I. TDR Theory

A. Determination of volumetric water content with TDR

Over the past three decades, TDR has become an accepted standard method for measuring volumetric water content (θ) of soils. With TDR, the propagation time of a fast rise electromagnetic wave along a transmission line (the TDR waveguide) is measured. The properties of the soil surrounding the TDR waveguide govern the propagation of the TDR pulse. The apparent dielectric permittivity of the soil (ε_{ra}) determines the speed of the wave propagation along the waveguide

$$v = \frac{c}{\div\varepsilon_{ra}} \qquad 1$$

where c is the speed of light in a vacuum (3×10^8 m/s) and v is the velocity of the electromagnetic wave (m/s). If the two-way travel time (t) is measured, v can be calculated

$$v = (2L/t) \qquad 2$$

where L is the length of the TDR waveguide. Combining equations 1 and 2 gives

$$\div\varepsilon_{ra} = (ct/2L)^2 \qquad 3$$

equation 3 can also be expressed as

$$\div\varepsilon_{ra} = L_a/L \qquad 4$$

where $L_a = ct/2$ and is the apparent length of the TDR waveguide.

Because the ε_{ra} of unfrozen water (~80) is much greater than the ε_{ra} of the other soil constituents (1-7), the ε_{ra} of bulk soil is strongly dependent on the unfrozen volumetric water content of the soil. A variety of empirical formulas equating ε_{ra} to θ have been developed. Topp & Reynolds (1998) found the relationship

$$\theta = 0.115 \div\varepsilon_{ra} \ \text{-}0/176 \qquad 5$$

to be widely applicable over a variety of soils.

The two-way travel time of the electromagnetic wave must be measured to achieve measurement of θ. A variety of instruments are available that will perform this measurement. In general, these instruments introduce a fast rise electromagnetic wave to the transmission line. The impedance change at the junction of the coaxial cable and the TDR waveguide reflects a signal back to the instrument, and the instrument records the magnitude of the reflected voltage or the reflection coefficient as a function of time. The beginning and end of the probe reflections are identified on the time-series waveform, and the two-way travel time is either calculated manually with a PC or automatically with the TDR instrument. Volumetric water content is then calculated from equations 3 and 4 or any of a variety of other empirical equations taken from the extensive TDR literature or developed by the user for specific media or applications.

B. Determination of electrical conductivity with TDR

When a TDR waveform is analyzed, the propagation time is dependant on the soil dielectric permittivity, while the amplitude of the reflected signal is dependant on the conduction of applied signal between the probe rods. The magnitude of the reflected signal is attenuated by ionic conduction in the soil solution. This inherent property is used to measure the bulk electrical conductivity of the soil solution with TDR. A commonly used expression describing this relationship is

$$\sigma = \frac{k_p}{z_c}\frac{1-\rho}{1+\rho} \qquad 6$$

where σ is the soil bulk electrical conductivity, k_p is the probe constant, z_c is the cable impedance (50 Ω), and ρ is the reflection coefficient, which is the ratio of the reflected voltage to the applied voltage, and ranges between -1 and 1. k_p can be determined by measuring ρ in solutions of known electrical conductivity, and is generally in the range of 7.5 – 8.5 (for output of S/m) for East 30 Sensors probes. The value of k_p should be determined individually for each East 30 Sensors waveguide. This can be accomplished easily with PCTDR if the Campbell Scientific TDR 100 system is used. Another method is to immerse TDR waveguides in several different solutions of known electrical conductivity and measure ρ. The known electrical conductivity is then regressed against

$$\frac{1}{z_c}\frac{1-\rho}{1+\rho}$$

, and the slope of the regression is k_p. This method is suggested if a high degree of accuracy is desired in bulk electrical conductivity measurements.

II. TDR measurements in high electrical conductivity soils

TDR reflected signal amplitude decreases as electrical conduction occurs between the probe rods. This inherent characteristic allows the measurement of bulk soil electrical conductivity (σ). However, this signal attenuation can affect the accuracy and resolution of volumetric water content measurement. In cases where the soil electrical conductivity is excessive, the reflected signal can be quenched, making volumetric water content and electrical conductivity measurements impossible.

A unique characteristic of East 30 Sensors mini-TDR model T-3 probes is the short length of the waveguides. Baker et al. (1996) showed that the maximum electrical conductivity that be measured by TDR is

$$\sigma_{\max} = \frac{\varepsilon_0 c}{L}\left\{\frac{Z_0}{Z_u}\right\}\beta_{\max} \qquad 7$$

where ε_0 is the permittivity of free space, c is the speed of light, Z_0 is the probe impedance, Z_u is the characteristic impedance of the cable tester, and $\beta_{\max}$ is a limiting quantity set by the cable tester. The only two quantities which may be altered by the user are the probe length L and the probe impedance Z_0. It is apparent from equation 7 that the maximum measurable electrical conductivity is inversely proportional to the length of the TDR waveguide. Therefore, signal attenuation is less pronounced with the East 30 Sensors probes, and these probes can make volumetric water content and electrical conductivity measurements in high electrical conductivity soils where longer probes fail.

A brief laboratory study was conducted to determine the approximate electrical conductivity threshold where signal attenuation prevents useful information from being derived from TDR waveforms with the East 30 Sensors probes. A fine textured soil (Houston Black Clay) was brought to water content somewhat beyond saturation ($\theta \approx 0.55$ m^3/m^3) with tap water. Monovalent and divalent soluble salts (NaCl and $CaCl_2$) were added to the soil paste to increase the electrical conductivity incrementally. After thorough mixing, the electrical conductivity of the soil paste was measured with a electrical conductivity meter (Cond 315i Set, WTW Measurement Systems, Ft. Meyers, FL). TDR waveforms were then collected from the soil paste with East 30 Sensors probes read by a Campbell Scientific TDR 100, and analyzed with Campbell Scientific PCTDR. At paste electrical conductivities $<$ 5.8 dS/m, no difficulties were encountered in reading and analyzing waveforms with PCTDR. However, at electrical conductivities $>$ 6.5 dS/m, the endpoint of the probe reflection was seldom recognizable. It should be noted that the absolute accuracy of the measurements of θ and electrical conductivity were not evaluated here, and numerous studies (i.e. Hook et al., 2004) have shown that the accuracy of TDR measurements of θ suffer in high electrical conductivity media.

East 30 Sensors probes are designed to interface with any standard coaxial cable tester or TDR control/analysis system. However, East 30 Sensors recommends and supports applications using the Campbell Scientific TDR 100 system and Campbell Scientific SDMX50 TDR multiplexers. Information on the CSI TDR100 system is available for download at http://campbellsci.com/tdr.html#tdr100, including manuals, application notes, and support software. The information available here will help the user interface East 30 Sensors probes with the TDR 100 system, measure all necessary probe characteristics (i.e. k_p, probe offset), and develop a good general knowledge of TDR theory and application. If a deeper understanding of TDR theory is desired, an excellent starting reference is Methods of Soil analysis Part 4: Physical Methods.

References

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