Design of a Multilevel-TDR Probe for Measuring Soil Water Content

by

Idris Ademuyiwa Adelakun

A Thesis submitted to the Faculty of Graduate studies of

The University of Manitoba

In partial fulfilment of the requirements of the degree of

MASTER OF SCIENCE

Department of Biosystems Engineering

University of Manitoba

Winnipeg, Manitoba, Canada.

THE UNIVERSITY OF MANITOBA
FACULTY OF GRADUATE STUDIES
FINAL ORALEXAMINATION OF THE MSC THESIS

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ABSTRACT

The TDR measures soil water content by measuring the travel time of an electromagnetic step pulse through a wave guide embedded in the soil. Damage during insertion and retrieval of the probe makes it unsuitable for repeated use. A multilevel-TDR probe with adequate protection for cable was designed and tested to overcome this problem.

Each section of the multilevel-TDR probe was constructed by embedding a 60 mm centre rod and a 63 mm outer loop in grooves on the outer wall of a 200 mm section of PVC pipe. Fifteen such probes were tested in the laboratory and the field by comparing it with the weighing method. Regression analysis between TDR-Θ_v and weighing method-Θ_v showed good correlation with an R^2 of 0.97 and 0.98 during two laboratory experiments and 0.51 during the field experiment. This multilevel probe is cost effective, reusable and can measure soil water content at different depths.

ACKNOWLEDGEMENTS

I would like to give thanks to God for his ever fulfilling grace and for sparing my life up till this moment. I also want to express my heartfelt thanks to my advisory committee, Dr. Wole Akinremi and Dr. Kris Dick for their valuable contributions to the success of this study.

My special thanks go to my indefatigable advisor, Dr. R. Sri Ranjan, for his immense contribution, guidance, constructive criticism, and unflinching support towards my program of study. In fact, I could not have asked for better because he is incredibly helpful and willing to help beyond my expectation. Your career is going to be interminable and rewarding.

I will be an ingrate if I fail to thank my amiable and assiduous Head of Department, Dr. Danny Mann for his leadership role and fatherly advice during my studies in this prestigious University. Many thanks also go to the Ph.D. students in Soil and Water Engineering Laboratory, Marcos Cordeiro and Sanjayan Satchithananthan, for their worthy advice and summer students, Grace and Mike. My sincere appreciation also go to my friends and well-wishers, Rotimi Ojo, Kibreab, Charles, Temple Didia, Taiwo Agboola, and Kazeem Adeogun for their words of encouragement. I would like to thank Dale Bourns and Robert Lavallee for their technical support. I also appreciate the effort of my siblings, Jide, Ayobami, Ayodeji, Folake, Olawumi, and my loving wife, Nofisat, for their kind gesture.

Finally, I wish to pay tribute to my loving parents, Mr. and Mrs. T.A.B Adelakun for their prayers and parental care throughout my program of study. You will reap the fruit of your labour. To all chronicles, both named and unnamed, I say a big thank you.

DEDICATION

I dedicate this research work to my loving wife, Adelakun, Nofisat Aderinola, my parents, and Shakira Bada for their unblinking support.

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ABBREVIATIONS

TDR = Time Domain Reflectometry

FDR = Frequency Domain Reflectometry

VWC = Volumetric Water Content

SWC = Soil Water Content

GPR = Ground Penetrating Radar

ASTM = American Soil Testing and Materials

SAS = Statistical Analysis System

Hr = Hour

in. = Inch

1.0 INTRODUCTION

1.1 Overview

The measurement of soil water content (SWC) within the root zone is essential for determining the amount of water that is needed as irrigation depth to replenish plant water uptake required for optimum growth. Besides, there is a need to understand the relationship between water content and the chemical, biological, and physical properties of soil (Hillel, 2004). Therefore, cost-effective, non-destructive, and safe methods are needed to monitor water content of the root zone.

There are a number of different methods for measuring the soil water content. Water content can be determined either directly or indirectly. In the direct approach, the gravimetric water content can be determined by taking the mass of soil-water that is held as a ratio of the unit mass of dry soil sample. This gravimetric water content is multiplied by the apparent specific gravity of the soil to obtain the volumetric water content, indirectly. The apparent specific gravity is defined as the ratio of the bulk density of soil to the density of water. Some of the indirect methods that can be used to measure soil water content are time domain reflectometry (TDR), neutron moisture meter (NMM) and frequency domain reflectometry (FDR). Ground- penetrating radar (GPR) can also be used effectively for measuring soil water content (Weiler et al., 1998; Lunt et al., 2005). The gravimetric method is the standard method used for measuring soil water content even though it is a destructive method (Cosh et al., 2005). The neutron moisture meter method is non-destructive but requires the use of a radiation source and is not accurate when used near the soil surface due to escape of neutron through the soil surface (Livingstone et al., 1988; Livingstone, 2001). The neutron moisture meter is suitable for measuring soil water content at greater depths below the soil surface (Song et al., 1998). The use of radioactive material requires that the neutron moisture meter users undergo special training before they can transport and use the meter in the field (Troxler, 2001; Bacchi et al., 2002).

The TDR method is relatively non-destructive as long as the probes are inserted into the measurement location with least disturbance of the surrounding soil (Logsdon, 2005; Mortl, 2010). The TDR technology has gained ground in recent years and is considered as the most widely used method for subsurface measurement of soil water content (Connor and Dowding, 1999; Yu et al., 2010). The TDR became widely known in the late 1980's. Time domain reflectometry was used initially for determining faults in high-speed communication cables used by the Telecommunication/Electrical industry (Topp et al., 2003). Presentations made by Topp at the Utah State Centennial Symposium showcasing five TDR papers from four countries that piqued the interest of researchers measuring soil water content. These seminal presentations on TDR served as an impetus for other researchers to pursue TDR as a method for measuring water content of soils (Topp et al., 2003).

The TDR probe determines the travel time of an electromagnetic wave along a wave guide embedded in the soil (Topp et al., 1980; Zupanc et al., 2005; Bitteli et al., 2008). Time Domain reflectometry is used by sending an electromagnetic pulse that moves along the coaxial cable and is reflected by the discontinuity in the coaxial cable as a result of impedance differences at the beginning and end of the TDR probe. The waveform is reflected back to the TDR device as the probe at the end of the coaxial cable encounters an impedance mismatch (ASTM D6565, 2005). With this scenario, the travel distance of the wave is 2L where the L is the length of the wave guide. It is possible to express the velocity of propagation (v) of an electromagnetic wave by:

$$\mathrm{V} = \frac{2l}{t} \tag{1.1}$$

where

t = time of travel

l = travel distance

The velocity of propagation of an electromagnetic step pulse in a void region is close to the speed of light (c) [3×10^8 m/s] (Quinones et al., 2003; Hillel, 2004). It is quite different in a medium that is occupied by a dielectric material. The propagation velocity in a medium can be calculated using Maxwell's equation (Gong, et al., 2003). This relationship can be expressed by:

$$V = \frac{C}{\sqrt{K}} \tag{1.2}$$

where

K = the dielectric constant of the medium.

Equation (1) and (2) can be combined to show the relationship between the dielectric constant, travel-time, propagation speed, speed of light and the travelled distance.

$$K = \left[\frac{tc}{2l}\right]^2 \tag{1.3}$$

The dielectric constants of air, soil and water are 1, 3-5, and approximately 80, respectively. A moist soil will have a mixture of these constituents and the composite dielectric constant will be a volume averaged dielectric constant of the individual materials that form an imaginary cylinder, having a diameter about two mm larger than the spacing between the outer rod, where the probe is embedded (Sri Ranjan and Domytrak, 1997). When the probe is embedded in the medium, the apparent length measured by the TDR can be used to calculate the apparent dielectric constant (K_a) of the medium as follows:

$$K_a = \left[\frac{l_a}{l}\right]^2 \tag{1.4}$$

where

l_a = apparent length

l = actual length

The apparent dielectric constant can further be related to the volumetric water content using the relationship developed by Topp et al. (1980) which is considered as a standard calibration equation [Grozic et al., 2000; Munoz-Carpena, 2004; Hillel, 2004; ASTM D6565 (2005); Mailapalli et al., 2008; Luigi and Greco, 2011].

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3 \tag{1.5}$$

The TDR has been used in a wide range of applications for monitoring soil water content. Evett et al. (1993) stated that an average of 88% total soil moisture profile variation occurs daily at the top 30 cm of soil. This was discovered when the TDR probe was used to measure changes in the top 40 cm of soil. Lungal and Si (2008) discovered that a coiled TDR sensor can measure soil matric potential ranging from 0 to -1.5 MPa while tensiometer and gypsum block are limited to measuring soil water content within the range of 0 to - 0.09 MPa and -0.09 to -0.5 MPa, respectively. A one-step TDR method is capable of determining soil water content and dry density of soil on the same soil sample simultaneously (Yu et al., 2004). Measurement of water content of the stem of lemon trees and in the root zone surrounding each tree can be done with TDR (Nadler et al., 2003). In addition, TDR can be used to monitor seasonal change in water content of mature trees (Irvine and Grace, 1997).

While the TDR probes are considered to be accurate, reliable and capable of a wide range of applications, it is still necessary to calibrate the TDR probes to ensure better accuracy. Calibration helps to correct mistakes made during the manufacturing process and reduces the errors during the experiment (Varble and Charvez, 2011). Serrarens et al. (2000) reported that calibration of TDR probes can be achieved either by using the empirical formula (Topp et al., 1980) or assumption deduced from physical mixing models (Yu et al., 1999). The accuracy of the calibration equation depends on the soil bulk density. An experiment showed that soil with bulk density between the ranges of 1.20 g/cm^3 to 1.40 g/cm^3 performed better with Topp equation but showed greater variation at lower bulk densities (Ju et al., 2010). Tomer et al. (1999) stipulated that soil with a bulk density of less than 1 g/cm^3 need to be calibrated. It is imperative to note that dielectric constant varies with a change in bulk density. Therefore, the determination of soil water content with TDR will change with the variation of the bulk density of the material. Besides, TDR signals overestimate the moisture content values when the bulk density is greater than 1.7 g/cm^3 and underestimate water content when it is less than 1 g/cm^3 (Quinones et al., 2003).

1.2 Scope

The ability to measure soil water content in a small volume of soil is dependent on the length of the TDR probe. Such point measurement of water content is needed to ascertain the soil moisture profile within the root zone. This requires the use of multiple TDR probes installed at different depths and locations in the soil profile. The coaxial cable used to connect the TDR probe to the cable tester is very delicate and cannot be subjected to extreme tension causing elongation of the cable. As a result, the TDR probes have been good for one installation during the season and they cannot be easily retrieved and re-used without damaging the cable especially when the cable access hole is sealed with bentonite during installation. Therefore, the need to protect the cable was identified as a pre-requisite for developing a TDR probe. Embedding the TDR probe on the outside wall of a conduit and encasing the coaxial cable within the conduit will protect it during installation and removal. However, research on partially embedded TDR probes as proposed in this design is sparse to none.

1.3 Objective

The objectives of this research were to design and test a multilevel TDR probe that is durable, reusable and cost-effective. A field installation tool for the insertion of the new probe was also designed and tested.

1.4 Organisation of the thesis

The first chapter of this thesis focussed on the overview of the study, the scope, objective, and the organization of the thesis. The second chapter presents the literature review with different sub sections discussing measurement of soil moisture, calibration of the probe, installation, soil water movement, impact of soil temperature and software for analysing soil moisture. The third chapter presents the methodology adopted in this research. The fourth chapter shows the data obtained from the experiments and the analysis. The performance of the reusable TDR probes was analyzed using the JMP Software (SAS Institute, Corp) and is presented as figures. The fifth chapter discusses the major conclusions and briefly explains the outcome of the experiments. Chapter Six highlights recommendations on areas that need to be improved for future study.

2.0 LITERATURE REVIEW

2.1 Soil Water Monitoring and Measurements

2.1.1 General

The measurement of soil water content is important in a variety of disciplines such as soil science, civil engineering, meteorology, agronomy, and hydrology. In addition, it is necessary to monitor the soil moisture movement for irrigation purposes especially in a catchment area where water is insufficient for high-value crops such as wine grapes (Lunt et al. 2005).

The soil water content can be determined by various methods. It is very difficult to find a method that can determine both the frozen and unfrozen water content simultaneously. The TDR can be used to measure the unfrozen water content (Kahimba et al. 2007). Gravimetric method is destructive and takes time before the soil water content can be determined (Lubelli et al. 2004; Cultrone et al. 2007 and Luigi and Greco, 2011). The development of radio frequencies to determine near surface electrical properties of the moon gave an insight into the discovery of TDR for measuring soil water content (Topp et al. 2003). The volumetric water content is estimated by the TDR probe using the dielectric constant in a third order polynomial which is based on the relationship between the volumetric water content and the dielectric constant of moist soils (Ledieu et al. 1986; Vaz et al. 2002; Mailapalli et al. 2008).

2.1.2 Measurements of soil moisture

Soil water content can be measured by using direct or indirect methods (Muñoz-Carpena and Dukes, 2008). The direct method can be regarded as the method of removing water from void spaces in the soil through heating. This is usually called as oven-drying method or gravimetric method. To convert the gravimetrically determined water content to volumetric water content the bulk density is used as a multiplier (Carter and Gregorich, 2008). One of the problems with the gravimetric method is that the result cannot be known immediately in the field due to the time it takes to dry the soil sample.

The indirect method can be classified into two groups. The first category is capable of measuring the energy status of the soil and can be considered as soil water potential determination. The second category indirectly measures the water available in the void space of the soil and can be regarded as soil water content determination (Tarantino et al. 2008). One of the sensors that can be used to measure the matrix potential of the soil is tensiometer (Lungal and Si, 2008). The tensiometer is capable of measuring soil matrix potential without specifically calibrating the soil to be used. (Munoz-Capena, 2004; Tarantino et al., 2008). The TDR can also be used indirectly to measure soil water content and soil salinity (Dalton and Van Genutchen, 1986). The Tektronix device which is capable of obtaining the waveform generated by the electromagnetic step pulse traveling through a waveguide (TDR probe) embedded in the soil can be used to measure soil water content (Dahan, et al. 2003).

2.2 Time Domain Reflectometry

The Time domain reflectometry (TDR) can be used with minimal soil disturbance unlike other methods of measuring soil water content (Ju et al. 2010). The TDR can effectively measure soil water content at 1 m depth below the soil surface (Topp and Ferre, 2006). The TDR works by measuring the travel time of an electromagnetic wave along the wave guide (Stafford, 1988). The reflection of the pulse at the end of the TDR probe is used to determine the travel time of the electromagnetic step-pulse through the soil medium in which it is embedded. The propagation velocity of the wave through the medium is obtained from the wave form (Hashmi et al. 2011; Yu et al. 2010). This propagation velocity can be regarded as a function of dielectric constant of the medium in which the TDR probes is embedded (Ledieu et al., 1986). The apparent dielectric constant can be related to the Topp's equation (1980) to indirectly calculate the soil water content.

2.2.1 Calibration relationship between soil apparent dielectric constant and volumetric water content

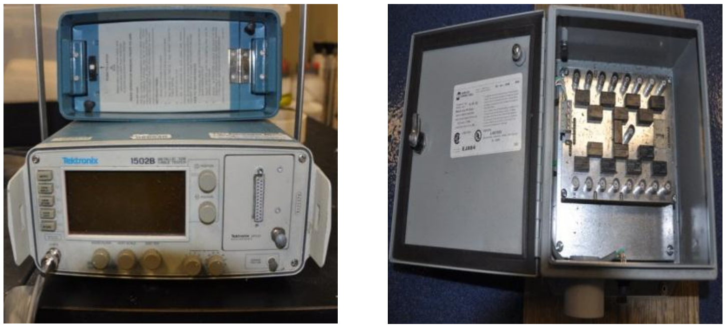
The calibration relationship given by the Topp's equation is a widely known equation for estimating soil water content. The dielectric constant of water is almost 81 at 20^{o} C, air is 1, and the dielectric constant of the soil is between the range of 3 and 5 depending on the soil constituents (Topp et al., 1980; Quinones et al., 2003). Water has a high dielectric constant in comparison to air and soil (Fares and Polyakov, 2006). Gong et al. (2003) stated that the dielectric constant of solid dry soil is within the range of 2 and 4, and air is close to 1. Therefore, it is possible to deduce the soil moisture from dielectric constant of the soil-water-air mixture. This measurement is possible because a small difference in the soil moisture will result in a large difference in dielectric constant (Nemali et al., 2007).

It is imperative to know that soils with high organic matter and clay content require calibration for a good degree of accuracy (Hook and Livingston, 1996; Quinones et al., 2003; Western and Seyfried, 2005). The ability of clay and organic matter to have more bound water, which has a much lower dielectric constant, will affect the accuracy of water content measured by the TDR. It is important to know that water molecules possess strong polarity. This implies that there will be a strong positive charge on one end of the molecule and a strong negative charge at the other end. This relationship makes the water molecules to bond to each other as well as other charged surfaces leading to bound water. The prevalence of bound water makes it necessary to calibrate the TDR for individual soils when the dielectric constant is related to soil water content (Scott et al., 2002; ASTM D6565, 2005).

The difference in dielectric constant with temperature should be adjusted for TDR probes at 25^{o}C (Kahimba and Sri Ranjan, 2007). However, soils with high amount of clay underestimates the soil moisture when the water content is low and overestimates when the water content is high (Gong et al., 2003; Namdar-Khojasteh et al., 2012). The adjusted dielectric constant can be inserted into empirical equation (5) from (Topp et al., 1980) to determine the volumetric water content for individual soils.

2.2.2 The TDR model for measuring soil water content

There are different models of TDR cable testers with the Tektronix 1502B being the more accurate model for measuring soil water content. However, its resolution can be affected as the cable length increases (Test Equipment Depot, 2012). The TDR cable can be connected to the Tektronix cable tester for measuring soil water content. The cable tester is meant to send the electromagnetic step pulse through the coaxial cable to the tip of the probe and generate the waveform. Fig. 2.1(a) shows a typical Tektronix 1502B cable tester. Fig 2.1(b) A multiplexer



(a) **(b)**

Fig. 2.1 The TDR cable tester and a multiplexer for measuring soil water content (a) Tektronix 1502B (b) A multiplexer

Multiplexers make it less laborious for collection of data both in the field and laboratory. A multiplexer as shown in Figure 2.1(b) has 16 channels for connecting 16 TDR coaxial cable. The SDMX50- SERIES multiplexer is capable of connecting up to 512 TDR probes and can be monitored with a data logger (Campbell Scientific, Inc. 2012). A multiplexer can be connected with TDR probes for combining multifold input signals from TDR into single data stream or output.

2.2.3 Soil moisture probes with a data logger

Different TDR probes have been designed for measuring soil water content. The TDR probe is capable of measuring soil water content of organic media in a container (Anisko et al. 1994). To measure the water content in a smaller volume of soil mini-TDR probes were developed and tested (Domytrak and Sri Ranjan, 2005). One of the advantages of mini-TDR probe is that it is not difficult to install due to the round head shape. Figure 2.2 is a typical three-wire 50-mm TDR mini-probe with a 5 mm spacing between each rod.

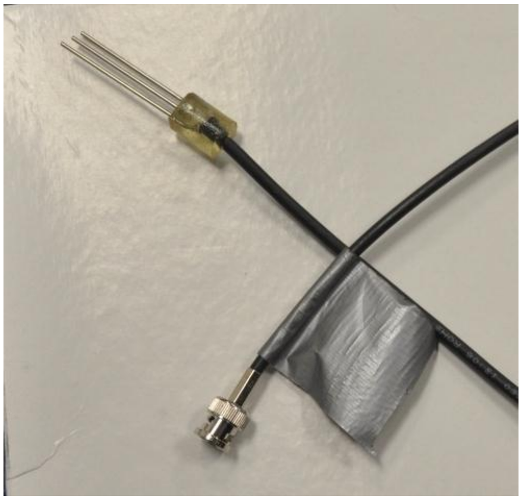


Fig. 2.2 The TDR Mini-probe

2.2.4 Installation of TDR probes

The TDR probe can be installed into the soil by embedding the probe below the ground surface for determination of moisture content ASTM D6565 (2005). The probes can be installed in a vertical, horizontal or inclined at an angle to the surface of the soil (Campbell Scientific, Inc. 2008). The installation of the TDR probes in a vertical direction is prevalent compared to the other methods. The prevalence of vertical installation is attributed to less effort in drilling a hole with a soil auger. However, vertical installation usually has a problem of air gap between the soil and the probe as a result of rapid movement of water in the porous medium. Preferential flow may occur if proper backfilled materials, such as bentonite, are not used (Dahan et al. 2003). Besides, preferential flow is pronounced most in structured clay soils as a result of large pores (Amstrong, 1983; Mc Intosh et al. 1999).

It is also possible to encounter the problem of air gap when TDR probes are installed and pulled out frequently (Ferré et al. 1998). Probes inserted into the soil at an angle are capable of minimizing the problem of air gap by allowing the probes to be in good contact with the soil (Dahan et al. 2003).

2.2.5 Impact of cable lengths in soil water content

The length of the cable is one of the factors that hinder the performance of a TDR probe. It is necessary to know that long coaxial cable affects the dielectric permittivity of the soil-water (Kahimba et al, 2007; Logsdon 2000). Pierce et al. (1994) conducted an experiment on a coaxial cable with a length ranging from 94 to 268-m. He discovered that an increase in the cable length resulted in a decrease in the resolution of the reflection signature. Kahimba et al (2007) found the maximum cable length of RG-58 coaxial cable to be 37 m for the TDR mini-probes that were used by them. Brendan (2003) suggested that the length of RG-58 coaxial cable should not exceed 35-m length to avoid signal attenuation and loss of resolution in the reflected wave. Other factors that affect the TDR probes are the length of the probe, methodology applied in calibration, analysis of waveform, temperature and soil texture. It is advisable to connect the TDR cable directly to the TDR instrument for best results. Tektronix, Inc. (1998) recommends that the battery of Tektronix 1502B should be maintained at temperature range of -15^{o}C to 55^{o}C during operation. Also, the battery needs to be charged within the temperature range of +20^{o}C to +25^{o}C for full capacity. However, Tektronix 1502B still has the tendency to work below +10^{o}C because of the heater incorporated into the system. The element created in the liquid crystal display (LCD) will heat up the display and ensure good working condition of the device (Tektronic, Inc.1998). Conversely, Blonquist et al. (2005) recommended a range of 5^{o}C to 55^{o}C. This development shows that it is necessary to create an enabling environment for the TDR instrument during the fall - winter period (Tektronix, Inc. 1998). The creation of an enclosure is because TDR instruments need to be operated in a warm area very close to where TDR probes are installed. This shows that another extension cable is needed to connect the TDR probes installed in the field to the enclosed TDR instrument (Kahimba et al. 2007). Multiplexers and extension cables are useful for measuring soil water content with multiple probes (Logsdon, 2000).

2.3 Infiltration of water into the soil

Infiltration is the process by which water enters the soil profile through the soil surface (Parlange et al.2006). There are a lot of forces that contribute to the infiltration of water into the soil (Chapin et al. 2011). The intensity of rainfall and the amount of total rainfall during a storm play a major role in water entry into the soil. The two major forces that enhance infiltration are gravity and capillarity (Warner, 2004). It is very important to know how water moves through the soil for proper application. The rate at which water moves through the surface layer of the soil is known as infiltration rate (Williams et al. 1998). The rate at which water moves through the soil layer is higher at the initial stage of water entry into the soil. An Infiltrometer can be used to measure the rate of infiltration (Liu et al. 2003). As the water infiltrates into the soil, the soil particles swell and begin to close the pore space resulting in decreased infiltration over time. When the infiltration declines over time and reaches a plateau or constant rate it is known as basic infiltration rate (FAO, 1988; Telis, 2001). The cumulative infiltration of water in the soil can be analysed as a function of time with Green and Ampt approach (Warrick et al. 2005).

Based on the physical distribution of the water within the soil profile during infiltration it can be divided into Saturation zone, Transmission zone, Wetting front and the Dry zone. The saturation zone is a region where the voids are occupied by water and is very close to the soil surface. The transmission zone is the next layer to the saturation zone. This zone is a region where water moves by gravitational force and the soil is not saturated. The wetting front is the area where there will be an increment in the water content of the soil as water continues to move through the soil surface. In addition, it serves as a link between the transmission zone and the wetting front. Finally, the wetting front is a boundary between the wet and dry soil beneath the soil layer (Koorevaar et al. 1999; Hillel, 2004; Kahimba, 2008).

Soil surface conditions, vegetation cover, physical properties of soil, and temperature of the water are some of the factors that hinder the movement of water through the soil surface (Parlange et al. 2006; Hiraoka and Onda, 2010).

2.4 Soil Temperature

2.4.1 Impact of temperature on soil water content and Dielectric constant

The effect of temperature can be alarming when a probe beginning point within the software has been predefined by the user. This effect occurs most when the TDR probe length is approximately 30 m or more. When the cable is long there will be shrinkage in the cable and contraction occurs as a function of temperature. It is a good way to protect the TDR cable to minimize thermal effect. However, the dielectric constant of the soil varies as a function of temperature ASTM D6565 (2005).

Temperature is one of the factors that can affect the performance of the TDR (ASTM D6565, 2005). The variation in temperature can be corrected by using the Topp's equation for temperature correction. The lower the temperature the higher the variations in the values obtained from the TDR mini-probes (Ledieu et al. 1986). The degree of accuracy of soil water content with TDR technique depends on the accurate measurement of the dielectric constant of the soil. Topp et al. (1980) thought that the effect of temperature should be ignored due to minimal effect on volumetric water content and soil factor with an accuracy of $0.013 m^3 m^{-3}$. Due to the variation in the temperature of soil profile which affects the performance of TDR, there is a need to develop a standard equation for correcting the temperature when TDR technology is used.

Campbell Scientific Inc. (2008) state an equation that relates the dielectric constant of free water with temperature can be used to determine actual dielectric permittivity of water. The equation was developed with a base temperature of 25^oC and is given as:

$$\varepsilon_w (T) = 78.54[1- 4.579 \times 10^{-3} (T-25) + 1.19 \times 10^{-5} (T-25)^2 -2.8 \times 10^{-8} (T-25)^3] \qquad (2.1)$$

where

ε_w (T) = dielectric permittivity of free water

T = Temperature in (^{o} C)

It is important to know that soil water content, soil texture, and soil temperature are interrelated. The TDR readings obtained from dielectric constant decreases as temperature rises when the water content is high. Conversely, there will be a net increase in the values deduced from dielectric constant as temperature increases under low soil water content. The reason is because an increase in temperature serves as a catalyst to speed up the movement of bound water (Or and Wrath 1999; Gong et al. 2003) as reported by (Kahimba et al. 2007).

2.4.2 Thermal properties of soil

Soil water content can be inferred from the dielectric permittivity and the dielectric permittivity is affected by soil temperature. Thermal properties such as thermal conductivity, volumetric heat capacity affect the temperature of the soil (Fuhrer and Schar, 2000; Hillel, 2004; Smiths et al. 2009). The thermal conduction determines the ability of soil to conduct heat between paricles. Other mechanism is through convection (Fuhrer and Schar, 2000). The temperature of the soil can be modelled by using the Simultaneous Heat and Water popularly known as (SHAW) model (Flerchinger, 2000).

2.5 Standard test for measuring water content in the soil

(ASTM D2974-07) stated that soil water content can be obtained with the following method:

- The soil sample can be dried at a temperature of 105^0C to determine its water content

- Another way of removing soil water content can be achieved in two sequential orders. The method is to evaporate the soil water content at room temperature and later dry the sample in an oven at 105^{0}C (ASTM D2974 - 07a).
- It shows that either oven drying or evaporation by weight method can be used to compare soil water content obtained using the TDR since gravimetric method is recommended by ASTM standards.

2.6 Software for analysing soil moisture

Different software can be used for analysing soil water content**.** The WinTDR software and TACQ program can be used to analyse soil moisture. The WinTDR is a Windows based software that can be downloaded on the computer system and can be used to analyse electrical conductivity, waveform, and measure the dielectric permittivity of a medium with Tektronix 1502B/C series of metallic TDR cable tester device (Or et al., 2004) .WinTDR was developed by soil physics group at the UTAH state University for analysing soil water content (Or et al. 2004).

WinTDR works by determining the dielectric permittivity from a TDR waveform. It determines the first reflection by allowing the TDR device to send an electromagnetic wave to pass through the coaxial cable to the head of the probe. The second reflection is determined when the pulse reaches the tip of the probe and the length of the stainless steel rod is a known fixed value. The travel distance along the probe length can be used to determine the dielectric permittivity, which can be converted to volumetric water content using the Topp’s equation (Or et al., 2004). The WinTDR software needs to be used according to the manufacturer’s instruction for better results (Or et al. 1998).

3.0 MATERIALS and METHODS

3.1 Design considerations

In selecting a proper enclosure for the cables connecting the TDR probe, the diameter was a major consideration. The smaller the diameter, the easier it is to install and retrieve the probe. A 1 in. PVC pipe (34 mm OD, 4 mm wall thickness) was chosen as the main body of the enclosure to protect the cable. The capital costs and the operating costs of the probe were considered before embarking on the design. Some other factors that were considered are as follows:

*The diameter of the PVC pipe***:** The outer diameter of the pipe was 34 mm. This size was chosen for ease of installation and retrieval.

*The length of the pipe section***:** It is customary to measure soil water content at increments of 0.2 m. The TDR probe is embedded on the outside wall of the conduit and the open ends are inserted through the wall of the conduit before the coaxial cable is soldered to make the electrical connection inside the conduit. The soldering has to be done through the open end of the conduit. Therefore, the length of the pipe section was limited to the depth increments at which soil water content measurements are needed.

*The thickness of the pipe***:** The thickness of the wall of the PVC pipe was 4 mm. This thickness was chosen in order to accommodate 1.6 mm stainless steel rods. The thickness served as a layer or platform where a groove to embed the stainless steel rod was made.

*The length of the stainless steel rods***:** The TDR probes tested in this research were 60 mm long, allowing the water content to be determined in a smaller volume of soil. This size was chosen based on over decade of experience gained in our lab with TDR mini-probes of similar size. The length of the stainless rod at the centre was 60 mm and the stainless rod forming the outer loop was 63 mm long as looped length.

The length of the coaxial cable: Coaxial cables of 2.2, 2.4, 2.6, 2.8 and 3.0 m length were used to connect the TDR probes at different distances from one end of the multilevel probe (BELDEN 8259 RG-58A coaxial cable of impedance 50Ω). The different lengths were chosen so that the open ends of the coaxial cable of the multi-level probes will be at the same location after joining each section of the mini-probe. Campbell Scientific (2008) recommended a maximum length of 15 m for probes with RG-58 cable and 25 m for RG8 cable. ASTM D6565 (2005) recommended that cable length should not exceed 30 m in length because of variation in temperature. The cable lengths used for the development of TDR probes are within the range of lengths proposed by ASTM standards.

3.2 Materials used in the construction of TDR probes

The materials used in the design of the multilevel TDR probes are durable, have adequate tensile capacity, and cost effective. A PVC pipe, coaxial cable, BNC connector, Epoxy resin, stainless steel rods, stoppers and thermocouple connector were used to construct the probe. The functions of the materials used for the development of the TDR probes are stated below:

1. *PVC pipe*: The function of the PVC pipe is to protect the coaxial cable and the stainless steel rods from being damaged. In addition, the PVC pipe serves as the main body where a machine engraves a series of grooves for the stainless steel rods to be embedded. A 1 inch PVC pipe was used for the development of the new TDR probes. The desired shape of the stainless steel rods was engraved on the 200 mm long pipe section with an electric drill.

2. *Coaxial cable*: The coaxial cable of BELDEN 8259 RG-58A was used to connect the TDR probe. The outer plastic sheath protects the cable and the woven copper shield was connected to the outer stainless steel loop. The inner dielectric insulator prevents woven copper sheath and the copper core from short circuiting. The BELDEN 8259 RG-58A used for the development of the TDR probe and its parts are shown in Fig. 3.1 below

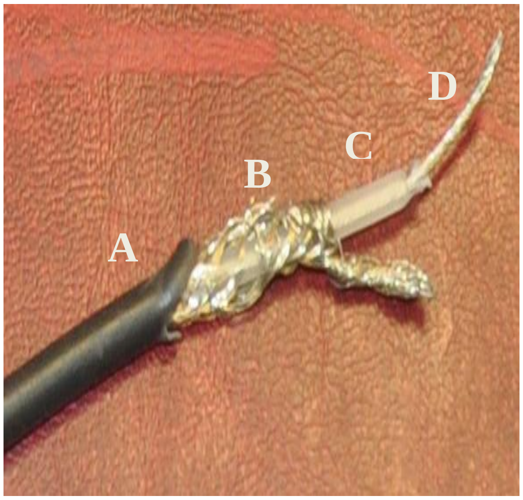


Fig. 3.1 Coaxial cable used in the design of the TDR probe

In Figure 3.1 the letters show: A the outer plastic sheath which protects the coaxial cable, B the woven copper shield, C the inner dielectric insulator and D the copper core which is connected to the centre 60 mm stainless steel rod.

3. *Stainless steel rods:* A 316L $\frac{1}{16}$" Stainless Steel Tie Rod (PRs 05018) was used as the TDR probe which was embedded on the outside wall of the PVC pipe. A centre rod and a loop were used in this design. The length of the stainless steel rods at the center was 60 mm and the outer loop was 63 mm in length.

4. *BNC connector:* The BNC connectors serve as the interface between the coaxial cable and the Tektronix device. The centre pin of the BNC connector was crimped onto the copper core of the

cable which was then fitted through the connector body. The crimp sleeve was further allowed to hook the woven copper shield to the BNC connector body. Fig. 3.2 represents the components of BNC connectors used for the development of the TDR probe.

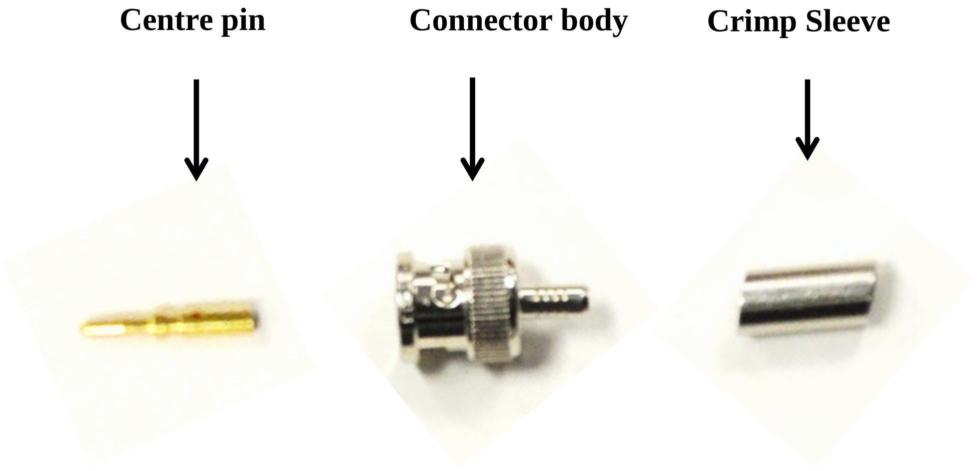
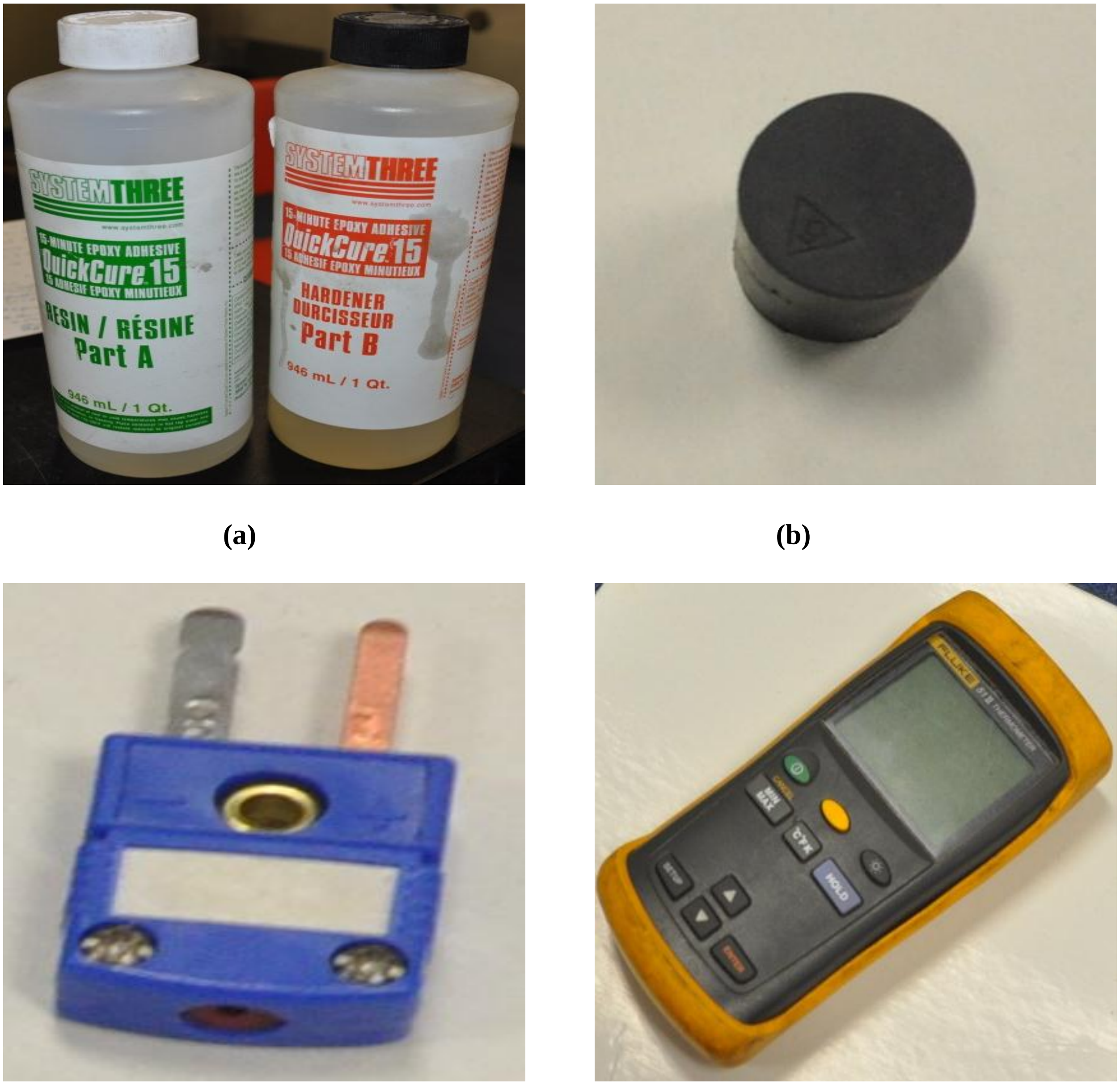


Fig. 3.2 A typical BNC male crimp plug for RG – 58A/U used for reusable TDR probe.

5. *Epoxy resin:* The epoxy resin was used to prevent water from entering the small holes made for the stainless steel rods that protrude through the interior part of the PVC pipe. Epoxy was used because it is water proof. The 15-minutes epoxy adhesive resin/hardener created a strong bond between the stainless steel rods and the inner part of the PVC pipe. Fig. 3.3 (a) represents the epoxy resin used for binding the stainless steel rods and the coaxial cables together.

6. *Stoppers:* The purpose of the stopper is to hydraulically isolate the holes at both ends of the pipe during testing. This approach is to prevent the water from entering the PVC pipes when the probes are installed in the soil. Size No.5 stopper was used to cover the holes. The TDR probe will malfunction if water is allowed to enter the probe ends inside the pipe. One of the stoppers was split in half to allow the insertion of the cable. Fig 3.3 (b) shows the view of the stopper used for the laboratory experiments.

7. *Thermocouple connector*: The connectors were attached to the thermocouple wire for temperature readings. Fig. 3.3 (c) and (d) show the thermocouple connector and a thermocouple thermometer used for the laboratory experiments.



(a) **(b)**

(c) **(d)**

Fig. 3.3 Some of the materials used for the development of the TDR probe

(a) Epoxy resin (b) Rubber stopper (c) Thermocouple connector

(d) Thermocouple Thermometer

3.3 Development of the TDR probes

AutoCAD and Solid Edge Software were used to prepare the shop diagrams for building the new TDR probes. The length from the point where the open ends of the looped rod protrudes through the pipe wall to the other end was 27 mm long. This length was picked for convenience in soldering the coaxial cable to the stainless steel rods and for easy application of epoxy resin through the open end of the pipe. While permitting soldering through this end, it had enough wall material to attach a connecting pipe from the next probe section. The spacing between each rod that makes up the TDR probe was 5 mm. This spacing was chosen to avoid interference based on the recommendation from past literature (Zegelin et al., 1992). All the dimensions in figure 1 are in millimeters. The diameter of the stainless steel rod was 1.6 mm which was easily embedded into the 2 mm groove on the wall of the pipe section. This clearance enabled the stainless steel rod to rest on the PVC pipe properly. Five sections of 0.2 m length TDR probe can be joined together to form a 1 m long multilevel probe. The looped rod was 3 mm longer than the middle rod to avoid any cross connection in the far end. The new reusable multilevel TDR probe is shown in Figure 3.4

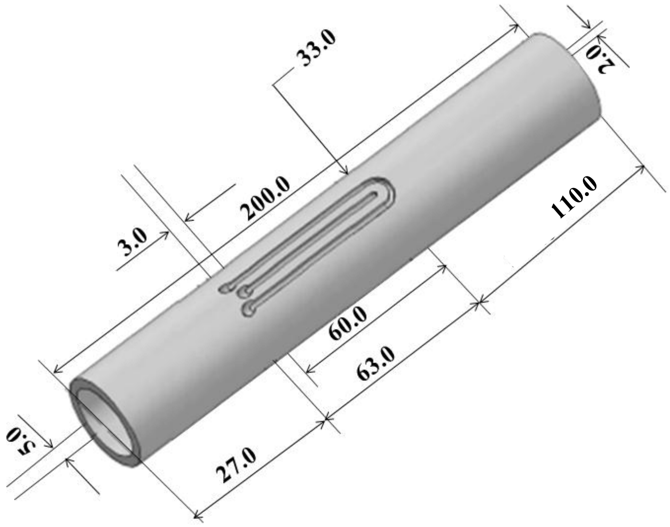


Fig. 3.4 Development of reusable probe in 3 - dimensional view.

3.4 Construction of the TDR probe

The TDR multilevel probes were designed and calibrated individually in our laboratory at an average temperature of $25\pm0.3^{o}C$ using soil columns. If the steps outlined here are closely followed during the construction of the probe, better results can be obtained. The 1” PVC pipe was cut into 0.2 m length with a power hack saw before it was later turned on a centre lathe for smoothing. A drill was used to cut the semi-circular groove of 0.002 m diameter with length of 0.063 m and linear groove shape of 0.060 m long at the centre on the PVC pipe as shown in Figure 3.5. The stainless steel rod was cut into the desired lengths with a cutting plier and bent by hand for proper fitting in the groove engraved on the outer wall of the PVC pipe. A master probe prepared by trial-and-error was used as a guide to bend the other rods. Holes were drilled through the pipe at a 45^{o} angle to enable the ends of the stainless steel rod to protrude inside the PVC pipe. This angle also permitted easy soldering of the rods to the coaxial cable. The co-axial cable soldered to the stainless steel rods at the interior of the pipe were encased in a blob of glue that electrically isolated the connections and provided mechanical support to the soldered ends. A small casing was made out of plastic sheets to act as the enclosure for the epoxy glue while it was curing. The probe section was allowed to set for 24 h before further work was carried out. The other end of the coaxial cable was connected to the BNC connector.

Since the TDR probe measurements are temperature sensitive, thermocouples were embedded near the TDR probes. Three millimeter diameter holes were drilled on the wall of the PVC pipe sections near the embedded TDR probe. Thermocouple wires were inserted through these holes. Epoxy resin was applied to all the holes left at the circumference of the 1 in. pipe to prevent water from entering the pipes. One section of the multilevel TDR probe is shown in figure 3.5 below:

Fig. 3.5 One section of the new multilevel TDR probe

Fifteen TDR probe sections were built for this study. The 3-stainless steel rods were embedded on the 1 inch PVC pipe. The centre-to-centre spacing between the looped rod and the middle rod was 0.005-m. The looped-rod configuration performed better than the 2-rod configuration. The two rod probe requires a balun transformer and has the tendency to cause signal loss ASTM D6565, (2005). The coaxial cable was soldered to the tip of the stainless steel rod protruding through one end of the section of PVC pipe. Probes with small diameter have the tendency of generating high impedance and peak (Mojid et al., 2003). Previous researchers recommended that the rod spacing needs to be greater than three times the diameter of the central rod to avoid any “Skin effect” in the looped-rod configuration (Zegelin et al., 1992; Kahimba et al., 2007). The spacing between the new TDR probe rods is 0.005m. It is 3.1 times the diameter of the rods. It implies that the design of this probe meets the necessary condition to avoid the skin effect.

Campbell Scientific, Inc. (2001) recommended that the TDR probe needs to be 0.04 m away from the edge of the soil-water column during calibration in the laboratory. This fact helps to prevent the energy field from extending outside the container. It is not advisable to use longer probes for measurement of soil water content. Longer probes tend to cause wave attenuation and leads to gradual energy loss along the probe at lower moisture range (Mojid et al., 2003). Caravetta et al., (2012) stated that the length of the TDR probes should not exceed 20-cm to achieve good results. A 15-cm long TDR measurement probe was used to measure dielectric permittivity in air and resulted in the delay of travel time of an electromagnetic wave of 8 ns (IMKO micromodultechnic, 2012). The probe length should not be less that 2.5 cm to avoid sharp variation in the pulse travel time of an electromagnetic wave (Mojid, 2002).

Before using the new TDR probes for measurement in soil, each section of the reusable probe was calibrated in pure water with its known dielectric constant using WinTDR Version 6.1software. Five such sections of PVC pipes were attached together to create each of the Multilevel TDR probe thus protecting the coaxial cable from being damaged during installation and removal.

Each section of the mini-probe was joined together with a screw and epoxy. Screws were used to connect each section of the probe to provide mechanical strength during installation and removal. The probes need to be cleaned and maintained after each operation for good precision and accuracy during experiment. The open end of the last probe section was capped with a cone shaped PVC piece to enable easy insertion into the soil and prevent any water from entering the interior of the multi-level probe. The new multilevel TDR probe can be used to determine the dielectric constant and electrical conductivity of soil with Tektronix 1502B metallic TDR cable tester within the range of 0.2 to 1 m depth (Tektronix, Beaverton, OR). The TDR cable tester sends an electromagnetic step pulse along the coaxial cable which passes through the stainless steel rods of the TDR probe which acts as a waveguide embedded in the soil. The PVC pipes also protected the cable from being damaged and minimize temperature variation during the experiment. Figure 3.7 shows the multilevel TDR probes developed in our laboratory.

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Fig. 3.6 The reusable multilevel TDR probes.

3.5 Calibration of the TDR probes under laboratory conditions

It is necessary to calibrate the TDR probes in order to accurately measure the soil water content in the field (Take et al., 2007). A calibration is essential for determining the effective length of the probes and enhances the accuracy of TDR measurement (Western and Seyfried. 2005)**.** All probes were initially calibrated in water to determine the probe offset with the known temperature as recommended by Campbell Scientific (2008). The TDR mini-probes can be calibrated with an average temperature of 25^{o}C ± 0.3^{0}C by using water maintained at constant temperature (Kahimba et al., 2007). The TDR probes were calibrated in distilled water at a temperature of 25^{o}C ± 0.3. During calibration, the point of initial reflection of the pulse corresponding to the beginning of the probe as well as the second reflection point corresponding to the end of the probe was determined. Each section of the multilevel TDR probe was inserted into a cylindrical water column (0.38 m depth and 0.3 m in diameter) during calibration. A minimum clearance of 0.14 m was maintained from the sides of the container.

The probe length, distance per division, and peak were set by using the WinTDR software [ASTM D6565, (2005)]. During the calibration of the TDR probe, the temperature of the water was taken into account and the adjusted probe length was determined when the TDR measured dielectric constant was found to be much closer to the actual value. Heimovaara, (1993), Logsdon (2000), and Robinson et al., (2003**) c**onfirmed that calibration of the TDR probes can be achieved with dielectric fluids such as water, oil, and air. Calibration improves the accuracy of the TDR probes when compared to the gravimetric method.

3.6 Soil selection and preparation of soil samples

The soil samples used for this study were taken from two different locations. A Fairland loamy sand was taken at a field site near Carberry, Assiniboine Delta Aquifer. Riverdale silty clay, obtained from the University of Manitoba, Fort Garry campus Research Station, (the point) was used for the second laboratory experiment. The soil samples were put through a 2-mm sieve to remove soil clods and debris. A soil packer was used to evenly spread the soil sample into the column. The volume of soil in the bin during the first experiment was 7296 cm^3 and 500 cm^3 during the second experiment. The weight of the water, soil sample, probes, and the container were determined before the experiment began. The bulk density of each soil sample was calculated. However, the gravimetric water content deduced from the experiment was multiplied by the bulk density to calculate the volumetric water content. Preparation of soil samples are shown in Fig. 3.7 (a) and 3.7 (b) below:

(a) (b)

Fig. 3.7 (a) Preparation of soil samples during first experiment, (b) Preparation of soil sample during second experiment.

3.7 Methods

3.7.1 Experiment 1

The major purpose of this test was to determine the accuracy of the partially embedded TDR probes. Five TDR probes were used for this test. A rectangular container, 0.28 m by 0.32 m by 0.14 m tall, was filled with a mixture of Fairland loamy sand. The TDR probe sections were buried horizontally at a depth of 33 mm below the soil surface. The lower side of the probe section was at 77 mm below the soil surface.

The five TDR probes were installed in a rectangular container filled with 9320 g of soil. The stainless steel rods of the probes were placed in the soil facing down. Part of the soil samples were poured in the container before the probes were embedded in the soil container. The remaining soil samples were distributed on top of the TDR probe with soil packer and funnel. Distilled water (3648 cm^3/3.6 L) was added to the soil in the container with a Marriott siphon. Distilled water was used for the experiment to avoid any influence from salinity issues. The soil sample was allowed to equilibrate before the readings were taken on the soil sample. The weight of the probes, amount of water added to the soil, dried sample, and the container were determined before the experiment began. Every 24 hours, the readings were taken by weighing the bin that contains soil samples, the probes. The difference between the two weights gave the amount of water lost within 24 hours. The water lost was subtracted from the initial water content added to the soil, to determine the water left in the soil. The gravimetric water content was determined by dividing the water left in the soil by the dry sample. The volumetric water content was determined by multiplying the values obtained from the bulk density to the gravimetric water content. The volumetric water content values from TDR were further compared with volumetric water content obtained by the gravimetric method.

3.7.2 Experiment 2

The aim of conducting the second experiment was to confirm the effectiveness of the new TDR probes based on the previous results obtained from the first experiment. Fifteen TDR probes were used for this experiment. An aluminium foil tray (0.223 m × 0.098 m, and 0.063 m height) was filled with a mixture of Riverdale silty clay. The TDR probes were embedded horizontally at a depth of 25 mm from the soil surface.

The fifteen TDR probes were installed individually in each aluminium foil tray filled with 560 g of soil. The probe was inserted at the centre of the aluminium foil tray after pouring part of the soil sample. The stainless steel rods of the probes were placed sideways in the soil. The remaining soil sample was poured on the TDR probe using a soil packer and funnel. Having prepared the soil samples, 0.29 L of distilled water was added to the soil with a Marriott's siphon. Distilled water was also used for the experiment to avoid salinity problem. The soil was allowed to equilibrate before the readings were taken on the soil sample on a daily basis. The weight of the probes, amount of water added to the soil, dried sample, and the container were determined before the experiment began. Every 24 hours, the readings were taken by weighing the aluminium foil tray that contained soil samples and the probes. The difference between the two weights gave the amount of water lost within 24 hours. The water lost was subtracted from the initial water content added to the soil, to determine the water left in the soil. The gravimetric water content was determined by dividing the water left in the soil to the dry sample. The volumetric water content was determined by multiplying the values obtained from the bulk density to the gravimetric water content.

3.7.3 Experiment 3

Installation of TDR probe in the Field

Monitoring of soil water content within the soil profile is very important for researchers and farmers. The water content within the soil profile helps to know when to irrigate or drain agricultural land. Soil moisture sensors can be used to determine the soil water content. The multilevel TDR probes were installed at the Point Research Station on the Fort Garry campus of the University of Manitoba to monitor the soil moisture profile. The multilevel TDR probes were installed at 0.2, 0.4, 0.6, 0.8, and 1.0-m from the ground surface. A soil auger (34-mm diameter) was specifically designed to create the access holes below the ground surface for the installation of the multilevel probes. Figure 3.8 shows the soil auger used for the installation of multilevel probe.

Fig. 3.8 A new soil auger designed for creating access holes in the soil.

Three multilevel TDR probes were tested and compared with the gravimetrically determined water content. Soil samples were taken at five depths (0.2, 0.4, 0.6, 0.8, 1.0m) and the gravimetric water content was determined. The soil bulk density was determined using soil samples taken in the same field at five different depths. The bulk density was obtained by determining the ratio of mass of the soil to the volume of the cylindrical auger used to take the soil samples at each depth. The gravimetric water content obtained from five different depths was multiplied by the bulk density to determine the volumetric water content at each depth. The volumetric water content obtained from the multilevel TDR probes were compared with the volumetric water content calculated from gravimetric measurements.

3.8 Measurements of soil water content in the laboratory

The soil water content was measured in the laboratory using the TDR probes. The aim was to determine the extent to which the TDR measured water content values agrees with the gravimetrically determined values as the soil water content decreased. The TDR probes were connected to the Tektronix 1502B cable tester (Tektronix Inc. Beaverton, OR), via BNC connectors. The volumetric water content was calculated using the empirical calibration equation of Topp et al. (1980) with the TDR-measured dielectric constant of the medium. The recorded TDR waveform and analysis was done using the WinTDR software. Three repeated readings were taken and the mean value of the dielectric constant was used for analysis of each column. The weighing method was used to determine the gravimetric water content in the laboratory. During this period, the soil samples were allowed to equilibrate after a known amount of water was added to the soil. The readings of the soil water content were taken after 24 h and continued on a daily basis till the end of the experiment. During this period, the amount of water left in the soil was determined on a daily basis by weighing. In addition, the bulk density of the soil was calculated from the data obtained from the dry weight of the soil and its volume. The volumetric water content of the soil was determined by multiplying the gravimetric water content by soil bulk density. The water content obtained from the TDR probes were further compared to the volumetric water content obtained from the weighing method. (Topp et al., 1980).

3.8.1 Measurements of soil water content using different lengths of coaxial cable.

After the calibration of the TDR probe was done on the multilevel probe, the fifteen coaxial cables of type RG-58, 50 ohm (Belden Electronics Division) and varying lengths (2.2 m, 2.4 m, 2.6 m, 2.8 m, and 3.0 m) in three replicates were used to measure the dielectric constant of soil in the laboratory. The room temperature was measured. Campbell Scientific (2008) stated that an increase in the cable length affects the shape of waveform, and can result in a variation of the water content values calculated.

3.9 Waveform analysis obtained from Win TDR

The WinTDR software was used to analyse the data during the experiment. It is a Windows-based program that can be used to calculate the dielectric constant, soil water content and electrical conductivity of the soil by controlling the Tektronix 15002B/C TDR cable tester. The coaxial cable was connected to the TDR cable tester with a BNC connector on one end and the other end connected to the TDR probe. The auto-analysis option was used in this analysis. Using the auto-analysis option, the data file was created by the Tektronix 1520B. The text file obtained from the cable tester was downloaded and plotted using a Microsoft Excel program. The tangents from the waveform that correspond to the first peak and end reflection were fitted automatically by the WinTDR program. The distance between the first peak and the end reflection point gives the apparent length L_a of the waveguide. However, during the initial calibration, the 0.063 m TDR probe was immersed in pure water at 25°C. The probe constant and probe identifier information was entered into the WinTDR software. The apparent length L_a of the waveguide is the distance between the first peak and the end reflection point (Or et al., 2004). Figure 3.9 shows the waveform created by TDR probe immersed in water prior to calibration.

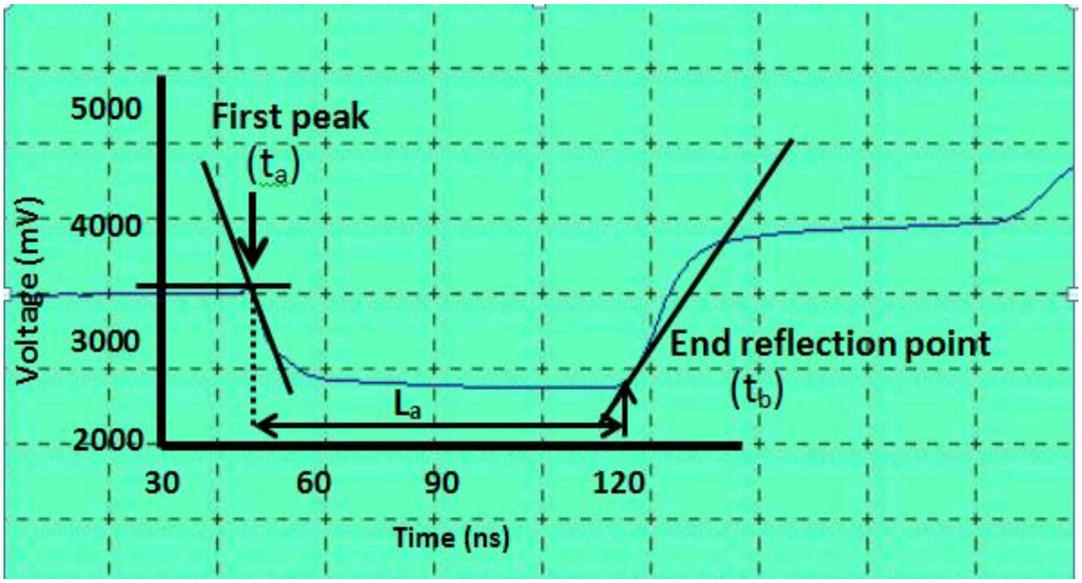

Fig. 3.9 A waveform analysis for a TDR probe immersed in water prior to calibration.

Mojid (2002) stated that a sharp and clear reflection can be seen from the TDR pulse if there is an increase in water content. One of the problems encountered when using WinTDR version 6.1 was that it was difficult to place the cursor at the right place on the waveform when the water content of the soil was extremely low.

4.0 RESULTS

4.1 Evaluation protocol

In evaluating the performance of newly designed equipment both accuracy and precision should be considered. Accuracy of a measurement can be described as how close the measurement of a quantity is to the true value. Precision can be regarded as the extent to which the repeated measurements under similar environmental conditions show the same result. Precision can also be termed as reproducibility. It is possible for a measurement to be accurate but not precise and vice versa. An example is when a measurement has some bias or systematic error, an increase in the sample size will improve the precision but still inaccurate. The success of a new instrument is determined by comparing the results to the true value or data obtained by a standard method. The gravimetric method, also known as the oven-drying method or weighing method, is the standard method for measuring soil water content [ASTM D2216, (2010)]. Ideally, plotting the results obtained by the TDR-θ_v as a function of weighing method-θ_v, after conversion to volumetric water content, should fit the 1:1 line. In this study, statistical analysis such as RMSE, and regression analysis were used to make a comparison between the volumetric water content obtained from multilevel TDR probe and measured volumetric water content.

4.2 Comparison of TDR-Θ_v and weighing method-Θ_v during experiment 1

The volumetric water content data obtained using the TDR mini-probes were compared to the gravimetrically determined water content.

Fig. 4.1 shows the comparison measurement of Θ_v, made by the gravimetric method, denoted by weighing method-Θ_v and TDR technique denoted by TDR-Θ_v for experiment 1. There was good agreement in experiment 1 over a wide range of water contents (0.14 - 0.39 $m^3 m^{-3}$)

obtained using the TDR-ϴ$_v$ and the weighing method ϴ$_v$. The 1:1 line obtained from the first experiment is shown in Fig. 4.1 below:

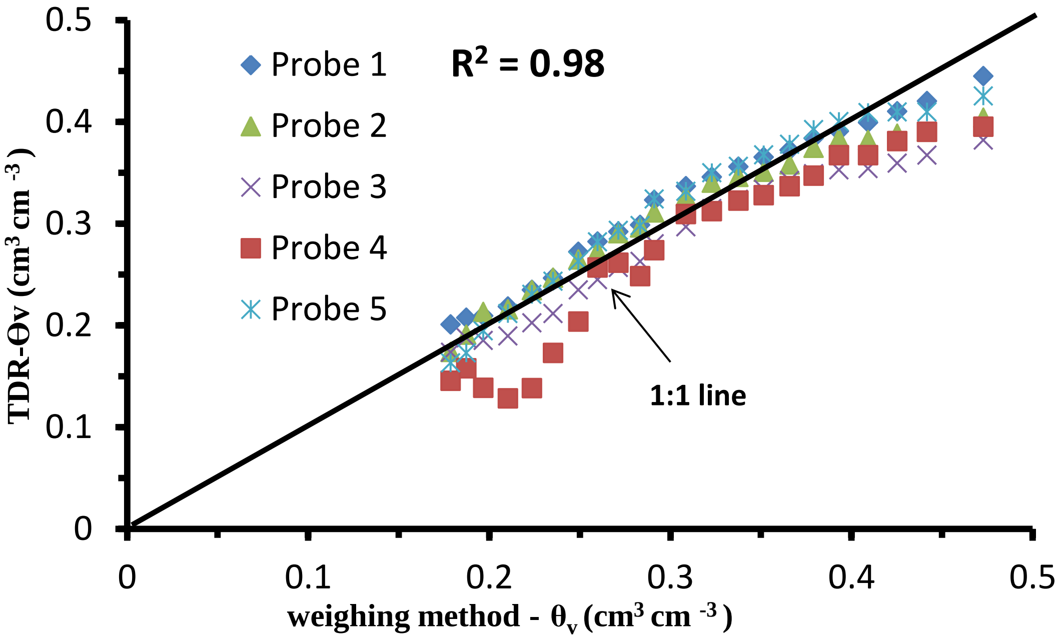

Fig. 4.1 Comparison of TDR- ϴv measured by multilevel TDR probes and weighing method-ϴv during first laboratory experiment.

Fig 4.1 shows good correlation from 44% moisture content to 18% moisture content in probe 1. At moisture contents below 18%, the TDR measurements widely varied due to the presence of air gap arising from soil separation from the probe.

4.3 Comparison of TDR-ϴ$_v$ and weighing method-ϴ$_v$ during experiment 2

In the second laboratory experiment, fifteen TDR probes were tested. Figure 4.2 shows the results obtained from the regression analysis. There was good agreement in experiment 2 for almost all the values obtained by averaging TDR-ϴ$_v$ readings and weighing method-ϴ$_v$. In experiment 2, the TDR probe slightly overestimated the values at lower water content. The observed bias between the weighing method-ϴ$_v$ and TDR technique in experiment could be attributed to higher than average drying near the soil surface.

The TDR probe was unable to read the soil water content properly when the soil became too dry (less than 5%) and separated from the soil. The depletion of soil moisture led to the shrinkage of the soil resulting in an air gap developing between the probe and the soil particles. Small aluminium foil trays (223 mm × 98 mm × 63 mm) were used in the second experiment conducted in our laboratory which helped reduce the cracks. Fig. 4.2 shows the 1:1 line along with the data obtained during the second experiment.

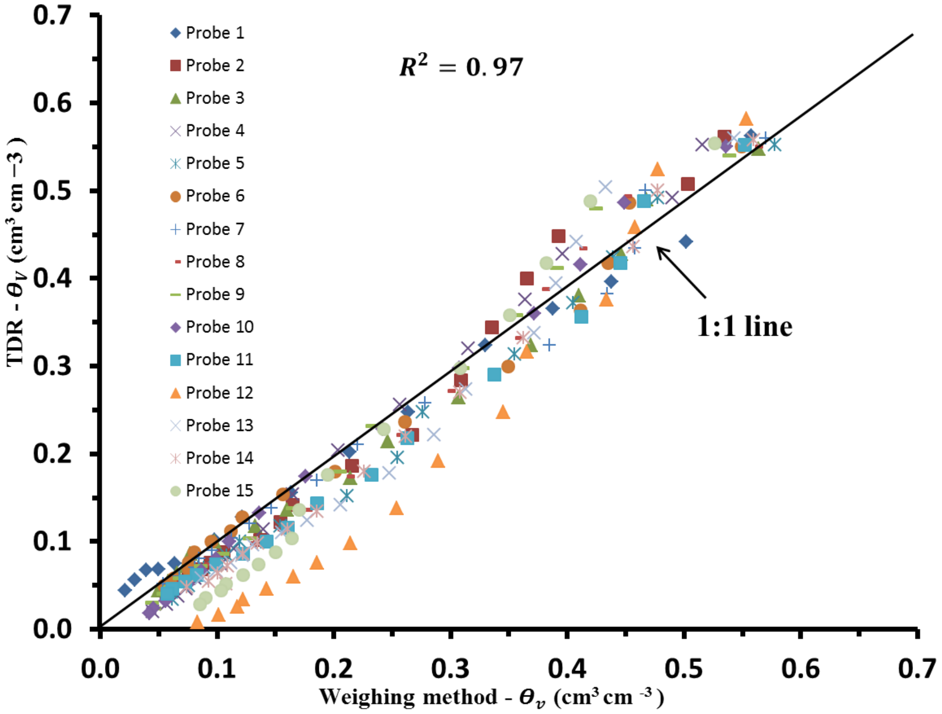

Fig. 4.2 Comparison of TDR- Ɵv estimated by multilevel TDR probes and weighing method-Ɵv during the second laboratory experiment.

Comparing the 1:1 fitted line between the first and the second experiment, it can be seen that the results obtained from experiment 2 are better than experiment 1. One of the reasons is because the problem of air gap was minimized. The smaller aluminium tray helped maintain the probe in good contact with the soil, thereby reducing the problem of air gap.

4.4 Comparison of average water content from TDR-Θ_v and weighing method-Θ_v with time during experiment 2

There was a high correlation in the values obtained in the first four days when the water content declined from 0.55 to 0.40. The improvement in the values obtained during the second experiment could be attributed to the reduction in the air gap problem. The crack was minimized when smaller aluminium foil container was used. Fig. 4.3 shows the average water content obtained from TDR-Θ_v and weighing method-Θ_v over a period of 16 days.

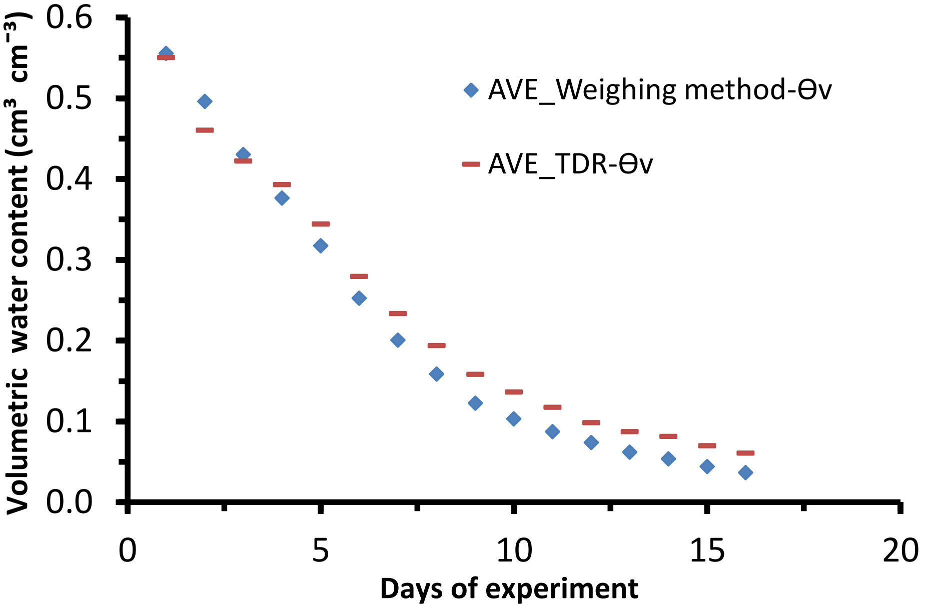

Fig. 4.3 Comparison of average water contents from TDR-Θ_v and weighing method-Θ_v obtained from experiment two.

During this period, the probes had good contact with the soil until the moisture content was below 5%. This result shows the accuracy of the new TDR probe. Therefore, it can be used as an alternative method for measuring soil water content.

4.5 Correlation between TDR- Ɵv and Oven- Ɵv during field experiment

The measurement of Θ_v, made by the gravimetric method, denoted by Oven-Θ_v and TDR technique denoted by TDR-Θ_v for experiment 3 had good correlation except for the values obtained from probe 4. During this experiment, the average readings from TDR probes had a maximum average value of ±0.03 difference throughout the experiment apart from the large variations of ±0.06 difference from probe 4. Soil water content measurements were taken at five different depths with forty-five data points. The results obtained from TDR- Θ_v and Oven- Θ_v gave a coefficient of determination of 0.51. The result obtained from the field experiment is an indication that the multilevel probes can be used in field experiments if field calibration and proper contact is maintained between the soil and the probe. Figure 4.4 shows the correlation between TDR- Θ_v and Oven- Θ_v during field experiment.

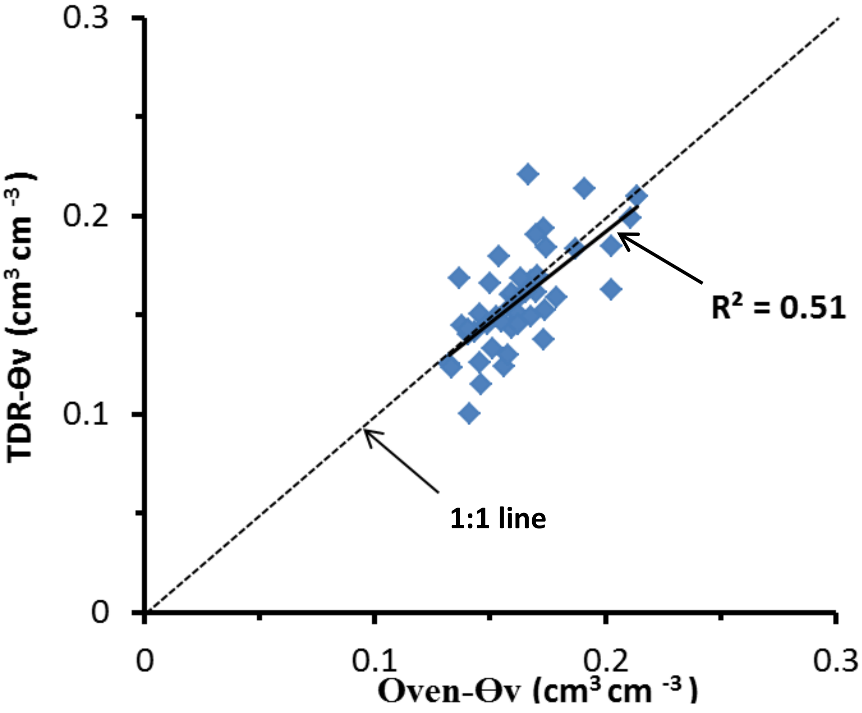

Fig. 4.4 Correlation between TDR- Ɵv and Oven- Ɵv during field experiment

5. 0 ANALYSIS

5.1 Impact of air gap in TDR measurements

It is imperative to know that an air gap between the probe and the soil will affect the performance of the TDR probe. The TDR readings will be under-estimated when there is a gap between the rod and the soil. The underestimation of the measurement occurs because the dielectric constant of air is small (Mojid and Cho, 2002**;** Quinones et al., 2003). Conversely, there will be overestimation of values when the space between the rod and the soil is filled with water (Quinones et al., 2003). The air gap between the probe and the soil is where the electromagnetic waves concentrate (Quinones et al., 2003). One of the problems encountered while using the reusable multilevel TDR probe was air gap. The problem occurred at low soil water content when the soil is more likely to shrink and separate from the probe. Maintaining good contact between the probe and the soil will reduce the air gap problem.

The stainless steel rods of the TDR probe lost contact with the soil when the moisture content was below five percent. When the probe fails depends on soil texture, structure, temperature of soil and the amount of water used for the experiment. The air gap problem can be minimized by using a tapered TDR probe. The cracks encountered in the soil as a result of drying will decrease the accuracy of the TDR probes (Ledieu et al. 1986). The cracks that created air gap are shown in Fig. 5.1 below:

Fig. 5.1 Cracks in the soil creating air gap.

5.2 Change in average measured and actual volumetric water content with time

The correlation between the volumetric water content obtained by the weighing method-ϴv and the TDR-ϴv for a period of 35 days during experiment 1 is presented in Fig 5.2. The soil was thoroughly saturated on day and allowed to equilibrate to reach the field capacity. The average measured water content and the actual volumetric water content were close when the soil reached field capacity. The values of VWC obtained from the trend on day 5 of the experiment were equal. Three sets of data for the dielectric constant of soil (K_a values) were taken for each probe. The aim was to determine the extent to which average SWC obtained from the TDR readings deviated from the actual water content for a period of thirty five days.

Fig. 5.2 shows the comparison of average measured and actual volumetric water content with time.

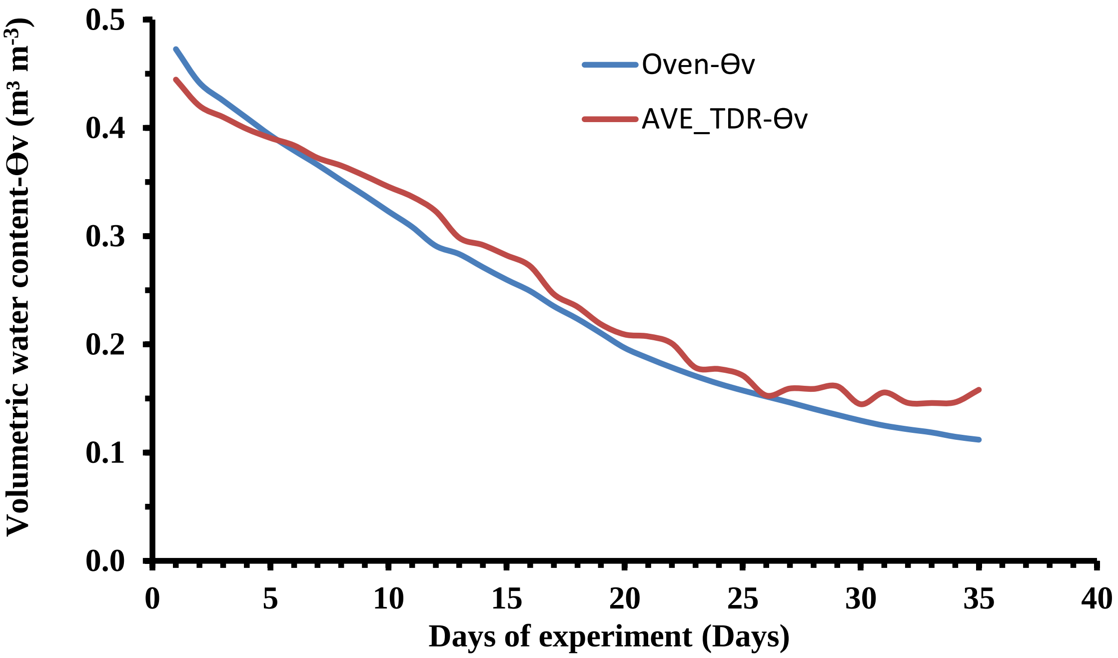

Fig. 5.2 Comparison of average measured and actual volumetric water content with time

The statistical software JMP 8.0.1 (SAS, Institute Corporation, Pacific Grove, California, USA), was used for the Regression analysis. The mean of three measurements were compared to the actual volumetric water content converted from the gravimetric measurements.

At Day 5, the average water content from the reusable TDR probe and the actual value was at par but there was a slight difference in the moisture content as the soil began to crack. There was a variation in the values of average measured and actual volumetric water content as a result of the air gap when the water content was below 5%. During this period, the probe did not have good contact with the soil. The temperature difference is likely to be one of the problems but all temperature readings obtained using the thermocouple thermometer were used to correct the Topp's equation of 1980 using the method suggested by Kahimba and Sri Ranjan (2007).

5.3 Evaluation of the Reusable TDR Probes in the laboratory experiment

The first laboratory experiment started on August 18, 2011 and ended on October 19, 2011. The values obtained from the TDR-Θv and weighing method-Θv from August 19 to 27 and September 12 2011 was almost at par for probe 1. The water content was equal for both measured and actual from August 22 to 24, 2011. The maximum difference between the values of probe 1 from August 18, 2011 to September 20, 2011 was ±0.03. This value corresponds to the maximum allowable difference proposed by Topp et al., (1980).

For probe 2, the maximum difference obtained from the TDR-Θv and weighing method-Θv from August 2, and September 5, 2011 was ±0.02. The TDR-Θv and weighing method-Θ_v values closely followed indicating a high degree of correlation between the two methods of measurement. The difference was less than three percent which is the allowable difference proposed by Topp et al., (1980). However, there was a slight variation in the readings from October 8 to 19, 2011. The variation from September 8, to October 19, 2012 was due to air gap. The overall result from this probe shows that the probe is in good working condition.

For probe 3, the readings obtained from the TDR- Θv and weighing method-Θv on September 7, 2011 was at par. The maximum difference between the values from August 23, 2011 to September 14, 2011 was also less than 3%. This value also corresponds to the maximum allowable difference proposed by Topp et al. (1980). However, there was a slight variation in the readings obtained from September 15, 2011 to October 19, 2011.

For probe 4, the readings obtained from the TDR- Θv and weighing method-Θv from September 10 to 13, 2011 were equal. The maximum difference between the values from August 22, 2011 to September 3, 2011 was also less than 3%. However, there was a slight variation in the readings obtained from September 2 to 6, and later improved to maximum difference of less than 3% from September 7 to 20, 2011. However, large differences > 3% occurred again from September 21, 2011 till the end of the experiment. The difference seen in the latter part of the experiment was a result of air gap. Probe 4 did not perform very well in this experiment and it affected the overall result by 3% as can be seen from the graph.

For probe 5, the readings obtained from the TDR- ϴv and weighing method-ϴv on August 3 to 6, 21, and September 12, 2011 was at par. The maximum difference between the values from August 23, 2011 to September 17, 2011 was also less than 3%. The overall results from these probes showed that they are in good working condition.

The second experiment was also conducted in our laboratory. Fifteen reusable TDR probes were tested during this experiment. There was a good agreement in experiment 2 for almost all the values obtained from average TDR-Θ_v and average weighing method-$\Theta_{v.}$ The maximum difference between the measurement from gravimetric method and average TDR technique throughout the experiment ranged from 0.5% to 3.5%. During this experiment, the average readings from TDR probes had a maximum average value of less than 3% difference throughout the experiment apart from two days with less than 4%.

5.4 Temperature correction of TDR measurements during laboratory conditions

The temperature readings obtained using the thermocouple attached to the reusable TDR probes were used in Equation 5.1 to correct the dielectric constants, (K_{adj}). The measured dielectric permittivity was also substituted into (Eq. 5.1) before the K_{adj} value was fitted in (Eq. 1.5) for determination of volumetric water content of the soil. The volumetric water content obtained from the new reusable TDR mini-probes were compared to the volumetric water content obtained by converting the gravimetric data. Regression analysis was used to compare the results. The soil water content, before performing temperature correction on the dielectric water content, was overestimated by an average of $0.01 m^3 m^{-3}$ above the weighing method-θ_v measured data. This difference did not occur after temperature correction in the laboratory.

$$K_{adj} = K_{field} + 3.572 \times 10^{-1} (T_{soil} - 25) - 8.250 \times 10^{-4} (T_{soil} - 25)^2 + 1.000 \times 10^{-6} (T_{soil} - 25)^3 \quad (5.1)$$

where

T_{soil} = actual field soil temperature at the depth of interest

K_{field} = dilectric permittivity obtained from the field

6.0 CONCLUSION

The results obtained from the new TDR probe showed that TDR technique can serve as a substitute to the standard method (Θ_v via gravimetric method) due to the high correlation. However, TDR technique can only be compared to the standard method if good contact is maintained between the soil and the probe. The analysis of the results showed that:

(1) There was a high correlation in the values obtained from the TDR- Θv and weighing method- Θv but there is a need for calibration to ensure good degree of accuracy.

(2) Compared to the conventional TDR probe which is fully surrounded by the soil, the new probe is only exposed on one side to the soil. Therefore, the calibration of the probe is essential to minimize the errors due to manufacturing variation.

(3) The correlation coefficient of 0.97 and 0.98 obtained from the two laboratory experiments showed that the probes are performing well. The TDR probe can be used continuously both in the laboratory and in the field for measurement of soil water content at different depths.

(4) The thermocouple are incorporated with the probes to help with the temperature correction.

(5) The new reusable multilevel probe can be used under field conditions with TDR multiplexers and data loggers for continuous measurement of soil water content at different depths within the soil profile.

(6) A new soil auger with 34-mm diameter designed for the installation of the PVC pipe ensured good contact between the soil and the probe in the field.

7.0 RECOMMENDATION

The performance of the TDR probes can be improved if some factors are considered. One of the problems encountered during testing was the formation of air gap. The problem of air gap can be solved by maintaining good contact between the soil and the probe. It is evident that the interior part of the PVC pipe serves as a protection for the coaxial cable from being damaged and the stainless steel rods embedded on the waveguide.

1. A thread can be made at the open ends of the interior parts of the probes to enable easy connection between the probes.
2. Each section of the probe should be tested before joining to form a multi-level to ensure all all probes are in good working condition.

REFERENCES

Anisko, T., D.S. Nesmith, and O.M. Lindstrom. 1994. Time-domain reflectometry for Measuring Water Content of Organic Growing Media in Containers. *Hort. Science*. 29 (12): 1511– 1513.

Armstrong, A. C. 1983. The measurement of water table levels in structured clay soils by means of open auger holes. *Earth Surf. Process*. Landforms, 8: 183–187.
doi: 10.1002/esp.3290080210.

ASTM D6565 (2005). "Standard test method for determination of water (moisture) content of soil by the Time Domain Reflectometry (TDR) method." *Annual book of ASTM standards*, Vol. 04.09.

Bacchi, O.O., K. Reichardt, and M. Calvache. 2002. Neutron and gamma probes: Their use in agronomy.2002. *International Atomic Energy Agency course series*. No 16, Vienna. P4.

Bittelli, M., F. Salvatorelli, and P. Pisa. 2008. Correction of TDR-based soil water content measurements in conductive soils. *Geoderma.* (143) 133–142.

Blonquist, J.M. Jr., S.B. Jones and D.A. Robinson. 2005. Standardizing characterization of electromagnetic water content sensors: Part 2. Evaluation of seven sensing systems.
Vadose Zone Journal. 4: 1059-1069.

Campbell Scientific, Inc. 2001. Reducing TDR probe rod length to improve water content measurements in soils with high electrical conductivity. Logan, UT: Campbell Scientific Inc, Application note. (435) 753-2342.

Campbell Scientific Inc. 2008. Instruction manual. TDR probes CS605, CS610, CS630, CS635, CS640, and CS645. Campbell Scientific Canada corp.

Campbell Scientific. Inc. 2012. Measurement and control product for long term monitoring. ISO 9001:2008.

Carter, M.R., and E.G. Gregorich. 2008. Soil Sampling and Method of Analysis. *Canadian Society of soil science*. 2nd ed. P 955.

Carravetta A., Paolis N.D, and Martino R. 2012. Field Scale water content measurement by TDR technique. In Unsaturated soils: Research and Applications. Part 1. 97-105, DOI: 10.000 7/978-3-642-31116-1_13

Chapin, F.S., P.A. Matson, and P.M. Vitousek. 2011. Principles of terrestrial ecosystem ecology. Springer New York Dordrecht Heidelberg, London. 2nd Ed.

Connor, K.M.O., and C. H. Dowding. 1999. *Geomeasurements by Pulsing TDR Cables and Probes*, CRC Press, Boca Raton, Fla. USA.

Cosh, M.H., T.J. Jackson, R. Bindlish, J.S. Famigliettie, and D. Ryu. 2005. Calibration of an impedance probe for estimation of surface soil water content over large regions. *Journal of Hydrology*. 311:49-58.

Cultrone, G., E. Sebastian, and H.M. Ortega. 2007. “Durability of mansory systems: A laboratory study”. *Const. Build. Matter*, 21, 41-51.

Dahan, O., E.V. Mc Donald, and M.H. Young. 2003. Flexible time domain reflectometry probe for deep vadose zone monitoring. *Vadose Zone Journal*. (2) 2: 270-275.

Dalton, F.N., and M.Th. Van Genuchten. 1986. The time-domain reflectometry methods for measuring soil water content and salinity. *Geoderma,* 38: 237- 250.

Evett, S.R., T.A Howell, J.L Steiner, and J.L Cresap. 1993. Evaporation by soil water balance using TDR and neutron scattering. 914-923. In R.G. Allen and C.M.U. Neale (eds) *Management of Irrigation and drainage Systems*, Integrated perspectives. Amer. Soc. Civ. Engr.

New York, NY. Proceedings of the National Conference on Irrigation and Drainage Engineering, park city, UT.

FAO corporate document repository. 1988. Irrigation water management: Irrigation methods. *Natural Resources management and environment department*. (5). S8684.

Fares, A.H. and V. Polyakov. 2006. Advances in crop water management using capacitance water sensors. *Advances in Agronomy*. 90: 43-47.

Ferré, P.A., J.H. Knight, D.L. Rudolph, and R.G. Kachanoski. 1998. The sample areas of conventional and alternative time domain reflectometry probes. *Water Resources Research* 34 (11): 2971–2979.

Flerchinger, G.N., 2000. The Simultaneous Heat and Water (SHAW) Model: User's Manual. Technical Report NWRC; USDA Agricultural Research Service, Boise, Idaho.

Fuhrer. O. and C. Schar. 2000. Inverse heat conduction in soils. A new approach towards recovering soil moisture from temperature records. Diploma thesis submitted to Sonia senevirantne climate research .ETH, Zurich.

Gong, Y., Q. Cao1, and Z. Sun. 2003. The effects of soil bulk density, clay content and temperature on soil water content measurement using time-domain reflectometry. *Hydrol. Process.* 17, 3601–3614.

Grozic, J.L.H., M.E. Lefebvre, P.K. Robertson, and N. R Morgenstern. 2000. Using time domain reflectometry in triaxial testing. *Canadian Geotechnical Journal*. 37(6): 1325-1332.

Hashmi, G.M., R. Papazyan, M. Lehtonen. 2011. Determining wave propagation characteristics of MV XLPE power cable using time domain reflectometry technique. *Turk J Elec. Eng. & Comp. Sci*, Vol. 19 (2): 207-219.

Heimovaara, T.J. 1993. Design of triple wire time domain reflectometry probes in practice and theory. *Soil Sci. Soc. Am*. J. 57: 1410-1417.

Hillel, D. 2004. *Introduction to Environmental Soil Physics*. Amsterdam, Holland: Elsevier Academic Press.

Hiraoka, M., and Y. Onda. 2010. Factors affecting infiltration rate in steep hillslope conifer plantation. The Smithsonian/NASA Astrophysics data system. *American Geophysical Union*. Fall meeting.

Hook, W.R., and N.J. Livingston. 1996. Errors in converting time domain reflectometry measurements of propagation velocity to estimates of soil water content. *Soil Science Society of America Journal,* 59(1): 35-41.

Irvine, J. and J. Grace. 1997. Non-destructive measurement of stem water content by time domain reflectometry using short probes. *Journal of Experimental Botany*, 48 (308): 813-818.

Ju, Z., X. Liu, T. Ren, and C. Hu. 2010. Measuring Soil Water Content with Time Domain Reflectometry: An Improved Calibration Considering Soil Bulk Density. *Soil Science*. 175(10): 469-473.

Kahimba, F.C. 2008. Infiltration and soil moisture redistribution under freeze-thaw conditions. Ph.D. thesis. Winnipeg, Manitoba: University of Manitoba, Department of Biosystems Engineering.

Kahimba, F.C and Sri Ranjan. 2007. Soil temperature correction of field TDR readings obtained under near freezing conditions. *Canadian Biosystems Engineering*.49: 1.19-1.26.

Kahimba, F.C., R. Sri Ranjan, and M. Krishnapillai. 2007. Impact of cable lengths on the accuracy of dielectric constant measurements by time domain reflectometry. *Canadian Biosystems Engineering* 49:1.11-1.18.

Koorevaar, P., G. Menelik, and C. Dirksen. 1999. Elements of Soil Physics; *Developments in soil science 1*3. Fifth Imp. Elsevier science, Amsterdam, The Netherland.

Ledieu, J., P. De Ridder, De Clerck, and S. Dautrebande, 1986. A method of measuring soil moisture by time domain reflectometry**.** *Journal of Hydrology*, 88. 319-328 319.

Liu, C.W., S.W. Cheng, W.S. Yu, and S.K. Chen. 2003. Water infiltration rate in cracked paddy soil. *Geoderma* 117: 169 – 181.

Livingston, R.A., L. Chang, L.S. Evans, and J.I. Trombka. 1988. The application of the neutron probe to the non-destructive examination of Architectural and Archaeological Materials MRS Proceedings. 123: 59 (6 pgs).

Livingston, R.A. 2001. Non-destructive Testing of Historic Structures. *Archives and Museum Informatics* 13: 249–271.

Logsdon, S.D. 2000. Effect of cable length on time domain reflectometry calibration for high surface area soils. *Soil Sci. Soc. Am. J.* 64:54–61.

Logsdon, S.D. 2005. Time Domain reflectometry range of accuracy for high surface area soils vadzone. 4: 1011–1019 10.2136/vzj2004.0108.

Lubelli, B., R.J.P. Van Hees, and C.J.W.P. Groot. (2004). "The role of sea salts in the occurrence of different damage mechanism and decay patterns on brick mansory". *Const. Build. Matter,* 119 -124.

Luigi, M. and R. Greco. 2011. Moisture measurement in masonry materials by time domain reflectometry. *Journal of materials in civil engineering*. 23. 4-441-444.

Lungal, M. and B.C. Si. 2008. Coiled time domain reflectometry matric potential sensor. *Soil Science Society of America Journal*. 72(5): 1422 – 1424.

Lunt, L.A., S.S. Hubbard, and Y. Rubina. 2005. Soil moisture content estimation using ground-penetrating radar reflection data. *Journal of Hydrology*. 307: 254-269.

Mailapalli, D.R., N. S. Raghuwanshi, R. Singh, G. H. Schmitz, and F. Lennartz. 2008. Evaluation of time domain reflectometry (TDR) for estimating furrow infiltration. *Irrigation Science*. 26:161–168.

McIntosh, J., J.J. McDonnell, and N. E. Peters. 1999. Tracer and hydrometric study of preferential flow in large undisturbed soil cores from the Georgia Piedmont, USA. *Hydrol. Process.* 13, 139-155.

Mojid, M.A. 2002. Practical considerations on the use of down-sized time-domain reflectometry (TDR) probe. *Hydrology and Earth System Sciences*, 6(5), *949–955.*

Mojid, M.A. and H. Cho. 2002. Response of the core and shield rods of time-domain reflectometry probe to transverse soil-water content heterogeineity. *Journal of Hydrology*, (262):1--4. 21- 27.

Mojid, M.A., G.C.L. Wyseure, and D.A. Rose. 2003. Electrical conductivity problems associated with time-domain reflectometry (TDR) measurement in geotechnical engineering. *Geotechnical and Geological Engineering* 21: 243–258.

Mortl A., R. Munoz- capena., D. Kaplan, and Y. Li. 2010. Calibration of a combined dielectric probe for soil moisture and pore water salinity measurement in organic and mineral coastal wetland soils. *Geoderma*. 161 .Iss. 1-2. 50-62.

Munoz-Carpena, R. 2004. Field devices for monitoring soil water content. Gainesville: University of Florida. IFAS Bulletin 343.

Muñoz-Carpena, R. and M.D. Dukes.2008. Automatic Irrigation Based on Soil Moisture for Vegetable Crops. ABE 356. *Institute of Food and Agricultural Sciences, University of Florida*. P.1.

Namdar-Kjojasteh, D., M. Shorafa, and M.Omid. 2012. Evaluation of dielectric constant by clay mineral and soil phy-sio chemical properties. *African journal of Agricultural research*. (7):2. 170-176.

Nadler. A, E. Raveh, U. Yermiyahu, and S. R. Green. 2003. Evaluation of TDR Use to Monitor Water Content in Stem of Lemon Trees and Soil and Their Response to Water Stress. *Soil Sci. Soc. Am*. J. 67:437–448.

Nemali, K.S., F. Montesano, S.K. Dove, and M.W. Van Iersel. 2007. Calibration and performance of moisture sensors in soilless substrates: ECH2O and Theta probes. *Scientia Horticulture*. 112: 227-234.

Or, D., B. Fisher, R.A. Hubscher, and J. Wraith. 1998. *WinTDR 98 V4.0: User's guide*. Utah State Univ., Logan, UT.

Or, D. and J.M. Wrath. 1999. Temperature effects on bulk dielectric permittivity measured by time domain reflectometry: A physical model. *Water Resources Research* 35(2): 371-383**.**

Or, D., S.B. Jones, J.R. Vanshaar, S. Humphries, and L. Koberstein. 2004. Win TDR. Soil analysis software. USU soil physics group. Version 6.1.

Parlange, J.Y., J.W. Hopmans, and S.Assouline. 2006. The handbook of Groundwater Engineering, 2nd ed.7-1—7-18.

Precision moisture measurement. IMKO micromodultechnic GMBH. 2012: General requirements to Capacitive-, Microwave and TDR Sensors for precise material moisture meter. www.imko.de . Accessed on November 15, 2012.

Quinones, H., P. Ruelle, and I. Nemeth.2003. Comparison of three Calibration Procedures for TDR Soil Moisture Sensors. *Irrig. and Drain*. 52: 203–217.

Rimon, Y., R. Nativ, and O. Dahan. 2011. Physical and chemical evidence for pore-scale dual flow in the vadose zone. *Vadose zone journal*, 10: 1105-1112.

Robinson, D.A., M. Schaap, S.B. Jones, S.P. Friedman, and C.M.K. Gardner. 2003. Considerations for improving the accuracy of permittivity measurement using TDR: Airwater calibration, effects of cable length. *Soil Science Society of America Journal* 67: 62-70.

SAS. 2009. JMP. 8.0.1. *Statistical discovery.* SAS Institute, Corp.

Scott B. J., M. Jon, Wraith, and O. Dani. 2002. Time domain reflectometry measurement principles and applications. *Hydrological Process*. 16, 141–153.

Serrarens, D., J.L. Macintyre, J.W. Hopmans, and L.H. Bassoi. 2000. Soil moisture calibration of TDR multiprobes. *Scientia Agricola*. (57):2.

Smiths. K.M., T. Sakaki, A. Limsuwat, and T.H Illangasekare. 2009. Determination of thermal conductivity of sand under varying moisture, drainage/wetting, and porosity conditions-applications in near-surface soil moisture distribution analysis. *Hydrology days. 57-65*

Song, Y, J.M Ham, M.B Kirkham, and G.J Kluitenberg. 1998. Measuring Soil Water Content under Turf grass using the Dual-probe Heat-pulse Technique. *J. Amer. Soc. Hor. Sci.* 123(5):937-941.

Sri Ranjan, R. and C.J. Domytrak. 1997. Effective volume measured by TDR miniprobes. Transactions of ASABE 40(4): 1059-1066

Staffrod , J.V.1988.Remote, Non-contact and in-situ Measurement of Soil Moisture Content: a Review *J. Agric. Engng Res*.41, 151-172

Take W.A., D.N. Arnepalli, R.W.I. Brachman, and R.K. Rowe. 2007. Laboratory and Field Calibration of TDR Probes for Water Content Measurement. *GeoEngineering Centre at Queen's-RMC – Queen's University, Kingston, ON, Canada*.

Tarantino, A., A.M. Ridley, and D. G. Toll. 2008. Field Measurement of Suction, Water Content, and Water Permeability .*Geotech Geol Eng* .26:751–782.

Tektronix, Inc.1998. Service manual, 1502B metallic time-domain reflectometer, 070-6267-04. Beaverton, OR: Tektronix, Inc.

Telis, P.A. 2001. Estimation of infiltration rates of saturated soils at selected sites in the Caloosahatchee River Basin, Southwestern Florida. *U.S. Geological Survey*. Open-file report.

Test equipment depot. 2012. Fotronic corporation. 800.517.8431.

Tomer, M.D, B.E. Clothier, I. Vogeler and S. Green. 1999. A dielectric- water content relationship for sandy volcanic soils in New Zealand. *Soil Science Society of America Journal* 63:777-781.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic Determination of Soil Water Content Using TDR: 11. Evaluation of Installation and Configuration of Parallel Transmission Lines. *Soil Science Society of America journal*. 4: 678-684.

Topp, G.C., J.L. Davis, and A.P. Annan. 2003. The Early Development of TDR for Soil Measurements. *Vadose Zone Journal*. 4:492-499.

Topp, G. C. and T. P. Ferré. 2006. Measuring Soil Water Content. *Encyclopedia of Hydrological Sciences.*

Troxler. 2001. Manual of operation and Instruction for model 4300 depth moisture gauge. Research Triangle Park, NC: Troxler Electronics laboratories.

Varble, J.L., and J.L Chavez. 2011. Performance evaluation and calibration of soil water content and potential sensors for agricultural soils in eastern Colorado. *Agricultural Water Management.* (101)1: 93-106

Vaz, C.M.P., J.W. Hopmans, A. Macedo, L. H. Bassoi, and D. Wildenschild. 2002. Soil Water Retention Measurements Using a Combined Tensiometer - Coiled Time Domain Reflectometry Probe. *Soil Sci. Soc. Am. J.* 66:1752–1759.

Warner, T.T. 2004. *Desert Meteorology*. United State of America by Cambridge University press.

Warrick, A.W., D. Zerihun, C. A. Sanchez, and A. Furman. 2005. Infiltration under Variable Ponding Depths of Water. *Journal of Irrigation and Drainage Engineering*, 131 :(4), 358-363.

Weiler, K.W., T.S Steenhuis, J. Boll, and K.J.S Kung. 1998. Comparison of ground penetrating radar and time-domain reflectometry as soil water sensors. *Soil Sci.Soc of Amr. J.* 62(5) 1237-1239.

Williams, J.R., Y. Ouyang, and J.S. Chen. 1998. Estimation of Infiltration rate in vadose zone: Application of selected mathematical models. Vol 2. Dynamic Corp. 68-C4-0031.

Western, A.W. and M. S. Seyfried. 2005. A calibration and temperature correction procedure for the water-content reflectometer. *Hydrological process*. 19, 3785–3793.

ering, 130 (9): 922–934.

Yu, C., W. Warrick and M.H. Conklin. 1999. Derived functions of time domain reflectometry for soil moisture measurements. Water Resources Research. 35(6): 1789-1796.

Yu, X. and V. P. Drnevich, 2004. Soil Water Content and Dry Density by Time Domain Reflectometry. *Journal of Geotechnical and Geoenvironmental Engineering*, 130 (9): 922–934.

Yu, X., B. Zhang, and X.B Yu. 2010. Comparison Study of Three Common Technologies for Freezing-Thawing Measurement. Advances in Civil Engineering, Article ID 239651, 10pgs.

Zegelin, S.J., I. White, and G.F. Russell. 1992. A critique of the time domain reflectometry technique for determining field soil-water content. In: Eds Topp et al. Advances in measurement of soil physical properties: Bringing theory into practice. *Soil Science Society of America Special publication* No. 30: 187-208.

Zupanc, V., G. Adam, and M. Pintar.2005. Comparison of laboratory TDR soil water measurements. *Acta agriculturae Slovenica*, 85 - 2, str.359 – 374

APPENDIXES

Appendix A: Comparison of TDR-Θ_v and Oven-Θ_v during laboratory experiment 1

Days of	Probe 1		Probe 2		Probe 3		Probe 4		Probe 5	
Experiment	Oven-Θ_v	TDR-Θ_v	Oven-Θ_v	TDR-Θ_v	Oven-Θ_v	TDR-Θ_v	Oven-Θ_v	TDR-Θ_v	Oven-Θ_v	TDR-Θ_v
Aug-18	0.47	0.44	0.47	0.4	0.47	0.38	0.47	0.4	0.47	0.43
Aug-19	0.44	0.42	0.44	0.39	0.44	0.37	0.44	0.39	0.44	0.41
Aug-20	0.43	0.41	0.43	0.39	0.43	0.36	0.43	0.38	0.43	0.41
Aug-21	0.41	0.4	0.41	0.38	0.41	0.35	0.41	0.37	0.41	0.41
Aug-22	0.39	0.39	0.39	0.38	0.39	0.35	0.39	0.37	0.39	0.4
Aug-23	0.38	0.38	0.38	0.37	0.38	0.35	0.38	0.35	0.38	0.39
Aug-24	0.37	0.37	0.37	0.36	0.37	0.34	0.37	0.34	0.37	0.38
Aug-25	0.35	0.37	0.35	0.35	0.35	0.33	0.35	0.33	0.35	0.37
Aug-26	0.34	0.36	0.34	0.35	0.34	0.32	0.34	0.32	0.34	0.36
Aug-27	0.32	0.35	0.32	0.34	0.32	0.31	0.32	0.31	0.32	0.35
Aug-28	0.31	0.34	0.31	0.33	0.31	0.3	0.31	0.31	0.31	0.33
Aug-29	0.29	0.32	0.29	0.31	0.29	0.28	0.29	0.27	0.29	0.32
Aug-30	0.28	0.3	0.28	0.3	0.28	0.26	0.28	0.25	0.28	0.3
Aug-31	0.27	0.29	0.27	0.29	0.27	0.26	0.27	0.26	0.27	0.29
Sep-01	0.26	0.28	0.26	0.27	0.26	0.24	0.26	0.26	0.26	0.28
Sep-02	0.25	0.27	0.25	0.26	0.25	0.23	0.25	0.2	0.25	0.26
Sep-03	0.24	0.25	0.24	0.25	0.24	0.21	0.24	0.17	0.24	0.24
Sep-04	0.22	0.23	0.22	0.23	0.22	0.2	0.22	0.14	0.22	0.23
Sep-05	0.21	0.22	0.21	0.22	0.21	0.19	0.21	0.13	0.21	0.21
Sep-06	0.2	0.21	0.2	0.21	0.2	0.19	0.2	0.14	0.2	0.19
Sep-07	0.19	0.21	0.19	0.19	0.19	0.19	0.19	0.16	0.19	0.17
Sep-08	0.18	0.2	0.18	0.17	0.18	0.17	0.18	0.15	0.18	0.16
Sep-09	0.17	0.18	0.17	0.17	0.17	0.18	0.17	0.15	0.17	0.16
Sep-10	0.16	0.18	0.16	0.18	0.16	0.18	0.16	0.16	0.16	0.17
Sep-11	0.16	0.17	0.16	0.18	0.16	0.18	0.16	0.16	0.16	0.17
Sep-12	0.15	0.15	0.15	0.16	0.15	0.17	0.15	0.15	0.15	0.15
Sep-13	0.15	0.16	0.15	0.17	0.15	0.17	0.15	0.15	0.15	0.16
Sep-14	0.14	0.16	0.14	0.17	0.14	0.17	0.14	0.15	0.14	0.16
Sep-15	0.14	0.16	0.14	0.18	0.14	0.18	0.14	0.16	0.14	0.16
Sep-16	0.13	0.14	0.13	0.16	0.13	0.16	0.13	0.15	0.13	0.15
Sep-17	0.13	0.16	0.13	0.16	0.13	0.17	0.13	0.15	0.13	0.16
Sep-18	0.12	0.15	0.12	0.16	0.12	0.17	0.12	0.14	0.12	0.16
Sep-19	0.12	0.15	0.12	0.16	0.12	0.17	0.12	0.15	0.12	0.15
Sep-20	0.11	0.15	0.11	0.16	0.11	0.16	0.11	0.14	0.11	0.15
Sep-21	0.11	0.16	0.11	0.17	0.11	0.17	0.11	0.15	0.11	0.16
Sep-22	0.11	0.17	0.11	0.18	0.11	0.18	0.11	0.16	0.11	0.17
Sep-23	0.1	0.15	0.1	0.17	0.1	0.17	0.1	0.15	0.1	0.16
Sep-24	0.1	0.15	0.1	0.17	0.1	0.18	0.1	0.15	0.1	0.16
Sep-25	0.1	0.15	0.1	0.17	0.1	0.17	0.1	0.15	0.1	0.16
Sep-26	0.09	0.15	0.09	0.16	0.09	0.16	0.09	0.14	0.09	0.16
Sep-27	0.09	0.15	0.09	0.17	0.09	0.17	0.09	0.15	0.09	0.16
Sep-28	0.09	0.15	0.09	0.16	0.09	0.18	0.09	0.15	0.09	0.16
Sep-29	0.09	0.16	0.09	0.17	0.09	0.17	0.09	0.16	0.09	0.16

Appendix A (Continuation)

Days of	Probe 1		Probe 2		Probe 3		Probe 4		Probe 5	
Experiment	Oven-Θ_v	TDR-Θ_v	Oven-Θ_v	TDR-Θ_v	Oven-Θ_v	TDR-Θ_v	Oven-Θ_v	TDR-Θ_v	Oven-Θ_v	TDR-Θ_v
Sep-30	0.08	0.15	0.08	0.16	0.08	0.17	0.08	0.15	0.08	0.16
Oct-01	0.08	0.15	0.08	0.16	0.08	0.17	0.08	0.15	0.08	0.16
Oct-02	0.08	0.15	0.08	0.16	0.08	0.17	0.08	0.15	0.08	0.16
Oct-03	0.08	0.15	0.08	0.16	0.08	0.18	0.08	0.15	0.08	0.16
Oct-04	0.07	0.16	0.07	0.17	0.07	0.18	0.07	0.16	0.07	0.16
Oct-05	0.07	0.15	0.07	0.17	0.07	0.18	0.07	0.15	0.07	0.16
Oct-06	0.07	0.16	0.07	0.17	0.07	0.18	0.07	0.16	0.07	0.16
Oct-07	0.07	0.15	0.07	0.16	0.07	0.17	0.07	0.15	0.07	0.16
Oct-08	0.07	0.15	0.07	0.17	0.07	0.18	0.07	0.15	0.07	0.16
Oct-09	0.06	0.15	0.06	0.17	0.06	0.17	0.06	0.15	0.06	0.16
Oct-10	0.06	0.15	0.06	0.16	0.06	0.17	0.06	0.15	0.06	0.15
Oct-11	0.06	0.15	0.06	0.16	0.06	0.17	0.06	0.15	0.06	0.15
Oct-12	0.06	0.15	0.06	0.16	0.06	0.17	0.06	0.15	0.06	0.16
Oct-13	0.06	0.15	0.06	0.17	0.06	0.18	0.06	0.15	0.06	0.16
Oct-14	0.05	0.15	0.05	0.17	0.05	0.18	0.05	0.16	0.05	0.16
Oct-15	0.05	0.14	0.05	0.16	0.05	0.17	0.05	0.14	0.05	0.15
Oct-16	0.05	0.15	0.05	0.16	0.05	0.17	0.05	0.15	0.05	0.16
Oct-17	0.05	0.14	0.05	0.16	0.05	0.17	0.05	0.16	0.05	0.15
Oct-18	0.05	0.14	0.05	0.16	0.05	0.16	0.05	0.14	0.05	0.15
Oct-19	0.04	0.15	0.04	0.16	0.04	0.17	0.04	0.15	0.04	0.15

Appendix B: Comparison of average TDR-Θ_v and Oven-Θ_v during experiment 2.

Date of experiment	Probes	AVE_ Oven - ϴv	AVE_ TDR - ϴv
Jan-10	1	0.5552	0.55
Jan-11	2	0.4956	0.46
Jan-12	3	0.4301	0.4221
Jan-13	4	0.376	0.3928
Jan-14	5	0.3172	0.3439
Jan-15	6	0.252	0.279
Jan-16	7	0.2001	0.2333
Jan-17	8	0.1581	0.1937
Jan-18	9	0.1221	0.1578
Jan-19	10	0.1029	0.1361
Jan-20	11	0.0872	0.1173
Jan-21	12	0.0736	0.983
Jan-22	13	0.0619	0.087
Jan-23	14	0.0533	0.0812
Jan-24	15	0.0439	0.0697
Jan-25	16	0.0363	0.0604