

Abstract

Time Domain Reflectometry (TDR) is becoming the method of choice for measurement of water content and electrical conductivity in earth materials. New TDR devices designed specifically for measurements in porous media are cheap, robust, and amenable to automation for continuous monitoring. TDR probes are often designed for direct insertion into soil or rock using only a few conductors to minimize disturbance while providing a representative sampling volume. Permittivity measurement and interpretation is often affected by ambient conditions and media physical properties. Solid surfaces hinder the rotational freedom of water at a greater extent with increasing surface area of the porous material and are also influenced by temperature. Saline soils are electrically conductive to the point of completely attenuating the TDR signal using conventional probe designs (e.g., 15 cm length). Innovative techniques for reducing signal attenuation or otherwise preserving waveform information, thereby extending the range of permittivity measurements in lossy porous media will be presented.

TDR Applications in Earth Sciences

The primary use of TDR in earth sciences is for measurement of bulk permittivity of moist porous media, ϵ , for inference of their volumetric water content, θ , (Topp et al., 1980). Standard interpretation of ϵ is based on travel time analysis along a probe embedded in the porous medium of interest. Additionally, TDR is capable of simultaneous measurement of permittivity, and electrical conductivity (EC) in the same soil volume (using the same probe) as was first demonstrated by Dalton et al. (1984). Figure 1 illustrates TDR signal travel time obtained from waveform reflections and the influence of EC as given by the ratio of waveform voltages, V_0 and V_f , written as

$$\epsilon = \left(\frac{c(t_2 - t_1)}{2L} \right)^2 \quad EC = \frac{K}{Z_c} \left(\frac{2V_0}{V_f} - 1 \right)$$

where c is the speed of light, L is probe length, K is the probe geometrical constant and Z_c is the cable impedance. In geotechnical applications, TDR has been applied to monitoring landslide and slope stability. Typical environmental applications include measurement of soil transport properties for ionic solutes under steady and non-steady flow conditions, monitoring of water and nitrogen status in plant root zone, and characterization of distribution of water and fertilizers in irrigated lands.

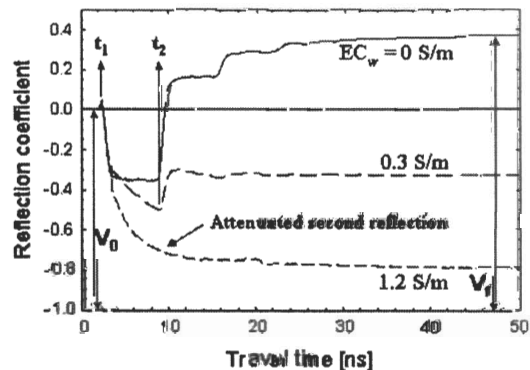


Figure 1. Waveform travel time analysis yields porous media permittivity. Analysis fails if the second reflection becomes completely attenuated. Electrical conductivity (EC) is obtained from the ratio of V_0/V_f .

Typical Probe Designs

A number of different geometrical probe configurations have been proposed based on an approximation to a coaxial design. Field applications requiring probe insertion into soils or rock necessitate minimization of conductor cross-sectional area. Probes typically have a single central conductor and from 1 to 6 outer conducting rods (Figure 2). The 2-wire probe has the advantage of minimal soil disturbance, but produces an unbalanced signal, leading to unwanted noise and signal loss (White and Zegelin, 1995). This problem may be minimized using a balun embedded in the probe head. The 3- or higher-rod probes provide a balanced signal, avoiding the balun requirement at the expense of additional soil disturbance. Though not commonly used in soils, the parallel plate probe provides a more uniform electrical field between plates. The highly concentrated electrical field converging on the central conductor of the multi-wire probes (Figure 2), more heavily weights the dielectric constant of constituents within this region. Ferre et al. (1998) demonstrated that two-rod probes have a much larger sample area compared to 3-rod, and that thin rod coatings (for reducing conductive losses) for any probes will reduce sampling area of the probe. Measurement error increases as air gaps develop when probes are repeatedly inserted and removed, or used in shrink-swell soils.

For conventional probe designs, water content is often assumed to be uniformly integrated along the probe's longitudinal axis. A recent study by Chan and Knight (1999) cautions against the accepted notion that if water is evenly distributed along the rods or concentrated in one or more 'pockets', the same measured mean dielectric constant results. Their analysis is based on the wavelength (λ) to layer (heterogeneity) thickness (t) ratio, λ/t . For $\lambda/t > 10$ the dielectric constant of the soil is computed as an arithmetic average (effective medium theory) of the layers, while for $\lambda/t < 1$ the geometric average (Ray theory) of the soil layers is used to compute the soil dielectric constant. Scattering effects which occur within the transition zone, $1 < \lambda/t < 10$, may cause measurement difficulties; the propagation direction of the EM wave relative to the layering is also an important consideration.

The particular spatial sensitivities of different probe configurations can be used to one's advantage in specific research applications. For example, a 2- or 3-rod probe placed horizontally serves as an effective point (plane) measurement for water or solute fronts moving vertically through soil profiles. Seven-rod or parallel plate designs, on the other hand, sample a more uniform spatially-weighted volume of soil which may be advantageous for some applications. Other TDR measurement techniques have been developed which provide information on the soil water energy status or matric potential, h , (Wraith and Or, 1999). These

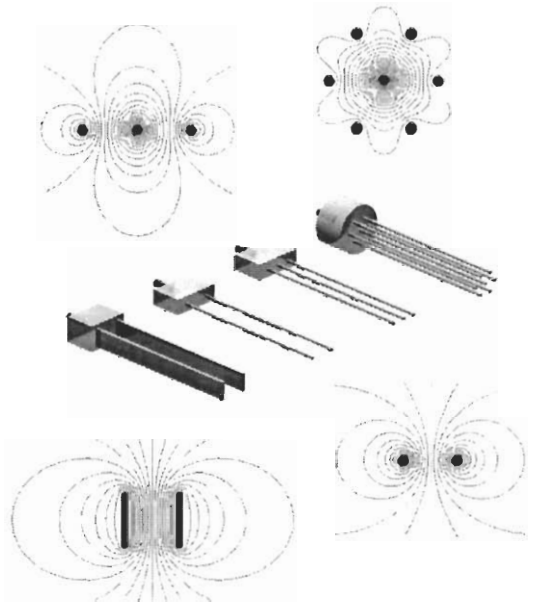


Figure 2. A variety of TDR probe geometries for earth sciences have been proposed, including multi-rod and parallel plate devices. Equipotential lines illustrate probe sampling area and fewer conductors mean less soil disturbance.

techniques may be used separately or paired with conventional probe designs to obtain simultaneous in situ measurements of water content and matric potential from which the soil water characteristic relationship, $\theta(h)$, may be elucidated.

Influence of ambient conditions on ϵ measurements

Water content is often the principle object of permittivity measurements. Its large dielectric constant (80) provides excellent contrast between permittivities of solids (5) and air (1). When the majority of water is in a free state, the permittivity of low surface area (sands) wet porous media decreases with increasing temperature (Figure 3a). However, water molecules in the vicinity of solid surfaces (1 to 3 monolayers) are subjected to interfacial forces that render them

rotationally hindered, and thereby reduce their permittivity relative to that of free water. High surface area porous media (e.g., clay minerals) bind a substantial fraction of the water phase, resulting in an increase in the dielectric with increasing temperature as shown in Figure 3b. This phenomenon is thought to be due to a reduction of the bound water layer thickness (bound water shifting to a free state), without any changes in the total mass of water (Or and Wraith, 1999). Interestingly, measurements of the dielectric response of wetted porous media under changing temperature may be useful in estimating the specific surface area ($m^2 kg^{-1}$), because of the fundamental relationship between bound water and solid surface area (Wraith and Or, 1999). Dielectric mixing theories describe the combined bound- plus free-water dielectric constant based on surface area and bulk density (Friedman, 1998) and temperature dependence (Jones and Or, 2001a).

Measurements in lossy porous media

This unique ability of TDR to measure both soil water content, θ , and apparent soil electrical conductivity, EC, using the same instrumentation and probes, and in the same soil volumes, has provided new opportunities to investigate salinity and the behavior of ionic solutes in soils. Critical frequencies for measurement of dielectric constant based on TDR travel-time are near 1 GHz, while The TDR EC measurement utilizes the lowest frequencies available (low kHz range). Measurement of electrical conductivity using TDR is based on attenuation of the applied signal voltage as it traverses probes buried in porous media. The signal energy is attenuated in proportion to the electrical conductivity of the solids and liquids encountered along the travel path. This proportional reduction in signal voltage is accurately related to the bulk soil electrical conductivity shown in Figure 1. Methods have been proposed to extend permittivity measurements in lossy porous media, including thin probe coatings and the use of shorter TDR probes (for reduced waveform attenuation), coupled with discrete fast Fourier transformation (DFFT) of the waveform. Jones and Or (2001b) have recently demonstrated the potential for extending

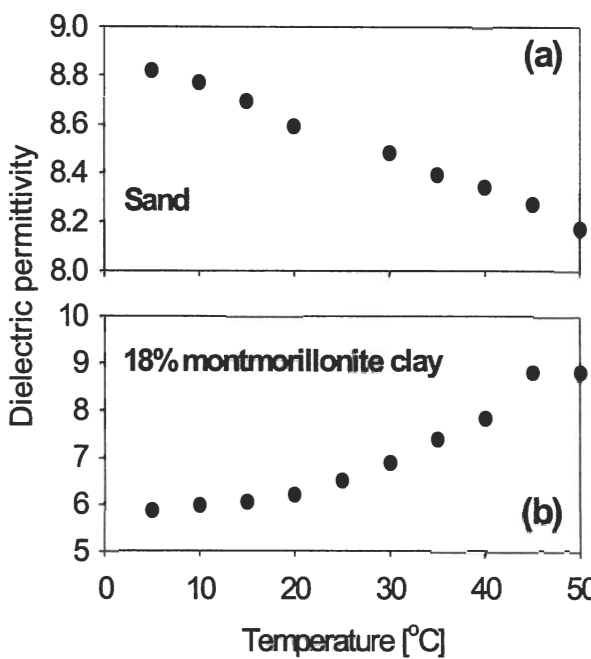


Figure 3. Effect of temperature on the permittivity of sand and a sand-clay mixture exhibiting the role of bound water in high surface area porous media.

the range of permittivity measurements in lossy porous media by modeling the frequency-dependent scatter function (S11), using the Cole-Cole (1941) model. The harmonics of the transformed waveform (Figure 4) were preserved well beyond typical EC levels (beyond 3 S/m) at which travel time analysis fails due to loss of the second reflection (Figure 1).

Outlook

A particularly important advantage of TDR relative to other methods is its ability to provide intensive time series measurements, at multiple locations, which are critical to resolution of many hydrological processes. Concurrent measurement of both θ and EC has also provided new research and management opportunities. Since its introduction in the early 1980's, the TDR method has stimulated increased interest in other electromagnetic methods based on different principles ranging from capacitance to frequency-shift sensors. This trend will undoubtedly continue with advances in technology and with reduction in costs of electronic components; there are already available several stand-alone and relatively inexpensive sensors for water content measurement based on dielectric properties. Moreover, the application of alternative methods of analysis such as frequency domain techniques provides a means to extend the useful range of utility as well as a potential for extraction of supplementary information concerning water and its interactions with porous media. Some potentially useful applications derived directly from the TDR method include measurement of specific surface area, and in situ determination of water retention properties of field soils.

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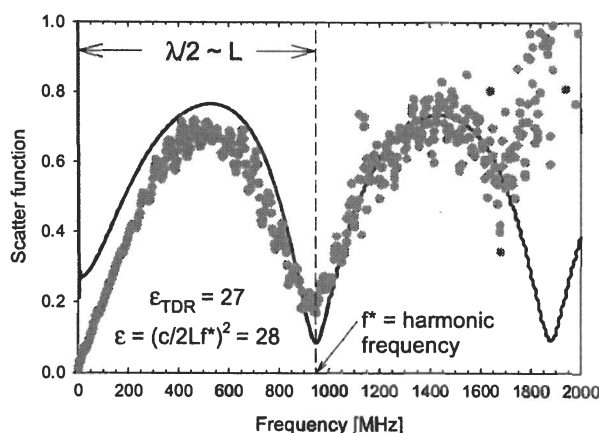


Figure 4. S11 function for saturated Millville silt loam with solution EC of 0.6 S/m measured using a 3 cm TDR probe and DFFT of the waveform.