

---

# The effects of soil bulk density, clay content and temperature on soil water content measurement using time-domain reflectometry

Yuanshi Gong,<sup>1</sup> Qiaohong Cao<sup>1</sup> and Zongjia Sun<sup>2\*</sup>

<sup>1</sup> *Department of Soil and Water Sciences, China Agricultural University, #2 Yuan-Ming-Yuan Xi Road, Beijing 100094, People's Republic of China*

<sup>2</sup> *ESI Environmental Sensors Inc., 100-4243 Glanford Avenue, Victoria, BC V8Z 4B9, Canada*

---

## Abstract:

Time-domain reflectometry (TDR) is increasingly used for field soil water estimation because the measurement is non-destructive and less affected by soil texture, bulk density and temperature. However, with the increase in instrument resolution, the influences of soil bulk density and temperature on TDR soil moisture measurements have been reported. The influence is primarily caused by changes in soil and water dielectric permittivity when soil compaction and temperature varies. The objective of this study is to quantify the influence of soil bulk density and temperature, and to provide the corresponding correction methods. Data collected from sand, sandy loam, loam and clay loam show a linear relationship between the square root of dielectric constant of dry soil and bulk density, and a bulk density correction formula has been developed. The dielectric permittivity of soil solids estimated using this formula is close to that of oxides of aluminium, silicon, magnesium and calcium. Data collection from sandy loam show a noticeable decrease in measured soil moisture with increase in temperature when the volumetric soil water content is above  $0.30 \text{ m}^3 \text{ m}^{-3}$ . A temperature-correction equation has been developed, which could provide the corrected soil moisture based on soil temperature and TDR-measured moisture. The effect of clay content has been detected, but it is not statistically significant. High clay contents cause the underestimation of soil water content in the low moisture range and overestimation of soil water content in the high moisture range. Copyright © 2003 John Wiley & Sons, Ltd.

**KEY WORDS** time domain reflectometry (TDR); volumetric water content; dielectric permittivity; time delay or travel time; soil bulk density

## INTRODUCTION

The accuracy of soil water content measurement using time-domain reflectometry (TDR) depends on (1) the accuracy of time delay measurement and (2) the calibration used to convert measured time delay to volumetric soil water content. Many techniques have been developed to improve the accuracy of time delay measurement. For example, the switching diode technique has been employed to obtain an unambiguous time mark in the Moisture•Point TDR soil moisture instrument (Hook *et al.*, 1992). Meanwhile, several calibration equations have been developed to explore the relationship between time delay and volumetric soil water content (Topp *et al.*, 1980; Ledieu *et al.*, 1986; Roth *et al.*, 1990; Herkelrath *et al.*, 1991). Topp *et al.* (1980) developed a well-known 'Universal' empirical calibration equation between apparent dielectric permittivity  $K_a$  and volumetric water content  $\theta_v$ . This universal calibration has been validated by numerous reports for two decades, when it is applied to general soil conditions. However, with the increase of resolution and accuracy of time delay measurement, a discrepancy between Topp *et al.*'s universal calibration and experimental results

---

\* Correspondence to: Zongjia Sun, ESI Environmental Sensors Inc., 100-4243 Glanford Avenue, Victoria, BC V8Z 4B9, Canada.  
E-mail: jason@esica.com

has been reported when the universal relationship of  $K_a$  versus  $\theta$  was applied to soil with high clay content and salinity (Dirksen and Dasberg, 1993; Jacobsen and Schjønning, 1993; Dalton, 1992; Wyseure *et al.*, 1997).

The apparent dielectric constant  $K_a$  of a material is determined by measuring the propagating time (time delay) of an electromagnetic (EM) wave in that material. In practice, an EM wave is sent through the material of interest along a transmission line (probe) buried in it, and the EM wave is reflected back at the end of the transmission line. The round-trip time  $T$  is then measured. According to Maxwell's equation, the velocity  $v$  of an EM wave propagating in a material medium with apparent dielectric permittivity  $K_a$  can be calculated thus:

$$v = \frac{C}{K_a^{0.5}} = \frac{2L}{T} \quad (1)$$

where  $C$  is the velocity of an EM wave in free space and  $L$  is the length of the transmission line. Multiplying by two accounts for a round trip.

Therefore, the apparent dielectric permittivity  $K_a$  is

$$K_a = \left( \frac{CT}{2L} \right)^2 \quad (2)$$

The time delay of an EM wave in air over the distance of  $2L$  is given by

$$T_a = \frac{2L}{C} \quad (3)$$

Combining Equations (1)–(3) we obtain

$$K_a = \left( \frac{T}{T_a} \right)^2$$

or

$$\sqrt{K_a} = \frac{T}{T_a} \quad (4)$$

The normalized time  $T/T_a$  is linked directly to the dielectric permittivity of the material and it will be referred to as the time delay in the rest of this paper.

As a porous medium, soil consists of materials in three phases: solid soil particles, liquid soil solution and air in soil. The dielectric permittivity of soil, and in turn the measured time delay  $T/T_a$ , is a function of the dielectric permittivity of each of its components and the volume fraction of each component.

The following linear relation between  $\theta_v$  and  $T/T_a$  has been developed by several researchers (Hook and Livingston, 1996):

$$\theta_v = \frac{(T/T_a) - (T_s/T_a)}{K_w^{0.5} - 1} \quad (5)$$

where  $T_s$  is the travel time in dry soil. Similar to Equation (4),  $T_s/T_a$  represents the square root of the dielectric permittivity of dry soil.  $K_w$  is the dielectric permittivity of the soil solution. By replacing  $T/T_a$  and  $T_s/T_a$  with  $K_a$  and  $K_s$  in equation (4) we obtain

$$\theta_v = \frac{K_a^{0.5} - K_s^{0.5}}{K_w^{0.5} - 1} \quad (6)$$

Equation (6) shows a linear relation between  $K_a^{0.5}$  and  $\theta_v$ , with slope of  $1/(K_w^{0.5} - 1)$  and intercept of  $K_s^{0.5}/(K_w^{0.5} - 1)$ .

Ledieu *et al.* (1986) reported that the calibration equation between  $K_a$  and  $\theta_v$  could be improved by considering soil bulk density, although the effects were relatively small.

Dry soil consists of solid particles and air. The dielectric permittivity of solid soil particles is in the range 2–5 and the dielectric constant of air is near unity. The denser the soil, the greater the volume ratio of solid particles to air, and the larger the dielectric permittivity of dry soil  $K_s$ . The intercept of Equation (6),  $K_s^{0.5}/(K_w^{0.5} - 1)$ , increases with increasing soil bulk density.

For soil with high clay contents, the bound water effects can not be ignored. The water phase in soil can be subdivided into a free water phase and a bound water phase. Free water, also called bulk water, is able to rotate freely following an alternating electrical field. Its dielectric permittivity is around 80 at 20 °C, attributed to its high degree of polarization under an external electrical field. In contrast, the bound water phase consists of water molecules that are bound to the soil surface by adhesive, cohesive and osmotic forces (Hilhorst *et al.*, 2001). The rotation of bound water molecules following an applied electrical field is restricted, resulting in less polarization compared with that of free water, and a low dielectric permittivity. Or and Wraith (1999) obtained the dielectric permittivity of bound water of 6, 10 and 14 by harmonic averaging for a bound-water region made up of one, two and three molecular thicknesses, respectively. Sun and Young (2001) obtained a value of 30.2 for the distance-weighted average dielectric permittivity of bound water, which consists of four water-molecule layers from the particle surface (first layer) to free water (fourth layer) in Rideau clay. Obviously, the slope of the calibration Equation (5),  $1/(K_w^{0.5} - 1)$ , will be different for soil containing different amounts of bound water, which is directly related to the clay content. The magnitude of the difference depends on the amount of clay and the clay minerals.

The electrical conductivity (EC) of clay soil imposes a great impact on soil water content measurement using TDR (Topp *et al.*, 1980, 2000; Malicki *et al.*, 1994; White *et al.*, 1994; Sun *et al.*, 2000). The soil EC comes from the electrolytes in soil solution and the electrical charged clay colloid surface. The elevated EC increases the apparent dielectric permittivity (White *et al.*, 1994; Sun *et al.*, 2000; Topp *et al.*, 2000), acting counter to that of bound water in TDR soil water content measurement, and making TDR less sensitive to soil texture.

The dielectric permittivity of free water  $K_w$  is temperature dependent. The change of dielectric permittivity of free water with temperature can be described by the following formula (Weast, 1986):

$$K_{\text{water}} = 78.54[1 - 4.579 \times 10^{-3}(t - 25) + 1.19 \times 10^{-5}(t - 25)^2 - 2.8 \times 10^{-8}(t - 25)^3] \quad (7)$$

where  $t$  is the water temperature in celsius.

When the temperature drops from 20 °C to 5 °C, the  $K_w$  will increase from 80.36 to 86.12, resulting in a change of the slope of Equation (5) from 0.1256 to 0.1208. It is clear that the temperature effects must be taken into account for an accurate soil water content measurement using TDR.

This experiment quantitatively studied the effects of soil bulk density, clay content and temperature on soil water content measurement using TDR, and attempts to provide practical calibrations for an accurate soil water content measurement.

## MATERIALS AND METHOD

The soils used in this study were sand, sandy loam, loam, silt loam and silt clay. Sand was dug from the riverbed of Xiao QingHe, Beijing, China. Sandy loam and loam were taken from the experimental field of China Agricultural University, Beijing, China. Silt clay loam (cinnamon soils) and silt clay (cinnamon soils) was taken from suburban Beijing, China. The soil type and texture are presented in Table I. The soil was air dried and sieved (mesh #10). Soil samples were oven dried at 105 °C for 48 h and cooled to 20 °C in a desiccating chamber for further use. Soil was packed in a PVC cylinder 10 cm in diameter and 40 cm in length. The time delay was measured using a TDR soil moisture instrument (MoisturePoint MP-917, E.S.I. Environmental Sensors Inc., Victoria, BC, Canada). The probe used in this experiment consists of two 30 cm rectangular stainless-steel bars (1.3 cm wide, 0.32 cm thick) separated by 1.5 cm with epoxy between them. Switching diodes were mounted at both ends of the probe to improve the accuracy of time delay measurement.

Table I. Particle size distribution of soils under investigation

Sample no.	Soil type	Sand (%) (2.0–0.05 mm)	Silt (%) (0.05–0.002 mm)	Clay (%) (<0.002 mm)
1	Sand	88.8	4.0	7.2
2	Sandy loam	68.8	21.0	10.2
3	Loam	40.8	38.0	21.2
4	Silt clay loam	20.8	44.2	34.5
5	Silt clay	0.8	50.4	48.8

(Hook *et al.*, 1992). The probe was installed in the centre of the soil column. At each moisture level, 20 data points were collected and averaged.

#### *The determination of $T_s/T_a$*

According to Equation (4),  $T_s/T_a$  represents the travel time of an EM wave in dry soil. Its value depends largely on soil texture and bulk density and has to be predetermined for an accurate calibration (Equation (5)). The values of  $T_s/T_a$  for four soil types, viz. sand, sandy loam, loam and silt clay loam, at three to four different bulk densities were determined in the laboratory. Differences in bulk density were achieved by filling the cylinder with an equal volume but a different mass of oven-dried soil. In order to achieve a uniform bulk density throughout the whole cylinder, the length of the cylinder was pre-marked with 5 cm increments and the total amount of soil to be filled was divided into five portions. The soil was added to the cylinder one portion at a each time and the added soil was compacted with a hammer until its top reached the mark before the next portion was added. The value of  $T_s/T_a$  was calculated using Equation (5) by assuming that the volumetric soil water content for oven-dried soil is zero. The top of the soil column matched the end of active section of the probe. The so-called active section refers to the probe part between the two switching diodes.

#### *Measurement of volumetric soil water content*

Oven-dried sandy loam and loam were packed into the PVC cylinder with bulk densities of  $1.3 \text{ g cm}^{-3}$  and  $1.4 \text{ g cm}^{-3}$ . Water was added to the bottom of the soil columns through two Mariotte bottles until the soil was saturated. The top of the soil column was sealed and 20 volumetric water content data were collected using TDR. Meanwhile, the PVC cylinder was placed on a scale (Precias 3000D, Switzerland; resolution: 0.1 g) and the volumetric water content was measured using a conventional gravimetric method (Figure 1). The soil column was then exposed to air, allowing water evaporating from the soil column surface. When the decrease in water content reached  $0.03 \text{ cm}^3 \text{ cm}^{-3}$ , the top was sealed and a new round of measurements took place. The above procedure was repeated until the soil water content reached below  $0.05 \text{ cm}^3 \text{ cm}^{-3}$ .

#### *Measurement of soil water content at different temperature*

The sandy loam soil was packed into two cylinders to a bulk density of  $1.3 \text{ g cm}^{-3}$ . One was used for soil water content measurement and other was used as a reference for soil temperature measurement. Six thermometers were installed in the reference soil column at depths of 30 cm, 20 cm and 10 cm to monitor the vertical temperature variation. At each depth, two thermometers were installed 3 cm apart to monitor the horizontal temperature variation. The difference in soil temperature was created by using a temperature chamber. Inside the chamber the temperature varied from 5 to 45 °C in increments of 5 °C. At each temperature, the soil column water content was changed from 0.00 to  $0.42 \text{ cm}^3 \text{ cm}^{-3}$  in steps of  $0.06 \text{ cm}^3 \text{ cm}^{-3}$  by adding water to the bottom of the column through the Mariotte bottles as shown in Figure 1. When the desired water content was reached, which was determined by measuring the weight of the soil columns, the top

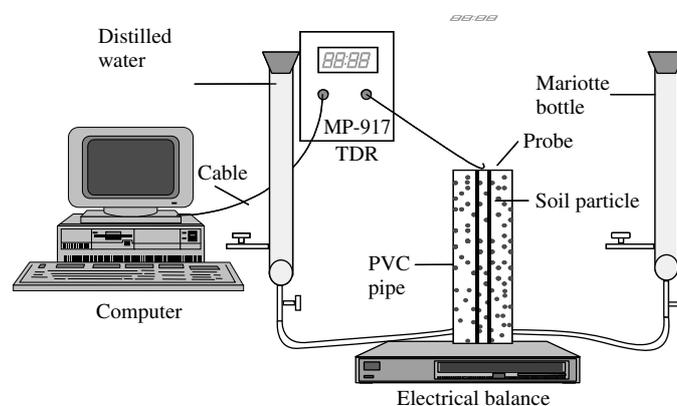


Figure 1. The experimental setup

of the cylinder was sealed to prevent water loss by evaporation. The soil columns were then moved to the temperature chamber. TDR measurement started 6 h later, assuming that the soil temperature had reached equilibrium.

#### *Measurement of water content for soil with different clay contents*

Three soil samples (loam, silt clay loam and silt clay) were packed into a cylinder with a bulk density of  $1.33 \text{ g cm}^{-3}$ . The water content of the soil column was increased from zero to  $0.45 \text{ cm}^3 \text{ cm}^{-3}$  in steps of  $0.03 \text{ cm}^3 \text{ cm}^{-3}$  by adding water from the bottom of the cylinder using a Mariotte bottle. The volumetric water content was measured using TDR and the gravimetric method at each water content level.

## RESULTS AND DISCUSSION

### *The linearity of the relationship between time delay ( $T/T_a$ ) and volumetric water content for the alternative probe*

The probe used in the experiment has an epoxy filling between two rectangular metal bars. It is an alternative probe structure compared with the common two or three metal rod TDR probes. The question has been raised about whether the time delay measured by this epoxy-filled probe is linearly related to that measured by the rod probe. If the relationship is not linear, then the epoxy-filled-probe-measured  $T/T_a$  cannot be simply converted to rod-probe-measured  $T/T_a$  using two calibration coefficients  $A$  and  $B$  (Moisture Point MP-917 Manual), and Equation (5) can not be used for the alternative probe. Studies have shown (Knight *et al.*, 1997) that any probe with its rods completely coated by a material with low permittivity has a relationship that is not linear. However, if the coating is partial, especially when the coating surrounds less than  $30^\circ$  of the rod circumference, then the effect of the coating is not significant. Hook *et al.* (1992) calibrated the epoxy-filled probe on the basis of a linear relationship between the travel time measured by this probe and by a two-rod probe with the same length. The linearity of this epoxy-filled probe has been further evaluated by Ferré *et al.* (2000) by using a numerical analysis presented by Knight *et al.* (1997). They concluded that this epoxy-filled probe has a highly linear response to the soil relative permittivity, which supports the choice of a linear calibration relationship. The testing conducted in this laboratory also shows a highly linear relationship ( $R^2 = 0.987$ ) between measured time delay and volumetric soil water content using this epoxy-filled probe in sandy soils (Sun *et al.*, 2000).

### *Soil layering effect*

The water content in the soil column was not uniform. The soil column was wetter at the bottom, because the water was added from the bottom of the column, and the soil was drier at the top because of evaporation from the surface. Topp *et al.* (1982) measured volumetric water content of layered profiles by TDR. They found that the travel time through different layers of soils is additive. Therefore, the TDR-measured volumetric water content of a layered soil column should be the weighted average of the actual water content of the layers. If the water content of a soil layer changes abruptly, then a reflection may arise at the boundary between the wet layer and dry layers, possibly resulting in an erroneous interpretation of the graphic waveform. In this experiment, the soil water content changes gradually from the top (dry) to bottom (wet), so no additional reflection was found between the start and end of the probe, the positions of which were precisely determined by the switching diodes at both ends of the probe. Nadler *et al.* (1991) measured soil moisture using TDR in two layers (dry/wet, wet/dry) combinations and concluded 'volumetric water contents were found to be accurately determined by the TDR method, regardless of soil layering'. Young *et al.* (1997) conducted an upward infiltration method to calibrate TDR system and concluded that this method provides a fast and repeatable calibration, consistent with conventional calibration.

### *Averaging error due to water-content-dependent sensitivity*

Ferré *et al.* (1996) defined the sensitivity of a TDR probe as the change in measured time delay per unit change of soil water content. If the sensitivity is dependent on soil water content, then the probe-length-weighted averaging soil water content will be incorrect if the water content varies along the probe. Unlike a TDR probe with two or three metal rods without coating, many alternative probes have nonmetallic materials placed in series with the soil, and the average water content measured will be biased towards the water content range of greatest sensitivity (Ferré *et al.*, 2000). However, in the same study, Ferré *et al.* (2000) found that the epoxy-filled probe used in this experiment showed 'very little water content dependence of its sensitivity and should therefore return average water content with little error due to incorrect averaging'.

### *Soil bulk density effects*

The value of  $T_s/T_a$  is a measure of the time delay for an EM wave travelling in a dry medium. It is expected that soils with high bulk density, or low porosity, will have a larger  $T_s/T_a$  value than soils with low bulk density and high porosity. The relationship between soil bulk density and its corresponding  $T_s/T_a$  is shown in Figure 2, which was generated by pooling all soil bulk densities and their corresponding  $T_s/T_a$  values. The linear relationship indicates that: (1) the increase in  $T_s/T_a$  is the result of increased mass of solid particles per unit volume, since solid particles possess a higher dielectric constant than that of air—Jacobsen and Schjonning came to (1993) the same conclusion in their experiment; (2) the difference in dielectric constants of solid particles among sand, silt and clay is small, since all the data fall onto a single linear regression line with a high  $R^2$  value.

Figure 3 compares the measured volumetric soil water contents in sandy loam and loam using TDR and the gravimetric method. The bulk densities for the sandy loam and loam are  $1.3 \text{ g cm}^{-3}$  and  $1.4 \text{ g cm}^{-3}$  respectively, and the corresponding  $T_s/T_a$  values are 1.67 and 1.74 respectively. The  $T_s/T_a$  value for individual soil was pre-input into the MoisturePoint MP-917 TDR soil moisture instrument. The TDR-measured moisture was found to be in agreement with those determined using the oven-dry method for water content range from zero to near saturation ( $0.40 \text{ m}^3 \text{ m}^{-3}$  volumetric water content). This indicates that the  $T_s/T_a$  value pre-installed in the instrument is correct and the relationship between soil bulk density and  $T_s/T_a$  shown in Figure 2 is valid.

According to the calibration equation in Figure 2, the  $T_s/T_a$  value increases  $0.0306$  for each  $0.1 \text{ g cm}^{-3}$  increase in soil bulk density, and this will translate to  $-0.004 \text{ m}^3 \text{ m}^{-3}$  measurement error in soil water content (by applying Equation (5)) if a proper calibration is not conducted. When the  $T_s/T_a$  value used is larger than expected, the measurement error is negative, and the soil water content is underestimated, and *vice versa*.

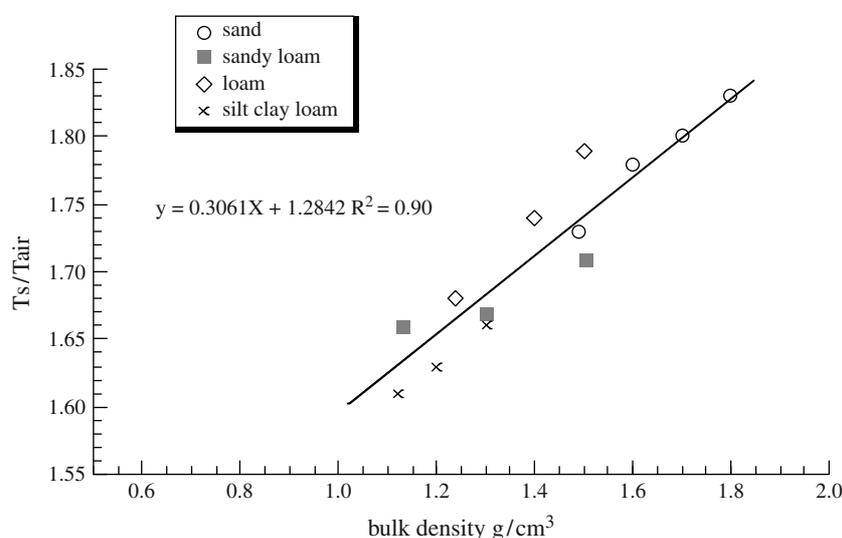


Figure 2. The relationship between soil bulk density and  $T_s/T_a$  value

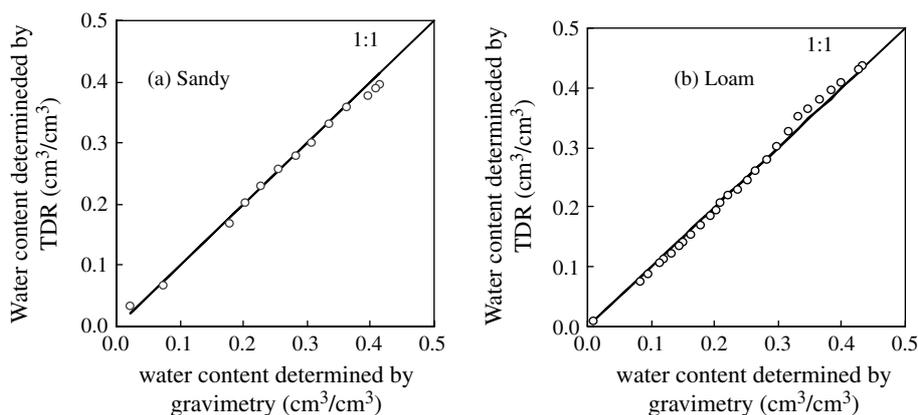


Figure 3. Comparison of soil water contents determined by TDR and gravimetric methods

The  $T_s/T_a$  value should be adjusted if an accurate soil water content measurement is required. For ordinary agricultural soils with bulk density approximately  $1.2 \text{ g cm}^{-3}$ , and according to Figure 2, the  $T_s/T_a$  value should be 1.65. This value is 0.1 higher than that suggested by Hook and Livingston (1996).

Malicki *et al.* (1996) studied the influence of a soil's solid phase on the dielectric permittivity of the soil over a range of water contents. They found the following relationship between the square root of the dielectric permittivity and soil bulk density:

$$\sqrt{K_a}(\theta, \rho) = 0.819 + 0.168\rho + 0.159\rho^2 + (7.17 + 1.18\rho)\theta$$

Table II compares the calculated square root of dielectric permittivity at different bulk density using the Malicki equation and using the calibration from Figure 2 and Equation (5). At  $0.30 \text{ m}^3 \text{ m}^{-3}$  soil water content level, the calculated  $\sqrt{K_a}$  values using these two methods agreed with each other. The increase in  $\sqrt{K_a}$  is 0.561 and 0.583, using the Malicki equation and using the calibration from Figure 2 and Equation (5) respectively, as soil bulk density going up from  $1.0 \text{ g cm}^{-3}$  to  $1.6 \text{ g cm}^{-3}$ . However, there is a substantial difference when

Table II. The square root of dielectric permittivity at different soil water content and bulk density calculated using Malicki's equation, the equation from Figure 2 and Equation (5), and Whalley's mixing model

Soil water content (m <sup>3</sup> m <sup>-3</sup> )	$\sqrt{K_a}$ at different bulk densities					
	Malicki equation		Calibration from Figure 2 and Equation (5)		Whalley mixture model	
	1.0 g cm <sup>-3</sup>	1.6 g cm <sup>-3</sup>	1.0 g cm <sup>-3</sup>	1.6 g cm <sup>-3</sup>	1.0 g cm <sup>-3</sup>	1.6 g cm <sup>-3</sup>
0.30	3.651	4.212	3.574	4.157	3.928	4.258
0.10	1.981	2.330	2.384	2.568	2.340	2.669
0.00	1.146	1.495	1.590	1.774	1.546	1.875

soil water content is low. The rate of increase in  $\sqrt{K_a}$  as soil bulk density increases as predicted by the Malicki equation is faster than that shown in Figure 2. For example, the Malicki equation predicts a 0.349 increase in  $\sqrt{K_a}$  as the soil bulk density goes up from 1.0 g cm<sup>-3</sup> to 1.6 g cm<sup>-3</sup> for dry soil ( $\theta = 0$ ). In the same circumstance, Figure 2 predicts only 0.184 increase in  $\sqrt{K_a}$ . The discrepancy may be caused by gradually underestimating the soil dielectric permittivity when using the Malicki equation when the soil bulk density is reducing. For example, for dry soil with 1.2 g cm<sup>-3</sup> bulk density, the calculated  $\sqrt{K_a}$  is only 1.250 using the Malicki equation, which gives  $K_a = 1.561$ . The value of  $K_a$  for dry loamy soil should be in the range of 2.48 to 2.55 from a frequency from 100 MHz to 3 GHz (Jordan, 1989). Using the calibration presented in Figure 2, the calculated  $K_a$  is 2.738, which is much closer to the published data.

Whalley (1993) presented a mixture model, which gives the dielectric permittivity of soil as

$$K_a^\alpha = \theta K_w^\alpha + (1 - \phi) K_s^\alpha + (\phi - \theta) K_g^\alpha$$

where  $K_a$  is the dielectric permittivity of the soil mixture,  $K_w$ ,  $K_s$  and  $K_g$  are the dielectric permittivities of water, solid and gas phase respectively;  $\phi$  is the total porosity. By choosing the geometric factor  $\alpha = 0.5$  as Whalley (1993) did, and  $K_s = 6.0$  (Jordan, 1989), the mixture model gives a  $\sqrt{K_a}$  values very close to that from the calibration in Figure 2 and Equation (5) (Table II), especially when the soil water content is low. However, the  $\sqrt{K_a}$  value calculated using the Malicki equation is substantially lower than that from the mixture model in the low moisture range.

#### Clay content effect

Table III shows that, as expected, the slope of the linear relationship between  $T/T_a$  and volumetric soil water content,  $1/(K_w^{0.5} - 1)$ , increases as the clay content increases. Only the time delay measured at below 0.20 m<sup>3</sup> m<sup>-3</sup> was used to calculate the slope, to avoid possible bulk soil electrical conductivity interference at high water content levels in clayey soil. The slope for loam and silt clay loam is not significantly different from that for pure sand. Silt clay shows a large increase in slope. For clayey soil at low water content, a substantial proportion of soil water is in the bound state, resulting in a reduced permittivity of soil water. By solving  $0.1319 = 1/(K_w^{0.5} - 1)$  we obtain  $K_w = 73.64$ ; this is the permittivity of soil water for silt clay at below 0.20 m<sup>3</sup> m<sup>-3</sup> water content, which is smaller than the 80.36 for the permittivity of free water at 20 °C.

Table III. The slope,  $1/(K_w^{0.5} - 1)$ , of Equation (5) for soils with different textures

Soil type	Silt clay	Silt clay loam	Loam	Pure sand
Clay content (%)	44.8	34.5	21.2	0
Slope	0.1319	0.1252	0.1258	0.1256

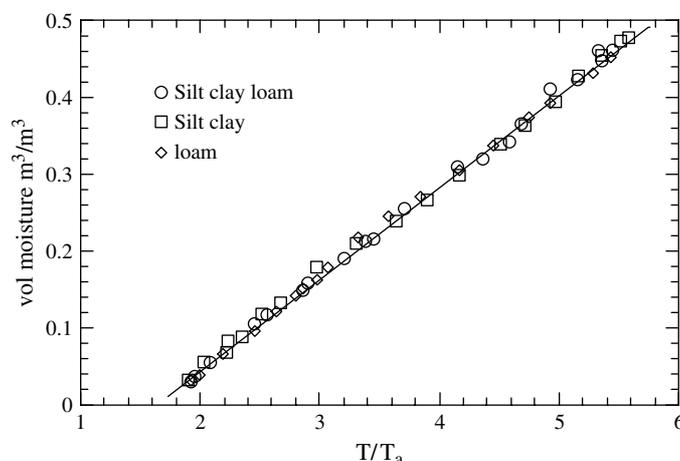


Figure 4. The relationship between time delay  $T/T_a$  and volumetric water content for silt clay loam, silt clay and loam

Topp *et al.* (2000) estimated the apparent relative permittivity for a soil in both the A and B horizons, where the clay content was 20% and 55% respectively. They found that, at the same soil water content level, the apparent relative permittivity in the B horizon is lower than that in the A horizon. At  $0.145 \text{ m}^3 \text{ m}^{-3}$  volumetric water content, the calculated  $K_w$  based on the apparent dielectric permittivity for horizons A and B is 71.1 and 53.78 respectively. Sun and Young (2001) tested the relationship between  $T/T_a$  and volumetric soil water content for Rideau clay that contains more than 55% of clay content. They found that, when soil water content is below  $0.15 \text{ m}^3 \text{ m}^{-3}$ , the slope of Equation (5) increased to 0.219 and the calculated  $K_w$  was only 31 because the majority of the water molecules are bound in this circumstance.

However, in general, the relationship between time delay  $T/T_a$  and volumetric soil water content in the test is not statistically significant different between silt clay loam, silt clay and loam (Figure 4). It has been suggested that the clay content may have a large influence on the relationship between time delay and volumetric water content. Firstly, the bound water associated with clay particles has a much lower dielectric constant than that of free water. This allows a faster propagating velocity for an EM wave, resulting in an underestimation of water content, especially in the low moisture range where the ratio of bound water to free water is high. Secondly, clay soils usually possess a higher bulk EC than sandy and loamy soils. The bulk soil EC comes from the ionic concentration in soil solution and from the charged particle surface. The EC would cause signal attenuation and an overestimation of water content, especially in the high water content range where the EC is high and the ratio of bound water to free water is low (Sun *et al.*, 2000). Therefore, the relationship between time delay  $T/T_a$  and volumetric soil water content will depart from linear (Sun and Young, 2001). Here, only silt clay with 48.8% clay content shows the above tendency, although it is not statistically significant (Figure 5). The EC of saturated extract of the tested silt clay is less than  $3 \text{ dS m}^{-1}$ . At  $0.40 \text{ m}^3 \text{ m}^{-3}$  water content, it contributes  $0.48 \text{ dS m}^{-1}$  to bulk soil EC by using the Rhoades *et al.* (1989) equation. However, its high clay content contributes  $1.10 \text{ dS m}^{-1}$  to bulk soil EC. Therefore, the threshold value for the EC of soil solution at which the soil bulk EC will show its effects is lower for clayey soil than that for sandy soil. There is a turning point at the  $0.20$  to  $0.25 \text{ m}^3 \text{ m}^{-3}$  moisture level, where the effect of bound water is balanced by the effect of EC. Below this level, TDR underestimates soil moisture, and above this level TDR overestimates soil moisture.

The soils under test did not show significant shrinkage or expansion when water was withdrawn or added, indicating that they do not contain a large amount montmorillonite. This may explain the lack of significant clay content effect. Kaolinite and illite have a much smaller specific surface and cation exchange

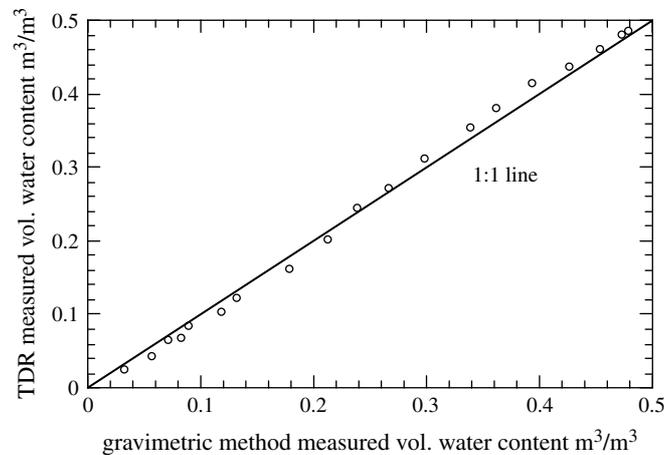


Figure 5. TDR-measured volumetric soil water content versus gravimetric method measured soil water content for silt clay

capacity than montmorillonite; therefore, they have far less bound water associated with them. The effect of difference in clay mineralogy on TDR soil water content measurement using TDR deserves further investigation.

#### Temperature effects

The dielectric permittivity of water decreases as temperature rises, leading to a shorter time delay and, consequently, an underestimation of soil water content. The dielectric permittivity of solid particles may also change with temperature; however, the change is negligible (Roth *et al.*, 1990). Figure 6 shows that the moisture measurement error is linearly related to the changes in temperature when soil water content is above  $0.30 \text{ m}^3 \text{ m}^{-3}$ . At  $20^\circ\text{C}$  the temperature effect should be zero, since the MoisturePoint MP-917 uses dielectric permittivity of water at that temperature to convert the measured time delay to soil water content. The slope of the regression line increases as soil water content increases, and this indicates a large temperature effect on soil dielectric permittivity as soil water content increases. Since the effect of temperature on TDR measurement varies with soil water content, the calibration equation requires the information of both soil temperature and soil water content.

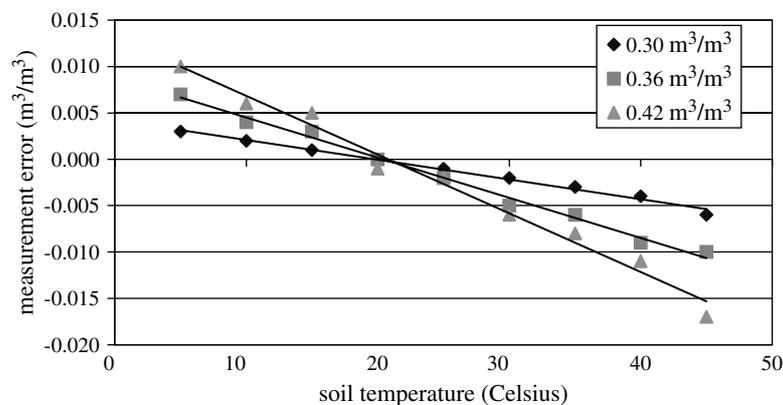


Figure 6. Measurement error changes with temperature at different soil moisture levels

The calibration equations at  $0.42 \text{ m}^3 \text{ m}^{-3}$ ,  $0.36 \text{ m}^3 \text{ m}^{-3}$  and  $0.30 \text{ m}^3 \text{ m}^{-3}$  water content level are given by Equations (8)–(10) respectively:

$$\Delta\theta = -0.0006t + 0.0132 \quad (8)$$

$$\Delta\theta = -0.0004t + 0.0088 \quad (9)$$

$$\Delta\theta = -0.0002t + 0.0042 \quad (10)$$

where  $\Delta\theta$  is the measurement error due to the temperature effect;  $\Delta\theta = \theta_m - \theta_v$ , where  $\theta_m$  and  $\theta_v$  are the TDR-measured and reference volumetric soil water content (gravimetric method determined) respectively, and  $t$  is soil temperature in celsius. The measurement error  $\Delta\theta$  should be zero when the test is conducted at  $20^\circ\text{C}$ ; however, by applying  $t = 20^\circ\text{C}$  to Equations (8)–(10), the calculated  $\Delta\theta$  is  $0.0008 \text{ m}^3 \text{ m}^{-3}$ ,  $-0.0008 \text{ m}^3 \text{ m}^{-3}$  and  $0.0002 \text{ m}^3 \text{ m}^{-3}$  respectively. The discrepancy is mainly caused by measurement noise, since the standard deviations for these measurement are  $0.002$ ,  $0.004$  and  $0.003 \text{ m}^3 \text{ m}^{-3}$ , which is in the same order or larger than the measured error ( $\Delta\theta$ ) at  $20^\circ\text{C}$ .

In general, the calibration equation can be written as

$$\Delta\theta = a(\theta)t + b(\theta) \quad (11)$$

where  $a(\theta)$  and  $b(\theta)$  are functions of soil water content. Using the values of slope and intercepts in Equations (8)–(10) we obtain

$$a(\theta) = -0.0033\theta_v + 0.0008 \quad (12)$$

$$b(\theta) = 0.0750\theta_v - 0.0183 \quad (13)$$

For soil water content ( $\theta_v$ ) of  $0.600 \text{ m}^3 \text{ m}^{-3}$ , the values of  $a(\theta)$  and  $b(\theta)$  calculated using Equations (12) and (13) are  $-0.00118$  and  $0.0267$ . On substituting these numbers into equation (11) we obtain

$$\Delta\theta = -0.00118t + 0.0267 \quad (14)$$

If the soil temperature is  $50^\circ\text{C}$ , then the magnitude of measurement error calculated using Equation (14) will be  $0.0323 \text{ m}^3 \text{ m}^{-3}$ . Pepin *et al.* (1995) suggested a temperature correction formula of  $0.001750\theta_v \text{ }^\circ\text{C}^{-1}$ . Their formula shows a  $0.0315 \text{ m}^3 \text{ m}^{-3}$  measurement error in the same situation. For soil with  $0.300 \text{ m}^3 \text{ m}^{-3}$  water content, the calculated measurement error at  $50^\circ\text{C}$  is reduced to  $0.0053 \text{ m}^3 \text{ m}^{-3}$ . The calibration is required only when soil water content is high and the measurement accuracy demanded is also high.

By substituting  $a(\theta)$  and  $b(\theta)$  of Equations (12) and (13) into Equation (11) we obtain

$$\Delta\theta = \theta_m - \theta_v = a(\theta)t + b(\theta) = (-0.0033\theta_v + 0.0008)t + (0.0750\theta_v - 0.0183)$$

By separating  $\theta_v$  and  $\theta_m$  we obtain

$$\theta_v = \frac{\theta_m - 0.0008t + 0.0183}{1.075 - 0.0033t} \quad (15)$$

Equation (15) can be used to obtain the correct soil water content  $\theta_v$  from TDR-displayed soil water content  $\theta_m$  if the soil temperature  $t$  is known. For example, when the TDR-displayed moisture is  $0.25 \text{ m}^3 \text{ m}^{-3}$  and soil temperature is  $40^\circ\text{C}$ , the correct water content calculated using Equation (15) will be  $0.2506 \text{ m}^3 \text{ m}^{-3}$ . The temperature effect is in the order of  $1/1000 \text{ m}^3 \text{ m}^{-3}$ . However, if the TDR-displayed water content is  $0.50 \text{ m}^3 \text{ m}^{-3}$  and soil temperature is  $50^\circ\text{C}$ , then the correct soil water content will be  $0.5226 \text{ m}^3 \text{ m}^{-3}$  when Equation (15) is applied. In this case the TDR-displayed soil water content is  $0.0226 \text{ m}^3 \text{ m}^{-3}$  less than the actual one, and error of this magnitude cannot be neglected in many applications.

Unlike many other temperature calibration formulas, in which a knowledge of the actual soil water contents is a prerequisite for calculating the temperature effect, Equation (15) will provide the correct water content from TDR-displayed soil moisture and soil temperature. It is more practical.

The negative correlation between soil temperature and bulk soil dielectric permittivity presented above is similar to the results from Wraith and Or (1999) on Kidman sandy loam. In their experiment, the TDR-measured volumetric water content decreased  $0.008 \text{ m}^3 \text{ m}^{-3}$  for soil with  $0.212 \text{ m}^3 \text{ m}^{-3}$  water content, and  $0.014 \text{ m}^3 \text{ m}^{-3}$  for soil with  $0.310 \text{ m}^3 \text{ m}^{-3}$  water content when soil temperature increased from  $25^\circ\text{C}$  to  $45^\circ\text{C}$ . However, when Equation (11) is applied, the decreases of soil water content are only  $0.002 \text{ m}^3 \text{ m}^{-3}$  and  $0.006 \text{ m}^3 \text{ m}^{-3}$ . The discrepancy comes from the difference in clay contents between the sandy loam used in the testing (10.2%) and Kidman sandy loam (3.0%). The results showed (Or and Wraith, 1999) that the thermodielectric response is affected by how much bound water is released from the soil particle surface as temperature increased. The released bound water offsets the decrease in bulk dielectric permittivity of free water caused by temperature increase, leading to less soil water content measurement error. Figure 7 shows that, for water content below  $0.30 \text{ m}^3 \text{ m}^{-3}$ , the measured soil moisture by TDR hardly varied with temperature. This is because at low soil water content a large proportion of water is held by solid surface, and its release from the bound state as temperature increases balances the effect of decrease of free water dielectric permittivity.

Applying  $K_w = 80.36$ , the dielectric permittivity of free water at  $20^\circ\text{C}$ , to Equation (5) results in  $0.02 \text{ m}^3 \text{ m}^{-3}$  underestimation of water content (Table IV) for tested sandy loam with  $0.36 \text{ m}^3 \text{ m}^{-3}$  water

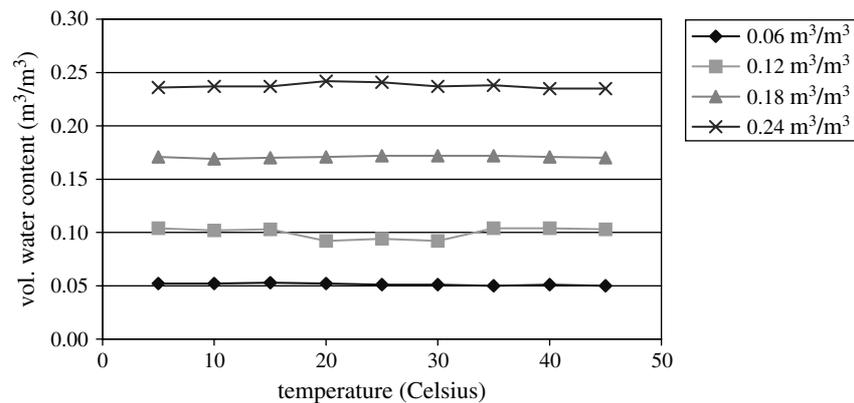


Figure 7. The relationship between temperature and measured volumetric soil water content when soil water content is below  $0.30 \text{ m}^3 \text{ m}^{-3}$

Table IV. The changes of dielectric permittivity of free water, measured time delay, and calculated water contents for sandy loam soil with  $0.36 \text{ m}^3 \text{ m}^{-3}$  water content

Temperature (°C)	$K_w$ (free water)	Measured time delay $T/T_a$	Calculated water content using $K_w = 80.36$	Calculated water content using $K_w$ from column #2 at corresponding temperature
20	80.36	4.510	0.360	0.359
25	78.54	4.494	0.358	0.362
30	76.76	4.470	0.355	0.363
35	75.03	4.462	0.354	0.367
40	73.35	4.438	0.351	0.369
45	71.70	4.400	0.340	0.370

and at 45 °C. However, the use of  $K_w = 71.7$ , the permittivity of free water at 45 °C, in Equation (5) results in  $0.01 \text{ m}^3 \text{ m}^{-3}$  over-correction of water content. A possible explanation is that the decrease in dielectric permittivity for water in soil is slower than that of free water described by Equation (7), because the decrease is buffered by the release of bound water. Therefore, Equation (7) cannot be used to predict the dielectric permittivity of soil water at different temperature for soil with high clay content.

A calibration that includes the clay content as an input parameter should be more universal than Equation (15). The EC of soil solution also increases as soil temperature increases, and this may lead to a noticeable overestimation of water content when the EC level exceeds a certain level. In this experiment, the EC of soil solution is low and surface conductivity is also low, since it is a sandy soil with only 10.2% clay content. For saline soils, the EC of soil solution may be an additional parameter that may need to be included in the calibration.

### CONCLUSIONS

The effect of soil bulk density, clay content and soil temperature on TDR soil water content measurement has been discussed. The time delay  $T/T_a$  or the square root of the apparent dielectric permittivity of soil  $K_a$  increases linearly with soil bulk density. A value of 1.65 for  $T_s/T_a$  (the square root of apparent dielectric permittivity of dry soil) was suggested. For soil with high clay contents, TDR underestimates soil water content in the low moisture range because the bound water effect is dominant. TDR will overestimate soil water content in the high moisture range because the soil EC effect is dominant. The extent of influence largely depends on the clay type. The temperature affects the TDR soil moisture measurement by changing the dielectric permittivity of free water and the releasing of bound water. A practical calibration equation has been developed, in which the information of soil temperature and TDR-instrument-displayed moisture is required.

### ACKNOWLEDGEMENTS

This research collaboration with the R & D Division of ESI Environmental Sensors Inc. in Canada, was supported financially by the Ministry of Science and Technology (G1999011709) and the Excellent Young Teachers Program of the Ministry of Education of the People's Republic of China.

### REFERENCES

- Dalton FN. 1992. Development of time domain reflectometry for measuring soil water content and bulk soil electrical conductivity. In *Advances in Measurement of Soil Physical Properties: Bring Theory into Practice*, Topp GC (ed.). Soil Science Society of America, Special Publication 30. Soil Science Society of America: Madison, WI; 143–167.
- Dirksen C, Dasberg SI. 1993. Improved calibration of time domain reflectometry soil water content measurements. *Soil Science Society of America Journal* **57**: 660–667.
- Ferré PA, Knight JH, Rudolph DL, Kachanoski RG. 1996. Spatial averaging of water content by time domain reflectometry: implications for twin rod probes with and without dielectric coatings. *Water Resources Research* **32**: 271–280.
- Ferré PA, Rudolph DL, Kachanoski RG. 2000. A numerically based analysis of the sensitivity of conventional and alternative time domain reflectometry probes. *Water Resources Research* **36**: 2461–2468.
- Herkelrath WN, Hamburg SP, Murphy F. 1991. Automatic real-time monitoring of soil moisture in a remote field area with time domain reflectometry. *Water Resources Research* **27**: 857–864.
- Hilhorst MA, Dirksen C, Kampers FWH, Feddes RA. 2001. Dielectric relaxation of bound water versus soil matric pressure. *Soil Science Society of America Journal* **65**: 311–314.
- Hook WR, Livingston NJ. 1996. Errors in converting time domain reflectometry measurements of propagation velocity to estimates of soil water content. *Soil Science Society of America Journal* **59**: 35–41.
- Hook WR, Livingston NJ, Sun ZJ, Hook PB. 1992. Remote diode shorting improves measurement soil water by time domain reflectometry. *Soil Science Society of America Journal* **56**: 1383–1391.
- Jacobsen OH, Schjonning P. 1993. A laboratory calibration of time domain reflectometry for soil water measurement including effects of bulk density and texture. *Journal of Hydrology* **151**: 147–157.

- Jordan EC. 1989. In *Reference Data for Engineers: Radio, Electronic, Computer, and Communications*, 7th edn. Howard W. Sam & Company: Indiana, USA; 4–23.
- Knight JH, Ferré PA, Rudolph DL, Kachanoski GR. 1997. A numerical analysis of the effects of coatings and gaps upon relative dielectric permittivity measurement with time domain reflectometry. *Water Resources Research* **33**(6): 1455–1460.
- Ledieu J, de Ridder P, Dautrebande S. 1986. A method of measuring soil moisture by time-domain reflectometry. *Journal of Hydrology* **88**: 319–328.
- Malicki MA, Walczak RT, Koch S, Fluhler H. 1994. Determining soil salinity from simultaneous readings of its electrical conductivity and permittivity using TDR. In *Symposium and Workshop on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications*, United States Department of Interior Bureau of Mines: 328–336.
- Malicki MA, Plagge R, Roth CH. 1996. Improving the calibration of dielectric TDR soil moisture determination taking into account the solid soil. *European Journal of Soil Science* **47**: 357–366.
- Nadler A, Dasberg S, Lapid I. 1991. Time domain reflectometry measurement of water content and electrical conductivity of layered soil columns. *Soil Science Society of America Journal* **55**: 938–943.
- Or D, Wraith JM. 1999. Temperature effects on soil bulk dielectric permittivity measured by time domain reflectometry: a physical model. *Water Resources Research* **35**: 371–383.
- Pepin S, Livingston NJ, Hook WR. 1995. Temperature dependent on measurement errors in time domain reflectometry determinations of soil water. *Soil Science Society of America Journal* **59**: 38–43.
- Rhoades JD, Manteghi NA, Shouse PJ, Alves WJ. 1989. Soil electrical conductivity and soil salinity: new formulations and calibrations. *Soil Science Society of America Journal* **53**: 433–439.
- Roth K, Schulin R, Fluhler H, Attinger W. 1990. Calibration of time domain reflectometry for water content measurement using a composite dielectric approach. *Water Resources Research* **26**: 2267–2273.
- Sun ZJ, Young GD. 2001. Saline clayey soil moisture measurement using time domain reflectometry. In *TDR 2001: The Second International Symposium and Workshop on Time-Domain Reflectometry for Innovative Geotechnical Applications*, North Western University, Illinois, USA.
- Sun ZJ, Young GD, McFarlane R, Chambers BM. 2000. The effect of soil electrical conductivity on moisture determination using time-domain-reflectometry in sandy soil. *Canadian Journal of Soil Science* **80**(1): 13–22.
- Topp GC, Davis JL, Annan AP. 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Resources Research* **16**: 574–582.
- Topp GC, Davis JL, Annan AP. 1982. Electromagnetic determination of soil water content using TDR: I. Applications to wetting fronts and steep gradients. *Soil Science Society of America Journal* **46**: 672–684.
- Topp GC, Zeglin S, White I. 2000. Impacts of real and imaginary components of relative permittivity on time domain reflectometry measurements in soil. *Soil Science Society of America Journal* **64**: 1244–1252.
- Weast RC (ed.). 1986. *Handbook of Physics and Chemistry*, 67th edn. CRC Press: Boca Raton, FL.
- Whalley WR. 1993. Considerations on the use of time-domain reflectometry (TDR) for measuring soil water content. *Journal of Soil Science* **44**: 1–9.
- White I, Zegelin SJ, Topp GC, Fish A. 1994. Effect of bulk electrical conductivity on TDR measurement of water content in porous media. In *Symposium and Workshop on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications*, United States Department of Interior Bureau of Mines; 294–308.
- Wraith JM, Or D. 1999. Temperature effects on soil bulk dielectric permittivity measured by time domain reflectometry: experimental evidence and hypothesis development. *Water Resources Research* **35**: 361–369.
- Wyseure GCL, Mojid MA, Malik MA. 1997. Measurement of volumetric water content by TDR in saline soils. *European Journal of Soil Science* **8**: 347–354.
- Young MH, Fleming JB, Wierenga PJ, Warrick AW. 1997. Rapid laboratory of time domain reflectometry using upward infiltration *Soil Science Society of America Journal* **61**: 707–712.