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A NEW METHOD OF MEASURING DENSITY
AND MOISTURE CONTENT OF SOIL
USING THE TECHNIQUE OF
TIME DOMAIN REFLECTOMETRY

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PURDUE UNIVERSITY

Final Report

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USING THE TECHNIQUE OF TIME DOMAIN REFLECTOMETRY

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16. Abstract A new method is developed for measuring in-place density and moisture content of soil using the technique of Time Domain Reflectometry (TDR). The method is applicable for construction control of earthworks. The method is extended for measuring moisture content of soil in the laboratory and in the field for various other geotechnical purposes. Laboratory uses include measuring moisture content of soil in compaction molds; field uses include measuring moisture content of soil in Shelby tubes and soil retrieved during drilling and sampling operations. In the course of achieving these goals, this study develops the principles of TDR probe design, test methodology, and relationships of TDR measured dielectric constant with density and moisture content of soil. TDR was originally developed to locate faults in cables and transmission lines. For the last 20 years, it has also been used (mostly in soil science) to measure the volumetric moisture content of soil by using its capability of measuring the dielectric constant of soil. Some use has been made for measuring moisture content for engineering applications but soil density had to be known before volumetric moisture content could be converted to gravimetric moisture content which is used in geotechnical engineering. This study proposes a method of using TDR technique for measuring density of soil and extends the use of TDR for measuring moisture content of soil for various geotechnical purposes. In order to achieve these goals, this work develops various transmission lines/probes and devices. It develops coaxial transmission line (CTL) probes, composed of coaxial apparatus (CA) and cylindrical cells (CC). It develops multiple rod probes (MRP) which extend the capabilities of existing multiple rod probes. Analytical and experimental investigations are made to design different parameters of the probes. Investigations are carried out to study the effect of probe rod installation on measurements and experimental methods. Experiments are conducted to develop calibration equations to relate dielectric constant with moisture content and density of soil. The work describes how the TDR method can be used to measure in-situ density and moisture content of soil. The procedure makes use of the designed probes and devices. The concept behind measuring both in-situ density and moisture content is that with a MRP and the TDR instrument, the dielectric constant is measured in-situ. A sample of soil in-situ is then quickly placed in a cylindrical cell (CC) with the assumption that moisture content does not change. In the CC, the soil density and the dielectric constant is measured, the former with an electronic balance and the latter with an appropriate coaxial apparatus (CA) and the TDR instrument. With the dielectric constant and density, the moisture content of the soil in the CC is determined by use of known and developed relationships. Again, with the dielectric constant and density of the soil in the CC and the dielectric constant of soil in-situ, and with the assumption that the moisture content of soil in-situ is identical to the moisture content of the soil in the CC, it is possible to calculate the in-situ density by use of developed relationships. Significant testing of the procedures on a variety of soil types, along with comparisons with other measures of density and oven dry moisture content indicates that this new method is quick, safe and sufficiently accurate for measuring in-place density and moisture content of soil. The use of the methods and the devices (CTL and MRP) are extended to measure moisture content of soil for various other geotechnical purposes. Laboratory compaction mold and Shelby tubes serve as CCs where density are measured using conventional methods and moisture content are measured using CAs and MRPs. A specially designed coaxial transmission line (CTL) can measure moisture content of a soil sample retrieved during drilling operations. Experimental results show that these methods provide accurate measurement of moisture content of soils.			
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IMPLEMENTATION REPORT

Use of Time Domain Reflectometry for Determination of Water Content and Density of Soil

Project Number: HPR-2094

Objectives: In geotechnical engineering, there is a need of a technique which can measure moisture content of soil quickly, precisely, and preferably, in a non-destructive manner. It is necessary to measure moisture content of compacted soil speedily both in laboratory, such as in the compaction test, and to measure moisture content and density in the field for construction control. It is also desirable to know moisture content of sampled soil during boring operations. The oven

drying method for soil moisture content determination requires long waiting time and the nuclear method requires extensive calibration, has an unknown influence zone, and is potentially hazardous. Also the nuclear methods can not be used conveniently in the laboratory.

The technique of time domain reflectometry (TDR) has the potential to eliminate the drawbacks of the existing methods. It has been successfully used for measuring volumetric moisture content (volume of moisture per total volume of soil) of soil mostly in soil sciences. This study extends the use of TDR for measuring gravimetric moisture content (mass of moisture per unit mass of soil solids) of soil in the laboratory and in the field for geotechnical purposes.

Work Plan: The project proceeded as follows:

1. Review the literature to get the state-of-art information about the use of TDR in measuring soil moisture content.
2. Design and fabricate devices for measuring moisture content of: soil in the compaction mold, soil in thin-walled sampling tubes and soil sample retrieved during the standard penetration test. Develop devices for measuring in-place soil moisture content for compaction control (Fig. 1). Conduct laboratory and field experiments with the devices

Fig. 1. Measurement of Soil Moisture Content Using the TDR Method

to study their performances in measuring moisture contents. Modify the devices and procedures for getting best possible results.

3. Convene meetings of the Study Advisory Committee to demonstrate the use of the devices developed and to exchange ideas to improve the devices and methodologies.

Date Started: September, 1993

Completion Date: February, 1996

Reports: Siddiqui, S. I., and Drnevich, V.P. "Time Domain Reflectometry Development for Use in Geotechnical Engineering," paper submitted for possible publication in *Journal of the Geotechnical Division*, ASCE, January, 1996.

Siddiqui, S. I., and Drnevich, V.P., "A New Method of Measuring in-Place Density and Moisture Content of Soil," paper submitted for possible publication in the *Geotechnical Testing Journal*, ASTM, February, 1996.

Findings: The study showed that TDR method has the potential for measuring soil moisture content for various geotechnical purposes. Devices and methodologies were developed for measuring moisture content of soil in the laboratory compaction mold, soil in a thin-walled sampling tube, a soil sample retrieved during a standard penetration test and in soil insitu for compaction control. Extensive experiments in the laboratory and in the field showed that developed devices and procedures measure moisture content of soil quickly and accurately. Study results showed that the method does not require soil specific calibration except possibly for heavy clays or organic soils. A breakthrough in research showed that the method can be used for measuring in-place soil density as well. Procedures were developed to measure in-place soil density along with in-place soil moisture content.

Anticipated Implementation: The results of this study allow one to obtain the moisture content of the soil after compaction in the laboratory with reasonable accuracy. With this method, it is possible to measure insitu moisture content and density with reasonable accuracy without imposing any health hazard. It would also be possible to measure moisture content of soil samples retrieved by thin-walled tube sampling and by the standard penetration test. Benefits include: improved construction quality control, very fast laboratory compaction information, borehole moisture information at time of making borings, and elimination of hazardous nuclear sources. Discussions are under way with manufacturers about further development and marketing of the equipment and procedures. A provisional patent application has been filed on the devices and procedures developed in the project. An implementation project is under way which will automate the procedure, develop draft standards for the test method, evaluate the procedure for a wider range of soils, and further enhance the reliability of the method. Additional insitu moisture and density testing will be done along side other methods currently being used.

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LIST OF SYMBOLS AND ABBREVIATIONS

The list is not complete, however, symbols are usually identified where used if use is different than given below. Not all subscripts are shown.

α	attenuation constant
β	phase constant = $2\pi/\text{wavelength}$
γ	unit weight of soil
δ	angle, deg or rad
ϵ	permittivity
ϵ_0	permittivity of vacuum
θ	volumetric moisture content
μ	electrical permeability
μ_0	electrical permeability of vacuum
ρ	density of soil
ρ_d	dry density of soil
ρ_w	density of water
σ	electrical conductivity
σ_b	bulk electrical conductivity of soil
σ_w	electrical conductivity of water
τ	transmission coefficient
ϕ	porosity of soil
ω	angular frequency
a	radius of central rod in a transmission line
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society of Testing and Materials
b	radius of the CC in a coaxial transmission line or the c/c spacing of the central to an outer rod in a multiple rod transmission line
c	damping coefficient
c	velocity of light in vacuum = 10^8 m/s
CA	coaxial apparatus
CC	cylindrical cell
CTL	coaxial transmission line
C_v	coefficient of variation
d	diameter
e	void ratio
E	electric field intensity
EC	electrical conductivity
EM	electromagnetic
F	spatial weighting function for dielectric constant
F	reflection coefficient
g	acceleration due to gravity
g	gram

G	specific gravity of soil solids
G	giga = 10^9 (prefix)
Hz	hertz = 1 cycle per second
INDOT	Indiana Department of Transportation
IP	plasticity index of soil
j	$\sqrt{-1}$
k	spring constant
K	TDR measured dielectric constant, dielectric constant
K_0	original dielectric constant
K_a	apparent dielectric constant
K_s	dielectric constant of soil solids
K_g	dielectric constant of air
l	apparent length
L	length of transmission line/probe, length
ln	natural logarithm (base e)
log	common logarithm (base 10)
m	milli (prefix)
M	mega = 10^6 (prefix)
MRP	multiple rod transmission line probe
p	pico = 10^{-12} (prefix)
pcf	pound per cubic feet
ppm	parts per million
q	charge
r_d	radius of zone of disturbance
R_d	ratio of densities
S	siemen
mS/m	millisiemen per meter
S_d	standard deviation
SE	standard error
SPT	standard penetration test
S_r	degree of saturation
t	time
t	air gap thickness
T	temperature
T_r	TDR rise time
TDR	time domain reflectometry
TDS	total dissolved solids
TL	transmission line
v	velocity of wave in transmission line
V	voltage
w	gravimetric moisture content
Z	impedance of transmission line
Z_0	characteristic impedance of transmission line

CHAPTER 1

INTRODUCTION (BACKGROUND, PROBLEM STATEMENT, AND OBJECTIVES)

In geotechnical engineering, there is a need of a technique to measure in-place density and moisture content of soil quickly, precisely, and preferably, in a non-destructive manner. There are several existing methods available for measuring in-place density and moisture content of soils. The sand-cone method (ASTM D 1556 1994), the rubber-balloon method (ASTM D 2167 1994) and the drive-cylinder method (ASTM D 2937 1994) are some conventional methods of measuring in-place wet density of soils. These methods are usually accompanied by the oven drying method of measuring moisture content (ASTM D2216 1994) in order to measure in-place dry density and moisture content of soil. None of these methods of measuring density is suitable for all types of soils. The oven-drying method of measuring moisture content requires a long waiting time. Another method, the nuclear method of measuring in-place soil moisture content and density requires extensive calibration. Moreover, the nuclear method is potentially hazardous because it utilizes radioactive materials. It is also necessary to measure moisture content of soil in the laboratory compaction mold, in Shelby tubes and soils retrieved during drilling operations. This study proposes a new, fast, safe and reasonably accurate method of measuring in-place density and moisture content of soil. This study also develops devices and procedures for measuring moisture content of soil in the laboratory compaction mold and in Shelby tubes and soil samples retrieved during drilling operations.

The high dielectric constant of water compared to soil solids makes the dielectric

constant of moist soil highly dependent on the moisture content of soil. This dependency has made the dielectric constant a viable tool for measuring moisture content of soil for over three decades. The TDR technique, originally developed to locate faults in transmission lines, was found to be a sophisticated and accurate method of measuring dielectric constant of soil (Davis and Chudubiak 1975). Topp et al. (1980) established a relationship between volumetric moisture content and the dielectric constant of soil. He used many soil types, and found a polynomial equation applicable to all soil types. Recent studies (Roth et al. 1992; Zegelin et al. 1992) have shown that Topp's equation does not provide sufficiently accurate results for: heavy clays, organic soils and soils having too low or too high densities. Recently developed semi-empirical calibration equations based on dielectric mixing laws have been found to be a significant improvement over the empirical equation. It has been found that, soil specific semi-empirical calibration equations provide highly accurate results.

Initial TDR research for measuring soil moisture content used coaxial transmission lines (Topp et al. 1980). For field applications, coaxial transmission lines were found to be inappropriate for installation. Two rod parallel transmission lines, instead of coaxial transmission lines were used for monitoring field moisture contents (Topp et al. 1982; Topp et al. 1984; Topp et al. 1985) but achieved limited success. They needed impedance matching transformers which tended to distort the shape of the signal. It was found that multiple rod probes better simulate coaxial transmission lines and do not require use of a balancing transformer. But it was found that with the increase of number of rods, installation difficulty as well as soil disturbance increases. A three rod probe was found to be the optimum one considering important desirable features: signal clarity, easiness of

installation and stability. Many authors have successfully used three rod probes (Kotdawala et al. 1994; Rada et al. 1994; Schelt et al. 1994) for measuring in-situ moisture content of soils. Almost all the field applications were for measuring moisture content on long term monitoring basis. Very little work was done to measure moisture content of soil on a repeated installation and withdrawal basis.

Much of this work was done in the soil sciences where moisture content is measured on volumetric basis. Some applications of TDR were made for monitoring moisture contents under highway pavements, but density of soil needed to be known for measuring gravimetric moisture contents from volumetric moisture contents.

This study extends the use of TDR for measuring moisture content of soil in the field and in the laboratory for geotechnical purposes. This study discovers a technique of using the TDR method for measuring in-place density of soil as well. In order to achieve these goals, this study develops the TDR principles of probe design and test methodology. Existing TDR probes have been almost always used for long-term installation and monitoring and generally not suitable for repeated installation and withdrawal. This raises the question of effect of probe rod insertion on measurement accuracy as well as the robustness of the probes and devices. This study requires the probes be suitable for repeated installation and withdrawal. Geometric parameters need to be appropriately designed to meet the requirements of the study. This study develops probes and devices suitable for these purposes and conducts analytical, experimental investigations to explore the effect of soil disturbances due to probe installation. The existing semi-empirical calibration equations are affected by the density of soil. This study modifies the existing semi-empirical equation to

reduce the effect of density on the calibration equations. The developed devices, methods, and calibration equations are used to measure density and moisture content of soil.

Chapter 2 discusses the relevant theories of the TDR technique and summarizes the progress of TDR research for measuring moisture content of soil. The chapter contains: history of use of dielectric constant for measuring moisture content of soil; principle of the TDR technique as a special way of measuring dielectric constant; frequency dependency of dielectric constant and dielectric losses; a review of the available calibration equations relating the dielectric constant and the volumetric moisture content of soil; and a review of available TDR transmission lines/probes and their uses. Finally, a summary of relevant conclusions is also given at the end of this chapter.

Chapter 3 develops the principles of designing transmission lines and test methodology. It develops principles of designing coaxial and multiple rod transmission lines to be used in this study. It identifies the factors involved in test methods that affect measurement accuracy. It contains the results of analytical and experimental investigations to study the characteristics of the factors and proposals to eliminate the effect of the factors.

Chapter 4 uses laboratory experimental data and analyzes those data to evaluate the existing calibration equations. It proposes new calibration equations. It also discusses the possible factors those affect the calibration equations.

Using the principles of probe design, test methods and calibration equations, a method of measuring in-place density and moisture content is developed. The method is established by performing experiments in the laboratory under ideal conditions. Then devices and test methods are developed to best replicate the ideal condition for actual in-situ experiment.

Chapter 5 presents the development of the method, devices and test results. It also contains a summary of the salient conclusions.

The devices and methods developed in chapter 5 are extended to measure moisture content in the laboratory compaction tests. Experiments are conducted to test the accuracy of moisture content measurement in the compaction mold. The methods and results are presented in chapter 6.

Chapter 7 presents the methods and devices for measuring moisture content during sampling and drilling operations. Methods, devices and experimental results are presented to measure moisture content of soil in Shelby tubes and soil retrieved as a part of the standard penetration test. The calibration equations developed in chapter 4 are used and the applicability of those equations in various cases are evaluated.

Chapter 8 summarizes the conclusions of the study and recommends areas where further research can be conducted.

Chapter 9 summarizes the methods in standard forms: scope, significance and uses, apparatus, test procedure, calculation, etc. This is helpful for implementing the results of the study.

CHAPTER 2

THE TDR METHOD AND AN OVERVIEW OF ITS PROGRESS

2.1 Introduction

The existence of a strong correlation between the dielectric constant and the volumetric moisture content of porous media has made it a viable tool for measuring moisture content of soil for over three decades. Early works made use of conventional capacitance measuring equipment for measuring dielectric constant of soil. TDR, a sophisticated way of accurately and directly measuring dielectric constant, was introduced to soils in mid-seventies. Due to its many good features, the TDR method became popular for measuring moisture content of soil. A lot of research has been done to develop TDR technology for measuring moisture content of soil, mostly in the soil sciences. Development and research progressed in developing dielectric constant-moisture content relationships, transmission lines and probes, etc. Most of the uses have been for long-term monitoring of moisture content. This chapter presents the theory of TDR technique and summarizes the important and up-to-date achievements of TDR research.

2.2 History of Use of Dielectric Constant for Measuring Moisture Content

The use of the dielectric constant for measuring moisture content of porous media is over 30 years old. Bell et al. (1963), Paquet (1971) investigated the determination of moisture content in hardened concrete based on its dielectric properties. Ballard (1973) used the property to measure moisture content of soil. He found that measurement of capacitance

(a measure of dielectric constant) was one of the simplest, inexpensive and fast method of measuring moisture content of soil. Since then many authors have explored dielectric properties of soils (Thomas 1966; Arunalondon et al. 1973; Selig and Mansukhani 1975; Selig et al. 1975; Okrasinski et al. 1978; Kuraz 1981, etc.). Selig and Mansukhani (1975) found that the dielectric constant was strongly related to the moisture content of soil. They also found that electrical conductivity was less suitable for measuring moisture content of soil, because it is influenced by soil chemicals. Okrasinski et al. (1978) found that the dielectric constant was strongly dependent on volumetric moisture content of soil, and determined that the dielectric constants of soil solids were very low and independent of soil type. Kuraz (1981) developed a field moisture meter by utilizing the relationship between dielectric constant and moisture content of soil. He studied the effect of density, salt concentration and temperature on the relationship. He found that the dielectric constant was not sensitive to salt concentration unless the concentration was high when it changed the calibration curves. He also found that the effect of temperature could be neglected for fluctuations of $\pm 5^{\circ}\text{C}$ and a simple linear correction was required for wider changes in temperature. Most of these works were basically laboratory oriented and were not suitable to use in field. Field probes or sensors developed by Thomas (1966), Lundien (1971), Kuraz (1981), etc. met only limited success. Some of the features of those sensors were: (1) because of the shape of the sensors, installation was not easy, (2) as the sensors measured capacitance, calibration for each sensor geometry was required, (3) measurements were sensitive to environmental variations, and (4) the procedure was not suitable for remote sensing. Also, for engineering purposes, independent measurement of density was required

to be able to determine the gravimetric moisture content from the measured volumetric moisture content. The TDR method, introduced to soils in mid-seventies, was found to have a high potential to eliminate some of the drawbacks of the conventional methods of measuring dielectric constant. Fellner-Feldegg (1969) first used the TDR technique for conveniently and accurately measuring electrical properties of organic liquids. Davis and Chuobiak (1975) used the TDR technique to measure dielectric constant of soil. Since then, many authors have done research to explore the technique for measuring moisture content of soil. It was found that TDR possessed many superior features over the conventional technique for measuring the dielectric constant of soil in the laboratory and in field. Some of these features were: (1) highly accurate measurement, (2) probes are simple and suitable to use in field, (3) measures the dielectric constant directly, no calibration for probe geometry is required, (4) can be automated, (5) measurement can be made remotely, and (6) the method is fast. This is why the TDR technique gained popularity over the last twenty years for measuring moisture content of soil.

2.3 The TDR Method

The TDR technique measures the velocity of the electromagnetic wave travelling through a transmission line (TL). This velocity (v) is related to the dielectric constant of the insulating medium between the conductors of the transmission line as given by

$$v = \frac{c}{\sqrt{K}} \quad [2.1]$$

where c is the velocity of light in vacuum and K is the dielectric constant of the medium. A TDR probe for measuring soil moisture content is actually a transmission line whose dielectric medium is soil when this probe is driven into soil. This probe is connected with the TDR instrument via a coaxial cable (Fig. 2.1). The TDR device sends a signal down the cable. When this signal reaches the beginning of the probe, due to impedance mismatch (explained later) between the cable and the soil probe, a portion of the signal is reflected back to the device. When the rest of the signal reaches the end of the probe, another reflection of the signal occurs. These two reflections cause two discontinuities in the resulting signal displayed on the TDR screen. The time difference between these two discontinuities is the time (t) required by the signal to travel twice the length (L) of the probe in soil (Fig. 2.2). So the wave propagation velocity in soil is

$$v = \frac{2L}{t} \quad [2.2]$$

and the dielectric constant of soil is (using Eq. 2.1 and 2.2)

$$K = \left(\frac{ct}{2L} \right)^2 \quad [2.3]$$

In commercial TDR instruments, the term $ct/2$ is reduced to an apparent length, l (Fig. 2.3), resulting in

$$K = \frac{l^2}{L^2} \quad [2.4]$$

Figure 2.1 Components of the TDR system.

(a) TDR System

(b) Wave Reflection Pattern

(c) Resultant Waveform

Figure 2.2 Voltage reflection pattern and resulting waveform.

Figure 2.3 A typical TDR waveform.

The dielectric constant of soil is directly related to the volumetric moisture content (θ) of soil as will be discussed in section 2.8. The volumetric moisture content of soil is related to the gravimetric moisture content (or simply moisture content), w , as follows:

$$w = \frac{\theta}{\rho_d / \rho_w}$$

where ρ_d and ρ_w are the dry density of soil and density of water, respectively.

2.3.1 The TDR Instrument

A TDR instrument is basically composed of a pulse generator and an oscilloscope. The pulse generator sends an electrical pulse along a coaxial cable and the oscilloscope is used to observe the echos returning back to the input. The TDR waveform shown in Fig. 2.2 is for the case when the TDR step pulse is ideal with a rise-time (time required by the pulse to reach the peak value, V_0 from the beginning of the rise) of zero picoseconds. With a finite rise-time pulse generator and oscilloscope, this waveform will no longer have sharp corners, but will have smooth rounded corners (Fig. 2.1, Fig 2.3). To have better spatial resolution (and better measurement accuracy), it is necessary to have a smaller (faster) rise-time (T_r). The minimum length resolution, $X_{\min}$, for a given T_r is given by (Andrews 1994):

$$X_{\min} = \frac{cT_r}{2\sqrt{K}}$$

As an example, with a 200 ps rise-time TDR system and ordinary RG-50 coax ($K=2.2$), the resolution would be 20 mm.

Much of the early TDR research (especially field research) of measuring soil moisture content made use of the Tektronix (Beaverton, OR) model 1502 TDR cable tester as the basic instrument, which used a fast rise-time (140 ps) step pulse. Malicki and Skierucha (1989) developed a TDR instrument using a 300-ps rise-time needle pulse. In recent years, a number of TDR instruments, specifically for soil moisture measurements, have been appearing on the market. No critical evaluation has been carried out documenting the performance limits of the various instruments. In the present study, the Tektronix (Beaverton, OR) model 1502B TDR cable tester is used.

2.4 The Complex Dielectric Constant

When electromagnetic waves propagate through an imperfect dielectric medium, their energy can be dissipated by two major factors. The first one is due to the fact that the constituent molecules or dipolar species within a sample require a finite time to adjust to the changing field strength of the imposed electric and magnetic fields (Debye 1929). This polarization or relaxation process gives rise to a phase lag between the imposed fields and the material's response to it. The phase lag is a function of the angular frequency, ω , of the imposed field. Because of this phase lag, dielectric constant must be represented as a complex quantity K^* , with real (in phase) $K'(\omega)$, and imaginary (out of phase), $K''(\omega)$, components. This is explained mathematically below.

The electron cloud of an atom in a dielectric becomes slightly displaced or asymmetrical when an electric field is applied. This produces an electric dipole (moment ql), and the atom is said to be polarized. When the electric field is removed, the atom returns to

its normal, unpolarized state. If the electric field is again applied but in the opposite direction, the dipole will be reversed. Thus, when an alternating field is applied to a dielectric atom, the dipole goes through the successive stages suggested in Fig. 2.4. An equivalent mechanical system is shown in Fig. 2.4. The large sphere represents the large mass of the nucleus. The small sphere represents the mass of the electron cloud.

The atom can be represented by an electromechanical system with mass m , damping coefficient c , and spring constant k . The equation of motion of the system is described by

$$m \frac{d^2 l}{dt^2} + c \frac{dl}{dt} + kl = qE_0 e^{j\omega t} \quad [2.5]$$

where:

m = mass of atom,

l = dipole length, separation,

q = charge of dipole, and

qE_0 = peak force resulting from harmonically applied electric field E .

A solution of the equation of motion is

$$l = l_0 e^{j\omega t}$$

where

Figure 2.4 (a) Behavior of atomic dipole in alternating electric field and, (b) equivalent mechanical system.

$$l_0 = \frac{(q/m)E_0}{\omega_0^2 - \omega^2 + j\omega c/m}$$

where:

ω = driving frequency, and

ω_0 = undamped natural frequency = $\sqrt{k/m}$.

The polarization or dipole moment per unit volume is

$$P = Nql = \frac{(Nq^2/m)E_0 e^{j\omega t}}{\omega_0^2 - \omega^2 + j\omega c/m} \quad [2.6]$$

Where N is the number of polarized atom per unit volume. The dipole moment is related to the permittivity as (Krauss, 1984)

$$\epsilon^* = \epsilon_0 + \frac{P}{E} \quad [2.7]$$

and with $E = E_0 e^{j\omega t}$, we get,

$$\epsilon^* = \epsilon_0 + \frac{Nq^2/m}{\omega_0^2 - \omega^2 + j\omega c/m} \quad [2.8]$$

The permittivity is a complex quantity as

$$\epsilon^* = \epsilon' - j\epsilon'' \quad [2.9]$$

where ϵ' and ϵ'' are real and imaginary parts of the complex permittivity ϵ^* expressed as

$$\epsilon' = \epsilon_0 \left(1 + \frac{(Nq^2/\epsilon_0 m)(\omega_0^2 - \omega^2)}{(\omega_0^2 - \omega^2)^2 + (\omega c/m)^2} \right)$$

and

$$\epsilon'' = \epsilon_0 \frac{(Nq^2/\epsilon_0 m)(\omega c/m)}{(\omega_0^2 - \omega^2)^2 + (\omega c/m)^2}$$

In terms of relative permittivities, $\epsilon_r' (= \epsilon'/\epsilon_0)$ and $\epsilon_r'' (= \epsilon''/\epsilon_0)$:

$$\epsilon_r' = 1 + \frac{(Nq^2/\epsilon_0 m)(\omega^2 - \omega_0^2)}{(\omega_0^2 - \omega^2)^2 + (\omega c/m)^2} \quad [2.10]$$

$$\epsilon_r'' = \frac{(Nq^2/\epsilon_0 m)(\omega c/m)}{(\omega_0^2 - \omega^2)^2 + (\omega c/m)^2} \quad [2.11]$$

Relative permittivity (ϵ_r^*) is also known as dielectric constant (K^*) although it is not really a constant, rather depends on frequency as evident from the Eqs. 2.10 and 2.11. In this study the popular term 'dielectric constant' instead of relative permittivity will be used. The real and imaginary parts of K^* will be noted as K' ($= \epsilon_r'$) and K'' ($= \epsilon_r''$), respectively.

The imaginary part contributes to the conductivity of the dielectric medium and is responsible for dielectric loss of the medium. The equivalent conductivity (Krauss, 1984) is

$$\sigma' = \sigma_{dc} + \omega \epsilon_0 K''$$

where σ_{dc} is the *dc* conductivity and $\omega \epsilon_0 K''$ is the conductivity associated with conduction current. At *dc* ($\omega = 0$ and $\omega \epsilon_0 K'' = 0$) power loss is small in a good dielectric for which σ_{dc} is small. However, at high frequencies losses can become larger as $\omega \epsilon_0 K''$ becomes significant. Therefore the real part of K^* is associated with the displacement-current density and hence, with the stored energy density ($= K' E^2$). The imaginary part (K'') is associated with the conduction-current density and, hence, with the power dissipated per unit volume as heat [$= (\sigma_{dc} + \omega \epsilon_0 K'') E^2 = \sigma' E^2$].

A more general form of complex K^* combines the two sources of dielectric loss as the imaginary part of the complex dielectric constant as

$$K^* = K' - j(K'' + \sigma_{dc}/\omega \epsilon_0) \quad [2.13]$$

2.5 The Propagation of Waves in a Transmission Line

The general equation of the voltage wave in a transmission line is given by

$$V = V_0 e^{\alpha x} e^{j\omega t - \beta x} \quad [2.14]$$

where v is the phase velocity and α is the attenuation constant expressed as:

$$\alpha = \text{Re} j \frac{2\pi}{\lambda_0} \sqrt{(\mu_r' - j\mu_r'') [\epsilon_r' - (j\epsilon_r'' + \frac{\sigma_{dc}}{\omega \epsilon_0})]} \quad [2.15]$$

The phase constant is

$$\beta = \text{Im} j \frac{2\pi}{\lambda_0} \sqrt{(\mu_r' - j\mu_r'') [\epsilon_r' - (j\epsilon_r'' + \frac{\sigma_{dc}}{\omega \epsilon_0})]} \quad [2.16]$$

where μ_r' and μ_r'' are the real and imaginary parts of the complex relative electrical permeability, respectively, and σ_{dc} is the dc electrical conductivity of the medium through which the waves propagate. Phase velocity, $v = c/\beta$, so

$$v = \frac{c}{\left(\frac{K'}{2} [1 + (1 + \tan^2 \delta)^{1/2}] \right)^{1/2}} \quad [2.17]$$

where $\tan\delta$ is the loss tangent expressed as

$$\tan\delta = \frac{K'' + \frac{\sigma_{dc}}{\omega\epsilon_0}}{K'} \quad [2.18]$$

The dielectric constant measured by TDR method is

$$K = \left(\frac{ct}{2L} \right)^2$$

This K , according to the definition of complex dielectric constant, is

$$K = K' [1 + \sqrt{(1 + \tan^2\delta)}] / 2 \quad [2.19]$$

Topp (1980) termed TDR measured K as K_a or apparent dielectric constant. The frequency dependency of K (Eq. 2.19) poses a problem for estimating it from the real and imaginary parts of K^* because TDR uses a band of frequencies rather than a single frequency.

Heimovaara et al. (1994) concluded that K was the real part of the relative permittivity at the highest frequency of the TDR setup. However, they also concluded that K was influenced by the imaginary component as well, which is consistent with Eq. 2.19. It is expected that the dielectric loss will cause K to be greater than K' at the same frequency. How much greater depends on the magnitude of $\tan\delta$. For pure water, the correction is much less than 1 % at TDR frequencies. For clayey soil, the contribution of the imaginary part may not be

negligible. The ionic double layer associated with colloidal soil particles influences dielectric constant measurements. That is why the behavior of heavy clay is different from that of nonclayey soils. For other soils, it is often valid to assume that $\tan \delta \ll 1$ for TDR applications in soils (Topp et al, 1980). In such cases

$$K' = K \left(\frac{ct}{2L} \right)^2 \quad [2.20]$$

It (K) has been found to be a unique function of moisture content for a variety of soils. TDR measured dielectric constant is the apparent dielectric constant termed as K .

2.6 Measurement of Electrical Conductivity (EC) from the TDR Signal

The signal strength decays as it travels through the soil. From the waveform as shown in Fig. 2.2 and Fig. 2.3, we have

$$V_2 = V_0(1+F) + V_0(1-F^2)e^{-2\alpha L} \quad [2.21]$$

From this we get

$$\alpha = \frac{1}{2L} \ln \frac{V_T}{V_R} \quad [2.22]$$

where: $V_R = V_2 - V_1$, $V_T = V_0(1-F^2)$, and F is the voltage reflection coefficient (defined later).

The decay constant, α , is given by (from Eq. 2.15)

$$\alpha = \frac{60\pi(\omega\epsilon_0 K'' + \sigma_{dc})}{\left(\frac{K'}{2}[1 + (1 + \tan^2 \delta)^{1/2}]\right)^{1/2}}$$

Combining these two, we get

$$\sigma = \frac{\sqrt{K'}}{120\pi L} \ln \frac{V_T}{V_R} \quad [2.23]$$

where:

$$\sigma = \sigma_{dc} + \omega\epsilon_0 K''$$

Using this equation σ_{dc} of moist soil can be calculated with reasonable accuracy assuming that K'' is negligible (Topp et al. 1988; Dalton et al. 1984). If EC is high, then most of the signal strength can be dissipated and no noticeable return signal can be observed (V_R becomes very small). To make measurements in such a medium, it may be necessary to use short probe.

2.7 The Characteristic Impedance and the Reflection Coefficient

The propagation of an EM wave in a transmission line is related to the characteristic impedance of the line. The characteristic impedance of a coaxial transmission line is defined

as (Krauss, 1984)

$$Z_0 = \frac{138}{\sqrt{K^*}} \log \frac{b}{a}$$

If $(K'' + \sigma_{dc}/\omega \epsilon_0) < K'$, then

$$Z_0 = \frac{138}{\sqrt{K'}} \log \frac{b}{a} \quad [2.24]$$

Figure 2.2 shows two transmission lines of characteristic impedances Z_0 and Z_1 connected together. If any EM wave propagates through the first transmission line and reaches the junction of the lines, a portion of the wave gets reflected. The remainder of the wave travels to the second transmission line. The reflection coefficient is given by (Krauss, 1984)

$$F = \frac{Z_1 - Z_0}{Z_1 + Z_0}, \quad -1 \leq F \leq +1 \quad [2.25]$$

and represents the ratio of the amplitudes of the reflected and incoming waves. The transmission coefficient is given by (Krauss, 1984)

$$\tau = 1 + F$$

and represents the ratio of the amplitudes of the transmitted and incoming waves.

In case of TDR, the output impedance of TDR (Z_0) is 50Ω , and Z_1 depends on the geometry

of the probe and the dielectric constant of the soil where the probe is installed. The shape of the waveform displayed on the screen (Fig. 2.1) depends on the relative magnitudes of Z_0 and Z_1 .

2.8 K - θ Relationships

The high dielectric constant of water compared to that of soil solids makes the dielectric constant of soil highly dependent on moisture content of soil. Based on this fact, TDR measured apparent dielectric constant has been related with the volumetric moisture content of soil. TDR measures apparent dielectric constant, K , which depends on both the real and imaginary components of the complex dielectric constant K^* . A common assumption in TDR measurements is that the imaginary component associated with losses due to both electrical conductivity and dipolar relaxations is at least one order of magnitude smaller than the real component. In reality that may not be true especially if the soil is conductive. Empirical calibration between K and θ avoids this complexity but requires soil specific calibrations. Theoretical calibration equations based on dielectric mixing models are better than empirical calibration but requires relevant soil data.

2.8.1 Empirical K - θ Relationships

Topp et al. (1980) developed an empirical K - θ relationship from laboratory experimental data obtained using coaxial transmission lines for a variety of soils. For a wide variety of light textured soils they showed that a single equation was adequate and was found to be independent of soil bulk density, temperature, salt content, etc. This equation is

$$\theta = -0.053 + 2.92 \times 10^{-2} K - 4.3 \times 10^{-4} K^2 + 5.5 \times 10^{-6} K^3 \quad [2.26]$$

This equation has been shown to be quite broadly applicable as verified by many authors (Dalton 1992; Dalton et al. 1986; Dalton et al. 1986; Dasberg et al. 1985; Drungil et al. 1989; Heimovaara 1994; Heimovaara et al. 1990; Topp et al. 1984; Topp et al. 1985; Zegelin 1989). However, recent studies have shown that this equation is not appropriate for soils having high clay content, or rich in organic matter (Roth et al. 1990; Dirksen et al. 1993; Zegelin et al. 1992). This is because the electrical conductivity of these soils causes the dielectric loss to be significant making K significantly different from K' . For materials, such as heavy clays, that display a quite different K - θ relationship from that given by Eq. 2.26, an individual empirical relationship may be obtained experimentally by comparing TDR measured K to gravimetrically determined water content and bulk density.

2.8.2 Theoretical/Semi-Empirical Approach

As Topp's 'universal equation' is not really a universal one, some efforts have been devoted to find alternative relationships between dielectric constant and moisture content (Dirksen et al. 1993; Paquet et al. 1993; Roth et al. 1992). The physics of the problem was explored to develop theoretical calibration equations. Calibration equations have been developed expressing excellent K - θ relationship for a given porous media. Theoretical K - θ relationships range from those based on Maxwell's equations for electromagnetic wave propagation, to semi-empirical mixing models. It has been found that these theoretical/semi-empirical models require parameters which differ depending on soil type, soil density, soil

moisture quality, etc., indicating a calibration equation of universal nature is not possible.

The semi-empirical models assume the porous material to be composed of three or four components. The dielectric constant of soil-water-air mixture comes from the dielectric constants of individual components depending on their volume fraction in the mixture expressed as (Birchak 1974; Roth et al. 1990)

$$K^{\alpha} = (1 - \phi)K_s^{\alpha} + \theta K_w^{\alpha} + (\phi - \theta)K_g^{\alpha} \quad [2.27]$$

where: K_s , K_w , K_g are the dielectric constants of soil solids, water, and air, respectively, ϕ is the porosity and θ is the volumetric moisture content, and α is related to the geometry and relative orientation of the mixture's constituents and their interaction with the applied electric field. With values between -1 and +1, α has been optimized to give closest relationship to measured data. In most cases α has a value of 0.5. It (α) can also account for any contributions from frequency-dependent complex dielectric constants of the soil components. To use this equation, the porosity of soil must be known in addition to other parameters like K and α which may not vary for different soils. This equation does not account for any interaction between water and solids. An extension of this equation include bound water as (Birchak et al. 1974)

$$K^{\alpha} = (1 - \phi)K_s^{\alpha} + (\theta - \theta_{bw})K_{fw}^{\alpha} + \theta_{bw}K_{bw}^{\alpha} + (\phi - \theta)K_a^{\alpha} \quad [2.28]$$

where θ_{bw} is the moisture content bound to the solid particles, θ_{fw} is the free fraction of the moisture content, K_{bw} is the dielectric constant of the bound water and K_{fw} is dielectric constant of the free water. Dobson et al. 1985) has simplified this equation by using an

empirical constant β , that parameterizes both the volume fraction and dielectric constant of bound water as:

$$K^\alpha = 1 + \frac{\rho_b}{G}(K_s^\alpha - 1) + \theta^\beta K_{fw}^\alpha - \theta \quad [2.29]$$

where ρ_b is the bulk density and G is the specific gravity of the material. Nelson (1992) has shown that this equation works good for granular materials with either $\alpha = 1/3$ or $\alpha = 1/2$, and $\beta = 1$.

Whalley (1993) has proposed a refractive index mixing law equivalent to Eq. 2.29 with $\alpha = 1/2$ and $\beta = 1$:

$$\sqrt{K} = 8.546\theta + 0.5698\sqrt{K_s} + 0.43 \quad [2.30]$$

This equation does not account for the bound water, so may not be suitable for non-granular soils.

The Maxwell-de Loor model (1964) is a four-component mixing model and include bound water as a parameter:

$$K = \frac{3K_s + 2(\theta - \theta_{bw})(K_{fw} - K_s) + 2\theta_{bw}(K_{bw} - K_s) + 2(\phi - \theta)(K_g - K_s)}{3 + (\theta - \theta_{bw})(K_g/K_{fw} - 1) + \theta_{bw}(K - s/K_{bw} - 1) + (\phi - \theta)(K_g/K_g - 1)} \quad [2.31]$$

Unlike other mixing models mentioned above, Eq. 2.31 does not have any of the empirical fitting parameters. But as K_{bw} or θ_{bw} are not known a priori, they become fitting parameters.

The volume fraction of bound water, θ_{bw} , should increase with increase in the plasticity index (IP) of clay. On the other hand, K_{bw} should decrease with increase in IP of clay. Bohl et al. (1994) applied their data set obtained from 40 mineral and organic soils with a wide spectrum of characteristics to the 3-phase model (Eq. 2.27), 4-phase model (Eq. 2.28) and de Loor model (Eq. 2.31) and found that de Loor model yielded the best results.

Figure 2.5 shows a comparison of empirical, theoretical and semi-empirical models presented above. The following physical and electrical properties were assumed for each of the models: $\rho_d = 1.6 \text{ Mg/m}^3$ (100 pcf), $G = 2.66$, $\phi = 0.4$, $\theta_{bw} = 0.05$, $K_s = 4$, $K_g = 1$, $K_{bw} = 7$, $K_{fw} = 81$, $\alpha = 0.5$, $\beta = 0.95$. The empirical equation and the de Loor theoretical curves are not linear and both predict a smaller K at lower water contents and larger K at higher water contents than the linear semi-empirical models (Eq. 2.27, Eq. 2.29). In the medium range of moisture contents ($\theta = 15\% - 40\%$), the differences between the linear and nonlinear models are minimal.

The linear calibration equation is a significant improvement over the empirical equation and can be applied where they are suitable (for non swelling soils). Calibration is easy, only two data points define the calibration line. For soils, where linear calibration is not applicable, nonlinear K - θ calibration must be developed and used. Heimovaara (1994) mentioned that validation and refinement of the dielectric mixing models should be made before they can be used reliably.

2.9 Probe Design and Installation

One of the most important areas of TDR research has been the development of TDR

Figure 2.5 Comparison of empirical, semi-empirical and theoretical calibration equations.

probes or transmission lines. Depending on the purpose and application, different kinds of transmission lines have been developed and used successfully. Some of the early and laboratory oriented works used coaxial transmission lines (Topp et al. 1980; Topp et al. 1988). For measuring moisture content in field, coaxial transmission lines were not suitable. Parallel rod transmission line, because of its open configuration and suitability for installation, was used for field measurements (Topp et al. 1982; Topp et al. 1984). Initial parallel rod transmission lines were composed of two rods. Impedance mismatch between coaxial output of TDR and parallel rod probe caused signal distortions and made signal interpretation difficult. Impedance matching-transformers (baluns) have been recommended between the coaxial output of the TDR and the balanced parallel-pair soil probes. The baluns tended to create noise in the signal passing the transformer and were too costly for use at each probe. Spaans and Baker (1993) have designed impedance matching transformers that appear to eliminate the signal distortion problems and high cost of those used previously. Zegelin et al. (1989) showed that multi-rod transmission lines better emulate coaxial transmission lines and do not require balancing transformers. The fabrication of this type of probe is simple, the probe is becoming widely used.

Attempts were made to measure moisture content variation with depth. Topp et al. (1982) developed a segmented probe but achieved limited success. Hook et al. (1992) have recently presented probe configuration and measurement procedures that can be applied to determine the distribution of water content along the length of the probe. The probes make use of a parallel-pair configuration mounted on a single core with diodes connected between the wires forming the parallel pair. The selective closing and opening of the diodes allow

measurements to be over selected lengths of the probe.

Probes developed in the past were mostly for permanent installation and long-term monitoring. Very little work was done to develop portable probes for rapid installation and withdrawal following one time measurement. Topp et al. (1984) developed a portable hand probe, composed of two parallel conductors. This needed use of a transformer. The multi-rod probe as developed by different researchers (Zegelin et al. 1989,) are not suitable for rapid insertion and removal following a one-time measurement.

TDR measurement has spatial bias. The electric field distribution around the wires of a TDR probe gives an approximate picture of the lateral spatial sensitivity. More exact information can be found from the distribution of electromagnetic energy within and around the probe. Knight (1992) recently estimated the approximate two dimensional spatial weighting function for coaxial and two-wire TDR probes by considering the effect of a small perturbation of dielectric constant to the spatial distribution of electromagnetic energy around the wires of the probe. It was observed that the probe is extremely sensitive to the "skin" immediately surrounding the wires, and that the sensitivity increases with the decrease in wire diameter. On the other hand the smaller size wire reduces the soil disturbance as it is inserted in soil. Knight (1992) suggested that the ratio of the wire radius r to the wire separation s should be ≥ 0.1 and that r should be as large as possible compared with the pore size of the material. Air gaps along the wires cause a very serious reduction in measured dielectric constant implying the need for very careful installation of probes to avoid air-gaps (Annan, 1977).

2.10 Summary and Conclusions

Dielectric constant is a complex quantity. TDR measures apparent dielectric constant of soil which depends both on the frequency content of the TDR signal and the conductivity of soil. For most soils, the contribution from the imaginary component has been found to be negligible. Since the dielectric constant of soil solids is very low compared to that of water, the TDR measured dielectric constant of soil has been shown to be strongly correlated with the volumetric moisture content of soil. The empirical calibration equation has been reported to be applicable for many soils. It has been found that soil specific calibration equations increase the accuracy of measurement.

TDR probes have been developed both for measurement in the laboratory and in the field. Coaxial type of probes have been used in the laboratory mainly for research purposes while multiple rod probes have been used for field applications.

Work has been done to determine the sampling volume spatial sensitivity of TDR measurement. Careful installation is necessary to avoid air-gaps. Soil disturbances should be minimized during installation.

To use the TDR technique or dielectric property to measure in-place gravimetric moisture content, independent measurement of density is required. No attempt was ever made to measure density of soil using the TDR technique or the dielectric property of soil. As the dielectric constant of soil is related to the volumetric moisture content of soil, the technique can be used to measure density of soil as well.

In geotechnical engineering, there are several cases where soil is compacted or retrieved in a metallic cylinder. The TDR transmission line can be formed using these

cylinders as the outer conductors and installing a rod along the centerline of the cylinders.

Special methods can be developed to install a central conductor to form the transmission line.

The existing multiple rod probes have been utilized for measuring moisture contents on long-term basis. To measure in-place moisture content for compaction control, it is necessary to install a probe and remove it for reuse. The existing design and test method is not suitable for that purpose. Installation techniques that allow snug contact between the rod and the soil are needed. Coaxial transmission line probes which have been developed are not suitable for measuring moisture contents in the compaction molds, Shelby tubes, etc.

For measuring density, it is necessary to correctly identify the effect of probe rod insertion. A previous study indicated that the disturbance caused by probe rod insertion changes the property of soil and recommended increasing the spacings of the conductors to reduce the disturbance. A rigorous analysis based on experimental and analytical study was never done.

Existing calibration equations have been reported to be affected by different factors, among which density is important. For measuring density, new calibration equations, eliminating the effect of density is necessary.

CHAPTER 3

DEVELOPMENT OF THE PRINCIPLES OF PROBE DESIGN AND TEST METHODOLOGY

3.1 Introduction

To develop methods of measuring density and moisture content of soil, it is necessary to develop the principles of probe design and test methodology. This chapter is aimed at developing the principles of designing different types of probes and test methodology. The factors involved in test methods that affect measurement accuracy are identified. Analytical and experimental investigations are conducted to study the characteristics of the factors and ways to eliminate the effect of the factors are proposed.

3.2 Transmission Line/Probe Design

Transmission lines for measuring soil moisture content are of two types: coaxial type and parallel rod type. The coaxial type of probe is composed of a cylindrical tube or cell (CC) acting as the outer conductor and a rod or wire along the centerline of the cylinder acting as a central conductor. The parallel rod type of probe is composed of two rods forming two conductors of a transmission line. Measurement of moisture content in the compaction mold or in a Shelby tube can be done using the cylindrical mold or tube as the outer conductor with the inner conductor being a rod inserted along the center line of the soil in the mold or cylinder. Measurement of in-place moisture content is more easily done with a parallel rod type transmission line. Figure 3.1 shows a coaxial transmission line (CTL).

Figure 3.1 A coaxial transmission line probe.

The cylinder contains the soil. The central rod is supported by a plastic dielectric in the head and is connected to the central conductor of the head, which in turn is connected to a coaxial cable. The connection between the rod and the central conductor of the coaxial connector is established through a pin attached on the top end of the rod which passes through a hole in the plastic dielectric. The head and the rod assembly is termed as coaxial apparatus (CA). The head itself forms a segment of transmission line, having the characteristic impedance given by

$$Z_{head} = \frac{138}{\sqrt{K_p}} \ln \left(\frac{b}{a} \right)$$

where K_p is the dielectric constant of plastic (usually 2 to 3), b and a are the radii of the outer (radius of the plastic dielectric) and the inner conductors, respectively. The ratio usually is in the range 4-8. The head and central rod assembly shown and discussed here is not robust enough to be pushed repeatedly into soil. To increase robustness, the central conductor is threaded into a metallic bloc which in turn is placed inside a plastic dielectric as shown in Fig. 3.2. The metallic bloc is connected with the coaxial connector through a pin connected on the top surface of the metallic bloc. The usual range of b/a now becomes much smaller, typical range is 1.5-2.5. The resulting waveform looks like as shown in Fig. 3.3. The first bump goes down as opposed to the previous case where the first bump goes up. The advantages of this kind of head are: it is stronger, more durable and robust compared to the other one; the central conductor may be replaced easily if needed as it is not connected through a pin to the coaxial connector.

Figure 3.2 A coaxial transmission line probe with modified probe head.

Figure 3.3 (a) Coaxial transmission line probe head, (b) waveform for (a), (c) modified transmission line probe head, (d) waveform for (c).

If the top surface of the soil specimen in the cylindrical mold is not a smooth plane, the base of the head may not properly touch the top end of the cylindrical wall of the mold. So it is necessary to keep a small step at the base of the head as shown in Fig. 3.1. Thus any irregularity on the soil surface in the cylinder can not obstruct electrical connection between the head and the cylinder. Obviously, the length of the central rod should be such that it does not touch the base plate when the head is seated on the end of the cylinder. The base plate, if metallic, may interfere with the signal propagation and reflection and distort the waveform. So it should be made of an insulating material. Or, if a metallic base plate is used, the CTL should be removed and placed on a nonmetallic base plate before making a measurement using the TDR apparatus. It may not be necessary to clamp the CC with the rods of the baseplate, except for removing the CA rod from the soil after a test is completed.

Doing a test in the cylindrical cell requires: making a pilot hole along the centerline of the soil in the mold using the hand penetrometer and the guide cap (Fig. 3.2), pushing the central conductor through the hole so that the head sits on the top of the mold, making connecting the CA to the TDR equipment, and making a measurement.

To make in-situ measurements, it is necessary to use a parallel rod type transmission line. As mentioned earlier, multiple rod probes have been developed by researchers for long-term installation for measuring the volumetric moisture content (dielectric constant) of soils. Zegelin et al. (1989) originally developed a multiple rod probe (MRP) to eliminate draw-backs of two-rod parallel-line probe. Because a multiple rod probe was developed to emulate a coaxial transmission line, it is also known as simulated coaxial probe. Various forms of multiple rod probes, following Zegelin, were designed and used successfully (Baran

1994; Kotadawala et al. 1994; Look et al. 1994; Rada et al. 1994). The basic concept behind these probes is that the central rod acts as the central conductor and the outer rods act as the outer conductor. The more the number of outer conductors, the closer the probe behaves as a coaxial transmission line (Zegelin et al. 1989). It has been found that the characteristics of a MRP with 3 outer rods is sufficiently close to that of a coaxial transmission line. These probes are almost always installed permanently in soil, and are generally not suitable for repeated installation and withdrawal. To make in-place measurements, it is necessary to modify existing multiple rod probe designs.

The design of the multiple rod probe (MRP) suitable for repeated installation and withdrawal should be such that it separates the conducting rods from the probe head. In conventional probes, the conducting rods are permanently connected with the probe head. In the MRP developed in this research, the connection is not permanent. The head is connected to the conducting rods independently after the rods have been driven into the soil. The head has four metallic studs threaded into the metallic head in place of the conducting rods. The lengths of the central stud and two of the outer studs are the same (about 25 mm). The fourth stud is a little (about 3 mm) shorter than the others. Conducting rods are driven at the same configuration as the configuration of the studs in the head. After the rods are driven, the head is placed on the heads of the rods in such a way that the central stud sit on top of the central rod and the two equal outer studs sit on top of the two outer rods. The length of the fourth stud is adjusted by turning it until proper connection is established. Figure 3.4 shows these features.

The probe thus developed is, in fact, a combination of two transmission lines. The

Figure 3.4 A multiple rod transmission line probe.

first segment (studs plus portion of rods above the soil surface) having air as the dielectric medium, and the second having soil as the dielectric medium. As the air has very low dielectric constant compared to moist-soil, a distinctive discontinuity in the reflected signal will appear at the air-soil interface which will allow proper measurement of dielectric constant of soil.

Different components and parameters of a transmission line are: length (L), spacings of the conductors (s), ratio of the radii of the conductors (b/a), etc. Some other features of a transmission line, such as sampling volume, effect of rod insertion, etc., depend on these parameters. Design characteristics of these parameters will be discussed next.

3.2.1 Length of Transmission Line

What would be the optimum length of a transmission line? For installation purposes, the shorter the length of probe, the easier is the installation. On the other hand, the shorter the length, the higher is the measurement variability. So a long length should be used. But the maximum length that can be used is again controlled by ease of installation and loss of signal strength along the length of the line. Based on all these factors, an optimum length can be chosen.

As the signal travels through a lossy (conductive) medium, its strength decays. The length of the probe should be such that a detectable reflection from the end of the probe occurs. The electrical conductivity of moist soil was given by Eq. 2.23, which is

$$\sigma = \frac{\sqrt{K}}{120\pi L} \ln \frac{V_T}{V_R} \quad [3.1]$$

So

$$\frac{V_R}{V_T} = \exp\left(\frac{120\pi L\sigma}{\sqrt{K}}\right) \quad [3.2]$$

To get a detectable return signal, the value of V_R/V_T must be greater than zero. This ratio decreases as L increases. Generally coarse grained soils have a lower conductivity than clayey or organic soils. So longer L can be used for coarse grained soil compared to clayey or organic soils.

On the other hand, the variability of TDR measurement increases with decreasing l (apparent length). The step pulse generated by the TDR pulse generator (Model 1502B, Tektronix, Inc., Beaverton, OR) has a rise time of 200 pico second (ps), which gives a length resolution of about 20 mm in a coaxial cable with dielectric constant of 2.2. So there is always a variability (error of estimate) in l which would be of the order of 20 mm. This is one of the greatest source of errors in TDR measurement. Generally, longer probes reduce the error involved in taking a reading of travel time, i.e., longer travel time reduces error involved in time measurement. The dielectric constant is given by

$$K = \frac{l^2}{L^2} \quad [3.3]$$

where l is the measured reading in m, L is the length of the probe in m. From this, the percent variability in measurement can be expressed as (using Taylor's series):

$$C_v^2(K) = (2)^2 C_v^2(l)$$

From which we get

$$S_d(K) = 2 C_v(l) K = \frac{2 S_d(l) \sqrt{K}}{L} \quad [3.4]$$

where:

$S_d(K)$, $S_d(l)$ = standard deviation of K and l , respectively, and

$C_v(K)$, $C_v(l)$ = coefficients of variations of K and l , respectively.

So the optimum L for given $S_d(K)$ and σ is

$$L = \sqrt{\frac{S_d(l)}{60\pi C_d(K)\sigma} \ln \frac{V_T}{V_R}} \quad [3.5]$$

The conductivity of moist soil usually ranges between 1-1000 mS/m (Siemen, $S = 1/\text{ohm}$).

For a least detectable return signal, a value for $V_R/V_T = 0.05$ can be assumed. Using Eq.

3.5, a maximum allowable length L can be computed for soils having different electrical conductivities and moisture content. The result is shown in a log-log plot in Fig. 3.5. A probe of about 50 mm length can measure conductivity of 1000 mS/m.

Figures 3.6 to 3.8 show experimental results for maximum allowable length for different types of soils. Fresh water was used for preparing the soil specimens. From these

Figure 3.5 Maximum allowable lengths (theoretical) of TLs that can be used for measurement in soils having different electrical conductivities.

Figure 3.6 Maximum allowable length (experimental) of TL that can be used for making measurements in Sandy Soils.

Figure 3.7 Maximum allowable length (experimental) of TL that can be used in cohesive soils (soil type: Kaolinite)

Figure 3.8 Maximum allowable length of TL (experimental) that can be used for making measurements in highly plastic soils (soil type: Bentonite).

figures it is observed that for sandy soil, a relatively longer probe can be used, while for cohesive soils, maximum allowable length decreases with increase in moisture contents. For sandy soil, a length of about 1 meter can be used; whereas for bentonite, maximum allowable length is about 1 m at low moisture contents and about 0.2 m at high moisture contents.

It may be necessary to measure moisture content of soil where the soil moisture is contaminated by chemicals or salts. Dissolved solids increase the electrical conductivity of water and bulk soil as well. So the length of the probe that can be used for such conditions must be selected carefully. It has been reported in literature that probes installed for measuring moisture content produced ambiguous, poor waveforms because of the presence of salinity in soil water (Kotdawala et al. 1994).

If soil water contains dissolved solids, the bulk electrical conductivity of the soil (granular) is (Archie, 1942)

$$\sigma_b = \sigma_w \phi^m \quad [3.6]$$

where:

σ_b = bulk conductivity of soil (mS/m),

σ_w = conductivity of soil water (mS/m),

ϕ = soil porosity, and

m = a factor which varies with particle shape from 1.2 for spheres to 1.9 for platy fragments.

If $\phi = 40\%$, and $m = 1.5$, then $\sigma_b / \sigma_w = 0.25$. According to McNeill (1990),

$$\sigma_w(mS/m) = \frac{1}{6} TDS(ppm) \quad [3.7]$$

Therefore

$$\sigma_b(mS/m) = \frac{1}{25} TDS(ppm) \quad [3.8]$$

So a concentration of 25 ppm of total dissolved solids increases the bulk conductivity of saturated soil by 1 mS/m. Maximum (theoretical) allowable lengths of probes that can be used for soils saturated with water having different ppm concentrations of total dissolved solids are shown in Fig. 3.9.

Some laboratory experiments were conducted to test the validity of Fig. 3.9. Solutions of NaCl were prepared at different concentrations of NaCl and coaxial probes of different lengths were used to make measurements. Figure 3.10 shows how the strength of the signal decays with increase in NaCl concentration. A detectable return signal was not available for concentration beyond 5000 ppm with a 50 mm long probe. This agrees well with the theoretical result (shown in Fig. 3.9). Figures 3.11 and 3.12 show the measured electrical conductivity for different concentrations of salt using CTLs of different lengths. These figures show that an increase of concentration of about 5 ppm increases the electrical conductivity of water by 1 mS/m. This compares well with Eq. 3.7. From these findings, it can be concluded that: (1) the length of probe should be short enough so that a detectable return signal can be obtained and, (2) the technique can be used to measure concentration of

Figure 3.9 Maximum allowable length of TL (theoretical) that can be used to make measurements in soils having different concentrations of total dissolved solids.

Figure 3.10 Effect of salinity on the waveform and dielectric property.

Figure 3.11 Measurement of electrical conductivity of aqueous solution of NaCl using a CTL (length of CTL = 50 mm).

Figure 3.12 Measurement of electrical conductivity of aqueous solution of NaCl using a CTL (length of CTL = 110 mm).

dissolved salts in water or electrical conductivity of soil water.

3.2.2 Sampling Volume in TDR Measurement

It is important to know the volume of soil that is sampled in TDR measurements. Also it is desirable to know whether any spatial bias exists or not in TDR measurements. The following section derives equations to study these.

Figure 3.13 shows the cross section of a coaxial probe. The radii of the inner and the outer conductors are a and b , respectively. From the theory of electromagnetic wave propagation in a coaxial transmission line, the velocity of an electromagnetic wave propagating through the line is given by

$$v = \frac{1}{\sqrt{LC}} \quad [3.9]$$

where L and C are the conductance and capacitance of the line per unit length, respectively, defined as

$$L = \frac{\mu}{2\pi} \int_a^b \frac{1}{r} dr \quad [3.10]$$

$$C = 2\pi\epsilon \frac{1}{\int_a^b \frac{1}{r} dr} \quad [3.11]$$

Where μ and ϵ are the electrical permeability and electrical permittivity of the medium in between the conductors, respectively. For non-ferromagnetic materials

$$\mu = \mu_0$$

where μ_0 is the permeability of the vacuum. Also

$$\epsilon = \epsilon_0 K$$

where ϵ_0 is the permittivity of the vacuum and K is the relative permittivity or dielectric constant of the medium. Therefore

$$v = \frac{c}{\sqrt{K}} \quad [3.12]$$

where c is the velocity of light in vacuum related with μ_0 and ϵ_0 as

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

In order to find the spatial sensitivity function for the dielectric constant of the medium in the coaxial line, let us consider a composite dielectric medium as shown in Fig. 3.13. The medium within the circle of radius r_1 has a dielectric constant of K_1 and the medium in the annular zone has a dielectric constant of K_2 . Using Eqs. 3.10 and 3.11, after performing necessary integrations, we get

Figure 3.13 Cross section of a CTL having composite dielectric mediums.

$$LC = \frac{1}{c^2} \frac{K_1 K_2 \ln(b/a)}{K_2 \ln(r_1/a) + K_1 \ln(b/r_1)} \quad [3.13]$$

Using Eqs. 3.9, 3.12 and 3.13, we get the composite dielectric constant as

$$K = \frac{K_1 K_2 \ln(b/a)}{K_2 \ln(r_1/a) + K_1 \ln(b/r_1)}$$

or

$$K = \frac{\ln(b/a)}{\frac{\ln(r_1/a)}{K_1} + \frac{\ln(b/r_1)}{K_2}} \quad [3.14]$$

In general, for n different mediums, we get

$$K = \frac{\ln(b/a)}{\frac{\ln(r_1/a)}{K_1} + \frac{\ln(r_2/r_1)}{K_2} + \dots + \frac{\ln(b/r_n)}{K_n}} \quad [3.15]$$

3.2.3 Spatial Weighting Function

From Eq. 3.14, if $K_1 = K_2$, we get

$$\frac{\ln(r_1/a)}{\ln(b/a)} + \frac{\ln(b/r_1)}{\ln(b/a)} = 1 \quad [3.16]$$

Therefore, the spatial sensitivity function can be written as

$$F(r) = \frac{\ln(r/a)}{\ln(b/a)} \quad [3.17]$$

at different probe geometries (probes having different b/a ratios) spatial weighting function (F) can be plotted as shown in Fig. 3.14. From this figure it is seen that, for $b/a = 100$, an area of 1 % of the total area around the central wire contributes to half of the measured dielectric constant. If the ratio $b/a = 10$, the central area increases to 10 % of the total area to make its contribution half of the total. So to sample a representative volume of soil, to lessen the effect of any heterogeneity of soil near around the central conductor, the ratio b/a should be kept lower (less than 10).

The spatial bias of a TDR measurement is not a problem if the moisture content and density of soil is uniform. In case the density or the moisture content is not uniform over the entire volume of soil, measurement of dielectric constant would be erroneous and proper precaution should be taken into account for that.

The nature of the spatial sensitivity function gives important insight into: design of probe, soil volume sampled, effect of probe installation technique, effect of soil disturbances,

Figure 3.14 Characteristics of the spatial sensitivity function $F(r)$ with respect to a CTL.

etc.

3.2.4 Effect of Conductor Spacings and Diameters on Waveforms

The shape of the waveform is very important for measuring dielectric constant. A waveform having a well defined end reflection will provide accurate measurement of dielectric constant. On the other hand, if the end reflection is not well defined, locating the point of end reflection will be ambiguous which might cause significant error in TDR measurements. The higher is the value of $(V_2 - V_1)$ (Fig. 2.2), the better is the end reflection. One of the factors that influence this value is the attenuation constant, α . Higher electrical conductivity of the dielectric medium increases the attenuation of signal energy and causes ill-defined reflection as was shown in Fig. 3.10. Another factor that influences the value of $(V_2 - V_1)$ is the reflection coefficient, F . The reflection coefficient, F , depends on the geometric parameter b/a (Eq. 2.25) of a TL. It is important to note that F does not depend on the spacings of the conductors. Figure 3.15 shows typical waveforms obtained for a soil at a given moisture content using CTLs having b/a ratios of 7.5 and 22. With the help of Fig. 3.15 and Eq. 2.25, following conclusions can be made:

1. Spacings of the conductors is not an influencing parameter. Rather the influencing parameter is the b/a ratio. In other words, two lines having the same b/a ratio, but different spacings are identical as far as the shape of the waveform is concerned.
2. Transmission lines of all practically possible b/a ratios are allowed.
3. Lower b/a ratios provide better possible end reflections.

Figure 3.15 Effect of b/a on the shape of waveform ($b/a = 7.5$ and 22 , $L = 200$ mm).

3.2.5 Effect of Air Gap

To use either a CTL or a MRP, it is necessary to install the rod (rods) of the probe in soil. A rod may sway laterally while inserted in soil. As a result, an air gap may remain around the rod or portion of the rod. From the nature of spatial weighting function, it is known that the measurement is sensitive to the dielectric property of the medium close to the central conductor. As the dielectric properties of air and soil are significantly different from each other, an air gap, especially around the central conductor of a CTL or MRP, may influence the measurement accuracy significantly. If the dielectric constant of soil is K_o and the dielectric constant of the composite medium with an air gap is K_{net} , then from Eq. 3.14 we get

$$K_{net} = \frac{\ln(b/a)}{\ln(r_a/a) + \frac{\ln(b/r_a)}{K_o}} \quad [3.18]$$

where r_a is the radius of the air gap with thickness t ($t = r_a - a$). The analytical solution obtained (Eq. 3.18) was used to plot K_{net}/K_o versus t/a for different probe geometries and different levels of moisture content of soil. Figures 3.16 to 3.18 show the effect of air gap on measurements at different possible conditions. A range of 5-15 was used for b/a and a range of 5-35 was used for K_o . A very low moisture content of soil is represented by $K_o = 5$ and a high moisture content is represented by $K_o = 35$. From Figs. 3.16 to 3.18, following observations can be made:

1. The ratio K_{net}/K_o is extremely sensitive to the presence of air gap. A very small air

Figure 3.16 Effect of air gap around the central rod of a CTL ($b/a = 5$) on the dielectric property of soil.

Figure 3.17 Effect of air gap around the central rod of a CTL ($b/a = 10$) on the dielectric property of soil.

Figure 3.18 Effect of air gap around the central rod of a CTL ($b/a = 15$) on the dielectric property of soil.

gap reduces the value of K_{net} significantly. For example, a thickness of about 0.25 mm in a CTL having $b = 35.7$ mm and $b/a = 15$ may cause an underestimation of the dielectric constant of soil by about 10-50 %.

2. The effect of air gap is higher for soils having high moisture contents than soils having low moisture contents. For a CTL with $b/a = 10$ (Fig. 3.17), it is observed that for $t/a = 0.075$, the value of K_{net}/K_o is equal to 0.88 for soil having low moisture content ($K_o = 5$) and equal to 0.52 for soil with high moisture content ($K_o = 30$).
3. The effect of air gap increases with increase in the value of b/a .

Experiments With Air Gap

Laboratory experiments were carried out to study the effect of air gap on dielectric constant measurement and check the validity of the analytical solution given by Eq. 3.18. A laboratory compaction mold having an internal diameter (d_o) of 101.6 mm (4 in.) and a height of 116.3 mm (4.58 in.) was used. The probe central rod used had a diameter (d_{in}) of 4.76 mm (0.1875 in.), which made the value of b/a equal to about 20. The soil characteristics used in the study were as shown in Table 3.1. Steps for doing the experiments were:

1. Compact the soil prepared at a moisture content in the compaction mold. Use the probe rod along the center line of the soil in the mold with extreme care to ensure a snug fit contact between the probe rod and the soil. To minimize soil disturbance due to probe rod insertion, pilot hole can be made with a drilling rod having a slightly smaller diameter than the probe rod diameter. Measure the dielectric constant of the

Table 3.1 Soil characteristics for experiments to study the effect of air gap.

Soil Type	Moisture Content (%)	Dielectric Constant, K_o (Measured)
Clayey Silt	15	9.8
Clayey Silt	24	17.1

soil which is assumed as the dielectric constant of the soil with no air gap (K_o in Table 3.1).

2. Remove the probe rod. Enlarge the size of the center hole by using a pilot rod having a slightly larger diameter than the probe rod diameter. Now make another measurement of dielectric constant. This is the dielectric constant of the soil having an air gap whose thickness is equal to half of the difference between the hole diameter and the probe rod diameter.
3. Repeat step 2 with different larger hole diameters.

Figures 3.19 and 3.20 show a comparison between the analytical and the experimental results. The agreement between the two methods is good. The analytical solution overestimates the effect due to air gap compared to the experimental results. The reason for this could be the possible soil densification during making holes in soil.

From these observations it can be concluded that for accurate measurement of

Figure 3.19 Comparison of the analytical and experimental results for the effect of air gap around the central rod of CTL ($b/a = 20$) on the dielectric property of soil ($K = 9.8$).

Effect of Air Gap; $K=17$
Compaction Mold, $b/a=20$

Figure 3.20 Comparison of the analytical and experimental results for the effect of air gap around the central rod of a CTL ($b/a = 20$) on the dielectric property of soil ($K = 17$).

dielectric constant, the probe rod has to be inserted in a way that ensures snug contact with the soil. Also a low value of b/a , i.e., large size probe rod for a given cell, would significantly reduce the effect of any possible air gap.

Detection of an Air Gap

For accurate measurements, it is necessary to make sure that no air gap exists. There are many reasons which may cause air gap. There are ways to detect whether or not air gap exists. If from the waveform shape, one could tell whether air gap exists or not, one would be able to redo the experiment. Figure 3.21 compares a few waveforms with and without air gaps. By looking at the waveforms it can be seen that, in presence of air gaps, the shape of the waveform is distorted from the usual shape of the waveform. However, it may not be possible to detect very small air gap.

If the waveform is distorted or of unusual shape, an air gap may be suspected. For conducting experiments in field, it is always possible to easily repeat the test to check whether data (apparent length) from two measurements match or not.

3.2.6 Effect of Soil Densification

Another problem associated with insertion of probe rod in soil is the disturbance of the soil around the rod. The displaced soil mass from the hole occupied by the rod is likely to change the density of soil in the disturbed zone. It is necessary to correctly visualize the nature of density variation due to rod insertion because: the dielectric property depends on the density of soil, and the dielectric constant of the medium in a coaxial, or simulated

Figure 3.21 Detection of air gap around the central conductor of a CTL by comparing the waveforms for different air gap thicknesses (soil type: Silt).

coaxial transmission line is sensitive to the dielectric property of the medium close to the central conductor. To quantify the effect of rod insertion on the dielectric constant measurement, it is necessary to know: (a) the zone of influence, (b) the nature of variation of density in the affected zone. If these are known, the effect on the measurement of dielectric constant can be quantified using Eq. 3.14.

The nature of change of density of soil due to insertion of a rod in soil is similar to the nature of density variation of soil due to cavity expansion in soil or compaction grouting in soil. There are some factors upon which the nature of density variation depends. These are: the initial density of soil, the ambient stress, type of soil, degree of saturation, etc. Loose soil undergoes increase in density in the affected zone. The magnitude of increase and zone of influence depends on the ambient stress. Under high ambient stress, maximum increase in density takes place, and the zone of influence extends to a maximum distance (radius of influenced zone could be as high as 10 times the radius of the rod). If the density of soil is high, the disturbance may cause reduction of the density of soil, if the ambient stress of soil is not high. Figures 3.22, 3.23 and 3.24 show some typical examples for liquefiable soils (sand, silty sand) about the type and extent of density variation due to cavity expansion.

In the present case, measurements are done near the surface and the ambient pressure to which soil is subjected is very low. The ambient stress of soil prepared in a CC is also very low. In case when a heavy guide template is used for installing multiple rods (for in-place measurement), it will partially restrain the surface heaving of soil during insertion of the rods. In other words, use of such template will increase the ambient stress of the soil.

Effect of Cavity Expansion
Initial Relative Density = 30%

Figure 3.22 Post cavity expansion relative density versus radial distance for an initial relative density (D_r) of 30 % and different ambient stress conditions. (After Boulanger et al., 1993).

Figure 3.23 Post cavity expansion relative density versus radial distance for an initial relative density (D_r) of 50 % and different ambient stress conditions. (After Boulanger et al., 1993).

Figure 3.24 Post cavity expansion relative density versus radial distance for an initial relative density (D_r) of 70 % and different ambient stress conditions. (After Boulanger et al., 1993).

Generally the disturbance may decrease the density of a dense soil and increase the density of a loose soil.

So the effect of rod insertion on dielectric constant measurement depends on different conditions. It may not be possible to adjust the measured data by applying a common correction factor to it. It will be worthwhile to seek for the upper bound effect of the phenomena (maximum increase or decrease, i.e., change of the dielectric constant from the original value) by considering all possible conditions. The following guidelines will be followed to reach an upper bound solution of the problem:

1. As the objective is to find the maximum change of the dielectric constant from the original value, and because of the fact that it is easy to model the increase of density in the affected zone, assume that the insertion increases the density of the soil. The resulting increase in the dielectric constant can be assumed to be the resulting change (increase or decrease) of the dielectric constant.
2. Consider different possible types of variations (uniform, linear, exponential, etc.) of change in density.
3. Consider different possible zones of influences. Assume that the displaced soil mass from the place of inserted rod increases the density of soil in the zone of influence.
4. Conduct experiments to validate and complement the analytical results.
5. Consider different possible values for the magnitude of the change in density. Magnitude of the change of density depends on the initial density. For a soil, the ratio of the maximum and the minimum densities can be expressed as

$$\frac{\rho_{d_{\max}}}{\rho_{d_{\min}}} = \frac{1+e_{\max}}{1+e_{\min}} \quad [3.19]$$

For granular soils, the ratio is not likely to exceed 1.3. For granular soils, assuming $e_{\max} = 0.9$, $e_{\min} = 0.5$, the ratio of maximum to minimum densities is about 1.25. Whereas for cohesive soils, the ratio could be much higher than that. However, for the experimental procedures involved here, it will be easy to keep the maximum value of the ratio below 1.25 irrespective of soil type.

Uniform Increase of Density

The displaced soil mass increases the density uniformly over the disturbed zone having a radius of r_d (r_d is a special case of r_1 shown in Fig. 3.13). The new density of the soil in the disturbed zone is

$$\rho_{d_{\text{new}}} = \frac{r_d^2}{r_d^2 - a^2} \rho_{d_o}$$

where ρ_{d_o} is the dry density of the undisturbed soil, a is the radius of the rod.

Rewriting the above equation as

$$R_d = \frac{r_d^2}{r_d^2 - a^2} \quad [3.20]$$

where $R_d = (\rho_d)_{net}/\rho_{do}$. If r_d is very small, this equation may yield a value of R_d which is more than the possible upper limit of R_d . So a restriction of $R_d \leq 1.25$ must be imposed on this equation. Using Eq. 4.2, if two soil specimens have the same moisture content w , but have different densities, then

$$\frac{\sqrt{K_{net}}}{\sqrt{K_o}} = \frac{\rho_{d_{net}}}{\rho_{d_o}}$$

Using this equation, we can find the dielectric constant of the soil in the disturbed zone as

$$K_{net} = K_o \left(\frac{r_d^2}{r_d^2 - a^2} \right)^2 \quad [3.21]$$

Combining the above two equations we get

$$\frac{K_{net}}{K_o} = \frac{\ln(b/a)}{\left(1 - \frac{a^2}{r_d^2}\right)^2 \ln(r_d/r_a) + \ln(b/r_d)} \quad [3.22]$$

Figure 3.25 shows the effect of soil densification (assuming maximum $R_d = 1.25$) due to probe insertion obtained using the analytical solution (Eq. 3.22).

Effect of Rod Insertion
Uniform Variation of Density

Figure 3.25 Effect of soil densification due to rod insertion in a CTL on the measured dielectric property of soil (assuming uniform variation of density around the rod and maximum $R_d = 1.25$).

Linear Variation of Soil Densification

Now it will be assumed that the magnitude of densification decreases linearly from the edge of the inner conductor to the radial direction. The displaced mass of soil m is given by

$$m = \int_a^{r_d} 2\pi r \frac{\kappa}{r_d - a} (r_d - r) dr$$

where:

$$m = \pi a^2 \rho_o, \text{ and}$$

$$\kappa = \text{increase in density at } r = a.$$

Therefore

$$\kappa = \frac{(r_d - a)a^2 \rho_o}{2\left(\frac{1}{6}r_d^3 - \frac{1}{2}r_d a^2 + \frac{1}{3}a^3\right)}$$

So density at any distance r is

$$\rho(r) = \rho_o + \frac{\kappa}{r_d - a} (r_d - r)$$

The dielectric constant at location r is

$$K(r) = K_o \left(1 + \frac{a^2(r_d - r)}{2[\frac{1}{6}r_d^3 - r_d\frac{a^2}{2} + \frac{a^3}{3}]} \right)^2 \quad [3.23]$$

Now Eq. 3.14 can be solved numerically using the variation of K as given by this equation. Results are plotted in Fig. 3.26. Maximum effect occurs when the radius of the zone of influence is about three times the radius of the central conductor. The maximum overestimation of the measured dielectric constant is about 13 % for $b/a = 10$.

Exponential Variation of Density

This model assumes that the magnitude of densification decays exponentially in the radial direction away from the inner conductor. The displaced soil mass

$$m = \int_a^{r_d} \kappa e^{-\alpha \frac{r-a}{r_d-a}} 2\pi r dr$$

where:

α = disturbance attenuation constant,

κ = increase in density at $r = a$, and

$m = \pi a^2 \rho_o$ (as before).

Carrying out required integrations,

Figure 3.26 Effect of soil densification due to rod insertion in a CTL on the measured dielectric property of soil (for linear variation of density around the rod and maximum $R_d = 1.25$).

$$\kappa = \frac{a^2 \rho_o}{2 \left[\left(\frac{a}{\xi} + \frac{1}{\xi^2} \right) - \left(\frac{r_d}{\xi} + \frac{1}{\xi^2} \right) e^{-\xi(r_d - a)} \right]}$$

where

$$\xi = \frac{\alpha}{r_d - a}$$

Therefore, new density at a distance r is

$$\rho(r) = \rho_o (1 + \kappa e^{-\alpha \frac{r_d - r}{r_d - a}})$$

Therefore, the dielectric constant at a distance r is given by

$$K(r) = (1 + \kappa e^{-\alpha \frac{r_d - r}{r_d - a}}) K_o \quad [3.24]$$

Equation 3.14 was solved numerically for the type of variation of K as expressed in this equation (for $\alpha = 3$) and results are plotted in Fig. 3.27.

Figures 3.25 to 3.27 were plotted for maximum $R_d = 1.25$. The same figures were reproduced for maximum $R_d = 1.10$ as shown in Figs. 3.28 to 3.30. Following observations

Figure 3.27 Effect of soil densification due to rod insertion in a CTL on the measured dielectric property of soil (for exponential variation of density around the rod and maximum $R_d = 1.25$).

Effect of Rod Insertion
Uniform Variation of Density

Figure 3.28 Effect of soil densification due to rod insertion in a CTL on the measured dielectric property of soil (for uniform variation of density around the rod and maximum $R_d = 1.1$).

Figure 3.29 Effect of soil densification due to rod insertion in a CTL on the measured dielectric property of soil (for linear variation of density around the rod and maximum $R_d = 1.1$).

Effect of Rod Insertion
Exponential Variation of Density

Figure 3.30 Effect of soil densification due to rod insertion in a CTL on the measured dielectric property of soil (for exponential variation of density around the rod and maximum $R_d = 1.1$).

can be made from the Figs. 3.25 to 3.30:

1. Densification significantly increases the measured value of the dielectric constant of soil. This increase depends on b/a ratio, initial density and type of variation of densification. The increase in the measured dielectric constant increases with decrease in the value of b/a . This is because a larger rod displaces more soil compared to a smaller rod. The increase in the measured dielectric constant is a maximum for exponential variation, and minimum for a uniform variation. This is because, the dielectric constant is sensitive to the property of soil close to the rod.
2. For uniform distribution of densification in loose soil (maximum $R_d = 1.25$), the maximum increase in dielectric constant is 13 % for $b/a = 10$ and 10 % for $b/a = 20$, both occur when the zone of influence is about twice the radius of the rod. The increase reduces quickly with increase in the zone of influence. For $r_d/a = 5$, the increase is less than 5 % for all values of b/a . In case of relatively denser soil (maximum $R_d = 1.10$), the increase reduces to some extent. Peak increase is 10 % for $b/a = 10$, and 7 % for $b/a = 20$.
3. For linear distribution of densification in loose soil (maximum $R_d = 1.25$), the maximum increase in dielectric constant is about the same as that for the uniform distribution. But for the exponential distribution, the increase is relatively higher. For $b/a = 10$ the increase is 20 %, for $b/a = 20$ the increase is 15 %. Also the peak increase occurs for a larger zone of influence ($r_d/a = 4$). For a relatively denser soil, the peak increase reduces to 14 % for $b/a = 10$ and 12 % for $b/a = 20$.
4. Unlike the effect of air-gap, the effect of densification does not depend on moisture

content as seen from Eqs. 3.22, 3.23 and 3.24.

5. The zone of influence depends on the initial density of soil. The zone of influence for loose soil is smaller than the zone of influence for dense soil.

Experiments to Study the Effect of Soil Densification

Limited experiments were conducted to study the effect of soil densification, and to verify the results obtained using analytical methods. Different types of soils were used for the experiments as shown in Table 3.2. As was explained before, the effect of rod insertion depends on b/a ratio, soil density, etc. Two CTLs, one having very low b/a ratio ($b/a = 7.5$) the other having high b/a ratio ($b/a = 16$), were used. To get the maximum effect of insertion, soil specimens were prepared at low-to-medium densities. Although analytical equations showed that the effect of rod insertion does not depend on moisture content of soil, specimens were prepared to cover a wide range of moisture contents. To detect the effect of soil densification, the following experimental procedures were followed:

1. Put the central conductor in place. Compact the soil in the annular space. Make a measurement. This is the dielectric constant of the undisturbed soil, termed as K_o .
2. Repeat step 1 without putting the central conductor in place. Compact the soil in the cell. The density should be very close to the density of the soil in step 1. Make a pilot hole. Insert the central conducting rod of the coaxial apparatus through the pilot hole. Make a measurement. This is the dielectric constant of the disturbed soil, termed as K_{ner} .
3. Calculate the ratio K_{ner}/K_o . If the densities of the two specimens are not the same

Table 3.2 Soil characteristics for experiments to study the effect of soil densification.

Soil Type	CTL with $b/a = 7.5$		CTL with $b/a = 16$	
	ρ_d (Mg/m ³)	w (%)	ρ_d (Mg/m ³)	w (%)
Fine sand	1.5-1.6	5-15	-	-
Silt	1.3-1.35	6-22	-	-
Cherry L. Soil	1.4-1.45	7-23	1.3-1.34	13-23
Crosby Till	1.3-1.34	14-28	1.3-1.33	13-24

then K_{net} and K_o should be normalized by the densities of the corresponding specimens and the ratio should be calculated using the normalized K s.

4. Repeat steps 1 through 3 for soils prepared at other moisture contents.

Results

Figures. 3.31 and 3.32 show the results obtained. The rod insertion changes the dielectric constant of soil significantly as was found from theoretical results. The magnitude of the change depends on the type of soil, initial density of soil, b/a ratio of the CTL, etc. as observed from the Figs. 3.31 and 3.32. For a b/a equal to 7, the maximum increase of K is 10 % for clay, about 5 % for silt. But for sand, the insertion caused a decrease in the measured K . From Fig. 3.32 it is observed that, K is reduced by about 8 % (maximum) for

Figure 3.31 Experimental results for the effect of soil densification due to rod insertion in a CTL ($b/a = 16$) on the measured dielectric property of soil.

Figure 3.32 Experimental results for the effect of soil densification due to rod insertion in a CTL ($b/a = 7.5$) on the measured dielectric property of soil.

sand. Obviously this is because insertion caused dilation of the soil around the rod. A peak increase or decrease of 10 % corresponds to $r_d/a = 5$ in the linear model. As expected, the peak effect of insertion for the CTL with $b/a = 16$ is lower than that for CTL with $b/a = 7$. For the CTL having $b/a = 16$, the value of K_{nd}/K_o is about 1.06 for both clay and clayey silt. This corresponds to a zone of influence of about 5 times the radius of the central rod in case of the linear model. On the other hand, in the exponential model, which is more close to some of the cases in the theoretical results shown before (Figs. 3.22 to 3.24), these results correspond to a much larger zone of influence (r_d/a is about 10).

As discussed earlier, liquefiable soil undergoes reduction in density due to the disturbance caused by cavity expansion, especially if the ambient stress is low. In the experiments for sand, the density of sand was medium to high, and ambient stress was very low. Experimental results showed that a reduction of density occurred due to rod insertion. This agrees very well with the theoretical results found by Boulanger et al. (1993) shown in Figs. 3.22 to 3.24. But in case of clayey soil, inspite of the fact that the ambient stress was very low, rod insertion caused increase in density.

3.3 Conclusions and Recommendations

From the discussion made earlier, it is observed that a probe of about 300 mm long would be applicable for all soil types at all moisture contents. But there are other constraints involved, such as the difficulty involved in rod indention, available thickness of soil, etc. Considering all factors involved it would be appropriate to use length in the range of 178 to 250 mm (7 to 10 in.). Under unusual circumstances shorter or longer probe may be used.

If soil water contains salts, it may be necessary to use a shorter probe. Or, depending on specific soil type, a longer probe may be used. If the soil is noncohesive, a much longer probe can be used for better accuracy.

Considering the influence of air gap on measurement accuracy, experimental methods and devices must be such that it avoids air gap. Using a low b/a ratio would reduce the effect of air gap, but that increases the effect of soil disturbance. So the best way would be to choose b/a to minimize the effect of soil disturbance and adopt experimental procedure that avoids air gap.

Air gaps can be avoided by using special testing procedures. A template having guide holes in it can be used to guide the conductors. In coaxial line, a guide cap can be used to make a pilot hole through which the central rod can be pushed. Of course the diameter of the pilot hole should be slightly smaller than that of the rod.

A high b/a ratio would reduce the effect of soil disturbance. Considering other constraints involved a ratio of 15 would be reasonable. Another way of minimizing soil disturbance is by making pilot holes by using drilling bits. After placing the template, hand drill can be used to make holes. Excavated soil will automatically come up on the surface. Of course the diameter of the drill bit has to be slightly smaller than the diameter of the conductor rod. Another way of eliminating soil disturbance in case of coaxial line is to compact the soil after placing the central conductor and compacting the soil in the annular space.

CHAPTER 4

DEVELOPMENT OF DIELECTRIC CONSTANT-MOISTURE CONTENT
RELATIONSHIP

4.1 Introduction

In Ch. 2, a review was made on different types of existing calibration equations. The aim of this chapter is to analyze the existing relationships with experimental data and propose ways to eliminate the drawbacks of the equations. The calibration equations depend on many factors. Among the factors are: density, installation technique, temperature, soil moisture chemical concentration, soil type, probe type and probe geometry, etc. Among these factors, some have already been explored by some researchers. Some are involved with the special types of probes and test methodology specific to this study. This chapter explores the effects of these factors. The results would be useful for specific uses as will be discussed in chapter 5, 6 and 7.

4.2 Materials and Methods

The CTL as shown in Fig. 3.2 was used for conducting experiments to measure dielectric constants of soils. The important dimensions of the CTL were: L (length of rod inserted in soil) = 220 mm, internal diameter of the central rod = 4.76 mm, and diameter of the cell = 72.6 mm. To develop calibration equations and to study the characteristics of the factors that influence the relationships, it was necessary to include all possible parameters in the experimental program. Accordingly, a variety of soil types were chosen. Soil

specimens were prepared at different moisture contents and densities to cover a wide range of moisture content and density. Table 4.1 shows the characteristics of the soils used in the experimental program. The main steps for an experiment were:

1. Prepare soil at a specified moisture content.
2. Compact the soil in the coaxial cell.
3. Make a pilot hole with the penetrometer. Push the CA rod in the pilot hole.
4. Make a measurement.
5. Measure the mass of soil in the cell and calculate the wet density (ρ_{wet}) of the specimen in the cell from the known cell volume.
6. Calculate the volumetric moisture content, θ , from the dielectric constant using a suitable calibration equation. Compute gravimetric moisture content of soil from the volumetric moisture content and wet density as follows:

$$w = \frac{\theta}{\rho_{wet} / \rho_w - \theta}$$

7. Repeat steps (1) to (6) for soil prepared at other moisture contents to cover a wide range of moisture content.

4.3 Results and Discussions

Topp's empirical equation (Eq. 2.26) was used to compute the volumetric moisture contents and results were compared with the actual volumetric moisture contents. Figure 4.1 shows this comparison. The result of regression analysis is: intercept = 0, slope = 0.981,

Table 4.1 Soil characteristics for experiments to develop calibration equations.

Soil Type	%	%	%	Range of Density	Range of Moisture
	Sand	Silt	Clay	(Mg/m ³)	Content (%)
Crosby Till	5	15	80	1.05-1.55	12-27
Silt	0	100	0	1.20-1.60	4-24
Fine Sand	100	0	0	1.40-1.68	1-13
Kaolinite	0	0	100	1.00-1.45	6-28
Cherry L. Soil	5	70	25	1.30-1.65	8-24

Figure 4.1 Comparison of the actual volumetric moisture content and the TDR measured volumetric moisture content for different types of soils (listed in Table 4.1) using Topp's empirical equation (Eq. 2.26).

$R^2 = 0.975$. The accuracy of measurement is about $\pm 2\%$ to $\pm 2.5\%$. This is what was obtained by other researchers using Topp's equation.

To obtain calibration equation of the form of Eq. 2.30, values of $\sqrt{K}$ were plotted with the actual volumetric moisture contents as shown in Fig. 4.2. The result of regression analysis is:

$$\sqrt{K} = 1.52 + 8.65\theta \quad [4.1]$$

Similar equations were obtained by other researchers (Alharthi et al. 1987; Ledieu et al. 1986). Using this equation, volumetric moisture contents were back calculated and compared with the actual volumetric moisture contents. Figure 4.3 shows the comparison. The results of regression analysis are: slope = 1, intercept = 0, $R^2 = 0.98$. Maximum error of measurement is about $\pm 1.5\%$. This shows some improvement over the Topp's empirical calibration equation. To obtain soil specific calibration equations, regression analyses were carried out for each soil type. Table 4.2 gives the coefficients of regression analyses and values of R^2 . The values of intercepts vary from 1.14 to 1.58, values of slopes vary from 8.26 to 9.78, correlation coefficients vary from 0.967 to 0.988. From these results it is clear that a common calibration equation may not be applicable for all soils. Soil specific calibration equations are necessary for highly accurate results.

Using the soil specific calibration equations as shown in Table 4.2, actual volumetric moisture contents were back calculated and results were plotted in Fig. 4.4. The result of regression analysis is: intercept = 0, slope = 1, $R^2 = 0.99$. Maximum error of measurement is about $\pm 1\%$. This is an improvement over the Topp's equation.

Figure 4.2 $\sqrt{K}$ vs. actual volumetric moisture content (θ) relationship.

Figure 4.3 Comparison of the actual volumetric moisture content and the TDR measured volumetric moisture content using general $\sqrt{K-\theta}$ linear calibration equation (Eq. 4.1).

Table 4.2 Regression analysis: $\sqrt{K} = c_1 + c_2\theta$

Soil Type	Sample Size	Const., c_1	Slope, c_2	R^2
Crosby Till	26	1.14	9.78	0.967
Silt	45	1.56	8.74	0.989
Fine Sand	55	1.59	8.26	0.987
Cherry L. Soil	33	1.31	8.96	0.988
Kaolinite	10	1.59	8.30	0.989

Figure 4.4 Comparison of the actual volumetric moisture content with the TDR measured volumetric moisture content using soil specific $\sqrt{K-\theta}$ calibration equations from Table 4.2.

Some authors have shown that the empirical K - θ relationship is influenced by the density of soil. It was found that, two soil specimens having the same volumetric moisture content but different densities, the dielectric constant of the specimen having the higher density may be higher than the one having the lower density. Figures 4.5 to 4.7 show experimental results of the effect of density on the K - θ relationship. These figures clearly show that the K - θ relationship is not independent of density. The way K - θ relationship gets affected depends on the soil type. But a general trend is that the intercept c_1 increases with increase in density (Tables 4.3, 4.4 and 4.5).

To find a relationship independent of density of soil, it would be reasonable to normalize $\sqrt{K}$ by density. It is also likely that a linear relationship might exist between $\sqrt{K\rho_w/\rho_d}$ and w . Figures 4.8 to 4.10 show $\sqrt{K\rho_w/\rho_d}$ - w relationships for different densities. The results of $\sqrt{K\rho_w/\rho_d}$ - w regression analyses for different soils at different densities are given in Tables 4.6, 4.7 and 4.8. From these figures and tables it is observed that the influence of density on $\sqrt{K\rho_w/\rho_d}$ - w relationship is less than that on $\sqrt{K}$ - θ relationship. General regression analysis for the $\sqrt{K\rho_w/\rho_d}$ - w relationship was carried out for each soil type for the entire range of density tested and result is shown in Table 4.9. This table shows that excellent linear relationship exists between $\sqrt{K\rho_w/\rho_d}$ and w . Comparing Table 4.2 and Table 4.9, it is observed that a better linear relationship exists between $\sqrt{K\rho_w/\rho_d}$ and w than the linear relationship between $\sqrt{K}$ and θ for almost all soil types. From Table 4.9, it is observed that the values of intercept a are close to 1 for all soils except Kaolinite for which it is 1.20. Similarly the values of slope b are in the range 8 to 9 except for kaolinite for which it is 7.8. From these it is obvious that a common calibration equation may not be suitable

Figure 4.5 Effect of density on $\sqrt{K-\theta}$ calibration equation (for Fine Sand).

Figure 4.6 Effect of density on $\sqrt{K-\theta}$ calibration equation (for Silt).

Figure 4.7 Effect of density on $\sqrt{K-\theta}$ calibration equation (for Cherry L. Soil).

Table 4.3 Regression analysis for Fine Sand for different densities: $\sqrt{K} = c_1 + c_2\theta$

Density (Mg/m ³)	Sample Size	Const., c_1	Slope, c_2	R^2
1.60-1.68	20	1.616	8.39	0.990
1.55-1.60	17	1.618	7.99	0.992
1.50-1.55	15	1.592	7.86	0.996
1.40-1.50	7	1.573	7.54	0.993

Table 4.4 Regression analysis for Silt for different densities: $\sqrt{K} = c_1 + c_2\theta$

Density (Mg/m ³)	Sample Size	Const., c_1	Slope, c_2	R^2
1.55-1.65	16	1.667	8.51	0.993
1.45-1.55	20	1.639	8.26	0.991
1.30-1.45	9	1.532	8.48	0.996

Table 4.5 Regression analysis for Cherry L. Soil for different densities: $\sqrt{K} = c_1 + c_2\theta$

Density (Mg/m ³)	Sample Size	Const., c_1	Slope, c_2	R^2
145-1.58	11	1.477	8.62	0.992
1.40-1.45	8	1.399	8.66	0.996
1.30-1.40	14	1.315	8.83	0.996

Table 4.6 Regression analysis for Fine Sand for different densities: $\sqrt{K\rho_w/\rho_d} = a + bw$

Density (Mg/m ³)	Sample Size	Const., c_1	Slope, c_2	R^2
1.60-1.68	20	0.998	8.320	0.990
1.55-1.60	17	1.025	7.990	0.989
1.50-1.60	15	1.040	7.840	0.996
1.40-1.50	7	1.070	7.600	0.997

Table 4.7 Regression analysis for Silt for different densities: $\sqrt{K\rho_w/\rho_d} = a + bw$

Density (Mg/m ³)	Sample Size	Const., c_1	Slope, c_2	R ²
155-1.65	16	1.064	8.39	0.993
1.45-1.55	20	1.105	8.11	0.993
1.30-1.45	9	1.088	8.46	0.998

Table 4.8 Regression analysis for Cherry L. Soil for different densities: $\sqrt{K\rho_w/\rho_d} = a + bw$

Density (Mg/m ³)	Sample Size	Const., c_1	Slope, c_2	R ²
145-1.58	11	1.004	8.565	0.995
1.40-1.45	8	1.001	8.585	0.997
1.30-1.40	14	0.979	8.770	0.994

Table 4.9 Regression analysis: $\sqrt{K\rho_w/\rho_d} = a + bw$

Soil Type	Intercept, a	Slope, b	R ²
Crosby Till	1.080	8.93	0.962
Silt	1.102	8.18	0.993
Fine Sand	1.034	7.96	0.992
Cherry L. Soil	0.993	8.65	0.995
Kaolinite	1.200	7.80	0.950

Figure 4.8 Effect of density on $\sqrt{K\rho_w/\rho_d}w$ linear relationship (for Fine Sand).

Figure 4.9 Effect of density on $\sqrt{K\rho_w/\rho_d}-w$ linear relationship (for Silt).

Figure 4.10 Effect of density on $\sqrt{K\rho_w/\rho_d}$ - w linear relationship (for Cherry L. Soil).

for all soil types. Figure 4.11 shows excellent linear correlation between $\sqrt{K\rho_w}/\rho_d$ and w for different types of soil. This observation shows that soil specimens having the same gravimetric moisture content have the same value for the ratio of $\sqrt{K\rho_w}/\rho_d$. To see whether the ratio $(\sqrt{K-c})\rho_w/\rho_d$ (refer to Eq. 2.30) has a better correlation with w than the $\sqrt{K\rho_w}/\rho_d$ - w correlation, the data were plotted for different values of c ranging from 0 to 1.0. Table 4.10 shows the results of regression analyses. It is seen that R^2 is not very sensitive to the values of c ranging from 0 to 1.0. From these results it can be concluded that

$$\frac{\sqrt{K}\rho_w}{\rho_d} = a + bw \quad [4.2]$$

where, depending on soil type, a may vary from 0.95 to 1.2 and b may vary from 7.5 to 9. For the parameters considered in this study, a general equation is

$$\sqrt{K}\rho_w/\rho_d = 1.00 + 8.95w \quad [4.3]$$

Equation 4.2 may be used for measuring gravimetric moisture content as

$$w = \frac{\sqrt{K} - a\rho_t/\rho_w}{b\rho_t/\rho_w - \sqrt{K}} \quad [4.4]$$

As the dielectric constant depends on the volumetric moisture content, and influenced by the density of soil, it may be likely that a very good correlation might exist between $\sqrt{K}$ and the degree of saturation of soil. Regression analyses for $\sqrt{K}$ - S_v were carried out. Table 4.11 shows the results of regression analyses. The correlation is very strong and in most

Figure 4.11 $\sqrt{K\rho_w/\rho_d}$ vs. w relationship for different types of soils (listed in Table 4.1).

Table 4.10 Regression analysis: $(\sqrt{K-c})\rho_w/\rho_d = a + bw$

c	a	b	R ²
0	1.007	8.95	0.986
0.3	0.797	8.89	0.987
0.5	0.667	8.85	0.988
0.7			0.986
1.0	0.340	8.76	0.988

Table 4.11 Regression analysis: $\sqrt{K} = c_1 + c_2 S_r$

Soil Type	Sample Size	Const., c ₁	Slope, c ₂	R ²
Crosby Till	50	1.589	3.983	0.950
Silt	52	1.655	3.530	0.992
Fine Sand	52	1.605	3.353	0.993
Cherry L. Soil	52	1.448	3.995	0.994
Kaolinite	23	1.872	3.673	0.970

cases the relationship is better than $\sqrt{K}-\theta$ relationship and as good as $\sqrt{K\rho_w/\rho_d}-w$ relationship.

A general regression for all soil types yield

$$\sqrt{K}=1.577+3.80S_r \quad [4.5]$$

with $R^2 = 0.967$. For calculating moisture content, this equation can be written as

$$w=\frac{\sqrt{K}-C_1}{C_2} (\rho_w/\rho_d-1/G_s) \quad [4.6]$$

To see whether the $\sqrt{K}-S_r$ relation is affected by the density of soil, $\sqrt{K}-S_r$ were plotted for different densities as shown in Figs. 4.12 to 4.14. The solid lines are the best fit lines through the experimental data points. These figures clearly shows that, the $\sqrt{K}-S_r$ relationship is not influenced by the density of soil at low moisture contents, but as the degree of saturation increases, the effect of density on the relationship also increases.

From this discussion, it is clear that, a true universal equation seems not to exist. The proposed two equations eliminates the effect of density to some extent. A reasonable good result may be obtained by using Eq. 4.2 developed here. Also if the density does not vary a lot, one single equation of the type $\sqrt{K}-\theta$ should provide sufficiently accurate result.

4.4 Other Factors Affecting Dielectric Constant Measurement

The calibration equations are affected by soil type and density of soil as discussed above. There are other factors that affect the equations. Among these are: type of probe or transmission line (will be discussed in Ch. 5), method of installation, geometry of probe,

Figure 4.12 Effect of density on $\sqrt{K-S}$, linear relationship (for Fine Sand).

Figure 4.13 Effect of density on $\sqrt{K}$ -S, linear relationship (for Silt).

Figure 4.14 Effect of density on $\sqrt{K}$ - S , linear relationship (for Cherry L. Soil).

temperature, chemical concentration, etc. Some of the results of effect of rod installation/insertion were presented in Ch. 3. The effect of rod insertion on calibration equation will be discussed here. The effect of soil water salinity on dielectric property will also be investigated here.

4.4.1 Effect of Rod Insertion

In Ch. 3, it was found that rod insertion changes the dielectric constant from the actual dielectric constant. It may be necessary to employ experimental procedure that needs insertion of rod for making measurements. The calibration equation for the push-in-rod method and in-place-rod method would be different. Experimental data plotted in Figs. 3.33 to 3.34 were replotted to compare the calibration equation obtained using the two procedures.

Figures 4.15 to 4.20 show the comparison between the calibration equations. It is observed that significant difference exists between the calibration equations associated with the two methods. In most cases the calibration equations are parallel to each other, indicating a clear effect of density change due to probe insertion. The effect of b/a on the calibration equation is also evident. With increase in the value of b/a , the difference between the calibration equations reduces.

So a significant error would result, if a calibration equation derived using one type of experimental method is used for another type of experimental method. The appropriate type of calibration equation should be used to measure moisture content.

Figure 4.15 Experimental results for the effect of rod insertion on the $\sqrt{K\rho_w/\rho_d}w$ linear relationship ($b/a = 7.5$, soil type = Fine Sand).

Figure 4.16 Experimental results for the effect of rod insertion on the $\sqrt{K_d/\rho_d}-w$ linear relationship ($b/a = 7.5$, soil type = Silt).

Figure 4.17 Experimental results for the effect of rod insertion on the $\sqrt{K\rho_w/\rho_d}w$ linear relationship ($b/a = 7.5$, soil type = Cherry L. Soil).

Figure 4.18 Experimental results for the effect of rod insertion on the $\sqrt{K\rho_w/\rho_d}w$ linear relationship ($b/a = 7.5$, soil type = Crosby Till).

Figure 4.19 Experimental results for the effect of rod insertion on the $\sqrt{K\rho_w/\rho_d}w$ linear relationship ($b/a = 16$, soil type = Cherry L. Soil).

Figure 4.20 Experimental results for the effect of rod insertion on the $\sqrt{K\rho_w/\rho_d}$ - w linear relationship ($b/a = 16$, soil type = Crosby Till).

4.4.2 Effect of Soil Water Salinity

The effect of dissolved salt in soil water on selecting the length of probe was discussed in section 3.2.1. In Fig. 3.10 was shown how salinity deforms the TDR waveform. This figure also showed that the dielectric constant (or the apparent length) does not change due salinity. Figure 4.21 shows dielectric constant of saline water at different concentrations of NaCl. From the figure, it is observed that there is no noticeable effect of salinity on the dielectric property of water. This property will also hold for soil (especially noncohesive soil) whose moisture is likely to be saline.

4.5 Conclusions

Experimental data were used to compare different types of linear calibration equations. It is found that excellent linear correlation exists between $\sqrt{K}$ and θ . Although density affects this relationship to some extent, still a single calibration equation of a given soil type would provide accurate measurement of θ over a wide range of density.

The new calibration equation of the form $\sqrt{K\rho_w/\rho_d}$ eliminates the effect of density to some extent, especially for granular soils. A very good correlation between $\sqrt{K}$ and S_r is found to exist. But the effect of density on this type of relationship is found to be more prominent than any of the two other forms of calibration equations.

A generalized equation of the form $\sqrt{K-\theta}$ or $\sqrt{K\rho_w/\rho_d-w}$ would provide similar accuracy as would Topp's equation. But specific calibration equation of the form $\sqrt{K-\theta}$ or $\sqrt{K\rho_w/\rho_d}$ would increase the accuracy of measurement significantly, especially for soils where they are applicable.

Figure 4.21 Effect of salinity on the dielectric property of water.

The calibration equation depends on the experimental method also. The effect of probe rod insertion on calibration equation may be significant. The intercept of $\sqrt{K\rho_w/\rho_d}$ form of calibration equation may increase for cohesive soils and decrease for sandy soil.

CHAPTER 5

MEASUREMENT OF IN-PLACE DENSITY AND MOISTURE CONTENT OF SOIL

5.1 Introduction

The principles and devices developed in Ch. 3 and Ch. 4 were used to measure in-place density and moisture content of soil. The CTL used in Ch. 4 to develop calibration equations showed that it could be used to measure moisture content of soil in the field. This chapter shows how, by making two separate measurements, it is possible to measure in-place density and moisture content of soil. Based on the principles of designing coaxial and multiple rod probes (MRP), probes are developed to make measurements. It was shown that there are many factors those influence TDR measurements. Experimental methods are developed to eliminate the effects of these factors. Laboratory and field experiments are conducted to establish the method of measuring in-place density and moisture content.

5.2 Theory

The dielectric constant of soil is directly related to the volumetric moisture content of soil. A MRP can measure dielectric constant of soil in place. Some soil can be quickly taken from the location of the in-place measurement and compacted in the CC of a CTL to measure the dielectric constant of the soil. The wet density of the soil in the CC can be measured, from which the gravimetric moisture content of the soil can be calculated. It can be assumed that the moisture content of the soil in the CC is the same as the moisture content of the soil in place. Using the dielectric constant and moisture content of soil in

place, the density of the soil in place can be determined.

It was found (in Ch. 4) that there exists a linear relationship between $\sqrt{K}$ and w of the form (rewriting Eq. 4.2)

$$\frac{\sqrt{K}}{\rho_d / \rho_w} = a + bw \quad [5.1]$$

If two soil specimens have the same moisture content w , but have different densities ρ_{d1} and ρ_{d2} , then from Eq. 5.1 we get

$$\frac{\sqrt{K_1}}{\sqrt{K_2}} = \frac{\rho_{d1}}{\rho_{d2}} \quad [5.2]$$

where K_1 and K_2 are the dielectric constants of the specimens having densities ρ_{d1} and ρ_{d2} , respectively. To assess the performance of Eq. 5.2 in measuring in-situ density, it is necessary to compare it with conventionally measured density. Also, it is necessary to test the performance of Eq. 5.2 for all possible parameters. Laboratory experiments using coaxial cells can be conducted to achieve these goals. If two soil specimens are prepared at the same moisture content, w , in two cylindrical cells, then the density of one of the specimens can be measured using the density of the other specimen using

$$\rho_{t_{cc2}} = \frac{\sqrt{K_{cc2}}}{\sqrt{K_{cc1}}} \rho_{t_{cc1}} \quad [5.3]$$

The density thus measured can be compared with the conventionally measured density of the soil specimen.

Steps for measuring in-place density and moisture content:

1. Use a MRP to measure the dielectric constant, $K_{in-situ}$ of the soil in place.
2. Dig out some soil from the location of the in-place measurement and compact it in the CC of a CTL. The MRP may also be used to make a measurement if the soil is compacted in a CC of appropriate size for the MRP.
3. Measure the dielectric constant, K_{CC} and determine the wet density $(\rho_{wet})_{CC}$ of the soil in the CC by measuring soil mass and known volume of the CC.
4. Use Eq. 5.2 to calculate in-place wet density.
5. Use, Topp's equation, or other suitable calibration equations, or oven dry method to measure moisture content of the soil in the CC.
6. Measure dry density from the wet density.

5.2.1 Variability of Density Measurement

There are some variability involved in TDR measurement which might introduce variability in density measurement. Ignoring all other sources of variation, the variability due to TDR equipment can be estimated. The ratio of densities of two soil specimens A and B having the same moisture content, w is

$$R_d = \frac{\rho_{dA}}{\rho_{dB}} = \frac{K_A^{0.5}}{K_B^{0.5}} \quad [5.4]$$

If the lengths of the TLs that measured the dielectric constants of specimens A and B are L_A and L_B respectively, then using Eqs. 2.1 and 5.5,

$$R_d = \frac{l_A / L_A}{l_B / L_B} \quad [5.5]$$

where l_A and l_B are measured apparent lengths for specimens A and B respectively. Using Taylor's series

$$[C_v(R_d)]^2 = [C_v(l_A)]^2 + [C_v(l_B)]^2 \quad [5.6]$$

Or

$$S_d(R_d) = S_d(l) R_d \sqrt{\frac{1}{l_A^2} + \frac{1}{l_B^2}} \quad [5.7]$$

where $S_d(R_d)$ = Standard deviation of R_d . If $L_A = L_B$, and R_d is close to 1, then it can be assumed that $l_A = l_B = l$. So

$$S_d(R_d) = \frac{\sqrt{2} S_d(l)}{l} R_d \quad [5.8]$$

This equation shows that, the coefficient of variation of density measurement is $\sqrt{2}$ times the coefficient of variation of measuring apparent length l . Obviously this equation ignores all other factors involved in density measurement. If the factors are identical in the two measurements, the accuracy of density measurement will increase with increase in l , i.e.,

length of probe.

5.3 Devices and Test Methodology

Measuring in-place density and moisture content requires two independent measurements of dielectric constants as described earlier. As highly accurate measurement of density is required for compaction control tests, it is very important to select and use devices and test methods which ensure accurate and reliable measurement of density.

It has been found that there are many factors which affect the measurement. For making moisture content measurement, it is sufficient to make one single measurement provided the density of soil is known, and thus it is possible to take account for the factors involved. For measuring density (and moisture content), two independent tests need to be conducted. For accurate measurements, it is necessary that any factor which might introduce some error in measurement, introduces the error identically in both the measurements, thus cancelling the effect of the factor. But a problem arises when the influencing factors affect each measurement differently from the other. It would be ideal to keep test methods, devices, specimens identical in both the experiment. Different factors that might influence measurement accuracy are discussed below:

- Type of TL: The shape of waveform depends on the type of TL. There is some approximation involved in locating the point of end reflection. To keep the degree of approximation similar in both measurements, it is necessary that the shape of waveforms be similar. Different types of TLs generate different shapes of waveforms.
- Effect of Rod Insertion: The effect of rod insertion may be different in the two tests. The

magnitude of soil disturbance depends on number of rods driven, the b/a ratio of the TL, surface boundary condition, etc.

- Ratio of Densities: The difference in density between the two soil specimens may be significantly different. This may also affect the accuracy of density measurement. The effect of rod insertion depends on density of soil. To keep the effect of rod insertion similar in both the measurements, it is better to keep the densities of the two specimens as close as possible. Moreover, the reliability of Eq. 5.2 for measuring density may reduce if the ratio of density is too high. This is especially true if the soil type is such that Eq. 5.1 does not exactly apply to it.
- Length of TL: From Eq. 5.8, it is observed that the accuracy of density measurement increases with increase in the length of TL. But this equation also shows that the accuracy does not depend on the ratio of the lengths of the TLs. But for other reasons, unequal lengths may introduce error in measurement.
- Moisture Loss: It is assumed that the moisture content of the soil taken out of the ground is identical to the moisture content of the soil in place. But that is not quite true. Digging the soil out of the ground, preparing the specimen, etc. require certain amount of time in which some moisture content may evaporate from the soil. This will make the moisture content of the soil in the CC lower than that in place.
- Representativity of Sampling: It is assumed that the sampled soil is representative of the soil in place. But that may not be true also.

So devices and experimental methods should be developed to minimize the errors and to control the quality of measurement. It is necessary to study the nature of these factors,

the resulting effect of the factors on measurement accuracy, the tolerance limits of variations of certain factors etc. The following discussion points provide guidelines for making accurate measurements:

- 1) In both the measurements (in place with the MRP and in the CTL) the effect of rod insertion should be the same. Although the effect of rod insertion depends on the density of soil, and it is not likely that the densities of the two specimens would be the same, the effect of density difference can be minimized by preparing the soil specimen at a density which is close to the density of soil in place. Similar installation techniques and the same b/a ratio should be used in both the cases.
- 2) As the effect of probe insertion depends on whether or not surface heaving is allowed to take place, and surface heaving depends on the type of guiding template used, similar guiding templates should be used for both the cases.
- 3) As was discussed in Ch. 3, the length of probe influences the measurement. To keep the influence identical in both the experiments, the lengths should be kept about the same in both tests.
- 4) It is convenient to use a coaxial type of TL for making measurements for the specimen prepared in the cell, where it is impossible to use a coaxial TL in field. A parallel rod type probe (MRP) is suitable for making measurements in field. The properties of a multiple rod probe is similar to that of a coaxial probe. So a multiple rod probe may be used for in-place measurements. Also, it must be determined whether coaxial and multiple rod probes measure the same dielectric constant of the same soil. It might be possible that two tests can be done with the same MRP, which

would eliminate any possible variation due to probe type. However, in either case, because of the fact that, the soil is confined in a CC as opposed to the soil in field, the effect of rod insertion may be different in the two cases. These issues need to be investigated to reach a decision about the devices and methods to be used for best possible results.

- 5) To eliminate error due to nonrepresentative sampling of soil, soil should be taken from around the central conductor for in-place measurement. Also soil should be taken uniformly from the entire depth of in-place measurement.
- 6) To reduce the moisture loss, the excavated soil should be directly placed in the CC and compacted as it is being placed.

The basic concept behind measuring in-place density and moisture content is that, it requires two measurements to be performed on two specimens of the same soil having the same moisture content. If the density of one of the specimens is known, then the density of the second specimen can be calculated using Eq. 5.2. Of course, the moisture content of the soil can be calculated using the measured dielectric constant of either specimen and its density. To explore how good is this concept, it is necessary to conduct experiments on a wide variety of soils, including all possible parameters (a wide range of moisture content and density etc.). Using two identical CTLs for that purpose would be ideal. Once the theory and concept is established, the actual field experiment can be conducted using the actual devices. To conduct experiments under ideal conditions, CTLs of the type as was shown in Fig. 3.2 can be used.

Actual field experiment requires two measurements: one in-place and the other one on

the specimen prepared in a cell by using the soil from in-place measurement. The TL to be used in field has to be a MRP. As recommended in Ch. 3, the conducting rods should be inserted using a guiding mechanism (template) to ensure a snug-fit contact between the rods and the soil. The most important part of the design is to develop an effective method for insertion of the rods. There are a few options as discussed below:

- 1) Nonconducting Template: A nonconducting template (wood for example) having guide holes at the spacings of the studs in the MRP head could be an option. Ordinary spikes having enlarged heads could be driven and the MRP head could be placed on top of the spike heads. The good thing about this method is that there is no need to remove the template. The spikes are sufficiently robust and durable and would not deform due to repeated hammering on it. The major problem with this type of template is that the wooden template may not be robust enough, wearing out or breaking after repeated use. The guide holes would deform and proper installation of the rods would not be possible. Using a hard plastic (e.g., delrin) may solve that problem but may not be economical. Both the wooden and plastic templates would tend to move due to their light weights during insertion of the rods.
- 2) Insulated Metallic Template: Another option could be using a metallic template, the center guide hole being isolated from the outer holes as shown in Fig. 5.1. After driving the rods through the holes, the MRP head studs could be placed on the head of the spikes. The problem with this type of arrangement is that, this would make the TL a combination of too many TLs, may cause distortions of the waveform around the first reflection point and ill-defined end reflections.

Figure 5.1 In-place measurement using a MRP with insulated metallic template.

3) **Metallic Template:** The third option is to use a metallic template with guide holes in it. Once the rods are driven, the template needs to be removed by moving it in the upward direction and the MRP head needs to be placed directly on top of the conducting rods as shown in Fig. 5.2. Ordinary spikes having enlarged heads can not be used; rather specially made rods must be used. To be able to remove the template, it is necessary that the diameters of the rods are sufficiently smaller than the diameters of the holes. Repeated pounding on the rods for driving will enlarge the end diameters. As the diameter of the holes in the metallic template should not be too large from the diameters of the rods, the enlargement might make it impossible to remove the template. This is the most problematic part of using this kind of metallic template. Pounding directly on the rod may be avoided by using an anvil as shown in Fig. 5.3. The anvil has a conical hole in which fits the conical head of the rods. A rod can be driven by placing the anvil on the rod and hammering on the top surface of the anvil. This way, end deformation of the rod can be avoided. Once the test is over, a pulling wrench can be used to pull out the rods for reusing. Or a small groove can be made near the top ends of the rods to pull them out using the claw-hammer.

Using a nonmetallic template may not be a viable option. Both the insulated metallic template method and metallic template method have advantages and disadvantages. The main problem with the insulated template method may be that it would distort the waveform. Figure 5.4 compares the waveforms obtained using the two methods. From this figure it is observed that the metallic template method offers a better signal with less signal distortion. The insulated metallic template shifts the first reflection point to the right. As a result the second reflection point also shifts to the right. Considering the advantages associated with

Figure 5.2 In-place measurement using a MRP with a metallic template.

Figure 5.3 Insertion of rods for in-place measurement using the metallic template.

Figure 5.4 Distortions of TDR waveform due to the use of the insulated metallic template.

the insulated template method, it can be used although it may not offer best possible waveform.

What about the second measurement? There are three options: (1) use a CTL as shown in Fig. 3.2, (2) use the same MRP as described above in a CC having a diameter larger than the equivalent diameter (twice the spacing of the center to the outer rods) of the MRP (Fig. 5.5) and, (3) a modified CTL composed of a MRP head, a rod and a CC (Fig. 5.6). The best method would be one which best matches the field experiment. It is necessary to figure out how the boundary of the CC affects the measurement. Also how the b/a ratio affects the measurement because with increase in b/a ratio for a given CC and rod diameter, the disturbance of the soil near the outer boundary increases. Also it is necessary to compare the performances of the MRP in CC and the CTL.

Experiments were conducted to find which devices and test method best simulates the in-place measurement. Different TLs (CTL, modified CTL, MRP in CC) with different b/a ratios were used in the experiments. Table 5.1 and 5.2 shows the types of TLs used and the results of the experiments. Figures 5.7 and 5.8 compare the calibration equations obtained using different TLs for the soil type mentioned in Tables 5.1 and 5.2. No significant effect of TL type on the calibration equation is observed. Experiments with different types of soils and different densities may reveal that TL type affects measurements. However, it can be concluded the second test may be performed with either a MRP or a CTL having the same b/a ratio as that of the MRP used for in-place measurement.

Figure 5.5 Using a MRP for measurement in a cylindrical cell.

Figure 5.6 A modified CTL, (a) rod is inserted using a template, (b) template removed and a MRP head is placed.

Table 5.1 Comparison of $\sqrt{K-\theta}$ calibration equations for different TLs.

Soil type	TL type	Intercept	Slope	R ²
Cherry L. Soil	MRP, $b/a = 14$	1.44	9.19	0.982
	MRP, $b/a = 19$	1.43	9.23	0.992
	Modified CTL $b/a = 21$	1.45	9.26	0.988
	CTL, $b/a = 14$	-	-	-

Table 5.2 Comparison of $\sqrt{K\rho_w/\rho_d-w}$ calibration equations for different TLs.

Soil Type	TL Type	a	b	R ²
Cherry L. Soil	MRP, $b/a = 14$	1.01	8.70	0.980
	MRP, $b/a = 19$	1.02	8.67	0.992
	Modified CTL $b/a = 21$	1.02	8.73	0.988
	CTL, $b/a = 14$	1.00	8.65	0.995

Figure 5.7 Effect of the variations of TL ($L = 213$ mm) characteristics on the measured dielectric constant.

Figure 5.8 Effect of the variations of TL ($L = 213 \text{ mm}$) characteristics on the measured dielectric constant.

5.4 Experimental Program to Measure Density and Moisture Content

The development of the procedure for determining in-place density required determination of the dielectric constants of soil specimens having the same moisture contents but having different dry densities. A wide range of parameters, i.e., soil type, moisture content, density etc. were needed to be covered for such measurements. Using CTLs was most easy and ideal for that purpose. The characteristics of the soils were exactly as was shown in Table 4.1. The data generated from this experimental program was also used to develop calibration equations as was discussed in Ch. 4. To assess the performance of the developed procedure for measuring density, field experiments were conducted using the devices as shown in Fig. 5.1. The sand-cone method was used to measure in-place density to compare with the density measured by the present technique. As there is no exact method of measuring in-place density to correctly assess the performance of the method developed for measuring density, it was necessary to conduct experiments in the laboratory under simulated field conditions to correctly assess the performance of measuring in-place density.

Important dimensions of the CTLs (Fig. 3.2) used for laboratory experiments were: effective length of probe, $L = 228$ mm, diameter of central rod, $d = 4.76$ mm, inside diameter of CC = 72.6 mm, outer diameter of CC = 76.2 mm. The main steps for the laboratory experiments are:

- 1) Prepare soil at a specified moisture content.
- 2) Compact the soil in two coaxial cells (CCs) in a way that soil in each cell has a different density. Specimens should be prepared in a way that the moisture content of each specimen remain the same.

- 3) Measure the dielectric constants of the specimens using the CA.
- 4) Determine the wet-densities of specimens in each cell. Take sample from each cell for measuring moisture content by oven drying method. Use oven dry moisture content to calculate dry densities.
- 5) Compute gravimetric moisture content of soil in each cell using the measured dielectric constant and wet density. Compute dry density using this gravimetric moisture content.
- 6) Use the dry density of one of the specimens measured in step (5) to measure the dry density of the other specimens. Compare this density with that calculated in step (4).
- 7) Compare the gravimetric moisture content computed in step (5) with oven dry moisture content.
- 8) Prepare additional pairs (at least four) of specimens with the soil prepared at the same moisture content used in step (1), but with different compacting efforts. Densities of the specimens should cover the whole range of densities (loosest to densest). Also the difference in density between the specimens in each pair should cover all possible ranges). Repeat steps (1) to (6) for soil prepared at other moisture contents to cover a wide range of moisture content.

The devices shown in Fig. 5.1 along with the CTL as described above were used for field experiments. The important dimensions of the devices (Fig. 5.1) were: diameter of the spikes, $d = 9.53 \text{ mm}$, length of the spikes, $L = 254 \text{ mm}$ [common spikes, readily available in sizes of $9.53 \text{ mm } d \times 254 \text{ mm } L$ ($3/8 \text{ in. } d \times 10 \text{ in. } L$) and $9.53 \text{ mm } d \times 304.8 \text{ mm } L$ ($3/8 \text{ in. } d \times 10 \text{ in. } L$)], center to center spacings of the inner to the outer rods, $b = 65 \text{ mm}$,

thickness of the template = 37 mm etc. The main steps for a field tests are:

- 1) Place the template on a levelled surface where measurement is to be made.
- 2) Drive the rods through the holes of the template. The outer rods should be driven first and then the central one. Remove the template. Check whether all rods were driven properly without any gap around the rods. In case any small gap is found around any rod, close it by pressing soil against the rod. If the insulated template method is used, then the template should not be removed after driving the spikes (rods).
- 4) Place the MRP head on the rods and adjust the short stud so that it touches the rod below it. Make a measurement.
- 5) Remove the rods and the template.
- 6) Dig out a sufficient quantity of soil from the location of the in-place measurement and uniformly compact it in the CC. Strike the surface level. The soil to be used in the CC should be taken uniformly from the entire depth of in-place measurement. Use the CA to make a measurement in it.
- 7) Determine the wet density of the soil in the CC. Calculate the volumetric and the gravimetric moisture content of the soil in the CC from the dielectric constant and measured densities. Calculate the dry density of the soil with the gravimetric moisture.
- 8) Relate the dry density of the soil in the CC to the dry density of the soil in place using the equation established from the laboratory experiments.
- 9) Determine the wet density of the soil at the place of in-place measurement by the

sand-cone method.

- 10) Take sample for measuring moisture content by oven drying method. Compute the dry density from the wet density measured by sand-cone method. Compare this dry density with that found in step (4).
- 11) Compare the moisture content measured by TDR method with that measured by oven drying method.

The simulated field experiment was conducted in the laboratory using the same devices those were used for the field experiments. The only difference here was that the soil whose in-place density and moisture content was to be measured was compacted in a large mold. The MRP was installed in the central area of the soil in the mold. The main steps of the method are:

- 1) Prepare soil at a desired moisture content and compact the soil in a big compaction mold (152.4 mm in diameter, 229 mm in height including the collar). Remove the base plate and place the mold (with the collar) on a plastic base plate.
- 2) Use the MRP to measure in-place dielectric constant of soil.
- 3) Measure the wet density of the soil in the mold.
- 4) Take soil from the mold to measure dielectric constant in the CC using the CA. Measure wet density of the soil in CC and compute volumetric, gravimetric, and dry density of the soil. Compute the dry density of the soil in the mold using these information. Take a sample of soil for measuring moisture content by oven drying method.
- 5) Repeat step (4) to perform at least 5 more tests. Each time compact soil in the CC at

a different density to cover a wide range of densities (loosest to densest).

- 6) Compute the actual dry density of the soil in the mold from measured wet density and oven dry moisture content.
- 7) Compare the measured dry density and moisture content with the actual dry density and oven dry moisture content.
- 8) Repeat the whole procedure for soils prepared at other moisture contents to cover a wide range of moisture content.

5.5 Results and Discussions

The dielectric constants of soil specimens having the same moisture content were measured in the laboratory using the CTLs following the procedures mentioned above. This generated the data to develop the method of measuring density and moisture content. The same data were used to develop calibration equations as was discussed in Ch. 4. Equation 5.2 was used to compute the density of one specimen using its dielectric constant and the density and the dielectric constant of another specimen. Since dry density is computed from the measured wet density and w , any error in measuring w would affect accuracy of measuring dry density.

To correctly assess the performance of Eq. 5.2 in measuring density, it would be better to compute wet density and compare it with actual wet density, thus isolating the effect of w on density measurement. Measured and actual wet densities were plotted as shown in Fig. 5.9. This figure shows a very good agreement between the measured and actual densities. The result of regression analysis is: slope = 0, intercept = 1.00, and $R^2 =$

Figure 5.9 Comparison of the actual wet density and measured wet density from experiments conducted on soils (Table 4.1) in the laboratory under ideal conditions.

0.975, SE = 0.022 Mg/m³ (1.37 pcf). From the figure it is observed that the maximum error of measurement is about ± 0.06 Mg/m³ (or ± 4 %).

The actual and the measured θ were plotted in Fig. 4.1. Topp's empirical equation was used to calculate θ . The gravimetric moisture contents were calculated from θ using the measured wet density of the soil in the CC and results were compared with oven dry moisture contents. Figure 5.10 shows this comparison. A very good correlation is obtained. The result of regression analysis is: intercept = 0, slope = 0.98, $R^2 = 0.98$, SE = 1.07 %. The accuracy of measurement is about ± 2 %.

Figure 4.2 showed relationship between K and actual θ . Using the generalized K - θ calibration equation, Eq. 4.1, moisture contents were calculated and plotted in Fig. 5.11. The results of regression analysis is: intercept = 0, slope = 1.00, $R^2 = 0.98$, SE = 1.05 %. The accuracy of measurement is about ± 2 %. The accuracy increases if soil specific calibration equations (from Table 4.2) are used. Results are shown in Fig. 5.12. The result of regression analysis is: intercept = 0, slope = 1.002, $R^2 = 0.988$, SE = 0.8 %. The accuracy of measurement is about ± 1 %.

Figure 4.11 showed relationship between $\sqrt{K\rho_w/\rho_d}$ and w . Equation 4.3 was used to calculate moisture contents and results are shown in Fig. 5.13. Using soil specific $\sqrt{K\rho_w/\rho_d}$ - w calibration equations (as given in Table 4.9), moisture contents were computed and results are plotted in Fig. 5.14. The result of regression analysis is: intercept = 0, slope = 1.00, $R^2 = 0.987$, SE = 0.80 %. The accuracy of measurement is about ± 1 %. So it is found that, using soil specific $\sqrt{K\rho_w/\rho_d}$ - w calibration equation gives as accurate result as the $\sqrt{K}$ - θ calibration equation. A general $\sqrt{K\rho_w/\rho_d}$ - w calibration equation also provides accuracy better

Figure 5.10 Comparison of the actual moisture content and measured moisture content using Topp's empirical equation.

Figure 5.11 Comparison of the actual moisture content and measured moisture content using general $\sqrt{K-\theta}$ linear calibration equation (Eq. 4.1).

Figure 5.12 Comparison of the actual moisture content and measured moisture content using soil specific $\sqrt{K-\theta}$ linear calibration equations from Table 4.2.

Figure 5.13 Comparison of the actual moisture content and measured moisture content using general $\sqrt{K\rho_w/\rho_d}$ -w linear calibration equation (Eq. 4.3).

Figure 5.14 Comparison of the actual moisture content and measured moisture content using soil specific $\sqrt{K\rho_w/\rho_d}w$ linear calibration equations from Table 4.9.

than that obtained using Topp's empirical equation.

The measured moisture contents (Fig. 5.12) were used to calculate dry densities from the measured wet densities. Results were compared with the conventionally measured dry density as shown in Fig. 5.15. The standard error is 0.025 Mg/m^3 (1.55 pcf), slightly higher than that for wet density, because of the error involved in measurement of gravimetric moisture content.

Figure 5.9 shows that there is scatter in the data. As mentioned earlier, some of the important factors that affect the density measurement accuracy are ratio of densities, moisture content etc. Percent error in density measurement was plotted with R_d as shown in Fig. 5.16. This figure does not show any noticeable trend of influence of R_d on percent error. But for some soil, high R_d ($R_d > 1.1$) may increase error involved in density measurement. Percent error is plotted with moisture content as shown in Fig. 5.17. No noticeable trend of the influence of moisture content on the measurement accuracy is observed.

The additional error in measuring dry density compared to that of wet density would be lower at higher moisture contents and when error involved in moisture content measurement is smaller.

Laboratory experimental data establishes the potential of the method of measuring density and moisture content. Experiments were conducted under ideal conditions. It is necessary to conduct actual experiment and try to reproduce the same quality data. Because it is difficult to conduct field experiments covering a wide range of moisture contents and densities for a given soil, experiments were first conducted in the laboratory under simulated field conditions. The soil used for the simulated field experiment was the Cherry L. Soil.

Figure 5.15 Comparison of the dry density and measured dry density from experiments conducted in the laboratory under ideal conditions.

Figure 5.16 Variation of error of density measurement with ratio of density (R_d).

Figure 5.17 Variation of percent error in density measurement with moisture content.

Densities were measured using Eq. 5.2. Figure 5.18 shows the comparison between the measured density and the conventionally measured density. The relationship of measured and the actual density follow a 1:1 line. The standard error of measurement is only 0.020 Mg/m^3 (1.25 pcf), less than what was obtained from the laboratory experiments. Percent error in density measurement was plotted with R_d and w as shown in Figs. 5.19 and 5.20 respectively. These figures show that the maximum error in density measurement is about 3 % ($\pm$). No noticeable trend of influence of R_d on measurement accuracy is observed. But, Fig. 5.20 shows that the error of measurement reduces as w increases. The measured gravimetric moisture contents using Eq. 4.3 is shown in Fig. 5.21. Dry densities computed using measured moisture contents (as shown in Fig. 5.21) are shown in Fig. 5.22. The standard error of measurement of dry density is very low (0.021 Mg/m^3). These results validate the procedures and equations developed for measuring density and moisture content. Figure 5.23 shows results of field experiments. Field experiments were conducted at a local field site known as Cherry Lane (the site soil was identified as Cherry L. Soil in Table 4.1). Density is compared with the density measured by the sand-cone method. The maximum variation of the measured density using the present method is about 3 %. Figure 5.23 shows that over a wide range of R_d , the measurement accuracy is consistent irrespective of the value of R_d .

5.6 Summary and Conclusions

The method of measuring in-place density and moisture content is developed in three stages. Firstly, the potential of the technique is explored by conducting experiments in the

Figure 5.18 Comparison of the actual wet density and measured wet density from experiments conducted under simulated field conditions (soil type: Cherry L. Soil).

Figure 5.19 Variation of percent error in density measurement with ratio of density (R_d) (soil type: Cherry L. Soil).

Figure 5.20 Variation of percent error in density measurement with moisture content (soil type: Cherry L. Soil).

Figure 5.21 Comparison of the actual moisture content and measured moisture content using Eq. 4.3 (simulated field experiment, soil type: Cherry L. Soil).

Figure 5.22 Comparison of the actual dry density and measured dry density from experiments conducted under simulated field conditions (soil type: Cherry L. Soil).

Figure 5.23 Comparison of the density measured by actual field experiment with the density measured by the Sand-Cone method.

laboratory under ideal conditions involving the least number of sources of errors. Secondly, the method is utilized to measure density and moisture content of soil by conducting experiments under simulated field conditions. Finally, actual field experiments are conducted to measure density and moisture content. The laboratory experiments used CTLs while field and simulated field experiments used a pair of TLs composed of a MRP and a CTL.

Results obtained from experiments conducted under ideal conditions show that the method has tremendous potential. Experimental results show that the density can be measured with a standard error and a maximum error of about $\pm 1.5\%$ and $\pm 5\%$, respectively. Precision depends on the equation used for relating ratio of density to the ratio of square roots of dielectric constants. A very simple 1:1 relationship between these two ratios gives a reasonably accurate measure of density for all types of soil.

The laboratory method of measuring density and moisture content used two identical CTLs and, most of the factors affecting the density measurement accuracy were absent from that method except the density difference between the two soil specimens, moisture content, accuracy of measuring moisture content, etc. Experimental results show that error in measuring density may increase if the ratio of density is too high ($R_d > 1.1$). Accuracy of measurement may increase at higher moisture contents compared to that at lower moisture contents. If measured moisture content is close to actual moisture content, accuracy of measuring dry density from wet density would be similar to the accuracy of measuring wet density.

The CTL accurately measures the gravimetric moisture content of soil. The standard and maximum errors of moisture content measurement using general calibration equations

(Topp's equation, or generalized $\sqrt{K-\theta}$ or $\sqrt{K\rho_w/\rho_d-w}$ equations) are about $\pm 1.0\%$ and $\pm 2\%$ respectively. Standard and maximum errors of measurement reduce to $\pm 0.8\%$ and $\pm 1\%$ respectively if $\sqrt{K-\theta}$ linear calibration equation for specific soil type is used. The standard error is about the same if the newly developed $\sqrt{K\rho_w/\rho_d-w}$ linear calibration equation for specific soil type is used.

The equation developed for measuring wet density of soil is almost independent of soil type. No soil specific calibration equation is necessary, especially if the ratio of densities is small.

Implementation of the method for actual field measurement required two measurements: one in-place measurement using a MRP, another measurement in a soil specimen prepared in a CC. Two types of rod installation methods were considered for in-place measurement: installation method using a metallic template and installation method using an insulated metallic template. The metallic template method required removal of the template before measurement and offered best possible waveforms. But it had a problem associated with the deformation of the rod ends due to the necessity of pounding on them which required use of a special anvil for driving the rods. The insulated metallic template method caused distortions of the waveforms but was found to be robust and it could use ordinary spikes. It is concluded that either method could be used for in-place measurement.

Investigations are carried out to find the method and device for performing the second test which best matches the in-place experiment. To use an identical MRP used for in-place measurement to make measurement in soil compacted in a large CC is found to be ideal. However experimental results show that a CTL or a modified CTL could also be used to

avoid insertion of too many rods as is the case with the MRP. However, to keep the effect of soil disturbance the same in both the experiments, it is found that both the TLs should have about the same b/a ratio and length.

Results of simulated field experiments and field experiments confirm the validity of the laboratory experimental results. Field experimental results reveal that the density could be measured with a standard error and maximum error of about $\pm 1.5\%$ and $\pm 4\%$ respectively which are in agreement with the laboratory findings.

CHAPTER 6

MEASURING MOISTURE CONTENT OF SOIL IN THE LABORATORY COMPACTION TESTS

6.1 Introduction

It is necessary to measure moisture content of soil in the laboratory compaction tests. As shown before, a CTL can be formed using the compaction mold as the outer conductor. Only problem here is that the length of the laboratory compaction mold is only about 120 mm, close to the lower limit of allowable TDR probe length. This chapter presents devices/methods to measure moisture content in the mold and experimental results to prove the validity of the methods.

6.2 Devices

It is easy to form a coaxial type of transmission line probe with the compaction mold. The mold already contains the soil and can be used as the outer conductor. If a rod can be inserted at the center of the mold, then a coaxial transmission line is formed. Figure 6.1 shows different components of the devices to be used in measuring moisture content in the standard compaction mold. To be able to insert the center rod easily, a pilot hole is necessary and the hand penetrometer and the guide cap are used for that. Important dimensions of different components of the devices are: diameter of the central rod = 4.76 mm, diameter of the penetrometer = 3.93 mm, diameter of the guide hole = 4.76 mm, length of the central conductor (to be inserted in soil) = 112 mm. Steps for doing a test

Figure 6.1 A coaxial transmission line (CTL) probe for measuring moisture content in the laboratory compaction mold.

are:

1. Determine the wet density of the soil in the mold by measuring the mass of soil in the known volume.
2. Use the guide cap and the hand penetrometer to make a hole along the center line of the soil in the mold. Remove the guide plate and the penetrometer.
3. Remove the mold from the base plate and place the mold on a wooden or nonmetallic base plate. This is because the metal base plate may interfere with the signal transmission and distort the waveform.
4. Push the central rod of the coaxial apparatus through the hole in the soil. Make sure that the cap sits on the end of the mold.
5. Make a measurement. Compute the dielectric constant and the moisture content of soil.

The devices shown in Fig. 6.1 may have some disadvantages, such as:

1. In hard soil, it may be difficult to make the pilot hole and even more difficult to push the central rod through the pilot hole.
2. Pushing the pilot hole may create air gap around the central rod.

To eliminate these limitations, the concept of modified CTL, composed of the mold, the central conductor and a MRP head (Fig. 5.6) can be used. Important dimensions of different components of the devices are: diameter of the central rod = 6.35 mm, length of the central rod = 151 mm, thickness of the template = 34.8 mm. The mold is the standard compaction mold having a diameter of 101.6 mm (4.0 in.) and a height of 116.3 mm

(4.58 in.). Steps for performing a test are:

1. Determine the wet density of the soil in the mold. The template is placed on the mold.
2. A specially made central conductor is driven through the guide hole until top end is at the level of the top surface of the template. Then the template is removed. The soil around the rod is pressed to close any gap that may appear near the surface.
3. Place the MRP head on the template such that the central stud sits on the top end of the rod. This will cause outer studs sit on the top end of the wall as well. Adjust the short outer stud so that it also touches the wall end.
4. Connect with the TDR equipment and make measurements.

Experiments were conducted to study the performances of the two methods.

Device for Measuring Moisture Content in Large Compaction Mold

The large compaction mold has a diameter of 152 mm (6 in.) and a length of 203 mm (8 in.). A coaxial type of probe is not very suitable for measuring moisture content of soil in this large mold. A multiple rod probe is more suitable to measure moisture content in this mold. The devices and procedures are exactly similar to the one for measuring in-place density and moisture content (Fig. 5.5), except the template as shown in Fig. 6.2 is used.

Figure 6.2 Measuring moisture content of soil in a large compaction mold using a MRP.

6.3 Experimental Program

To test the performance of the devices and the procedures for measuring moisture content, an experimental program was conducted in the laboratory. Different types of soils as shown in Table 6.1 were used. Each soil type was tested over a wide range of moisture content. Specimens were prepared in the compaction mold at different densities. The measured moisture content was compared with that obtained using oven drying technique.

Limited experiments were conducted to measure moisture content in the compaction mold with a modified CTL (as Fig 5.6). Experiments also were conducted to measure moisture content in a large compaction mold.

6.4 Results and Discussion

The dielectric constants measured using the CTL probe (Fig. 6.1) were used to measure moisture contents using Topp's equation. Results were compared with that obtained using oven drying method. The results were plotted as shown in Fig. 6.3. The figure shows a very good correlation between the measured and actual moisture content. A high correlation coefficients ($R^2 = 0.967$), slope close to 1 and intercept equal to zero proves the validity of the method and devices.

Square root of dielectric constant were plotted with the volumetric moisture contents. Figure 6.4 shows an excellent correlation of the two parameters. Table 6.2 shows results of regression analysis for each soil type. A general regression analysis applicable to all soil type yield an equation

$$\sqrt{K} = 1.65 + 8.44 \theta$$

[6.1]

Table 6.1 Soil characteristics for experiments to measure moisture content in the laboratory compaction tests.

Soil Type	%	%	%	Range of Density	Range of Moisture
	Sand	Silt	Clay	(Mg/m ³)	Content (%)
Crosby Till	5	15	80	1.38-1.52	12-27
Silt	0	100	0	1.54-1.68	4-31
Fine Sand	100	0	0	1.47-1.72	1-13
Crushed Silica				1.50-1.67	3-30
Cherry L. Soil	5	70	25	1.50-1.62	9-24

Figure 6.3 Comparison of the actual moisture content and measured moisture content of soil (Table 6.1) in the laboratory compaction mold using Topp's empirical equation.

Table 6.2 Regression analysis: $\sqrt{K} = c_1 + c_2\theta$

Soil type	Intercept, c_1	Slope, c_2	R^2
Crosby Till	1.40	8.65	0.990
Silt	1.73	8.40	0.989
Fine Sand	1.62	8.42	0.984
Cherry L. Soil	1.26	10.4	0.989
Crushed Silica	1.67	8.40	0.989

Figure 6.4 $\sqrt{K}$ vs. θ relationship for data obtained from experiments conducted in the laboratory compaction mold.

with R^2 value of 0.984. Using soil specific calibration equations from table 6.2, moisture contents were calculated and results are shown in Fig. 6.5.

The general calibration equation, Eq. 4.1, developed in Ch. 4 was used to measure moisture contents. Figure 6.6 shows the result. From this figure, it is observed that the accuracy of measurement varies with the soil type. However, correlation is good in general. This proves the validity of equation 4.1.

A plot of $\sqrt{K\rho_w/\rho_d}$ vs. w is shown in Fig. 6.7 for different types of soils. The results of regression analysis is shown in Table 6.3. The correlation between $\sqrt{K\rho_w/\rho_d}$ and w is generally not better than that between $\sqrt{K}$ and θ . Soil specific $\sqrt{K\rho_w/\rho_d}$ - w calibration equations given in Table 6.3 were used to calculate moisture contents. The results were plotted and shown in Fig. 6.8. The accuracy of measurement is about ± 1.5 %. Equation 4.3 was also used to calculate moisture content. Figure 6.9 shows the result.

Table 6.4 compares the performances of three different types of equations. The maximum error of measurement using Topp's equation is about ± 2.5 %, while that using soil specific $\sqrt{K}$ - θ equation is about ± 1.5 % and using soil specific $\sqrt{K\rho_w/\rho_d}$ - w equation is about ± 1.5 %.

Fig. 6.10 and 6.11 show results obtained from measurements made in a large compaction mold using a MRP and in ordinary mold using the modified CTL respectively. The accuracies of measurements are as good as the accuracy of measurement using the other method using the devices shown in Fig. 6.1.

Figure 6.5 Comparison of the actual moisture content and measured moisture content in the laboratory compaction mold using soil specific $\sqrt{K-\theta}$ calibration equations (obtained from Table 6.2).

Figure 6.6 Comparison of the actual moisture content and measured moisture content in the laboratory compaction mold using general $\sqrt{K-\theta}$ calibration equation (Eq. 4.1).

Figure 6.7 $\sqrt{K\rho_w/\rho_d}$ vs. w relationship for data from experiments conducted in the laboratory compaction mold.

Table 6.3 Regression analysis: $\sqrt{K\rho_w/\rho_d} = a + bw$

Soil Type	Intercept, a	Slope, b	R ²
Crosby Till	0.97	8.40	0.990
Silt	1.20	7.74	0.984
Fine Sand	1.02	7.99	0.963
Cherry L. Soil	0.83	10.3	0.980
Crushed Silica	1.16	8.00	0.992

Table 6.4 Regression analysis: $w_{\text{measured}} = a + b w_{\text{actual}}$

Eq. Used	a	b	R ²	Maximum Error (%)
Topp's Eq.	0	0.95	0.967	±2.0 %
$\sqrt{K-\theta}$ (Table 6.2)	0	0.99	0.98	±1.2 %
$\sqrt{K\rho_w/\rho_d}-w$ (Table 6.3)	0	0.99	0.981	±1.2 %

Figure 6.8 Comparison of the actual moisture content and measured moisture content in the laboratory compaction mold using soil specific $\sqrt{K\rho_w/\rho_d}w$ calibration equation.

Figure 6.9 Comparison of the actual moisture content and measured moisture content in the laboratory compaction mold using general $\sqrt{K\rho_w/\rho_d}w$ calibration equation (Eq. 4.3).

Figure 6.10 Comparison of the actual moisture content and measured moisture content in the large laboratory compaction mold using Topp's empirical equation.

Figure 6.11 Comparison of the actual moisture content and measured moisture content in the laboratory compaction mold using modified CTL method (Topp's empirical equation was used to calculate moisture contents).

6.5 Conclusions

The devices accurately measured the moisture content of soil compared to oven dry moisture contents. The accuracy of measurement is about ± 2.5 % without using soil specific calibration equation. Accuracy is about ± 1.5 % if specific calibration is used.

The simple coaxial apparatus is the simplest and quickest way of measurement. But difficulties were faced with this device when soil was very hard. The modified method using the template was used successfully in those situations. But the modified method may not be preferred in cases where the other method can be used.

The MRP assembly for the large compaction mold accurately measured moisture content. The procedure is simple, and quick. The performance of the device could be expected to be better than the performance of the device used for the standard compaction mold because of the longer length of the TL.

The methods provide quick laboratory compaction information. Although the general calibration equation provides sufficiently accurate results for most soil types, soil specific calibration would increase the accuracy of measurement.

CHAPTER 7

MEASUREMENT OF MOISTURE CONTENT OF SOIL DURING SAMPLING AND DRILLING OPERATIONS

7.1 Introduction

The developed devices and methods can be used to measure moisture content of soil retrieved during drilling and sampling operations. It is necessary to measure moisture content of a soil sample retrieved in a Shelby tube, a soil sample retrieved during SPT test, etc. Moisture content of soil can be measured directly in Shelby tube while the soil retrieved during SPT test can be recompacted in a CC of a CTL where measurement can be made. The CTL can be used to measure moisture content of any other soil which is usually brought in the laboratory for measuring moisture content. This chapter presents specific devices and methods to be used for each cases.

7.2 Measurement of Moisture Content in Shelby Tube

The devices shown in Fig. 3.2 (except the CC) can be used for measuring moisture content in a Shelby tube. One end of the tube (of about 180 mm long) can be used for measuring moisture content (Fig. 7.1). This portion of the soil in the Shelby tube can not be used for anything other than measuring index tests such as Atterberg limits.

Steps for doing a test are:

1. Hold the Shelby tube vertically. Clean loose soil from the tube and make sure the soil surface is flat and perpendicular to the axis of the tube.

Figure 7.1 Measurement of moisture content of soil in a Shelby tube..

2. Measure the depth of soil in the tube. Calculate the length of probe as:

$$L_{eff} = L_{pr} - h_s \quad [7.1]$$

where: L_{eff} , L_{pr} and h_s are the effective length of probe, total length of probe, and the depth of soil surface from the end of the tube, respectively.

3. Take the weight of the tube. Measure the wet density of the soil in the tube by dividing the weight of the soil in the tube by the volume of the soil in the tube.
4. Make a guide hole with the hand penetrometer and the guide rod.
5. Push the central rod of the central rod assembly.
6. Make a measurement.
7. Calculate the dry density from the measured wet density.

Experiments were conducted in a piece of Shelby tube and results were presented in Ch. 4. Measurement in actual (full length) Shelby tube is almost the same. The end of Shelby tube which will be used for measurement may be empty near the surface. This may change the waveform from the usual one. Figure 7.2 shows waveforms showing the effect of emptiness near the end of the tube. The initial reflection point shifts to the right due to the presence of a gap. Some experiments were conducted keeping gaps at the top end of the tube. Figure 7.3 shows the results of the experiments. The accuracy of measurement does not seem to be influenced by the gaps.

If the soil is very hard in a Shelby tube, it may be difficult to make a guide hole, or push the central rod through the guide hole. In such cases, the alternate method using a

Figure 7.2 Variations of the shapes of waveforms due to the variations of the depths of soil surfaces in the Shelby tube from the end of the tube used for measurement.

Figure 7.3 Comparison of the actual and the measured moisture content of soil in Shelby tube using Topp's empirical equation.

template (as was shown in Fig. 5.6) can be used. These are the steps for a test:

1. Place the guiding template.
2. Drive the central conductor through the guide hole, using a hammer.
3. Remove the guide plate. Place the MRP head on top of the tube such that the studs sit on the central and outer conductors (Fig. 7.4).
4. Connect with TDR equipment and make measurements.

The disadvantage of this method is that it may take little longer time to perform a test compared to the other method.

7.3 Measurement of Moisture Content of Soil Retrieved During Drilling Operations

Any soil that is retrieved during drilling operations fall in this category. Let us consider measurement of moisture content of a soil sample retrieved during a SPT test.

7.3.1 Devices

The soil sample retrieved in split spoon sampler has a diameter of about 35 mm (1.375 in.), and a maximum length of 457 mm (18 in.). A portion of this soil sample can be used for measuring moisture content. A coaxial probe as shown in Fig. 7.5a can be considered. The CC has a diameter of 38.1 mm, and length of about 178 mm (7 in.). As the diameter of the cell is very small, a central rod of about 4.76 mm diameter would make the ratio b/a only about 7.5. Insertion of the central rod would have the following problems:

1. As the cell diameter is very small, it would be very difficult to make a pilot hole, and

Figure 7.4 A modified CTL to measure moisture content in Shelby tube.

(a) In-place-rod Method

(b) Push-in-rod Method

Figure 7.5 CTLs for measuring moisture content of soil retrieved in split spoon sampler, (a) in-place-rod method, (b) push-in-rod method.

push the central rod through the pilot hole. Of course if the soil is compacted to a loose to medium density, insertion of rod may not be difficult.

2. The b/a ratio is too small. So the effect of rod insertion on measurement accuracy would be significant. In Ch.4, it was shown that rod insertion may change the actual dielectric constant by as much as 20% in a CTL having b/a equal to 7.5.

To overcome these difficulties some modifications of the devices and methods are necessary. A cell having larger diameter can be used. But as the amount of soil available is fixed, the length of the cell should be reduced. If a cell having a diameter of 50.8 mm (2 in.) is used, the maximum length of the cell that can be used would be about 114 mm (4.5 in.) (such a length is close to the lower limit of allowable probe length). A rod diameter of 4.76 mm would make $b/a = 10$ for this cell.

Another way to solve the problem is to use a probe where the central conductor is placed before the soil is compacted in it. Figure 7.5b shows the device. The test method with this device is:

1. The central rod is kept in place.
2. Soil is compacted in the annular space with a small tamper. Care must be taken so that the soil is uniformly compacted and no gap remains around the central rod.
3. Once the tube is full, the cell is place upside down and connection is made with the TDR equipment to make a measurement.
4. The central rod assembly is pulled out of the cell.

This method is named as in-place-rod method. The advantages of this method are:

1. No disturbance which arises due to rod insertion.
2. No air gap problem.
3. Difficulty involved in probe rod insertion is eliminated.

This device was used for conducting tests. The important dimensions of this device are: internal diameter of the cell = 34.9 mm, diameter of the rod = 4.76 mm, length of probe = 190.5 mm.

If the soil sample retrieved in split spoon sampler is soft, then it can be remolded and recompacted in the tube. If the soil is hard then it would be necessary to cut it into small pieces and compact it in the annular space. Once the test is completed, the soil can be reused for index tests such as Atterberg limits.

7.3.2 Experimental Program

Experiments were conducted to check the performance of the devices and methods discussed. Both the in-place-rod technique devices (Fig. 7.5a) and in push-in-rod technique devices (Fig. 7.5b) were used in the experiments. The characteristics of the soils tested and important parameters are shown in Table 7.1.

7.3.3 Results and Discussion

Moisture contents were calculated using Topp's equation. Results were compared with that obtained using oven drying method. The results were plotted as shown in Fig. 7.6

Table 7.1 Soil characteristics for experiments to measure moisture content of soil retrieved during SPT test.

Soil Type	%	%	%	Range of Density	Range of Moisture
	Sand	Silt	Clay	(Mg/m ³)	Content (%)
Crosby Till	5	15	80	1.30-1.40	15-27
Silt	0	100	0	1.40-1.60	7-21
Fine Sand	100	0	0	1.47-1.72	5-14
Cherry L. Soil	5	70	25	1.40-1.50	14-26

Figure 7.6 Comparison of the actual and measured moisture content of soil (Table 7.1) retrieved during SPT test using push-in-rod method. (Topp's empirical equation was used to calculate moisture content from measured dielectric constant).

(for the push-in-rod method). The figure shows a very good correlation between the measured and the actual moisture content. A high correlation coefficient ($R^2 = 0.96$), slope close to 1 (slope = 0.996) and intercept close to zero (intercept = 0.11%) prove the validity of the methods and devices.

Moisture contents were also calculated using the general $\sqrt{K}-\theta$ calibration equation (Eq. 4.1) found in Ch. 4. The results were plotted in Fig. 7.7. The accuracy of measurement is better than that obtained using Topp's equation. Equation 4.1 was found from experimental data obtained using a different size of CTL (Fig. 3.2). To obtain $\sqrt{K}-\theta$ equation specific to the CTL used here, they were plotted as shown in Fig. 7.8. Figure 7.8 shows an excellent correlation between the two parameters. Table 7.2 shows results of regression analysis for each soil type. A general regression analysis applicable to all soil types tested yield the equation

$$\sqrt{K}=1.56+8.50\theta \quad [7.2]$$

with a R^2 value of 0.98. As expected this equation is almost the same as Eq. 4.1.

Moisture contents were also calculated using the $\sqrt{K\rho_w/\rho_d}-w$ type equation derived in Ch. 4 (Eq. 4.3). Results are shown in Fig. 7.9. The accuracy is higher than that obtained using the empirical equation. A general calibration equation of the form $\sqrt{K\rho_w/\rho_d}-w$ (refer to Fig. 7.10) was also found using the test data obtained using the present devices which is

$$\sqrt{K/\rho_d}=1.04+8.68w \quad [7.3]$$

As expected, this equation is close to Eq. 4.3. Specific calibration equations (obtained from

Figure 7.7 Comparison of the actual and measured moisture content of soil retrieved during SPT test using Eq. 4.1 (push-in-rod method).

Figure 7.8 $\sqrt{K}$ vs. θ relationship for push-in-rod method.

Table 7.2 Regression analysis for push-in-rod method: $\sqrt{K} = c_1 + c_2\theta$

Soil Type	Intercept, c_1	Slope, c_2	R^2
Crosby Till	1.29	9.07	0.996
Silt	1.61	8.93	0.989
Fine Sand	1.69	7.15	0.990
Cherry L. Soil	1.49	8.87	0.995

Figure 7.9 Comparison of the actual and measured moisture content of soil retrieved during SPT test using Eq. 4.3 (push-in-rod method).

Figure 7.10 $\sqrt{K\rho_w/\rho_d}$ vs. w relationship for push-in-rod method.

Table 7.3) were used to calculate moisture contents. Results are shown in Fig. 7.11. The accuracy is better than that obtained using the other equations. Table 7.4 compares the performances of different calibration equations in measuring moisture contents.

Results presented in Figs. 7.6 to 7.11 and Tables 7.2 to 7.4 were obtained using the devices shown in Fig. 7.5b (push-in-rod technique). Now results obtained using the in-place-rod technique (Fig. 7.5a) will be presented. Figures 7.12 to 7.16 and Tables 7.5 to 7.7 show the results obtained using this method. Figure 7.17 compares the $\sqrt{K\rho_w/\rho_d-w}$ type calibration equations obtained using the two methods. Equation 4.3 (which was obtained using push-in-rod method) is also shown in this figure for comparison. It is observed that, there is some difference between the push-in-rod and in-place-rod methods. The push-in-rod method overestimates the dielectric constant the reason of which was explored in Ch. 3. As expected, the two equations obtained using push-in-rod method (Eq. 4.3 and the one developed here) are almost identical. Figure 7.18 compares different $\sqrt{K-\theta}$ type calibration equations (Eq. 4.1 and two $\sqrt{K-\theta}$ type equations based on the two methods developed here). This figure also shows excellent similarity between the two push-in-rod technique equations and some dissimilarity between the in-place-rod technique equation and push-in-rod technique equations.

7.4 Conclusions

Devices and methods have been presented to measure moisture contents of soil during drilling and sampling operations. Test results have been presented to show the performances of the devices and methods.

Table 7.3 Regression analysis for push-in-rod method: $\sqrt{K\rho_w/\rho_d} = a + bw$

Soil Type	Intercept, a	Slope, b	R ²
Crosby Till	0.94	9.22	0.992
Silt	1.15	8.17	0.979
Fine Sand	1.10	7.20	0.996
Cherry L. Soil	1.08	8.40	0.997

Table 7.4 Regression analysis for push-in-rod method: $w_{\text{measured}} = a + bw_{\text{actual}}$

Eq. Used	a	b	R ²	Maximum Error (%)
Topp's Eq.	0	0.95	0.967	±2.0
Specific $\sqrt{K-\theta}$ Cal. Eq.	0	1.00	0.992	±0.8
Specific $\sqrt{K\rho_w/\rho_d-w}$ Cal. Eq.	0	1.00	0.987	±1.0

Figure 7.11 Comparison of the actual and measured moisture content of soil retrieved during SPT test using soil specific $\sqrt{K\rho_w/\rho_d}-w$ calibration equations from Table 7.3 (push-in-rod method).

Table 7.5 Regression analysis for in-place-rod method: $\sqrt{K} = c_1 + c_2\theta$

Soil Type	Intercept, c_1	Slope, c_2	R^2
Crosby Till	1.16	9.06	0.996
Silt	1.65	8.77	0.998
Fine Sand	1.69	7.92	0.994
Cherry L. Soil	1.41	8.95	0.997

Table 7.6 Regression analysis for in-place-rod method: $\sqrt{K\rho_w/\rho_d} = a + bw$

Soil Type	Intercept, a	Slope, b	R^2
Crosby Till	0.85	9.28	0.999
Silt	1.11	8.25	0.997
Fine Sand	1.09	7.84	0.998
Cherry L. Soil	0.99	8.40	0.997

Table 7.7 Regression analysis for in-place-rod method: $w_{\text{measured}} = a + b w_{\text{actual}}$

Eq. Used	a	b	R ²	Maximum Error (%)
Topp's Eq.	0	0.950	0.967	±2.0
Specific $\sqrt{K-\theta}$	0	0.970	0.984	±1.0
Cal. Eq.				
Specific	0	1.002	0.998	±0.5
$\sqrt{K\rho_w/\rho_d-w}$ Eq.

Figure 7.12 Comparison of the actual and measured moisture content of soil retrieved during SPT test using in-place-rod method. (Topp's empirical equation was used to calculate moisture content from measured dielectric constant).

Figure 7.13 Comparison of the actual and measured moisture content of soil retrieved during SPT test using Eq. 4.1 (in-place-rod method).

Figure 7.14 Comparison of the actual and measured moisture content of soil retrieved during SPT test using Eq. 4.3 (in-place-rod method).

Figure 7.15 $\sqrt{K\rho_w/\rho_d}$ vs. w relationship for in-place-rod method.

Figure 7.16 Comparison of the actual and measured moisture content of soil retrieved during SPT test using soil specific $\sqrt{K\rho_w/\rho_d}w$ calibration equations from Table 7.6 (in-place-rod method).

Figure 7.17 Comparison of the $\sqrt{K\rho_w/\rho_d}w$ calibration equations obtained using different methods.

Figure 7.18 Comparison of the $\sqrt{K}-\theta$ calibration equations obtained using different methods.

The devices developed for measuring moisture content in a Shelby tube is similar to the CTL (Fig. 3.2) presented in Ch. 4. Procedures for using this CTL in a full length Shelby tube is shown. The results are as good as that obtained using the CTL in Ch. 4.

The modified method that uses a template, a rod, and a MRP head, also is found to be a convenient way of measuring moisture content in Shelby tube. This method would be suitable for making measurements in hard soils.

The devices and methods have been presented to measure moisture content of soil retrieved during SPT test. Two types of devices have been presented. One uses a CTL using the usual push-in-rod technique while the other one uses a CTL with in-place-rod technique. Both the methods provide quite satisfactory results.

The calibration equations found in Ch. 4 were used to measure moisture content from the measured dielectric constants. The accuracy of measurement is very good. Calibration equations are also found using the present test data. A better correlation is obtained for $\sqrt{K\rho_w/\rho_d-w}$ calibration equation compared to $\sqrt{K-\theta}$ calibration equation.

The calibration equations obtained using the two methods are found to be different. As discussed in Ch. 3 and Ch. 4, in most cases the push-in-rod-method overestimated the dielectric constant compared to in-place-rod technique. However, the error in measuring moisture content due to the effect of rod insertion is not found to be significant as opposed to the case of measuring density.

CHAPTER 8

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary and Conclusions

A new method of measuring in-place density and moisture content of soil is developed. The method is extended to measure moisture content of soil in the laboratory compaction tests and in the field during sampling and drilling operations. In order to achieve these goals, principles of TDR probe design and test methodology are developed. Also TDR calibration equations are reviewed and new calibration equations are proposed.

The method of measuring moisture content and density is based on TDR measurement of dielectric constant of soil which in turn is correlated with density and moisture content of soil. To measure dielectric constant of soil in the field and in the laboratory, different types of probes and devices are developed. The coaxial transmission line probes are developed to determine the dielectric constant of soil in the compaction mold, in the Shelby tube, or soil retrieved during drilling and sampling operations. This type of probe is also used along with another probe, a multiple rod probe to measure in-place moisture content and density. The multiple rod probe developed in this research (a simulated coaxial transmission line probe) modifies existing multiple rod probes, and is used to make measurements in-situ or in a mold. Different parameters (length of probe, diameters of the conductors, etc.) of the probes are selected to make accurate measurements. It is found that length of probe depends on the type of soil, electrical conductivity of soil moisture, and desired accuracy of measurement. Accuracy of measurement increases with increase in the length of probe, while the maximum

possible length decreases with increase in conductivity of soil moisture or soil solids. It is found that a length of 200-300 mm can be used for all soils for all moisture contents. In case the soil moisture contains dissolved salts the moisture, shorter probes may have to be used.

It is found that the TDR measurement has a spatial bias which depends on the ratio of the diameters of the central to the outer conductor (b/a). Analytical solutions are found to predict the sensitivity of measurement with the b/a . It is found that the measurement is sensitive to the properties of the soil close to the central conductor and this sensitivity increases with increase in b/a ratio.

Most measurement of dielectric constant of soil in-situ or in the laboratory requires that the probe rods be inserted into the soil. Investigations to find the effect of rod insertion show that the effect of probe rod insertion affects the measurement significantly. Analytical and experimental results show that any air gap around the central rod can reduce the measured value of dielectric constant and moisture content significantly. On the other hand, the disturbance of soil due to rod insertion may change (increase or decrease) the density of soil which affects the measurement significantly. Different types of analytical models are considered to find the effect of rod insertion. It is found that a probe having b/a ratio of about 10 may experience a change of the measured dielectric constant by as much as 20% of the original values. It is found that the effect of rod insertion reduces with increase of the value of b/a . It is recommended that the b/a ratio be about 15 to reduce the effect of rod insertion. Also to ensure snug-fit installation of the rods, a special test method is recommended. For making measurement with CTL, it is recommended that a pilot hole with

diameter less than (by about 0.50 mm) the diameter of the rod be made through which the rod can be inserted. Another way, especially for MRP, a metallic template with guide holes in it is recommended.

The calibration equations are reviewed. It is found that soil specific linear calibration equation of the form $\sqrt{K-\theta}$ increases the accuracy of measurement from that obtained using Topp's equation. It is also found that the $\sqrt{K-\theta}$ type equation is influenced by density of soil. A linear calibration equation of the form $\sqrt{K\rho_w/\rho_d-w}$ is found to eliminate the effect of density especially for granular soils. A specific calibration equation of either form ($\sqrt{K-\theta}$ or $\sqrt{K\rho_w/\rho_d-w}$) provides accurate results. Another form of calibration equation of the form $\sqrt{K-S_r}$ provides very good correlation only if the density does not vary much.

The method of measuring in-place density and moisture content is developed in three stages. Firstly, the potential of the technique is explored by conducting experiments in the laboratory under nearly ideal conditions where there are reduced sources of errors. Secondly, the method is utilized to measure density and moisture content of soil by conducting experiments under simulated field conditions. Finally, actual field experiments are conducted to measure density and moisture content. The laboratory experiments used CTLs while field and simulated field experiments used a pair of TLs composed of a MRP and a CTL.

Results obtained from experiments conducted under ideal condition show that the method has tremendous potential. Experimental results show that the density can be measured with a standard error and a maximum error of about $\pm 1.5\%$ (or 0.02 to 0.025 Mg/m³) and $\pm 5\%$, respectively. Precision depends on the equation used for relating ratio of

density to the ratio of square roots of dielectric constants. A very simple 1:1 relationship between these two ratios gives a reasonably accurate measure of density for all types of soil.

The laboratory method of measuring density and moisture content used two identical CTLs. Most of the factors affecting the density measurement accuracy were absent from that method except the density difference between the two soil specimens, moisture content difference, accuracy of measuring moisture content, etc. Test results show that error in measuring density may increase if the ratio of density is too high ($R_d > 1.1$). Accuracy of measurement may increase at higher moisture contents compared to that at lower moisture contents. If measured moisture content is close to actual moisture content, accuracy of measuring dry density from wet density would be similar to the accuracy of measuring wet density.

The CTL accurately measures the gravimetric moisture content of soil. The standard and maximum errors of moisture content measurement using general calibration equations (Topp's equation, or generalized $\sqrt{K-\theta}$ or $\sqrt{K\rho_w/\rho_d-w}$ equations) are about 1.0% and $\pm 2\%$, respectively. Standard and maximum errors of measurement reduce to 0.8% and $\pm 1\%$, respectively if $\sqrt{K-\theta}$ linear calibration equation for specific soil type is used. The standard error is about the same if the newly developed $\sqrt{K\rho_w/\rho_d-w}$ linear calibration equation for specific soil type is used.

The equation developed for measuring wet density of soil is almost independent of soil type. No soil specific calibration equation is necessary, especially if the ratio of densities is small.

Implementation of the method for actual field measurement required two

measurements: one in place measurement using a MRP, another measurement in a soil specimen prepared in a CC. Three types of rod installation methods were considered for in-place measurement: installation using an insulating template (hard wood), installation method using a metallic template, and installation method using an insulated metallic template. The metallic template method required removal of the template before measurement and offered the best possible waveform. But it had a problem associated with the deformation of the rod ends due to the necessity of pounding on them. The use of an anvil for driving the rods reduced this problem. The insulated metallic template method caused distortions of the waveforms but was found to be robust as it uses ordinary spikes. The insulating (hard wood) template had the problem of not being robust enough and was found susceptible to wearing out or breaking after repeated use. It is concluded that any of the three methods could be used for in-place measurement.

Investigations are carried out to find the method and device for performing the second experiment which best matches the in-place experiment. To use the same MRP used for in-place measurement to make measurement in soil compacted in a large CC is found to be ideal. However, test results show that a CTL or a modified CTL could also be used to avoid insertion of too many rods as is the case with the MRP. However, to keep the effect of soil disturbance the same in both the experiments, it is found that both the TLs should have about the same b/a ratio and length.

Results of simulated field experiments and field experiments prove the validity of the laboratory test results. Field test results reveal that the density could be measured with a standard error and maximum error of about 0.022 Mg/m^3 (1.37 pcf) and $\pm 4\%$, respectively,

which are in agreement with the laboratory findings.

Devices are developed for measuring moisture content of soil in laboratory compaction tests. The accuracy of measurement is about $\pm 2\%$ without using soil specific calibration equation. Accuracy is about $\pm 1\%$ if specific calibration is used.

The simple coaxial apparatus is the simplest and quickest way of measurement. But difficulties may be faced with this device when soil is very hard. The modified method using the template can be used successfully in such cases. But the modified method may not be preferred in cases where the other method can be used.

The MRP for the large compaction mold accurately measures moisture content. The procedure is simple and quick. The performance of the device is expected to be better than the performance of the device used for the standard compaction mold because of the longer length of the probe.

The methods provide quick laboratory compaction information. Although the general calibration equation provides sufficiently accurate results for most soil types, specific calibration would increase the accuracy of measurement.

Devices and methods are presented to measure moisture contents of soil during drilling and sampling operations. Experimental results are presented to show the performances of the devices and methods.

A CTL is used to make measurements in a Shelby tube. A second method, that uses a rod and a MRP head, is also developed. This method would be suitable for making

measurements in hard soils.

The devices and methods are presented to measure moisture content of soil retrieved during SPT test. Two types of devices are presented. One uses a CTL using the usual push-in-rod technique while the other one uses a CTL with in-place-rod technique. Because of the small quantity of soil retrieved, a small size CTL (having b/a ratio of about 7), the push-in-rod technique requires the soil be compacted to a loose to medium density to facilitate rod insertion. The in-place-rod technique avoids that difficulty. Both the methods provide satisfactory results.

8.2 Recommendations for Further Research

Additional field experiments of the developed devices and methods for measuring in-place density and moisture content can be conducted to study the field performances of the alternative devices and methods mentioned in the study. Results can be compared with density and moisture content measured by other methods. Different techniques have been developed for inserting rods in soil. Although it has been concluded that the insulated metallic template method would be the best method, comparative study is necessary to find the best technique in terms of accuracy of measurement and robustness of the equipment. Likewise, different methods of performing experiment in the CC have been discussed. Further study can focus on the comparative study of those different methods for wider ranges of soil types.

Existing and developed calibration equations are not suitable for organic soils, highly plastic soils or for other soil like materials such as fly-ash. While specific calibration

equations for these soils are desirable for accurate measurements of moisture content, the general procedures developed for measuring density can still be made applicable for those soils and materials. As discussed, if the density of the prepared soil specimen is close to the density of soil in-situ, the error involved in measurements might not be high. Investigations can be made to develop such procedures which are feasible and accurate.

It has been recommended that, for accurate measurement of in-place density, the density of the specimen prepared in the CC be close to the density of soil in-situ. This can be achieved if the soil in the CC is compacted with a medium compacting effort such that the specimen does not become too loose to too dense. Another alternative is to obtain the specimen by driving the CC into the ground. Specimens prepared this way will not only have density close to the density of soil in-situ but might also save time needed for preparing the specimen using digging and compacting method. Future research work can be directed to further explore the feasibility of this method.

Data acquisition and data reduction were performed manually for all the experiments conducted in this study. The method of data acquisition and data reduction can be automated. A test involves: taking a reading from the waveform displayed on TDR screen, reduction of the reading to moisture contents and density using appropriate equations. Some skill is necessary to correctly take the reading from the waveform. Significant variation in the measured moisture content and density may occur if test is performed by unskilled technician. Also, reduction of data to obtain moisture content and density is time consuming. All these processes can be automated through development of computer software. The software should be able to perform the following tasks: acquire and analyze the waveforms,

reduce the waveforms to moisture contents and densities using appropriate equations.

In order to implement the results of the project, it is necessary to have ASTM/AASHTO standards for the new procedures developed. Without the standards, INDOT and others may not be able to implement the results of the project. Further work can be directed toward ASTM/AASHTO standards for the testing procedures developed herein.

This study developed methods for measuring density and moisture content of soil only. INDOT has used bottom ash for constructing highway embankments and will use fly-ash, bottom-ash and mixtures of ashes in future projects. The currently used method, the nuclear method, to measure moisture content and density in fly-ash produces less than satisfactory results. During the course of this research project, limited laboratory experiments were carried out to look into the probable potential of the technique for measuring moisture content of fly ash. The results were encouraging and the method can likely be extended to measure moisture content and density of fly-ash and bottom-ash as well.

The use of the developed devices and methods can be easily extended to measure moisture content of concrete and possibly other materials.

CHAPTER 9

IMPLEMENTATION SUGGESTIONS

9.1 Introduction

The results of the study proves that the new method of measuring density and moisture content is accurate, fast and does not use hazardous nuclear sources. The results of this study would allow one to measure in-situ moisture content and density with reasonable accuracy without imposing any health hazard. The developed method of measuring in-situ moisture content and density can be applied for construction control of earthworks. It would be possible to obtain the moisture content of the soil after compaction in the laboratory with reasonable accuracy. It would also be possible to measure moisture content of soil sample retrieved during drilling and sampling operations. The benefits of the results of the study include: improved construction quality control, very fast laboratory compaction information, borehole moisture information at time of making borings, and elimination of hazardous nuclear sources.

This chapter is aimed at giving recommendations on how INDOT should implement the findings of the study. The methods developed are summarized in standard form: scope, significance and uses, apparatus, test procedures, calculations, etc.

9.2 Method of Measuring In-Place Density and Moisture Content of Soil

9.2.1 Scope

This test method may be used to determine the in-place density and moisture content

of soils.

This test method may not be suitable for soils having appreciable amount of rocks or coarse particles in excess of 38 mm (1.5 in.) in diameter. Also this method may not be suitable for organic and highly plastic soils.

9.2.2 Summary of Test Method

The dielectric constant of the soil in-situ is determined using a MRP and TDR equipment. Then some soil is quickly dug out from the place of in-situ measurement and compacted in a cell where the wet density and dielectric constant is determined, the former with a balance and the later with a CA and TDR equipment. Using these, the moisture content and density of soil in-situ are determined.

9.2.3 Significance and Use

This test method can be used to determine the density and moisture content of compacted soils placed during the construction of earth embankments, road fill, and structural backfill.

This test method can be used to determine the in-place density and moisture content of natural soil deposits.

This test method may not be suitable for organic or highly plastic soils.

9.2.4 Apparatus

1. Template: An insulated metallic (steel) template (Fig. 5.1) having a thickness of 34.3-38.1 mm (1.35-1.5 in.). It shall have four guide holes. The center to center spacing between the central hole and the outer holes shall be 63.5 mm (2.5 in.). The diameter of the holes shall be 10.0 mm (0.395 in.).
2. MRP head: The head shall have four metallic studs, the center to center spacing between the central and the studs shall be 69.8 mm (2.75 in.). The configuration of the studs shall be exactly the same as that of the guide holes in the template. The length and diameter of the studs shall be 20.3-30.5 mm (0.8-1.2 in.) and 9.53 mm (0.375 in.) respectively. The central and two of the outer studs shall have the same length. The length of the fourth stud shall be 2.54 mm (0.1 in.) shorter than the rests.
3. Spikes: Four common spikes having lengths of 254 mm (10 in.) and uniform diameters of 9.53 mm (3/8 in.).
4. A CTL (Fig. 3.2): The CC shall have 72.6 mm (2.86 in.) internal diameter, a length of 222.3 mm (8.75 in.). The rod of the CA shall have a diameter of 4.76 mm (3/16 in.) and length (from the inner bottom surface of the head) of 215.9 mm (8.5 in.). The height of the step at the base of the head (measured from the inner bottom surface of the head) shall be about 2 mm (0.08 in.). The penetrometer rod shall have a diameter of 3.94 mm (0.155 in.). The guide hole of the guide cap shall have a diameter of 4.3 mm (0.17 in.) and a height of 38.1 mm (1.5 in.).
5. TDR equipment
6. Balance: An electronic balance having a capacity of 15000 g and a readability of 1 g.
7. Miscellaneous Equipment-Hammer, chisel, small trowel, screwdriver, or spoons for

digging holes and breaking soils, calculator, notebook or test forms, etc.

9.2.5 Procedure

1. Prepare the surface at the test location so that it is plane and level.
2. Seat the template on the plane surface.
3. Drive the spikes through the guide holes so that the bottom surfaces of the spike heads touch the template.
4. Clean the top surfaces of the spike heads and ends of the studs. Place the MRP head on the template such that the studs sit on the spike heads. Adjust the length of the short outer stud so that it touches the spike head.
5. Measure the apparent length with the TDR equipment.
6. Remove the spikes and the template.
7. Dig out some soil from the place of testing and quickly compact it in the CC. Soil should be taken uniformly from over the entire depth of in-place measurement. Compaction should be uniform and density should be close to the density of the soil in place.
8. Measure the mass of the soil and CC. Also measure the mass of the CC.
9. Install the CA in the CC to complete a CTL and measure the apparent length for the soil.

9.2.6 Calculation

1. Calculate the dielectric constant of soil in place as

$$K_{insitu} = \left(\frac{l}{L} \right)^2 \quad [9.1]$$

where l and L are the measured apparent length and length of the spikes inserted in soil, respectively.

2. Calculate the dielectric constant of soil in the CC (K_{CC}) using Eq. 9.1.
3. Calculate the mass of the soil in the CC by subtracting the mass of the CC from the mass of the soil and CC. Calculate the wet density of the soil in the CC, $(\rho_{wet})_{CC}$, by dividing the mass of the soil by the volume of the CC.
4. Calculate the volumetric moisture content (θ) of soil in the CC using Eq. 2.26 or using specific calibration equation of the form of Eq. 4.1.
5. Calculate the gravimetric moisture content (w) from the volumetric moisture content using as

$$w = \frac{\theta}{(\rho_{wet})_{CC} / \rho_w - \theta} \quad [9.2]$$

6. Calculate in-place dry density of soil as

$$(\rho_d)_{insitu} = \frac{\sqrt{K}_{insitu}}{\sqrt{K}_{CC}} \times \frac{(\rho_{wet})_{CC}}{1+w} \quad [9.3]$$

9.3 Method of Measuring Moisture Content of Soil in the Laboratory Compaction Tests

9.3.1 Scope

This method can be used with the laboratory compaction tests to determine the relationship between water content and dry density of soils (compaction curve) compacted in a 4 or 6-in (101.6 or 152.4 mm) diameter mold. While the wet density of the compacted

soil is measured gravimetrically, the moisture content of it can be determined using the test method described here.

9.3.2 Summary of Test Method

After the wet density of the compacted soil in the mold is measured, the dielectric constant of the soil is measured using the devices described in section 9.3.3. Using the dielectric constant and the wet density, moisture content of soil is determined.

9.3.3 Equipment

1. Coaxial apparatus (Fig. 6.1): The rod shall have a diameter of 4.76 mm. The inner diameter of the cap shall be slightly larger (1 to 2 mm) than the outer diameter of the mold at the top end.
2. Guide cap and hand penetrometer (Fig. 6.1): The diameter of the penetrometer rod shall be 3.94 mm. The guide hole of the guide cap shall have a diameter of 4.31 mm and a height of 38.1 mm.
2. TDR equipment
3. Wooden base plate: The dimensions of the wooden base plate shall be the same as that of the base plate of the mold.
4. Balance: Having a capacity of 15000 g and a readability of 1 g.

9.3.4 Procedures

1. Measure the mass of the soil and mold. Also measure the mass of the mold.
1. Place the guide cap on the mold
2. Make a pilot hole with the hand penetrometer
3. Insert the rod of the coaxial apparatus
4. Remove the mold with coaxial apparatus on it and place it on the wooden base plate
5. Make a measurement

9.3.5 Calculation

1. Calculate the dielectric constant of soil using Eq. 9.1.
2. Calculate the mass of the soil in the mold by subtracting the mass of the mold from the mass of the soil and mold. Calculate the wet density (ρ_{wet}) of the soil by dividing the mass of the soil by the volume of the mold.
2. Calculate the moisture content of soil using the procedures described in steps 2 and 3 of section 9.2.6. Note that, $(\rho_{wet})_{CC}$ in Eq. 9.2 should be replaced by the wet density (ρ_{wet}) of the soil in the mold.

9.4 Method of Measuring Moisture Content of Soil During Drilling and Sampling Operations

9.4.1 Scope

Test methods can be used to measure moisture content of soil in Shelby tube or soil retrieved during standard penetration test.

9.4.2 Equipment

Equipment to Measure Moisture Content of Soil in Shelby Tube:

1. Coaxial apparatus.
2. Guide cap, hand penetrometer
3. Measuring stick/depth caliper.
4. Balance: Having a capacity of 15000 g and readability of 1 g.
5. TDR equipment

Equipment to Measure Moisture Content of Soil Retrieved During SPT Test

1. CTL (Fig. 7.5a): The CTL shall have a length of about 200 mm. The diameters of the central rod and the cell shall be 4.76 mm and 35-45 mm respectively.
2. Balance: An electronic balance having a capacity of 15000 g and readability of 1 g.
3. TDR equipment

9.4.3 Procedures

Measuring Moisture Content in Shelby Tube

1. Clean loose soil and level soil surface at both ends. Measure the depth to the soil in the tube at the end which will be used to make measurement. Also measure the total length of tube and the depth from the other end to the soil.
2. Determine the mass of the soil in the tube.
3. Make a pilot hole in the soil using the guide cap and the hand penetrometer.
4. Insert the Coaxial apparatus rod through the pilot hole
5. Measure the apparent length for the soil using the TDR apparatus.

Measuring Moisture Content of Soil retrieved during SPT Test

1. Compact the soil in the annular space of the CTL and trim the surface flush.
2. Measure the apparent length for the soil using the TDR apparatus.
3. Determine the mass of the soil in the CTL.

9.4.4 Calculation

1. Calculate the dielectric constant of soil using Eq. 9.1.
2. Calculate the wet density (ρ_{wet}) of soil by dividing the mass of the soil by the volume of the soil.
2. Calculate moisture contents using the procedures described in steps 2 and 3 of section 9.2.6.

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