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Response of the core and shield rods of time-domain reflectometry probe to transverse soil-water content heterogeneity

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Abstract

The effect of the speed of a time-domain reflectometry (TDR) pulse through the core rod and the shield rod(s) of TDR probes on the dielectric constant and water content of a soil with heterogeneous water content distribution in the transverse direction to the probe length was investigated. Soil samples were prepared using sands of two different water contents, which were kept side by side to get transverse heterogeneous water content distribution. The dielectric constant and water content of these samples (here after denoted by $\varepsilon_{\mathrm{TDR}}$ and θ_{TDR}, respectively) were measured by TDR. The expected dielectric constants of the samples, ε_{g}, were calculated using the equation of Topp et al. (1980) from the volumetric soil-water contents, θ_{g}, measured gravimetrically assuming that this equation was applicable to our soil. The TDR pulse traveled faster through the probe rod inserted in the dry sand due to its low dielectric constant than through the probe rod inserted in the wet sand. So, early reflection of the pulse occurred in the dry sand, which shortened the travel path of the pulse and caused underestimation of the dielectric constant and soil-water content. The degree of this underestimation was higher when the core rod of the probe was in dry sand than when was this same rod in wet sand. Although TDR measurements were apparently controlled by the dry part of the sample, θ_{TDR} was always higher than the water content of the dry sand, θ_{dry}, in the sample. TDR thus could measure neither the average dielectric constant and soil-water content of the sample nor it measured those for the dry part or for the wet part of the sample when soil-water distribution was heterogeneous in the transverse direction of the probe rods.

Keywords: Time-domain reflectometry probe; Core and shield rods; Transverse heterogeneous; Soil-water content

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1. Introduction

Time-domain reflectometry (TDR) has become a widely used technique for measuring soil-water content, since its introduction to measure the dielectric constant of soil by Davis and Chudobiak (1975) and the development of a calibration equation between the dielectric constant and soil-water content by Topp et al. (1980). Topp et al. (1982) and Ferré et al. (1996) showed that TDR measured the average dielectric constant of the soil volume sampled by its measurement system when water content variation occurred along the length of the probe. However, a heterogeneous soil profile with wet soil overlaid dry soil reduced accuracy in the determination of dielectric constant by TDR (Nadler et al., 1991; Dasberg and Hopmans, 1992) and TDR significantly underestimated dielectric constant when

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the difference in water content between the dry and wet soil was large.

While comprehensive results of TDR measurements in case of axially varying soil-water contents have been reported, measurements in soil with transverse water content heterogeneity are very limited and inadequate. Hokett et al. (1992) studied soil-water content heterogeneity in the transverse direction to the TDR probe by (1) inserting one rod of a two-rod probe in dry sand and the other rod in wet sand, and (2) separating dry and wet sands by an artificially made air- or water-filled crack. They obtained biased TDR measurement towards the dry sand that underestimated the dielectric constant and the dry sand separated by air-filled crack only slightly influenced the TDR-measured dielectric constant. TDR-measured dielectric constant was significantly low in their study when wet sand was separated by air-filled crack. The effect of water-filled cracks was small in both dry and wet sands.

The main current of the TDR pulse transmitted through the core rod of a TDR probe and the intensity of the electrical potential was much higher around the core rod than around the shield rod. As a result, the transverse heterogeneous soil-water distribution might affect the TDR-measured dielectric constant depending on which probe rod was in dry soil and which probe rod was in wet soil. Hokett et al. (1992) did not consider this factor in their study. The objective of this study was therefore to evaluate the effect of the speed of TDR pulse through the core and shield rods of two- and three-rod TDR probes on the dielectric constant and water content of the soil having transverse heterogeneous water content distribution.

2. Background theory

A direct analysis to describe the response of TDR probe to dielectric materials distributed heterogeneously in the transverse plane is yet not available, since the weighting function, $w(x,y)$, for the TDR measurement depends on the distribution of dielectric constants, $\varepsilon(x,y)$ (Knight, 1992). Hokett et al. (1992) approximated the effective dielectric constant for the case of a water- or air-filled gap between probe rods by applying a capacitive transmission line model. Assuming that the different dielectric constants of the two homogeneous media (soil and water- or air-filled gap) formed layers of different capacitance parallel to the probe rods, they expressed the dielectric constant to be measured by TDR as

$$\varepsilon_{\mathrm{TDR}} = \frac{l_{\mathrm{T}}}{\left[\dfrac{l_1}{\varepsilon_1} + \dfrac{l_2}{\varepsilon_2}\right]} \tag{1}$$

where l_{T} is the total thickness between the probe rods and ε_1 and l_1 are the dielectric constant and thickness of layer 1, and so on. Eq. (1) did not consider the non-uniform weighting function of the TDR measurement system and hence it over predicted $\varepsilon_{\mathrm{TDR}}$. This equation, however, closely predicted the measured $\varepsilon_{\mathrm{TDR}}$ after applying a weighting factor of 5 to the soil only as

$$\varepsilon_{\mathrm{TDR}} = \frac{l_{\mathrm{T}}}{\left[\dfrac{5l_1}{\varepsilon_1} + \dfrac{l_2}{\varepsilon_2}\right]} \tag{2}$$

Knight (1992) expressed the weighting function for TDR measurement $w(x,y)$ as

$$w(x,y) = \frac{|\nabla\phi|^2}{\displaystyle\int\!\!\int_v |\nabla\phi_0|^2\,\mathrm{d}A} \tag{3}$$

where $\phi_0(x,y)$ is the electrostatic potential distribution for uniform value of dielectric constant in the region, v, surrounding the probe, and $\phi(x,y)$ is the electrostatic potential distribution for non-uniform distribution of dielectric constant $\varepsilon(x,y)$. The dielectric constant to be measured by TDR was then defined by

$$\varepsilon_{\mathrm{TDR}} = \int\!\!\int_v \varepsilon(x,y)w(x,y)\mathrm{d}A \tag{4}$$

Ferré et al. (1996) analytically described the measured dielectric constant of materials placed as eccentric rings around two-rod probes by an inverse averaging model with non-uniform spatial weighting. A non-eccentric distribution of materials introduced complications and their analytical solution could not be applied in such cases.

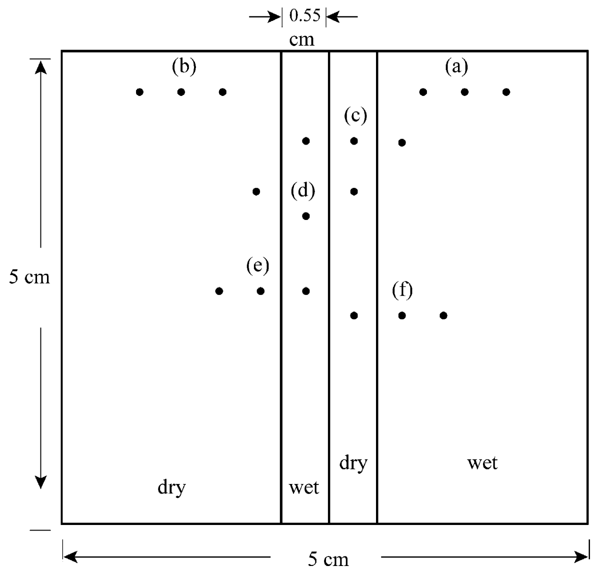

Fig. 1. Layout of the locations of TDR probe rods on the top view of the rectangular sample box for the measurement of dielectric constant and soil-water content with a three-rod probe.

3. TDR principle to measure dielectric constant and soil-water content

TDR cable tester sends a high frequency transverse electromagnetic (TEM) pulse through a probe. The launched pulse travels with a speed v given by

$$v = \frac{c}{\sqrt{\varepsilon}} \tag{5}$$

where c is the speed of light (3×10^8 m s^{-1}) and ε is the dielectric constant of the medium surrounding the probe (in this note, ε is denoted by $\varepsilon_{\mathrm{TDR}}$ when measured by TDR). The launched pulse reflects back when it encounters a change in impedance on its travel path. The pulse thus bounces back and forth from the two ends of the probe. All the reflected pulses superimpose on the launched pulse and are displayed as a resultant waveform in time, which is transformed into the length of travel path L of the pulse in case of a Tektronix 1502C cable tester. The distance between two specific points on the waveform that correspond to the starting and end points of the probe rods provides the apparent travel path L of the TDR pulse through the probe. The average composite dielectric constant of the soil-water–air mixture and L are related by

$$L = \frac{ct}{\sqrt{\varepsilon}} \tag{6}$$

where t is the travel time of the pulse through the probe rod. The average dielectric constant ε of the soil-water–air mixture sampled by the cable tester's measurement system surrounding a probe is calculated by

$$\varepsilon = \left(\frac{L}{L_{\mathrm{s}} v_{\mathrm{p}}} \right)^2 \tag{7}$$

where L_{s} is the length of the probe (10 cm in this study) and v_{p} is the ratio of the velocity of TDR pulse in a medium to that in free space and was set at 0.99 in this study. For relatively coarse textured soils, the volumetric soil-water content θ (in this note, θ is denoted by θ_{TDR} when measured by TDR) is related to ε by the equation of Topp et al. (1980) as

$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}\varepsilon - 5.5 \times 10^{-4}\varepsilon^2 + 4.3 \times 10^{-6}\varepsilon^3 \tag{8}$$

4. Materials and methods

We used two types of TDR probe, one from the Easy Test Ltd, Poland, and the other constructed in this study, with a Tektronix 1502C cable tester of Tektronix Ltd, and the WinTDR98 software developed by Or et al. (1998) for our experiments. The Polish TDR probe consisted of two rods of 10 cm length; the diameter and spacing between the rods were 0.1 and 0.5 cm, respectively. There was an 8-cm epoxy transition between the rods of the probe and the coaxial cable to hold the coaxial cable and probe rods firmly. The other probe had three rods of 10 cm length. The probe head consisted of 1 cm thick, 0.8 cm wide and 1.8 cm long acrylic block. The center-to-center spacing of the two outer rods was 1.1 cm and that between the central and outer rods was 0.55 cm. The diameter of the probe rod was 0.1 cm.

These small size probes, though not always suitable for field use, enabled easy and accurate measurements in our laboratory experiments. The results obtained

Table 1
The average TDR-measured dielectric constants ($\varepsilon_{\mathrm{TDR}}$) for the two-rod probe and the expected average dielectric constant (ε_g) calculated by Eq. (8) from the volumetric water contents measured gravimetrically. Also listed are the TDR-measured and gravimetrically measured soil-water contents (θ_{TDR} and θ_g) and the water contents of the dry and wet sands (θ_{dry} and θ_{wet}) in the samples

Trial number	Probe rods' location in the sample[a]	$\varepsilon_{\mathrm{TDR}}$	ε_g	θ_{TDR} ($m^3\ m^{-3}$)	θ_g ($m^3\ m^{-3}$)	θ_{dry} ($m^3\ m^{-3}$)	θ_{wet} ($m^3\ m^{-3}$)
1	a	9.63	11.64	0.177	0.225	0.10	0.35
	b	7.82	11.64	0.142	0.225	0.10	0.35
2	a	5.97	5.91	0.102	0.115	0.05	0.18
	b	5.18	5.91	0.083	0.115	0.05	0.18
3	a	13.44	16.88	0.241	0.30	0.25	0.35
	b	12.35	16.89	0.224	0.30	0.25	0.35
4	a	7.80	8.72	0.142	0.175	0.10	0.25
	b	6.82	8.72	0.121	0.175	0.10	0.25
5	a	8.26	8.72	0.151	0.175	0.10	0.25
	b	7.14	8.72	0.128	0.175	0.10	0.25
6	A	5.89	16.89	0.100	0.30	0.25	0.35
	B	4.64	16.89	0.069	0.30	0.25	0.35

[a] (a) core rod in wet sand and shield rod in dry sand; (b) core rod in dry sand and shield rod in wet sand; (A) core rod in wet sand and shield rod in air; and (B) core rod in air and shield rod in wet sand.

for the small probes are expected to be of general type and should be applicable for other size probes of conventional type. This is because, the transmission characteristics of TDR pulse, both in the small and large probes, are basically the same. The weighting pattern of the measured sample volume by both probes is also same and is a function of the electrical potential distribution around the probe rods (Knight, 1992).

A 10 cm × 5 cm × 5 cm rectangular hollow sample box was constructed with thin plastic plates. The bottom of the box was closed with a plastic plate. The inside of this box was partitioned longitudinally into four compartments using thin polyethylene sheets and adhesive tape. Fig. 1 shows schematically the top view of the sample box with the four compartments. The width of the two inner compartments was kept 0.55 cm, so that it matched with the spacing between the probe rods. The four compartments of the sample box were filled alternately with sands of two different, but pre-known water contents prepared purposively. The bulk density of the sands in each compartment was maintained at 1.6 Mg m^{-3}. First, one two-rod probe (the Polish probe) was inserted in the soil column keeping the core and shield rods in two different compartments. The average dielectric constant $\varepsilon_{\mathrm{TDR}}$ and water content θ_{TDR} of the sand was measured by TDR. The waveform was also recorded for each measurement. The measurement of $\varepsilon_{\mathrm{TDR}}$ and θ_{TDR} was repeated by interchanging the mutual positions of the two rods of the probe in the dry and wet part of the sample. Total five measurements of this type, three for different water contents of the dry and wet sands and two for different volume of dry sand sampled by the core and shield rods in the same dry and wet sand combination were carried out. In another set of measurement, $\varepsilon_{\mathrm{TDR}}$, θ_{TDR} and waveforms were recorded inserting (a) the core rod of the probe in wet sand and the shield rod in air, and (b) the shield rod in wet sand and the core rod in air. Similar measurements were carried out with the three-rod probe keeping: (a) all three rods in wet sand, (b) all three rods in dry sand, (c) the core rod in dry sand and the two shield rods in wet sand, (d) the core rod in wet sand and the two shield rods in dry sand, (e) the core rod and one shield rod in dry sand, and the other shield rod in wet sand, and (f) the core rod and one shield rod in wet sand, and the other shield rod in dry sand. The layout of the probe rod position for the three-rod probe is shown on the top view of the sample box in Fig. 1. The expected dielectric constant ε_g for the six different positions of the probe rods in the sample was calculated from the gravimetrically measured water content θ_g of the sample by using Eq. (8).

The θ_g for each measurement was calculated based on the assumption that the diameter of the soil volume

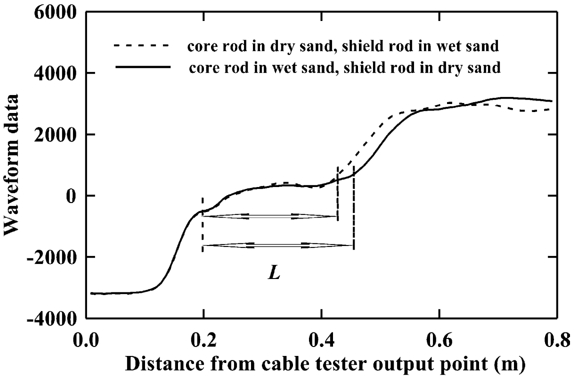

Fig. 2. TDR waveforms in a sand sample with transverse heterogeneous soil-water content distribution. The variation of the pulse travel path *L* with the relative positions of the core and shield rods of a two-rod probe in the dry and wet sands of the sample are shown.

sampled by the TDR probe was approximately 1.4 times the spacing of the probe rods (Zegelin et al., 1989). For the two-rod probe, the soil-water contents of the two compartments of the sample box were equally weighted (by taking the average) to calculate θ_g. Since, for each measurement with this probe, the rods were equidistant from the partition wall (0.25 cm), the volume ratio of the wet to dry sand between the rods was 1:1. On the other hand, the soil-water contents of the different compartments, in the case of the three-rod probe, were weighted by the respective cross-sectional area of the sand sampled by the probe rods to estimate θ_g.

5. Results and discussion

TDR-measured dielectric constant $\varepsilon_{\mathrm{TDR}}$ and soil-water content θ_{TDR} are compared with the average expected dielectric constant ε_g and gravimetrically measured average soil-water content θ_g, respectively, in Table 1 for the two-rod probe. This table also lists the gravimetrically measured soil-water contents of the dry and wet sands (θ_{dry} and θ_{wet}) that comprised the samples. A comparison of $\varepsilon_{\mathrm{TDR}}$ with ε_g and θ_{TDR} with θ_g reveals that TDR underestimated dielectric constant and water content of the sand in all our measurements. When the core rod of the probe was in dry sand, the under estimation was remarkably high. The degree of underestimation depended on the volume of the dry sand sampled by the probe and increased with increasing proportion of the dry sand. This is evident in the results of the fourth and fifth trials provided in Table 1, in which cases θ_{dry} and θ_{wet} remained unchanged and only the changing probe position in the sample resulted in different $\varepsilon_{\mathrm{TDR}}$ and θ_{TDR}. It may be noted here that the TDR probe sampled a cylindrical volume of the sand with a length equal to the length of the probe rod and a diameter approximately equal to 1.4 times the spacing of the probe rods (Zegelin et al., 1989). Because of the small dielectric constant of the dry sand, the TDR pulse traveled faster in the dry sand than in the wet sand according to Eq. (5). For example, the pulse would travel with a speed of $1.28 \times 10^8\ \mathrm{m\ s^{-1}}$ in a sand with $0.10\ \mathrm{m^3\ m^{-3}}$ water content and an approximate dielectric constant 5.49; while the pulse speed would be $9.80 \times 10^7\ \mathrm{m\ s^{-1}}$ in a sand with $0.20\ \mathrm{m^3\ m^{-3}}$ water content and approximate dielectric constant 9.42. The launched pulse thus reflected back earlier from the probe rod(s) inserted in the dry sand than from the probe rod(s) inserted in the wet sand. The early reflected pulse from the dry sand and the delayed reflected pulse from the wet sand superimposed on the launched pulse and generated a resultant waveform. The algorithm of the TDR support software, such as the WinTDR98, considered the first major reflection from the end of the probe in estimating the travel path of the pulse *L*. Consequently, *L* was shorter than that obtained when all the probe rods were in the wet sand. The shortened *L* underestimated dielectric constant according to Eq. (7) and subsequently soil-water content according to Eq. (8).

The mutual interchange of the core rod and the shield rod of the probe in the dry and wet portions of the same sample resulted in two different dielectric constants (Table 1). This different estimate of the dielectric constant could be explained by the characteristics of the coaxial cable connected to the probe and the TEM wave launched by the TDR cable tester. The main conductive current of the TDR pulse transmitted through the core of the coaxial cable and to the core rod of the probe. Only a small displacement current, produced in the shield rod due to the induction of the main current, transmitted through the shield rod of the probe. Due to these different magnitudes of the transmitting current in the core and shield rods, the intensity of the electrical potential was much higher around the core rod than that around the shield

Table 2
The average TDR-measured dielectric constants ($\varepsilon_{\mathrm{TDR}}$) for the three-rod probe and the expected average dielectric constant (ε_{g}) calculated by Eq. (8) from the volumetric water contents measured gravimetrically. Also listed are the TDR-measured and gravimetrically measured soil-water contents (θ_{TDR} and θ_{g}) and the water contents of the dry and wet sands (θ_{dry} and θ_{wet}) in the sample

Trial number	Probe rods' location in the sample	$\varepsilon_{\mathrm{TDR}}$	ε_{g}	θ_{TDR} ($\mathrm{m^3\ m^{-3}}$)	θ_{g} ($\mathrm{m^3\ m^{-3}}$)	θ_{dry} ($\mathrm{m^3\ m^{-3}}$)	θ_{wet} ($\mathrm{m^3\ m^{-3}}$)
1	All rods in wet sand	9.42	7.45	0.197	0.15	0.10	0.20
2	All rods in dry sand	5.49	5.34	0.104	0.10	0.10	0.20
3	Core rod in dry sand, shield rods in wet sand	6.63	7.94	0.118	0.16	0.10	0.20
4	Core rod in wet sand, shield rods in dry sand	8.03	6.98	0.148	0.14	0.10	0.20
5	Core rod and one shield rod in dry sand, the other shield rod in wet sand	6.67	6.54	0.119	0.13	0.10	0.20
6	Core rod and one shield rod in wet sand, the other shield rod in dry sand	8.05	8.45	0.149	0.17	0.10	0.20

rod (Zegelin et al., 1989). TDR thus, due to the high intensity of the electrical potential, exerted much greater weights on the sand around the core rod than on the sand around the shield rod. Baker and Lascano (1989) demonstrated that TDR measurements are several times more sensitive to the material properties near the probe rods than that in between the rods. So, when the core rod was in the wet sand, the estimate of $\varepsilon_{\mathrm{TDR}}$ and θ_{TDR} was larger than those estimated when the core rod was in the dry sand.

Fig. 2 compares two waveforms and demonstrates the pulse speed as affected by the different weighting systems of the TDR method around the core and shield rod of the two-rod probe. One of these waveforms was recorded by inserting the core rod of the two-rod probe in wet sand and the shield rod in dry sand. Interchanging the mutual positions of the two rods in the same sample retrieved the other waveform. The location of the reflection of the pulse on the waveform from the probe end was different for the two waveforms; the travel path of the pulse L was shorter when the core rod was in dry sand than when this rod was in wet sand. Consequently, Eq. (7) resulted in $\varepsilon_{\mathrm{TDR}}$, which was higher when the core rod was in wet sand than when this rod was in dry sand.

Table 2 furnishes the values of $\varepsilon_{\mathrm{TDR}}$, ε_{g}, θ_{TDR}, θ_{g}, θ_{dry} and θ_{wet} measured in the samples by the three-rod probe. A comparison of ε_{g} with $\varepsilon_{\mathrm{TDR}}$ and θ_{g} with θ_{TDR} in this table and evaluation of the travel path of the pulse L on the six waveforms shown in Fig. 3 show the effects of the core and shield rods on the measured dielectric constant and water content of the samples. These effects were exactly similar to that obtained for the two-rod probe. The travel path of the pulse L was always controlled predominantly by the dry part of the soil sampled by the probe. Fig. 3 clearly shows the largest L when all the probe rods were in wet sand and the smallest L when all the probe rods were in dry sand. For other arrangements of the core and shield rods in the dry and wet sand (Table 2), the travel paths of the pulse were very similar and were between the

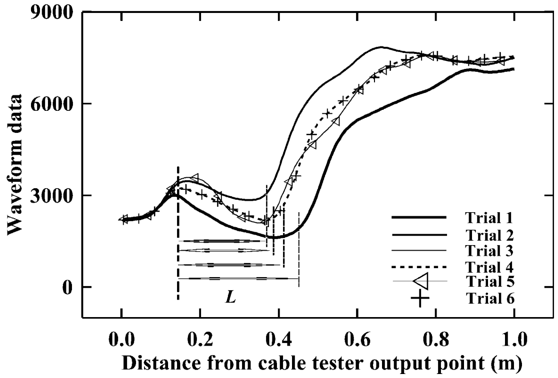

Fig. 3. TDR waveforms in a sand sample with transverse heterogeneous soil-water content distribution. The variation of the pulse travel path L with the relative position of the core and shield rods of a three-rod probe in the dry and wet sands of the sample are shown. The six waveforms were retrieved under the six trials described in Table 2.

largest and smallest values of L; L was larger when the core rod was in wet sand than when this rod was in dry sand. When only one shield rod was in dry sand, L was only slightly larger than that obtained with both the shield rods in dry sand. It is important to mention that $\varepsilon_{\mathrm{TDR}}$ and θ_{TDR} were always higher than that for the dry part of the sample (Tables 1 and 2).

The TDR measurement was based on the beginning of the pulse reflected from the probe end and TDR was expected to measure the dielectric constant and water content of the dry sand. This was only approximately true as because the presence of the dry–wet interface influenced the propagation speed in the dry sand. The resultant waveform obtained in a sample was generated from a convolution integral of the to-and-fro motions of the numerous reflected signals occurring both in the dry and wet sands in a sample. Such a waveform consequently provided a distance of travel L of the pulse, which was some where between the travel path of the pulse in the dry sand and that in the wet sand. Of course, the dry sand dominantly influenced L. The results observed in this study intuitively explain that TDR could not measure the average dielectric constant of the sampled volume across the probe when there was a transverse heterogeneous soil-water distribution.

6. Conclusions

In case of soil-water content heterogeneity in the transverse direction to the length of the probe rod, the TDR pulse traveled faster through the probe rod inserted in dry sand than through the rod(s) inserted in wet sand. As a result of this difference in the pulse speed, the launched pulse reflected back early from the end of the probe inserted in dry sand and shortened the travel path of the pulse on the resultant waveform. Consequently, TDR always underestimated the dielectric constant and soil-water content, the degree of which was high when the core rod of the probe was in dry sand. The dry part of the sample predominantly controlled the TDR measurement, but the measured dielectric constant and soil-water content were always higher than those for the dry sand in the sample. Thus, TDR could neither measure the average dielectric constant and water content of the sample nor these parameters for the dry part or for the wet part of the sample when the distribution of soil-water content was heterogeneous across the length of the TDR probe. In order to obtain accurate measurement of dielectric constant and soil-water content, it is, therefore, recommended to insert TDR probe in uniformly wet soils. In difficult situations, the core rod of the probe must be inserted in the wet part of the soil to have, at least, a good approximation.

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