SSC 107 – Laboratory Exercise 4

Measurement of Soil-Water Content by Time Domain Reflectometry

Introduction

Time domain reflectometry (TDR) is a technique which is used to measure soil-water contents both in the field and the laboratory. The TDR method measures the dielectric constant of a material from which the water content can be determined. In the frequency range of 1 MHZ to 1 GHz air and soil have small dielectric constants (1 and 3-7, respectively) and water has a high dielectric constant (80). In soil changes in the dielectric contant will be due primarily to changes in water content.

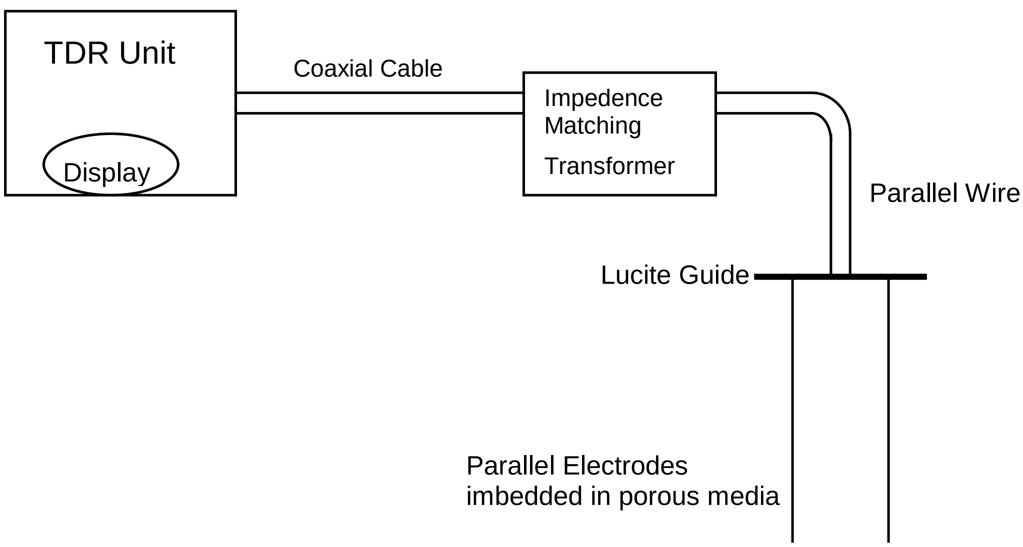

Figure 4-1: Schematic Diagram of TDR apparatus.

In the TDR method, a voltage pulse is launched along a pair of parallel rods (wave guides) inserted into the soil (Figure 4-1). At the end of the wave guides, the pulse is reflected back to its source. The path length is twice the length of the rods. If the transit time along the wave guides is measured, the propagation velocity of the pulse can be calculated from

$$v = \frac{2L}{t} \qquad \text{[Eqn. 1]}$$

where v is the propagation velocity, L is the length of the rods, and t is the transit time. Electromagnetic theory shows that

$$v = \frac{c}{\sqrt{\varepsilon}} \qquad \text{[Eqn. 2]}$$

where c is the velocity of light and ε is the dielectric constant.

Combining equations [1] and [2] gives

$$\varepsilon = \left(\frac{ct}{2L} \right)^2 \qquad \text{[Eqn. 3]}$$

In order to estimate bulk soil volumetric water content, it is assumed that each soil component (soil, water, and air) contributes independently to the total travel time of the voltage pulse in each segment. The contribution of each component will be in proportion to the amount of the component present and its dielectric constant:

$$t = t_{air}^* + t_w^* + t_s^* \qquad \text{[Eqn. 4]}$$

The subscripts air, w, and s represent air, water, and soil, respectively, and the superscripts denote that the time measurement is limited to one phase. The voltage travel time for the wave-guide in air is:

$$t_{air}^* = \frac{2L\sqrt{\varepsilon_{air}}}{c} = \frac{2L}{c} \qquad \text{[Eqn. 5]}$$

where ε_{air} =1. Substituting Eqn. [3] into Eqn. [4], and dividing each side by Eqn.[5], we obtain:

$$\frac{t}{t_{air}^*} = \frac{L_{air}}{L} + \frac{L_w\sqrt{\varepsilon_w}}{L} + \frac{L_s\sqrt{\varepsilon_s}}{L} \qquad \text{[Eqn. 6]}$$

Substituting $L_{air} = L - L_s - L_w$ and $\theta_{TDR} = L_w / L$ (where θ_{TDR} is the volumetric soil-water content as determined by TDR) into Eqn. [6] and rearranging, we obtain

$$\frac{t}{t_{air}^*} = 1 + \theta_{TDR}\left(\sqrt{\varepsilon_w} - 1\right) + \frac{L_s}{L}\left(\sqrt{\varepsilon_s} - 1\right) \text{[Eqn. 7]}$$

For oven dry conditions, θ = 0, and Eqn.[7] becomes

$$\frac{t_s}{t_{air}^*} = \frac{L_s\left(\sqrt{\varepsilon_s} - 1\right)}{L} + 1 \qquad \text{[Eqn. 8]}$$

where t_s is the travel time in oven-dry soil (including the air component). Substituting Eqn. [8] into Eqn. [7] and solving for θ_{TDR}, Hook and Livingston (1996) obtained:

$$\theta_{TDR} = \frac{\left({t}/{t^*_{air}} - {t_s}/{t^*_{air}} \right)}{\sqrt{\varepsilon_w} - 1} \qquad \text{[Eqn. 9]}$$

which is used to estimate θ_{TDR} from travel times in air and soil.

The soil-water content will be automatically calculated when using an instrument such as the multilevel TDR probe described in the Appendix. When the traditional single-depth TDR is used the method for calculating θ_{TDR} is slightly more complicated. The dielectric constant of the soil is calculated from the following equation:

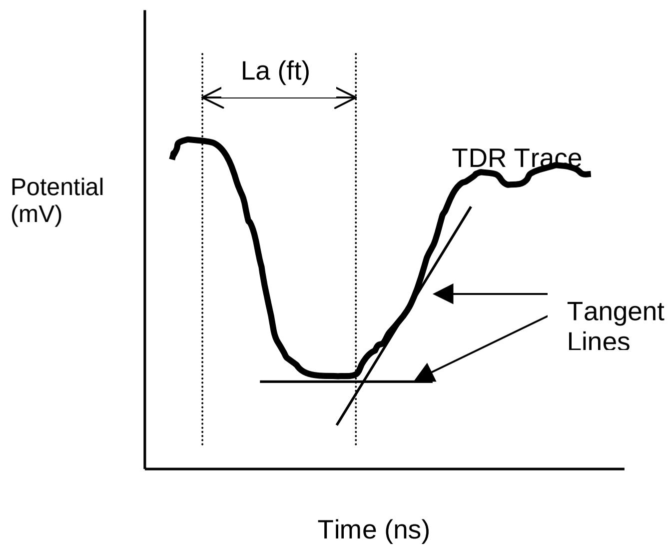

Figure 4-2: Example display from TDR unit.

$$\varepsilon = \left(\frac{L_a C_m}{L V^*_p} \right)^2 \qquad \text{[Eqn. 10]}$$

where L is the length of the TDR probe, C_m is a measured machine constant, V_p^* is the velocity of the voltage pulse in the cable leading to the probe divided by the velocity of light, and L_a is the apparent length of the probe (measured on the machine, see Figure 4-2). Once ε has been obtained in this manner θ_{TDR} can be calculated using a correlation equation.

A relationship between the dielectric constant and volumetric water content, θ_{TDR}, has been determined by regression analysis for several soils. The following equation has been found to provide reasonable estimates of water content relationships for a wide variety of soils.

$$\theta_{TDR} = \frac{\left(-530 + 292\varepsilon - 5.5\varepsilon^{2} + 0.043\varepsilon^{3}\right)}{10000} \qquad \text{[Eqn. 11]}$$

Note: TDR can also be used to measure electrical conductivity(EC), which indicates the level of salinity in solution. The EM wave will be attenuated due to the conductance of electricity between the rods of the wave guide (Dalton and Van Genuchten, 1986).

References

Dalton, F.N. and M. Th. Van Genuchten. 1986. The time-domain reflectometry method for measuring soil-water content and salinity. Geoderma 38: 237-250.

Hillel, D. 1982. Introduction to Soil Physics. Academic Press, Inc.

Hook, W.R. and N.J. Livingston. 1996. Errors in converting time domain reflectometry measurements of propagation velocity to estimates of soil moisture content. Soil Sci. Soc. of Am. J. 60:35-41.

Hook, W.R., N.J. Livingston, Z.R. Sun, and P.B. Hook. 1992. Remote diode shorting improves measurement of soil water by time domain reflectometry .Soil Sci. Soc. Am. J. 56:1384-1391.

Appendix: Multilevel TDR Probe

A new probe has been developed using remote diode shorting and differential wave form detection (Hook et al., 1992). Diodes separating two wavelengths act as a short when turned on, and provide an open circuit when turned off. Subtracting the shorted wave-form from the open circuit wave-form distinctly labels the location of the diode, thereby allowing for an accurate measurement of the EM wave’s travel time.

Two parallel rods of 1.2 m length each are used to construct the multi-level probe (141.5 cm x 1.9 cm x 1.3 cm). Diodes separating the rods effectively divide the rods into 5 TDR probes in series of lengths 15, 15, 30, 30,and 30 cm. The TDR control-system, the MP-917, measures and interprets the signal moving through the multilevel probe, returning both volumetric soil water content (theta TDR)and travel time (in nanoseconds)for each segment. For a more complete and in-depth description of this system see Hook and Livingston (1996) and Hook et al. (1992).