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Soil Water Measurement by Time Domain Reflectometry

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INTRODUCTION

Time domain reflectometry (TDR) became known as a useful method for soil water content and bulk electrical conductivity measurement in the 1980s through the publication of a series of papers by Topp, Dalton and others. [1—5] Automated TDR systems for water content measurement have been described in Refs. 6—10. Commercial systems became available in the late 1980s and continue to evolve with TDR instruments, probes, and multiplexers (e.g., see Ref. 11) available from a few companies.

THEORY

In the TDR method, a very fast rise time (approx. 200 ps) step voltage increase is injected into a waveguide (usually coaxial cable) that carries the pulse to a probe placed in the soil or other porous medium (Fig. 1). The velocity of the pulse in the probe is measured and related to soil water content, with smaller velocities indicating wetter soils. In a typical field installation, probes are connected to the instrument through a network of coaxial cables and multiplexers. Part of the TDR instrument (e.g. Tektronix[1] model 1502B/C) provides the voltage step and another part, essentially a fast oscilloscope, captures the reflected waveform. The oscilloscope can capture waveforms that represent all, or any part of, the waveguide (this includes cables, multiplexers and probes), beginning from a location that is actually inside the instrument. For example, Fig. 1 shows a waveform that represents the waveguide from a point inside the cable tester, before the step pulse is injected, and extending beyond the pulse injection point to a point that is 4.2 m from the cable tester. The relative height of the waveform represents a voltage, which is proportional to the impedance of the waveguide. Although most TDR instruments display the horizontal axis in units of length (a holdover from the primary use of these instruments in detecting the location of cable faults), the horizontal axis is actually measured in units of time.

The TDR instrument converts the time measurement to length units by using the relative propagation velocity factor setting, v_p, which is a fraction of the speed of light in a vacuum. For a given cable, the correct value of v_p is inversely proportional to the permittivity, ε, of the dielectric (insulating plastic) between the inner and outer conductors of the cable

$$v_p = v/c_o = (\varepsilon\mu)^{-0.5} \quad (1)$$

where v is the propagation velocity of the pulse along the cable, c_o is the speed of light in a vacuum, and μ is the magnetic permeability of the dielectric material. For a TDR probe in a soil, the dielectric between the probe rods is a complex mixture of air, water and soil particles that exhibits a variable apparent permittivity, ε_a. Water is the largest determinant of permittivity in soils. It has a permittivity of approx. 80, whereas the permittivity of soil minerals varies in the range of 3 to 5; the permittivity of organic matter is likewise low; and the permittivity of air is unity. Also, soil water is the only rapidly changing determinant of ε_a. Thus, we are able to usefully calibrate soil water content vs. measured ε_a. The fact that frozen water has a low permittivity impedes accurate measurement of frozen water content, but allows the use of TDR for investigations of freezing depth and extent. [12]

The TDR method relies on graphical interpretation of the waveform reflected from that part of the waveguide that is the probe (Fig. 2). An example of waveform interpretation for a 20 cm TDR probe in wet sand shows how tangent lines are fitted to several waveform features (Fig. 3). Intersections of the tangent lines define times related to (i) the separation of the outer braid from the coaxial cable so that it can be connected to one of the probe rods in the handle, *t1.bis*; (ii) the time when the pulse exits the handle and enters the soil, *t1*; and (iii) the time when the pulse reaches the ends of the probe rods, *t2*. The time taken for the step voltage pulse to travel along the probe rods, $t_t = t2 - t1$, is related to the propagation velocity as

$$t_t = 2L/v \quad (2)$$

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

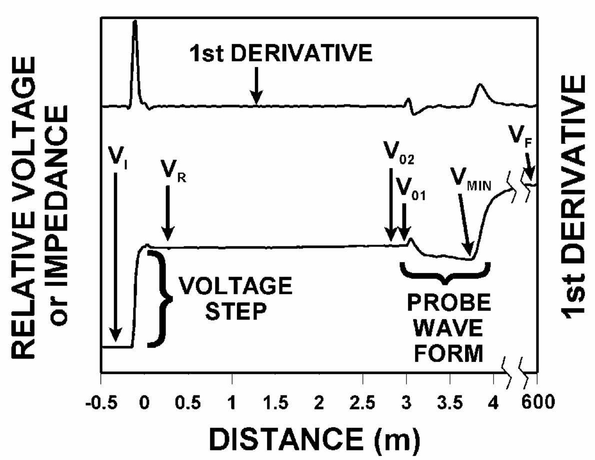

Fig. 1. Plot of waveform and its first derivative from a Tektronix 1502C TDR cable tester set to begin at -0.5 m (inside the cable tester). The voltage step is shown to be injected just before the zero point (BNC connector on instrument front panel). The propagation velocity factor, v_p, was set to 0.67 because electricity travels at 0.67 of the speed of light in the coaxial cable. At 3 m from the instrument, a TDR probe is connected to the cable. The relative voltage levels, V_I, V_R, etc. are used in calculations of the bulk electrical conductivity of the medium in which the probe is inserted. Inflections in the first derivative of the waveform are used in software or firmware to help determine pulse travel times, which, for the probe, are proportional to water content.

where L is the length of the rods (Fig. 2), and the factor 2 signifies two-way travel.

Substituting ε_a and Eq. 2 into Eq. 1, and assuming $\mu = 1$, one sees that ε_a may be determined for a probe of known length, L, by measuring t_t

$$\varepsilon_a = [c_o t_t/(2L)]^2 \tag{3}$$

Topp et al. [1] found that a single polynomial function described the relationship between volumetric water content, θ_v, and values of ε_a determined from Eq. 3 for four mineral soils.

$$\theta_v = (-530 + 292\varepsilon_a - 5.5\varepsilon_a^2 + 0.043\varepsilon_a^3)/10^4 \tag{4}$$

Since 1980, other researchers have noted that the quantity $[t_t/(2L)]$ in Eq. 3 is quadratic, and have shown that the relationship between θ_v and $t_t/(2L)$ is practically linear (e.g., Ref. 15). Several attempts have been made to predict ε_a of soils from theoretical considerations using dielectric mixing models that

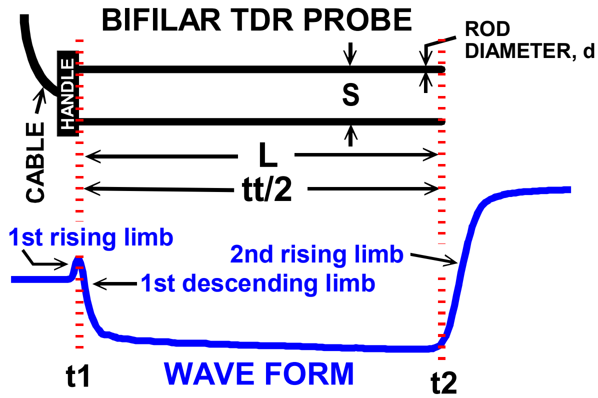

Fig. 2. Schematic of a typical bifilar TDR probe and the corresponding waveform, illustrating probe rod length, L; one way travel time, $t_t/2$; rod spacing, s; and rod diameter, d.

consider the volumetric proportions of soil mineral, organic, water, and air constituents, as well as soil mineralogy and particle shape and packing considerations (e.g., Refs. 16—8). Success could lead to a more universal calibration, but has been elusive; [19] so that Eq. 4 and like empirical calibrations for specific soils (particularly electrically conductive soils including clays with high charge, and organic soils) are still considered to be the accepted standards.

APPLICABILITY

For most soils, excluding those very high in organic matter (OM>10%), the TDR method provides water content in the range from zero to 0.5 m^3 m^{-3} with accuracy better than 0.01 to 0.02 m^3 m^{-3} without calibration. With calibration, accuracy of better than 0.01 m^3 m^{-3} for a specific soil is attainable. Repeatability is excellent, with standard deviations of measurement ranging from 0.0006 m^3 m^{-3} (11) to 0.003 m^3 m^{-3}.[8] Probe lengths reported in the literature range from 0.05 to 1.5 m. Probe rod spacing, s, may vary also, so long as $d/s \le 0.1$ where d is the rod diameter (Fig. 2). [20] As d/s becomes much smaller than 0.1, the volume of soil sensed becomes very small and TDR measurements may become overly sensitive to soil heterogeneity close to the rods. Because of this flexibility in probe width and length, TDR probes may be designed to measure a wide range of soil volumes. Because the volume measured extends only 1 to 2 cm

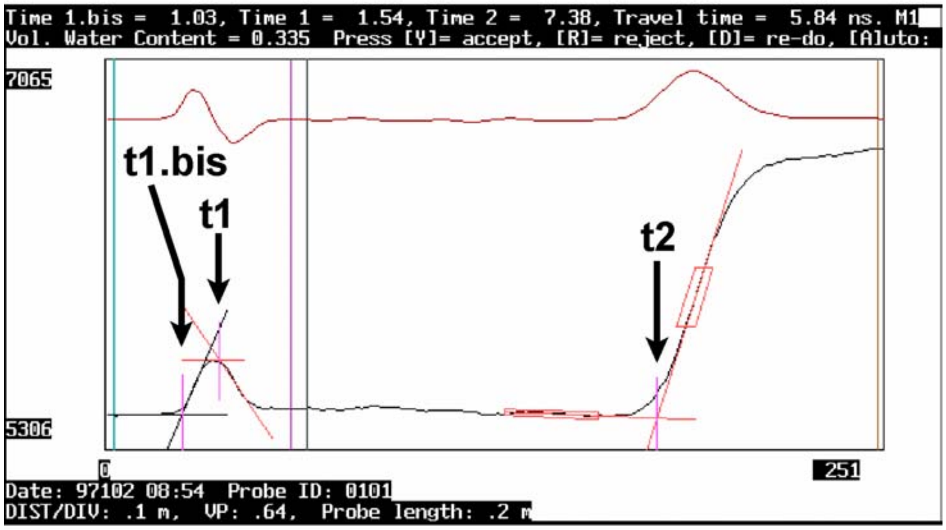

Figure 3. Example of graphical interpretation of a waveform from a probe in wet sand using the TACQ computer program.[13, 14] Vertical lines denoting times t1.bis, t1, and t2 have been marked by arrows and labels. The first peak in the waveform occurs just before t1. A horizontal line, drawn tangent to the waveform base line at the far left, intersects with a line drawn tangent to the first rising limb of the waveform to define t1.bis. A horizontal line drawn tangent to the peak intersects with a line drawn tangent to the descending waveform after the peak to define t1. Time t2 is defined by the intersection of a line fitted to the waveform before t2, and a line fitted to the second rising limb of the waveform after t2. The water content is calculated from Eq. 4. The width of the waveform window is 1 m, or 5.2 ns with the cable tester set to $v_p = 0.64$.

above and below the plane of the rods for most probe designs, TDR is ideal for measurements in thin layers near the soil surface. It is also very useful in root water uptake studies where information from discrete parts of the root zone is desired. Because TDR accurately integrates soil water content changes occurring along the length of the probe rods, TDR probes may be inserted vertically into soils to accurately assess mean water content over the length of the rods, even in soils exhibiting sharp water content changes with depth.

WAVEFORM INTERPRETATION

Graphical interpretation (e.g., Fig. 3) depends on the fact that the probe design itself introduces impedance changes in the waveguide. The impedance, Z (Ω), of a transmission line (i.e. waveguide) is

$$Z = Z_0(\varepsilon)^{-0.5} \quad (5)$$

where Z_0 is the characteristic impedance of the line (when air fills the space between conductors) and ε is the permittivity of the homogeneous medium filling the space between conductors. For a parallel transmission line (the two rods in the soil), the characteristic impedance is a function[21] of the wire diameter, d, and spacing, s (Fig. 2):

$$Z_0 = 120 \ln\{2s/d + [(s/d)^2 - 1]^{0.5}\} \quad (6)$$

or, if $d \ll s$:

$$Z_0 = 120 \ln(2s/d) \quad (7)$$

For a coaxial transmission line, the characteristic impedance is:

$$Z_0 = 60 \ln(D/d) \quad (8)$$

where D and d are the diameters of the outer and inner conductors, respectively.

From Eqs. 5—8 it is apparent that impedance, Z, increases as wire spacing increases, and decreases as ε (or water content) increases for any probe type (Fig. 4). In the probe handle, the wire spacing increases from that of the coaxial cable to that of the probe rods. The resulting impedance increase causes the waveform level to rise (first rising limb in Fig. 2). If the porous medium in which the probe rods are embedded is wet,

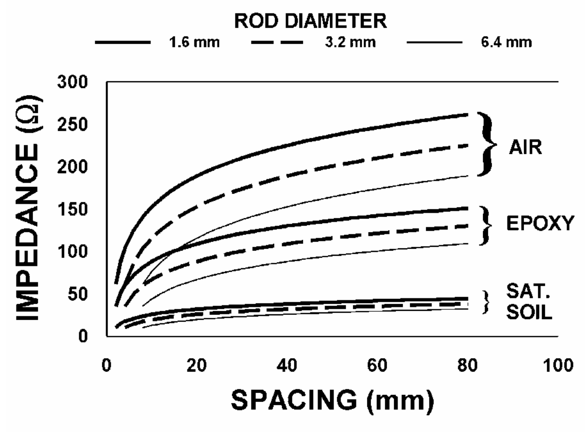

Figure 4. Influence of rod spacing, rod diameter, and permittivity of the medium on impedance of the waveguide according to Eq. 6. Permittivities are: AIR, unity; EPOXY, close to 3; and SATurated SOIL, approx. 35.

then the permittivity of that medium will be higher than that of the epoxy probe handle. This causes a decrease in impedance, which results in the descent of the reflected waveform level as the step voltage leaves the handle and enters the rods in the soil (first descending limb, Fig. 2). The combination of impedance increase at the handle and impedance decrease after the handle gives the peak in the waveform. The rod ends are another impedance change in the waveguide, in this case an open circuit. The remaining energy in the voltage step is reflected back at the rod ends, which represent an impedance increase (second rising limb, Fig. 2). Although a bifilar probe design is illustrated in Fig. 2, the most common design uses three parallel and coplanar rods. Such trifilar probes are electrically unbalanced (signal is on the middle rod) as is the connecting coaxial cable. Thus, impedance is more closely matched between cable and probe and the waveform has less noise and is more easily interpretable. [22]

Waveform shapes different from those shown in Figs. 1—3 result from different soil types and conditions (e.g. dry soil, saline soils, wet clays, etc.). Different methods from the literature, used for graphical interpretation of the waveform, can cause errors in water content as large as 0.05 m^3 m^{-3}.[14] Therefore, choice of interpretation methods or computer programs for automatic interpretation is important. Manufacturers' equipment contains embedded interpretation algorithms that are not usually made public. Two computer programs available to the public and well documented are TACQ[13, 14, 23] and WinTDR.[24] An improved signal to noise ratio results from the shorting diode approach[25] in which the waveform is alternately captured with and without the probe shorted to ground at the ends of the rods. This approach has not been popular however, due to increased cost and complexity of switching, and problems with designing probes that ensure signal penetration into the soil.

BULK ELECTRICAL CONDUCTIVITY MEASUREMENT

An important use of the TDR method is to calculate the soil bulk electrical conductivity (BEC) from values of the waveform relative voltage or impedance at various points along the waveguide (Fig. 1) (e.g. Refs. 2—5, 22, 26—30). The measured load impedance, Z_L, (ohms) is used in most methods of calculating bulk electrical conductivity:

$$Z_L = Z_{REF}(1 + \rho)/(1 - \rho) \tag{9}$$

where Z_{REF} is the output impedance of the cable tester (e.g. 50 ohms), and:

$$\rho = E\text{-}/E\text{+} \tag{10}$$

where

$$E\text{-} = V_F - V_{O2} \tag{11}$$

$$E\text{+} = V_{O2} - V_I \tag{12}$$

and where V_{O2}, V_I, and V_F are defined in Figure 1. For most methods, only V_{O2}, V_I, and V_F are needed. Calculation of BEC from TDR data is still a subject of active research. The other values of relative voltage illustrated in Fig. 1 are used in other methods of calculating BEC reported in the literature. The TDR method has even been extended to measurement of atmospheric CO_2 based on the solution electrical conductivity increase caused by its dissolution in water.[31]

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