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Engineering

UNIVERSITY OF
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Calibration and Accuracy Assessment of the TDR One-Step Method for Quality Control of Compacted Soils

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Final Report

Florida Department of Transportation
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Disclaimer

Metric Conversion Table

Symbol	When you know	Multiply by	To find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

Symbol	When you know	Multiply by	To find	Symbol
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

Symbol	When you know	Multiply by	To find	Symbol
FORCE and PRESSURE or STRESS				
lbf	Pound-force	4.45	newtons	N
lbf/in^2	Pound-force per square inch	6.89	kiloPascals	kPa

Technical Report Documentation Page

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16. Abstract

The use of time domain reflectometry to measure soil density and water content in geotechnical engineering is relatively new. The TDR one-step method, now accepted as the ASTM Standard Method (D6780-05), outlines the procedure for obtaining the water content and the dry density of a given soil. The method requires the calibration of two soils constants, f and g, to relate the dielectric constant to the bulk electrical conductivity of the soil. The two soil constants, f and g, are dependent on soil type, pore fluid conductivity, and water content. The field process can be completed in less than 5 minutes, which provides a significant advantage over the two-step procedure. In this report, an extensive research program is carried out to obtain the TDR calibration constants for sandy soils commonly encountered in Florida. More importantly, the influence of the electrical conductivity of the pore fluid, EC_w, on the accuracy of the results is evaluated. A critical assessment of the TDR one-step method's accuracy and precision is also conducted.

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Executive Summary

Quality control of compacted fills and roadway embankments remains a challenging problem. Although the most accurate measurement method for water content remains the ASTM oven-drying procedure, it requires 24 hours of oven-drying before the results are available. Nuclear density and moisture gages require special certification, due to the potential hazards associated with the use of a radioactive material. As such, the FDOT has undertaken research over the past several years to evaluate the TDR method as an alternative to in-situ density and moisture measurement. The research was part of a nationwide Beta Testing program initiated by the Indiana DOT and Purdue University. As a result of these efforts, the method was standardized in 2002 by ASTM under Designation D 6780.

While the newly-introduced ASTM Method calls for a two-step process that requires excavation and re-compaction of the field soil, a new one-step method was developed concurrently by Purdue University researchers and represents a breakthrough since no excavation is needed. The procedure requires the calibration of four soils constants, a, b, c, and d, to relate the dielectric constant and the bulk electrical conductivity of the soil to its water content. From these, two additional soils constants, f and g, can be calculated to directly relate the dielectric constant to the bulk electrical conductivity. The field process can be completed in less than 5 minutes, which provides a significant advantage over the existing two-step. The two soil constants, f and g, are dependent on soil type, pore fluid conductivity, and water content. Determining these new soil constants for typical highway construction soils in Florida is a crucial step in the progress and eventual widespread usage of the one-step method.

The goal of the proposed work is to improve upon the ASTM Standard Method for TDR measurement of soil water content and density. The work relies on the new concept introduced by Purdue University researchers to obtain a simultaneous measurement of electrical resistivity in conjunction with the dielectric constant from the TDR measurement. Both measurements are then used to back-calculate the water content and density in a single step, without the need to excavate and re-compact. The specific objectives of the research were: (1) determine the calibration constants, f and g, for typical construction materials used in Florida, (2) examine the

accuracy of the one-step TDR method, and (3) compare the TDR method with other widely accepted methods such as the nuclear gage and the sand cone. It is worth noting that due to the necessity to drive metal spikes in the ground as part of the procedure, the TDR method is not suitable for granular base materials.

Laboratory and field programs were carried out to determine the calibration constants, f and g, for typical sands available in Florida for roadway construction. The findings provide the necessary information to accurately measure moisture content and density with a one-step procedure in the field, and eliminate the need to excavate the compacted soil.

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1. Introduction

1.1. Background

Compaction quality control is essential to virtually all earthwork and highway construction projects. This is done to ensure that design conditions are actually met in the field. It is essential to measure the in-place moisture content and density when evaluating the quality compaction control of an earthwork project. Currently there are many methods used for determination of these important parameters. This project is primarily concerned with the evaluation of a new method for measuring soil water content and density involving time domain reflectometry (TDR). Although TDR technology has been used for some time in other fields it is relatively new to the field of geotechnical engineering and is an altogether different approach to measuring soil properties than traditional geotechnical methods. Current methods used to measure soil density and moisture content relies, in most cases, on separate and independent tests that are often run on different soil samples. The TDR method measures both density and water content at the same time using the same soil sample by evaluating an electromagnetic wave that is sent into the soil medium. The TDR method for measuring in-situ water content and density was recently standardized in the form of ASTM D6780. The formation of ASTM D6780 is credited largely to work done at Purdue University; hence the method is sometimes referred to as the Purdue TDR Method.

1.2. Problem Statement

Quality control of compacted fills and roadway embankments has been and remains a challenging problem. Although the most accurate measurement method for water content remains the ASTM oven-drying procedure, the procedure requires 24 hours of oven-drying before the results are available. Nuclear density and moisture gages require special certification, due to the potential hazards associated with the use of a radioactive material. As such, the Florida Department of Transportation has undertaken a research study over the past two years to evaluate the TDR method as an alternative for in-situ density and moisture measurement. The study was part of a nationwide Beta Testing program initiated by the Indiana DOT and Purdue University.

As a result of these efforts, the method was standardized in 2002 by ASTM under Designation D 6780.

While the newly-introduced ASTM Method calls for a two-step process that requires excavation and re-compaction of the field soil, a new **one-step method** was developed concurrently by Purdue University researchers and represents a breakthrough since no excavation is needed. The procedure requires the calibration of two soils constants, f and g, to relate the dielectric constant to the bulk electrical conductivity of the soil. The field process can be completed in less than 5 minutes, which provides a significant advantage over the existing procedure. The two soil constants, f and g, are dependent on soil type, pore fluid conductivity, and water content. Determining these new soil constants for typical highway construction soils in Florida is a crucial step in the progress and eventual widespread usage of the one-step method. It is important to note that the new method is suitable for most coarse grained soils, but is unsuitable for granular base materials – due to the need to drive the spikes in the ground – and clays – due to their high electrical conductivity which weakens the TDR signal.

Another problem that is the current lack of any methods to evaluate the accuracy of the density measured using TDR and other quality control methods. FDOT normal procedures currently utilize nuclear density gage for wet density measurement and nuclear moisture gage in base materials. For testing in soils, FDOT stipulates the measurement of wet density with the nuclear gage and moisture content with the speedy device in order to obtain the dry density. TDR measurements cannot be objectively evaluated against sand cone, nuclear gage, or speedy moisture since the accuracy of these methods remains, in itself, in question. While oven dry measurements are broadly accepted as the “standard” for water content, no such method is available for in-place density. In order to compare the methods to a baseline, it is necessary to accurately determine the moisture content and in-place density of the tested material. Sand cone measurements are highly sensitive to densification of the standard sand. Nuclear density gages that rely on back scatter to measure moisture content are representative of the water content within only the top few inches of soil. While a reliable method for in-place density measurement is crucial for meaningful comparison of the accuracy of the various methods, TDR can be still evaluated against current FDOT practice, which calls for nuclear gage and speedy moisture.

1.3. Project Objectives

The goal of the work was to improve upon the ASTM Standard Method for TDR measurement of Soil Water Content and Density. The work relied on a new concept introduced by Purdue University researchers to obtain a simultaneous measurement of electrical resistivity in conjunction with the dielectric constant from the TDR measurement. Both measurements were then used to back calculate the water content and density in a single step, without the need to excavate and re-compact. The specific objectives are:

- To determine the calibration constants, f and g, for typical construction materials used in Florida
- To examine the accuracy of the one-step TDR method
- To compare the TDR method with other widely accepted methods such as the nuclear gage and the sand cone.

Laboratory and field programs were carried out to determine the calibration constants, f and g, for typical soil types available in Florida for roadway construction. The findings provide the necessary information to accurately measure moisture content and density with a one-step procedure in the field, and eliminate the need to excavate the compacted soil.

The specific project tasks are as follows:

Task 1: Literature search and information collection

A broad literature review has been conducted. Because of the rapid evolution in the field of TDR, the literature review information has been continuously updated through the project. Of specific interest was the work published by Purdue researchers on the one-step method.

Task 2: Calibration of soil constants

A wide range of tests was performed to determine the new constants, c and d, f and g on soils similar to those used earlier for determining the soil constants “a” and “b”. The experiments were performed under various conditions and using soils encountered in typical FDOT projects.

Testing was performed under different environmental conditions (temperature, moisture, etc.) to evaluate the reproducibility of the new system. More importantly, the influence of the electrical conductivity of the pore fluid, EC_w, on the accuracy of the results was evaluated.

Task 3: Comparison between TDR and other methods

To compare the TDR against other widely accepted field methods, an experimental study was conducted where side-by-side field tests were performed. The accuracy of the TDR against methods such as nuclear density, sand cone, and speedy moisture were evaluated.

Task 4: Development of final guidelines for TDR testing

The current procedure for TDR measurement of soil density and moisture relies on the two-step (excavation) method. The procedure was revised to be consistent with improvements in equipment and procedures developed as part of this project. Significant progress toward standardization occurred during the project. Final guidelines are drafted regarding the accuracy, bias, and precision of the TDR method (compared to other existing methods), and recommendations for standard testing procedures are made.

1.4. Report Organization

This report is organized in six chapters, and a list of references. A comprehensive review of time domain reflectometry and its relation to the field of geotechnical engineering is presented in Chapter 2. Also included in the chapter is a review of current geotechnical measurement methods as well as the basic concepts associated with the soil parameters extracted from TDR waveforms. Chapter 3 presents both the equipment and procedure used in conjunction with the ASTM and one-step TDR methods. Calibration procedures are also outlined within the chapter. A detailed review of the calibration constants used with the one-step TDR method is presented in Chapter 4. The results from a study on the effects of pore fluid conductivity on TDR calibration constants are also included in the chapter. Chapter 5 includes results obtained from a testing program carried out to evaluate the accuracy of the one-step TDR method. Included within the chapter are comparative results with traditional geotechnical testing methods. Finally, Chapter 6 provides a summary and conclusions from the work presented within this report.

2. Literature Review

2.1. Introduction

Time domain reflectometry was introduced in the 1990s to the field of geotechnical engineering as a reliable tool for in-situ measurement. Several traditional methods have been traditionally used to measure both in-situ soil density and water content; however, many of these methods are limited in their application. An understanding of traditional methods and their limitations is presented to demonstrate the need for an alternative comprehensive method. Time domain reflectometry, being a relatively new method in geotechnical engineering, must be throroughly evaluated in terms of its advantages and limitations for in-situ soil moisture and density measurement. The theory behind the use of time domain reflectometry as it relates to geotechnical engineering is discussed in this chapter as well as the implementation aspects. A review of recent work relating to the ASTM TDR method is also presented.

2.2. Methods for Determining Moisture Content

Several methods are used for determining soil moisture content in both the field and the laboratory. The following is a brief summary of these tests with commentary on the advantages and limitations of each.

2.2.1. Laboratory Oven Drying Method

Equivalent Methods: AASHTO T 265 and ASTM D2216

This method is widely known in geotechnical practice as the “Oven Dry Method”. The underlying principle behind this test is to determine both the weight of solids and weight of water contained in the given soil sample. The sample is placed in a conventional oven at 110°C for a time period of 24 hours. The wet and dry weights of the sample are determined before and after drying. The apparatus consists of: a drying oven, balances and specimen containers. The oven dry method has traditionally been accepted as the baseline standard for geotechnical applications. The methods main limitation is the amount of time required to perform the test.

The procedure can be summarized in the following steps:

1. Determine and record the weight of the empty container.
2. Select a representative wet soil sample.
3. Place the wet specimen into the container and determine the weight of the wet soil plus the container.
4. Place the container in the oven at 110°C up to the desired time length (usually 24 hrs).
5. After the material has dried to a constant mass, allow the container to cool down and determine the weight of the dry soil plus the container.
6. Calculate the water content of the specimen accordingly.

The method is not suitable for materials containing extraneous matter, some organic material that may be decomposed by oven dried, and materials containing gypsum. Material containing water with soluble solids will give higher mass of solids than the true value. The method should not be used with contaminated soils unless adequate health and safety precautions are taken.

2.2.2. Microwave Oven Method

Equivalent Method: ASTM D 4643

The microwave oven method is similar to the oven dry procedure, except a microwave oven is used in place of a conventional oven.

The procedure can be summarized as follows:

1. Determine and record the weight of the empty container.
2. Select a representative wet soil sample.
3. Place the wet specimen into the container and determine the weight of the wet soil plus the container.
4. Place the soil and the container in a microwave oven for about 3 min.

5. Remove the container, let it cool down, and determine the weight of the container plus soil.
6. With a small spatula carefully mix the soil.
7. Place the soil and the container in the microwave oven again for about 1 min.
8. Repeat steps 5, 6, 7 until the change between two constitutive mass determinations is insignificant.
9. Use the final mass measurement to calculate the water content.

Highly organic soils or soil containing oil or other contaminants may ignite during microwave drying. This method is best suited to “minus No. 4” sized materials. The use of this method is not preferred when highly accurate results are required.

2.2.3. Direct Heating Method (ASTM D4959)

The idea behind this method is the same as the previous two methods, but the difference is in the use of direct heat source such as a hotplate, stove, or blowtorch for drying the sample. The method yields results faster than the oven dry method, but is less accurate. A moist sample is placed in a container and the weight is determined. The soil is allowed to dry using direct heating and is then weighed. This procedure is continued until the change in the dry weight becomes negligible. Using this dry weight, the water content can be determined. The direct heating method yields faster results than the oven dry method, but again, is less accurate.

2.2.4. Calcium Carbide Gas Pressure Tester Method (FM 5-507)

Equivalent Methods: AASHTO T 217 and ASTM D4944

Referred to as the “speedy moisture content” method, this method is used for determining the water content of soil from the results of a chemical reaction using calcium carbide as a reagent to react with the soil pore water. Two steel balls are used to ensure that the reagent will contact all the available water in the soil, producing Acetylene gas. A measurement is made of the gas pressure produced when a specified mass of wet soil is mixed in the testing device with an appropriate volume of reagent. The apparatus consists of a calcium carbide pressure tester set, a small scoop, two steel balls, No. 4 sieve, a supply of calcium carbide, and clothing/safety equipment (Figure 2-1).

The procedure is summarized in the following steps:

1. Remove the cap from the testing chamber and place the desired amount of calcium carbide reagent along with the two steel balls into the testing chamber.
2. Obtain a specimen of soil according to the amount recommended by the device manufacturer.
3. Place the soil specimen in the testing chamber cap.
4. Shake the apparatus vigorously with a rotating motion so that the steel balls roll around the inside circumference and cause a grinding effect on the soil and reagent.
5. When the pressure dial gage needle stops moving, read the dial while holding the apparatus into a horizontal position.
6. Use the appropriate calibration curve to determine the corrected water content in percent of dry mass of soil.

Speedy Moisture Tester (Courtesy of Soiltest, Inc.)

Figure 2-1 Speedy moisture content device

The method is not accurate for highly plastic clays and soils containing minerals that dehydrate with heat. The test method is limited to soils with particles less than No. 4 sieve size. Since flammable and explosive acetylene gas is involved, appropriate safety guidelines and rules should be followed by the operator.

2.2.5. Nuclear Method (Shallow Depth) (FM 1-T 238)

Equivalent Methods: AASHTO T 310 and ASTM D3017

In this method, a fast neutron source is applied to the surface of the soil. Using a surface slow neutron detector, the slowing ratio of the fast neutron is measured. Using this ratio and the calibration data, the moisture content of the soil is calculated. The hydrogen present in water is the main factor in this test. The apparatus consists of fast neutron source and detector, readout device, housing, reference standard, and site preparation equipment.

The procedure can be summarized in the following steps:

1. Standardize the instrument.
2. Select a test location and remove all disturbed materials (total contact is required).
3. Seat the instrument firmly and place the source in its position and take a reading.
4. Determine the ratio of the reading to the standard count and determine the in-place water content from the calibration data and adjusted reading.

The apparatus is highly sensitive to water contained in the top 2 to 3 inches of soil. Hydrogen in forms other than water will cause readings to be in excess of the true value. Some chemical elements such as boron, chlorine, and minute quantities of cadmium cause measurements to be lower than the true value.

2.3. Methods for Determining In-place Density

Several methods are used for determining the in-place density of soil. The following is a summary of the test procedures and limitations for each of these methods.

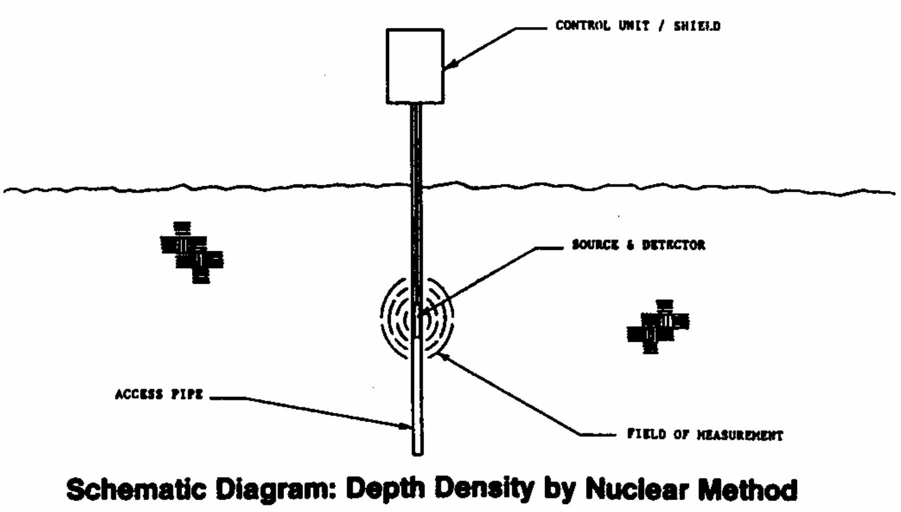
2.3.1. Nuclear Method (FM 1-T 238)

Equivalent Method: ASTM D5195

The nuclear method requires that a radiation tube be inserted into the soil to the desired depth. The tube contains a source and a detector of gamma radiation which are used to measure the attenuation of gamma radiation through soil. The soil density is then determined by comparing the detected rate of gamma radiation with previously established calibration data. The apparatus consists of a sealed source of high-energy gamma radiation, gamma detector, timed scale and power supply, cylindrical probe, reference standard, access tubing, and hand auger or drilling equipment (Figure 2-2).

The test procedure can be summarized as follows:

1. Drill the access tube hole and install the access tube.
2. Record the ground water table and, if saturated conditions are expected, seal the tube.
3. Lower a dummy probe down the access tube to verify proper clearance.
4. Standardize the apparatus.
5. Seat the apparatus firmly on the access tube and take readings at the selected time period. Then, using the calibration data, determine the in-place density.



Schematic Diagram: Depth Density by Nuclear Method

Figure 2-2. Nuclear method for determining in-field density

If the dry unit weight is required, the measurement of the in-place water content is needed. Measurements will be higher than the actual values if some elements with greater atomic numbers than 20 are encountered. Voids around the access tube can greatly affect the measurements. The equipment utilizes radioactive materials that may cause hazards, so proper precautions have to be taken by the operator.

2.3.2. Nuclear Method (shallow depth) (FM 1-T 238)

Equivalent Methods: AASHTO T 310 and ASTM D3017

The shallow depth nuclear method is the same as the regular nuclear method, but either the source and detector remains on the surface (Backscatter Method) or one of them is at the surface while the other is at a known depth up to 300mm (Direct Transmission Method). The same limitations apply as with the other nuclear methods.

2.3.3. Sleeve Method (ASTM D4564)

The sleeve method requires the insertion of a metal sleeve into the soil. The soil within the sleeve is then removed, and a determination of the dry mass of soil removed per linear inch of the depth of the excavation is obtained. The mass per linear inch is related to the dry density of the in-place soil through a simple calibration equation. The sleeve method is used for soils that are predominantly fine gravel size with a maximum of 5% fines and a maximum grain size of ¾" (19 mm). For each particular soil type to be tested, the calibration equation is predetermined. The test is applicable for cohesionless soils in a confined or limited space since the test method requires less working area compared to the other methods. The sleeve apparatus consists of a template, a sleeve, a measurement plate, and a driver. Balances, driving equipment, and miscellaneous equipments are also required for the complete set up (Figure 2-3).

The procedure can be summarized in the following steps:

1. Prepare a smooth, level working area.
2. Put the template and place the beveled edge on the soil surface inside the hole of the template.

3. Place the driver on the sleeve and slowly rotate the sleeve clockwise while pushing the sleeve into the soil.
4. Remove the driver, extract the soil from inside the sleeve, and place the extracted soil in a moisture-proof container.
5. Continue rotating and advancing the sleeve, and extracting material in the sequence determined in the calibration procedure until the driver rests on the template.
6. Flatten the bottom of the hole as much as possible, place the measurement plate on the soil at the bottom of the hole, and rotate gently to seat it.
7. Measure and record the depth of the hole from the top of the measurement plate to the top of the template.
8. Determine and record the mass of the soil removed from the test hole.
9. Determine the water content of the material removed from the hole.
10. Calculate the dry mass per inch of the test hole.
11. Using the calibration equation, calculate the in-place dry density.

Consistency in the soil gradation and particle angularity is of critical importance to the test. The procedure is also operator sensitive. The sleeve should be checked periodically for wear.

2.3.4. Drive-Cylinder Method

Equivalent Methods: AASHTO T 204 and ASTM D2937

The drive-cylinder method requires that a thin-wall steel cylinder be driven into a smoothed soil surface using a fall hammer. The soil is then excavated from around the cylinder to allow for removal of the steel cylinder. Using a straightedge, the ends of the cylinder are then trimmed. The weight and the volume of the empty cylinder are known and the weight of the removed soil can be determined. Using this information the unit weight of the soil can be determined. To get the dry unit weight of the soil, the moisture content has to be determined using a standard method. The apparatus consists of a drive cylinder that meets the clearance ratio requirements of Hvorslev, a drive head, a steel straightedge, a shovel, balances, drying equipment, and miscellaneous equipment (Figure 2-4). The test is not applicable for organic soils, very hard natural soils, heavily compacted soils, and soils which contain appreciable amount of sand. The cutting edge of the cylinder should be examined after each test to ensure that it is still sharp. If any damage occurs to the cylinder edge or body, the test results should be discarded.

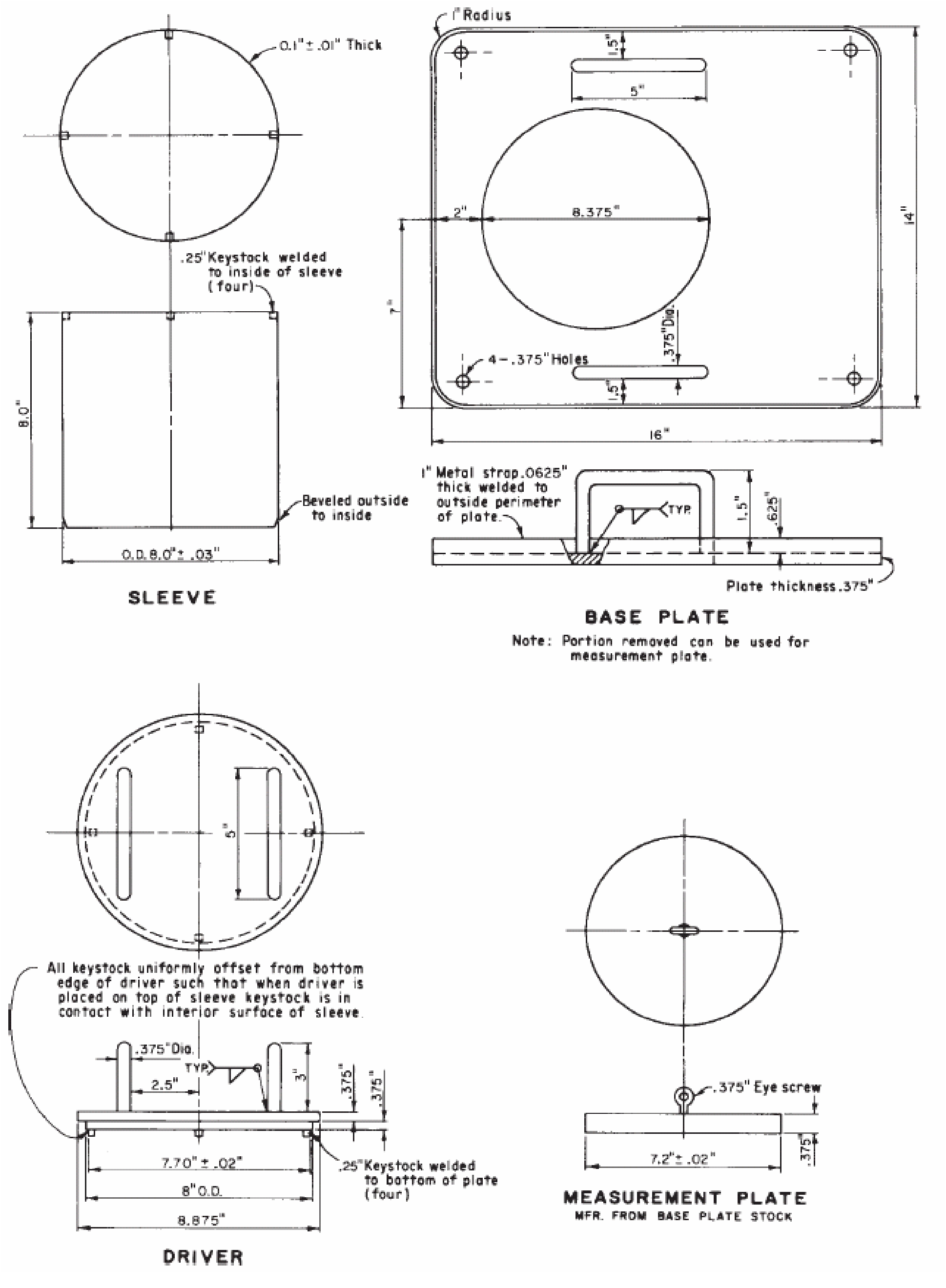


Figure 2-3. Sleeve method for determining in-field density

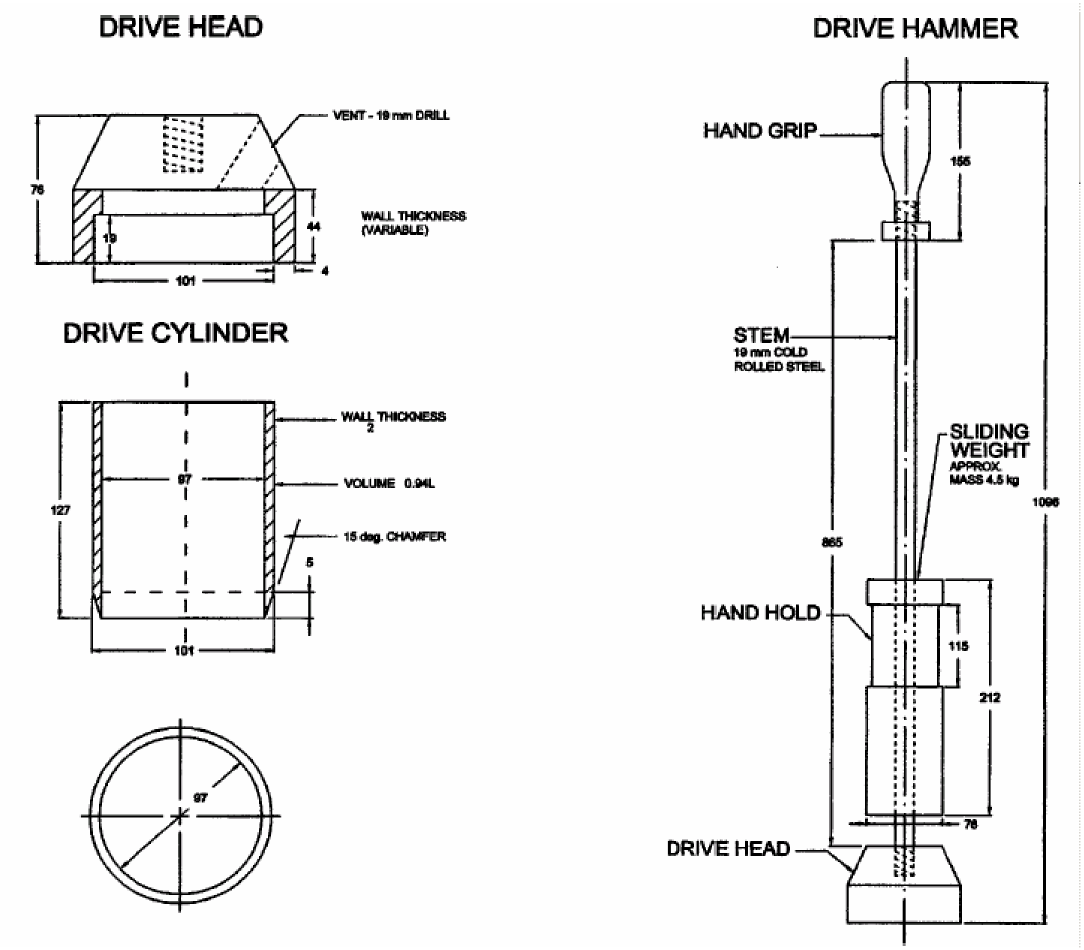


Figure 2-4. Drive cylinder for determining in-field density

2.3.5. Sand-Cone Method (AASHTO T 191)

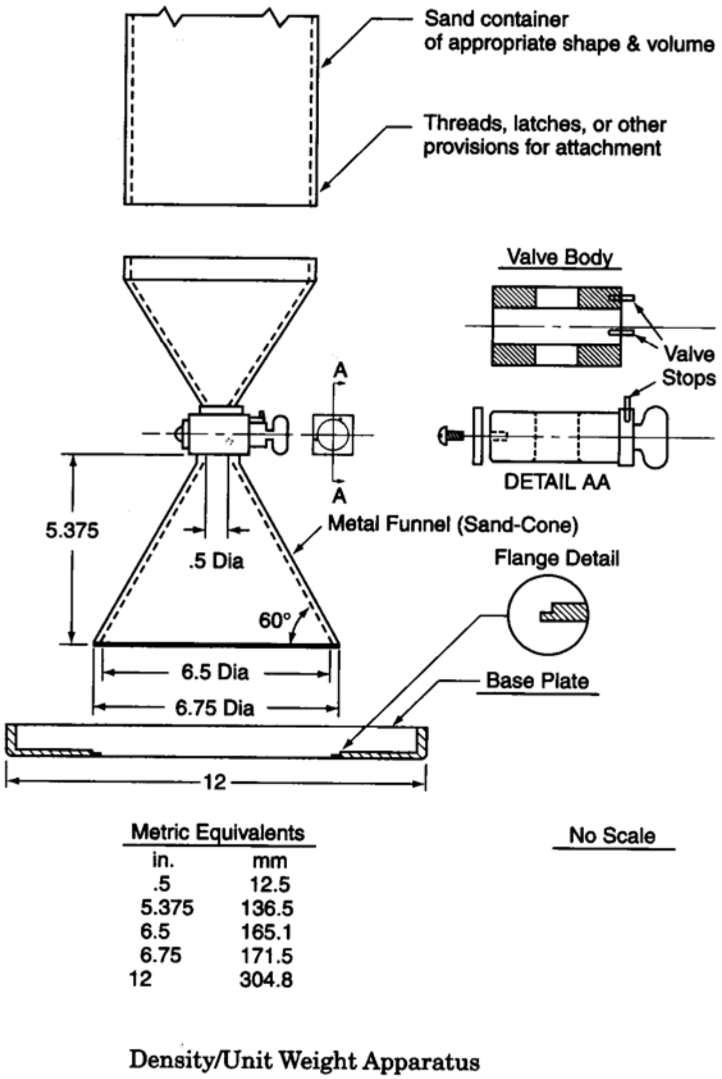
Equivalent Method: ASTM D1556

In the Sand Cone Method a hole is excavated in the ground and the excavated soil is weighed. The volume of the hole is then determined using standard sand replacement. The standard sand should be dry, clean, uniform, uncemented, durable, and free flowing. Knowing the weight of the standard sand fill and its density, the volume of the hole can be calculated. The density of the excavated soil can be computed accordingly. To obtain the dry density of the soil, the water content of the extracted portion is determined using a standard method. The method is not suitable for saturated, soft, organic, deformable or highly compressible soils. It is also not suitable for soils that contain appreciable amount of rock or coarse materials (larger than 38mm). In the Sand Cone Method, a hole is excavated in the ground and the excavated soil is weighed. The volume of the hole is then determined using standard sand replacement. The sand used should be dry, clean, uniform, uncemented, durable, and free flowing. Knowing the weight of the standard sand filling the hole and the density of the sand, the volume of the hole can be calculated. The density of the excavated soil can be computed accordingly. To obtain the dry density of the soil, the water content of the extracted portion is determined using a standard method. Finally the dry density of soil can be determined using both wet density and water content. The apparatus consists of sand-cone density apparatus, standard sand, balances, drying equipment, and miscellaneous equipment (Figure 2-5).

The procedure can be summarized in the following steps:

1. Select a test location and prepare the surface.
2. Seat the template on the plane surface and dig a hole through the center hole of the template.
3. Invert the sand-cone apparatus and seat the sand-cone funnel into the flanged hole of the template. Allow the sand to flow into the hole and the cone by opening the valve.
4. Determine the weight of the apparatus with the remaining sand. Knowing the weight of the apparatus when full, and the standard sand weight required to fill the cone and the template, we can get the weight of sand in the hole. The volume of the hole and the wet density of the excavated soil can therefore be determined.
5. The dry density of the excavated soil can be determined knowing both the wet density and the water content.

The method is not suitable for saturated, soft, organic, deformable or highly compressible soils. It is also not suitable for soils that contain appreciable amount of rock or coarse materials (more than 38mm). The procedure is highly operator dependent, and estimates of the density of the standard sand are often inaccurate. The test is destructive as a hole is dug in the ground. Because of its numerous limitations as well as its inaccuracy, the Sand Cone Method has become less accepted than other advanced non-destructive methods.



Metric Equivalents

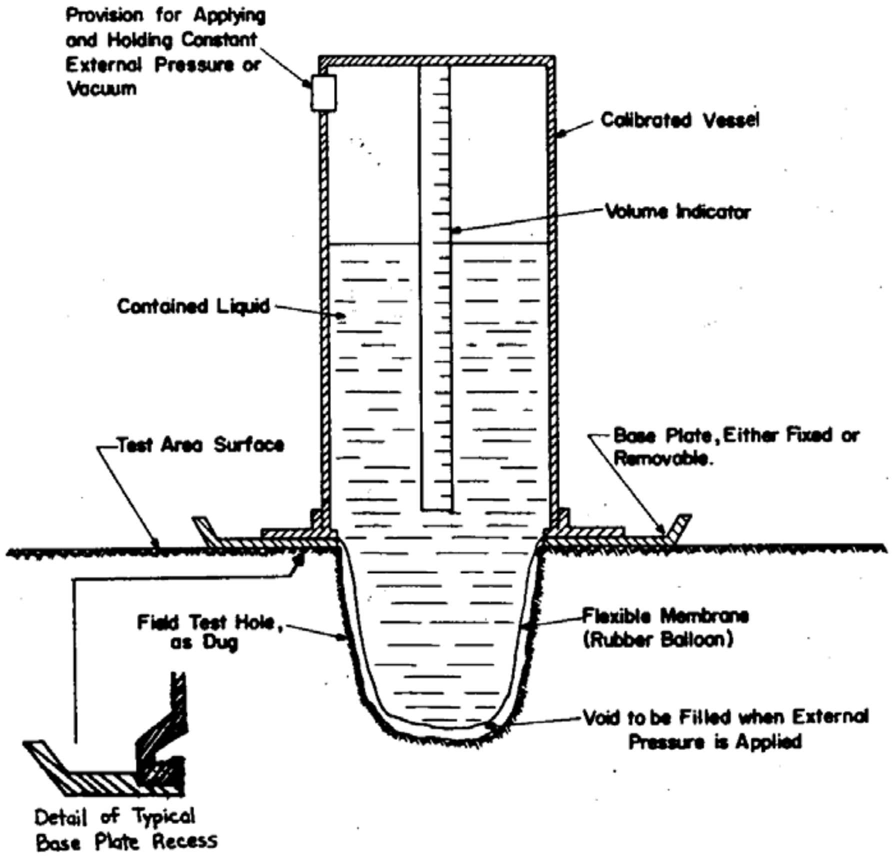
in.	mm
.5	12.5
5.375	136.5
6.5	165.1
6.75	171.5
12	304.8

Density/Unit Weight Apparatus

Figure 2-5. Sand cone method for determining in-field density

2.3.6. Rubber Balloon Method (ASTM D2167)

The rubber balloon method relies on the same concept as the sand-cone method, but instead of replacing the soil with standard sand, water and a balloon are used. A flexible membrane filled with water and connected to a water-filled calibrated vessel is used to measure the volume of the hole after extracting the soil. The equipment consists of rubber balloon apparatus, template, balances, drying equipment, and miscellaneous equipments (Figure 2-6).



Schematic Drawing of Calibrated Vessel Indicating Principle (Not to Scale)

Figure 2-6. Rubber balloon method for determining in-field density

The procedure can be summarized as follows:

1. Prepare the surface at the test location.
2. Assemble the template and the rubber balloon apparatus (using the same pressure and surcharge load used during calibration) and take an initial reading on the volume indicator.
3. Dig a hole within the template.

4. Place the apparatus over the template and apply the same pressure and surcharge load used during calibration and take final reading.
5. Using the two readings, the volume of the hole can be determined. Knowing the weight of the extracted soil, the wet density can be calculated.
6. The dry density of soil can be determined knowing both wet density and water content.

Prior to first use, the apparatus should be calibrated. The suitability of this method is the same as the sand-cone method. In addition, the method is not suitable if angular grains are present.

2.4. Summary of Existing Methods

The nuclear method is the most commonly used method in current practice for soil moisture and density measurement. The nuclear method requires training and special licensing to operate and field measurements are only as good as the calibration of the device. The drive sleeve method is also commonly used, but is a destructive method. Both the Sand Cone and Rubber Balloon methods are less frequently used and rely heavily on the skill of the test operator and as a result measurements vary considerably. Further discussion on the comparison of these tests with the ASTM TDR method will be addressed in Chapter 5. A summary of key points of the more commonly run tests is displayed in Table 2-1.

Table 2-1. Comparison of Current Methods.

Test	Application	Required Time	Major Source of Error
Oven Dry	Water Content	24 hours	Considered as baseline measurement
Speedy Moisture	Water Content	10-15 min + calibration	Operator's ability to perform test correctly
Nuclear Method	Wc and Density	10-15 min + calibration	Highly dependant on proficient calibration
Sand Cone	Density	30 min + calibration	Operator dependant

2.5. Historical Summary of Time Domain Reflectometry

The power and telecommunication industries first implemented the use of time domain reflectometry in the 1950s to locate transmission line discontinuities (O’Conner and Dowding, 1999). Hugo Freller-Feldegg (1969) expanded the use of time domain reflectometry to the measurement of the dielectric permittivity of liquids. Topp et al. (1980) furthered the applications of TDR by demonstrating that the apparent dielectric constant of a soil is strongly dependent on the amount of water contained within the soil. Further developments by Topp and Davis (1985) led to the transmission of TDR signals into in-situ soil using metallic rods. Researchers then began to incorporate the use of bulk electrical conductivity TDR measurements in an effort to estimate soil salinity (Dasberg and Dalton, 1985). As a result, TDR has been widely utilized in agricultural applications, where the soil water content of crops can be monitored to optimize irrigation procedures. The use of TDR has since been expanded to a wide variety of applications including: soil/rock deformation, structural deformation and air-liquid interface monitoring (O'Conner and Dowding, 1999). Recent improvements to soil moisture monitoring systems by researchers at Purdue University have led to the development of the ASTM TDR method for measuring in-situ soil gravimetric water content and density (Siddiqui and Drnevich, 1995; Yu and Drnevich, 2004). These more recent developments from Purdue University are of great interest to the field of geotechnical measurement.

2.6. TDR Basics

Time domain reflectometry is derived from the same technology used in radars, which have been in use since the 1930s. TDR is similar to radar in that a short electromagnetic pulse is first emitted, and then a reflection is measured. TDR can be defined as a measurement device that relies on the use of remote electrical sampling to determine the location and nature of objects. A TDR system essentially consists of a pulser, a sampler, an oscilloscope and a coaxial cable (Figure 2-7).

The TDR pulser generates an electronic step pulse that travels into the coaxial line. As the pulse travels down the coaxial line, a potential difference is created between the inner and outer conductors of the coaxial line creating an electromagnetic field between the conductors (Figure 2-8).

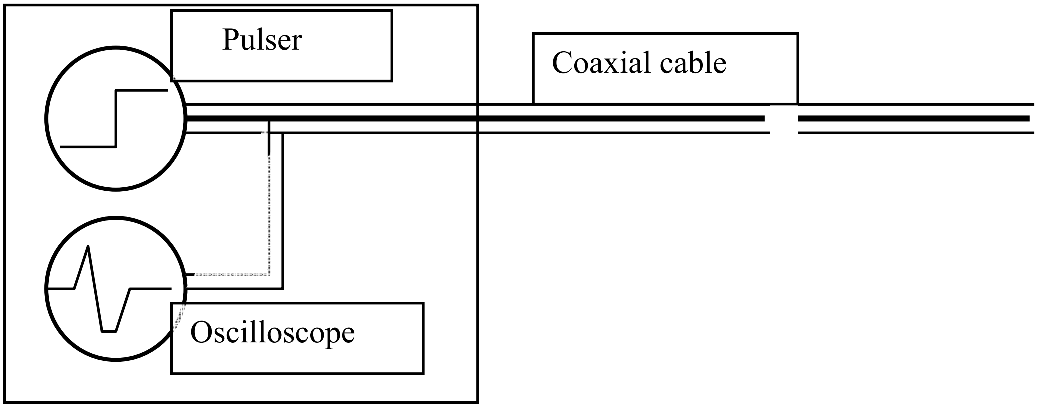


Figure 2-7. Basic TDR Setup. Source: O'Conner and Dowding (1999)

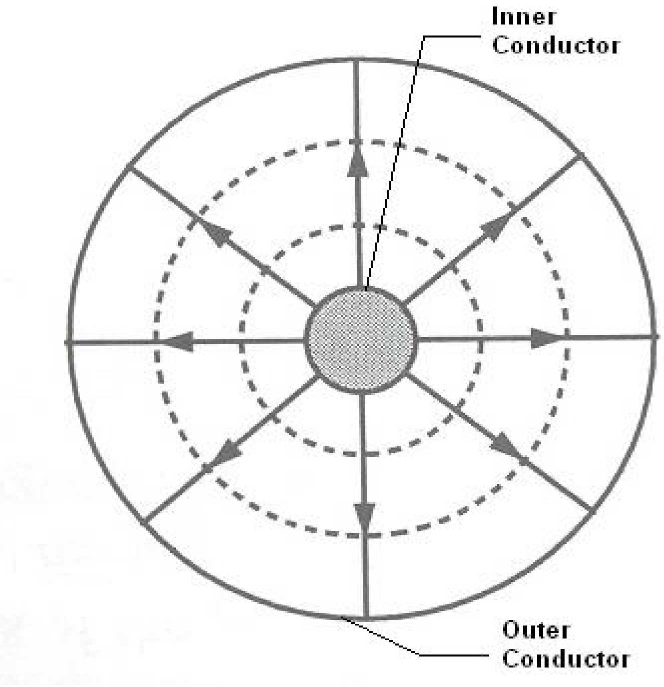


Figure 2-8. Electromagnetic Field in Coaxial Line. Source: O'Conner and Dowding (1999)

As this electromagnetic field travels through the coaxial line it creates a wave. If the medium between the inner and outer conductors is uniform both geometrically and physically, its measured reflection is also uniform. However, if a discontinuity in the coaxial line is encountered (i.e. a change in cable geometry or the medium between conductors) a distinct reflection jump is observed. The time it takes for a reflection to occur along with its sign, length and amplitude are useful in determining both the location of the fault as well as its nature. For soil moisture monitoring purposes, the coaxial line is transmitted into the soil using metallic spikes (See Figure 2-9).

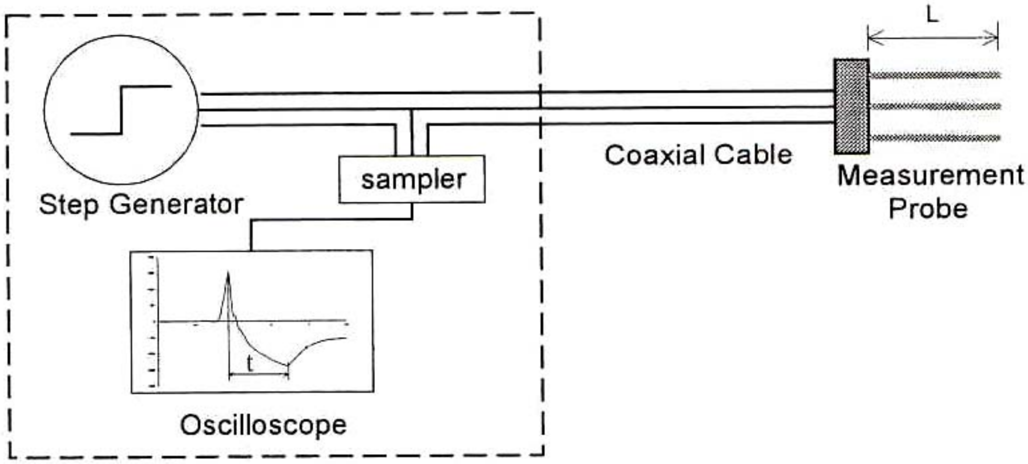


Figure 2-9. TDR Soil Moisture System Configuration. Source: Drnevich et al. 2000.

Soil properties can be extracted from TDR reflections measured by the configuration displayed in Figure 2-9. A typical TDR wave reflection is shown in Figure 2-10 (O'Conner and Dowding, 1999).

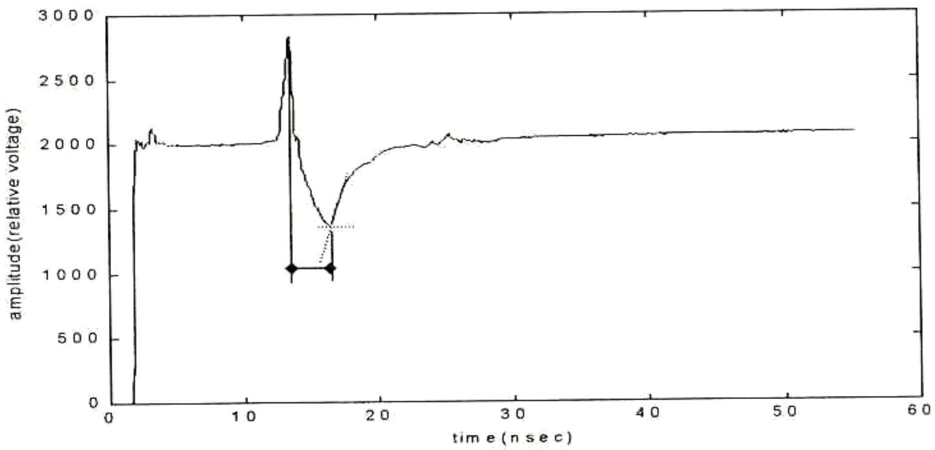


Figure 2-10. Typical TDR Output Voltage.

2.7. Development of the ASTM TDR Measurement System

Topp et al. (1980) suggested that research be carried out to develop transmission line components that would be sufficiently accurate for water content measurement purposes. Several research projects were carried out to evaluate different transmission line configurations (Ledieu et al., 1986; Topp et al., 1982; and Dasberg and Dalton, 1985). Although results from these tests indicated a reliable relationship existed between the dielectric constant and volumetric water content, the need for a reliable and routine field technique to measure gravimetric water content was still evident. Zeglin et al. (1989) studied several coaxial soil probe configurations and found that three and four wire configurations were superior to a two wire system. Studies investigating cable length, quality and type of probe and cable dimensions were carried out by Heimovaara (1993) to determine their influence on the accuracy of TDR measurements. These improvements led researchers at Purdue University (Drnevich et al., 2000) to develop the ASTM TDR measurement system. Their work warranted acceptance of the method in the form of ASTM standard D 6780 in 2002. The basic TDR measurement system used for this research was obtained from Purdue University and is displayed in Figure 2-11. It includes a Campbell Scientific TDR100 tester which is then connected to a Multiple Rod Probe (MRP) Head. The MRP sits on a series of spikes that are driven into the soil.

2.8. TDR Electromagnetic Wave

The propagation of an electromagnetic field through a transmission line is governed by the wave equation derived from Maxwell's equations. Drnevich et al. (2000) stated that "there are two important components of the wave equation solution; the characteristic impedance (Z) and the propagation constant (γ).

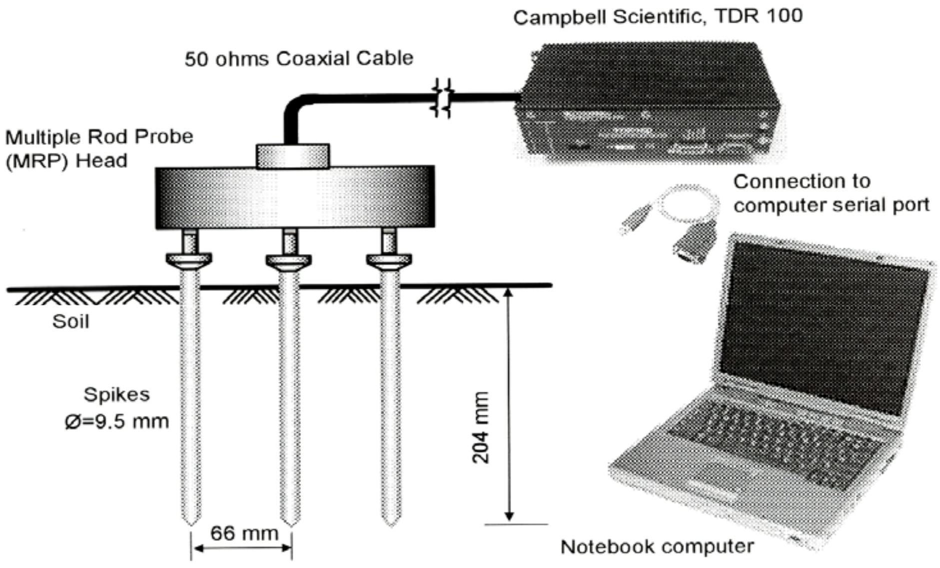


Figure 2-11. TDR Measurement System. Source: Yu and Drnevich (2004).

The characteristic impedance is the ratio of voltage to current propagating along the line. It is a function of the geometry of the transmission line and the dielectric permittivity of the insulating material." It can be derived for a coaxial line as:

$$Z = \frac{Ln\left(\frac{b}{a}\right)}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{1}{\sqrt{\varepsilon_r^*}} = \frac{Z_p}{\sqrt{\varepsilon_r^*}} \tag{2-1}$$

Where "b" is the inner diameter of the outer conductor, "a" is the outer diameter of the inner conductor, ε_0 is the vacuum permittivity (8.854x 10^{-12}), μ_0 is the vacuum permeability ($4\pi x10^{-7}$ H/m), ε_r^* is the equivalent dielectric permittivity, and Z_p is defined as the impedance of the same line filled with air as the medium (Krauss, 1984).

The propagation constant is the other intrinsic property of a transmission line. It is only a function of the dielectric permittivity of the insulating material. It can be derived, for a coaxial line, as:

$$\gamma = \frac{j2\pi f}{c}\sqrt{\varepsilon_r^*} = \alpha + j\beta \tag{2-2}$$

In which c is the velocity of the electromagnetic waves in free space, and α and β are the real and imaginary parts of the propagation constant, respectively. The real part represents the attenuation of the wave, whereas the imaginary part is the spatial frequency, which gives the velocity of wave propagation when divided by temporal frequency ($2\pi f$). The TDR waveform recorded by sampling oscilloscope is a result of multiple reflections and dispersions. As the water content, conductivity, mineral content, density, and chemical composition of the soil vary, different wave reflections are expected. Wave reflection analysis can then be used to determine soil properties (O'Conner and Dowding, 1999). The relevant parameters derived from wave reflection analysis used in conjunction with the ASTM TDR method are the complex dielectric permittivity and the bulk electrical conductivity.

2.9. Complex Dielectric Permittivity

The complex dielectric permittivity of a material consists of a real and an imaginary portion. The imaginary portion is attributed to electrical loss and the real portion is a measure of the amount of energy stored in the material (Drnevich et al., 2000). In low loss materials the imaginary portion of the complex permittivity is not significant enough to alter the propagation velocity and thus the complex dielectric permittivity can be estimated as the real portion. Additionally, Davis and Annan (1977) demonstrated that the real portion of a soils complex permittivity was much more prominent than the imaginary portion over the frequency range of 1 MHz to 1 GHz. As a result, the real portion of the dielectric permittivity is referred to as the apparent dielectric constant of the soil (Topp et al., 1980).

2.10. Soil Dielectric Constant from TDR Waveforms

There are two general approaches to measuring the permittivity of a material: 1) placing the material between two plates of a capacitor and 2) placing the material into a coaxial line and measuring its complex impedance. The second approach is used in TDR technology. For a complete characterization of the material several measurements are to be taken over a wide range of frequencies. However, the same information can be obtained in the time domain by using an electronic pulse that is sent down the coaxial line (Fellner-Feldegg, 1969). After Fellner-Feldegg (1969), TDR has been used extensively to measure the complex dielectric permittivity of polar and non-polar liquids (Giese and Tiemann, 1975; Clarkson et al., 1977). A typical measured TDR wave reflection from a TDR soil measurement system is displayed in Figure 2-12.

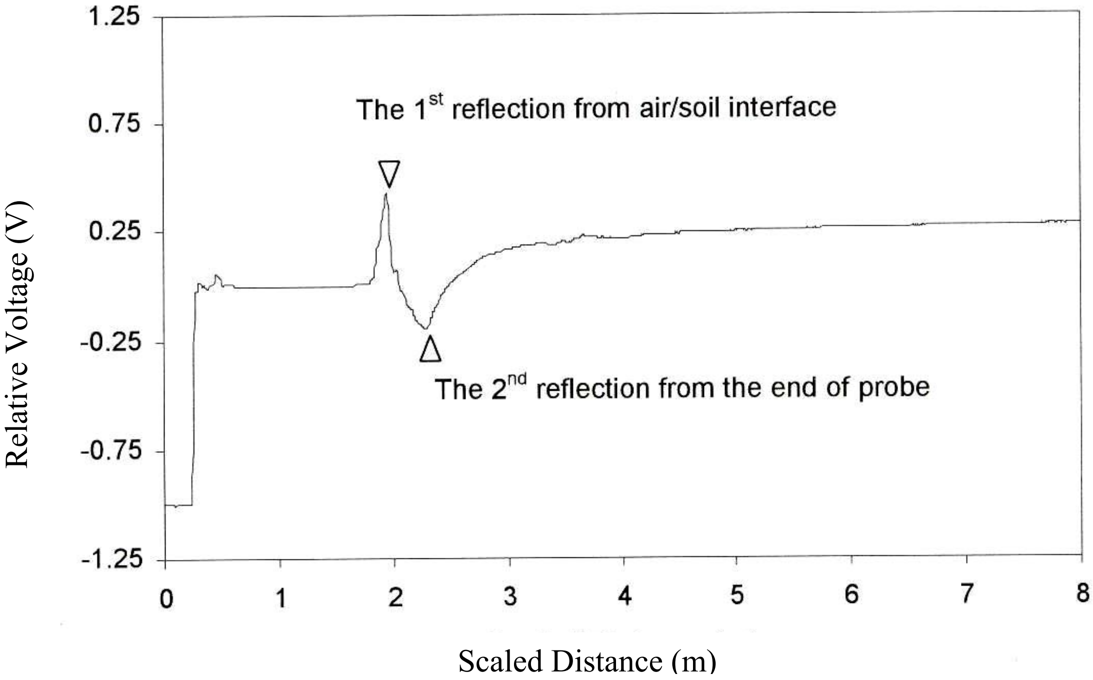


Figure 2-12. Typical TDR Wave Reflection. Source: Yu and Drnevich (2004).

Two distinct reflections can be noted from the measured TDR reflection. The first reflection occurs at the air and soil interface and the second occurs at the end of the TDR probe (Yu and Drnevich, 2004). Topp et al. (1980) previously defined the apparent dielectric constant (K_a) as being related to the velocity of the electromagnetic wave traveling through the transmission line. The apparent propagation velocity of an electromagnetic wave can be related to the dielectric constant by the following:

$$v = \frac{c}{\sqrt{K_a}} \tag{2-3}$$

Where (v) is the apparent propagation velocity and (c) is the velocity of an electromagnetic wave in free space (2.998×10^8 m/s). The apparent propagation velocity can also be related to the travel time between reflection points by the following:

$$v = \frac{2L}{t} \tag{2-4}$$

Where t is the travel time and L is the length of the probe in the soil. Combining Equations 2-3 and 2-4, the apparent dielectric can be expressed as:

$$K_a = \left(\frac{ct}{2L}\right)^2 \tag{2-5}$$

The term $\frac{ct}{2}$ can be expressed as the apparent length (L_a) (Baker and Allmaras, 1990) and Equation 2-5 can be reduced to a simplified form as:

$$K_a = \left(\frac{L_a}{L_p}\right)^2 \tag{2-6}$$

This relationship is then used to determine the apparent dielectric from the measured TDR reflection. Where L_a is the apparent length, which is a scaled horizontal distance between the two reflection points and L_p is the length of the soil probe (Yu and Drnevich, 2004). Several methods have been proposed to select the reflection points displayed in Figure 2-12 (Topp et al., 1982; Baker and Allmaras, 1990). Researchers at Purdue University have adopted an algorithm developed by Drnevich and Yu (2001) for use with the Purdue TDR method (Yu and Drnevich, 2004). The reflection points are used to determine the apparent length (L_a) and then the dielectric constant (K_a) can be computed using Equation (2-6).

The soil apparent dielectric constant from TDR measurements is affected by soil temperature. Although temperature effects on the apparent dielectric constant of soil solids are almost negligible, that of water experiences a decrease with increasing temperature (Drnevich et al., 2001). In an effort to improve the accuracy of the ASTM TDR method, Drnevich et al. (2001) studied the effects of soil temperature on soil dielectric constant by TDR. Their results indicate that apparent dielectric constants in soils are somewhat dependant on soil temperature. For sands a decrease in dielectric constant was observed with increasing temperature, whereas in clays the opposite behavior was observed. It was also determined that within 5°C of 20°C temperature effects could be neglected. The following linear temperature correction functions (TCF) were proposed for temperatures ranging between 4°C and 40°C:

$$TCF = 0.97 + 0.0015\ T_{test}\ for\ cohesionless\ soil \tag{2-7}$$

$$TCF = 1.10 - 0.005 T_{test}\ for\ cohesive\ soil \tag{2-8}$$

The TCF function is then used to make the temperature correction to the measured value of K_a in the following form:

$$K_{a,20^\circ C} = K_{a,T^\circ C} * TCF \tag{2-9}$$

Although the linear corrections derived do not account for all factors relating to the soil apparent dielectric constant, the method has yielded satisfactory results (Drnevich et al., 2001).

2.11. Soil Apparent Dielectric Constant Relationships

For most soil solids the dielectric constant is between three and four, whereas the dielectric constant of water is near eighty. Due to the difference between the dielectric constants of water and soil solids, it has been determined that the real part of permittivity of wet soil is dominated by the volumetric water content (O'Conner and Dowding 1999). Topp et al. (1980) incorporated these ideas to develop an empirical relationship between the apparent dielectric permittivity (K_a) and volumetric water content (θ) of soil (Equation 2-10), this relationship has since been used by several researchers with good results in a wide variety of soils (Dasberg and Dalton, 1985; Heimovaara, 1994; Roth et al., 1992; Topp et al., 1984; Zeglin et al., 1992).

$$\theta = 4.3x10^{-6} K_a{}^3 - 5.5x10^{-4} K_a{}^2 + 2.92x10^{-2} K_a - 5.3x10^{-2} \tag{2-10}$$

Where the volumetric water content (θ) is defined as:

$$\theta = \frac{V_{water}}{V_{solids}} \tag{2-11}$$

Although Topp's equation has been used with fairly accurate results using a wide variety of soils, several researchers have indicated that the calibration is not suitable for organics soil, fine-textured soils and clays (Dobson et al., 1985; Roth et al., 1992; Dirksen and Dasberg, 1993). Variation in Topp's dielectric relationship with soil volumetric water content is attributed mainly to soil density and texture effects (Abdula et al., 1988).

Several other researchers (Ledieu et al., 1986; Alharthi and Lange, 1987) assumed a linear relationship between the square root of the apparent dielectric constant ($K_a^{0.5}$) and the volumetric water content (θ):

$$\sqrt{K_a} = a + b\theta \tag{2-12}$$

Where “a” and “b” are calibration constants: “a” = 1.545 and “b” = 8.787 in Ledieu et al. (1986); “a” =1.59 and “b” = 7.83 in Alharthi and Lange (1987).

Ledieu et al. (1986) demonstrated that an improved relationship could be obtained by adding bulk dry density:

$$\sqrt{K_a} = a\rho_d + b\theta + c \tag{2-13}$$

Where “a,” “b” and “c” are calibration constants: “a” = 0.297, “b” = 8.79, “c” = 1.344 and ρ_d is the bulk dry density in grams/cm^3.

Ferre et al. (1996), Malicki et al. (1996) and Yu et al. (1997) also assumed a linear calibration similar to Eqn. (2-12):

$$\theta = b'\sqrt{K_a} + a' \tag{2-14}$$

Where a ' and b ' are soil constants obtained by regression analysis.

Malicki et al. (1996) suggested the idea of accounting for density effects of the soil:

$$\theta = \frac{{K_a}^{0.5} - 0.819 - 0.618\rho_b + 0.159{\rho_b}^2}{7.17 + 1.18\rho_b} \tag{2-15}$$

Where ρ_b is measured in units of grams/cm^3.

Yu and Drnevich (2004) point out that these calibration equations are difficult to apply to the field of geotechnical engineering for two reasons: 1) the calibration equations are expressed in terms of volumetric water content, whereas gravimetric water content is used in the field of geotechnical engineering and 2) calibrations which have incorporated the density effect such as Malicki et al. (1996) are complex and difficult to apply (Yu and Drnevich, 2004). As a result, Siddiqui and Drnevich (1995) developed the following expression:

$$\sqrt{K_a}\frac{\rho_w}{\rho_d} = a + bw \qquad (2\text{-}16)$$

Where "a" and "b" are soil specific calibration constants, ρ_d is the dry density of the soil, ρ_w is the density of water and *w* is the gravimetric water content. The Siddiqui-Drnevich equation has been used with satisfactory results using a wide variety soils (Drnevich et al., 2002; Sallam et al., 2004). Further treatment of this equation and its constants will be addressed in chapter 4.

The gravimetric water content (*w*) is defined as:

$$w = \frac{W_{water}}{W_{solids}} \qquad (2\text{-}17)$$

The gravimetric water content (*w*) is related to the volumetric water content (θ) by the following:

$$\theta = w\frac{\rho_d}{\rho_w} \qquad (2\text{-}18)$$

If Eqn. (2-18) is combined with Eqn. (2-16) the following is obtained:

$$\sqrt{K_a} = a\frac{\rho_d}{\rho_w} + b\theta \qquad (2\text{-}19)$$

Eqn. (2-19) is the Siddiqui-Drnevich (1995) equation expressed in terms of volumetric water content and is comparable to the linear calibrations derived in Eqns. (2-12), (2-13) and (2-14).

2.12. Bulk Electrical Conductivity

When an electromagnetic field travels through soil energy dissipation into the soil is expected. There are two major causes for TDR signal attenuation: 1) Losses due to the complex nature of a materials dielectric permittivity which causes the wave to have an out of phase portion and 2) the electrical conductivity of the medium. Electrical conductivity of a medium is caused by surface conduction that results from electrically charged particles on the surface of the solids and from ionic conductance that is a result of dissolved electrolytes in the pore water (White et al., 1994).

2.13. Bulk Electrical Conductivity from TDR Waveforms

Dalton et al. (1984) proposed the simultaneous measurement of the apparent dielectric constant as well as the bulk electrical conductivity of soil in an attempt to estimate pore fluid conductivity from TDR measurements. This work led to the following expression for bulk electrical conductivity (EC_b):

$$EC_b = \frac{\sqrt{K_a}}{120\pi L_p} \ln\left(\frac{V_1}{V_2}\right) \tag{2-20}$$

Where K_a and L_p are previously defined, and V_1 and V_2 are defined in Figure 2-13.

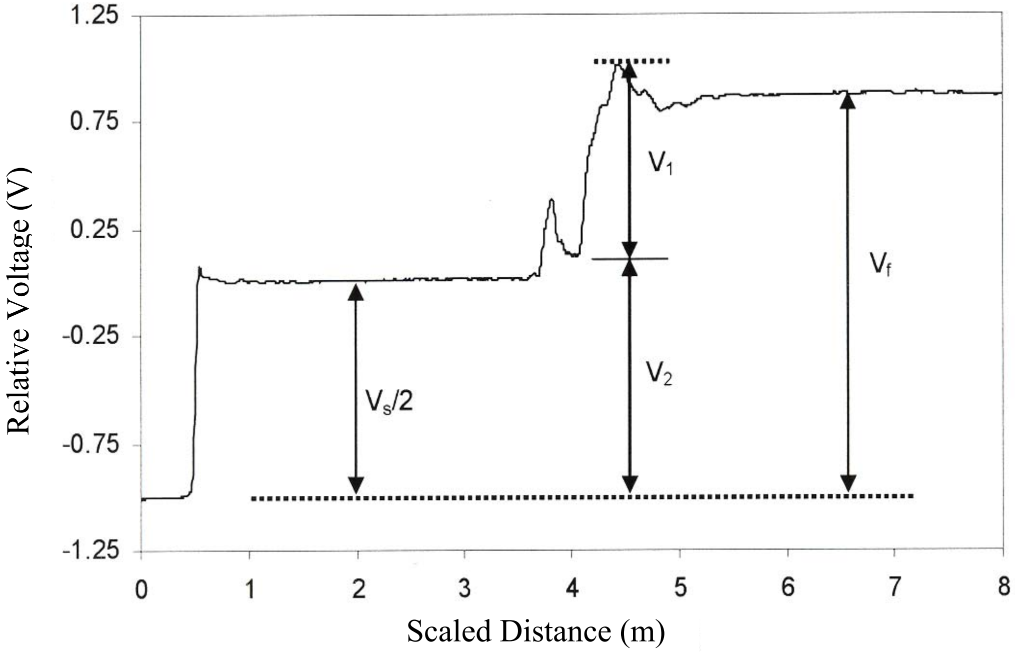


Figure 2-13. Electrical Conductivity Wave Analysis. Yu and Drnevich (2004).

Dalton (1992) later modified his approach by accounting for the intervening coaxial cable and the impedance matching transformer. Also Zeglin (1989) made further improvements by adding the multiple reflection idea. Yu and Drnevich (2004) argue that the aforementioned methods have two major shortcomings: 1) EC_b is coupled with K_a, which may be a source of error and 2) selecting accurate values of V_1 and V_2 may be problematic. As a result they propose that a long term response analysis be used to determine the bulk electrical conductivity:

$$EC_b = \frac{1}{C}\left(\frac{Vs}{V_f} - 1\right) \tag{2-21}$$

Where, V_s is the voltage source which is twice the step pulse and V_f is the long term voltage level (Figure 2-13) (Yu and Drnevich, 2004).

C is a constant related to the probe configuration that is obtained through calibration. For coaxial probes:

$$C = \frac{2\pi L_p R_s}{\ln\left(\frac{d_0}{d_1}\right)} \tag{2-22}$$

Where L_p is the probe length in the soil, R_s is the internal resistance of the pulse generator and d_0 and d_1 are the inner and outer conductor diameters (Giese and Tiemann, 1975). Results obtained by Topp et al. (1988) and Yu and Drnevich (2004) indicate that these relationships yield satisfactory results for electrical conductivity measurement.

The bulk electrical conductivity measurement is affected by soil temperature. Unlike temperature effects for soil apparent dielectric constant, those for bulk electrical conductivity measurement are consistent for both cohesive and cohesionless soils (Yu and Drnevich, 2004). Conductivity increases in a linear fashion with temperature for temperature ranges generally encountered in construction (Abu-Hassanein et al., 1996; Rinaldi and Cuestas, 2002). While a temperature correction function could be developed similar to that for apparent dielectric constant, a simplified approach is taken by Yu and Drnevich (2004). The approach is based on a developed relation between apparent dielectric constant and bulk electrical conductivity of the soil, where the field measurement is adjusted to the calibration temperature. This relationship will be discussed later in this chapter.

2.14. Bulk Soil Electrical Conductivity Calibrations

Soil electrical conductivity is influenced by several factors including: pore water, mineralogy, soil structure, degree of saturation and surface conductance. Due to the complex nature of soil electrical conductivity, theoretical equations are not available for use (Yu and Drnevich, 2004). However, several empirical correlations have been developed that have yielded satisfactory results (Rhoades et al., 1990; Mitchell, 1993; Malicki et al., 1994).

Rhoades et al. (1976) attempted to relate bulk electrical conductivity to pore fluid conductivity, volumetric water content and the soil surface conductance in the following form:

$$EC_b = T\theta EC_w + EC_s \qquad (2\text{-}23)$$

Where EC_w is the pore fluid conductivity, EC_s is the soil surface conductance, T is a geometric factor (T=a '+b 'θ, where a ' and b ' are soil specific constants) and θ is volumetric water content. The bulk electrical conductivity of soil can then be expressed as:

$$EC_b = a' EC_w \theta^2 + b' EC_w \theta + EC_s \qquad (2\text{-}24)$$

The above relationship has been used with fairly accurate results (Kalinski and Kelly, 1993). However, Yu and Drnevich (2004) argue that the equation is inadequate for geotechnical engineering applications for the following reasons: 1) it does not account for soil skeleton density and 2) electrical conductivity is expressed in terms of volumetric water content (Yu and Drnevich, 2004).

Yu and Drnevich (2004) further argue that the electrical conductivity from the pore fluid is typically the dominating factor in the determination of the bulk electrical conductivity of soil. As a result, the amount of pore fluid present in the soil generally dominates the bulk electrical conductivity of the soil. This phenomenon is also noted in the measurement of the apparent dielectric constant. As previously mentioned, due to the large difference in dielectric constants between water and soil solids the apparent dielectric constant of wet soil is dominated by the volumetric water content (Dowding and O'Conner, 1999). Due to the dominance of the pore fluid in the apparent dielectric constant and bulk electrical conductivity measurement, a relationship is derived for bulk electrical conductivity and gravimetric water content that is similar to the Siddiqui-Drnevich equation for apparent dielectric constant and gravimetric water content (Yu and Drnevich, 2004). The proposed relationship can be expressed as:

$$\sqrt{EC_b}\,\frac{\rho_w}{\rho_d} = c + dw \qquad (2\text{-}25)$$

Where "c" and "d" are soil specific calibration constants. Yu and Drnevich (2004) state that Eqn. (2-25) has several advantages including: 1) gravimetric water content is used, thus it is more suitable to the geotechnical field; 2) conduction from the pore water and soil surface is accounted for; 3) soil skeleton density is accounted for; and 4) the equation is simple in format and easy to apply. The relationship has been investigated by Feng (1999) and Lin (1999) and their findings are consistent with previous research done by White et al. (1994) and Hilhorst (2000). Also, data from Amenta et al. (2000) indicates that a good linear relation exists when applying Eqn. (2-25). Further treatment of this equation and its constants will be addressed in chapter 4.

2.15. Dielectric Constant and Bulk Electrical Conductivity Relationship for Soil

Although apparent dielectric constant and bulk electrical conductivity are typically viewed as independent measurements obtained from the TDR waveform, the two parameters can be related and used to simplify TDR measurements and make them more accurate (Yu and Drnevich, 2004). Both Malicki et al. (1994) and Hilhorst (2000) found that a good linear relationship existed between the apparent dielectric constant and bulk soil electrical conductivity. Also, White et al. (1994) noted a linear relationship between the apparent dielectric constant of the water phase and the square root of the bulk electrical conductivity of the water phase. Yu and Drnevich (2004) point out that Equations (2-16) and (2-25) are two independent equations that both are functions of water content and dry density of the soil. As a result, Yu and Drnevich (2004) suggest that the apparent dielectric constant (K_a) and bulk electrical conductivity (EC_b) must be related to one another. If Eqns. (2-16) and (2-25) are combined, the following is obtained:

$$\sqrt{EC_b} = \frac{b \cdot c - a \cdot d}{b} \frac{\rho_d}{\rho_w} + \frac{d}{b}\sqrt{K_a} \tag{2-26}$$

Eqn. (2-26) can be expressed as:

$$\sqrt{EC_b} = f + g\sqrt{K_a} \tag{2-27}$$

Where "f" and "g" are soil specific calibration constants. Application of Equation (2-27) as well as the calibration of "f" and "g" will be treated more in depth in chapter 4.

2.16. One-step TDR Methodology

After the TDR calibration constants are determined for a particular soil the dry density (ρ_d) and the water content can be computed in the field by solving for Eqns. (2-16) and (2-25). The dielectric constant (K_a) and the bulk electrical conductivity (EC_b) are measured and the following equations can be used to determine field dry density and water content:

$$\rho_d = \frac{d\sqrt{K_a} - b\sqrt{EC_b}}{ad - cb} \tag{2-28}$$

$$w = \frac{c\sqrt{K_a} - a\sqrt{EC_b}}{b\sqrt{EC_b} - d\sqrt{K_a}} \tag{2-29}$$

However, Yu and Drnevich (2004) point out that when Eqns. (2-28) and (2-29) are applied satisfactory results are typically not obtained. This is due to the dominance of pore fluid conductivity on Eqn. (2-25). When calibration is performed in the laboratory, the pore fluid conductivity measured does not generally correspond to the field condition and as a result, accurate measurements are not obtained.

Yu and Drnevich (2004) propose to "adjust" the field sample to the laboratory calibration. Figure 2-14 is a graphic representation of the adjustment procedure.

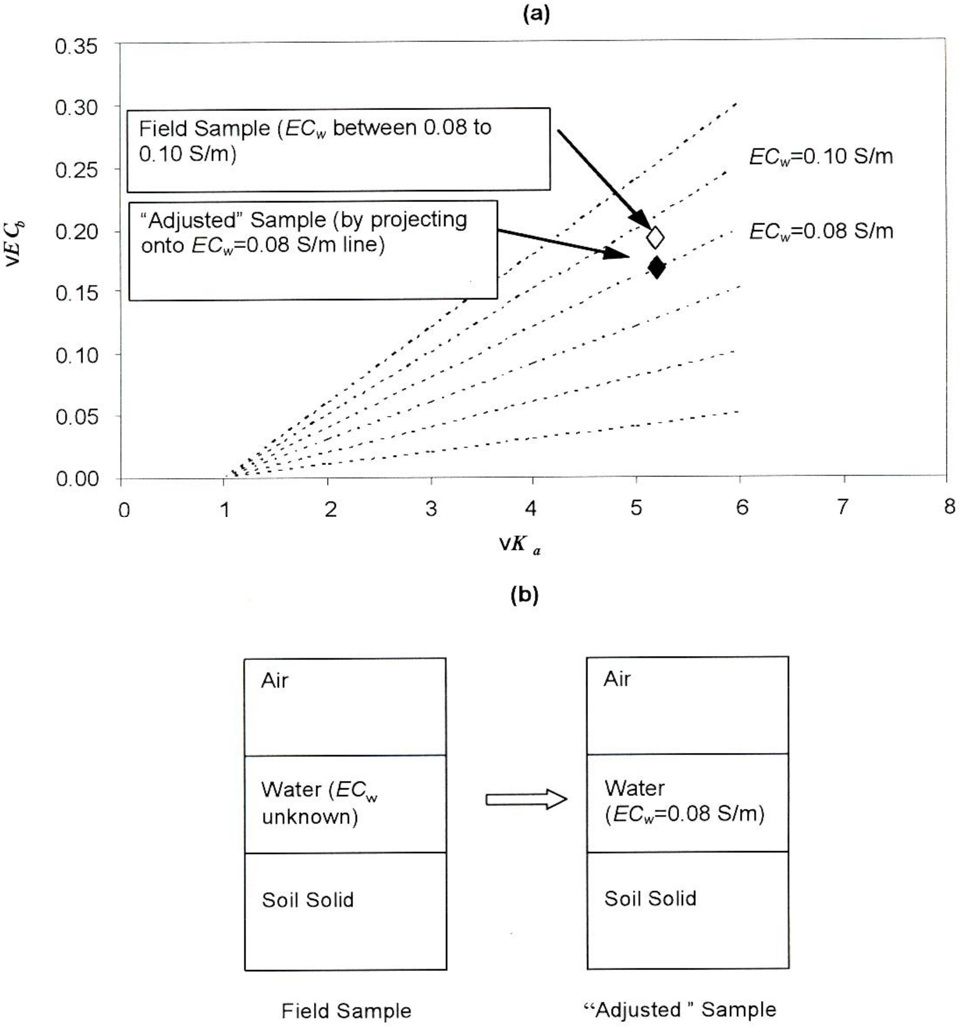


Figure 2-14. Adjusting the Field Sample to the Laboratory Calibration.
Source: Yu and Drnevich (2004).

The dotted lines represent the calibration lines obtained for different values of pore fluid conductivities. If a TDR measurement is taken in the field and lies somewhere between an EC_w of 0.08 and 0.10 S/m the sample can be adjusted to any laboratory calibration line (in this case the EC_w = 0.08 S/m line). This is done by replacing the same amount of pore fluid of the field sample with that of the laboratory calibration (see Figure 2-14). In this manner the adjusted sample has the same water content and dry density of the field sample, the only difference being the pore fluid conductivity. The bulk electrical conductivity of the adjusted sample changes due to the replacement of the field pore fluid with the laboratory pore fluid. However, the dielectric constant of the adjusted sample is the same as the original field sample. This is due to insensitivity of the Siddiqui-Drnevich equation (Eqn. 2-16) to pore fluid conductivity. The adjustment applied to the field condition is thus a vertical projection to the laboratory calibration line.

The water content and dry density of the field sample can then be calculated using Eqns. (2-28) and (2-29) with the adjusted values of $K_{a,\ adj}$ and $EC_{b,\ adj}$.

$$K_{a,adj} = K_{a,field} \tag{2-30}$$

$$EC_{b,adj} = \left(f + g\sqrt{K_{a,f}}\right)^2 \tag{2-31}$$

As mentioned previously and as displayed in Eqn. (2-30) no adjustment is necessary to the measured dielectric constant. Calibration values of “f” and “g” are required to determine the adjusted bulk electrical conductivity and as a result no measurement of pore fluid conductivity need be taken except that it remains constant during calibration. Tap water is recommended for accurate laboratory calibration (Yu and Drnevich, 2004).

2.17. Limitations of TDR Measurement

Significant research has been carried out to determine possible sources of error in TDR measurements. Particularly problems with “lossy” materials and multiple reflections have received attention. Mojid et al. (2003) studied problems with geotechnical TDR measurement in lossy materials. In highly conductive materials, a dispersive or lossy phenomenon is observed. These lossy or dispersive materials are fine-grained materials or conductive materials where large amounts of ions are present in the pore water (Mojid et al. 2003). Yanuka et al. (1988) also discussed the significant error that arises when taking TDR measurements in conductive materials. These same observations were made by Topp et al. (2000). Without equipment or method modifications, the TDR procedure discussed herein is not applicable to highly dispersive materials such as fat clays at high water contents and concentrated ionic solutions (Yu and Drnevich, 2004).

3. Equipment and Procedure

3.1. Introduction

Siddiqui and Drnevich (1995) studied the factors which influence the wave transmission and as a result, transmission line components were designed and built. These components were designed to be robust, easy to use, and provide superior wave transmission for field measurement of the soil apparent dielectric constant. The TDR system was standardized in the form of ASTM D6780. The method outlined in ASTM D6780 is referred to as the two-step Purdue TDR method. Two steps in that the method calls for two tests to be run (one in-situ and one in a compaction mold) to determine the in-situ water content and density. Several lab and field investigations have been carried out by researchers at Purdue University as well as through a beta testing program designed to evaluate the accuracy of the method. Results indicate that the method is sufficiently accurate for geotechnical applications (Lin, 1999; Siddiqui et al., 2000; Drnevich et al., 2002; Sallam et al., 2004).

However, the two-step method was determined to be somewhat limited in its application. It only made use of the soil apparent dielectric constant, the method was destructive (requiring the excavation of the soil to be tested) and time consuming compared with other methods. In an effort to streamline the two-step method, Yu and Drnevich (2004) proposed the use of a bulk electrical conductivity measurement to improve the accuracy of the two-step method as well as to eliminate the need to perform a second test in a compaction mold. This improved method is referred to as the one-step Purdue TDR method. The equipment used is essentially the same but, only one in-situ measurement is required to obtain both water content and density. The test is non-destructive and the need for excavation is eliminated (Yu and Drnevich, 2004).

3.2. TDR Measurement System

The system configuration of the basic Purdue TDR device is shown in Figure 3-1. The TDR device used in this study was acquired from Purdue University and its central components include a Campbell Scientific TDR 100 Time Domain Reflectometer, 3 feet of Intcom 50- Ω cable as well as soil probe equipment. The soil probe is essentially comprised of three main components: 1) the coaxial cable; 2) the coaxial head (CH); and 3) either a coaxial cylinder (CC) (used for calibration purposes) or multiple rod probe (MRP) (used for field measurement) (Drnevich et al., 2001).

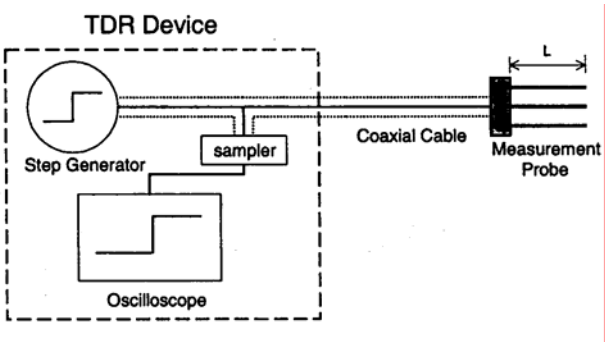


Figure 3-1. TDR System Configuration. Source: Lin et al. (2000).

The coaxial cable consists of a center conducting wire surrounded by a cylinder casing, which acts as the outer conductor (Lin et al., 2000). The coaxial head (CH) (Figure 3-2) is a transition from the coaxial cable to either the CC or MRP and consists of three components: 1) a 50- Ω mating BNC connector; 2) a metal cylindrical head with an insulating material; and 3) a multiple rod section that contains three perimeter rods and one center rod. The coaxial head (CH) has one center stud and three perimeter studs. The center stud and two of the perimeter studs are of the same length (21mm), whereas the third perimeter stud can be adjusted to ensure full contact with either the MRP or CC.

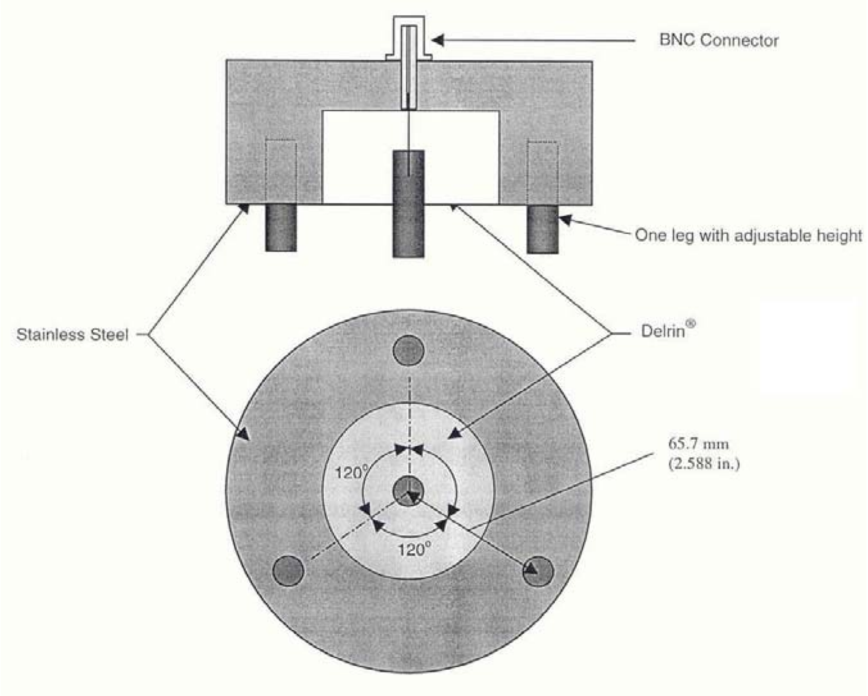


Figure 3-2. Configuration of Coaxial Head. Source: TDR User's Manual

The coaxial cylinder (CC) transmission line consists of a CC mold, a ring, and a central rod all made of stainless steel (Figure 3-3). The CC mold is essentially a modified compaction mold with an inner diameter of 102 mm and a length of 203 mm. The CC ring rests on top of the CC mold. It acts as an extension during the compaction process and as a part of the coaxial cylinder (CC) during measurement. A central rod is driven after the soil has been compacted into the mold to complete the coaxial line (the mold acts as the outer conductor). The central rod is made of stainless steel and has a diameter of 8 mm. A template is used to guide the central rod during driving stage (Drnevich et al., 2001).

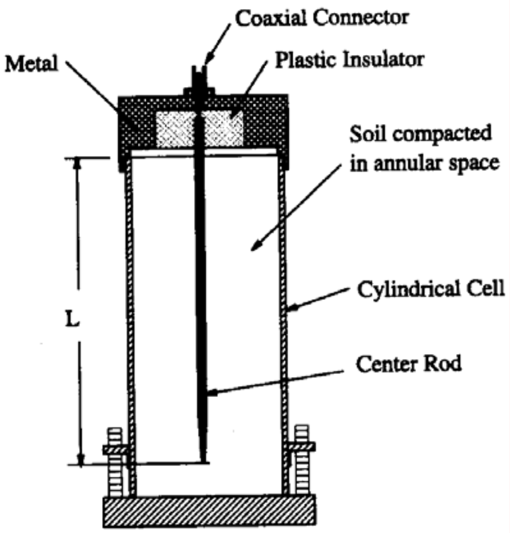


Figure 3-3. The Coaxial Cylinder (CC) Transmission Line.
Source: Siddiqui and Drnevich (1995).

Other equipment relevant to the CC test includes: a tamping rod for compacting soil, a guide for installing the center rod, an acrylic hammer for driving the center rod, a metal screed for leveling the surface of the soil in mold, a brush and a digital scale (Drnevich et al., 2001).

The multiple rod probe (MRP) consists of one central rod and three perimeter rods (9.5 mm diameter and a length of 236 mm), which are driven into the soil. The configuration of the MRP rods is made to match the coaxial head (CH) by means of a detachable template. After the spikes have been driven, the template is removed and the coaxial head (CH) is placed on top of the spikes (Figure 3-4). This forms a coaxial line in the soil (Drnevich et al., 2001).

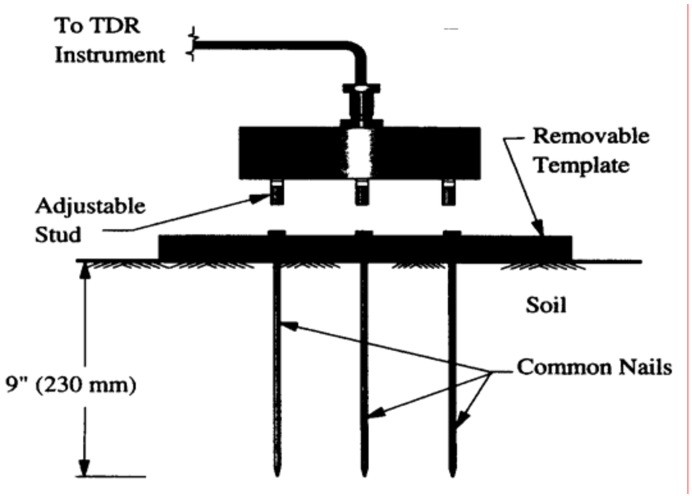


Figure 3-4. The Multiple Rod Probe (MRP).

Source: Siddiqui and Drnevich (1995).

Other equipment relevant to the MRP field test includes: a brass hammer to drive the spikes, a tool for loosening the template and a tool for removing the spikes (Drnevich et al., 2001).

3.3. Data Acquisition

A laptop computer is connected to SP232 serial communication module to retrieve data obtained from the Campbell Scientific TDR100 Time Domain Reflectometer. Computer software named TDR++ was developed by Feng et al. (1998) to automate TDR data acquisition. A rugged, oversized briefcase (Figure 3-5) was designed for field measurement. The briefcase houses the CS TDR100, a power supply for the TDR100, a 120-volt charger, a laptop computer, a charger for the laptop, a BNC cable to connect the TDR100 to the MRP head and a cable to connect the chargers to a 120 V AC source (Drnevich et al., 2001).

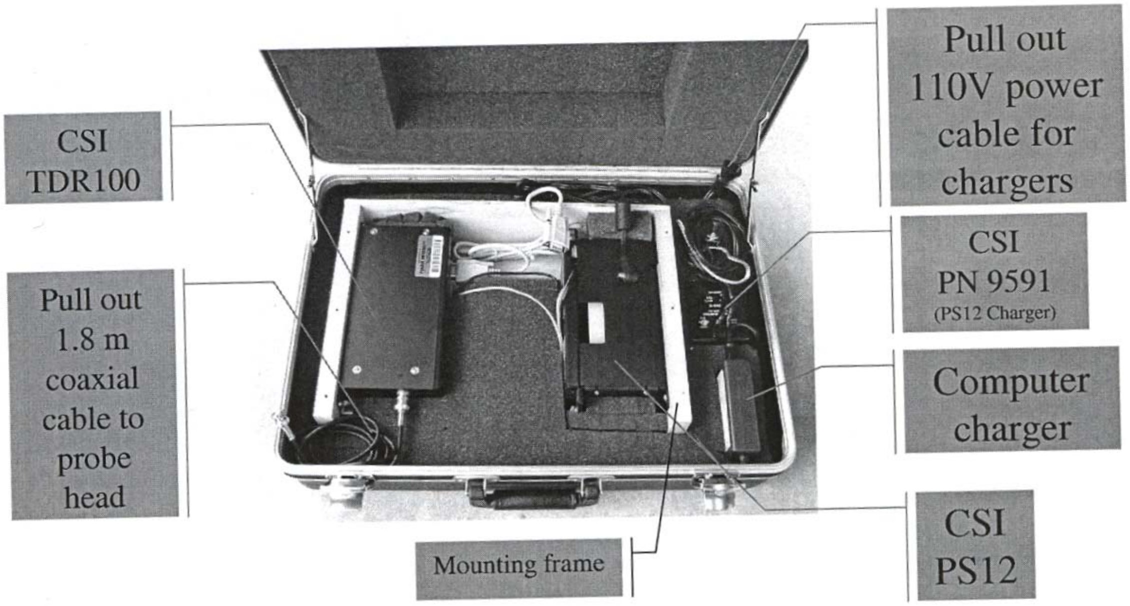
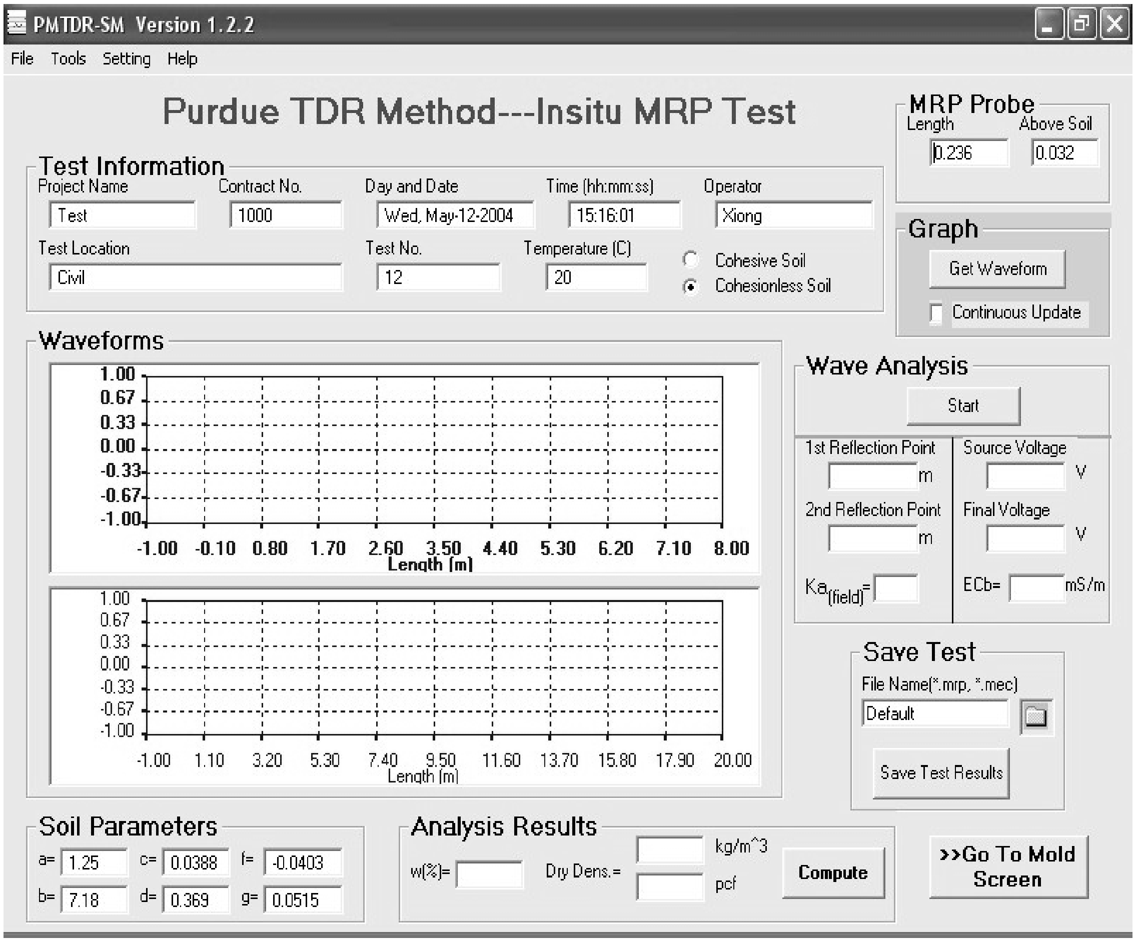


Figure 3-5. TDR Field Measurement Case. Source: TDR User's Manual.

3.4. TDR Software (PMTDR-SM)

The Purdue Method TDR Simplified Method (PMTDR-SM) is an updated version of the two-step software developed for ASTM D6780. PMTDR-SM Version 1.2.2 was the most current version available at the time this research was conducted. Researchers continue to update and improve the software. The software was designed with a user-friendly interface. It consists of two input screens. The first screen is the In-Situ MRP Test which prompts the user to input project name, contract No., operator, test location, test number, temperature, and type of soil (cohesive or cohesionless) (Figure 3-6). Other input parameters include the MRP probe configuration measurements and the soil specific constants for the soil being tested. The software obtains a TDR waveform from the aforementioned configuration by using the "Get Waveform" command. A TDR wave analysis can then be performed by using the "Start" function. The analysis is consistent with that discussed in Chapter 2 and will determine the in-situ apparent dielectric constant (K_a) and the in-situ bulk electrical conductivity (EC_b). The gravimetric water content and the dry density can then be computed with the inputted soil specific calibration constants using the "Compute" function. Test results can then be saved using the "Save Test Results" command.



Test Information

Project Name: Test

Contract No.: 1000

Day and Date: Wed, May-12-2004

Time (hh:mm:ss): 15:16:01

Operator: Xiong

Test Location: Civil

Test No.: 12

Temperature (C): 20

○ Cohesive Soil

● Cohesionless Soil

MRP Probe

Length: 0.236

Above Soil: 0.032

☐ Continuous Update

File Name(*.mrp, *.mec): Default

Soil Parameters

a= 1.25

c= 0.0388

f= -0.0403

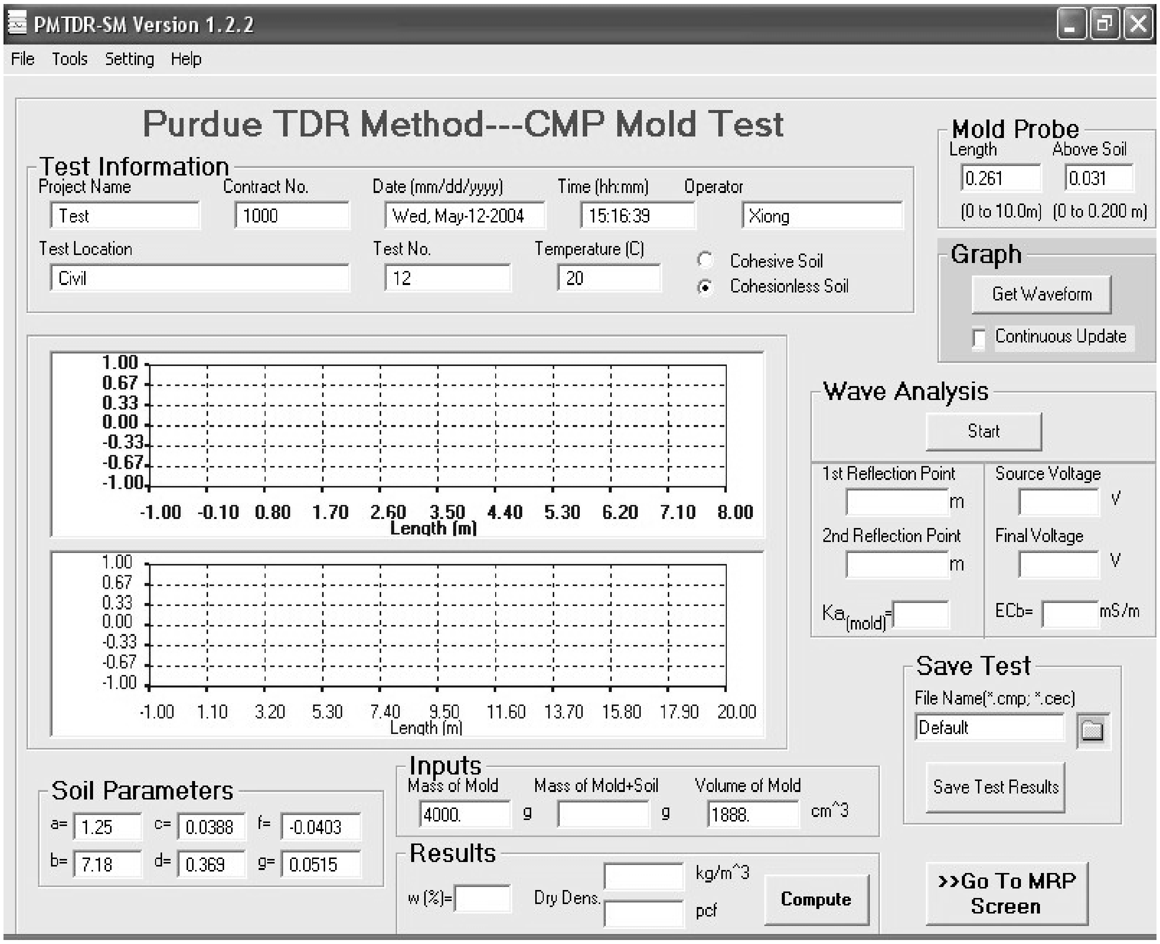
b= 7.18

d= 0.369

g= 0.0515

Figure 3-6. In-situ MRP Input Screen. Source: PMTDR-SM.

The second screen is used for the CC Mold Test in which the user is prompted to input the same parameters mentioned for the In-situ MRP test as well as the mass of empty mold, mass of mold, wet soil and the volume of mold and the mold probe dimensions (Figure 3-7). The waveform is obtained in the same manner mentioned previously and the wave analysis is also performed in the same manner. The mold moisture content and dry density can then be calculated.



Test Information

Project Name: Test

Contract No.: 1000

Date (mm/dd/yyyy): Wed, May-12-2004

Time (hh:mm): 15:16:39

Operator: Xiong

Test Location: Civil

Test No.: 12

Temperature (C): 20

○ Cohesive Soil

● Cohesionless Soil

Mold Probe

Length: 0.261 (0 to 10.0m)

Above Soil: 0.031 (0 to 0.200 m)

☐ Continuous Update

Soil Parameters

a= 1.25 c= 0.0388 f= -0.0403

b= 7.18 d= 0.369 g= 0.0515

Inputs

Mass of Mold: 4000. g

Mass of Mold+Soil: g

Volume of Mold: 1888. cm^3

Save Test

File Name(*.cmp; *.cec): Default

Figure 3-7. CC Mold Test Input Screen. Source: PMTDR-SM.

3.5. Testing Procedure

Testing includes two parts: 1) a soil specific calibration is performed in the lab prior to field testing and 2) field tests are carried out with the calibration constants obtained in part (1).

3.5.1. Calibration

Calibration should be carried out in a similar fashion as the procedure outlined in ASTM D6780 – Annex 2. The laboratory calibration can be performed in conjunction with ASTM D698 and ASTM D1557 in order to determine the optimum water content and the maximum dry density for field compaction control. Typical calibration requires that at least 3 or 4 tests be performed at different water contents that encompass the expected field conditions. The calibration tests are performed in the cylindrical mold (CC). Proper calibration will yield the soil specific calibration constants (a, b, c, d, f and g). Calibration should be carried out with soil temperatures in the range of 15°C to 25°C.

The calibration phase can be summarized by the following steps:

1) Determine the length of the central rod (typically 0.263m), the volume of the mold (typically 1888 cm^3) and the mass of the empty mold (typically 4,380 g). These values should be consistent with those outlined in ASTM D6780.
2) Obtain a representative soil sample from the testing site.
3) Air-dry the soil sample.
4) Prepare an adequate number of specimens having water contents that encompass the expected range of values anticipated in the field. Water contents should vary by about 2-3%.
5) Place the soil into the cylindrical mold in six uniform lifts applying ten blows per lift with the supplied aluminum tamping rod (Figure 3-8).

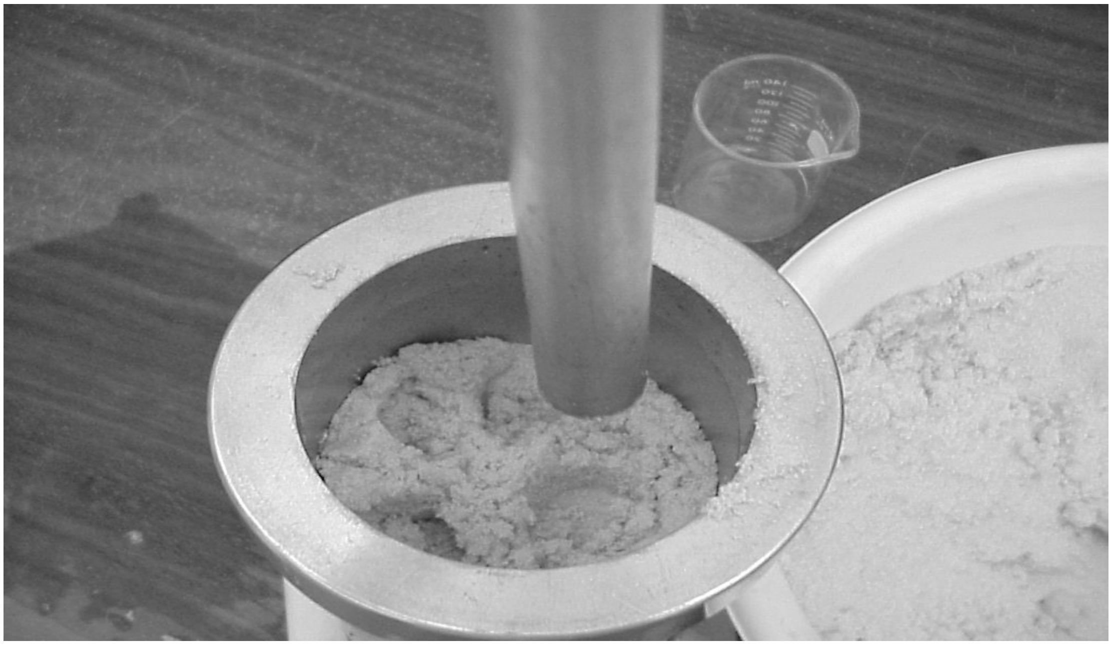


Figure 3-8. Compaction by Tamping with Aluminum Rod.

6) Remove the ring collar and level the soil surface.
7) Remove any excess soil from the mold and then weigh the mold with the wet soil (Figure 3-9).

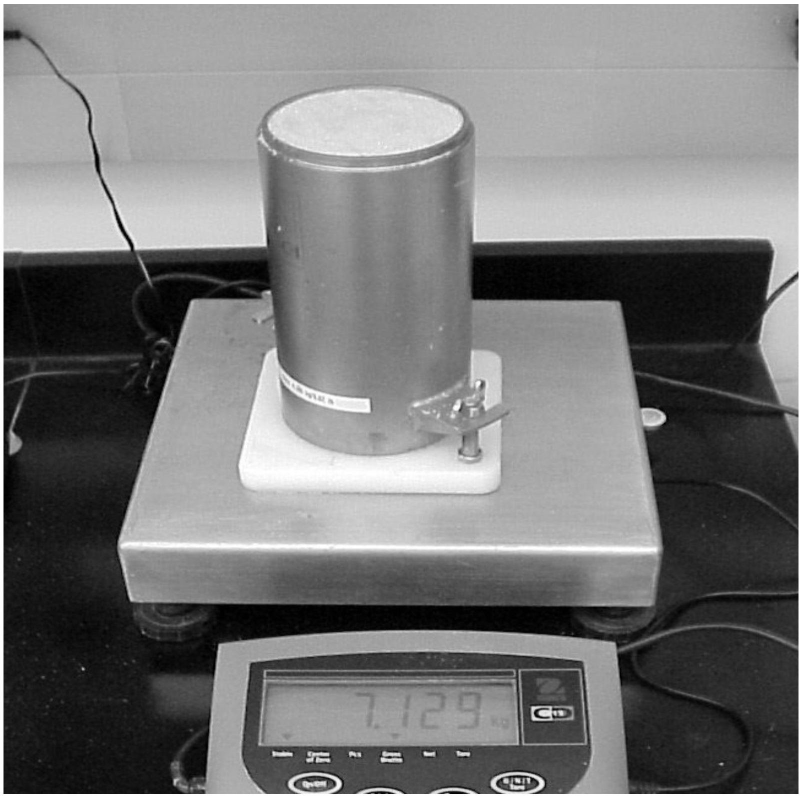


Figure 3-9. Mold and Wet Sample Being Weighed.

8) Place the driving template over the mold and drive the central spike (Figure 3-10).
9) Replace the ring collar and place the coaxial head such that all four legs are in contact with the mold or central spike.
10) Obtain a TDR wave using the TDR measurement system and software (Figure 3-11).

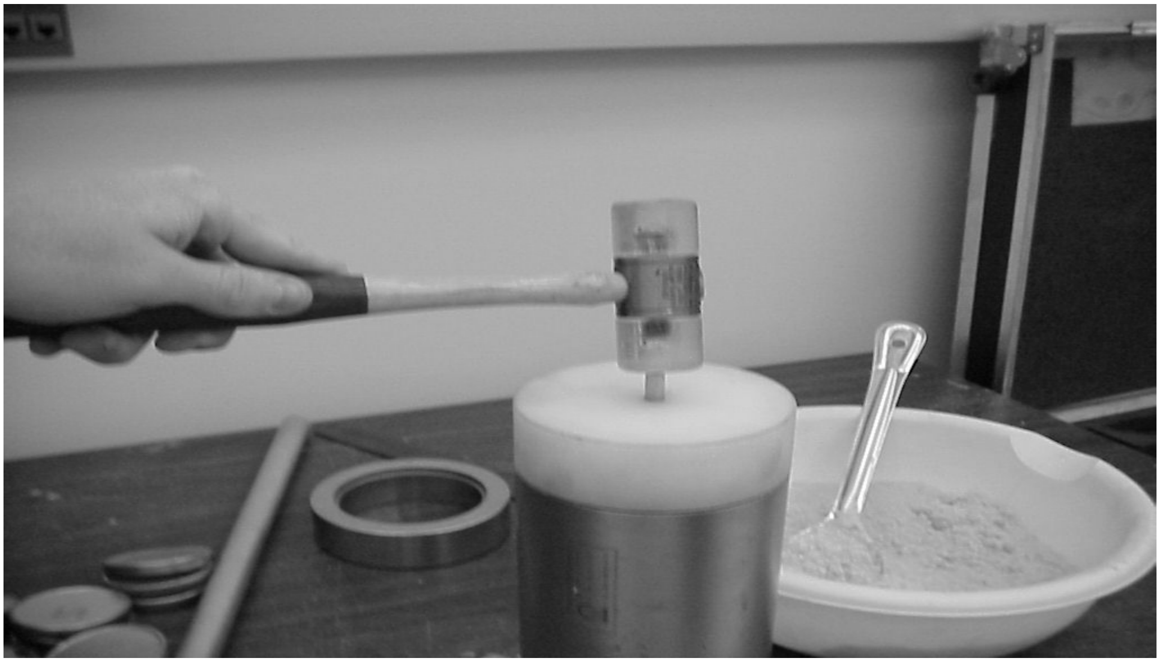


Figure 3-10. Central Spike Being Driven Through the Guide and into the Sample.

Figure 3-11. Taking the TDR Measurement.

11) Remove the soil from the mold and retain a sufficient sample to obtain the water content in accordance with ASTM D 2216.
12) Repeat steps (5) through (11) until the desired number of measurements are obtained.

For each of the specimens the water content (from the oven dry method), dry density (from mold and wet soil measurement), apparent dielectric constant (K_a), and bulk electrical conductivity (EC_b) can be calculated. Specific constants for the soil being calibrated can be obtained through a series of linear regression plots.

Soil constants "a" and "b" are found by plotting $\sqrt{K_a}\frac{\rho_w}{\rho_d}\ vs\ w_{oven}$, where K_a is the measured apparent dielectric constant, ρ_d is the dry density of the soil in the mold, ρ_w is the density of water (1000 kg/m^3), and w_{oven} is the oven dry water content. A best fit linear line is then fitted to the data and "a" is the zero intercept of the line and "b" is the slope of the line. Figure 3-12 is an example calibration for Ottawa Sand.

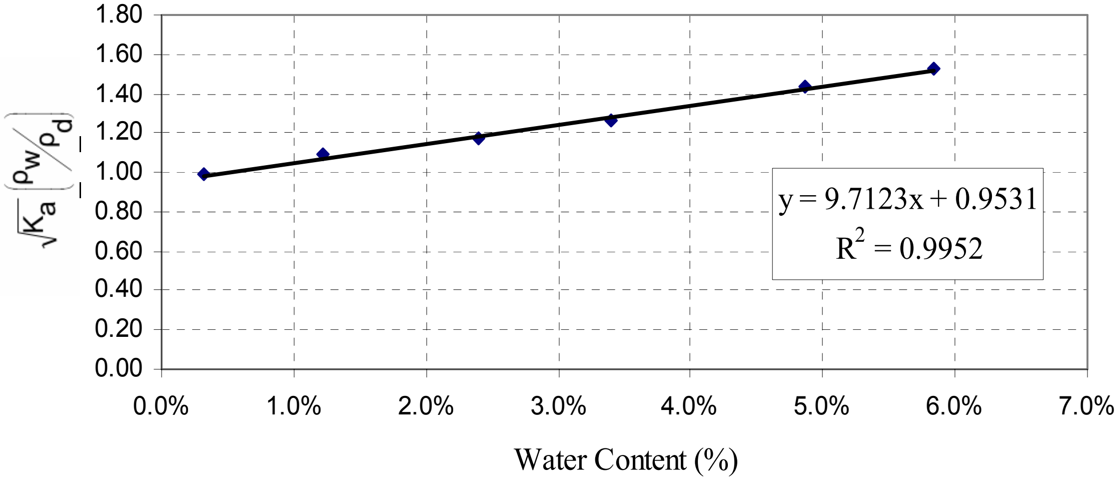


Figure 3-12. Example of "a" and "b" Calibration for Ottawa Sand.

Soil constants "c" and "d" are found by plotting $\sqrt{EC_b}\frac{\rho_w}{\rho_d}\ vs\ w_{oven}$, where EC_b is the measured bulk electrical conductivity, ρ_d is the dry density of the soil in the mold, ρ_w is the density of water

(1000 kg/m^3), and w_{oven} is the oven dry water content. A best fit straight line is then fitted to the data and "c" is the zero intercept of the line and "d" is the slope of the line. Figure 3-13 is an example calibration for Ottawa Sand.

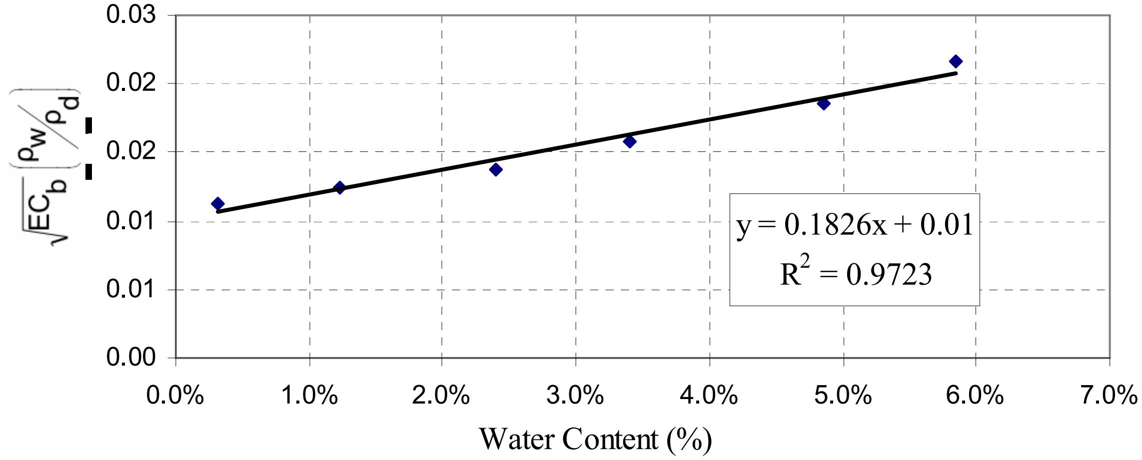


Figure 3-13. Example of "c" and "d" Calibration for Ottawa Sand.

Soil constants "f" and "g" are found by plotting $\sqrt{EC_b}\ vs\sqrt{K_a}$, where EC_b is the measured bulk electrical conductivity and K_a is the apparent dielectric constant. A best fit straight line is then fitted to the data and "f" is the zero intercept of the line and "g" is the slope of the line. Figure 3-14 is an example calibration for Ottawa Sand.

In order to facilitate the calibration process PMTDR-SM has incorporated a calibration tool (Figure 3-15). The data points obtained from calibration are inputted into the appropriate fields and the tool will automatically generate the desired calibration plots. The calibration results from bet fit regression line analysis are then displayed. The soil specific constants can then be uploaded into either the field testing input screen (Figure 3-6) or the mold input screen (3-7) for later use.

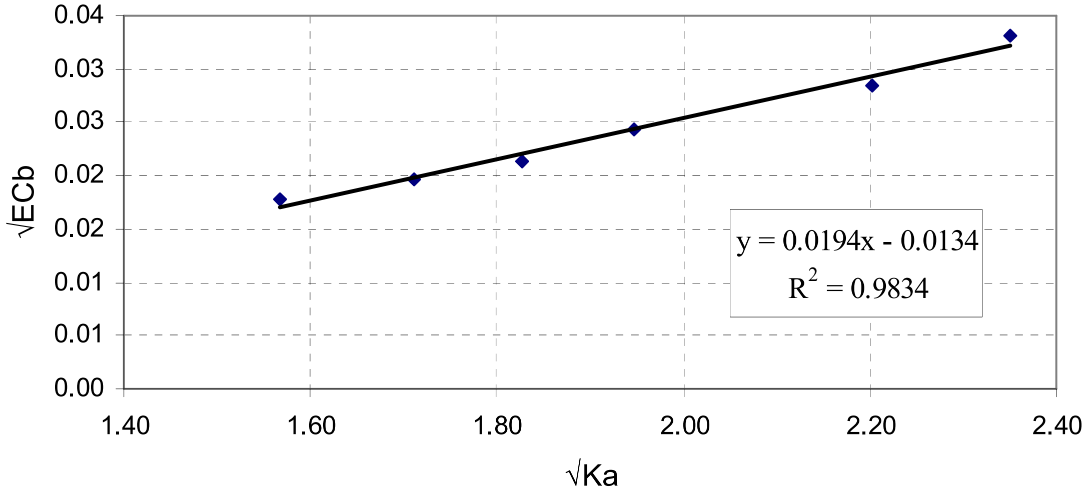
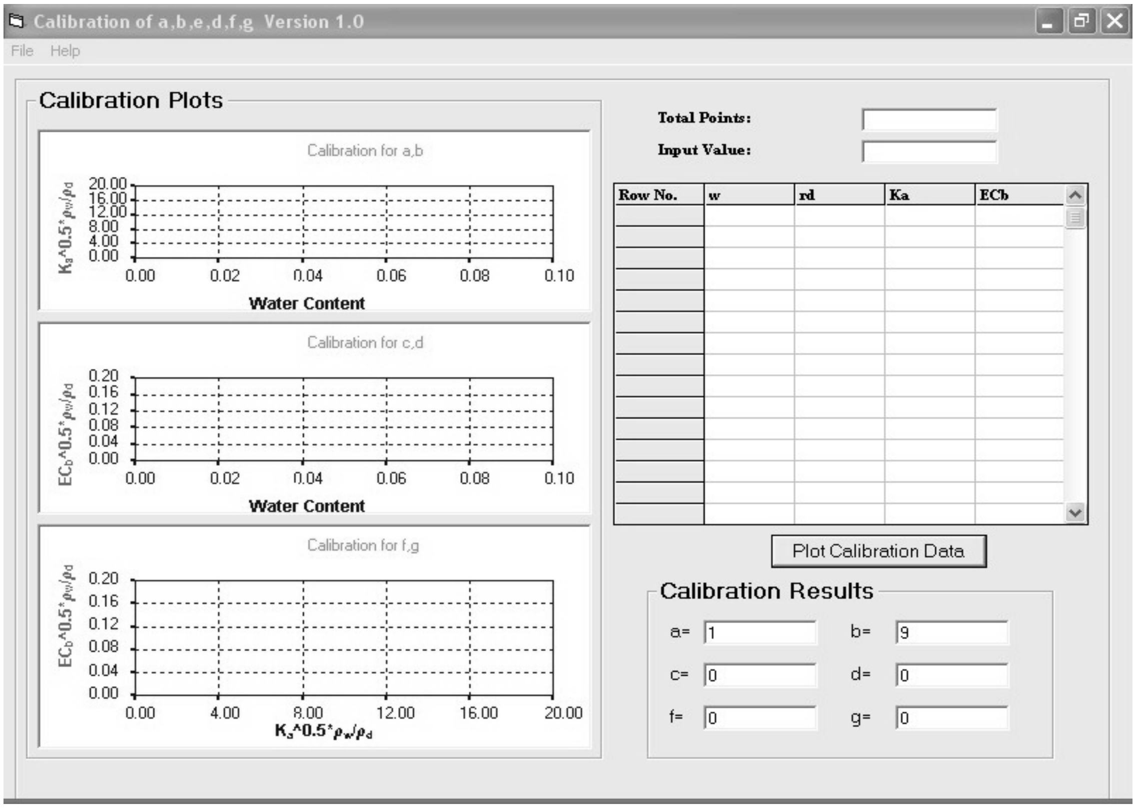


Figure 3-14. Example of “f” and “g” Calibration for Ottawa Sand.



Total Points:

Input Value:

Row No.	w	rd	Ka	ECb

Calibration Results

a= 1
b= 9
c= 0
d= 0
f= 0
g= 0

Figure 3-15. PMTDR-SM Calibration Tool. Source: PMTDR-SM Software.

The entire calibration process requires at least 24 hours to perform. The calibration constants can then be used for the same soil encountered in the field under a wide variety of in-situ conditions. It may be possible to catalog commonly encountered soils and their constants to avoid the calibration process (Yu and Drnevich, 2004).

3.5.2. In-situ Testing

Field testing is similar to the procedure outlined in ASTM D6780. However, there is no need to remove the soil for a compaction mold measurement. Field testing should be carried out with the soil specific calibration constants obtained in the calibration phase.

The in-situ testing procedure can be summarized by the following steps:

1) Level the soil surface that is to be tested. If the soil surface has been exposed such that it is dried out or wet from recent rain, the top inch of soil may be removed. The leveled surface should be free of voids and if they are present, they should be filled.
2) Place the driving template on the leveled soil surface, making sure the locking pin is in place. Ensure that the soil is in full contact with the template.
3) Drive the three outer spikes through the template and into the soil with the brass hammer (Figure 3-16). The central spike should be driven last. Ensure that all spikes are touching the template.
4) Remove the locking pin from the template. Spread the template apart and remove it (Figure 3-17).
5) Place the coaxial head (CH) on top of the driven spikes so that each spike makes contact with the CH. It may be necessary to slide or rotate the CH to ensure good contact with the spikes (Figure 3-18).

Figure 3-16. Driving Spikes through Template into Soil.
Source: TDR Manual.

Figure 3-17. Removal of the Template. Source: TDR Manual.

Figure 3-18. Placement of Coaxial Head (CH) on Spikes.
Source: TDR Manual.

6) The coaxial head (CH) is then connected to the CS TDR100 by the provided coaxial cable.
7) Obtain a TDR measurement using the TDR measurement system and software.

The field testing procedure requires only a few minutes of setup and about 2 to 3 minutes to run the test. This is a significant reduction in the time required to run the test than the two-step method and is comparable to the nuclear test. After the equipment is setup, several tests can be performed in succession in a relatively short amount of time (Yu and Drnevich, 2004).

4. Evaluation of TDR Soil Parameters

4.1. Introduction

For accurate one-step TDR field measurement, a series of soil specific calibration constants must be obtained previously. Soil constants "a" and "b" are parameters that relate the gravimetric moisture content to the soil dielectric constant. Constants "c" and "d" relate the gravimetric moisture content to the bulk electrical conductivity of the soil. Finally, constants "f" and "g" relate the dielectric constant to the bulk electrical conductivity. The soil constants described can vary widely with soil composition and site specific conditions. A critical factor affecting calibration is the pore fluid conductivity of the soil. This chapter presents experimental results from a study on the effect of initial salinity on the calibration constants. Also an effort is made to determine the typical range of TDR constants for Florida sand by performing a series of TDR tests in the calibration mold for several soils obtained at local construction projects in the vicinity of Tampa.

4.2. Calibration Constants "a" and "b"

The Siddiqui and Drnevich (1995) relationship (Eqn. 2-16) is used to determine soil constants "a" and "b." The process for obtaining calibration constants "a" and "b" was previously discussed in Chapter 3. Substituting the volumetric water content into Eqn. (2-16), the following relationship is obtained:

$$\sqrt{K_a} = a\frac{\rho_d}{\rho_w} + b\theta \qquad (4\text{-}1)$$

When the volumetric water content (θ) is zero:

$$a = \sqrt{K_{a,s}}\frac{\rho_w}{\rho_d} \tag{4-2}$$

Soil constant "a" is thus termed the refraction index of the soil solids that is normalized by the soil dry density. Typical values of "a" range from 0.7 to 1.85 (Yu and Drnevich, 2004).

When the volumetric water content (θ) is 100 percent:

$$b = \sqrt{K_{a,w}} \tag{4-3}$$

Soil constant "b" is defined as the refraction index of the pore fluid. Typical values of $K_{a,w}$ measured by TDR are close to 81 at 20°C. This yields a "b" value of about 9 (Yu and Drnevich, 2004).

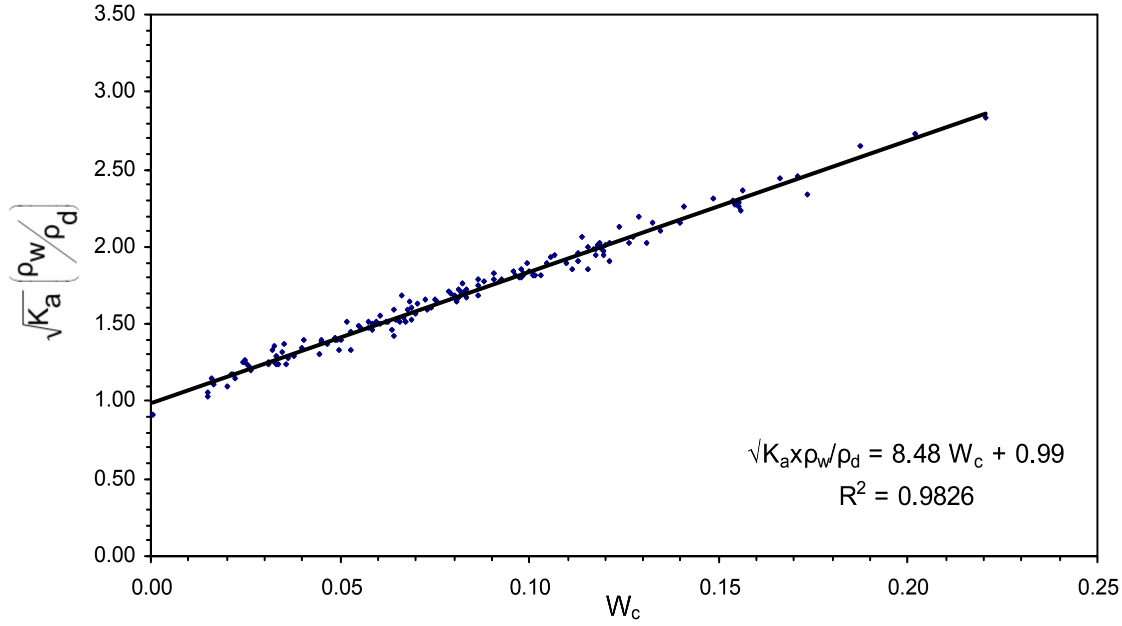


Figure 4-1. Final Calibration Results for "a" and "b." Source: Sallam et al. (2004).

Table 4-1. Values of Constants “a” and “b” for Various Sands.

Source: Sallam et al., (2004).

Test	Description	Operator	USCS	AASHTO	a	b	Comment
1	Ottawa Sand	Amr	SP	A-1-b	1.22	11.68	Discarded
1-a	Ottawa Sand	Brian	SP	A-1-b	0.95	9.00	Accepted
1-b	Ottawa Sand	Both	SP	A-1-b	0.91	9.41	Accepted
				Average	**0.93**	**9.21**	
2	Outside Lab	Amr	SP	A-3	1.00	8.20	Accepted
2-a	Outside Lab	Brian	SP	A-3	1.03	8.35	Accepted
				Average	**1.02**	**8.28**	
3	MP-1	Amr	SP	A-1-b	0.93	8.78	Accepted
3-a	MP-1	Brian	SP	A-1-b	1.01	7.48	Accepted
3-b	MP-1	Brian	SP	A-1-b	0.98	8.21	Accepted
				Average	**0.97**	**8.16**	
4	Sample # 515	Both	SP	A-3	1.05	8.19	Accepted
4-a	Sample # 515	Brian	SP	A-3	1.01	8.93	Accepted
4-a	Sample # 515	Brian	SP	A-3	1.03	8.73	Accepted
				Average	**1.03**	**8.62**	
5	Sample # 2	Amr	SP	A-1-b	1.10	7.40	Accepted
5-a	Sample # 2	Both	SP	A-1-b	1.04	8.06	Accepted
				Average	**1.07**	**7.73**	
6	Sample # 6944	Amr	SP	A-3	1.08	8.09	Accepted
6-a	Sample # 6944	Brian	SP	A-3	0.99	8.65	Accepted
				Average	**1.04**	**8.37**	
7	Sample with # 6944	Brian	SP	A-1-b	**0.99**	**8.80**	Accepted
8	Sample # 6965	Both	SW	A-1-b	0.99	8.80	Study the effect of compaction
8-a	Sample # 6965	Both	SW	A-1-b	1.04	8.03	Study the effect of compaction
8-b	Sample # 6965	Both	SW	A-1-b	0.99	8.31	Study the effect of compaction
8-c	Sample # 6965	Both	SW	A-1-b	1.00	7.96	Study the effect of compaction
				Average	**1.01**	**8.28**	
9	Sample With # 6965	Brian	SP	A-1-b	**1.02**	**8.20**	Accepted
10	Sample # 6974	Brian	SP	A-1-b	**0.99**	**8.27**	Accepted
11	Sample # 6978	Brian	SP	A-1-b	**1.02**	**7.93**	Accepted
12	Sample # 6926	Brian	SP	A-1-b	0.90	9.24	Accepted
13	Sample # 6927	Brian	SP	A-1-b	0.87	9.83	Accepted

Note – Test 1 was discarded for incorrect testing procedures.

Sallam et al. (2004) determined the calibration parameters “a” and “b” encountered in common soils in the state of Florida. A final recommendation of “a” = 1 and “b” = 8.5 was made (Figure 4-1). Soils tested in the study were mainly Florida sands that can be characterized as A-3 or A-1-b soils (Table 4-1).

Sallam et al. (2004) performed a series of tests to study the factors influencing the calibration of “a” and “b.” It was concluded that the compaction energy only slightly affects the value of constants “a” and “b” (Figure 4-2). Operator dependency was also found to have an insignificant influence on testing results.

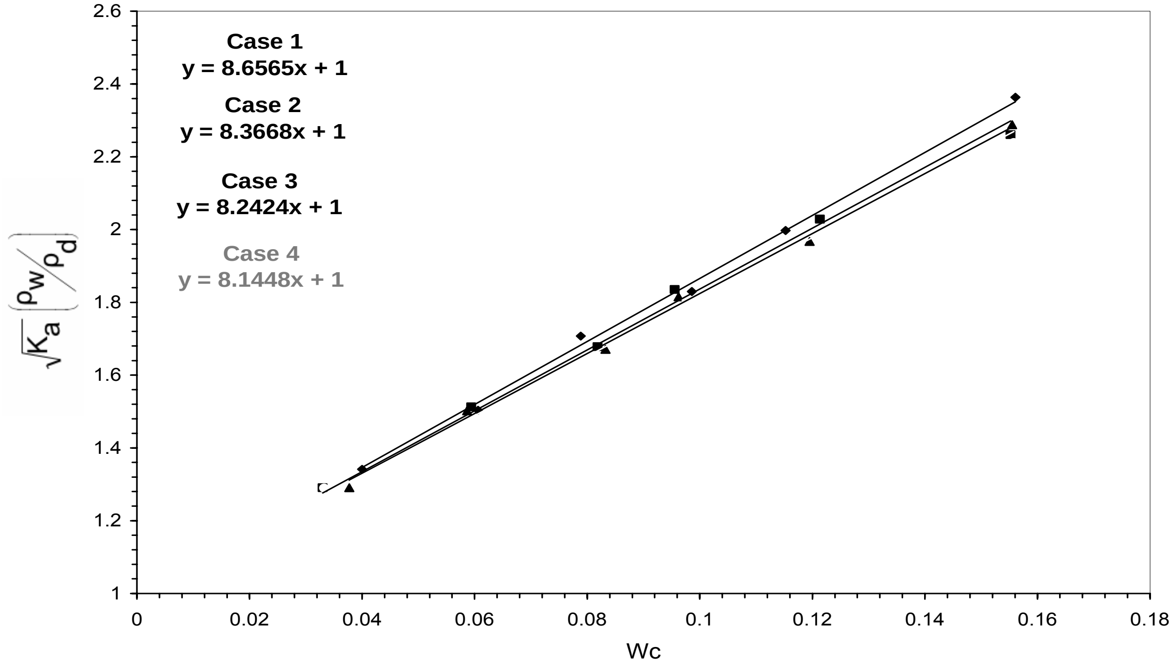


Figure 4-2. Effect of Compaction Energy on Constants “a” and “b.”
Source: Sallam et al., (2004).

The effect of variation or inaccuracy in determining “a” and “b” on field measurement of water content and dry density was also studied. The effect of changing constant “b” was more critical than the effect of changing constant “a” in water content measurement. The predicted value of the moisture content changes noticeably as “b” varies, especially when the actual value is surpassed by ± 1.0 (Table 4-2). It was also noted that at higher K_a values the error in predicting the moisture content increased. This is expected since a change in the predicted moisture content resulting from a variation in “b” (which is the slope of the straight line) is likely dramatic.

Table 4-2. Error Resulting from Variation of “b” on Predicted Moisture Content.
Source: Sallam et al., (2004).

Wc	**Δb**								
	-1	-0.75	-0.5	-0.25	0	0.25	0.5	0.75	1
	ΔW_c, %ge								
0.02	0.31	0.23	0.15	0.07	0.00	-0.07	-0.13	-0.19	-0.24
0.05	0.81	0.59	0.38	0.18	0.00	-0.17	-0.33	-0.48	-0.61
0.1	1.72	1.24	0.79	0.38	0.00	-0.35	-0.68	-0.99	-1.28
0.15	2.72	1.95	1.25	0.60	0.00	-0.55	-1.07	-1.55	-1.99
0.2	3.81	2.73	1.74	0.83	0.00	-0.77	-1.48	-2.14	-2.76
0.25	5.00	3.57	2.27	1.09	0.00	-1.00	-1.92	-2.78	-3.57

Variability in both constants “a” and “b” was determined to have a significant effect on dry density measurement (Tables 4-3 and 4-4). Also, inaccurate water content measurement added significant error in dry density measurement (Sallam et al., 2004).

Table 4-3. Error Resulting from Variation of “a” on Predicted Dry Density.
Source: Sallam et al., (2004).

Wc	**Δa**								
	-0.2	-0.15	-0.1	-0.05	0	0.05	0.1	0.15	0.2
	$\Delta\rho_d/\rho_{d,true}$, %ge								
0.02	-2.60	-1.96	-1.32	-0.66	0.00	0.67	1.35	2.04	2.74
0.05	-2.60	-1.96	-1.32	-0.66	0.00	0.67	1.35	2.04	2.74
0.1	-2.60	-1.96	-1.32	-0.66	0.00	0.67	1.35	2.04	2.74
0.15	-2.60	-1.96	-1.32	-0.66	0.00	0.67	1.35	2.04	2.74
0.2	-2.60	-1.96	-1.32	-0.66	0.00	0.67	1.35	2.04	2.74
0.25	-2.60	-1.96	-1.32	-0.66	0.00	0.67	1.35	2.04	2.74

Table 4-4. Error Resulting from Variation of "b" on Predicted Dry Density.

Source: Sallam et al., (2004).

Wc	**Δb**								
	-1	-0.75	-0.5	-0.25	0	0.25	0.5	0.75	1
	$\Delta\rho_d/\rho_{d,true}$, %ge								
0.02	-0.31	-0.22	-0.14	-0.07	0.00	0.06	0.12	0.18	0.24
0.05	-0.77	-0.56	-0.36	-0.17	0.00	0.16	0.31	0.45	0.59
0.1	-1.54	-1.11	-0.71	-0.34	0.00	0.32	0.63	0.91	1.18
0.15	-2.31	-1.67	-1.07	-0.52	0.00	0.48	0.94	1.36	1.76
0.2	-3.08	-2.22	-1.43	-0.69	0.00	0.65	1.25	1.82	2.35
0.25	-3.85	-2.78	-1.79	-0.86	0.00	0.81	1.56	2.27	2.94

4.3. Calibration Constants "c" and "d"

Equation (2-25) is used in conjunction with the procedure outlined in Chapter 3 to determine constants "c" and "d." If Eqn. (2-25) is expressed in terms of volumetric water content the following expression is obtained:

$$\sqrt{EC_b} = c\frac{\rho_d}{\rho_w} + d\theta \tag{4-4}$$

When the volumetric water content is zero:

$$c = \frac{\rho_w}{\rho_d}\sqrt{EC_s} \tag{4-5}$$

Soil constant "c" is related to surface conductance of the soil particles normalized by dry density (Yu and Drnevich, 2004). Typical values for "c" have not yet been established. However, data taken from Sallam et al., (2004) using the ASTM TDR method was uploaded into the Purdue one-step software. Values of "c" ranged between 0.0036 and 0.0593 for Florida sands. Further discussion of the value of "c" is addressed later in this chapter.

When the volumetric water content is 100 percent:

$$d = \sqrt{EC_b} \tag{4-6}$$

Eqn. (4-6) expressed in terms of Rhoades equation (Eqn. 2-24):

$$d = \sqrt{a' EC_w} \tag{4-7}$$

Soil constant "d" accounts for the effect of soil type and pore fluid properties (Yu and Drnevich, 2004). Again, no typical range of values has been established for "d." This is predominantly due to the dependence of "d" on the pore fluid conductivity of the soil being tested. This phenomenon is addressed later in the chapter. Values obtained for Florida sands ranged from 0.146 to 0.801.

4.4. Calibration Constants "f" and "g"

Equation (2-27) is used with the calibration procedure outlined in Chapter 3 to determine soil constants "f" and "g." Eqn. (2-27) can be expressed as:

$$\sqrt{EC_b} = \frac{b \cdot c - a \cdot d}{b} \frac{\rho_d}{\rho_w} + \frac{d}{b}\sqrt{K_a} \tag{4-8}$$

Constant "g" is a function of "d" and "b" and is therefore related to pore fluid properties and is largely dependant on the pore fluid conductivity. Typical values for both "f" and "g" have not been established. For Florida sands, values of "f" range from -0.0873 to 0.0157, and values of "g" ranged from 0.021 to 0.0754. A summary of one-step TDR constants for Florida sands is displayed in Table 4-5. Figures 4-3 and 4-4 display each individual calibration point used in obtaining the calibration constants "c", "d", "f", and "g" for the 36 different soils listed in Table 4-5.

Table 4-5. TDR Soil Constants for Florida Sands.

Sample	Soil Type	a	b	c	d	f	g
#6974 br	SP or A-1-b	0.986	8.28	0.0199	0.326	-0.0286	0.0385
#6926 NKW	SP or A-1-b	1.000	8.83	0.0056	0.632	-0.0873	0.0681
#6926 br	SP or A-1-b	0.929	9.13	0.0064	0.517	-0.0582	0.0526
#6978 NKW	SP or A-1-b	0.969	8.80	0.0164	0.486	-0.0532	0.0549
#6978 br	SP or A-1-b	1.010	8.09	0.0217	0.223	-0.0081	0.0270
#6944 br	SP or A-1-b	0.987	8.82	0.0091	0.485	-0.0578	0.0521
#6965 br	SP or A-1-b	1.020	8.22	0.0171	0.342	-0.0372	0.0402
#6965 Amr/Br 1	SP or A-1-b	0.982	8.85	0.0073	0.464	-0.0488	0.0462
#6965 Amr/Br 2	SP or A-1-b	1.010	8.43	0.0086	0.471	-0.0564	0.0498
#6965 Amr/Br 3	SP or A-1-b	0.993	8.34	0.0105	0.437	-0.0499	0.0469
#6965 Amr/Br 4	SP or A-1-b	0.993	8.39	0.0078	0.502	-0.0577	0.0505
#6927 br	SP or A-1-b	0.875	9.88	0.0123	0.446	-0.0448	0.0462
#515 6-11 br	SP or A-3	1.030	8.76	0.0359	0.671	-0.0635	0.0754
#515 5-28 br	SP or A-3	1.020	8.92	0.0191	0.367	-0.0331	0.0404
#515 5-22-02 Amr/Br	SP or A-3	1.040	8.37	0.0179	0.308	-0.0294	0.0359
#mp-1br 5-21-02	SP or A-1-b	1.000	7.48	0.0155	0.217	-0.0220	0.0291
#mp-1br 6-11-02	SP or A-1-b	0.983	8.15	0.0218	0.397	-0.0428	0.0494
#mp-1 amr 5-15-2002	SP or A-1-b	0.961	7.94	0.0051	0.258	-0.0412	0.0324
Clayey Sand br	SP or A-3	1.050	8.24	0.0116	0.236	-0.0253	0.0281
Clayey Sand Amr	SP or A-3	1.030	8.27	0.0117	0.235	-0.0212	0.0266
Beach Sand Br	SP or A-1-b	0.960	9.06	0.0088	0.348	-0.0490	0.0406
Beach Sand Amr	SP or A-1-b	0.958	8.51	0.0221	0.215	-0.0022	0.0248
Beach Sand Amr/Br	SP or A-1-b	0.877	10.15	0.0090	0.386	-0.0394	0.0380
#2 Amr 6-11-02	SP or A-1-b	1.080	7.49	0.0334	0.146	0.0157	0.0210
#2 Amr/Br 5-23-02	SP or A-1-b	1.030	8.22	0.0234	0.391	-0.0264	0.0426
#6944 Amr 6-10-02	SP or A-3	1.070	8.27	0.0243	0.294	-0.0203	0.0354
#om br	A-3	0.975	8.62	0.0202	0.801	-0.0895	0.0836
#232 br	A-2-4	1.012	8.29	0.0219	0.466	-0.0484	0.0524
#234 br	A-2-4	1.076	7.95	0.0371	0.399	-0.0180	0.0467
#239 br	A-2-4	1.042	8.68	0.0593	0.269	0.0285	0.0362
I-4 interchange br	SP or A-3	0.977	8.36	0.0145	0.275	-0.0258	0.0315
#301-1 br	SP or A-3	0.995	8.74	0.0170	0.531	-0.0586	0.0551
#301-2 br	SP or A-3	1.061	8.10	0.0157	0.625	-0.0845	0.0679
#301-3 br	SP or A-3	1.064	8.13	0.0172	0.707	-0.0923	0.0759
alex-rd-1 br	SP or A-3	0.942	8.97	0.0036	0.487	-0.0605	0.0471
alex-rd-2 br	SP or A-3	1.018	8.38	0.0179	0.369	-0.0393	0.0421

Max		1.080	10.15	0.0593	0.801	0.0285	0.0836
Min		0.875	7.48	0.0036	0.146	-0.0923	0.0210
Averages		1.000	8.50	0.0174	0.409	-0.0410	0.0453

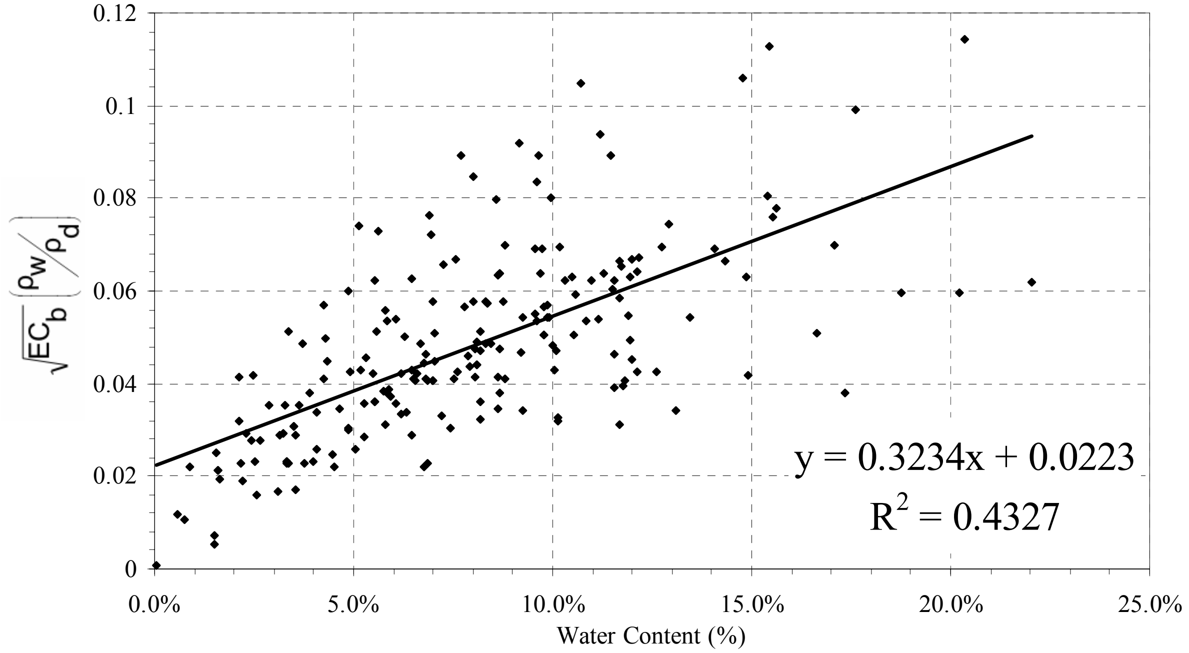


Figure 4-3. Individual calibration points for obtaining “c” and “d”.

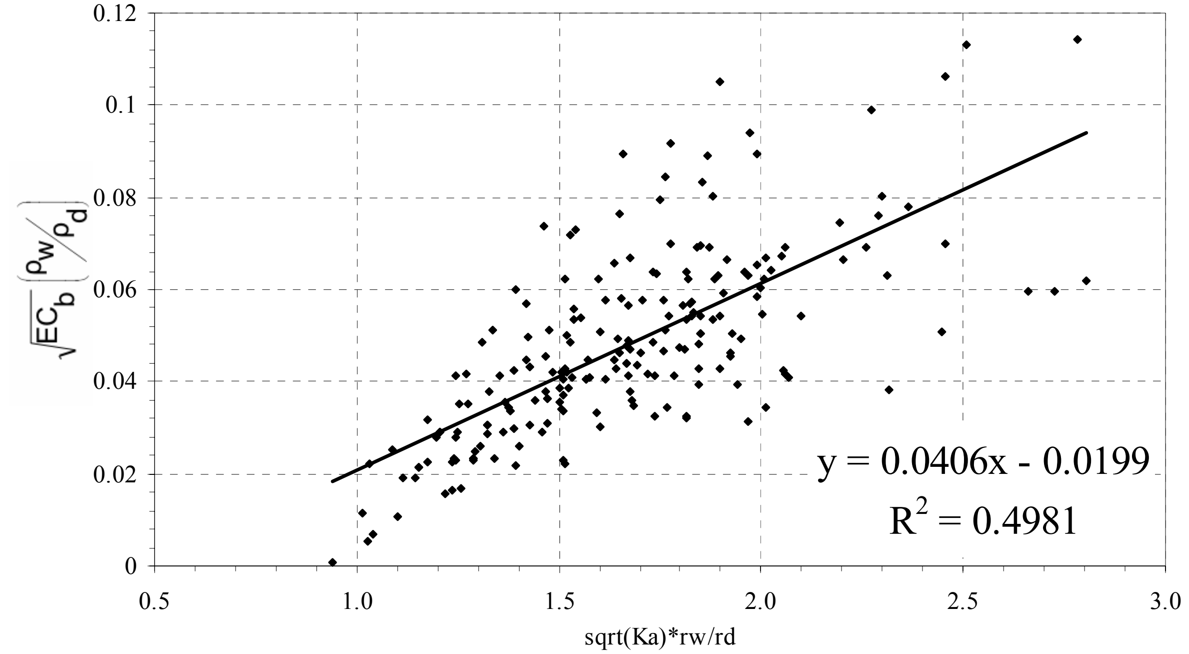


Figure 4-4. Individual calibration points for obtaining “f” and “g”.

When the volumetric water content is zero, the value of $K_{a,s}$ can be extracted from Eqn. (4-2). This value should remain constant for a given soil as long as a standardized compaction procedure is followed. Similarly, the value of $EC_{b,s}$ can be obtained from Eqn. (4-5). Again, assuming that the variation of dry density is small, the value of $EC_{b,s}$ should remain constant. If both $K_{a,s}$ and $EC_{b,s}$ remain constant with a consistent compaction procedure, a unique point may be defined at zero water content through which all calibration plots for constants "f" and "g" must pass for a given soil. This concept is discussed and demonstrated in the subsequent section.

4.5. The Effect of Pore Fluid Conductivity on Calibration Constants

In an effort to better characterize the effect of pore fluid conductivity on the one-step TDR calibration constants, several calibrations were carried out using varying pore fluid conductivities on three different sands. Ottawa Sand and two local materials (Sample #6978 and Florida Sand #2) were selected for testing.

4.5.1. Effect on Constants "a" and "b"

The values of constant "b" were recorded for every pore fluid conductivity tested and then plotted for each soil. Results are displayed in Figures 4-5, 4-6 and 4-7.

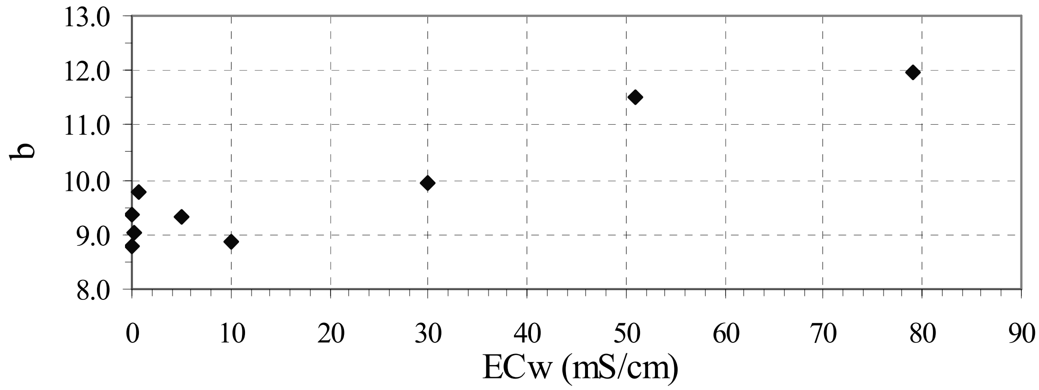


Figure 4-5. Ottawa Sand Variation of "b" with Pore Fluid Conductivity.

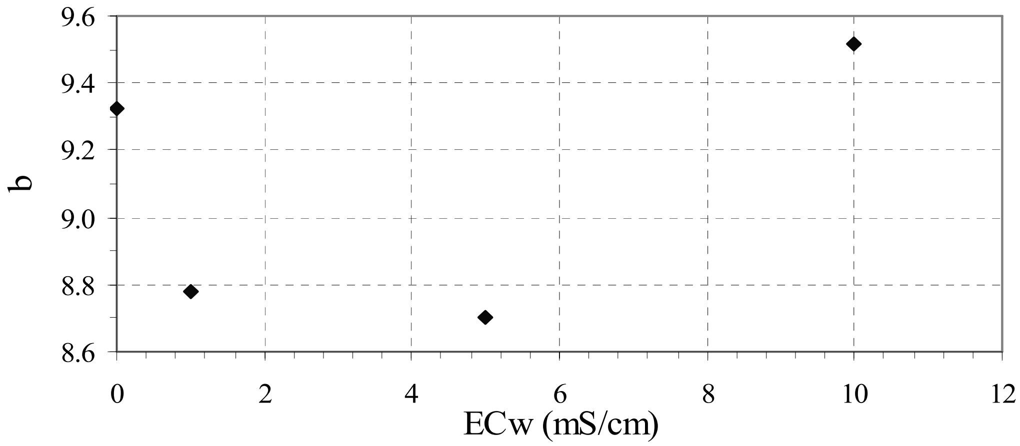


Figure 4-6. Sample #6978 Variation of “b” with Pore Fluid Conductivity.

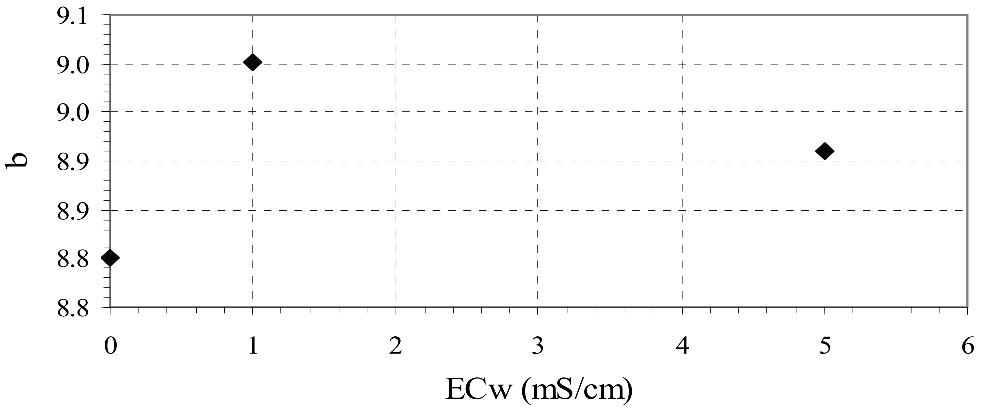


Figure 4-7. Fl Sand #2 Variation of “b” with Pore Fluid Conductivity.

From Figures 4-5, 4-6 and 4-7 it appears that no definite relationship exists between pore fluid conductivity and constant “b.” Also, constant “a” is virtually unaffected by changes in pore fluid conductivity. This observation is consistent with past research that has indicated that pore fluid conductivity has little effect on calibration for the dielectric constant in common soils (Dalton, 1982; Topp et al., 1988; White et al., 1994).

4.5.2. Effect on Constants “c” and “d”

The values of constant “d” were recorded for every pore fluid conductivity tested and then plotted for each soil. Results are displayed in Figures 4-8, 4-9 and 4-10.

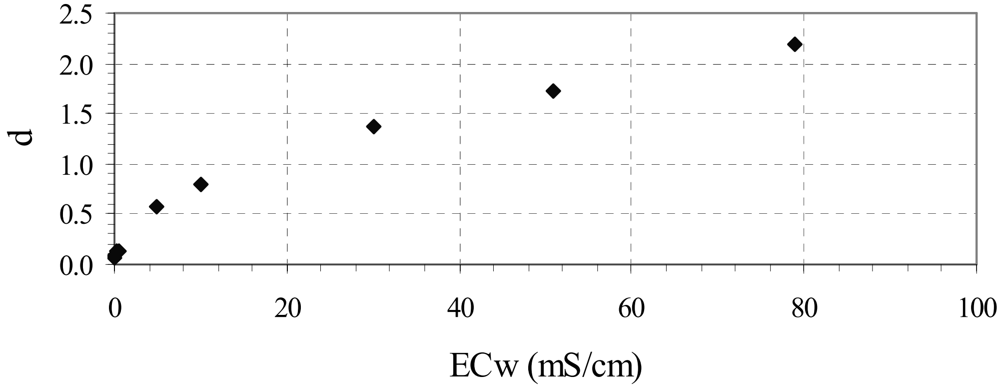


Figure 4-8. Ottawa Sand Variation of “d” with Pore Fluid Conductivity.

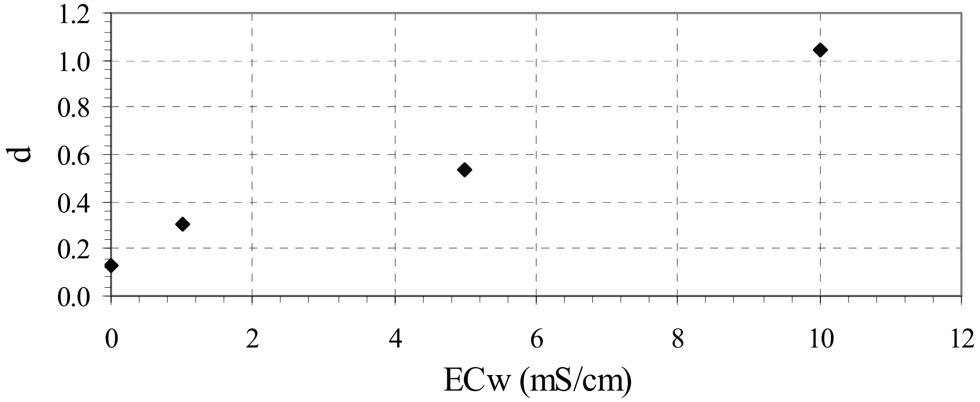


Figure 4-9. Sample #6978 Variation of “d” with Pore Fluid Conductivity.

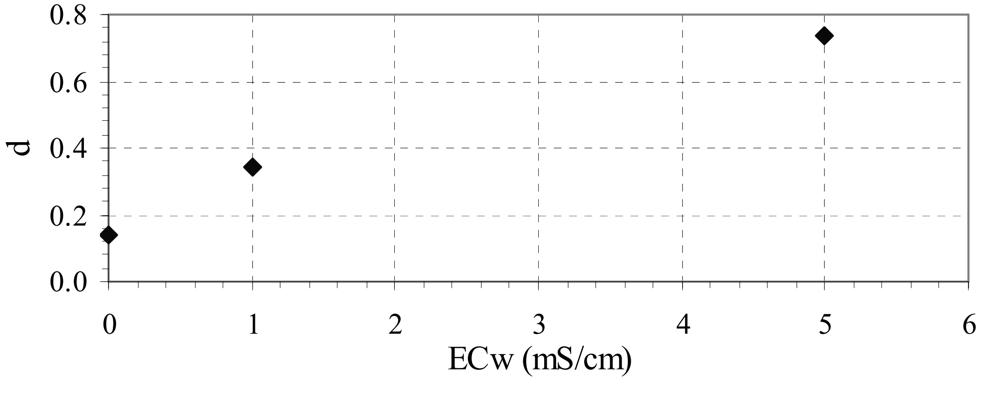


Figure 4-10. Fl Sand #2 Variation of “d” with Pore Fluid Conductivity.

Figures 4-8, 4-9 and 4-10 show that a relationship exists between pore fluid conductivity and constant “d.” Constant “d” increases with pore fluid conductivity. The relationship appears to assume a parabolic form. It has been noted previously that pore fluid conductivity has a large effect on the calibration of soil bulk electrical conductivity. Data from Amenta et al. (2000) demonstrates the effect of pore fluid conductivity on bulk electrical conductivity calibration (Figure 4-11).

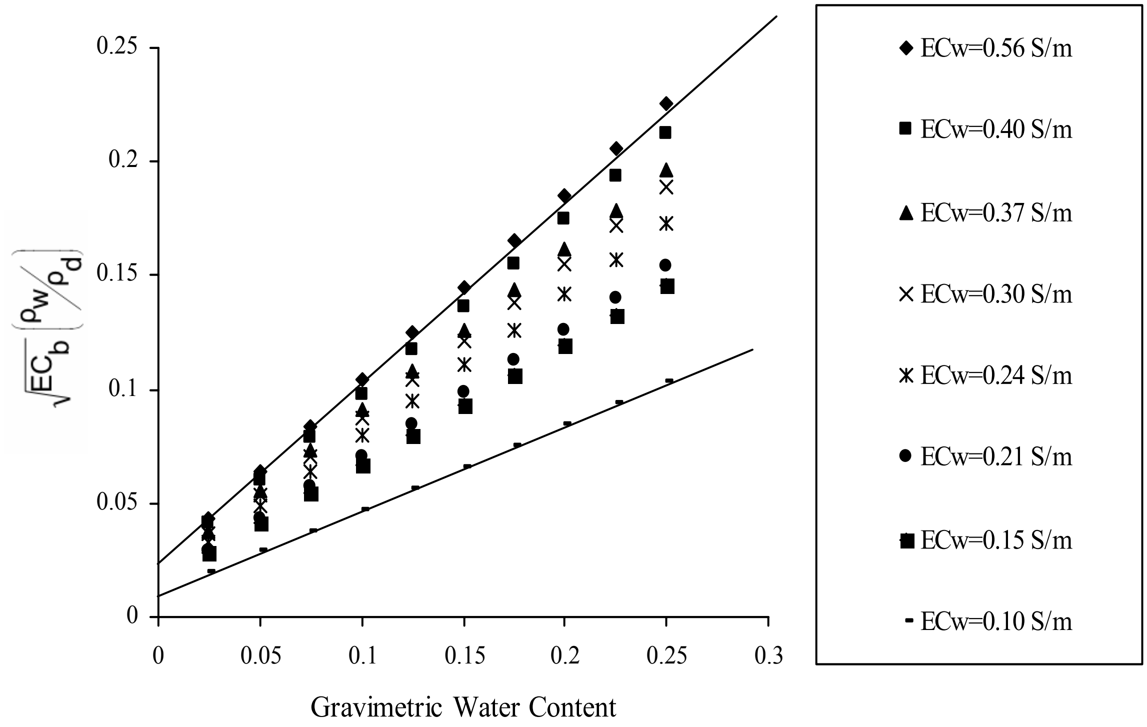


Figure 4-11. Relationship between EC_b and Gravimetric Water Content.
Source: Amenta et al. (2000).

As displayed in Figure 4-11 the slope of the calibration line (constant “d”) systematically increases with an increase in pore fluid conductivity. This is consistent with the previous discussion of the dominance of the pore fluid on bulk electrical conductivity measurement. Although pore fluid conductivity largely governs the calibration of “d,” constant “c” should be affected to a lesser degree. This is seen in Figure 4-11 where the y-intercept (constant “c”) varies little. It appears that calibration lines pivot around constant “c” at the y-axis. Further discussion as to the significance of constant “c” is addressed later in this chapter.

4.5.3. Effect on Constants “f” and “g”

The values of constant “g” were recorded for every pore fluid conductivity tested and then plotted for each soil. Results are displayed in Figures 4-12, 4-13 and 4-14.

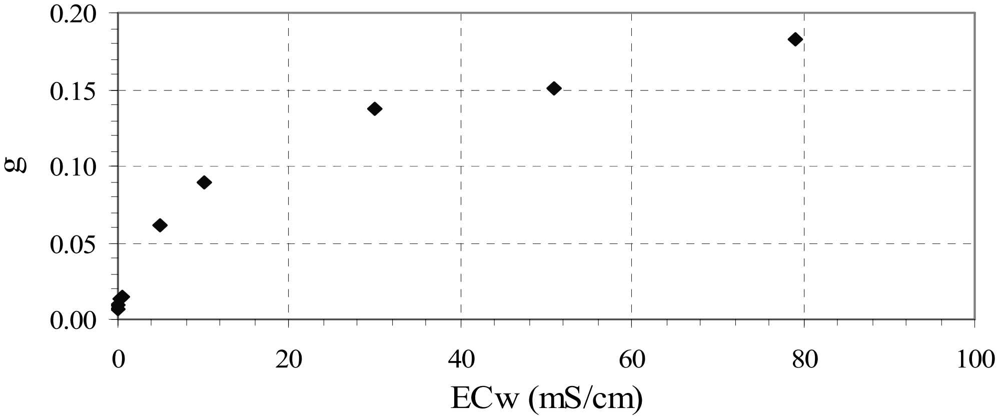


Figure 4-12. Ottawa Sand Variation of “g” with Pore Fluid Conductivity.

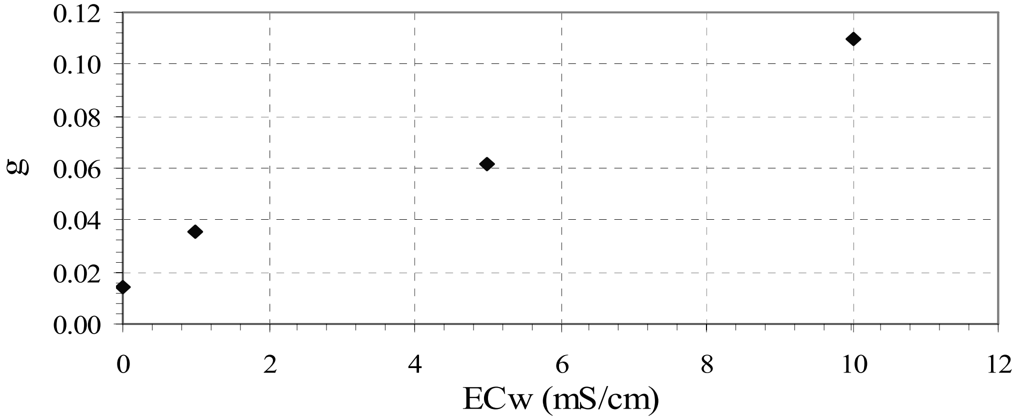


Figure 4-13. Sample #6978 Variation of “g” with Pore Fluid conductivity.

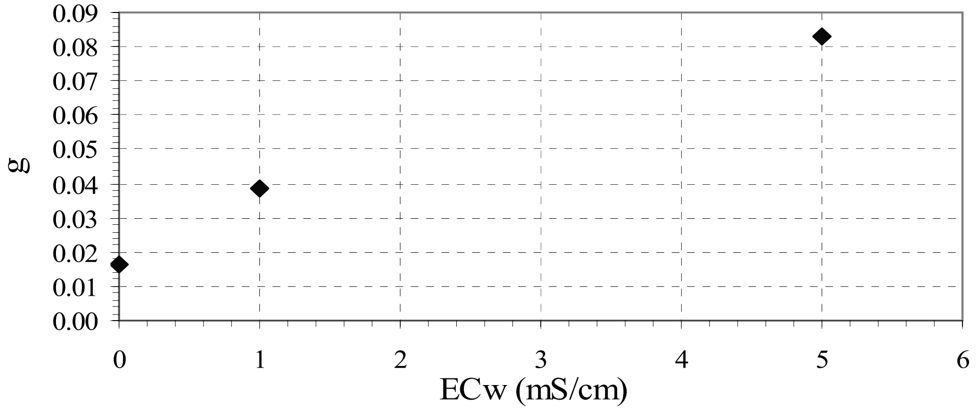


Figure 4-14. Fl Sand #2 Variation of “g” with Pore Fluid Conductivity.

Figures 4-12, 4-13 and 4-14 display a similar trend to that seen with constant “d.” This is expected, as constant “g” is dependant on constant “d.” Constant “f” varies widely as constant “g” changes with pore fluid conductivity. This is due to the nature of the bulk electrical conductivity and dielectric constant calibration. Calibration lines pass through a point that is defined by the dry calibration point, which is not located on the y-axis. As a result a change in slope will significantly affect the y-intercept. This concept will be further developed in the subsequent section.

4.5.4. Summary

Although there are several possible calibrations for “c,” “d,” “f” and “g” depending on pore fluid conductivity, Yu and Drnevich (2004) point out that only one calibration is needed to adjust the field measurement to the calibration condition. The assumption is that the pore fluid conductivity remains constant during calibration. Calibration with tap water is recommended for accurate parameter evaluation.

4.6. Effect of Initial Salt Content on Calibration Constants

If a soil contains an appreciable amount of salts, it is reasonable to assume that the pore fluid conductivity does not remain constant during the calibration phase. With the addition of tap water to a salty soil, the salt will dissolve into the tap water and increase the pore fluid conductivity. As more water is added, the pore fluid conductivity will decrease as the dissolved salt is diluted. The system will eventually reach a constant pore fluid conductivity at higher water contents. Under these conditions it is clear that the pore fluid conductivity will not be constant during calibration and will not yield the true calibration constants.

4.6.1. Initial Salt Content Testing

In an effort to demonstrate the effect of initial salt content on the calibration of the one-step method, a series of tests were carried out on three soil types (Table 4-6). Ottawa Sand and two local sand samples were used with varying amounts of fines. Each soil was prepared by cleaning the sample with deionized water until a low initial pore fluid conductivity was obtained. For the three samples tested, the pore fluid conductivity values after washing are displayed in Table 4-6.

Table 4-6. Testing Material Summary.

Soil	Classification	% Fines	ECw Cleaned
Ottawa Sand	SP or A-1-b	0	< 10 µS/cm
#6978	SP or A-1-b	1.36	< 35 µS/cm
Fl Sand #2	SP or A-3	1.82	< 45 µS/cm

After the samples had been washed, they were calibrated with water at several different pore fluid conductivities. These calibrations were termed "true" calibrations. The samples were then calibrated with an initial salt concentration by either soaking the sand in a known pore fluid conductivity or by testing the soil in its natural condition. The samples were then calibrated with tap water and compared to the true calibrations.

The testing procedure can be summarized as follows:

1) Add deionized water to the sample and vigorously mix the soil with the deionized water (Figure 4-15).
2) Allow the sample to stabilize by allowing the fine-grained particles to settle (time varies depending on the amount of fines contained in the soil).

3) Drain the excess water from the sample. For Ottawa Sand (low fines content) the sample was placed in a geofabric and drained (Figure 4-16). For the other samples (higher fines content) the excess water was siphoned from the sample after all fines had settled.

4) Repeat steps 1) through 3) several times until the pore fluid conductivity reaches an acceptable level (washed values are recorded in Table 4-6).

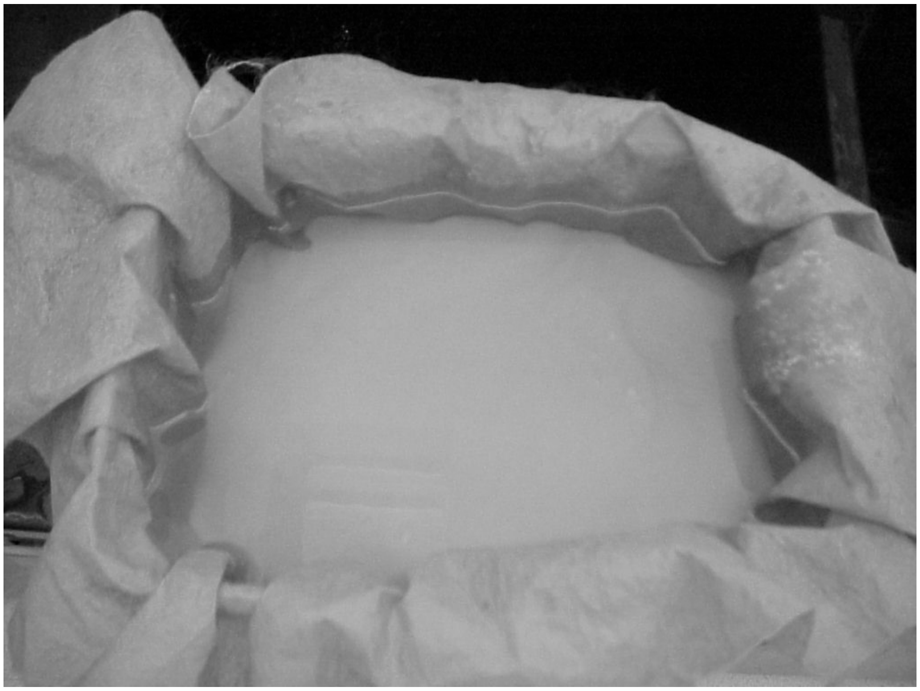


Figure 4-15 Mixing Soil with Deionized Water.

Figure 4-16. Draining Water from Sample.

5) Perform calibration outlined in Chapter 3 to obtain soil. Calibration should be performed at several known pore fluid conductivities to obtain the “true” calibrations. After each calibration the sample should be washed using the procedure outlined in steps 1) through 4).
6) Add a known amount of salt content to the sample and then perform a calibration using tap water.

4.6.2. Results and Discussion for “a” and “b”

Each of the three sands was calibrated at several different pore fluid conductivities ranging from deionized water (EC_w = 0 mS/cm) to 79 mS/cm. For Ottawa Sand and Sample #6978 a sample was soaked in 2 mS/cm water, dried and calibrated with tap water. For Florida Sand #2, a sample was calibrated in its natural condition with tap water. Figure 4-17 displays calibration results for “a” and “b” for Ottawa Sand, Figure 4-18 displays results for Sample #6978 and Figure 4-19 displays results for Florida Sand #2. The open diamonds represent the calibration that was performed with an initial amount of salt. The solid lines represent the true calibrations obtained after washing the sample.

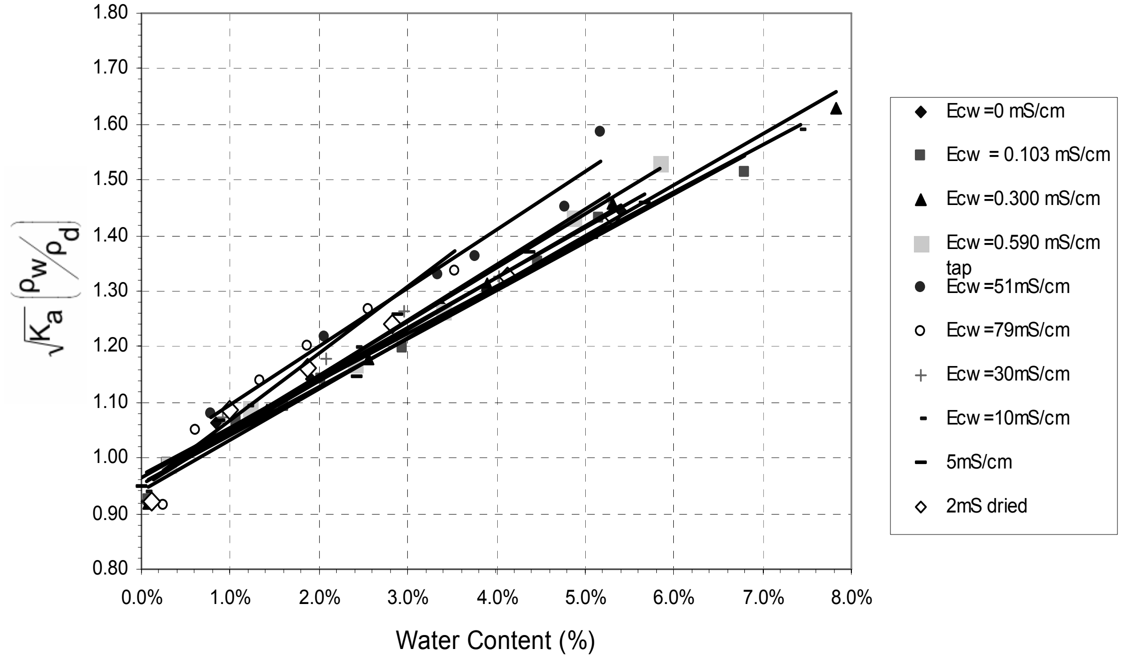


Figure 4-17. Ottawa Sand Calibration for “a” and “b.”

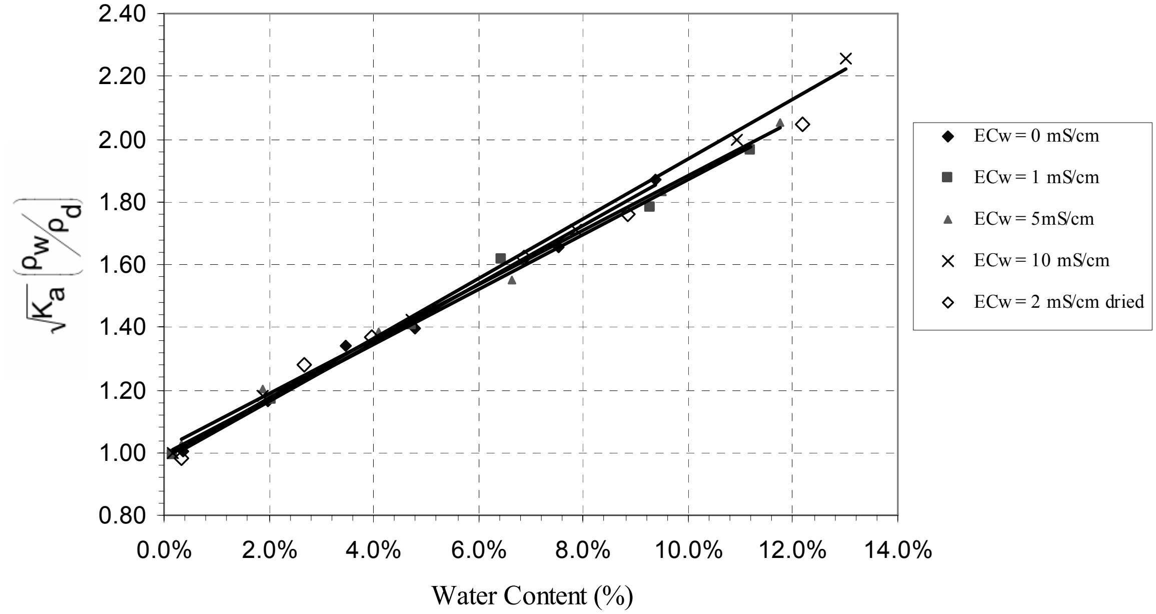


Figure 4-18. Sample #6978 Calibration for “a” and “b.”

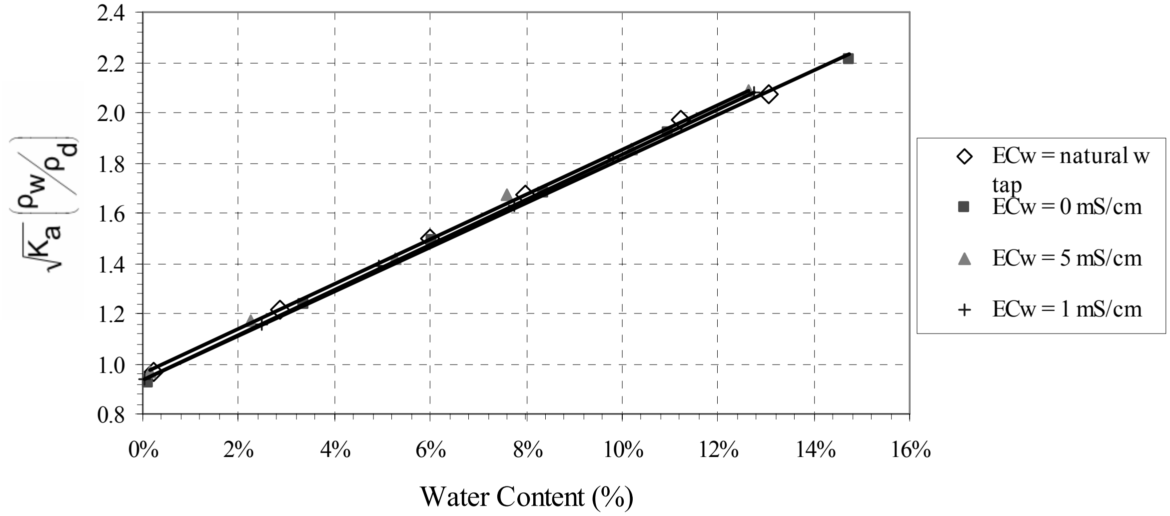


Figure 4-19. Fl Sand #2 Calibration for "a" and "b."

Results from Figures 4-17, 4-18 and 4-19 show that the true calibrations are similar to the calibrations that contained an initial amount of salt, indicating that initial salt content does not affect the calibration of soil constant "a" and "b." This was expected as it has been shown that pore fluid conductivity has little to no effect on dielectric constant calibration for common geotechnical materials.

4.6.3. Results and Discussion for "c" and "d"

Figure 4-20 displays calibration results for "c" and "d" for Ottawa Sand. Figure 4-21 displays results for Sample #6978, and Figure 4-22 displays results for Florida Sand #2. The open diamonds represent the calibration that was performed with an initial amount of salt. The solid lines represent the true calibrations obtained after washing the sample.

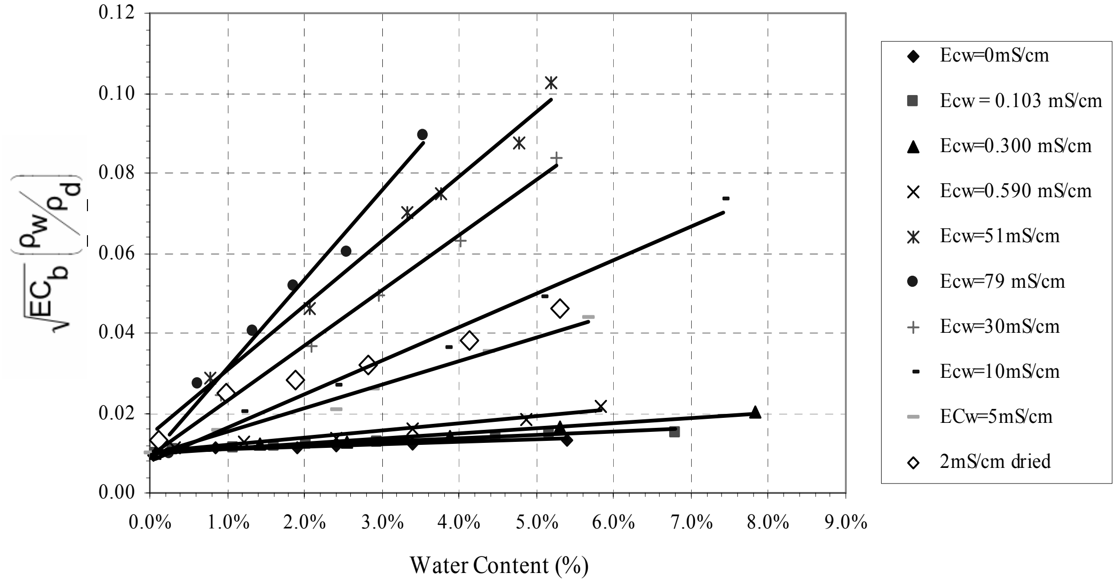


Figure 4-20. Ottawa Sand Calibration for “c” and “d.”

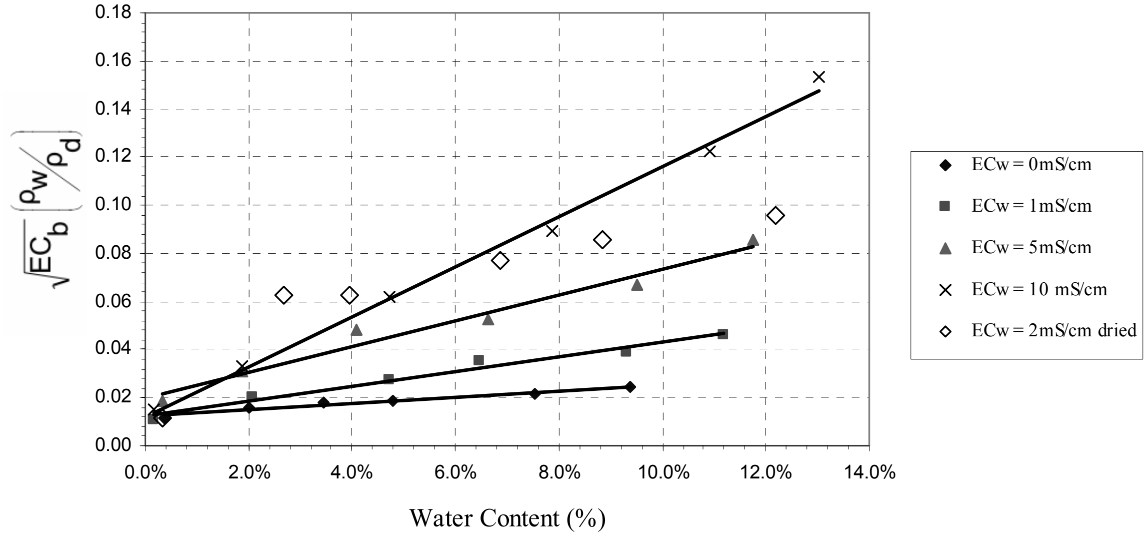


Figure 4-21. Sample #6978 Calibration for “c” and “d.”

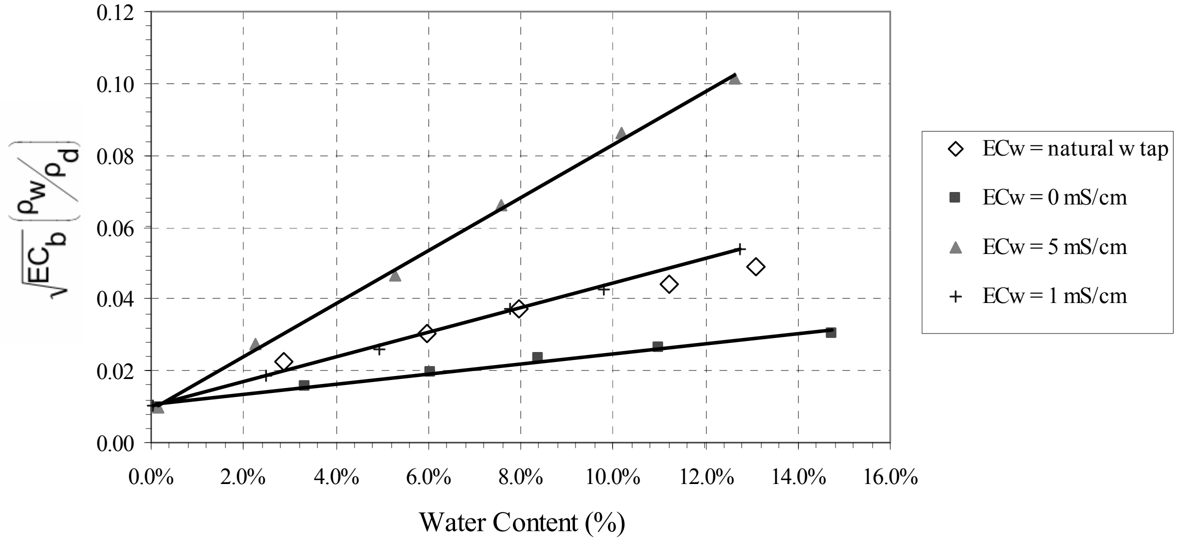


Figure 4-22. Fl Sand #2 Calibration for “c” and “d.”

In Figures 4-20, 4-21 and 4-22 the slopes of the true calibration lines vary systematically with pore fluid conductivity as demonstrated by Amenta et al. (2000) Figure 4-11). The open diamonds indicate the calibration points that were determined with an initially salty sample. Clearly these points demonstrate that a calibration obtained with an initially salty soil will not yield the true calibration constants; rather the slope (constant “d”) will be less than the true value and the intercept (constant “c”) will be slightly higher than the true value. This can be explained by the initial amount of salt dissolving into the tap water and increasing the pore fluid conductivity. This causes the calibration to follow a higher pore fluid conductivity calibration. As more tap water is added, the pore fluid conductivity will decrease and the calibration will follow a lower calibration line. This process will continue until the pore fluid conductivity stabilizes or in this case reaches that of the tap water being added. The calibration obtained is therefore not a true calibration, but a calibration that is being subjected to a constantly changing pore fluid conductivity. Such a calibration would not be valid under the requirement set forth by Yu and Drnevich (2004) that a constant pore fluid conductivity be used during calibration.

Constant “c” varies only slightly for each calibration regardless of the pore fluid conductivity of water that is used for calibration. The true calibrations obtained all passed through or near this point. All true calibrated values of “c” were close to 0.01 for each of the three sands tested. Constant “c” may be unique for sands similar to those tested and will vary only slightly with dry density according to Eqn. (4-5). This indicates that the electrical conductivity of the soil solid particles for sands is essentially constant and does not depend on an initial amount of salt contained within the sample or the pore fluid conductivity used to calibrate the sample since the soil is dry.

4.6.4. Results and Discussion for “f” and “g”

Figure 4-23 displays Ottawa Sand calibration results for “c” and “d.” Figure 4-24 displays results for Sample #6978, and Figure 4-25 displays results for Florida Sand #2. The open diamonds represent the calibration that was performed with an initial amount of salt. The solid lines represent the true calibrations obtained after washing the sample.

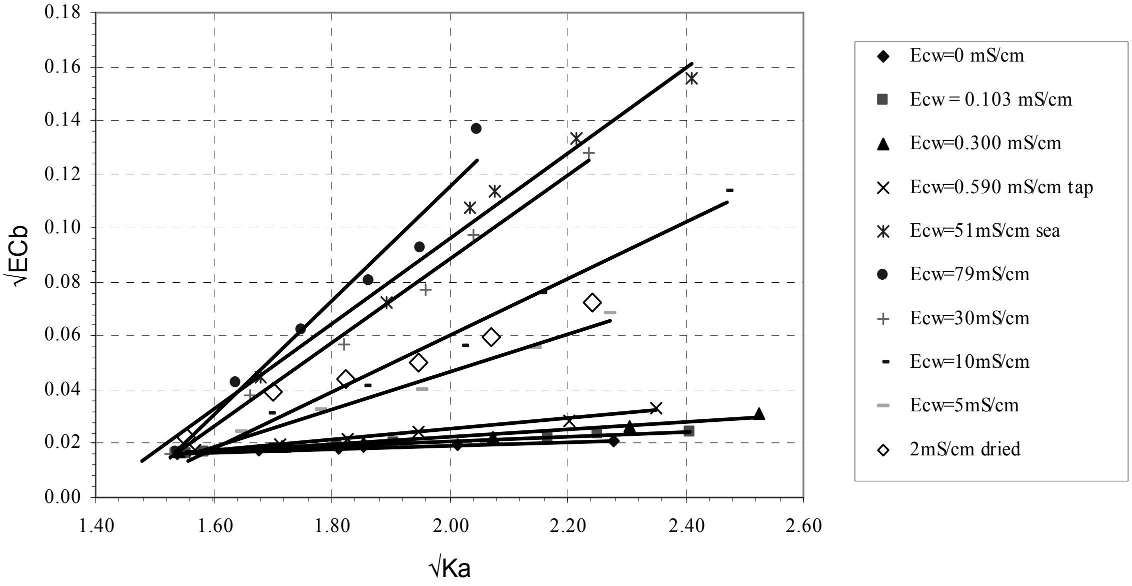


Figure 4-23. Ottawa Sand Calibration for “f” and “g.”

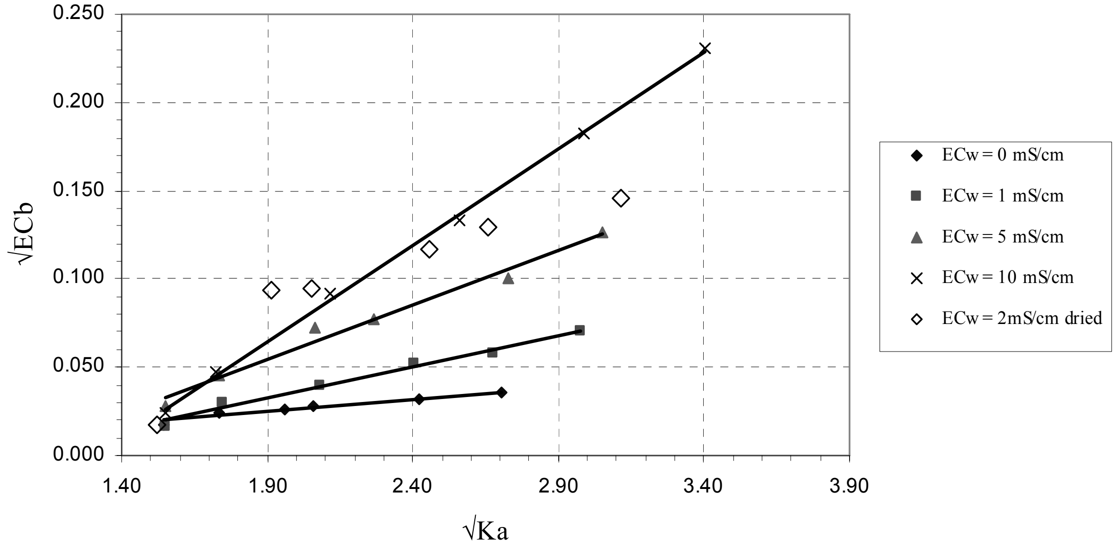


Figure 4-24. Sample #6978 Calibration for "f" and "g."

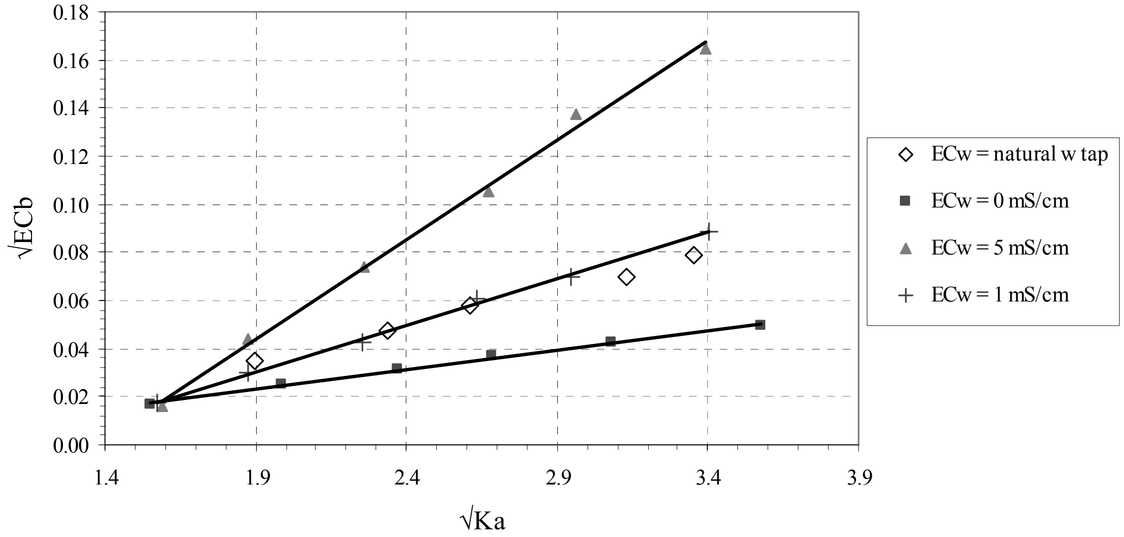


Figure 4-25. Fl Sand #2 Calibration for "f" and "g."

Figures 4-23, 4-24 and 4-25 yield results that are similar to those obtained for "c" and "d." Soil constant "g" varies systematically with pore fluid conductivity as does constant "d." This was expected as "g" is a function of "d" and "b." Since "b" is largely unaffected by pore fluid conductivity, the variation of “g” with pore fluid conductivity is attributed to changes in “d.” The open diamonds indicate the calibration points that were determined with an initially salty sample. Results indicate that constant “g” will be smaller than the true value and that “f” will be slightly higher than the true value. Since constant “g” varies closely with constant “d,” similar behavior in terms of the effect of initial salt content is expected.

Figures 4-23, 4-24 and 4-25 show that the true calibration values for “f” and “g” pass through virtually the same point corresponding to the dry condition. It appears that this point will be unique for a given soil that will vary slightly with dry density. This indicates that the bulk electrical conductivity of the soil solids is not affected by the presence of salt under dry conditions.

4.7. Summary

The results presented in this chapter indicate that calibrations obtained for the dielectric constant (“a” and “b”) are unaffected by initial salt content. Calibrations obtained for electrical conductivity are affected by the initial salt content according to amount present in the sample. True calibrations that are unaffected by initial salt content can be obtained by washing the sample with deionized water and then calibrating the sample.

Calibration points obtained at zero water content appear to be “true” calibration points regardless of salt content. Constant “c” may be a true calibration constant regardless of initial salt content and pore fluid conductivity. As such, the zero-moisture condition in the bulk electrical conductivity and dielectric constant plots may be a unique point regardless of pore fluid conductivity and initial salt content.

If calibration constant “c” is a unique value for a given soil, it may be possible to extract a true calibration from this point. This may be done by obtaining the remainder of the calibration points at high water contents where the pore fluid conductivity can be assumed to be constant as the solution will be dilute. The calibration points along with the zero water content point may be used to extract the true calibration slope (constant “d”). Another option may be to generate a calibration line with only constant “c” being known. Knowing that the value of “d” varies systematically with pore fluid conductivity, an arbitrary slope can be selected within a typical range of values. The pore fluid conductivity of such a calibration would not be known; however it would be a true calibration line as it passes through the zero water content intercept point. If a unique point can be defined at the zero water content point for the “f” and “g” calibration a similar process may be used to extract a true calibration line from the known dry point. This would require a back calculation of the value of “g” from the arbitrarily selected value of “d” and a previously calibrated value of constant “b.” The validity of any such extraction of true calibration lines from known dry points requires further validation. However, such a process would eliminate the need to wash a soil to obtain a true calibration that is unaffected by initial salt concentration.

5. ASTM TDR Method Compared to Traditional Methods

5.1. Introduction

The advances in TDR technology that led to the development of the one-step TDR method has been the focus of previous chapters. Due to the recent nature of these developments a testing program has been implemented to compare the one-step method with traditional methods. In April of 2004 phase-one of the TDR method report was submitted to the state by the University of South Florida. The report detailed a field study that was carried out in conjunction with the Florida Department of Transportation (FDOT) to evaluate the relative accuracy of the ASTM TDR two-step method. The testing program included a series of side by side tests with the TDR two-step method and the nuclear, sand cone and drive sleeve methods. In keeping with this testing regime a similar study was conducted to evaluate the ASTM TDR one-step method. The nuclear method was selected for purposes of this study to assess the TDR one-step method. This method was selected based on its widespread use across the state. The drive sleeve and the sand cone methods discussed in chapter two were not considered in this particular study.

The nuclear method is only used by FDOT for rock base materials, not for embankment or subgrade soils. Because the nuclear moisture measurement uses the back scatter method and has a limited depth of measurement, the speedy moisture method is typically used for embankments and subgrades. In the context of the comparative study outlined in this chapter, all three methods speedy, nuclear, and TDR moistures were addressed. The oven dry moisture content was taken in order to get the most accurate baseline.

5.2. Testing Program

The widespread use of the nuclear method by the Florida DOT allows for ready access to a large amount of data. The nuclear method is commonly implanted at a variety of job sites across the state of Florida. TDR measurements can easily be taken simultaneously with routine nuclear gauge testing using the ASTM TDR method. Samples were collected from all testing locations and were taken to the laboratory to obtain a baseline oven dry water content. Due to the lack of a baseline method for measuring in-situ soil dry density, the nuclear moist density was used as a baseline, with the dry density back-calculated from the oven dry moisture content. This, of course, is not entirely accurate, however it was the method most readily available.

5.3. Results

A series of side-by-side tests were carried out at several locations throughout Florida using the speedy moisture, nuclear gauge and the TDR one-step method. Calibration values were determined using the calibration procedures outlined in chapter three. These unique calibration constants were used for field TDR measurements. A summary of test locations and soil types for the nuclear to ASTM TDR comparison is displayed in Table 5-1. Testing was carried out at two highway projects. Several tests were run at each location. All samples tested were common construction soils encountered in Florida (A-3 sands).

Table 5-1. Testing Locations and Information.

Location	County/City	No. of TDR	No. of Speedy and Nuclear	Soil Type(s)
I-4	Tampa	3	6	A-3
US 301	Hillsborough	10	30	A-3

Table 5-2 displays the ASTM TDR, speedy and nuclear water content measurements recorded at each test site along with the oven dry baseline water content measured in the laboratory. The percent error and absolute error was then calculated by comparing the field water content measurements to the baseline water content values. The data from Table 5-2 is displayed graphically in Figures 5-1 and 5-2. Data points for speedy, nuclear and ASTM TDR testing were plotted along with a 1:1 line.

Table 5-2. Water Content Comparison Results.

Location	Test	Oven w_c	TDR w_c	Speedy w_c	Nuclear w_c	% Error TDR	% Error Speedy	% Error Nuclear	Absolute TDR	Absolute Speedy	Absolute Nuclear
I-4	1	5.3	6.5	6.7	5.6	23.6%	27.4%	6.5%	1.24%	1.44%	0.34%
I-4	2	3.8	4.4	4.6	4.0	16.4%	21.7%	5.8%	0.62%	0.82%	0.22%
I-4	3	4.3	5.1	4.9	3.5	17.8%	12.0%	-19.2%	0.77%	0.52%	-0.83%
US 301	1a	9.3	9	7.4	10.1	-3.2%	-20.4%	8.6%	-0.30%	-1.90%	0.80%
US 301	1b	9.2		8.3	7.9		-9.8%	-14.1%		-0.90%	-1.30%
US 301	1c	9.5		8.6	9.2		-9.5%	-3.2%		-0.90%	-0.30%
US 301	2a	6.5	6.8	7.3	6	4.6%	12.3%	-7.7%	0.30%	0.80%	-0.50%
US 301	2b	8.3		6.9	6.1		-16.9%	-26.5%		-1.40%	-2.20%
US 301	2c	6.5		7.6	6.4		16.9%	-1.5%		1.10%	-0.10%
US 301	3a	4.7	5.8	4.8	5.1	23.4%	2.1%	8.5%	1.10%	0.10%	0.40%
US 301	3b	5.9		5.8	4.7		-1.7%	-20.3%		-0.10%	-1.20%
US 301	3c	7.3		4.6	6.5		-37.0%	-11.0%		-2.70%	-0.80%
US 301	4a	6.4	6.7	6.8	5.5	4.7%	6.2%	-14.1%	0.30%	0.40%	-0.90%
US 301	4b	5.4		6.5	4.3		20.4%	-20.4%		1.10%	-1.10%
US 301	4c	5.1		5.8	4.2		13.7%	-17.6%		0.70%	-0.90%
US 301	5a	8.1	6.7	9.2	7.8	-17.3%	13.6%	-3.7%	-1.40%	1.10%	-0.30%
US 301	5b	5.3		6	4.7		13.2%	-11.3%		0.70%	-0.60%
US 301	5c	6.7		7.3	6.2		9.0%	-7.5%		0.60%	-0.50%
US 301	6a	6.6	6.9	3.5	7.1	4.5%	-47.0%	7.6%	0.30%	-3.10%	0.50%
US 301	6b	7.9		8	7.9		1.3%	0.0%		0.10%	0.00%
US 301	6c	6.3		6.4	5.5		1.6%	-12.7%		0.10%	-0.80%
US 301	7a	10.5	9.7	10.1	11.1	-7.6%	-3.8%	5.7%	-0.80%	-0.40%	0.60%
US 301	7b	10.0		5.6	10.8		-44.0%	8.0%		-4.40%	0.80%
US 301	7c	8.0		3.6	6.9		-55.0%	-13.8%		-4.40%	-1.10%
US 301	8a	7.6	6.9	7.3	6.4	-9.2%	-3.9%	-15.8%	-0.70%	-0.30%	-1.20%
US 301	8b	7.2		7.6	7.1		5.6%	-1.4%		0.40%	-0.10%
US 301	8c	7.2		7.6	6.5		5.6%	-9.7%		0.40%	-0.70%
US 301	9a	7.6	8.1	8	7.1	6.6%	5.3%	-6.6%	0.50%	0.40%	-0.50%
US 301	9b	7.9		8.3	6.9		5.1%	-12.7%		0.40%	-1.00%
US 301	9c	8.3		8.5	8.2		2.4%	-1.2%		0.20%	-0.10%
US 301	10a	8.3	8	8.3	8.1	-3.6%	0.0%	-2.4%	-0.30%	0.00%	-0.20%
US 301	10b	9.0		8.1	7.9		-10.0%	-12.2%		-0.90%	-1.10%
US 301	10c	7.5		8	6.1		6.7%	-18.7%		0.50%	-1.40%

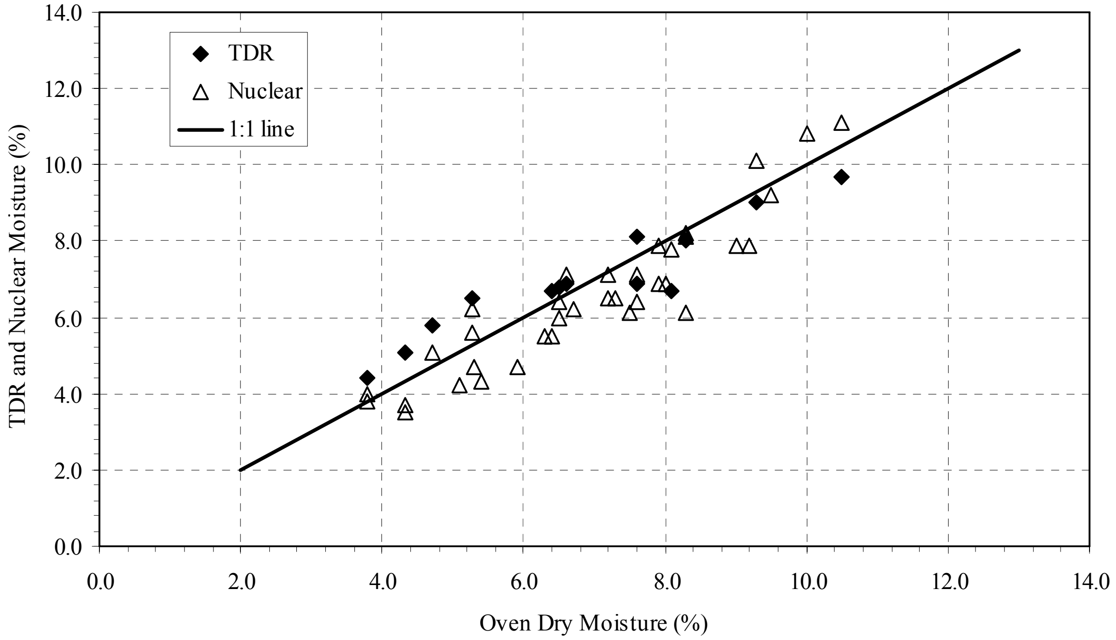


Figure 5-1. Nuclear Moisture versus ASTM TDR Water Content.

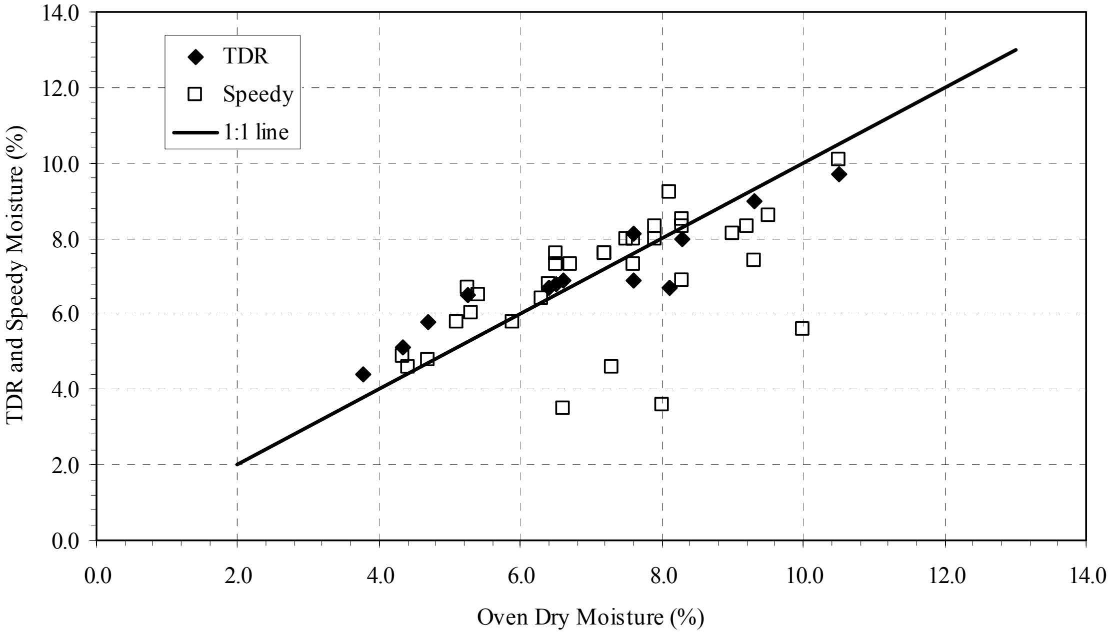


Figure 5-2. Speedy Moisture versus ASTM TDR Water Content.

Table 5-3. Dry Density Comparison Results.

Location	Test	Oven ρ_d	TDR ρ_d	Speedy ρ_d	Nuclear ρ_d	% error TDR	% error Speedy	% error Nuclear	Absolute TDR	Absolute Speedy	Absolute Nuclear
I-4	1a	112.1	103.9	110.5	111.7	-7.3%	-1.4%	-0.4%	-8.20	-1.60	-0.40
I-4	1b	115.7		114.2	114.7		-1.3%	-0.9%		-1.50	-1.00
I-4	2a	105.9	102.1	105.2	105.8	-3.6%	-0.7%	-0.1%	-3.80	-0.70	-0.10
I-4	2b	109.7		108.9	109.7		-0.7%	0.0%		-0.80	0.00
I-4	3a	108.6	102.8	108.0	109.4	-5.3%	-0.6%	0.7%	-5.80	-0.60	0.80
I-4	3b	111.4		110.9	112.1		-0.4%	0.6%		-0.50	0.70
US 301	1a	111.9	109.6	113.9	111.1	-2.1%	1.8%	-0.7%	-2.29	1.98	-0.81
US 301	1b	112.1		113.0	113.4		0.8%	1.2%		0.93	1.35
US 301	1c	110.7		111.6	111.0		0.8%	0.3%		0.92	0.30
US 301	2a	110.2	106.1	109.4	110.8	-3.8%	-0.7%	0.5%	-4.13	-0.82	0.52
US 301	2b	106.8		108.2	109.0		1.3%	2.1%		1.40	2.22
US 301	2c	107.5		106.4	107.6		-1.0%	0.1%		-1.10	0.10
US 301	3a	109.1	104.6	109.0	108.7	-4.1%	-0.1%	-0.4%	-4.47	-0.10	-0.42
US 301	3b	106.3		106.4	107.5		0.1%	1.1%		0.10	1.22
US 301	3c	108.3		111.1	109.1		2.6%	0.8%		2.80	0.81
US 301	4a	111.3	105.1	110.9	112.2	-5.6%	-0.4%	0.9%	-6.18	-0.42	0.95
US 301	4b	112.1		111.0	113.3		-1.0%	1.1%		-1.16	1.18
US 301	4c	109.4		108.7	110.4		-0.7%	0.9%		-0.72	0.95
US 301	5a	109.9	105.9	108.8	110.2	-3.6%	-1.0%	0.3%	-4.00	-1.11	0.31
US 301	5b	105.4		104.7	106.0		-0.7%	0.6%		-0.70	0.60
US 301	5c	109.5		108.9	110.0		-0.6%	0.5%		-0.61	0.52
US 301	6a	108.3	106.2	111.5	107.7	-1.9%	3.0%	-0.5%	-2.06	3.24	-0.51
US 301	6b	107.0		106.9	107.0		-0.1%	0.0%		-0.10	0.00
US 301	6c	111.2		111.1	112.0		-0.1%	0.8%		-0.10	0.84
US 301	7a	112.6	110.8	113.0	112.0	-1.6%	0.4%	-0.5%	-1.78	0.41	-0.61
US 301	7b	112.3		117.0	111.5		4.2%	-0.7%		4.68	-0.81
US 301	7c	113.1		118.0	114.3		4.2%	1.0%		4.81	1.16
US 301	8a	110.8	106.2	111.1	112.0	-4.1%	0.3%	1.1%	-4.58	0.31	1.25
US 301	8b	109.7		109.3	109.8		-0.4%	0.1%		-0.41	0.10
US 301	8c	107.1		106.7	107.8		-0.4%	0.7%		-0.40	0.70
US 301	9a	112.8	108.1	112.4	113.4	-4.2%	-0.4%	0.5%	-4.73	-0.42	0.53
US 301	9b	113.3		112.8	114.3		-0.4%	0.9%		-0.42	1.06
US 301	9c	114.5		114.3	114.6		-0.2%	0.1%		-0.21	0.11
US 301	10a	111.2	108.0	111.2	111.4	-2.9%	0.0%	0.2%	-3.17	0.00	0.21
US 301	10b	109.4		110.4	110.6		0.8%	1.0%		0.91	1.12
US 301	10c	112.5		111.9	113.9		-0.5%	1.3%		-0.52	1.48

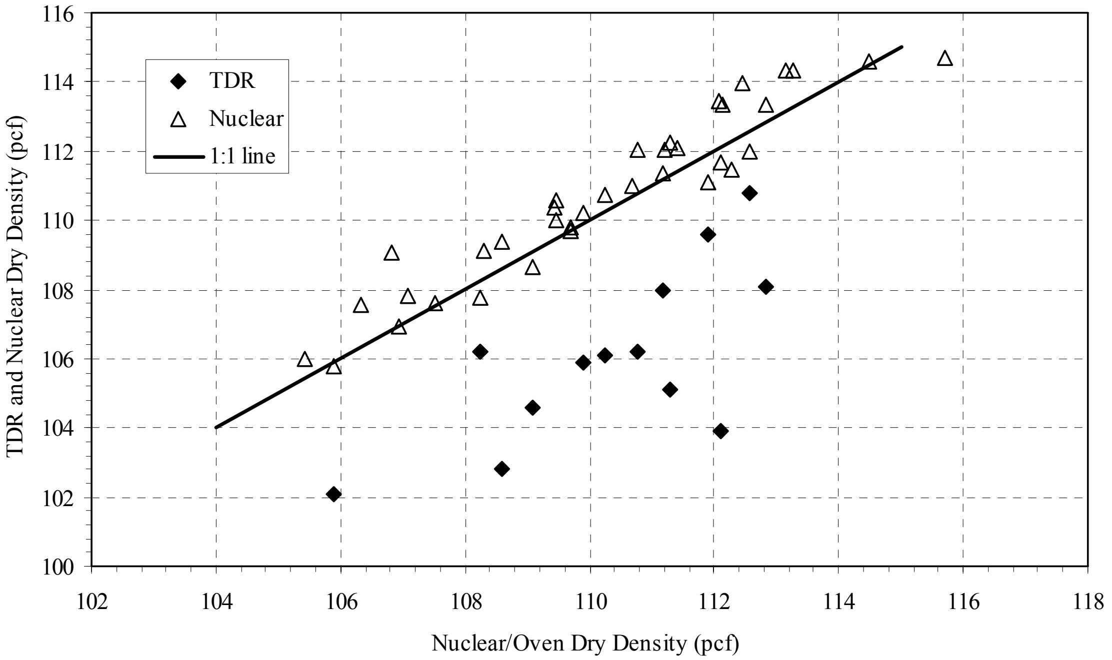


Figure 5-3. Nuclear Density/Nuclear Moisture versus ASTM TDR dry density.

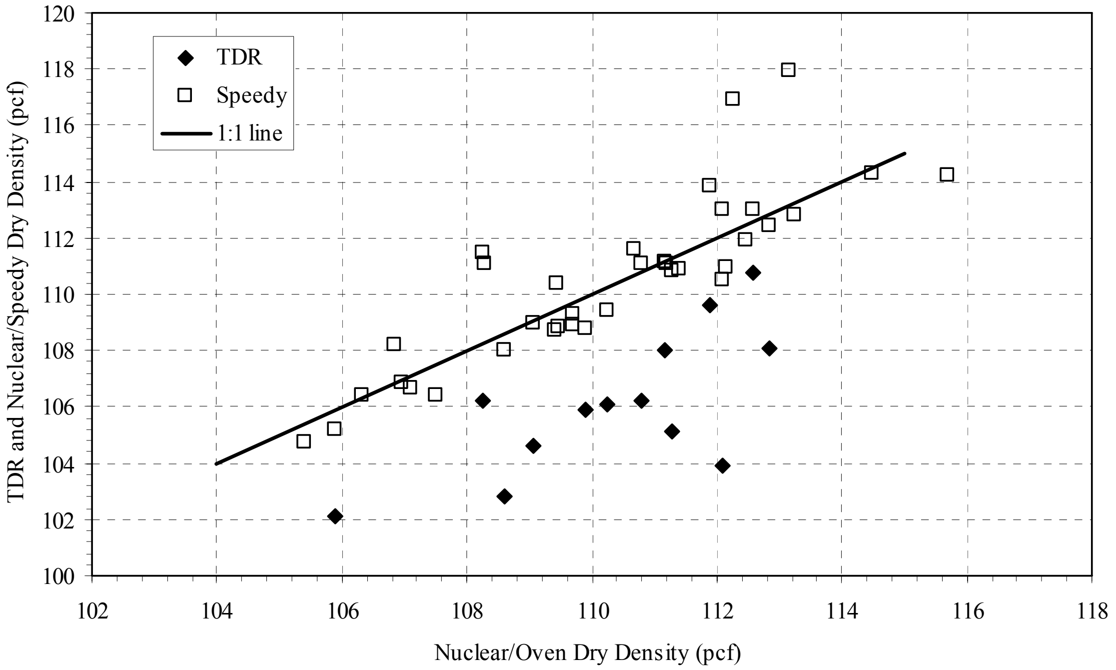


Figure 5-4. Nuclear Density/Speedy Moisture versus ASTM TDR dry density.

Table 5-3 summarizes the corresponding ASTM TDR dry density measurements, dry density back calculated using the wet nuclear density and the speedy moisture content, and dry density back calculated using the wet nuclear density and the nuclear moisture content along with the dry density back calculated using the wet nuclear density and the oven dry water content. The values were compared and percent and absolute error were calculated. All data points for both the nuclear and ASTM TDR tests were plotted in Figures 5-3 and 5-4 along with a 1:1 line.

5.4. Water Content Measurement Discussion

The water content measurement comparison displayed in Table 5-2 shows the absolute error for both the ASTM TDR and nuclear methods varied similarly (ASTM TDR between -0.01 and 0.01 while the nuclear varied between -0.02 and 0.01). The speedy moisture was slightly more variable with a range of -0.04 and 0.01. A graphic representation of scatter for speedy, nuclear and TDR methods compared to the oven dry method is displayed in Figures 5-1 and 5-2. It can be seen in both view graphs that the ASTM TDR one-step method shows less scatter than both nuclear and speedy moisture content when compared to the baseline oven dry water content. The study performed by Sallam et al. (2004) indicated that the ASTM TDR two-step method is likely to underpredict water content, this trend was not apparent in the one-step method. That is there is not sufficient evidence to say that the TDR one-step method either under or over predicts the moisture content. The ASTM TDR measurements have a higher correlation coefficient with the oven dry measurements than the nuclear or the speedy measurements (0.897 for the ASTM TDR method compared to 0.857 for the nuclear method and 0.334 for the speedy moisture).

5.4.1. Variation of Water Content

In an effort to study the variability of moisture content within a given site a series of field moisture test were performed using the ASTM TDR one-step method on a compacted subgrade. Measurements of water content were taken every 20 feet for a 100 foot by 4 foot section of compacted subgrade. Water content for each of the test locations were also determined by oven drying (ASTM D2216). The soil used for calibration had an A-3 classification which is typical for the state of Florida. A summary of one-step TDR and oven dry measurements is displayed in Table 5-4. The results from the field test for water content are plotted in Figure 5-5.

Table 5-4. Testing Locations and Measurements.

Test Position	Oven Dry	TDR
10	9.35	8.3
30	8.79	8.7
50	8.41	7.9
70	9.68	8.3
90	9.26	8.7

maximum	9.68	8.7
minimum	8.41	7.9
average	9.10	8.38
standard deviation	0.4992	0.3347

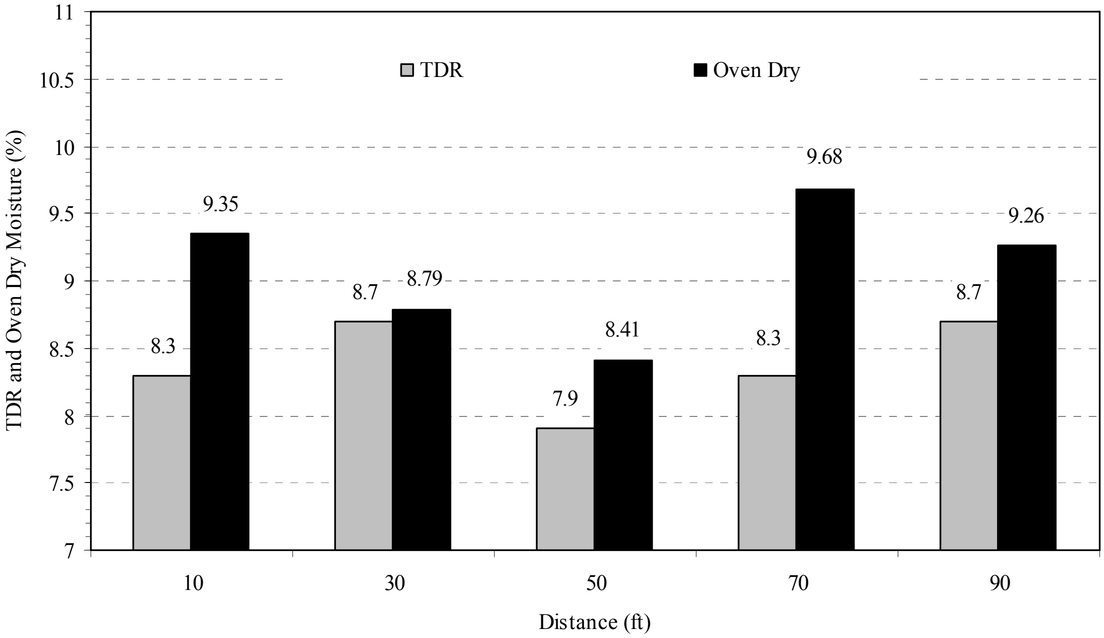


Figure 5-5. Water content variability within a site.

It can be seen from the site variability study that the site itself varies nearly 1.3 percent from the maximum to the minimum water content measurements. In this particular study the maximum and minimum values were recorded only twenty feet apart. It is evident that the spatial variability within the site is higher than the difference between TDR and oven dry moisture.

This is a very valuable finding in terms of evaluating the implementation of the one-step TDR method. It can be argued that since the “error” in TDR measurement is smaller than the spatial variability within the site, TDR is a reliable estimator of in-situ water content; however, more testing would be needed to certify the validity of this conclusion. It is also noted that the results of the variability study show that TDR under predicted the moisture content, which supports earlier observations by Sallam et al. (2004).

5.5. Dry Density Discussion

Due to the fact that the baseline dry density was calculated from a combination of the nuclear moist density and the oven dry moisture content results should not be viewed as an assessment of the absolute accuracy of the TDR method. Because the nuclear method represents current FDOT practice, the results presented in this Chapter represent a comparison between TDR and current FDOT standards. If the true accuracy of the ASTM TDR method is needed, the use of an independent point of reference for dry density is needed. However, the results presented above indicate that ASTM TDR dry density was consistently below the nuclear baseline value. In other words the ASTM TDR dry density provided a more conservative measurement than its nuclear counterpart. In addition, the results indicate that TDR measurements exhibit more scatter than their nuclear gage counterpart, possibly due to the reasons cited above.

5.6. Summary

Side-by side measurements comparing the ASTM TDR method to the nuclear method for water content measurement on Florida construction soils indicate that the ASTM TDR method displays less scatter than the speedy and nuclear gauge and as a result is likely more accurate with the proper selection of calibration constants “a”, “b”, “c”, “d”, “f”, and “g”. It thus appears that the TDR method is more reliable than the nuclear and speedy method. This statement is an echo of the Sallam et al. (2004) report which featured a field study on the ASTM TDR two-step method. However, a comparison of the data shows that the scatter between methods is comparable, with TDR exhibiting less scatter in terms of water content than the nuclear gage and the speedy moisture, and more scatter in terms of density. In general the TDR dry density readings are more conservative than the nuclear method. More comprehensive evaluations of the density variation within a given site, similar to that done for the water content discussed in section 5.4.1, would be of use during future implementation of the TDR method.

6. Summary, Conclusions and Recommendations

6.1. Summary

A comprehensive review of time domain reflectometry and its course to the field of geotechnical engineering was performed. Also a detailed review of work done at Purdue University in the development of both the ASTM TDR one-step method was completed. Testing was carried out to evaluate the effect of pore fluid conductivity and initial salt content on the soil specific calibration of TDR constants. A greater understanding of the soil specific TDR constants was obtained. The accuracy of the TDR one-step method was compared to that of current geotechnical testing methods used in the state of Florida. Research has lead to a greater understanding of the one-step TDR method that will aid in its further development and implementation to the field of geotechnical measurement.

6.2. Conclusions

Investigation into the soil specific TDR calibration constants proved to be valuable. Soil constants “a” and “b” were found to behave consistently with previous studies. It appears that soil constant “c” is a unique point for a given soil and it may be possible to catalog values based on soil type. For typical construction soils in Florida, and in the absence of soil-specific calibration data, a value of 0.01 should be used for constant “c”. Soil constant “d” was demonstrated to change systematically with pore fluid conductivity as previous research had indicated. Soil constants “f” and “g” change with the pore fluid conductivity of the soil since they are calculated from constant “a”, “b”, “c”, and “d”. Constant “g” behaves, in general, similar to constant “d.” It is also noted that for a calibration plot of the dielectric constant and the bulk electrical conductivity there may exist a unique point at the dry condition for a particular soil at which true calibration lines intersect.

Further investigation into the effect of pore fluid conductivity on the calibration to obtain the soil specific TDR constants revealed that the initial salt content affects calibration. A soil containing an appreciable amount of salt will alter calibration constants “c,” “d,” “f” and “g.” This is due to the constant change of pore fluid conductivity as the soil is calibrated. Values of “c” will be slightly higher than the true calibration value for initially salty soils, especially if the calibration is carried out at high water contents and “c” is extrapolated back onto the vertical axis of the calibration chart. In contrast, constant “d” will always be lower than the true calibration value. Similarly, constant “f” will typically be higher than the true calibration value and constant “g” will be lower. For a true calibration to be obtained a soil must be washed to remove salts since conductivity increases due to the presence of ions upon hydration. It must be noted that the true calibration of constant “c” may be determined at a dry soil condition. The intersect value “c” may be obtained regardless of salt content as long as the soil is tested at zero water content. To avoid washing a soil to obtain a true calibration line, it is recommended to obtain the true calibration constant “c” under dry conditions. Constant “d” will always be dependent on the electrical conductivity of the pore fluid. In order to obtain the “true” value of “d”, it is recommended that a calibration is performed at a high water content such that the salts will be diluted within the pore fluid and will have minimal effects on the calibration. As such, and if the blanket value of 0.01 for “c” is assumed, only one calibration point at the highest possible water content is needed to determine “d”.

Several tests were performed side-by-side using the ASTM TDR one-step method, nuclear gage, and speedy moisture. Data was compared for both moisture content and dry density measurement. Results indicate that the ASTM TDR method displays less scatter than the nuclear method for moisture content measurement and may be more accurate with the proper selection of calibration constants. Spatial analysis of the water content within a given site was studied. Results indicate that the site itself has a significant variation relative to the variation between the various methods. Dry density results showed that the ASTM TDR one-step measurements displayed larger scatter but consistently yielded lower densities than the nuclear density/speedy moisture measurements, and are therefore more conservative.

Research carried out further validates the ASTM TDR method as a viable tool for geotechnical measurement. A greater understanding of the soil specific constants used in conjunction with the one-step TDR method was also achieved. The results of studies carried out to evaluate the effects of pore fluid conductivity on calibration will be valuable to establishing the one-step TDR method as a reliable geotechnical measurement system.

6.3. Recommendations

In the absence of soil-specific calibration information, a value of 1.00 should be used for soil constant "a" and a value of 8.50 for soil constant "b" for sandy construction soils (A-3, A-1-b and A-2-4 soils) in the state of Florida. For A-2-4 soils, the percent fines must be below 15%. Also, a value of 0.01 should be used for soil constant "c" for both A-3 and A-1-b soils. The value of "d" can be determined by performing a single calibration test for the soil at a high value of water content, typically between 20% and 25%. Table 6-1 presents a summary of the recommended TDR calibration constants for use with Florida soils.

Table 6-1. Recommended values of TDR calibration constants for Florida soils, in the absence of a soil-specific calibration.

Soil Type	***a***	***b***	***c****	***d*** $^{+}$
A-1-b	1.0	8.50	0.01	0.2 to 0.5
A-2-4	1.0	8.50	0.02 to 0.05	0.3 to 0.5
A-3	1.0	8.50	0.01	0.3 to 0.7

[*] Lower values of *c* are associated with small percentages of fines, and vice versa.

[+] Higher values of d are associated with high pore fluid conductivity (or high salt content), and vice versa

Further routine evaluation by the FDOT State Materials Office (SMO) relating to the one-step method should be focused on building a history of the range of each constant and its relation to soil classification and gradation. As only sands were tested in research presented within this study, testing on soils with higher fines content is needed to validate the conclusions made herein for sands. The evaluation of measurement variability within a site must also be addressed in routine evaluations of TDR, nuclear, and other methods. A testing program involving the TDR one-step method and traditional methods would be of benefit in validating the accuracy. A comparison between dry density measurements would be of particular value.

One of the main issues currently impeding further evaluation of the absolute TDR accuracy is the lack of a standard against which to measure the density. One possibility is the use of sleeve or drive cylinder as an independent measure. However, the drive cylinder works well with only specific soil types. A method is currently being developed at the University of South Florida and is similar in concept to the sand cone, but relies on a viscous fluid (bentonite-cement slurry) to fill in the hole instead of sand. The density of the fluid is calibrated in its container prior to the test. Provisions will be made by controlling the viscosity of the fluid to ensure that it does not permeate out of the hole into the soil. The procedure is time-consuming, but gives an accurate value of density, and is thus an extremely valuable tool in evaluating the accuracy of the various other methods. Pilot testing using the method will be carried out in June-August 2006 and the results will be shared with FDOT.

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