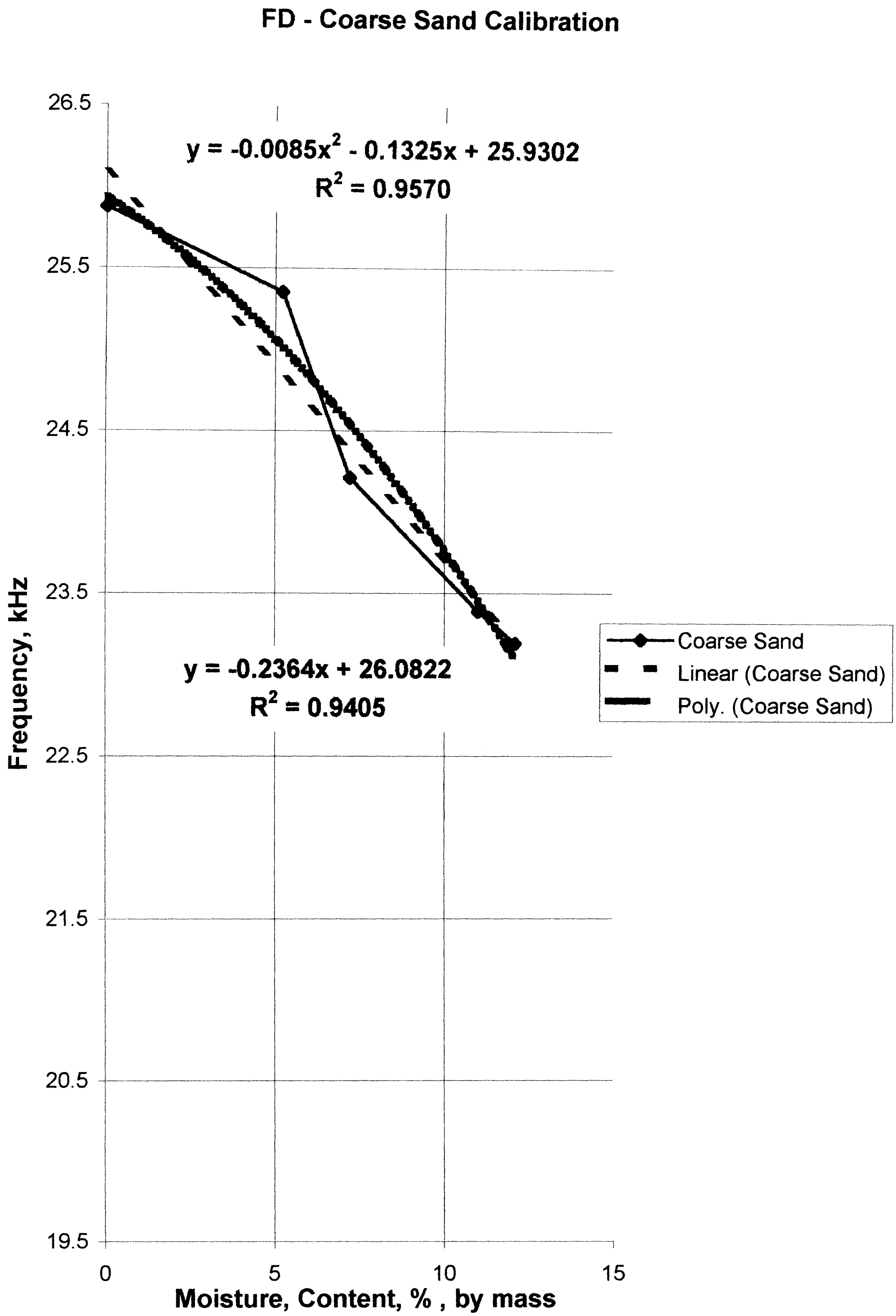

FD - Coarse Sand Calibration
y = -0.0085x2 - 0.1325x + 25.9302
R2 = 0.9570
y = -0.2364x + 26.0822
R2 = 0.9405
Frequency, kHz
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0
5
10
15
Coarse Sand
Linear (Coarse Sand)
Poly. (Coarse Sand)
Moisture, Content, % , by mass

Figure 5.2

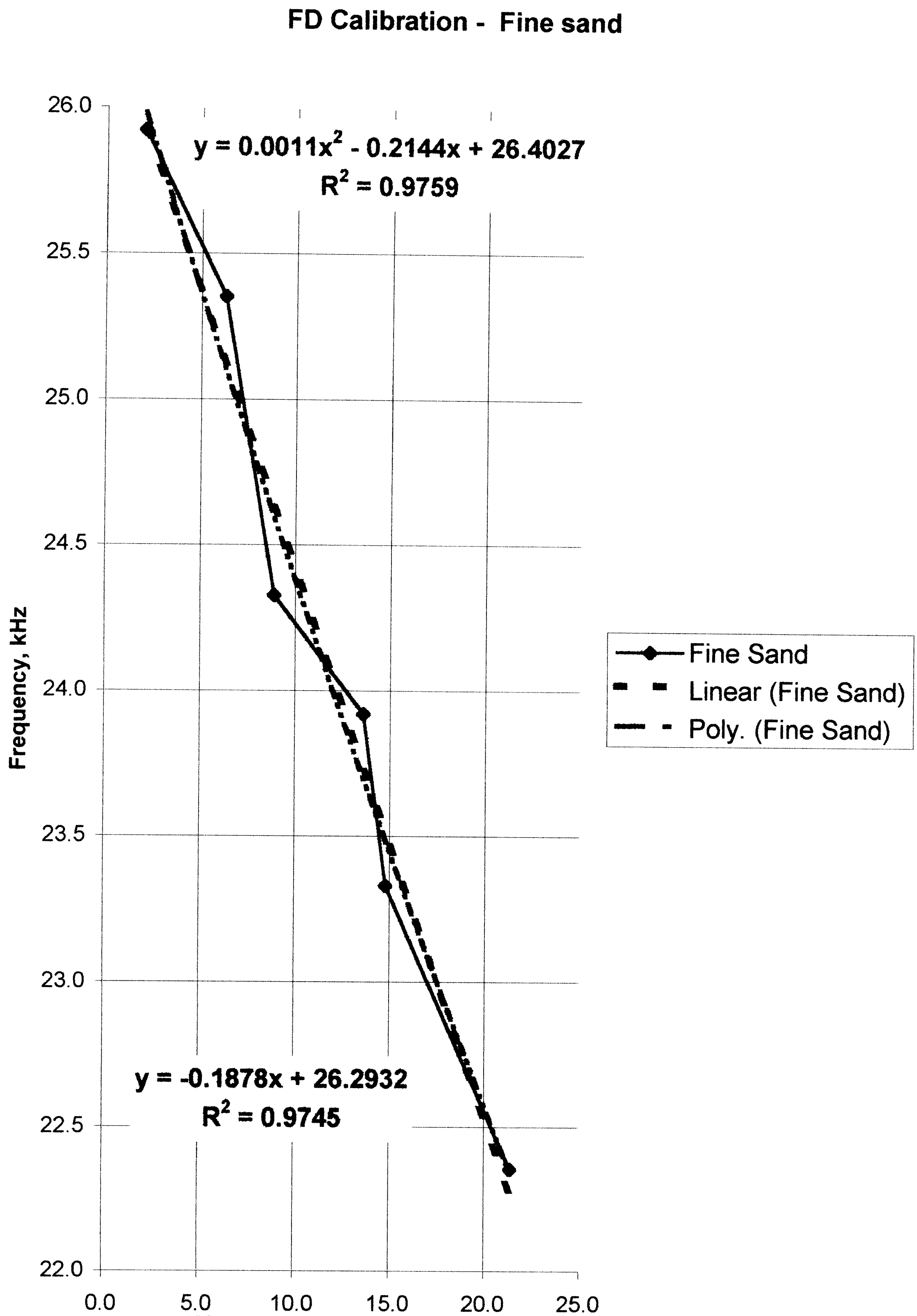
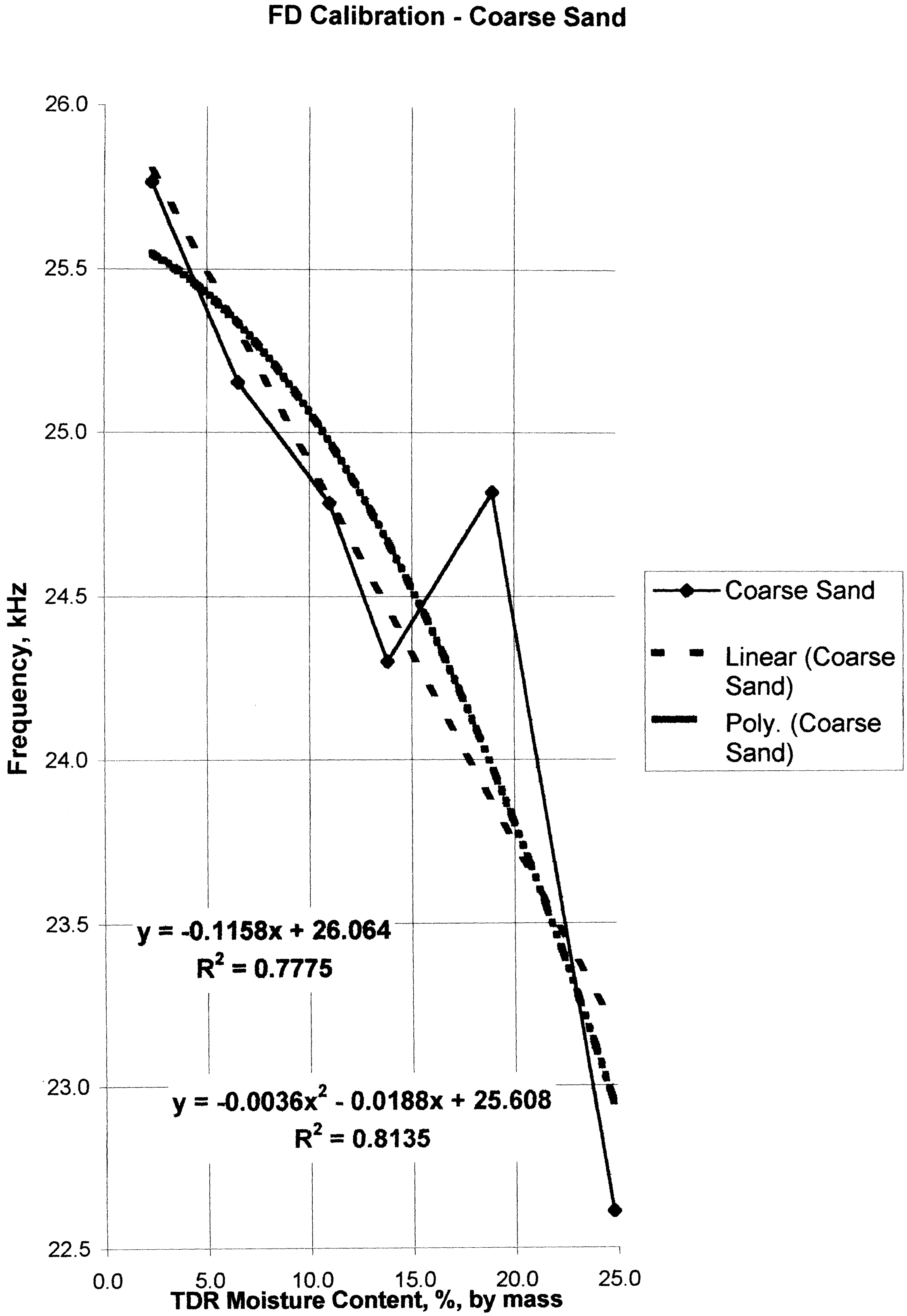

FD Calibration - Fine sand
y = 0.0011x² - 0.2144x + 26.4027
R² = 0.9759
y = -0.1878x + 26.2932
R² = 0.9745
Frequency, kHz
26.0
25.5
25.0
24.5
24.0
23.5
23.0
22.5
22.0
0.0
5.0
10.0
15.0
20.0
25.0
TDR Moisture, %, by mass
Fine Sand
Linear (Fine Sand)
Poly. (Fine Sand)

Figure 5.3



FD Calibration - Coarse Sand
Frequency, kHz
26.0
25.5
25.0
24.5
24.0
23.5
23.0
22.5
0.0
5.0
10.0
15.0
20.0
25.0
TDR Moisture Content, %, by mass
Coarse Sand
Linear (Coarse Sand)
Poly. (Coarse Sand)
y = -0.1158x + 26.064
R2 = 0.7775
y = -0.0036x2 - 0.0188x + 25.608
R2 = 0.8135

Figure 5.4

By examining the slope and y intercept of the graphs, it is apparent that the coarse sand has a lower dielectric response than the fine sand. This is caused by the greater porosity. The higher porosity indicates a higher volume of air present, which lowers the dielectric constant of the material. A greater difference between the water's and the soil's dielectric constants is created. The results would be a greater degree of accuracy in soil moisture measurements, if not for the drainage problems encountered. The overall difference in the dielectric constants between the fine sand and the coarse sand can be determined by looking at the slopes and y intercepts values for the two materials. The slopes of both sands indicate a relationship that follows general theory of non-cohesive soils and electrical behavior. The frequency is attenuated at a faster rate than other soils, indicating the water within the soil matrix is free and not bound. Adhesive forces that exist between the soil and the surface area of the soil particle are present. These forces have more of an effect at lower moisture contents; however, they are not prevalent on the graphical data. The linearity of the equations for both the fine and coarse grained sands is given confidence by a statistical evaluation of the data. Regression coefficient (R^2) values of 0.9083 for fine sand and 0.9405 for coarse sand validate the theorized assumptions. With an approximate difference of 0.142 for the y intercept and 0.0369 for the slopes, the sands are similar in the way they respond to the oscillating current. Even though there is a marked physical difference between the two types of sand, the electrical similarity is reason to create a single mathematical relationship for the two soils. Combining the two sands' results provides an equation that could be used for a wide range of grain size distributions for sands that have not been calibrated. The results of this combination of data can be seen in Figure 5.5.

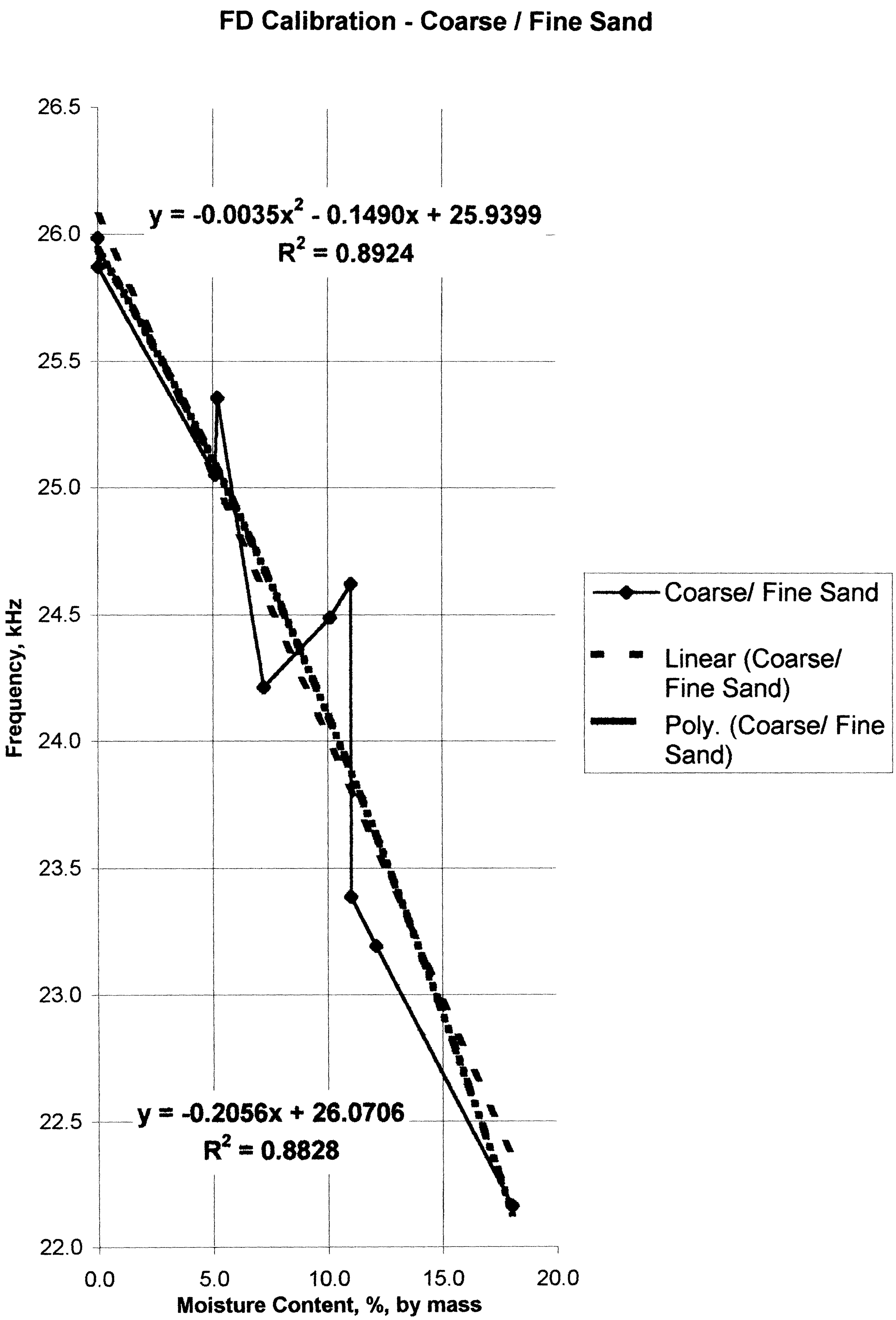

FD Calibration - Coarse / Fine Sand
y = -0.0035x2 - 0.1490x + 25.9399
R2 = 0.8924
y = -0.2056x + 26.0706
R2 = 0.8828
Frequency, kHz
26.5
26.0
25.5
25.0
24.5
24.0
23.5
23.0
22.5
22.0
0.0
5.0
10.0
15.0
20.0
Moisture Content, %, by mass
Coarse/ Fine Sand
Linear (Coarse/ Fine Sand)
Poly. (Coarse/ Fine Sand)

Figure 5.5

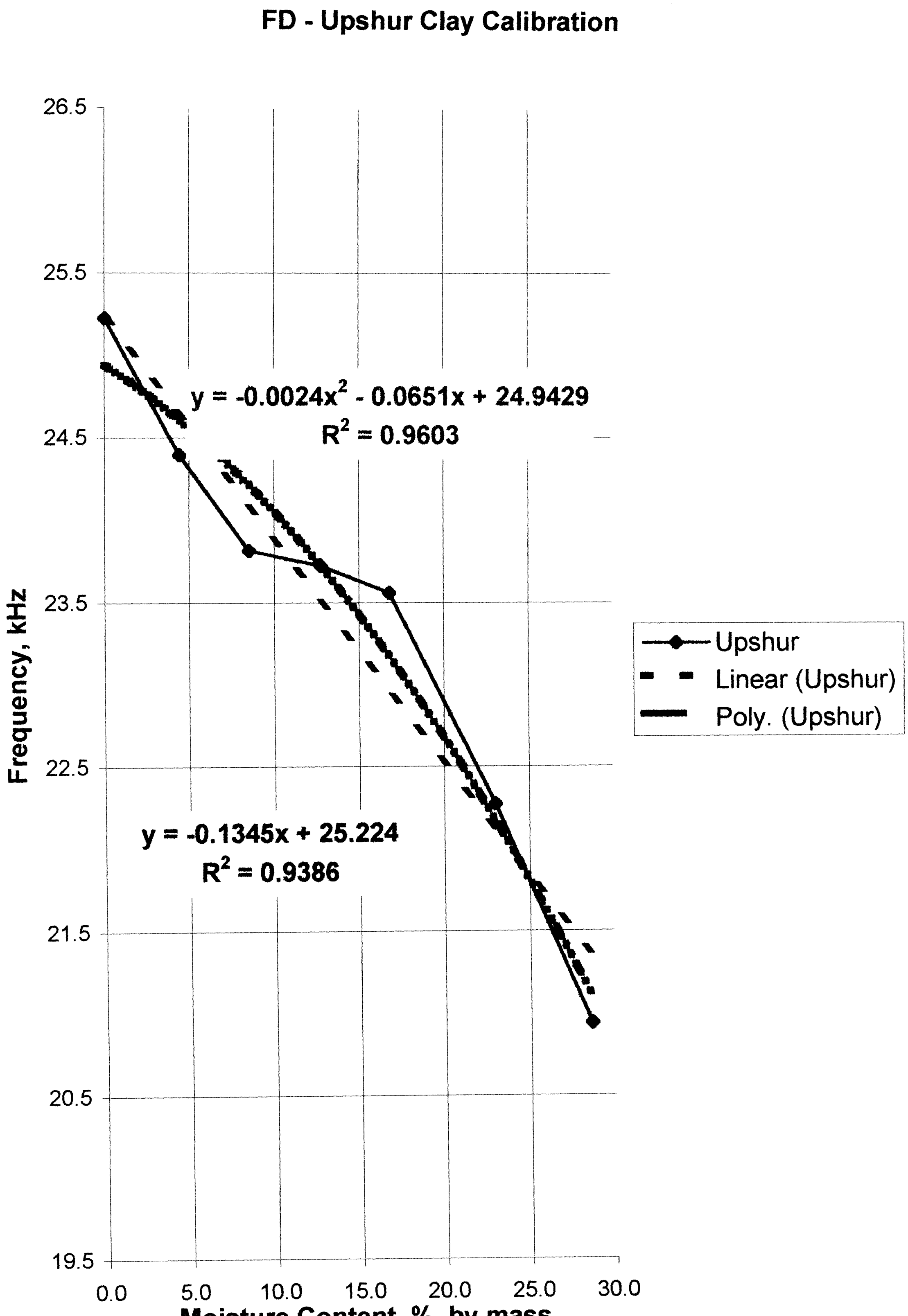
The data analysis for the coarse and fine sands using the polynomial curve fitting equation shows a very flat or linear relationship. However, the R^2 values for the curves indicate a better correlation to the data than the linear curve fit. This suggests that there might be some small influences affecting the measurements at the high and low moisture levels. However, this does not necessarily indicate a problem with the FD probes' capabilities. If need be, the quadratic curve can be used for actual data analysis.

5.3 Upshur and Gurnsey Clay

The results from the tests of Upshur and Guernsey clays are in Figures 5.6 and 5.7, respectively. The data from these two tests are located in Tables 5.3 and 5.4.

TABLE 5.3 UPSHUR CLAY

Frequency Response, kHz	Gravimetric Moisture Content, %
25.2235	0.00
24.3940	4.40
23.8153	8.50
23.7200	12.80
23.5571	16.80
22.2740	23.00
20.9385	28.60



FD - Upshur Clay Calibration
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Frequency, kHz
Moisture Content, %, by mass
y = -0.0024x^2 - 0.0651x + 24.9429
R^2 = 0.9603
y = -0.1345x + 25.224
R^2 = 0.9386
Upshur
Linear (Upshur)
Poly. (Upshur)

Figure 5.6

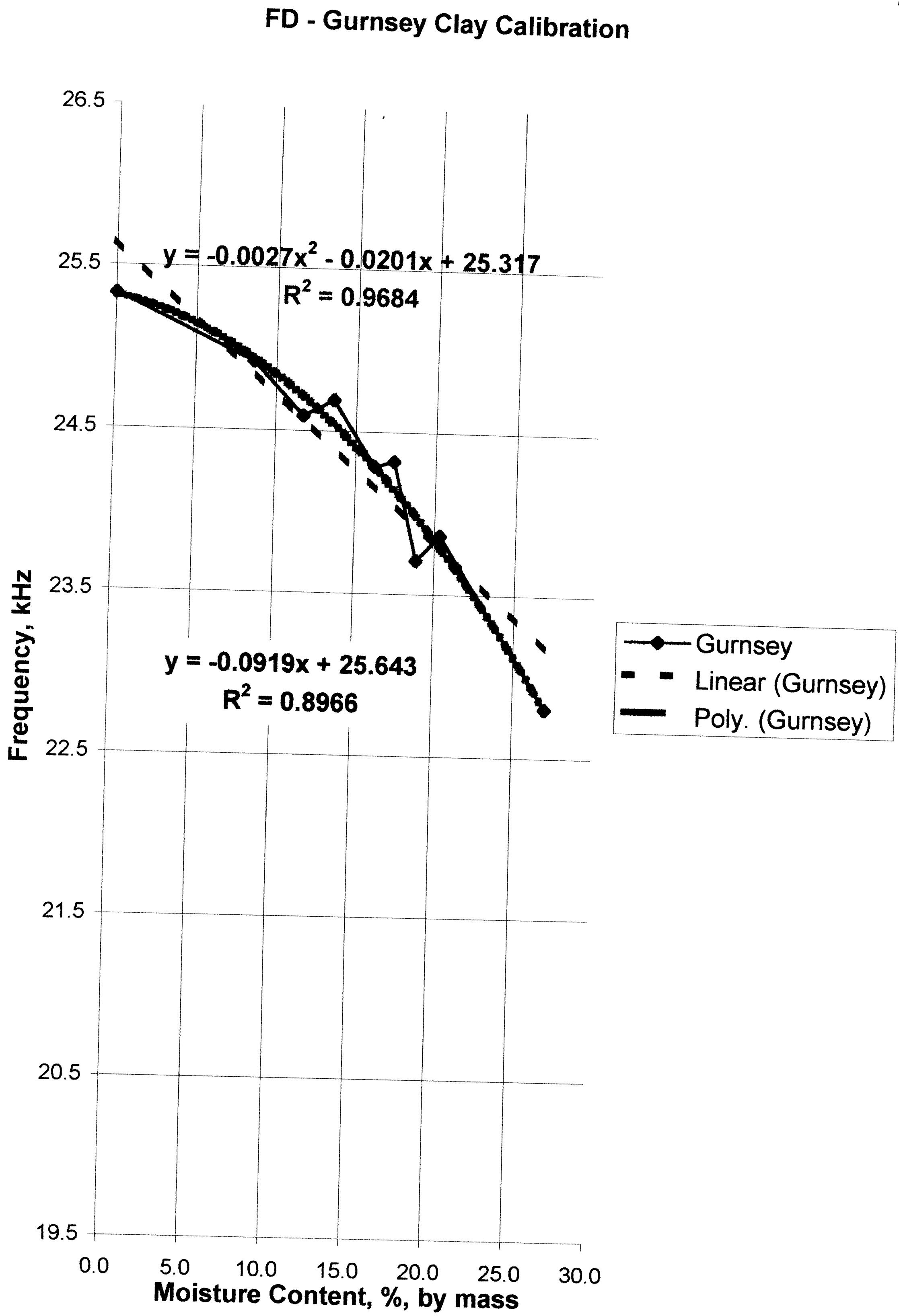

FD - Gurnsey Clay Calibration
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
Frequency, kHz
y = -0.0027x^2 - 0.0201x + 25.317
R^2 = 0.9684
y = -0.0919x + 25.643
R^2 = 0.8966
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Moisture Content, %, by mass
Gurnsey
Linear (Gurnsey)
Poly. (Gurnsey)

Figure 5.7

TABLE 5.4 GUERNSEY CLAY

Frequency Response, kHz	Gravimetric Moisture Content, %
25.3269	0.00
24.9210	8.60
24.5906	11.70
24.6900	13.60
24.2838	16.20
24.3175	17.38
23.7100	18.85
23.8650	20.30
22.8030	27.00

The data from the clays indicate a marked difference in electrical behavior when compared to the coarser materials. A number of trials using different curve fitting techniques are represented. The different trials model the relationship the clays exhibit, which is quite different when compared to the sands. The clays tend to be more nonlinear at the lower soil moistures and return to a more linear relationship at the higher moisture content. The clay's natural absorption ability has a direct impact upon the results of the soil moisture - frequency response. With the water at lower moisture contents being readily absorbed and tightly bound to the clay particles, the FD relationship is a complicated one. The soil - water matrix becomes more of a homogenous material than two separate entities, making it difficult to determine the soil moisture by way of dielectric means. When looking at the other curve fitting techniques employed there can be some concern or question with what is actually happening with the frequency - soil moisture relationship. A third order polynomial fit shows the best overall fit for both the

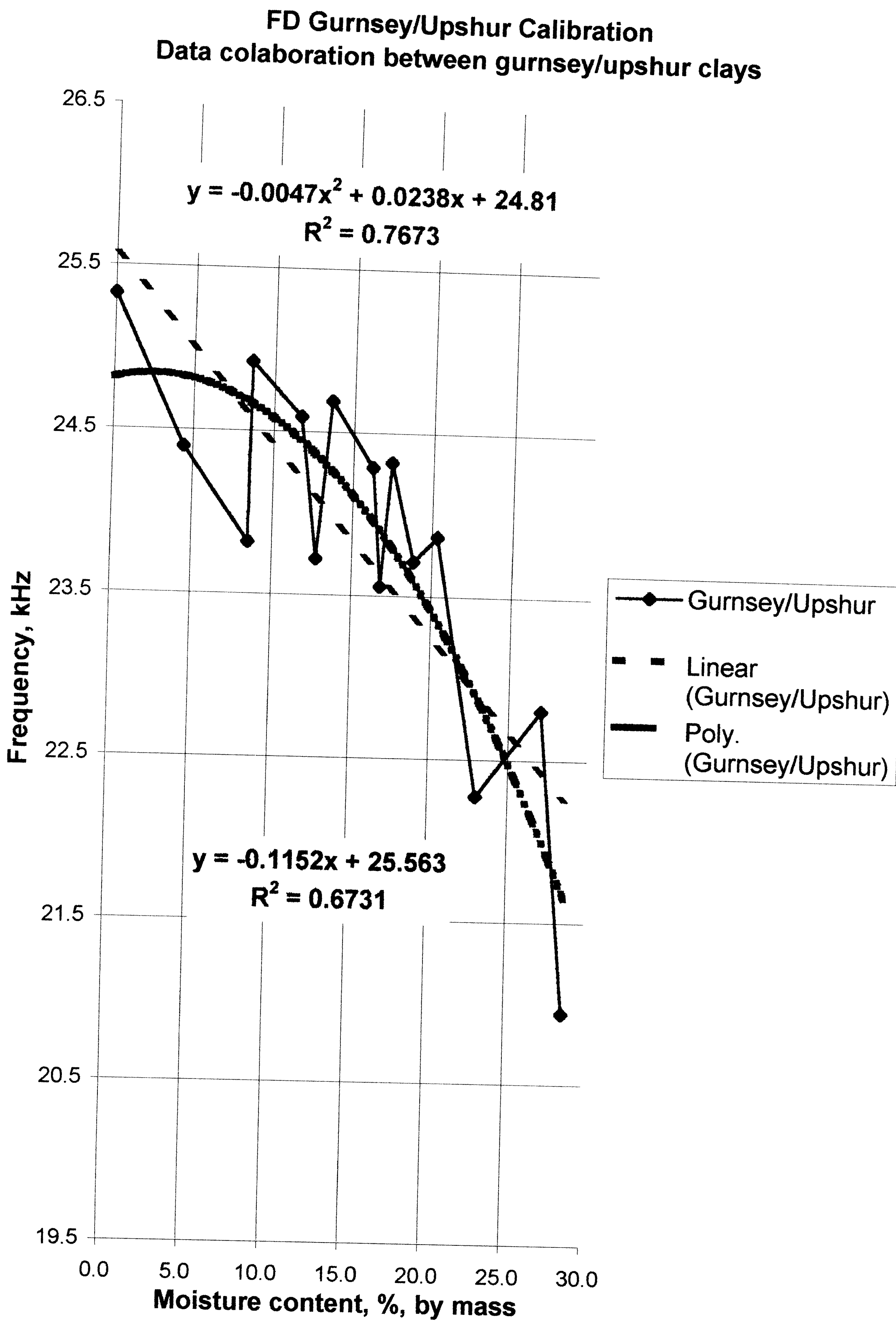

FD Gurnsey/Upshur Calibration
Data colaboration between gurnsey/upshur clays
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
Frequency, kHz
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Moisture content, %, by mass
y = -0.0047x² + 0.0238x + 24.81
R² = 0.7673
y = -0.1152x + 25.563
R² = 0.6731
Gurnsey/Upshur
Linear (Gurnsey/Upshur)
Poly. (Gurnsey/Upshur)

Figure 5.8

Upshur and Gurnsey clay. The results may indicate invalid data points, or might truly dictate the relationship for that particular soil. Using the polynomial curve instead of the linear fit seems to be the most accurate for field use and analysis.

A combination of the two results from the Upshur and Guernsey clays can be seen in Figure 5.8. As with the sand, the combination of the two relationships provides a calibration curve that is useful for a number of different clay types as well as possible un-calibrated clay types.

One major problem with the tests of clays is the degree of compaction. Unlike coarse grain soil, clays are prone to a large range of compaction. Since the degree of compaction changes the distribution and size of the internal pore spacing, consolidation of clays presents a potential calibration problem. The clays used in the experimentation were compacted to the same degree for each individual test. Field calibrations for clays that are normally or over-consolidated are essential for accurate soil moisture measurements.

The results for the series of tests that were performed on normally compacted and over compacted (see Chapter 3)Upshur clay can be seen in Figure 5.9. The tabulated results are shown in Table 5.5

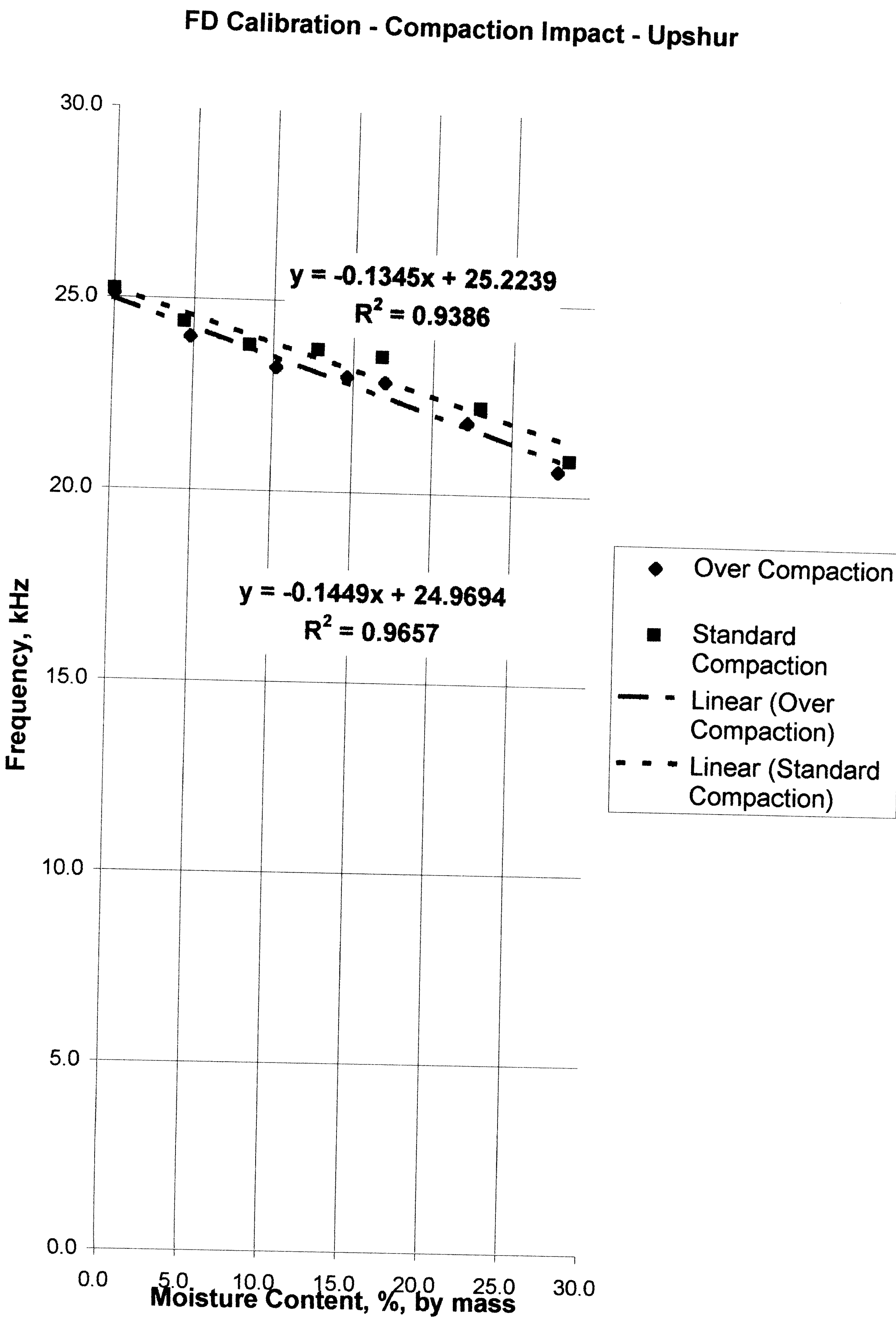

FD Calibration - Compaction Impact - Upshur
y = -0.1345x + 25.2239
R² = 0.9386
y = -0.1449x + 24.9694
R² = 0.9657
Frequency, kHz
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Moisture Content, %, by mass
Over Compaction
Standard Compaction
Linear (Over Compaction)
Linear (Standard Compaction)

Figure 5.9

TABLE 5.5 UPSHUR CLAY - COMPACTION TEST

Frequency Response, kHz	Gravimetric Moisture Content, %
25.2235	0.00
24.3940	4.40
23.8153	8.50
23.7200	12.80
23.5571	16.80
22.2740	23.00
20.9385	28.60

The over compacted test results show a slight deviation in slope and y intercept for the relationship. The compaction effort seems to make a larger impact on frequency response at higher moisture contents. The reason behind the deviation is most likely due to the pore spaces of the soil being condensed. Reducing the pore size can possibly affect the probe in several different ways:

- remove air from the voids, and in return raises the dielectric constant of the matrix
- If near saturation, water might be pushed from within the voids, allowing more free water to be available and raising the dielectric response.
- Compaction of soil around the probe can cause increased accuracy of soil moisture measurements due to the lack of voids that might be caused when the probe is pushed into the soil.

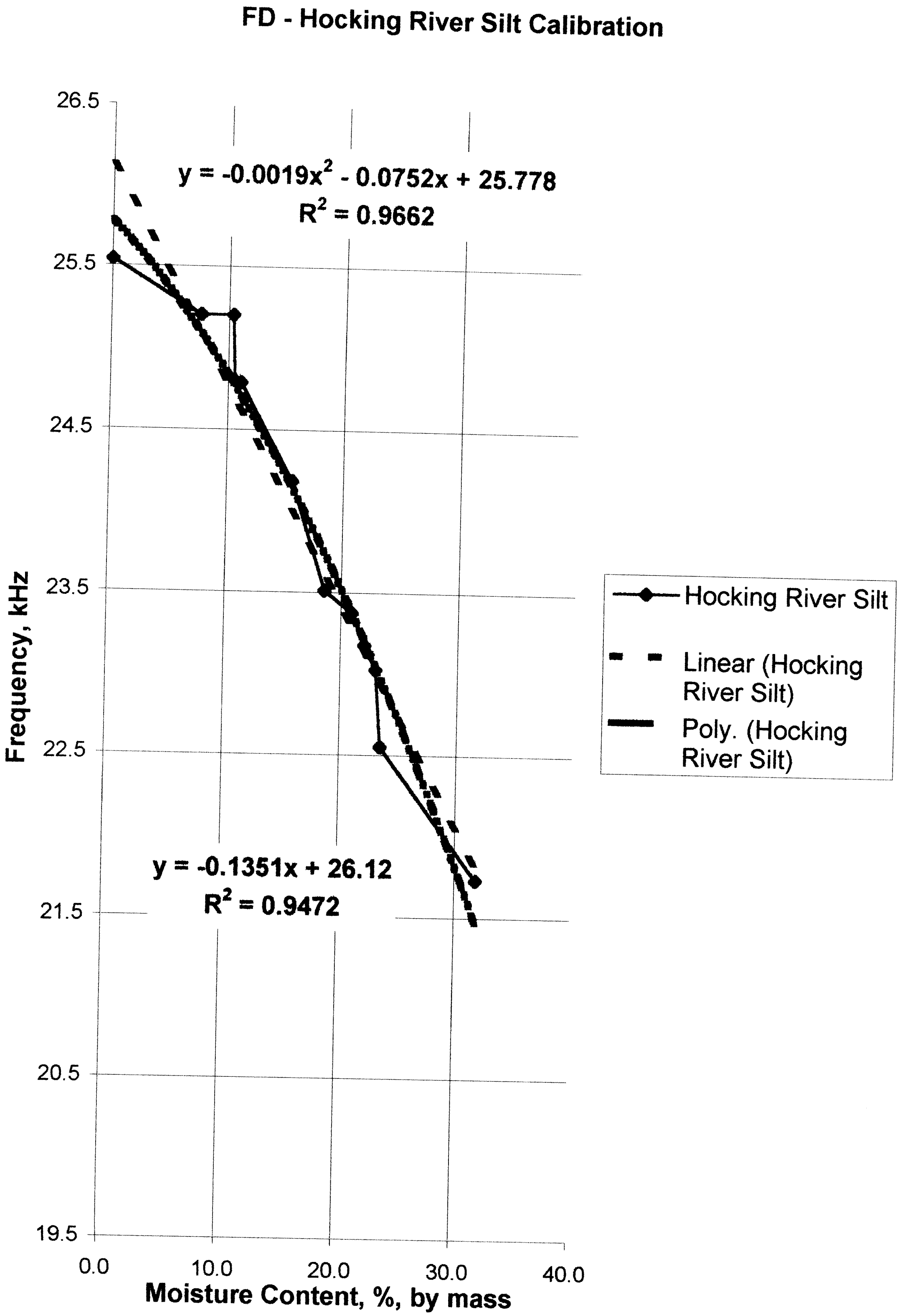
5.4 Hocking River Silt

The results of the tests for the Hocking River Silt are in Table 5.6 The graphical results are located in Figure 5.10.

TABLE 5.6 HOCKING RIVER SILT

Frequency Response, kHz	Gravimetric Moisture Content, %
25.5200	0.00
25.2044	7.65
25.2052	10.40
24.8000	10.56
24.7886	11.13
24.1830	15.61
23.5105	18.52
23.3736	20.91
23.1759	22.00
23.0267	23.00
22.5500	23.5
21.7300	31.8

The overall conclusions for the silt are consistent with the previous results of the sands and the clays. With the grain size distribution of the silt between the clays and the sands, the electrical response follows the same pattern. The silt showed excellent reproducibility after two trials. This might indicate how the balance of adhesive and cohesive forces are working within the soil and effecting the electrical response of the material. A balance between the two types of attractive forces allows for the water



FD - Hocking River Silt Calibration
y = -0.0019x2 - 0.0752x + 25.778
R2 = 0.9662
y = -0.1351x + 26.12
R2 = 0.9472
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
Frequency, kHz
0.0
10.0
20.0
30.0
40.0
Moisture Content, %, by mass
Hocking River Silt
Linear (Hocking River Silt)
Poly. (Hocking River Silt)

Figure 5.10

within the soil matrix to be evenly mixed and not completely bound to the inner soil particles. An even mix through the soil matrix allows for better correlation between gravimetric and frequency response data.

5.5 Silty Sand

The data that was collected from testing the silty sand, which was comprised of 35 % Hocking River silt and 65% coarse river sand (by weight) are tabulated in Table 5.7 The graphical data can be viewed in Figure 5.11.

TABLE 5.7 SILTY SAND

Frequency Response, kHz	Gravimetric Moisture Content, %
25.3391	0.00
24.9300	6.70
23.8290	13.20
22.9034	17.50
22.7400	19.00

The silty sand's grain distribution places itself in the size range of the fine sand. Electrically, the silty sand reacted differently than either the coarse sand or silt. This is most likely due to physical nature of the soil. The moistened mixture differs drastically from when it is dry. Physically, the mixture of silt and sand is more like a fine sand when dry and tends to become more of a thicker substance when water is added. With a higher overall volume of silt than sand (due to the silt's lower bulk density) in the mixture, the cohesive forces are very apparent in the mixture. The mixture gave good calibration results due to the prevention of the water draining out of the sand, and the sand's prevention of all of the available water to become bonded to the silt's larger surface area.

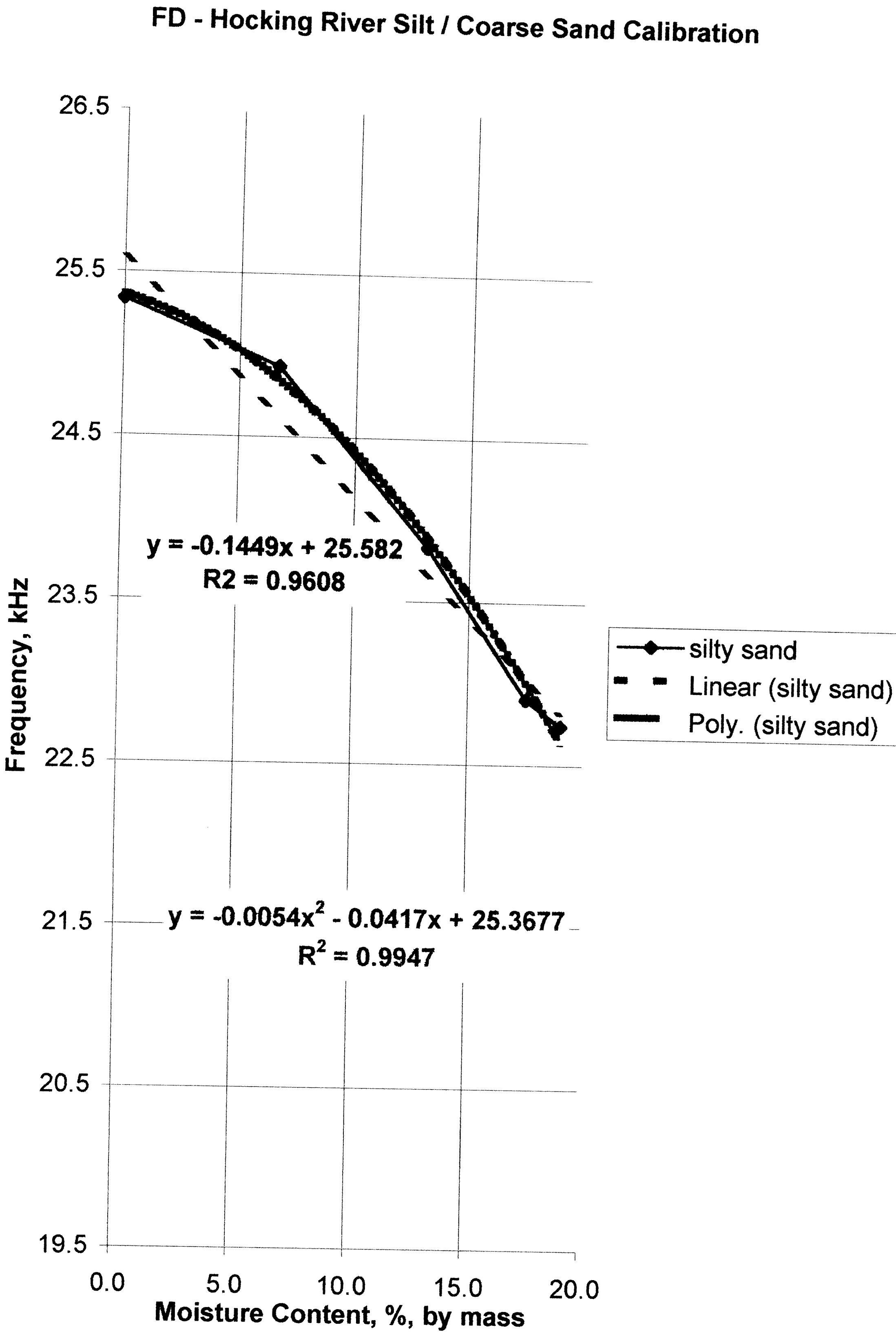

FD - Hocking River Silt / Coarse Sand Calibration
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0.0
5.0
10.0
15.0
20.0
Frequency, kHz
Moisture Content, %, by mass
y = -0.1449x + 25.582
R2 = 0.9608
y = -0.0054x2 - 0.0417x + 25.3677
R2 = 0.9947
silty sand
Linear (silty sand)
Poly. (silty sand)

Figure 5.11

5.6 Clayey Coarse Sand and Clayey Fine Sand

The data from the clayey coarse sand are in Table 5.8. The graphical results are illustrated in Figure 5.12. The data of the clayey fine sand are in Table 5.9. The graphical results are located in Figure 5.13.

TABLE 5.8 CLAYEY COARSE SAND

Frequency Response, kHz	Gravimetric Moisture Content, %
25.1833	0.00
25.0195	5.60
23.8947	10.40
22.3300	15.40
22.1087	17.00
21.8460	19.60

TABLE 5.9 CLAYEY FINE SAND

Frequency Response, kHz	Gravimetric Moisture Content, %
25.5600	0.00
24.2248	5.00
23.8950	10.66
22.6225	15.30
22.3883	19.39

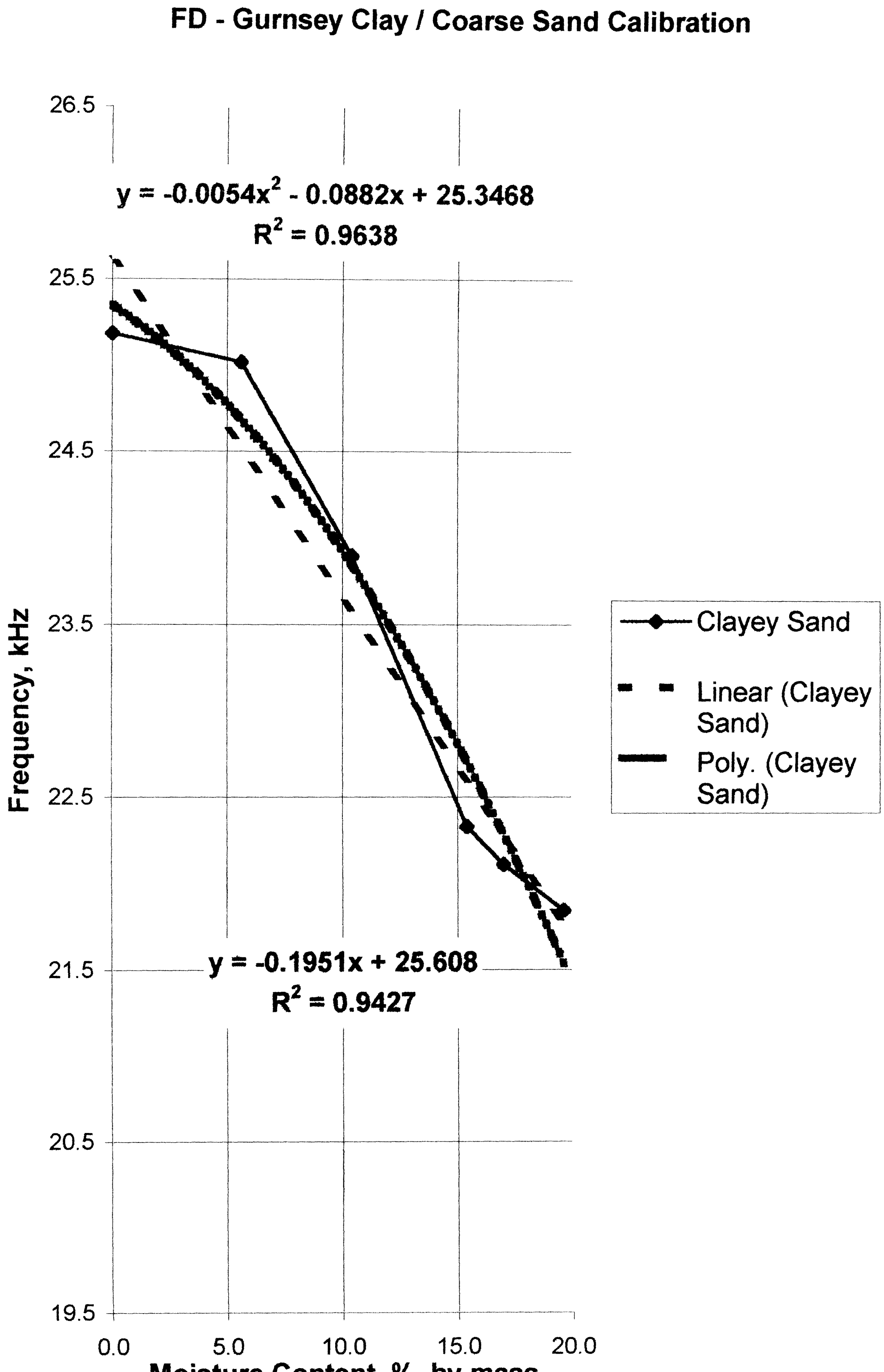

FD - Gurnsey Clay / Coarse Sand Calibration
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
y = -0.0054x2 - 0.0882x + 25.3468
R2 = 0.9638
y = -0.1951x + 25.608
R2 = 0.9427
Frequency, kHz
0.0
5.0
10.0
15.0
20.0
Moisture Content, %, by mass
Clayey Sand
Linear (Clayey Sand)
Poly. (Clayey Sand)

Figure 5.12

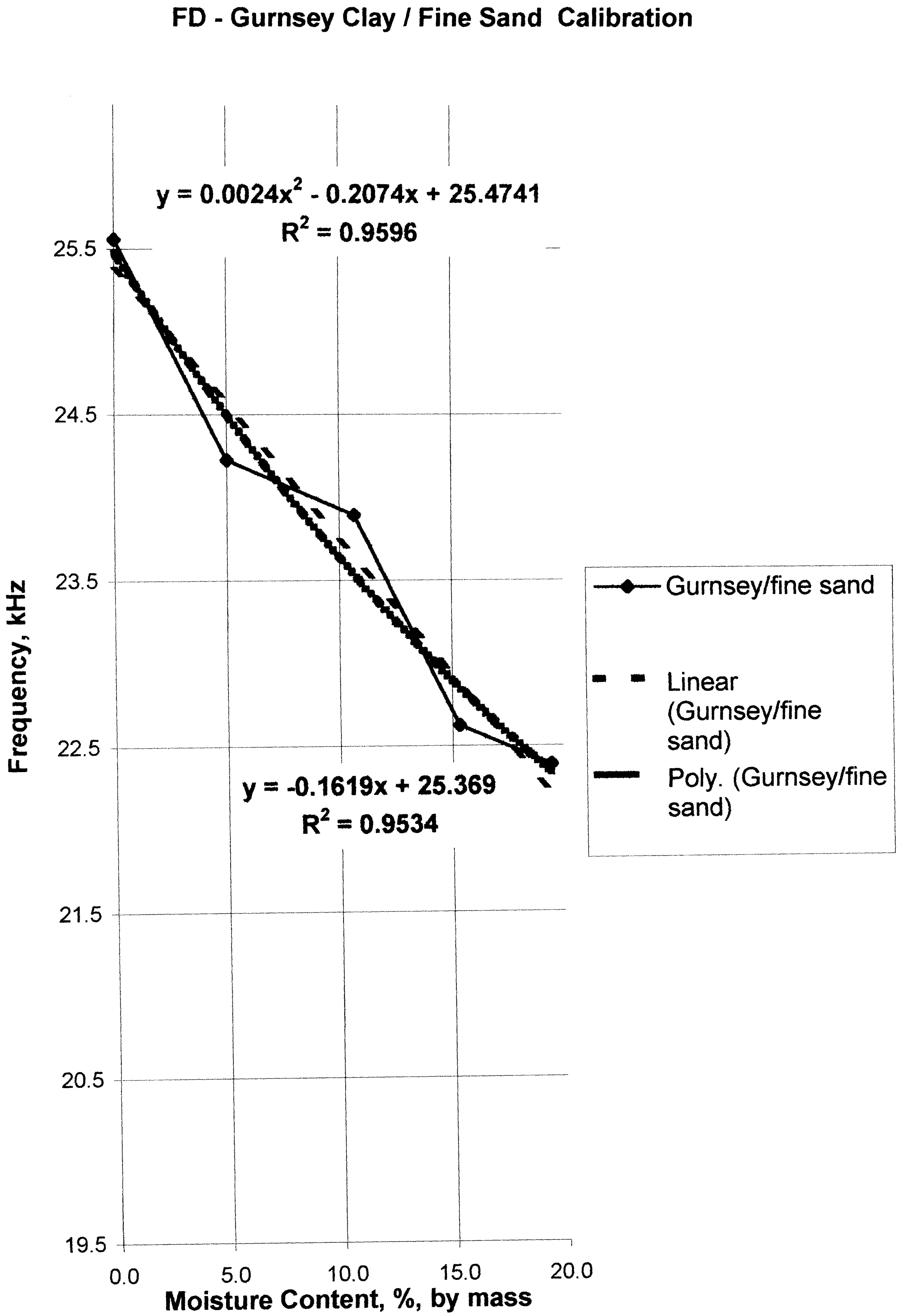

FD - Gurnsey Clay / Fine Sand Calibration
y = 0.0024x^2 - 0.2074x + 25.4741
R^2 = 0.9596
y = -0.1619x + 25.369
R^2 = 0.9534
25.5
24.5
23.5
22.5
21.5
20.5
19.5
Frequency, kHz
0.0
5.0
10.0
15.0
20.0
Moisture Content, %, by mass
Gurnsey/fine sand
Linear (Gurnsey/fine sand)
Poly. (Gurnsey/fine sand)

Figure 5.13

As can be seen from the results, the third order polynomial equation fits and describes the existing relationships for both materials better than the linear equations. The low ends of the water content on the curve are where there is deviation from both a linear and polynomial trend. This attribute of the curves can be accounted by the water content not being equally distributed at the low end of moisture.

It is also important to compare the silty coarse sand with the clay and fine and coarse grained sand's mixtures. The differences between the silty coarse sand and the clayey coarse sand is found by examining the relationships at the higher moisture contents. At higher moistures, the clayey coarse sand attenuates the frequency response at a greater rate than the silty sand. This is most likely attributed to the difference in soil fabric and compaction. The soil fabric is more likely to play a larger role in the attenuation due to the consistency of which the soil was compacted.

The difference between the clayey fine sand, clayey coarse sand, and silty coarse sand can be seen by comparing Figures 5.13, 5.12, and 5.11, respectively. One would expect the mixture of silty sands to attenuate the frequency response faster than the clayey sands. However, by observing the trends seen in the data, this is not the case. The clayey sands attenuate the signal at a higher rate than the silty sand. Typically, one would expect the silty sand to have the most free water available as compared to the clayey fine sand, which would have the least free water available. The differences might be explained by not having a homogenous or thorough mix of the clay and fine and coarse grained sands or the silt and coarse grained sand.

5.7 Overall Results

The test results presented within this thesis are useful from several aspects. The first and foremost is the determination of soil moisture from the specific soils tested. The results of the test can also be used conservatively with un-calibrated soils. The tests also represent a benchmark for continuing research with the FD probe and soil moisture determination. The individual mathematical relationships for each soil and the frequency response allows for the CPT operator or engineer to evaluate the soil moisture profile for a given soil for a given frequency response.

The overall results of the test are shown in Figure 5.14. As can be seen from looking at this figure, the trends for all of the soils are approximately the same. The results indicate the relationship between soil moisture and frequency response is valid and reproducible for a porous medium such as soil. The window of data also allows for the probe to give a rough estimate of soil moisture in an un-calibrated soil type.

All soils were analyzed separately using curve fitting and regression techniques. This provided a mathematical relationship that could be studied and compared with the other results. It can also be used to provide information on the accuracy and precision of the FD probe, which is essential for engineering purposes. Several types of curves or lines were fitted to the frequency - soil moisture relationships: linear and higher order polynomials. These curves show some consistency for the soils. The linear fit shows the best correlation between the frequency - soil moisture relationship and the physical attributes or characteristics of the soil. That is, the finer soils attenuate the electrical current at a lessor rate than the coarser soils. When using the other curve types, the relationships do not follow the typical trend that was found or observed by the linear fits. However, with R^2 values that approach one, other types of curves describe the relationships more accurately.

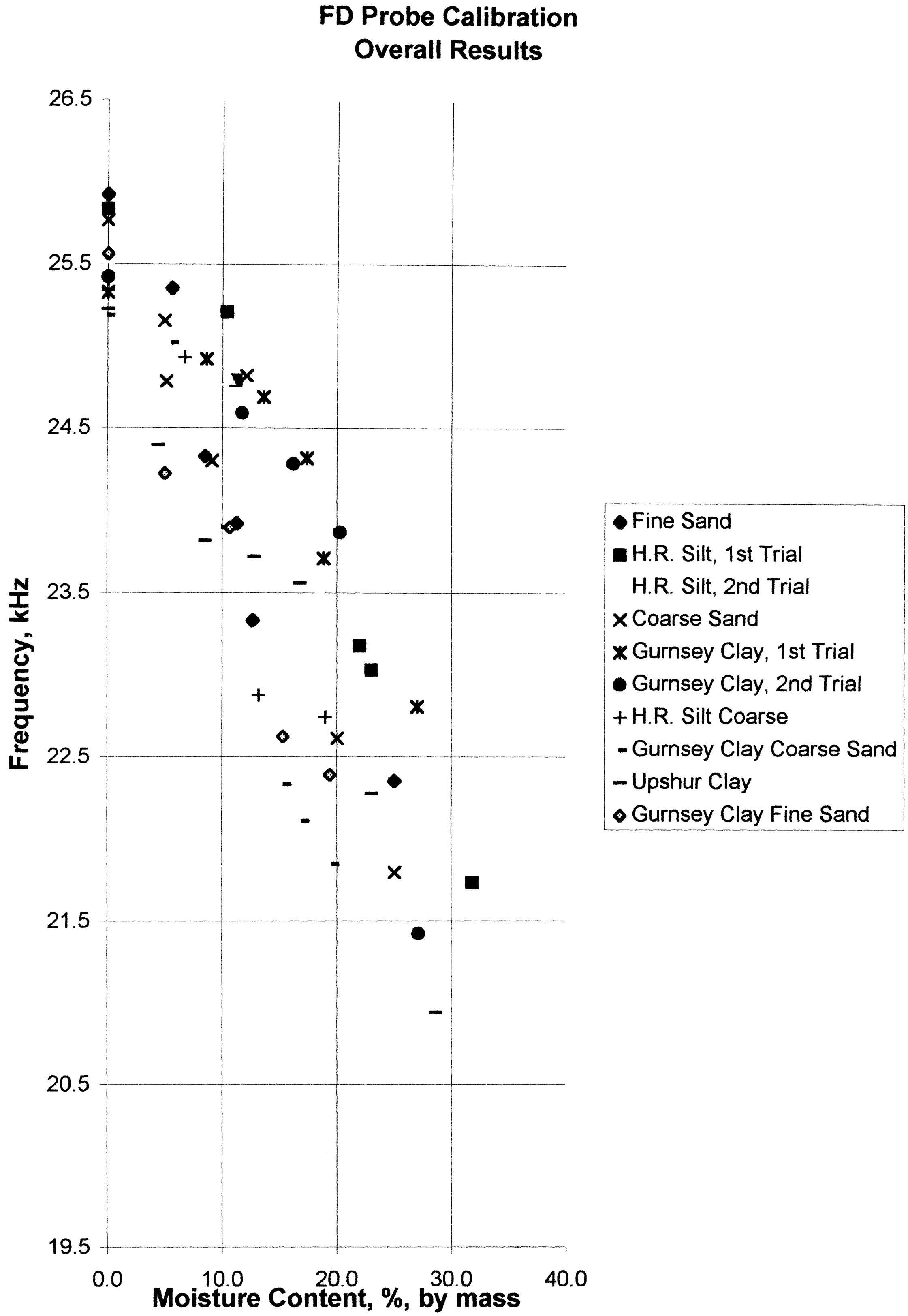

FD Probe Calibration
Overall Results
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
Frequency, kHz
0.0
10.0
20.0
30.0
40.0
Moisture Content, %, by mass
Fine Sand
H.R. Silt, 1st Trial
H.R. Silt, 2nd Trial
Coarse Sand
Gurnsey Clay, 1st Trial
Gurnsey Clay, 2nd Trial
H.R. Silt Coarse
Gurnsey Clay Coarse Sand
Upshur Clay
Gurnsey Clay Fine Sand

Figure 5.14

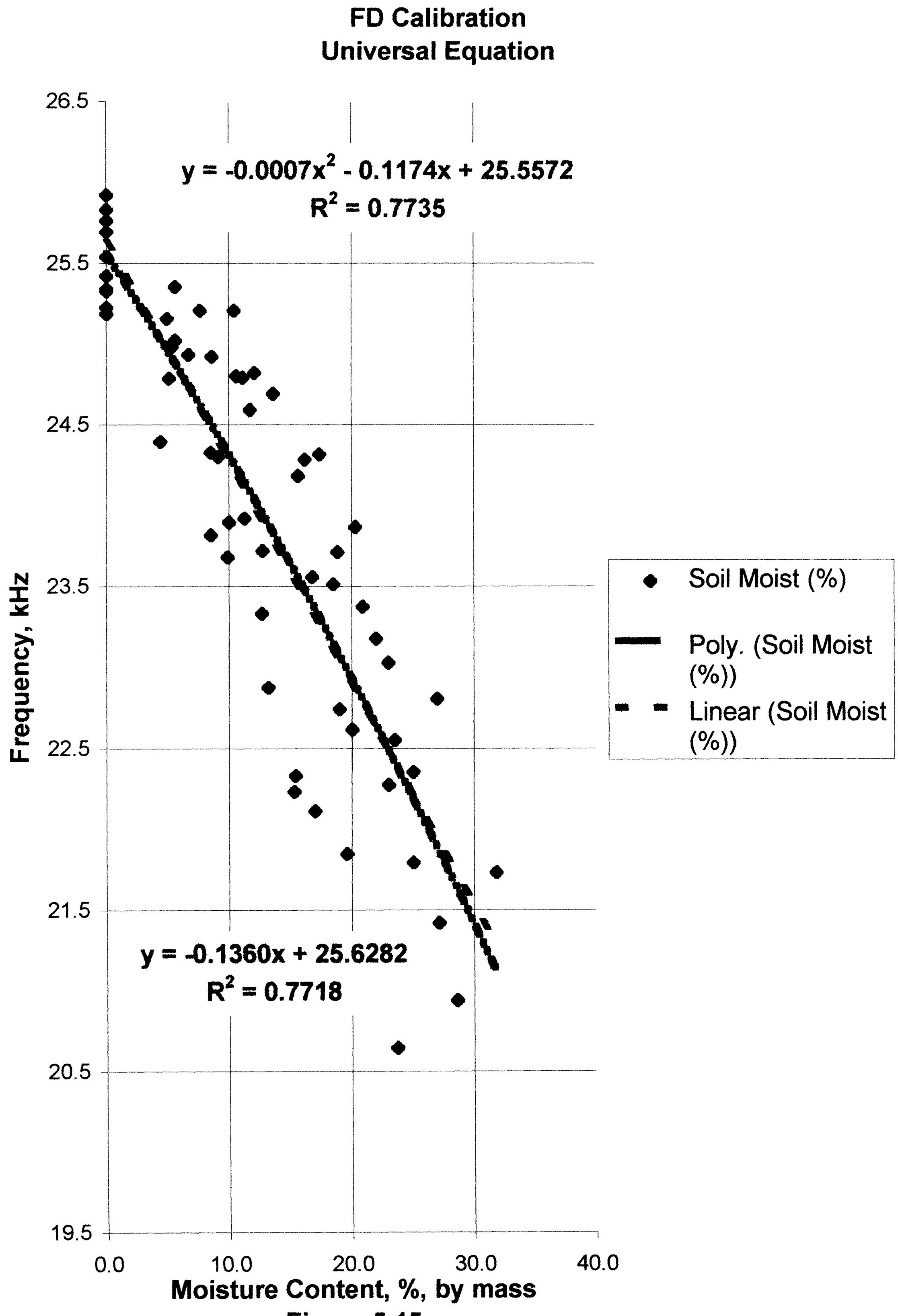
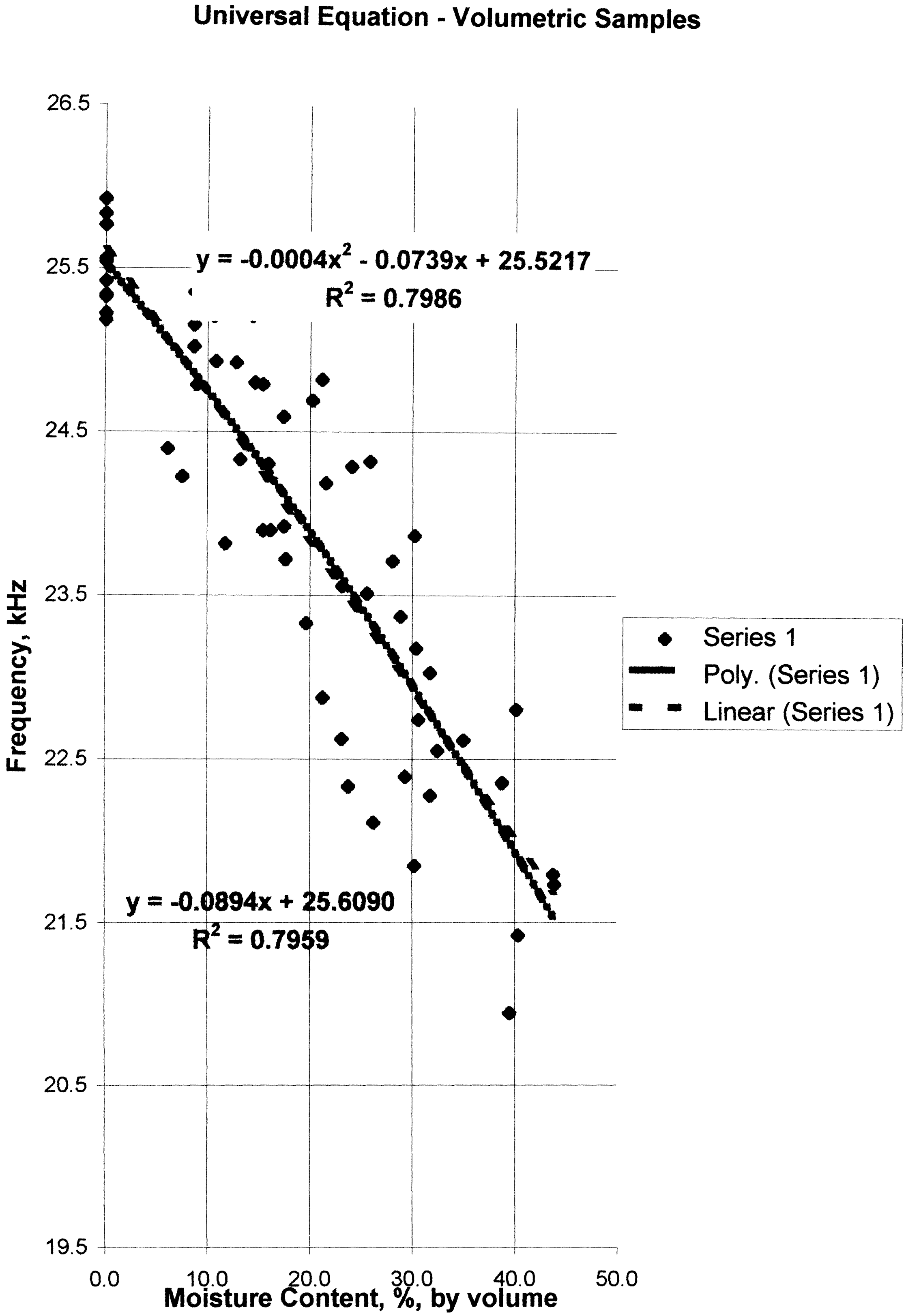

FD Calibration
Universal Equation
y = -0.0007x2 - 0.1174x + 25.5572
R2 = 0.7735
y = -0.1360x + 25.6282
R2 = 0.7718
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
Frequency, kHz
0.0
10.0
20.0
30.0
40.0
Moisture Content, %, by mass
Soil Moist (%)
Poly. (Soil Moist (%))
Linear (Soil Moist (%))

Figure 5.15

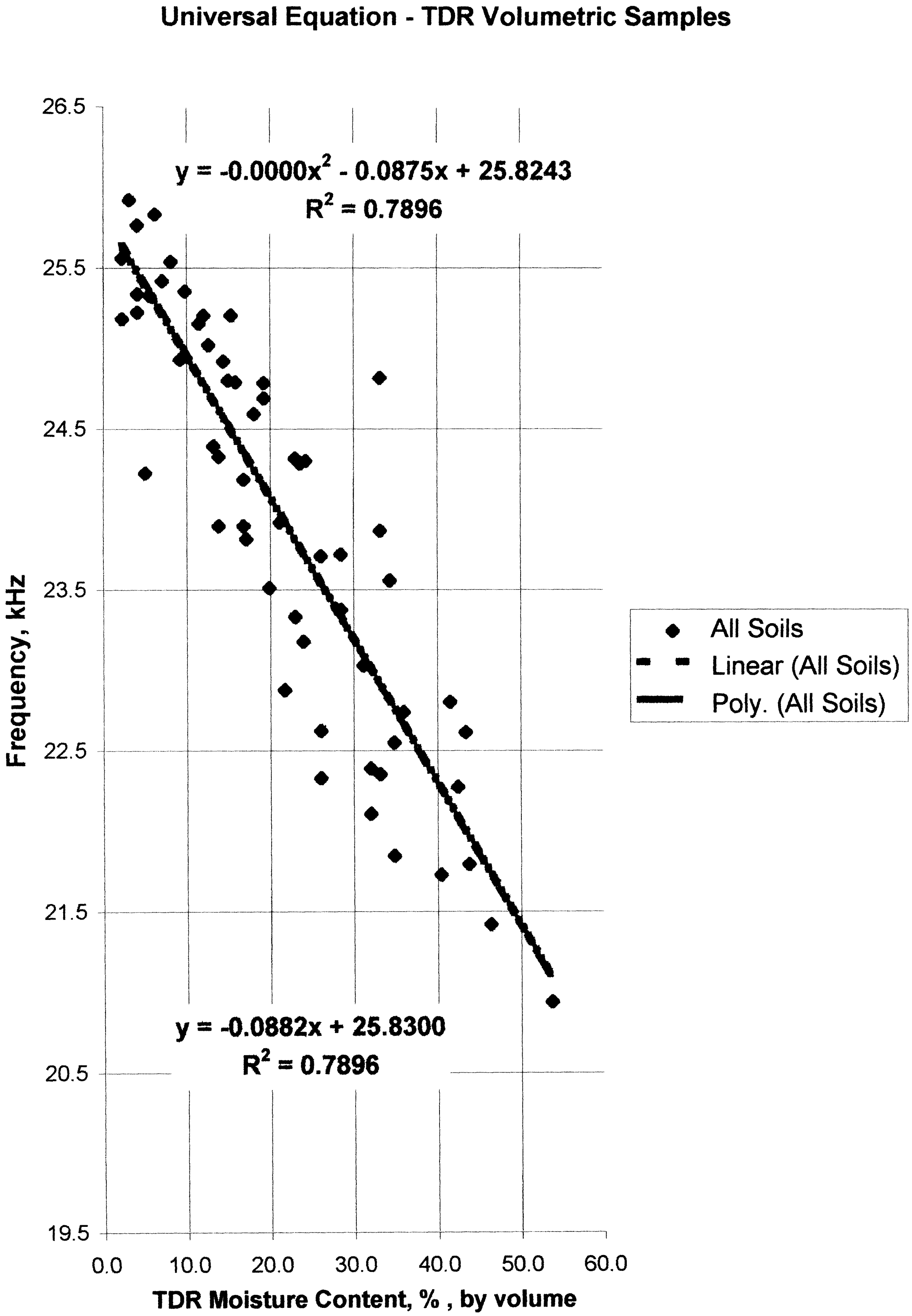
A non-specific or universal equation for the tested soils was developed using the complete set of data from all tests. A graphical interpretation of the third order polynomial universal equation can be seen in Figure 5.15. The same type of analysis was performed using volumetric water contents, as well as using TDR volumetric and gravimetrically converted water contents. The results of this analyses can be seen in Figures 5.16, 5.17, and 5.18. The interpretation of the data is not theoretically correct, but can provide an important point of reference when wanting to compare relative differences in soil moisture. The graphs also give an indication of how accurate the FD probe is compared to the TDR probes and Topp's Equation. As can be seen from the graphs the FD probe results are quite close to those of the TDR probe. As was stated in Chapter 4, the TDR operating frequency of 1 GHz is ideal for soil moisture determination, and has provided the most independent relationship between the dielectric constant and soil moisture. Considering this, the accuracy and validity of the FD probe are solidified. When trying to make a decision on what method to use, either FD or TDR, one must keep in mind that for the best results from either method specific calibration of the soil must be performed. One of the largest problems using TDR probes for CPT technology is based on the shape of the rods. The design and construction of the FD-CPT probe is much more simplistic than that of a TDR probe designed for the CPT. Creating a TDR-CPT probe with the necessary length of rods is almost impossible. Another significant problem using TDR systems is the analysis of the waveforms. Without using a datalogger and a computer analysis program to interpret the waveforms, all interpretation is done by hand. This can introduce significant errors when determining the soil moisture content. The FD system consists of reading frequencies from a frequency counter.

An analysis of the results for all the soils were done by using one of the soils, the Hocking River Silt, as a zeroing point. The analysis shows the dependence that the



Universal Equation - Volumetric Samples
y = -0.0004x2 - 0.0739x + 25.5217
R2 = 0.7986
y = -0.0894x + 25.6090
R2 = 0.7959
Series 1
Poly. (Series 1)
Linear (Series 1)
Frequency, kHz
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0.0
10.0
20.0
30.0
40.0
50.0
Moisture Content, %, by volume

Figure 5.16



Universal Equation - TDR Volumetric Samples
y = -0.0000x^2 - 0.0875x + 25.8243
R^2 = 0.7896
y = -0.0882x + 25.8300
R^2 = 0.7896
Frequency, kHz
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0.0
10.0
20.0
30.0
40.0
50.0
60.0
TDR Moisture Content, % , by volume
All Soils
Linear (All Soils)
Poly. (All Soils)

Figure 5.17

frequency response has on soil type. The analysis is in Figure 5.19. It also gives an indication of how soils compare to each other.

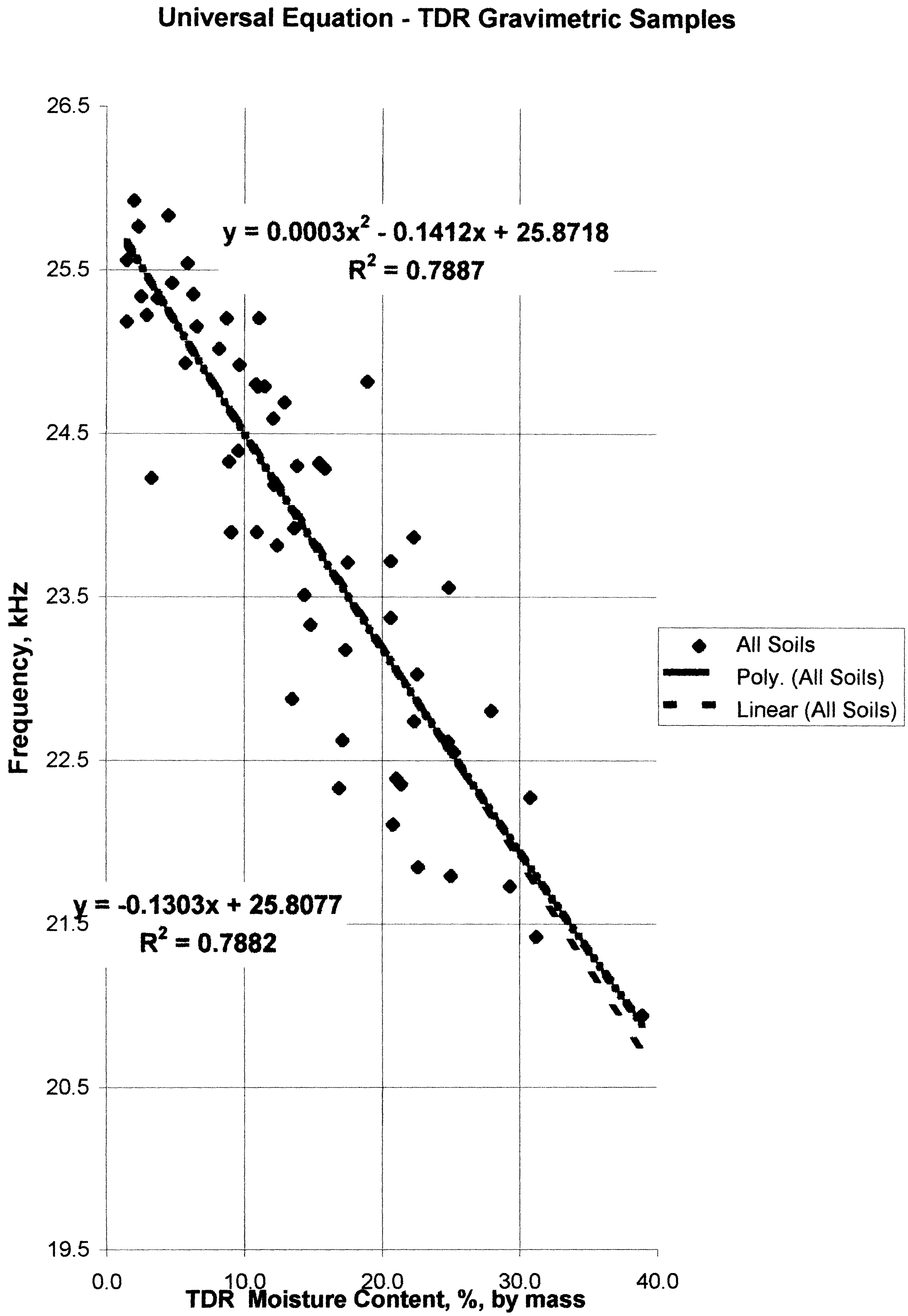
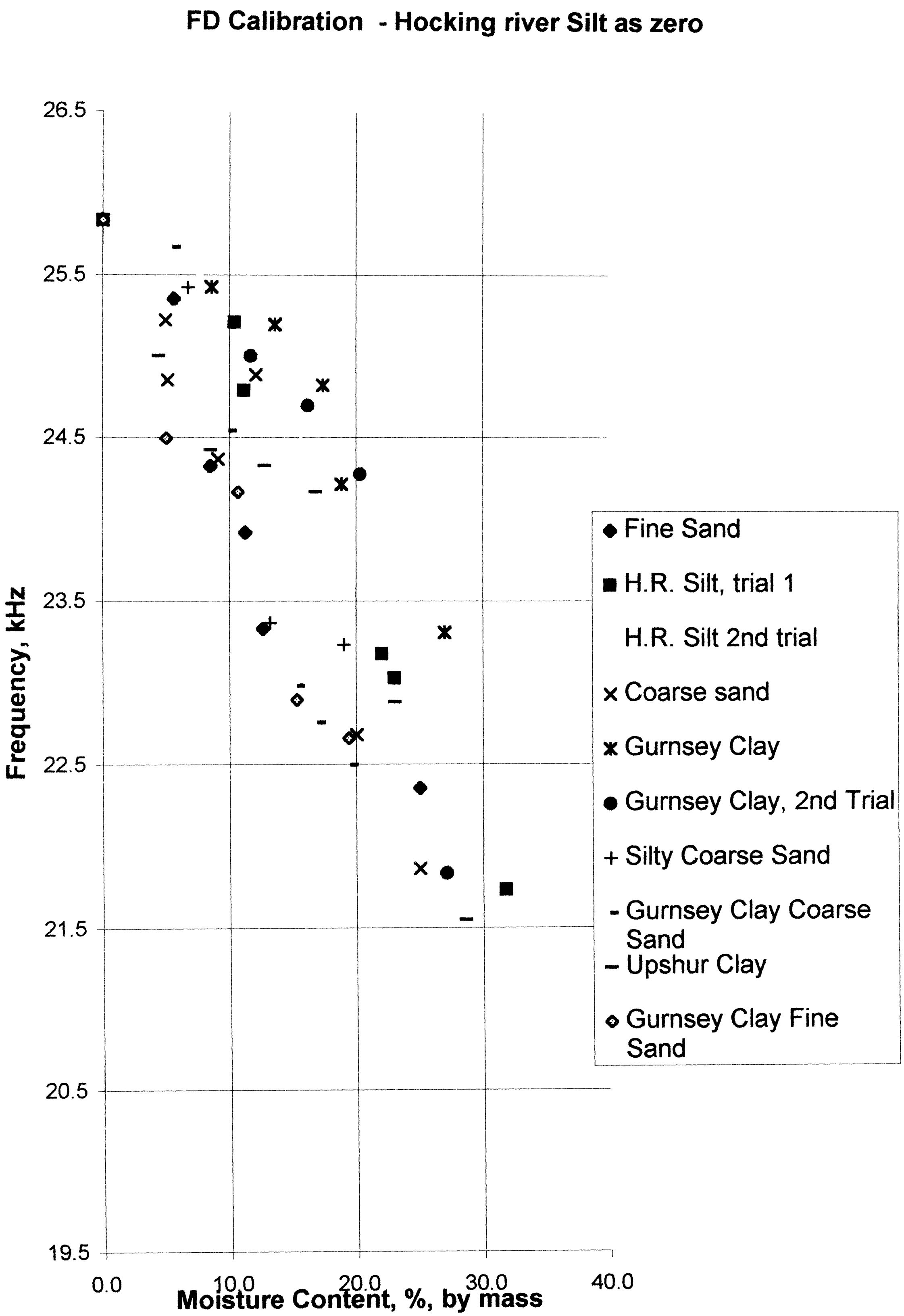

Universal Equation - TDR Gravimetric Samples
y = 0.0003x2 - 0.1412x + 25.8718
R2 = 0.7887
y = -0.1303x + 25.8077
R2 = 0.7882
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0.0
10.0
20.0
30.0
40.0
Frequency, kHz
TDR Moisture Content, %, by mass
All Soils
Poly. (All Soils)
Linear (All Soils)

Figure 5.18



FD Calibration - Hocking river Silt as zero
Frequency, kHz
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0.0
10.0
20.0
30.0
40.0
Moisture Content, %, by mass
Fine Sand
H.R. Silt, trial 1
H.R. Silt 2nd trial
Coarse sand
Gurnsey Clay
Gurnsey Clay, 2nd Trial
Silty Coarse Sand
Gurnsey Clay Coarse Sand
Upshur Clay
Gurnsey Clay Fine Sand

Figure 5.19

Even though using a universal equation from the complete data set is not correct and can cause erroneous soil moisture contents to be determined, several equations for different soil types and possible field combinations of soils were presented. The equations will be more aimed at a soil specific use than universal use. The equation could be used in a situation where the soil profile type has been preliminarily identified and soil specific calibration is either unwarranted or impossible.

5.8 Overall Electrical Effects From Physical Characteristics

As was discussed in Chapter 4, Theory of Electrical Response of Soil, soil properties can effect the way soil particles behave when subjected to an electrical current. Particle size, specific surface area, pore size, and base materials are important factors that must be taken into account when analyzing the data from the FD probe tests. The following determinations and observances use the linear curve fit equations for comparison.

The specific surface area of a soil relates to the amount of attractive forces that are possible for the individual soil particle. The specific surface area of the soils are listed in Table 5.10.

TABLE 5.10 SPECIFIC SURFACE AREAS

Soil Name	Particle Diameter mm	Specific Surface Area, m^2/g	Relative Frequency Attenuation
Hocking River Coarse Sand	0.25 -2.00	2.27×10^{-6}	Greatest
Lake Erie Fine Sand	0.25 -0.10	9.36×10^{-8}	
Hocking River Silt	0.075 - 0.01	5 - 10	
Silty Coarse Sand	Mixture of	Mixture of	to
Clayey Coarse Sand	Mixture of	Mixture of	
Clayey Fine Sand	Mixture of	Mixture of	
Upshur Clay	>0.002	10 -15	
Guernsey Clay	>0.002	15 -20	Least

The soils follow a trend of lower electrical attenuation with higher specific surface area. This correlates well with the high bonding forces that are encountered and associated with high specific surface area soils such as clays and silts.

There is also good overall correlation between the types of soils and the their adhesion or cohesion properties that allow water to be somewhat or greatly bonded to the individual soil particles. The sands and coarse materials exhibited a tendency to attenuate the electrical current faster than the finer soils.

The pore size of the soils, which affect the amount of water the soil can hold, also showed a trend that made pore size and electrical attenuation a direct relationship. As the pore size decreased, the electrical attenuation decreased.

The base material type is ultimately going to have an effect on the frequency response/soil moisture relationships due to the mixing model theory of moisture content determination. With a soil that has a higher dielectric constant, the accuracy of the probe will decrease due to the smaller original difference between the dielectric constant of water (80) and soil (3-5). The material types, such as clays or silts, will tend not to conduct the electric current as well as the sands due to the organic or other type of materials that make up the constituents.

5.9 TDR - FD Comparison

Looking at Tables 5.11 - 5.18, the percent differences between the moisture content determined by TDR and gravimetric methods can be observed. The volumetric water content was changed to gravimetric by using the predetermined bulk densities of the samples. In some cases the TDR water contents are quite different from the gravimetrically determined water content. Analysis of these results shows that the average percent difference for all of the tests is approximately 9 %. The average percent difference for the sands were considerably better at around 6%. The clays had an average percent difference of 14%. These results are within the acceptable range of difference for TDR moisture measurements

TABLE 5.11 TDR/GRAVIMETRIC % DIFFERENCE

Soil Type	Gravimetric Moisture, %	TDR Gravim. Moist., %	(%) Percent Difference
Fine Sand	0.00	1.81	na
	5.60	5.68	-1.34
	8.50	8.04	5.47
	11.25	12.32	-9.48
	12.65	13.40	-5.95
	25.00	19.37	22.52

TABLE 5.12 TDR/GRAVIMETRIC % DIFFERENCE

Soil Type	Gravimetric Moisture, %	TDR Gravim. Moist., %	(%) Percent Difference
Coarse Sand			
	0.00	2.34	NA
	4.93	6.63	-34.48
	9.1	11.17	-22.71
	12.08	14.04	-16.26
	20.00	19.26	3.71
	25.00	25.21	-0.83

TABLE 5.13 TDR/GRAVIMETRIC % DIFFERENCE

Soil Type	Gravimetric Moisture, %	TDR Gravim. Moist., %	(%) Percent Difference
Upshur Clay			
	0.00	2.91	NA
	4.40	9.53	-32.77
	8.50	12.36	-32.46
	12.80	20.60	-47.77
	16.80	24.82	-35.57
	23.00	30.76	-26.20
	28.60	38.88	-31.13

TABLE 5.14 TDR/GRAVIMETRIC % DIFFERENCE

Soil Type	Gravimetric Moisture, %	TDR Gravim. Moist., %	(%) Percent Difference
Guernsey Clay			
	0.00	3.60	NA
	8.60	9.43	-9.67
	13.6	12.64	7.09
	17.38	15.08	13.24
	18.85	17.11	9.26
	27.00	27.31	-1.14

TABLE 5.15 TDR/GRAVIMETRIC % DIFFERENCE

Soil Type	Gravimetric Moisture, %	TDR Gravim. Moist., %	(%) Percent Difference
Hocking River Silt			
	0.00	5.84	NA
	7.65	8.68	13.48
	10.56	10.82	2.42
	15.61	14.37	7.48
	18.52	20.60	-11.24
	20.91	25.22	-20.63
	23.5	37.78	-60.75

TABLE 5.16 TDR/GRAVIMETRIC % DIFFERENCE

Soil Type	Gravimetric Moisture, %	TDR Gravim. Moist., %	(%) Percent Difference
Silty Sand			
	0.00	2.49	NA
	6.70	5.68	15.17
	13.20	13.47	-2.02
	17.50	22.30	-27.44
	19.0	24.88	-30.94

TABLE 5.17 TDR/GRAVIMETRIC % DIFFERENCE

Soil Type	Gravimetric Moisture, %	TDR Gravim. Moist., %	(%) Percent Difference
Clayey Coarse Sand			
	0.00	2.92	NA
	5.60	8.16	-25.18
	10.40	14.48	-12.21
	15.40	21.51	0.75
	17.00	29.56	-8.59
	19.60	27.86	-15.32

TABLE 5.18 TDR/GRAVIMETRIC % DIFFERENCE

Soil Type	Gravimetric Moisture, %	TDR Gravim. Moist., %	(%) Percent Difference
Clayey Fine Sand			
	0.00	1.45	NA
	5.00	3.27	34.51
	10.66	9.03	15.20
	15.30	17.10	-11.8
	19.39	21.06	-8.49

The percent difference can be caused from many influences. The most prominent of these is the error in reading the wave forms or traces of the TDR output. This is especially true with the higher absorbing clays and silts. The trace does not make the second inflection point at saturation, which makes it difficult to obtain a dielectric constant and water content from the results. The TDR measurements, however, did provide a valid examination of the water content in the sands. Having the probes in place alleviated the problem of drainage and the displacement of water when obtaining gravimetric samples. The results of the frequency - TDR moisture content tests for all soils can be seen in Figures 5.20 - 5.27.

Comparing these figures to the gravimetric analysis that was done for the FD response shows similar relationships for all soils. The similarity of the relationships gives confidence and validity to the FD - Gravimetric relationship. As can be see from the different figures, some soils have better correlation to the linear and polynomial fits. Since the data analysis was done using Topp's Equation (Topp,1980), the fine grained soils cause errors to arise.

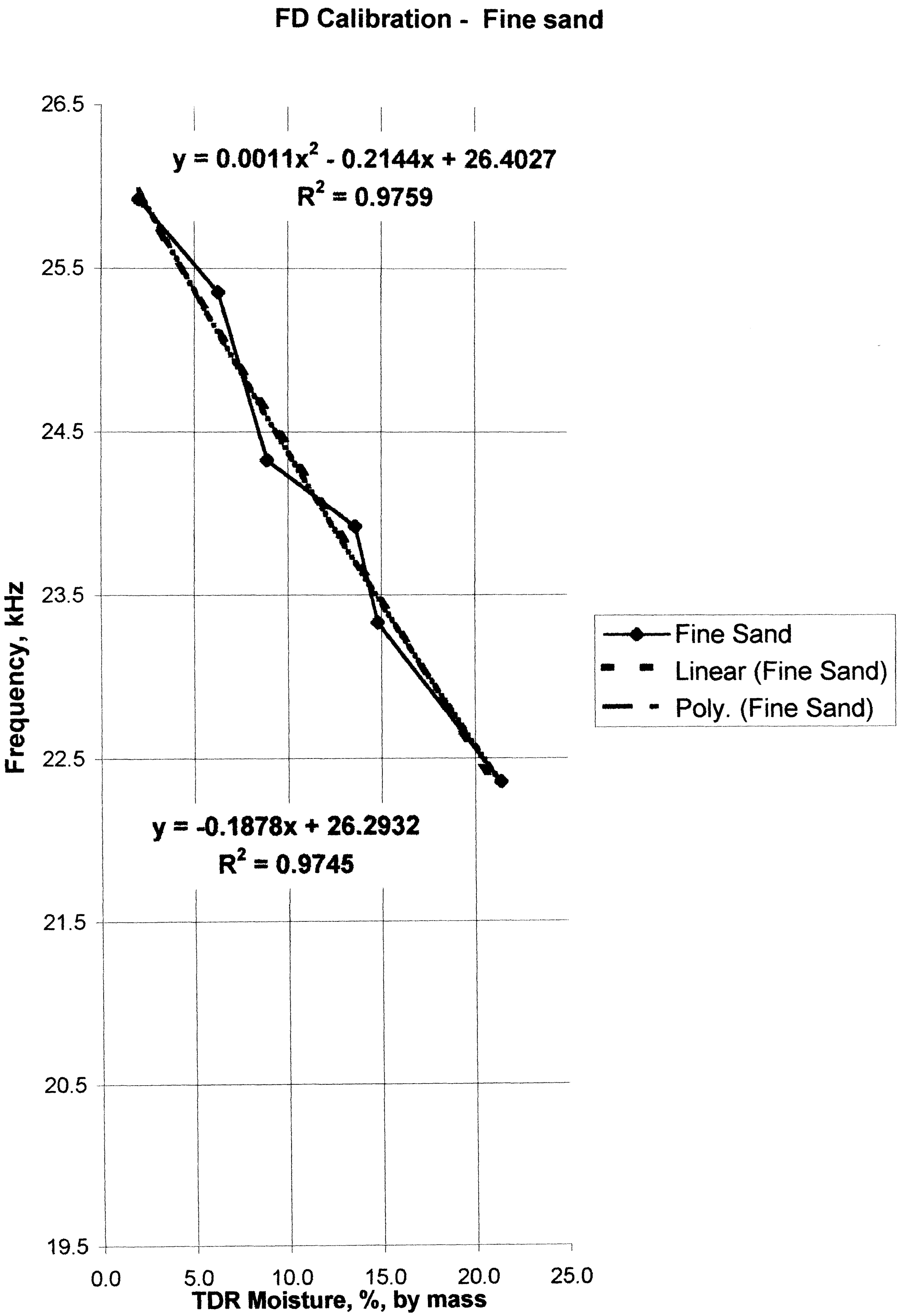

FD Calibration - Fine sand
y = 0.0011x^2 - 0.2144x + 26.4027
R^2 = 0.9759
y = -0.1878x + 26.2932
R^2 = 0.9745
Frequency, kHz
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0.0
5.0
10.0
15.0
20.0
25.0
TDR Moisture, %, by mass
Fine Sand
Linear (Fine Sand)
Poly. (Fine Sand)

Figure 5.20

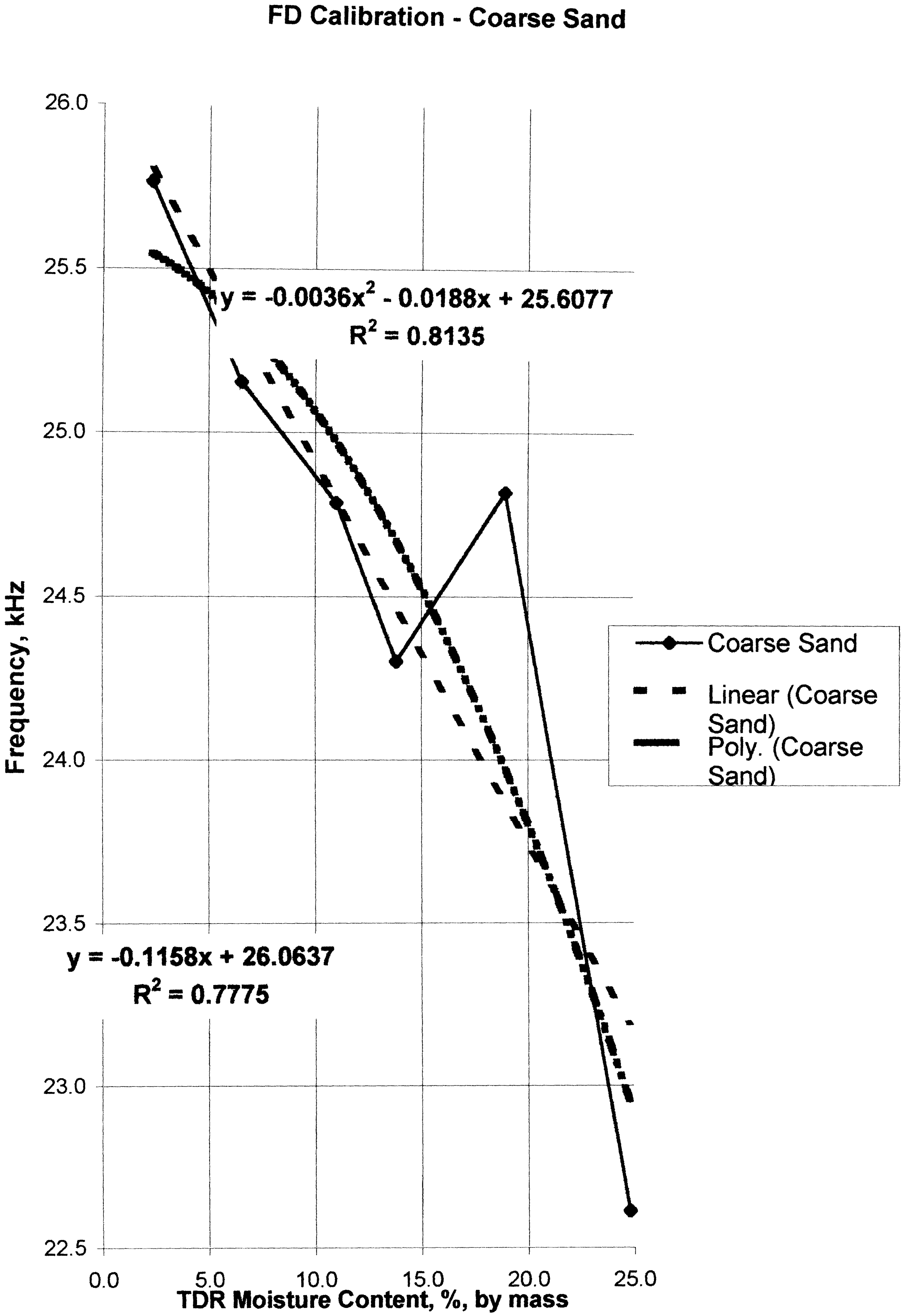
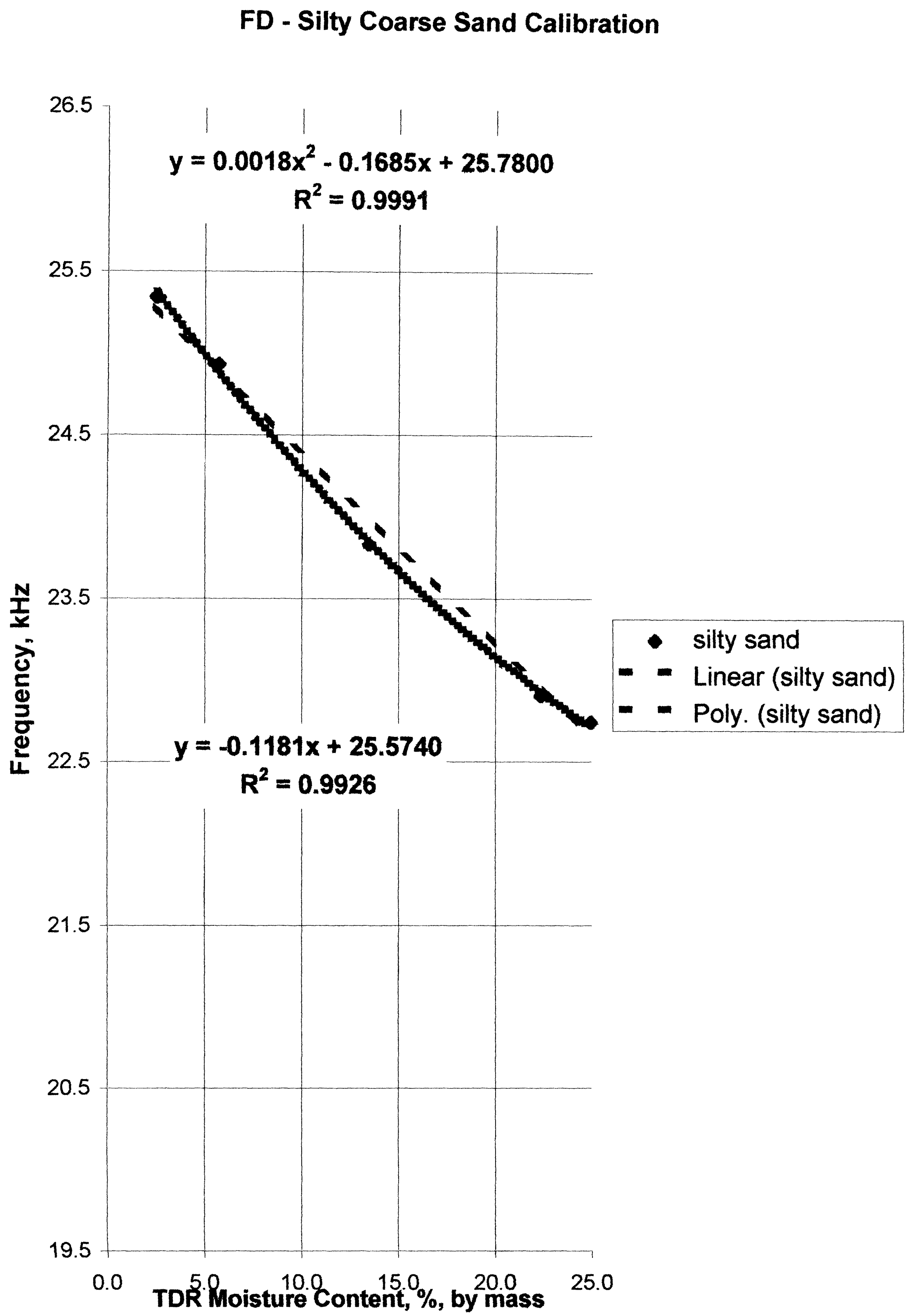

FD Calibration - Coarse Sand
Frequency, kHz
TDR Moisture Content, %, by mass
26.0
25.5
25.0
24.5
24.0
23.5
23.0
22.5
0.0
5.0
10.0
15.0
20.0
25.0
y = -0.0036x2 - 0.0188x + 25.6077
R2 = 0.8135
y = -0.1158x + 26.0637
R2 = 0.7775
Coarse Sand
Linear (Coarse Sand)
Poly. (Coarse Sand)

Figure 5.21



FD - Silty Coarse Sand Calibration
y = 0.0018x² - 0.1685x + 25.7800
R² = 0.9991
y = -0.1181x + 25.5740
R² = 0.9926
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0.0
5.0
10.0
15.0
20.0
25.0
Frequency, kHz
TDR Moisture Content, %, by mass
silty sand
Linear (silty sand)
Poly. (silty sand)

Figure 5.22

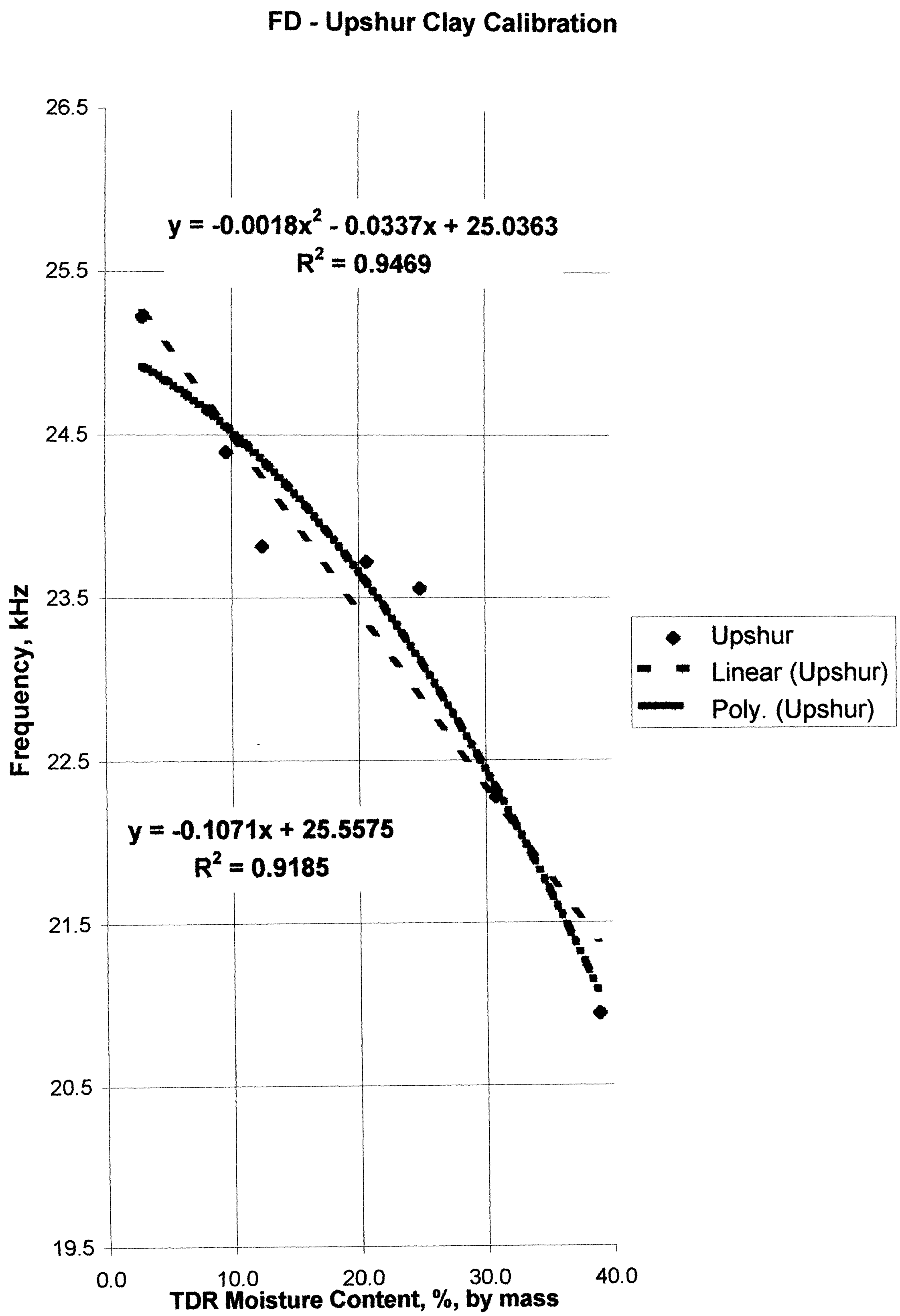

FD - Upshur Clay Calibration
$y = -0.0018x^2 - 0.0337x + 25.0363$
$R^2 = 0.9469$
$y = -0.1071x + 25.5575$
$R^2 = 0.9185$
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0.0
10.0
20.0
30.0
40.0
Frequency, kHz
TDR Moisture Content, %, by mass
Upshur
Linear (Upshur)
Poly. (Upshur)

Figure 5.23

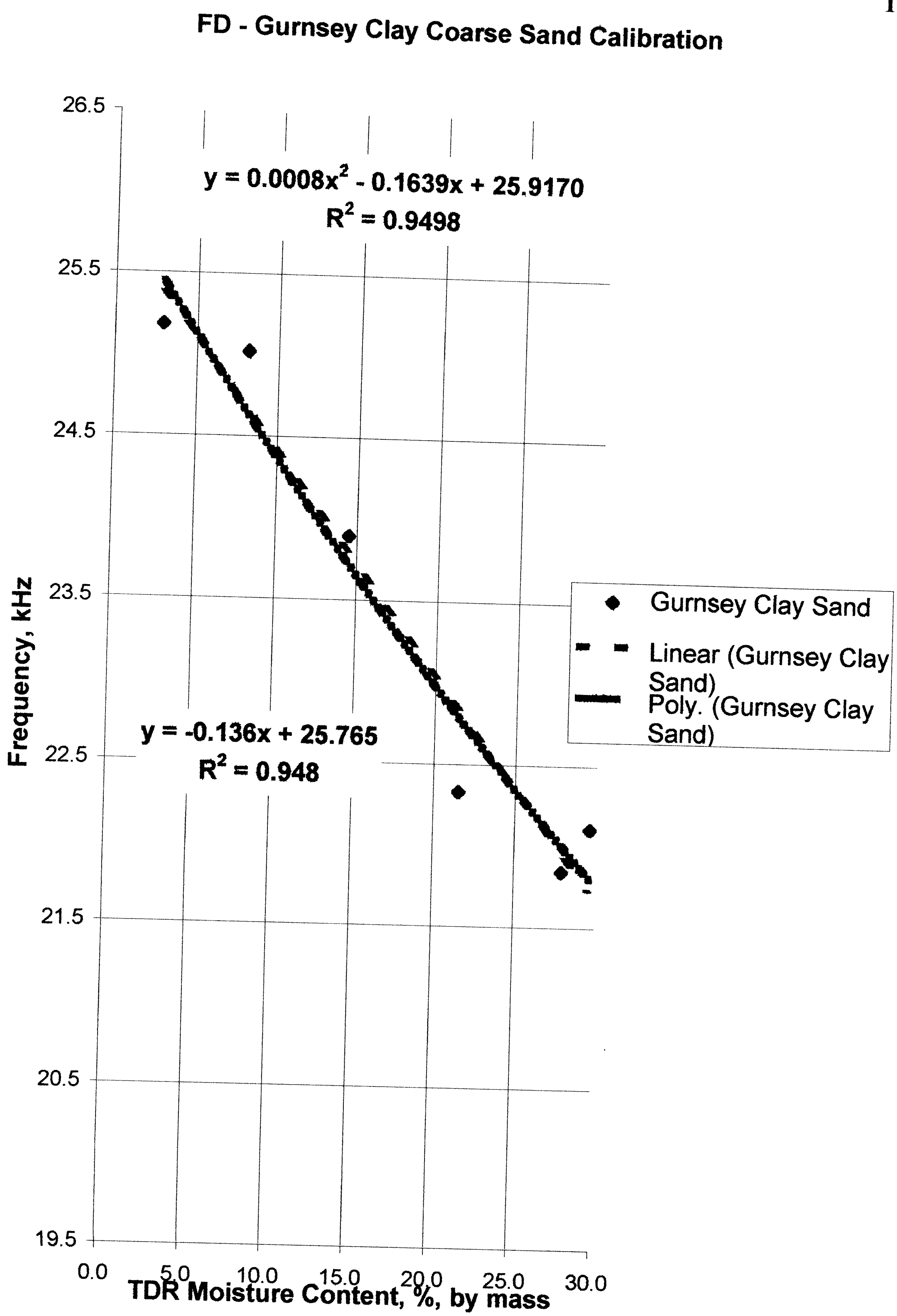

FD - Gurnsey Clay Coarse Sand Calibration
y = 0.0008x^2 - 0.1639x + 25.9170
R^2 = 0.9498
y = -0.136x + 25.765
R^2 = 0.948
Frequency, kHz
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0.0
5.0
10.0
15.0
20.0
25.0
30.0
TDR Moisture Content, %, by mass
Gurnsey Clay Sand
Linear (Gurnsey Clay Sand)
Poly. (Gurnsey Clay Sand)

Figure 5.24

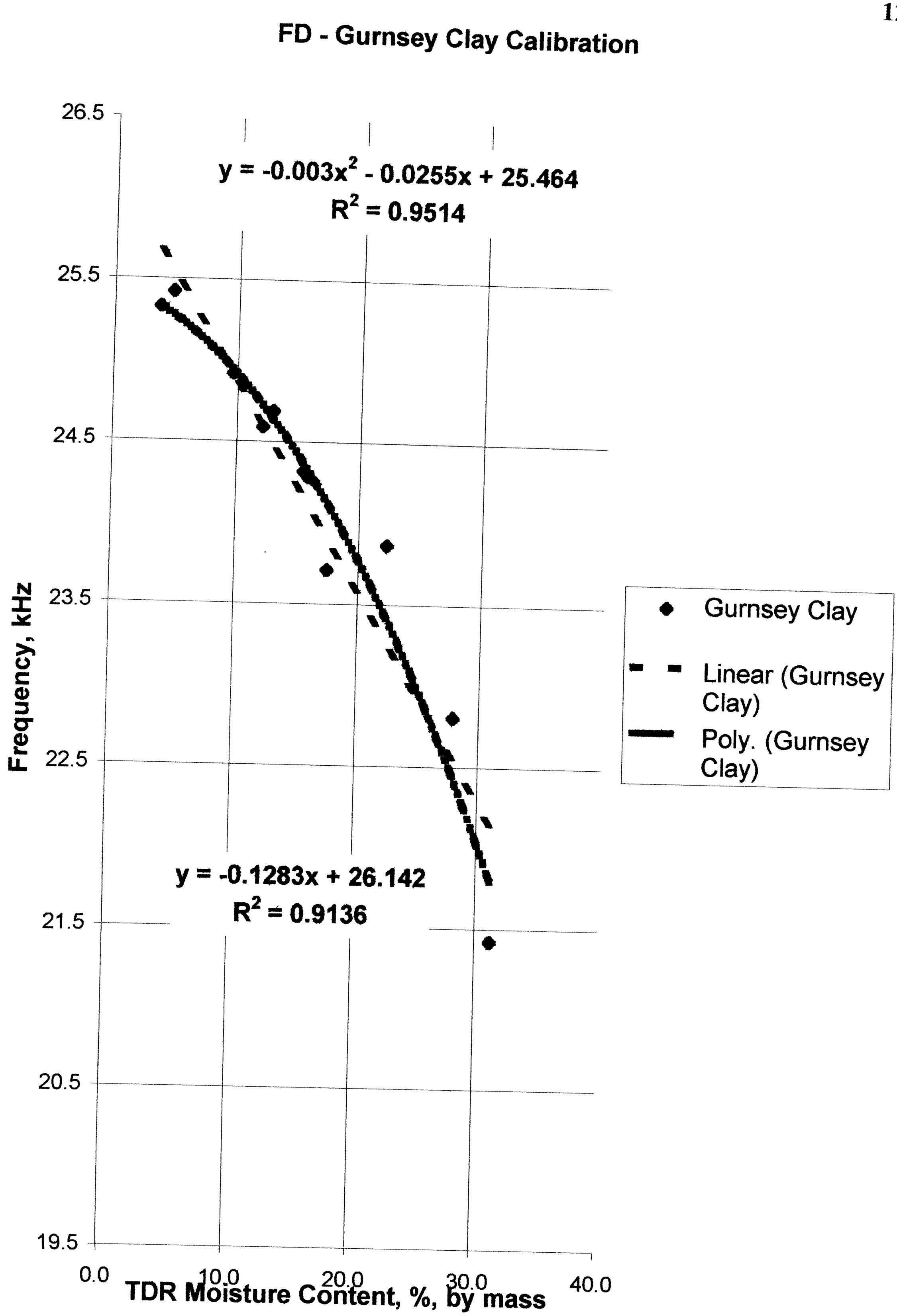

FD - Gurnsey Clay Calibration
y = -0.003x2 - 0.0255x + 25.464
R2 = 0.9514
y = -0.1283x + 26.142
R2 = 0.9136
Frequency, kHz
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0.0
10.0
20.0
30.0
40.0
TDR Moisture Content, %, by mass
Gurnsey Clay
Linear (Gurnsey Clay)
Poly. (Gurnsey Clay)

Figure 5.25

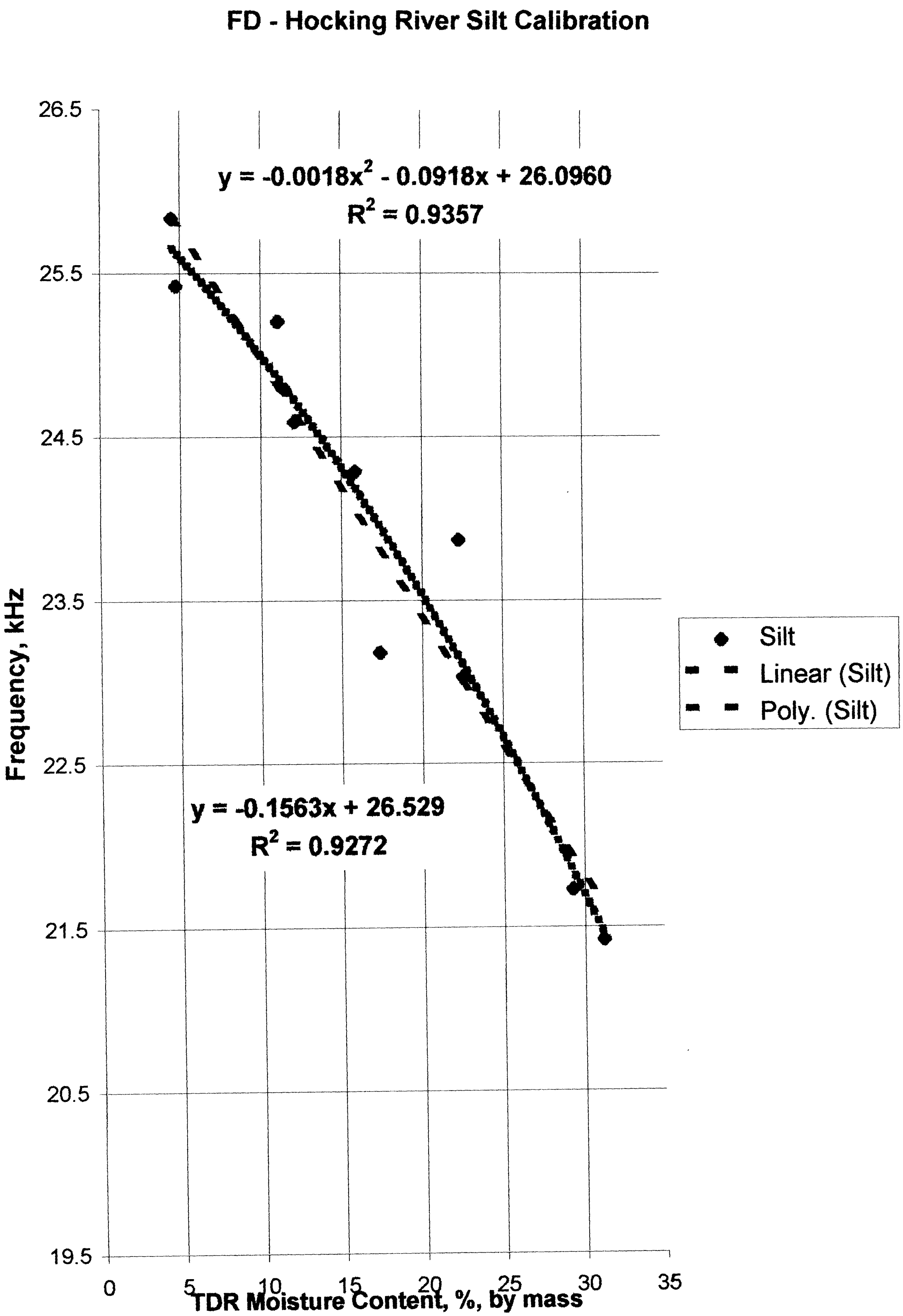

FD - Hocking River Silt Calibration
y = -0.0018x2 - 0.0918x + 26.0960
R2 = 0.9357
y = -0.1563x + 26.529
R2 = 0.9272
Frequency, kHz
TDR Moisture Content, %, by mass
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0
5
10
15
20
25
30
35
Silt
Linear (Silt)
Poly. (Silt)

Figure 5.26

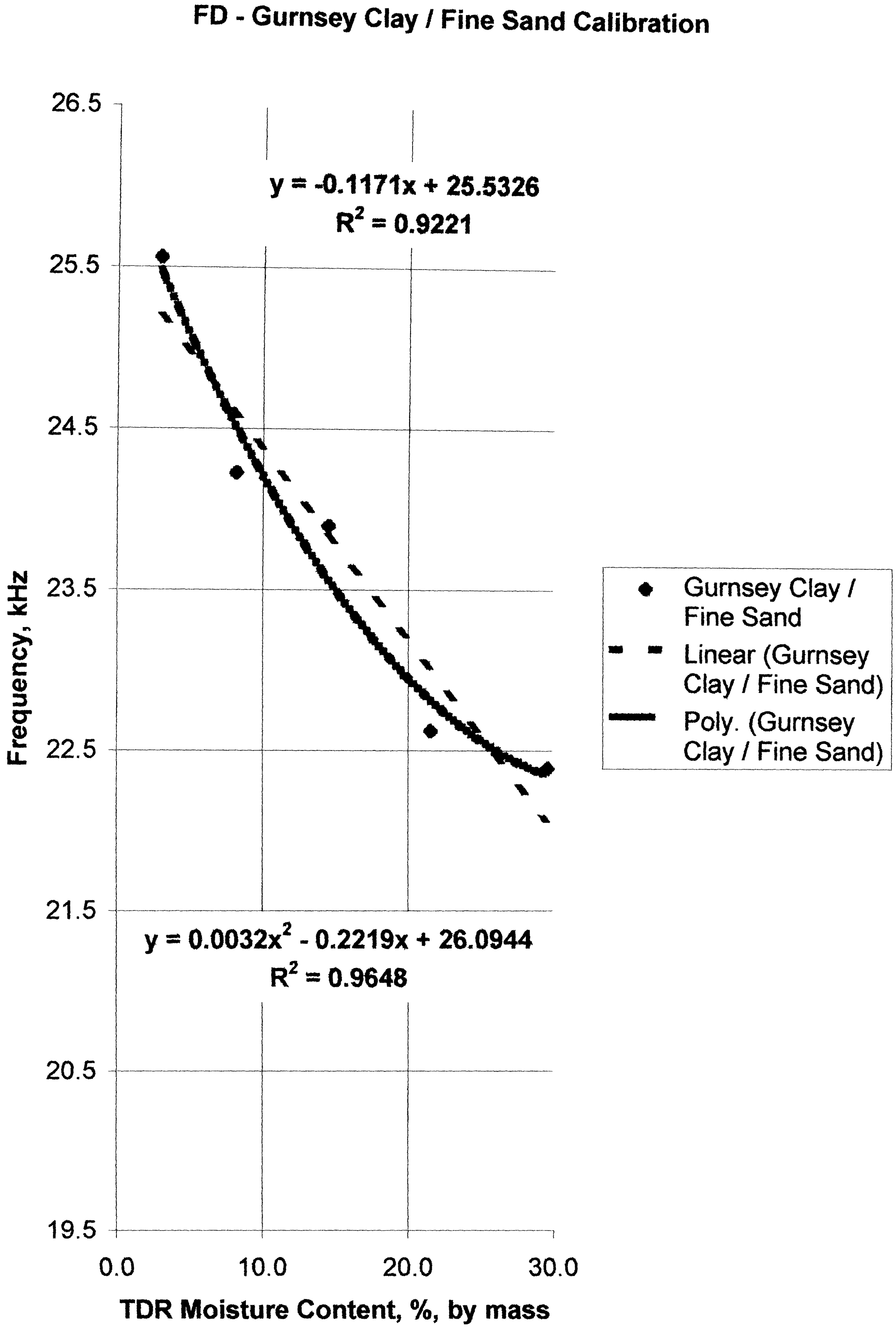
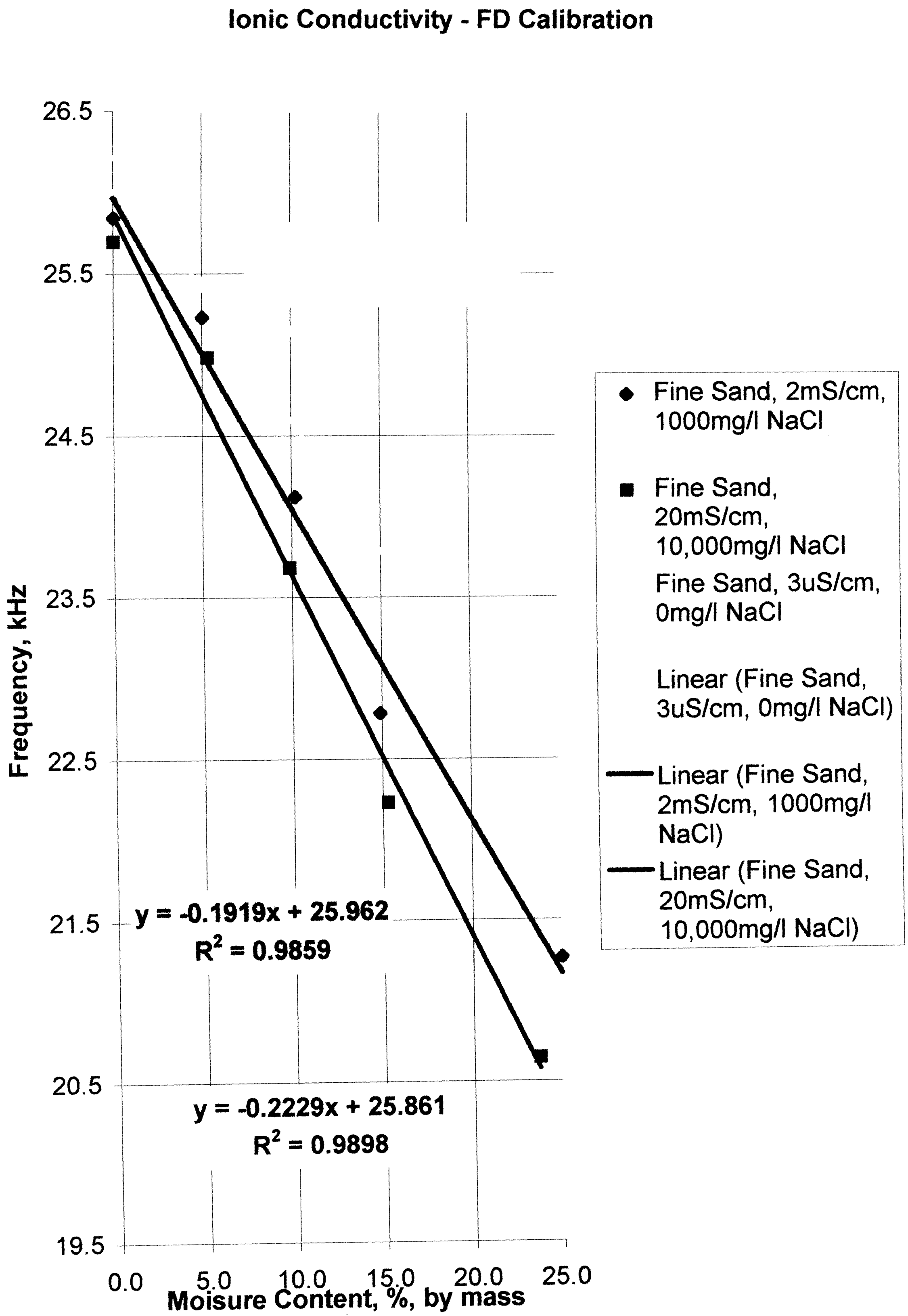

FD - Gurnsey Clay / Fine Sand Calibration
y = -0.1171x + 25.5326
R² = 0.9221
y = 0.0032x² - 0.2219x + 26.0944
R² = 0.9648
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
0.0
10.0
20.0
30.0
Frequency, kHz
TDR Moisture Content, %, by mass
Gurnsey Clay / Fine Sand
Linear (Gurnsey Clay / Fine Sand)
Poly. (Gurnsey Clay / Fine Sand)

Figure 5.27

5.10 Analysis of Ionic Conductivity Test

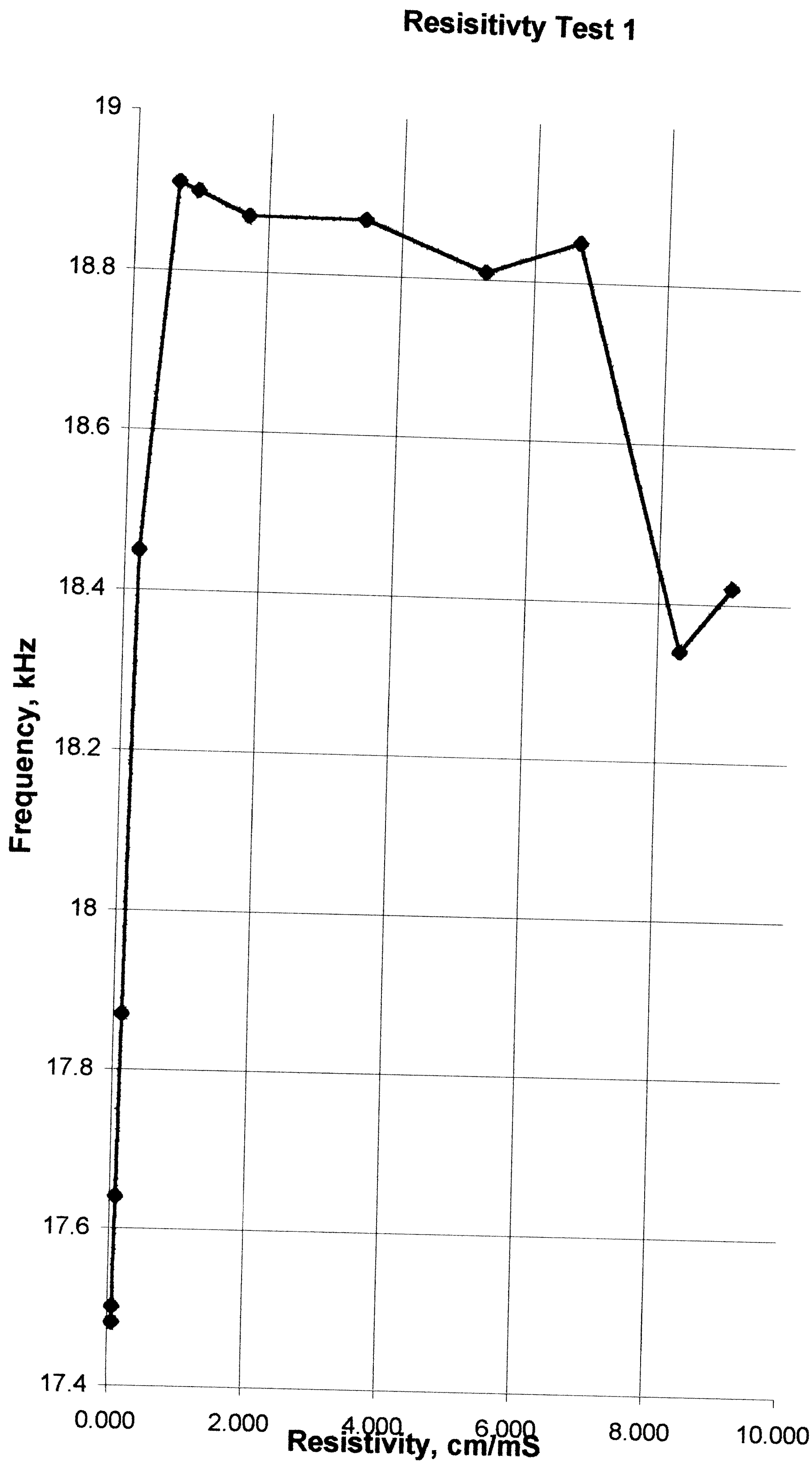
The results of the ionic conductivity tests for the frequency domain probe are tabulated in Tables 5.19 through 5.22 The graphical analysis can be seen in Figures 5.28 through 5.30. These tests were conducted with salt water.

Evaluating the graphical data in Figure 5.28 shows an increase in frequency attenuation as the ionic conductivity increases. This inherently makes good sense. The same type of results would be found if taking the electrical conductivity of a jar of salt water. As the salt concentration increased, so would the conductivity. The increased frequency attenuation that was seen in the sands at 2mS/cm and 20 mS/cm is due to the salt concentration increasing from 1000 mg/l to 10,000 mg/l. Observing the slopes from 5.28 gives an indication on how the probe would respond to soils that have high ionic conductivity or areas that have aquifers that consist mainly of salt water. The difference in slopes from normal sand (which has a ionic conductivity of around 3uS/cm) to 2mS/cm, and 20mS/cm mixtures are minimal, showing that the ionic conductivity of a soil has little bearing on soil moisture determination. These results are validated by Figures 5.29 and 5.30. The probe's frequency response shows an independence of the ionic conductivity of the material. As with the other conditions encountered with the other soils that were calibrated, using the right calibration curve for the appropriate situation is imperative.



Ionic Conductivity - FD Calibration
26.5
25.5
24.5
23.5
22.5
21.5
20.5
19.5
Frequency, kHz
0.0
5.0
10.0
15.0
20.0
25.0
Moisure Content, %, by mass
y = -0.1919x + 25.962
R² = 0.9859
y = -0.2229x + 25.861
R² = 0.9898
Fine Sand, 2mS/cm, 1000mg/l NaCl
Fine Sand, 20mS/cm, 10,000mg/l NaCl
Fine Sand, 3uS/cm, 0mg/l NaCl
Linear (Fine Sand, 3uS/cm, 0mg/l NaCl)
Linear (Fine Sand, 2mS/cm, 1000mg/l NaCl)
Linear (Fine Sand, 20mS/cm, 10,000mg/l NaCl)

Figure 5.28



Resisitivty Test 1
19
18.8
18.6
18.4
18.2
18
17.8
17.6
17.4
Frequency, kHz
0.000
2.000
4.000
6.000
8.000
10.000
Resistivity, cm/mS

Figure 5.29

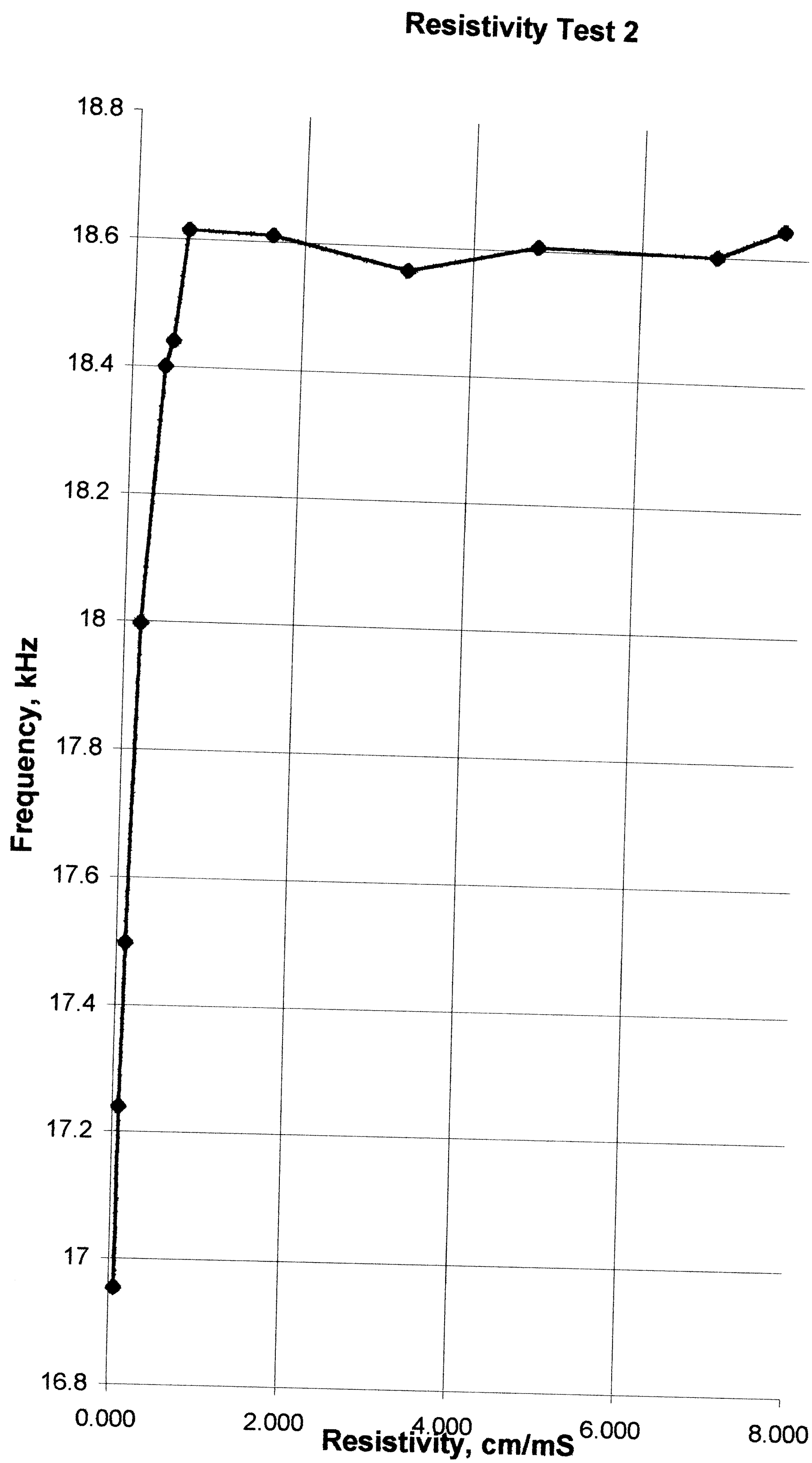

Resistivity Test 2
18.8
18.6
18.4
18.2
18
17.8
17.6
17.4
17.2
17
16.8
Frequency, kHz
0.000
2.000
4.000
6.000
8.000
Resistivity, cm/mS

Figure 5.30

TABLE 5.19 IONIC CONDUCTIVITY TEST 1 - SALT WATER ONLY

Salt Added	Concentration	Conductivity	Resistivity	Frequency
grams	g/l	mS/cm	cm/Sm	kHz
0.00	0.0000	0.11	9.091	18.4200
0.00	0.0000	0.12	8.333	18.3400
0.39	0.0134	0.15	6.667	18.8509
1.42	0.0489	0.19	5.263	18.8106
2.85	0.0982	0.29	3.448	18.8700
7.12	0.2456	0.59	1.695	18.8704
14.25	0.4913	1.08	0.926	18.9030
21.37	0.7370	1.56	0.641	18.9100
28.50	0.9827	4.80	0.208	18.4554
71.25	2.4568	8.75	0.114	17.8756
142.50	4.9137	12.92	0.077	17.6400
213.75	7.3706	17.00	0.059	17.4800
285.00	9.8275	17.30	0.058	17.5000

TABLE 5.20 IONIC CONDUCTIVITY TEST 2 - SALT WATER ONLY

salt added	Concentration	Conductivity	Resistivity	Frequency
grams	g/l	mS/cm	cm/Sm	kHz
0	0	0.13	7.692	18.6443
0.428	0.013375	0.14	6.897	18.6325
1.575	0.049219	0.21	4.762	18.6062
3.150	0.098438	0.31	3.226	18.5632
7.875	0.246094	0.62	1.613	18.6099
15.750	0.492188	1.63	0.613	18.6150
23.625	0.738281	2.11	0.474	18.4400
31.500	0.984375	2.59	0.386	18.4004
78.750	2.460938	5.31	0.188	17.9968
157.500	4.921875	9.75	0.103	17.4975
236.250	7.382813	14.08	0.071	17.2401
315.000	9.84375	18.21	0.055	16.9532

TABLE 5.21 2 mS/CM

Gravimetric	Frequency
Moisture, %	kHz
0.00	25.8423
5.00	25.2300
10.20	24.1245
14.90	22.7800
25.00	21.2650

TABLE 5.22 20 mS/CM

Gravimetric	Frequency
Moisture, %	kHz
0.00	25.6946
5.30	24.9800
9.87	23.6800
15.30	22.2312
23.70	20.6451

5.11 TDR Test Analysis

The purpose of these tests were twofold; 1) to become accustomed to TDR data interpretation and operation, and 2) to determine the range of clay percentage in which the TDR moisture content determination system is inapplicable using Topps "universal" equation. The graphical results for the ten different sand clay specimens can be seen in Figures 5.31, 5.32, and 5.33. Figure 5.32 represents the comparison of gravimetrically determined (oven dried) samples and TDR moisture samples. The TDR moisture contents were determined by Topp's "universal" equation. As can be seen from the figure, as the clay range increases the deviation from the actual gravimetric moisture content increases. From Figure 5.32, the range that Topp's equation is applicable is up to around 30 to 35 % clay. From Figure 5.32, it is also possible to determine that the 30 - 35 % clay range is below the 10 % margin of error from a range of 5.0 to around 20.0 % moisture content. Figure 5.33 is a calibration for the TDR probes. The equation gives an approximate moisture content for coarse grained soils with 10 to 75 % clay. Figure 5.34 is a comparison of the TDR results to the universal equation by Topp. As can be seen there is a drastic difference between the two lines as the moisture content increases. These results indicate the need for soil specific moisture content calibration.

TDR Clay - Coarse Sand Calibration

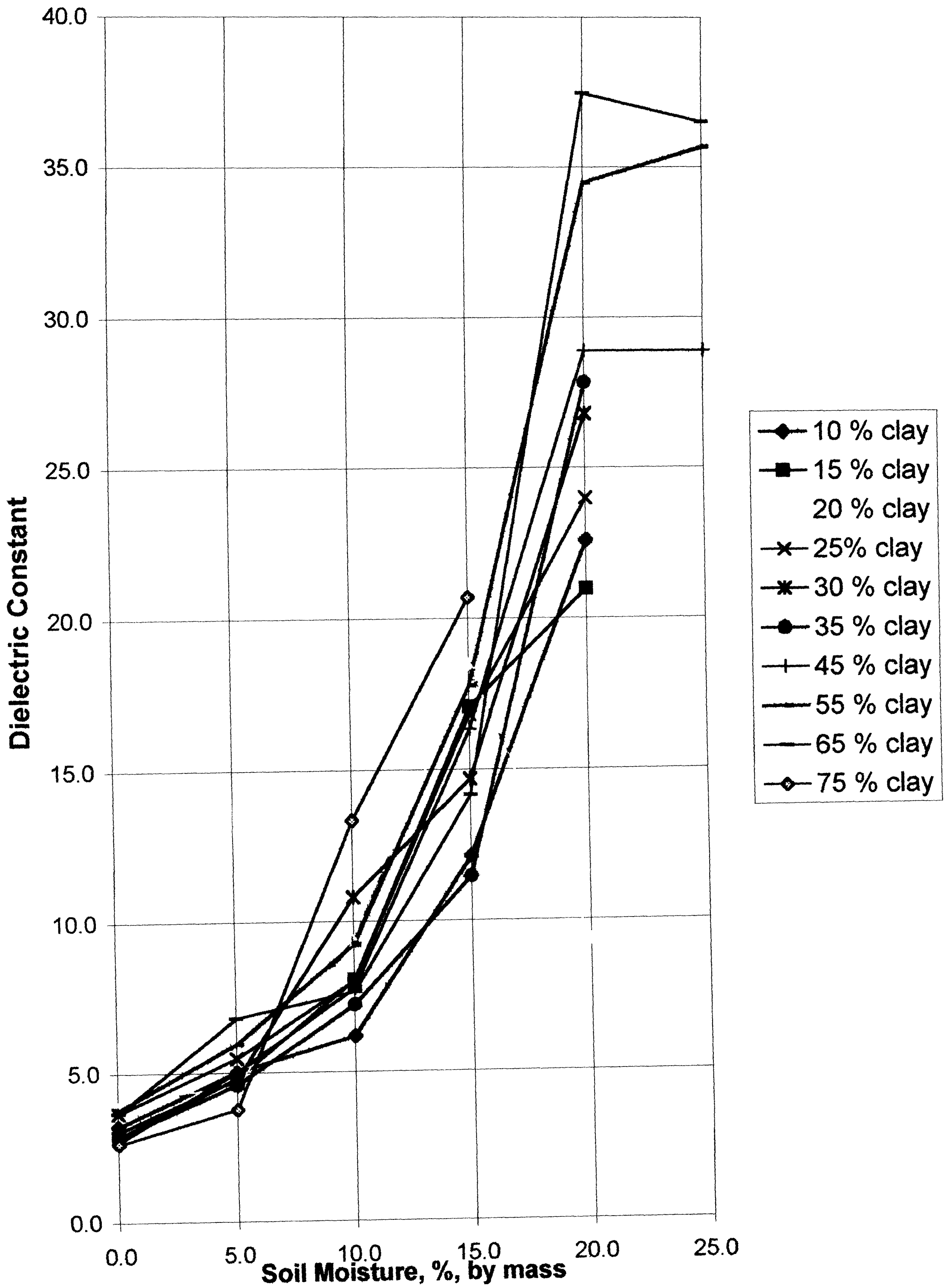
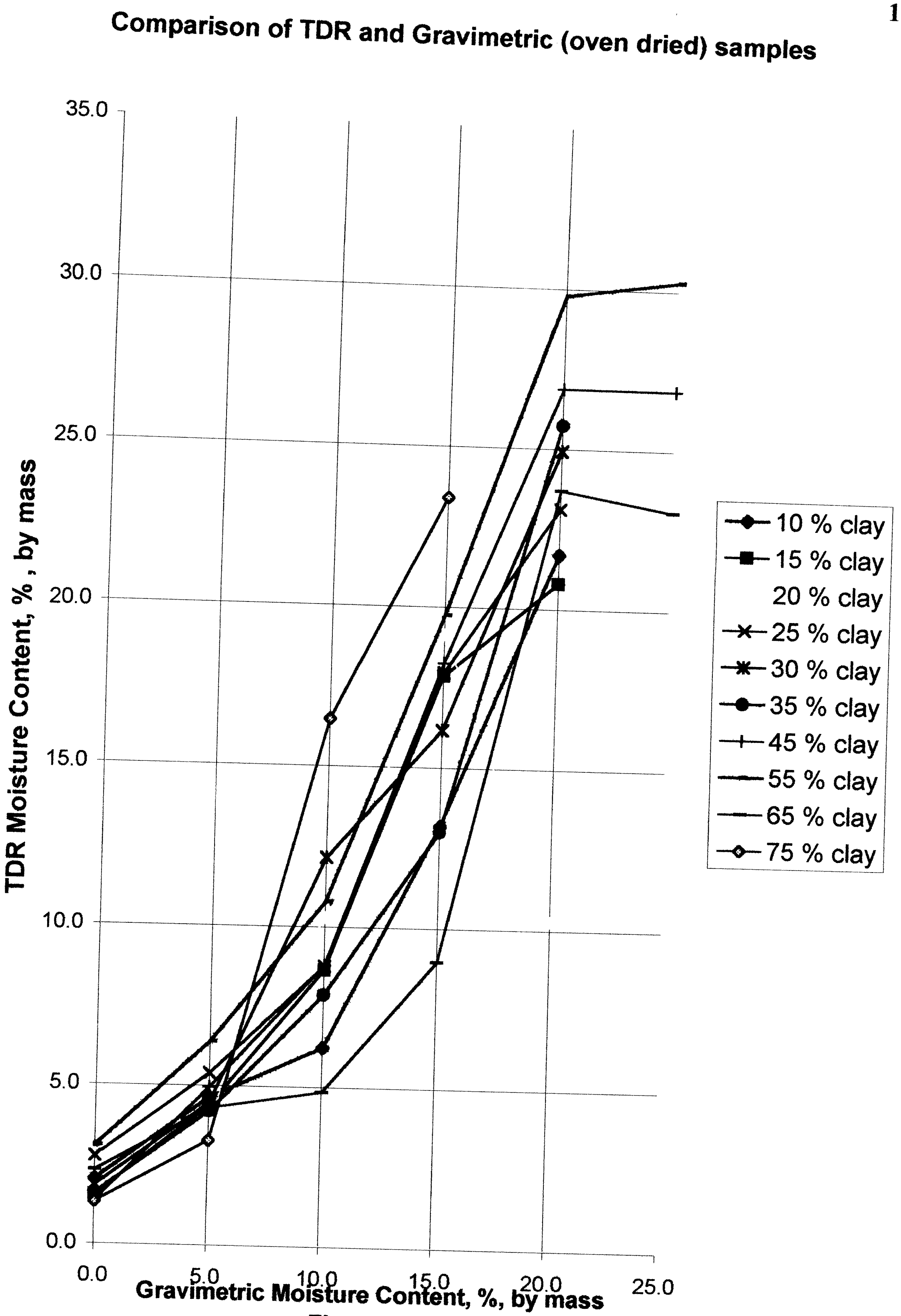
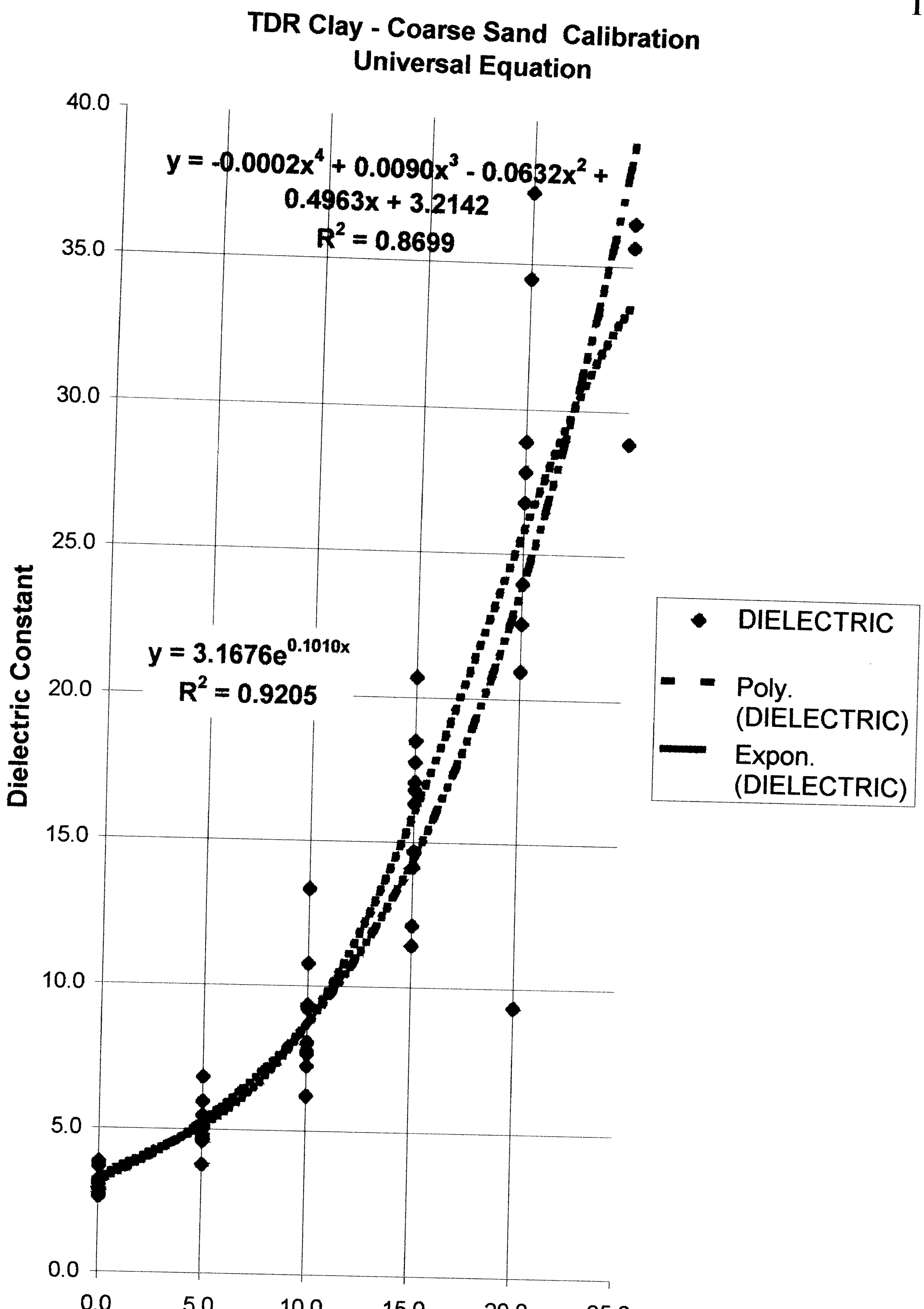


Figure 5.31



Comparison of TDR and Gravimetric (oven dried) samples
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
5.0
10.0
15.0
20.0
25.0
TDR Moisture Content, % , by mass
Gravimetric Moisture Content, %, by mass
10 % clay
15 % clay
20 % clay
25 % clay
30 % clay
35 % clay
45 % clay
55 % clay
65 % clay
75 % clay

Figure 5.32



Moisture Content, %, by mass

Figure 5.33

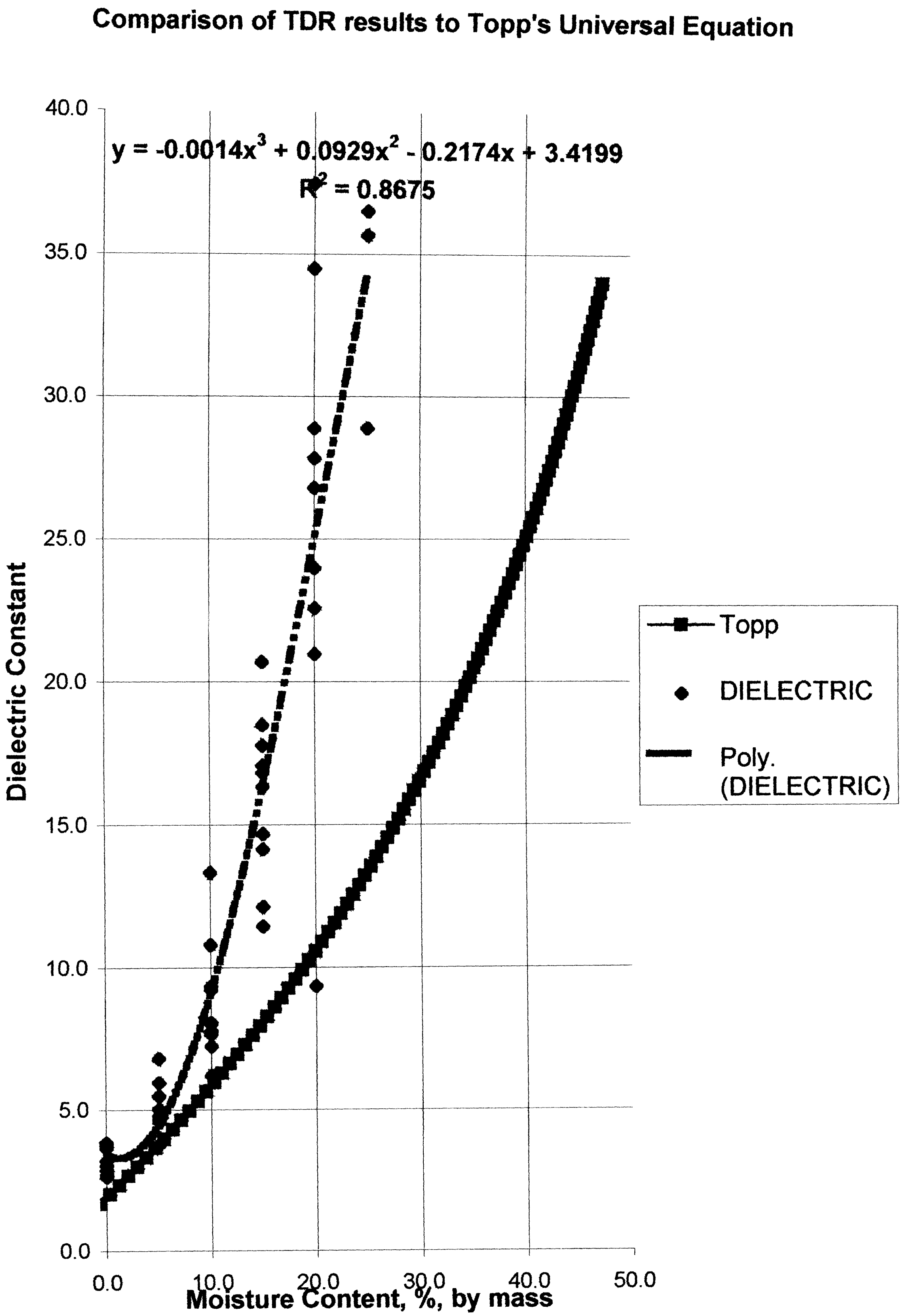

Comparison of TDR results to Topp's Universal Equation
y = -0.0014x³ + 0.0929x² - 0.2174x + 3.4199
R² = 0.8675
Dielectric Constant
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
Moisture Content, %, by mass
Topp
DIELECTRIC
Poly. (DIELECTRIC)

Figure 5.34

CHAPTER 6
CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

The objectives set forth in Chapter 1 were fulfilled through experimentation and analysis of the test data. The SM/R Frequency Domain probe for a full size cone penetrometer vehicle was calibrated and validated by way of laboratory testing.

Eight different soils were tested using both Time and Frequency Domain soil moisture determination techniques. All soils were tested from dry to saturation conditions. The results of the individual tests provide a relationship between frequency response and soil moisture which can be used to determine in situ soil moistures. The results of the tests also concluded that the Hocking River Silt showed the best overall reproducibility, while the sands showed the poorest reproducibility.

The compilation of data from the tests of the individual soils yielded an equation that covers a wide range of soil grain distributions. The equation allows for investigation of soil moisture for unknown soil types with a certain amount of validity.

The overall trend for all of the soils tested provides a benchmark for this and other research. The information also allows for continued research on topics tangent to the preliminary research conducted within this thesis.

Several factors were identified that influenced the frequency response of the SM/R probe. Soil type, compaction effort, and ionic conductivity had the largest impact on the frequency measurements taken. The FD measurements were affected by the coarseness and fineness of the individual soil types as well as the inherent soil fabric.

The ionic conductivity of the soil can effects the FD measurements at extreme conductivities. At high ionic conductivity's, the soils showed the influence that salt water might have when pushing through aquifers with salt water intrusion. With smaller concentrations of salt or smaller conductivities the problem is not as significant. Compaction of the soil showed small, but significant effects on the FD measurements. The compaction of the soil will have a bearing on the amount of air and water that are within the soil's voids. This will and did effect the frequency response of the FD probe. The compaction rate tested for the procedure is small in comparison to the overburden that the soil would be subjected to for the depths reached at deep penetrations using the CPT.

Comparing and contrasting the TDR and FD techniques for determining soil moisture allow conclusions to be drawn about what method is best suited for soil moisture determination for the CPT. The construction of the probe, data collection, and ease of data analysis are all valid reasons to use FD technology and not TDR for CPT field investigations.

6.2 Limitations

Limitations of the research are based on the heterogeneity of the materials. The complexity of soil lends a significant question mark to the validity of the observed relationships. However, successful repetitions of tests provide a secure foundation for the preliminary testing done here. Other limitations include the design of the test container, the number of TDR probes available, and the investigator's inexperience in soil moisture determination using TDR and FD methods.

6.3 Recommendations

The research presented here is a "first try " calibration and investigation of the SM/R frequency domain probe. It is recommended that the probe be tested repeatedly with a wide variety of soil types and conditions, both in the laboratory and the field. After doing this, the valid and proven relationship can be used without questioning the accuracy of the results obtained. Furthermore, a more complete experimental procedure on the effects of compaction needs to be performed. Both field and lab tests can indicate the effect compaction has on the frequency response.

Another recommendation for the SM/R probe is to use it as a material sensor, that is, use it to detect materials such as pollutants or aqueous media other than water such as organics and inorganics chemicals contaminating the subsurface. Since the probe will react differently from water compared to other materials, calibrations for the specific material must be performed in order to use the SM/R probe to find them.

With respect to the experimental equipment used in this procedure, continuing research projects with the SM/R probe would benefit from the use of data acquisition equipment and a better defined test container. Having a test container that would allow the probe to be pushed through a soil matrix of several feet would simulate in situ conditions more accurately. The data acquisition equipment would allow for the soil moisture profile to be well defined through the push of the probe.

The most important recommendation for continued research for the SM/R probe is to run as many in situ tests in known soil strata under as many different conditions as possible. This is truly the only way to calibrate the SM/R probe.

References

1. Lambe, T. W., Whitman, R.V. Soil Mechanics. John Wiley and Sons, New York. 1969

2. Rada, G.R., Elkins, G.E. LTPP Seasonal Monitoring Program: Instrumentation Installation and Data Collection Guidelines. National Technical Information Service, Springfeild, VA. 1995

3. Patterson, D.E., Smith, M.W. The Measurement of Unfrozen Water Content by TDR: Results from Laboratory Tests. Canadian Geotechnical Journal. V. 18, pg 131-144. 1981

4. Dalton, F.N., Herkelrath, W.N., Rawlins, D.S. TDR: Simultaneous Measurment of Soil Water Content and Electrical Conductivity with a Single Probe. Water Resources Research. V. 20 pg. 989-990. June 1, 1984

5. Kaya, A., Lovell, C.W., Altschaeffl, A.G. The Effective Use of TDR in Geotechnical Engineering. Proceedings on TDR Applications, Chicago Ill. 1994

6. Zegelin, S.J., White, I. Calibration of TDR for Applications in Mining, Grains, and Fruit Storage and Handling. Proceedings on TDR Applications, Chicago Ill. 1994

7. Topp, G.C., Zegelin, S.J., White, I. Monitoring Soil Water Content Using TDR: An Overview of Progress. Proceedings on TDR Applications, Chicago Ill. 1994

8. Malicki, M.A., Plagge, R., Roth, C. H.. Influence of Matrix on TDR Soil Moisture Readings and its Elimination. Proceedings on TDR Applications, Chicago Ill. 1994

9. Malicki, M.A., Walczak, R.T., Koch, S. Determining Soil Salinity from Simultaneous Readings of its Electrical Conductivity and Permittivity using TDR. Proceedings on TDR Applications, Chicago Ill. 1994

10. van Schelt, W., de Jong-Hanninen, M.K., van der Aa, J. Feild and Laboratory Experiments with TDR as a Moisture Monitoring System in Road Structures. Proceedings on TDR Applications, Chicago Ill. 1994

11. Logsdon, S. Calibrating TDR with Undisturbed Soil Cores for TDR use in Monitoring Subsurface Lateral Water Flow. Proceedings on TDR Applications, Chicago Ill. 1994

12. Baker, T.H.W., Davis, J.L., Topp, G.C.. Locating the Frozen-Unfrozen interface in soils using TDR. Canadian Geotechnical Journal, V. 19 1982

13. Dirksen, C., Dasberg, S. Improved Calibration of Time Domain Reflectometry Soil Water Content Measurement. Soil Science Society of America Journal. V. 57, 1993

14. Ansoult, M., De Backer, L.W., Declercq, M. Statistical Relationship Between Dilectric Constant and Water Content in Porous Media. Soil Science Society of

Dilectric Constant and Water Content in Porous Media. Soil Science Society of America Journal. V. 49, 1985

15. Topp, G.C., Davis, J.L., Annan, A.P. Electromagnetic Determination of Soil Water Content: Measurement in Coaxial Transmission Lines. Water Resources Research. V. 16 Pg. 574-581 1980

16. Davis, J.L., Chudobiak, W. J. *IN SITU METER FOR MEASURING RELATIVE PERMITTIVITY OF SOILS.* Geol. Surv. Can. pg. 75- 79, 1985.

17. Dean, T.J., Bell, J.P., Baty, A.J. *Soil Moisture Measurementby an Improved Capacitance Technique, Part 1and 2.* Journal of Hydrology, pg. 67 - 90, 1987.

18. Selig, E.T., Mansukhani, S. *Relationship of Soil Moisture to the Dielectric Property.* Jour. of Geotech. Eng. Divsion, pg. 755 - 770, 1975.

19. Thomas, A.M. *In Situ Measurement of Moisture in Soil and Similar Substances by "Fringe" Capacitance.* J. Sci. Instrum., 1966 vol 43. Pg 21 -27.

20. Thevanayagam, S. *Frequency Domain Analysis of Electrical Dispersion of Soils.* Jour. of Geotech. Eng. 1995, pg. 618 -628.

21. Hoekstra, P., Delaney, A. *Dielectric Properties of Soil at UHF and Microwave Frequencies.* Journal of Geophysical Research, 1974 pg. 1699 - 1708

22. Heimova, T.J. *Frequency domain Analysis of Time Domain Reflectrometry Waveforms, Parts 1 and 2.* Water Resources Research, 1994 pg. 189 - 209

23. Wang, J. R., Schmugge, T.J. *An Empirical Model for the Complex Dielectric Permittivity of Soils as a Function of Water Content.* IEEE Trans. On Geoscience and Remote Sensing, 1980 pg. 288 -295

24. Wobschall, D. *A Theory of the Complex Dielectric Permittivity of Soil Containing Water: The Semidispersed Model.* . IEEE Trans. On Geoscience Electronics, 1977 pg. 49 - 58

25. Dobson, M.C., Ulbay, F.T. *Microwave Behavoir of Wet Soil - Part II: Dielectric Mixing Models.* IEEE Trans. On Geoscience and Remote Sensing, 1985 pg. 35 -45

26. Dasberg, S., Dalton, F.N. *Time Domain ReflectrometryField Measurements of Soil Water Content and Electrical Conductivity.* Soil Sci. Soc. Am. J. Vol. 49, 1985 pg. 293 -297

27. Rhoades, J.D., Manteghi, N.A., Shouse, P.J. *Soil Electrical Conductivity and Soil Salinity: New Formulations and Calibrations.* Soil Sci. Soc. Am. J. Vol. 53, 1989 pg. 433 - 439

28. Gupta, S.C., Hanks, R.J. *Influence of Water Content on Electrical Conductivity of the Soil.* Soil Sci. Soc. Am. J. Vol. 36, 1972 pg. 855 -857

29. Ledieu, J., De Ridder, P., De Clerck, P. *A Method of Measuring Soil Moisture by Time Domain Reflectrometry.* Journal of Hydrology Vol. 88, 1986. Pg. 319 - 328

30. Rhoades, J.D., Raats, Raats, A.C., Prather, R.J. *Effects of Liquid-Phase Electrical Conductivity, Water Content, and Surface Conductivity on Bulk Soil Conductivity.* Soil Sci. Soc. Am. J. Vol. 40, 1976 pg. 651 -655

31. Thevanayagam, S. *Electrical Response of Two - Phase Soil: Theory and Applications.* Journal of Geotechnical Engineering Vol. 19, 1993 pg. 1250 - 1275

32. Gur, Y., Ravina, I., Babchin, A.J. *On the Electrical Double Layer Theory: 1. A Numerical Method for Solving a Generalized Poisson - Boltzmann Equation.* Journal of Colloid and Interface Science, Vol. 64, 1978 pg. 326 -332

33. Gur, Y., Ravina, I., Babchin, A.J. *On the Electrical Double Layer Theory: 2. The Poisson - Boltzmann Equation including Hydration Forces.* Journal of Colloid and Interface Science, Vol. 64, 1978 pg. 333 - 341

35. Hausenbuiler, R.L. *Soil Science: Principles and Practices, 3rd edt.* Wm. C. Brown Publishers, Duuque, Iowa. 1985

36. *1502B Metallic Time Domain Reflectometer Operator Manual, 070-6266-01* Tektronix, 1993

37. Jones, A. *Overview of "Effects of Highway Deicing Chemicals on Shallow Unconsolidated Aquifers in Ohio."* USGS, 1996

ABSTRACT

Previous research has shed light on using attenuation of an electrical signal to determine the water content of soils. A majority of this research has focused on using the time domain to analyze the results. This research looks at using the frequency domain to determine the moisture content of several different soils. The research employs a 100 MHz probe designed for full size cone penetrometer use. A range of coarse sands to fine clays were tested with the probe. The data collected from each soil was analyzed for its individual characteristics and test reproducibility. The probe's resiliency against the effect of ionic conductivity was analyzed in a sand based mixture. The compaction of the soil was also briefly investigated for its effects on the probe. The research produced results that allowed the probe to be defined as a reliable way to measure soil moisture. The results were validated with the use of gravimetric and TDR moisture determination. Along with fore mentioned research, the effects of fine grained soils on TDR soil moisture measurements were also investigated. Past research has shown that fine grained soils attenuate the TDR signal to the point where it makes it hard to determine the moisture content. With the use of a sand-clay mixture, strong attenuation that fine grained soils exhibit on TDR measurements were studied. The results of this study proved that soil specific calibrations are a necessity, when working in fine grained soils in order to make use of TDR to determine soil moisture.