REAL TIME MONITORING OF INFRASTRUCTURE USING TDR TECHNOLOGY : PRINCIPLES

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ABSTRACT

This presentation is intended to provide background on the principles involved in geotechnical and infrastructure applications of Time Domain Reflectometry (TDR). TDR is basically radar in which a voltage pulse is launched along a coaxial cable. A reflection of the voltage pulse occurs at every location where the cable is being deformed and each location is distinguished by the reflection travel time. For example, localized shear in a rock or soil mass will deform a cable grouted into a borehole and the TDR reflection magnitude is proportional to the magnitude of cable deformation. In one variation of this principle, a hollow coaxial cable can be installed in a monitoring well and a reflection will occur at the air-water interface. This strong reflection makes it possible to monitor changes in water level. In another variation, parallel rods can be embedded in soil and TDR is used to measure travel time of pulses reflected from the ends of the rods. The voltage pulse travel time is proportional to the dielectric constant of soil which is heavily influenced by changes in free-water content and makes it possible to monitor changes in water content using TDR. This paper presents a summary of the principles involved in these various applications and a companion paper presents case histories of infrastructure monitoring. This paper begins with a discussion of pulse testing then defines transmission line parameters pertinent to TDR technology. This is followed by defining the TDR reflection coefficient and how it is used to measure cable deformation. Finally, the paper discusses measurement of pulse propagation velocity and how it is used to measure changes in soil water content.

PULSE TESTING

Time Domain Reflectometry (TDR) is a remote sensing electrical measurement technique that has been used for many years to determine the spatial location and nature of various objects (Andrews, 1994). Radar is an early form of TDR, dating from the 1930s, with which most people are familiar. Radar consists of a radio transmitter which emits a short pulse of electromagnetic energy, a directional antenna, and a sensitive radio receiver. After the transmitter has radiated the pulse, the receiver then listens for an echo to return from a distant object, such as an airplane or ship. By measuring the elapsed time between transmission and echo, the distance to the reflecting object may be easily calculated. Detailed analysis of the echo can reveal additional details of the reflecting object which aid in identification. The same principles that hold for radar also hold for metallic cable TDR.

There are a number of commercially available cable testers and the Tektronix 1500 series is a typical example (Figure 1). An ultra-fast rise time (200 psec) voltage step is launched into a test cable every 200 µsec. When the pulses encounter a change in characteristic impedance (i.e., a cable fault), reflected pulses are returned to the cable tester. Many transmitted and reflected pulses are generated by the TDR which displays a stable scan. This scan is a plot of reflection coefficient (i.e., ratio of reflected to transmitted voltage) versus travel time. The travel time of each reflection uniquely determines each cable fault location. Additional information can be obtained by analyzing the sign, length, and amplitude of a TDR reflection (e.g., the negative spike displayed on the screen in Figure 1) which define the type and severity of the cable fault.

TRANSMISSION LINE PARAMETERS

There are a variety of transmission lines that can be interrogated using TDR. These include parallel wire cables and coaxial cables. Propagation of voltage pulses along these cables, as well as the creation and characteristics of reflected pulses, can be described using circuit theory or Maxwell's equations of electromagnetic wave theory. Details can be found in O'Connor and Dowding (1999).

A coaxial cable is composed of an outer and inner conductor as shown in Figure 2a. In a longitudinal view,

Figure 1. TDR cable tester; shown with X-Y recorder that can be interchanged with a serial communications port for acquisition of digital TDR traces. The negative spike TDR reflection in the middle of the screen is created by a crimp in the cable being interrogated.

the cable may be represented by an ideal, two-wire transmission line having forward and return conductors to represent the outer and inner conductor respectively (Figure 2b). A voltage pulse, V, is launched into the line and creates a potential difference between the two conductors. As the voltage pulse propagates, the potential difference creates current, I, along and between the conductors. Propagation of a pulse along a coaxial cable, i.e., the current and voltage propagating along a two-wire transmission line, can be described using the four parameters shown in Figure 2c:

1) the voltage difference between the outer and inner conductors depends on the cable's capacity to store electric energy which is expressed as capacitance, C, in units of farads per meter;
2) current flowing along the conductors induces a magnetic field, the strength of which is controlled by the cable inductance, L, in units of henries per meter;
3) the dissipation of energy is denoted by resistance, R, in units of ohms per meter;
4) the dielectric between the two conductors has a small conductivity, G, in units of siemens per meter which also dissipates energy.

The propagation constant of a transmission line is defined as (Spergel, 1972; Dworsky, 1979)

$$\gamma = \sqrt{ZY} = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{1}$$

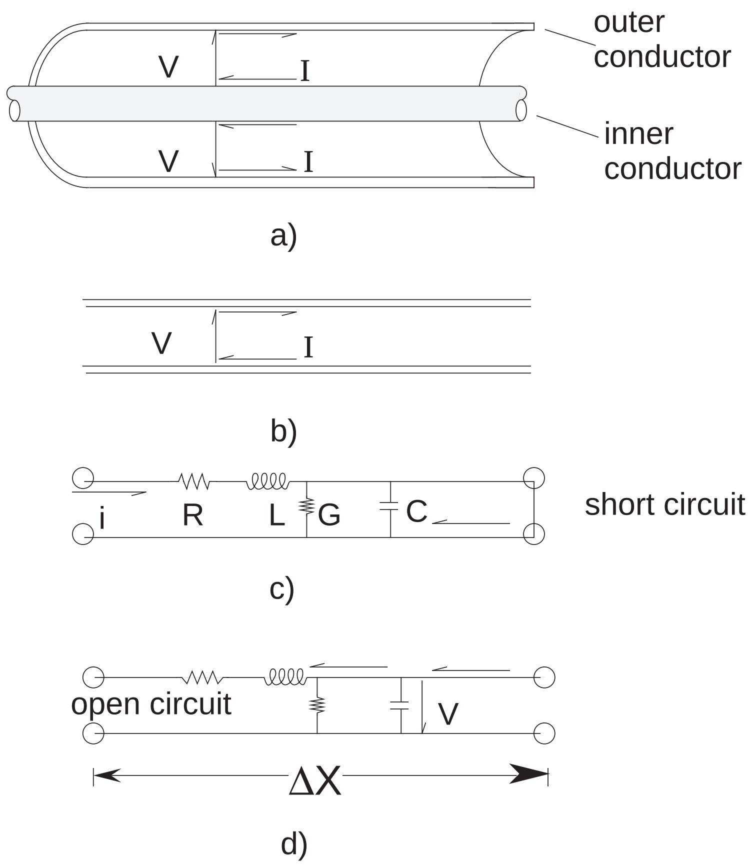


Figure 2. Lumped transmission line parameters:
(a) coaxial cable; (b) parallel wire transmission line;
(c) lumped parameters with short circuit to define
impedance, ZI=RI+jωLI; (d) lumped parameters with open
circuit to define admittance, YV=GV+jωCV(Spergel,1972).

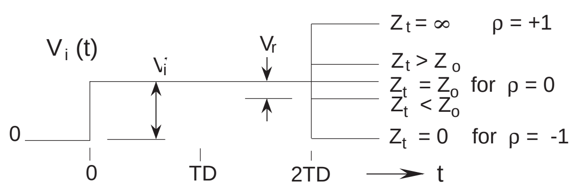
Another important parameter is the characteristic impedance of the transmission line in units of ohms,

$$Z_o=\sqrt{\frac{Z}{Y}}=\sqrt{\frac{R+j\omega L}{G+j\omega C}}\ . \qquad (2)$$

The angular frequency $\omega = 2\pi f$ so that for radio frequencies (f = 0.3 MHZ to 30 GHz), $R \ll \omega L$ and $G \ll \omega C$. So, the transmission line parameters are dominated by L and C, and the propagation constant in Equation 1 becomes

$$\gamma = \sqrt{LC}. \qquad (3)$$

Its inverse is the propagation velocity with which an electromagnetic wave can travel along the transmission line



a)

Figure 3. TDR traces for ideal resistive terminations. TD = time delay between transmission of pulse and return of reflected pulse.

$$V_p = \frac{1}{\sqrt{LC}} \tag{4}$$

and it is typically expressed as a percentage of the speed of light (e.g., V_p = 0.81, or 81% of 3 x 10^8 m/sec). The characteristic impedance of a transmission line from Equation 2 is

$$Z_o = \sqrt{\frac{L}{C}} \ . \tag{5}$$

TDR REFLECTION COEFFICIENT

The reflection observed with a TDR cable tester depends on several factors, including the type of cable fault. It is a major advantage of TDR that you can locate faults by virtue of the travel time and also identify the type of cable fault by the reflection characteristics. Faults are basically changes in the transmission line properties (R, C, and L) which are measured as changes in impedance (Z) using TDR. We assume that the TDR unit launches a step voltage pulse of magnitude V_i as shown in Figure 3. When it reaches the end of the cable, a portion of the voltage is reflected. The reflected voltage, V_r, is displayed by the TDR unit as the reflection coefficient, ρ or rho, which is defined as

$$\rho = V_r \ / \ V_i \ . \tag{6}$$

When electromagnetic wave theory is used to arrive at the transmission line parameters, the solution of the wave equation contains the term (Dworak et al., 1977)

$$\rho = (Z_t - Z_o)/(Z_t + Z_o) \tag{7}$$

which is the reflectivity due to a load impedance mismatch. This expression is equivalent to the reflection coefficient in Equation 6. Rearranging terms,

$$Z_t = Z_o * (1+\rho)/(1-\rho). \tag{8}$$

TDR reflections for various pure resistive terminations, $Z_t = R_t$, are shown in Figure 3 (Andrews, 1994). If a 50 ohm termination is connected to the end of a 50 ohm coaxial cable, $Z_t = Z_o$ and $\rho = 0$. For an open circuit, $Z_t = \infty$ ohms and $\rho = +1$. For a short circuit, $Z_t = 0$ ohms and $\rho = -1$. If Z_t is greater than Z_o, then a positive step is observed. For Z_t less than Z_o, a negative step is observed. The actual value of Z_t may be calculated from the reflection coefficient displayed by the TDR unit. Equations 6 through 8 hold for both pure resistive terminations and connections to other transmission lines of different characteristic impedances. In fact, these reflective properties are also pertinent to one-dimensional compressive stress wave propagation along rods and beams.

CHARACTERISTIC IMPEDANCE AND MEASUREMENT OF CABLE DEFORMATION

For the coaxial cable shown in Figure 4b, the capacitance per unit length, C, and inductance per unit length, L, are functions of cable geometry (Halliday and Resnick, 1962),

$$C = 2\pi\epsilon/\ln(a/b) \tag{9}$$

$$L = (\mu/2\pi)\ln(a/b) \tag{10}$$

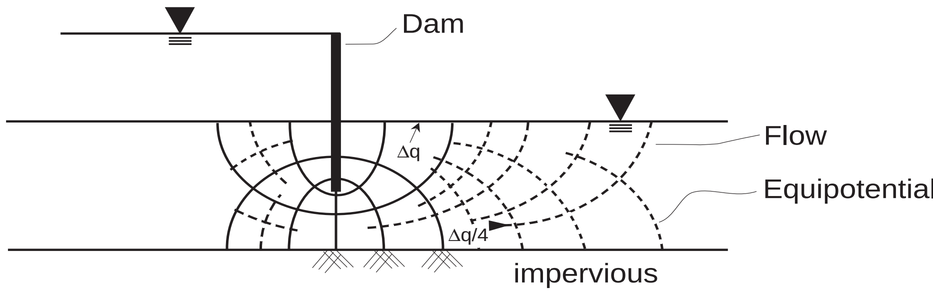
where a and b are the radii of the outer and inner conductors; μ and ϵ are the magnetic permeability and dielectric permittivity, respectively, of the material between the conductors. Substituting Equations 9 and 10 into Equation 5,

$$Z = \sqrt{\frac{L}{C}} = \frac{1}{2\pi}\ln(\frac{a}{b})\sqrt{\frac{\mu}{\epsilon}}. \tag{11}$$

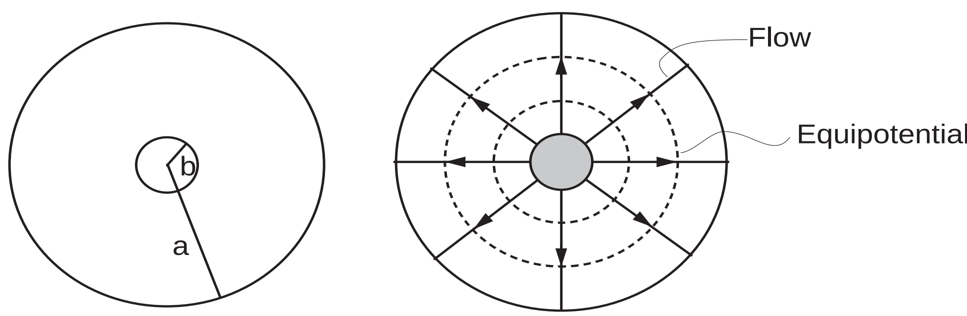
Therefore, the characteristic impedance, Z, is also a function of cable geometry. This geometric dependence can be summarized as

$$Z = f_1(a/b) \tag{12}$$

$$C = f_2(a/b). \tag{13}$$



(a)



(b)

Figure 4. Analogy between flow through porous media and electromagnetic wave propagation in coaxial cable: (a) flow net for water seeping beneath a dam (Cedergren, 1967); (b) flow net for current flow from inner to outer connector (from Su, 1987).

As an electromagnetic pulse propagates along a coaxial cable, the energy is constantly being transformed from an electric field to a magnetic field and vice versa. Consider a transverse cross section of the cable at one instant in time. The electric field associated with a electromagnetic pulse as it passes through the plane of this cross section is equivalent, mathematically, to a laminar flow field produced by steady state seepage (Cedergren, 1967). Both fields consist of perpendicular equipotential and flow (or stream) lines as shown by the comparison of water flowing below a dam and current flowing between the inner and outer conductor of a coaxial cable in Figure 4.

Using finite element techniques, Su (1987) approximated the effect of cable deformation on capacitance by computing an equivalent capacitance per unit length for different deformed geometries. Su designated the impedance and capacitance of the original cable cross section as Z_o and C_o, respectively, and assumed that μ and ϵ did not change as the cable was deformed. He designated impedance and capacitance of a deformed cross section as Z_1 and C_1 and, based on Equations 12 and 13, proposed that the ratio Z_1 / Z_0 is linearly proportional to the ratio C_0 / C_1,

$$Z_1 = (C_o/C_1)Z_o. \tag{14}$$

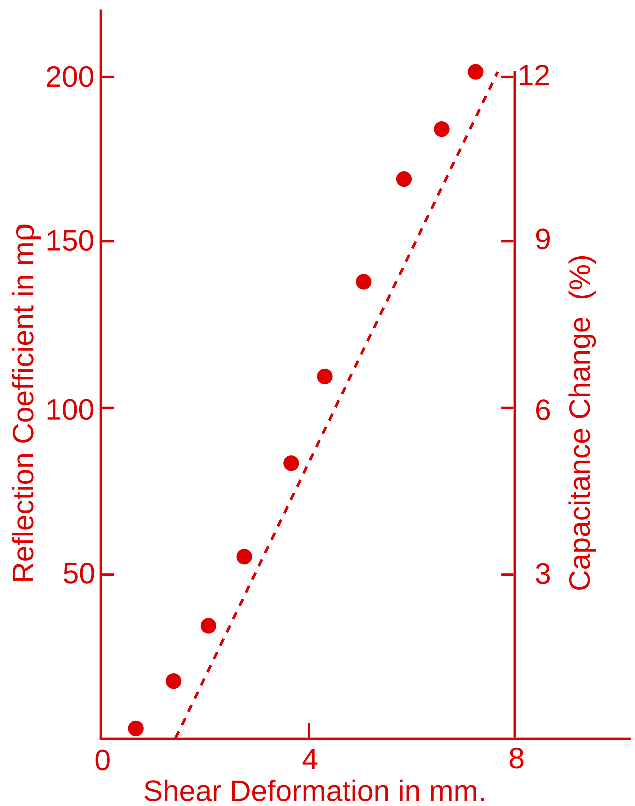


Figure 5. Capacitance change for 1.5 m long cable subjected to shear deformation; solid dots from numerical model; dashed line from trend of laboratory measurements (from Su, 1987).

Figure 5 compares calculated and measured capacitance change (as a percentage of C_o) versus shear deformation for a 12.7 mm diameter coaxial cable. As shown, the increase in equivalent capacitance is proportional to the increase in cable deformation and it produced an increase in the TDR reflection coefficient.

TDR reflections created by cable deformation are shown in shown in Figure 6b. The negative spikes have been created by crimping the coaxial cable prior to installation in a borehole and by deformation caused by movement of the soil or rock in which the cable was embedded. The magnitude of the reflection is proportional to the magnitude of deformation as shown in Figure 5.

A variation of this principle allows TDR to be used for monitoring fluid levels. The TDR traces in Figure 6a were obtained by interrogating an air-dielectric coaxial cable installed in a monitoring well. The impedance below the air-water interface is greatly reduced and so a large negative reflection has been created at this interface (Dowding et al, 1996). As the water level rises within the well, and within the annular space of the cable, the pulse travel time decreases so TDR can be used to rapidly track changes in water level.

PULSE VELOCITY AND MEASUREMENT OF DIELECTRIC CONSTANT

The TDR technique of measuring electrical properties of materials was introduced by Fellner-Feldegg (1969) using alcohols in coaxial cylinders. Topp et al. (1980) extended this application to earth materials by using TDR to determine the volumetric water content of soils in coaxial sample holders. The coaxial cylinders were not suitable for field measurements, so Topp and Davis (1985) used a transmission line consisting of parallel rods based on the work of Davis and Chudobiak (1975). The basic TDR circuit is illustrated in Figure 7. The TDR trace, as displayed on the oscilloscope screen, develops as follows: the cable tester applies a fast rise-time voltage step to the coaxial cable and triggers a sampler. The step pulse travels down the coaxial cable, through an impedance-matching transformer (or balun), and into a shielded two-wire television cable

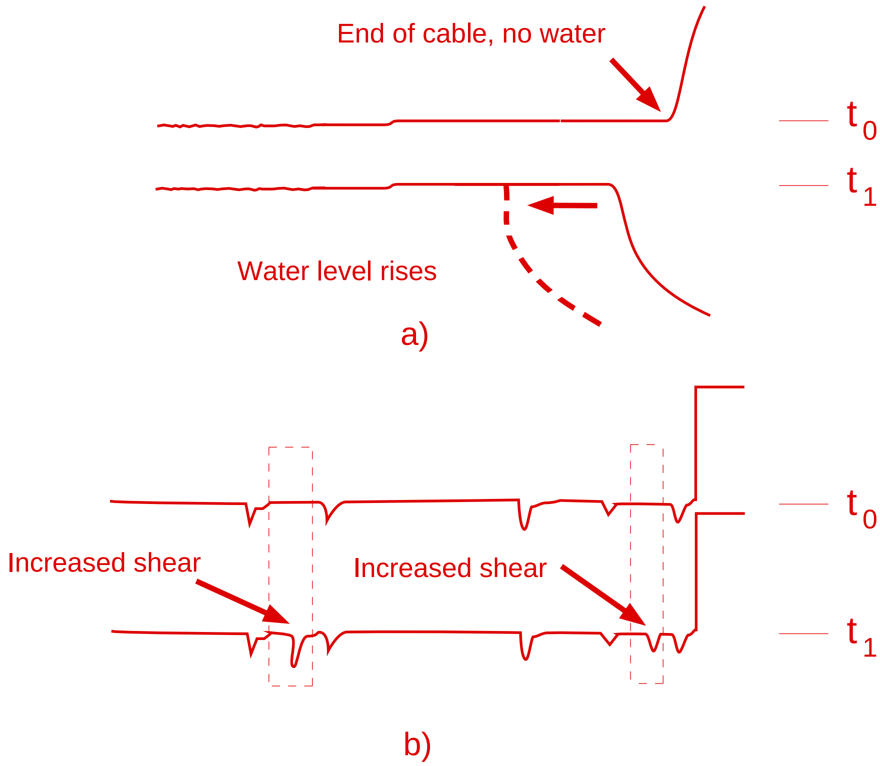


Figure 6. Change in TDR traces compared with baseline at time, t_0; (a) air-dielectric coaxial cable in water; (b) coaxial cable sheared by rock or soil deformation.

(a balanced line). The signal travels along the cable until it reaches the soil electrodes, where, because there is an impedance mismatch at the soil surface, part of the signal is reflected back toward the cable tester and part of the signal passes along the parallel rods in the ground. The signal traveling in the ground ultimately reaches the end of the rods, sending a second reflection back toward the cable tester. By repeating this process many times, a stable trace is developed as shown in the insert of Figure 7. This trace reveals the time between arrival of reflections from the soil surface and from the end of the rods.

The propagation velocity, V_p , of a voltage pulse traveling along a transmission probe of a known length, l_p , is

$$V_p = 2l_p/t \tag{15}$$

where t is the time between reflections from the top and bottom of the probe, and $2l_p$ indicates that the pulse travels twice (i.e., down and back) along the probe. In order to convert this measured propagation velocity to a material property, Topp et al. (1980) considered electrical properties of heterogeneous materials. The velocity at which an electromagnetic wave can travel through a medium is dependent on the permittivity of the medium

$$\epsilon = K\epsilon_0 \tag{16}$$

where K is the dielectric constant and ϵ_0 is the permittivity of a vacuum (8.85×10^{-12} farad/m). The propagation velocity is defined as

$$V_p = c/\epsilon^{1/2} \tag{17}$$

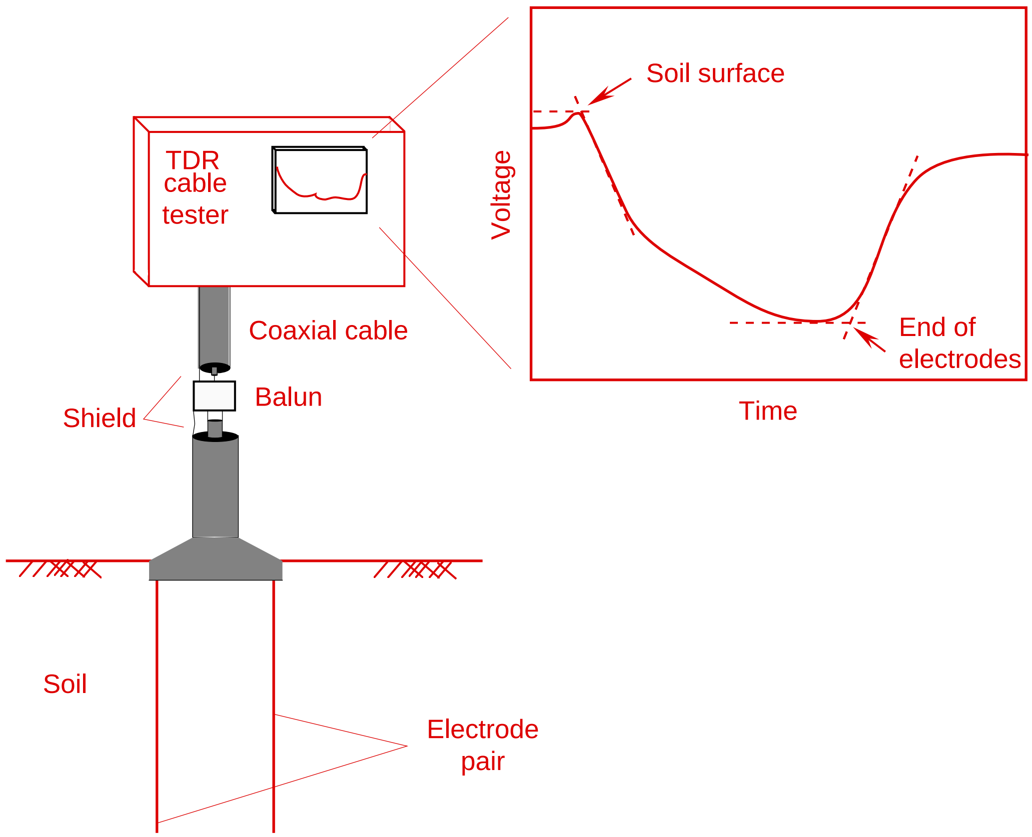


Figure 7. System for measurement of dielectric constant of material between two parallel rods (from Herkelrath et al., 1991).

where c is the speed of an electromagnetic wave in free space (3 x 10^8 m/sec). This is equivalent to the definition of propagation velocity given in Equation 10, but it is derived from electromagnetic wave theory using distributed parameters rather than transmission line theory with lumped parameters. Rearranging Equation 17 to define dielectric permittivity as a function of the propagation constant,

$$\epsilon = (c/V_p)^2. \tag{18}$$

The dielectric permittivity is actually a complex quantity (Hilhorst and Dirksen, 1994),

$$\epsilon = \epsilon' - j\epsilon'' \tag{19}$$

where the real part, ϵ', is a measure of the polarizability of the material constituents. The imaginary part, ϵ'', represents energy absorption by dielectric losses and ionic conduction. Even though the effects of dielectric loss were not measured, Topp et al. (1980) felt that these did exist in their estimate and defined an apparent dielectric constant (note that permittivity of a vacuum $\epsilon_o = 1$ in the CGS system),

$$K_a = \epsilon'/\epsilon_0 \approx \epsilon \tag{20}$$

Inserting Equation 15 into 18, and using the approximation in Equation 20, they defined the apparent dielectric constant measured with TDR as

$$K_a \approx (c/V_p)^2 = [(ct)/(21_p)]^2. \qquad (21)$$

Since the dielectric constant of water K_{water} = 81 and for mineral soil grains K_{grains} = 3 to 5, the bulk apparent K_a is very dependent on water content. This is measured indirectly as travel time, t. This principle is utilized to measure the in situ water content of soils using TDR.

SUMMARY OF TDR APPLICATIONS

The range of TDR applications allows a variety of measurements to be made with one TDR cable tester (O'Connor and Dowding, 1999). The data acquisition system may be required to record an assortment TDR traces. For example, assume that a project requires monitoring water level, rock/soil shearing, and soil moisture simultaneously. A multiplexing system can be deployed to fulfill this requirement with a single TDR unit. A 100 m long low-loss lead cable could be attached to the first channel. At the end of this low-loss lead cable, a 10 to 20 m long air-dielectric coaxial cable could be employed as a probe to measure water level changes. A 100 m long solid aluminum coaxial cable could be connected to the second channel to measure rock/soil shearing. Similarly, a 50 m long low-loss lead cable could be attached to a third channel and connected to a parallel rod probe to monitor soil moisture. Figures 6 and 7 show the variety of TDR traces that would be acquired in this situation. Each channel would be programmed for different acquisition settings to be compatible with the different TDR traces.

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