The Canadian society for engineering in agricultural, food, and biological systems

CSAE SCGR

La société canadienne de génie agroalimentaire et biologique

Paper No. 05-048

INFLUENCE OF CABLE LENGTHS AND PROBE LENGTHS ON THE ACCURACY OF PERMITTIVITY MEASUREMENTS BY TIME DOMAIN REFLECTOMETRY

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Written for presentation at the

CSAE/SCGR 2005 Meeting

Winnipeg, Manitoba

June 26 - 29, 2005

Abstract

Influences of varying extension cable lengths and probe lengths on the response of time domain reflectometry waveguide for water content measurements were investigated using laboratory experiments. Measurements were made using ten coaxial cables (RG58–50Ω) with extension lengths 2.5, 5.0, 9.5, 12.9, 17.4, 19.9, 30.0, 40.0, 42.5, and 50.4 m. The cable lengths experiment was conducted using TDR probes with 1.6 mm diameter and 35 mm long stainless steel rods (3-wire configuration), connected to the cables using Bayonet Nelson connectors at a constant temperature of 17^{o}C. For the case of probe lengths, eight probes were used with lengths ranging from 34 to 120 mm. A 2.5 m coaxial cable was used for measuring the dielectric constant of water using these probes. The resulting waveforms were plotted and compared. Physical probe lengths for various probes were also compared against their corresponding electrical lengths at the same temperature. Results indicated that using extension cables, sensitivity of measurements decreased with the increase in cable length. The reflection depth of the waveforms also decreased with increase in cable length. Considering probe lengths, the difference between physical and electrical length decreased with increase in probe length. Shorter probes were less accurate compared to longer probes. Regression equations were derived that relate physical and electrical cable lengths. The derived equations could be used to determine the electrical lengths for a given physical length for moisture contents and electrical conductivity measurements with TDR. If extension cables are to be used, optimum length should be selected that will generate waveforms that can be interpreted easily. The probes should also be calibrated along with the selected extension cables.

Keywords: TDR, waveform, probe length, extension cables, electrical length.

INTRODUCTION

Time Domain Reflectometry (TDR) is widely being used as a method for measuring soil moisture content and electrical conductivity. The ability to non-destructively measure both water content (WC) and electrical conductivity (EC) simultaneously makes it a very important method for measuring water content and nutrient movement in porous media (Robinson et al. 2003a; Vanclooster et al. 1998). The accuracy of measurement with TDR instruments depend on a number of factors such as proper construction of the TDR probes, method of calibration, temperature, cable lengths, and probe lengths (Logsdon 2000; Robinson et al. 2003b).

Extension cables

When measuring soil water content using coaxial cables, ideally shorter lengths (e.g. 2.5 m), have been used for connecting individual probes to the TDR. In this experimental setup, the cable tester is moved from one probe to another until readings from all the cables have been recorded. However, the narrow temperature range in which the TDR instrument can be operated makes it impossible to use in the winter time when the temperatures remain below zero for several days. Therefore, TDR is expected to be housed in a warm cubicle with an extension cable connecting it to the different probes in the field. Other researchers have also used extension cables to automate the TDR measurement with multiple probes (Reece 1998; Logsdon 2000). However, to minimize the errors in calculating the travel time of the electromagnetic waves within the probe, they used equally long cables to connect to the different probes. Studies have also been made to simplify further the measurement of several sets of TDR probes by taking simultaneous measurements using automated multiplexers and the extension cables (Heimovaara 1993; Herkelrath and Delin 1999; Serrarens et al. 2000). The use of extension cables however affects the accuracy of TDR measurements depending on the type and size of the cable used, length extended, temperature, and type and size of the probes used (Deutsch et al. 1994). The change in extension cable length makes it difficult to obtain an accurate measure of the apparent dielectric constant of the material being tested.

Various studies have been conducted on the effects of extension cables. Pierce (1994) used a 22.2 mm diameter coaxial cable and found that when the cable length is increased from 94 to 268 m, the reflection amplitude is reduced by 500%. Brendan (2003) investigated the RG-58 and RG-8 extension cables for multiple measurements and found that an extension cable filters high frequency electromagnetic waves causing a loss of resolution in the reflected wave. The decrease in the returning EM wave-energy causes a decline in the slope used for the automatic end-point determination. Brendan recommends a maximum extension of 30 m for RG-58 cables. Brendan (2003) also noted that the cables with heavier shield have lower signal loss; hence they can be used for extensions up to 60 m.

TDR probes

TDR probes are used as waveguides for measuring water content and solute concentrations in the soil. Several companies manufacture ready-made industrial probes of various sizes depending on user requirements (Campbell Scientific, Inc. 2001). The probes can also be fabricated locally using materials such as stainless steel rods, Bayonet Nelson Connectors (BNC) and plastic insulators. The probes can be made using two-wire or three-wire configurations. Considering the 3-wire configuration, it is recommended that the critical wire spacing should be greater than three times the diameter of the central rods to avoid the “skin effect” (Zengelin et al. 1992). It is also suggested that when performing laboratory calibration of the probes, no part of the probe should be within 40 mm of the container used for calibration (Campbell Scientific, Inc. 2001).

In measuring the dielectric constant of water, the physical length of the probe (the beginning and the end of the steel rods), is related to its apparent length (the length between the beginning and the end points of the waveform (Lopez 2002). The length of TDR probes influence the accuracy of TDR measurements. Mojid (2002) compared measurement accuracy of nine probes from 20 to 100 mm. He found that the accuracy of measurement decreased with decreasing probe lengths. Specifically, probes < 25 mm were found to be inaccurate, and the measured pulse travel time for these probes had greater variation compared to the predicted pulse travel time. The sharpness of the pulse reflection increased with increase in probe length and moisture contents.

In this study, laboratory experiments were conducted to determine the influence of probe lengths and cable lengths on the accuracy of TDR measurements. The experiments were performed using extension cables ranging from 2.5 to 50.4 m and probe lengths from 34 to 120 mm. The objectives were to determine the effect of cable lengths on accuracy of TDR measurements; effect of probe rod lengths on water content and electrical conductivity measurements; and to relate the physical cable length and electrical length sensed by the TDR (distance to cursor) and generate equations for determining electrical lengths for any given physical cable length.

MATERIALS AND METHODS

Measurement using different cable lengths at the same temperature

Measurements were made using ten coaxial cables (RG58– 50Ω) of different extension lengths 2.50, 5.00, 9.55, 12.85, 17.40, 19.90, 30.00, 40.00, 42.50, and 50.35 m. The experiment was performed at a constant temperature of 17^{o}C using a TDR probe made of stainless steel rods with diameter 1.6 mm and length of 35 mm (3-wire configuration). The measurements were done by inserting the probe in a water column 250 mm deep and 280 mm in diameter. The waveform captured by a *Tektronix 1502B* metallic cable tester for each cable was recorded. The captured waveforms were plotted on the same scale and compared. Electrical length of the cable was determined by inserting the probe into water of known dielectric constant at the same temperature. The physical and electrical lengths obtained are tabulated as shown in Table 1.

Table 1. Comparison of physical and electrical lengths for WC and EC measurements

Cable No.	Physical cable length (mm)	Electrical length WC (mm)	Electrical length EC (mm)
1	2500	3000	2750
2	5000	6220	5790
3	9550	11750	10650
4	12850	15960	14450
5	17400	21520	19430
6	19900	24700	22300
7	30000	37550	33850
8	40000	49700	44800
9	42500	52900	47680
10	50350	62700	56500

Table 1 shows the physical and the corresponding electrical cable lengths for both WC and EC measurement.

Using statistical analysis, the correlations between physical and electrical lengths were established and equations were created, which determine the required electrical lengths for a given physical cable length for both WC and EC measurement.

Measurement using different probe lengths

The dielectric constant of water was measured using eight probes of different lengths at a constant temperature of 17°C. Probe lengths used were 34.34, 40.16, 42.78, 50.98, 60.50, 81.11, 100.12, and 120.04 mm. The physical lengths were measured using a two-digit digital Vernier caliper. A 2.5 m coaxial cable was used for taking the measurements. Waveform produced for each probe length was plotted on the same graph and changes in waveform with increasing probe length were examined. The physical probe lengths for different probes were also compared against their corresponding electrical lengths. For each specific physical length of the probe, iterations were made by adjusting the electrical length in the program until a measured dielectric constant was obtained (k-value ≈81.478 at 17°C) as shown in Table 2. To account for the effect of probe length on accuracy of measurements, the values measured using shorter probes were compared against values measured using longer probes.

Table 2: Measurement of K-values using different probe lengths at constant temperature

Probe Id	Physical Length (mm)	Electrical length (mm)	Length Difference (mm)	Percentage difference (%)	K-Value	Water content θ(m^3/m^3)	Deviation from θ aver.
1	34.34	35.25	0.91	2.65	81.442	1.000	-0.001
2	40.16	40.92	0.76	1.89	81.405	0.999	-0.002
3	42.78	43.52	0.74	1.74	81.523	1.002	0.001
4	50.98	51.69	0.71	1.39	81.520	1.002	0.001
5	60.50	61.21	0.71	1.17	81.444	1.000	-0.001
6	81.11	81.83	0.72	0.88	81.529	1.002	0.001
7	100.12	100.80	0.68	0.68	56.500	0.617	-
8	120.04	120.64	0.60	0.50	3.603	0.045	-
Average of the 1st six probes					81.477	1.001	

RESULTS AND DISCUSSION

Measurements using different cable lengths at constant temperature

Differences in shapes of the waveform for different cable lengths are shown in figure 1. Results indicated that the apex at the start point of the waveform was approximately the same for the cable lengths from 3.0 m to 17.4 m. As the cable length increased, the reflection point at the apex disappeared making it difficult for detecting the actual point where the wave left the probe base. Similarly, the end reflection point became continuously wider with increase in cable length, and finally it disappeared completely. The reflection depth of the waveforms decreased with increase in cable length and it disappeared from 40 m beyond. Similar results were also obtained by Logsdon (2000), Brendan (2003), and Robinson et al. (2003).

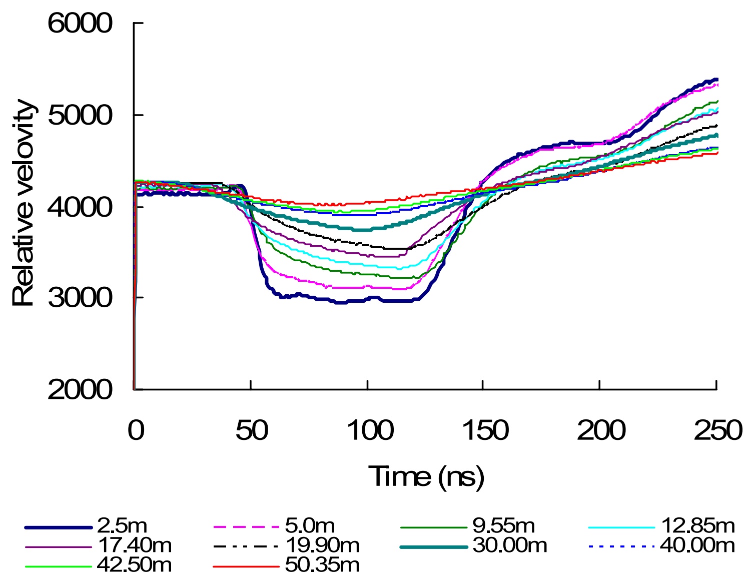

Fig. 1. TDR waveforms for different cable lengths at the same temperature

Figure 1 shows the variation in TDR waveforms with increase in cable length. Since the distorted shape of the waveform could not be accurately interpreted, use of very long extension cables gave erroneous results. The optimum extension length to be used with 35 mm probes was found to be 30 m.

Comparison of physical and electrical cable lengths for WC and EC measurements

Regression equations for determining the electrical lengths for WC and EC measurement from given physical cable lengths are shown in figures 2a and 2b below.

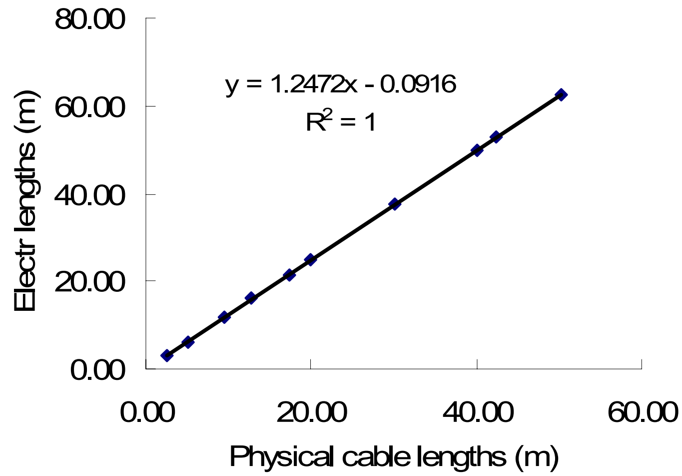

Fig. 2a. Comparison of physical and electrical lengths for WC measurements

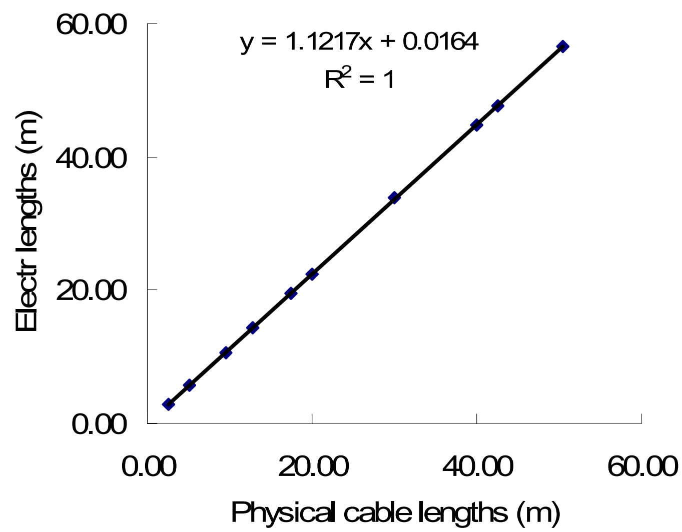

Fig. 2b: Comparison of physical and electrical lengths for EC measurements

From figures 2a and 2b, the electrical length for water content measurements could be obtained for any given physical length using the following equations (R^2 = 0.999):

$$y_1 = 1.2472x - 0.0916 \tag{1}$$

$$y_2 = 1.1217x - 0.0164 \tag{2}$$

Where: y_1 = Electrical length for WC (mm)

y_2 = Electrical length for EC (mm)

x = Physical cable length (mm)

Measurement using different probe lengths

Changes in shapes of the waveforms with increase in probe length are shown in Fig 3 below.

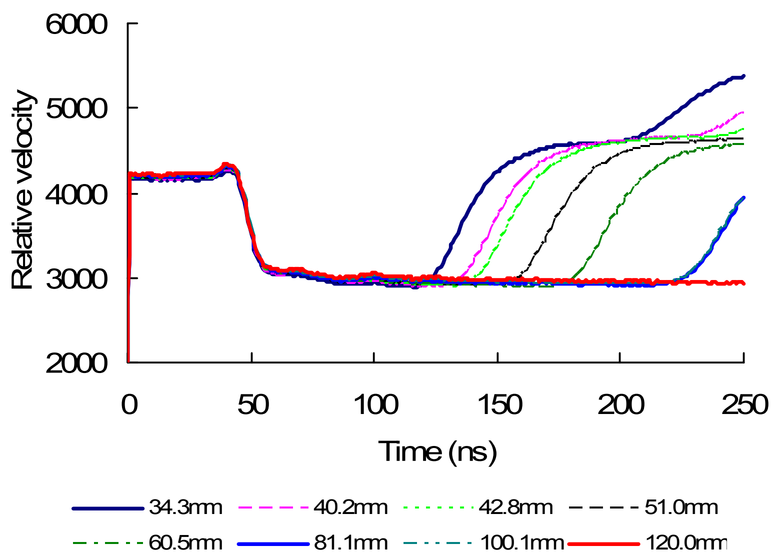

Fig. 3. Variation of TDR waveform with probe lengths

From Fig 3, the depth of waveform (relative velocity) remained approximately constant with increase in length of probes. The apex at the start point of the waveform also did not change with increase in probe lengths. This suggested that the time at which the wave left the base of probe and entered the fluid medium was not affected by the change in probe length. However, the end reflection point increased with increase in probe length and the waveform became wider with increasing probe length, since the generated waves traveled a longer distance on longer probes. The end reflection point for probe lengths 100 mm and above could not be seen on the cable tester screen. This implied that for a given diameter and separation of the probe rods, there was optimum length of the probe, which could give a detectable shape of waveform.

Considering the difference between physical and electrical probe lengths (Table 2), the physical length was shorter than the electrical length. The percentage difference between physical length and electrical length decreased with increase in probe lengths from 2.65% for 34 mm probes to 0.5% for 120 mm probes. In a study performed by Robinson et al. (2003), and Campbell (2004) physical probe lengths were compared with electrical lengths and similar results were obtained. Regarding the accuracy in measuring water content, values obtained using shorter probes were less accurate compared to values obtained using longer probes up to probe length of 80 mm. Beyond 80 mm, the measurements did not give meaningful results indicating that there was a limit of probe length for each specific probe diameter and rod separation. The discrepancy with these longer probes as discussed earlier was because the end reflection point of the waveform could not be detected within the range. The same results were also obtained by Mojid (2002). Hence, rods of 1.6 mm diameter and 6 mm rod separation produced a waveform with detectable start point apex and end reflection points with probes up to a length of about 80 mm.

CONCLUSIONS

Laboratory experiments were conducted to determine the influence of cable lengths on the response of waveguides in TDR measurements. Effects of probe lengths on accuracy of the measurements were also demonstrated. Extension cables used for the experiments (RG58– 50Ω coaxial cable) ranged from 2.50 to 50.35 m. The TDR probes were varied from 34 mm to 120 mm.

Use of longer extension cables affected the accuracy of TDR measurement. As the extension cables became longer, the reflection point at the apex disappeared making it difficult for detecting the actual point where the wave left the probe base. The end reflection point also became continuously wider and undetectable. The reflection depth of the waveforms decreased with increase in cable length and it disappeared for cable lengths beyond 30 m. This suggest that if extension cables are to be used, optimum cable length has to be determined which provides the shape of waveform that can be interpreted easily by producing detectable peak at the starting point where the wave enters the metal rod, and sharp dip signifying the end of the probe. Probes should also be calibrated along with the selected extension cables. The optimum cable length for the 35 mm probes used was found to be 30 m.

Physical cable lengths were compared with their corresponding electrical lengths. Equations were derived, which could be used to determine the corresponding electrical lengths for each given physical cable length for water content and electrical conductivity measurements.

Considering variation in probe lengths, the apex at the start point of the waveform did not shift with increase in probe lengths. The end reflection point however increased with increase in probe length and the waveform became wider. Shorter probes were less accurate compared to longer probes up to 80 mm. The difference between the probes' physical lengths and electrical lengths decreased with increase in probe lengths. For each specific rod diameter and separation, there was a maximum length of probe that can give accurate results. In this experiment, TDR probes with 1.6 mm diameter and 6 mm rod separations produced a waveform with detectable start point apex and end reflection points for water content measurements with probe lengths up to 80 mm long. Further studies are needed to establish the relationship between probe rod diameter, separations and the corresponding optimum rod lengths. Further studies are also proposed to determine the optimum extension cable lengths to be used, which give a detectable waveform for given sizes of coaxial cables and probe dimensions.

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