COMPARISON OF GROUND PENETRATING RADAR AND TIME-DOMAIN REFLECTOMETRY AS SOIL WATER SENSORS

KIRK W. WEILER, TAMMO S. STEENHUIS,* JAN BOLL, AND K.-J. SAMUEL KUNG

Abstract

Robust and noninvasive techniques for in situ measurement of soil water content are essential for monitoring and research of many hydrologic processes. Although in situ measurement of soil water content by means of a soil's electric and dielectric properties has been explored extensively, the use of ground-penetrating radar (GPR) for this purpose is not well established. We compared the soil's dielectric constant as measured by GPR and time domain reflectometry (TDR) and its relationship to water content determined independently in auger holes. We propose a calibration equation relating soil water to GPR-measured dielectric constants. The difference in calibration equations between GPR and TDR was partially attributed to the difference in frequency ranges in which TDR and GPR operate and the zero offset of the GPR.

ACCURATE MEASUREMENT of soil water content is important in irrigation scheduling, modeling, and a variety of other hydrological applications. The accepted standard technique for measuring water content involves oven drying a soil sample at a prescribed temperature and duration (Gardner, 1986). This method, however, involves destructive sampling, is time consuming, and thus is not well suited for field monitoring during which multiple measurements are required. In situ methods employing the electric and dielectric properties of the soil as a means to determine soil water content have expanded during the last 20 yr with advances in electronics and the arrival of microcomputers (Birchack, 1974; White and Zegelin, 1995). Specifically, the use of TDR has increased since the work of Topp et al. (1980).

A considerable amount of research has been devoted to the use of GPR, most often as a tool for detecting buried objects. More recently, it has been employed to detect soil water content differences caused by static subsurface features (Davis and Annan, 1989; Boll et al., 1993, 1996; Kung and Lu, 1993; Shih and Doolittle, 1984). Du and Rummel (1994) utilized the GPR ground wave, in conjunction with Topp (1980), to determine soil moisture contents in the near subsurface. In other applications, GPR was used to follow the wetting front movement under irrigation in sandy soils (Vellidis et al., 1990). But, as of yet, very little research has centered on using GPR as an in situ water detector (White and Zegelin, 1995).

The objective of this study was to determine if GPR can be used as an in situ water sensor on sandy soils. In particular, we examined whether the TDR calibration equation between soil dielectric constant and soil water is valid for use with the GPR.

Background

The relationship between the apparent dielectric constant, ε_a, and water content must be established before GPR (and TDR) can be used as a water sensor device. Although this task of predicting water content using dielectric constants has been attempted for sometime (White and Zegelin, 1995), there is no universal agreement on one best method.

Currently, there are two approaches toward correlating water content with dielectric constant (White and Zegelin, 1995): semitheoretical and empirical. Based on the work of Whalley (1993) and Birchack et al. (1974), the semitheoretical approach leads to a simplified equation of the form (assuming that water in the vapor phase and water bound to the soil particles are negligible)

$$\varepsilon_a^{0.5} = C_1\theta + C_2 \quad [1]$$

where θ is the volumetric water content, ε_a is the dielectric constant, and C_1 and C_2 are constants. For soils with a higher clay content than the sandy loam at the experimental farm, the power in the equation might not be equal to 0.5 (Dirksen and Dasberg, 1993; Roth et al., 1990).

Using TDR, Topp et al. (1980) empirically related the water content of a soil to its dielectric constant with the following third-order polynomial:

$$\theta = -0.053 + 0.0292\varepsilon_a - 0.00055\varepsilon_a^2 + 0.0000043\varepsilon_a^3 \quad [2]$$

They found that this equation applied for a wide variety of soils and was independent of bulk density, soil temperature, and soil salinity. Dirksen and Dasberg (1993) found very similar results on a theoretical basis in sandy, low-salinity soils with bulk densities between 1.35 and 1.5 g/cm^3.

Ground-penetrating radar and TDR were used to measure the dielectric constant. Both emit electromagnetic (EM) microwaves, but each measures dielectric constant slightly differently. The TDR EM wave is constrained to travel along and between the probe's guide wires. Ground-penetrating radar uses a free wave that propagates and spreads in the soil, where it will reflect off interfaces with different dielectric constants. In both cases, ε_a can be found from

$$\varepsilon_a \approx \left(\frac{c}{v}\right)^2 \quad [3]$$

where c is the speed of light and v is the velocity of the EM wave that can be calculated for TDR from the travel time through the guide wires. For GPR, the EM wave speed can be determined with the common midpoint (CMP) method or from the travel time to a layer of known depth with a distinct ε_a. In this study we have used both methods.

Materials and Methods

The testing of GPR and TDR was carried out on the University of Massachusetts Agronomy Research Farm near South Deerfield, MA. The soil is classified as a Hadley fine sandy loam (coarse, mixed mesic Fluventic Dystrochrept) and is of

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K.W. Weiler, T.S. Steenhuis, and J. Boll, Dep. of Agricultural and Biological Engineering, Cornell Univ., Ithaca NY 14853; and K.-J.S. Kung, Dep. of Soil Science, Univ. of Wisconsin, Madison, WI 53706. Received 12 July 1996. *Corresponding author (tss1@cornell.edu).

Published in Soil Sci. Soc. Am. J. 62:1237–1239 (1998).

Abbreviations: CMP, common midpoint; EM, electromagnetic; GPR, ground-penetrating radar; TDR, time-domain reflectometry.

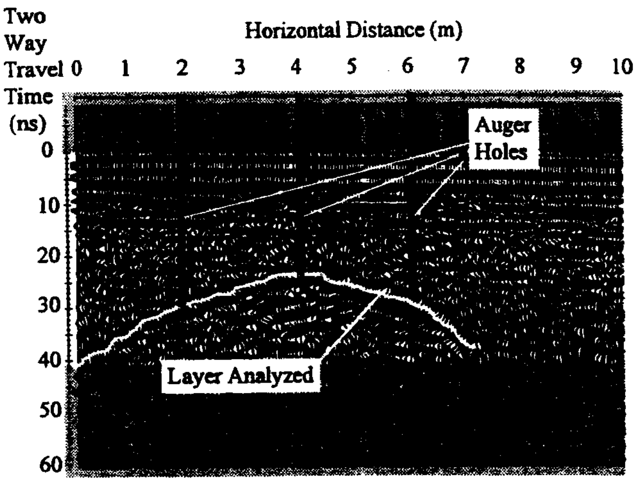

Fig. 1. Typical transect with auger hole placement shown.

a recent alluvial deposit (Mott and Fuller, 1967). Coarse sand lenses are interbedded in a very fine sandy soil. The coarse sand lenses have been found at depths of 50 cm and deeper. The thickness of the coarse layers ranges from a few centimeters to 1 m.

A Tektronix cable tester (Beaverton, OR) and a pulseEKKO GPR system (Sensors and Software, Mississauga, ON, Canada) were used. The Tektronix series 1502 cable tester emits a wave packet that has a frequency range of 1 MHz to 1.5 GHz. A three-rod probe design was used, as described in Zegelin et al. (1989); the probes consisted of three stainless steel rods 0.5 cm in diameter, each having an exposed length of 14.5 cm and a center-line separation of 2.5 cm. The rods were directly attached to the coaxial cable leading to the cable tester. A pulseEKKO 1000 GPR system consisted of a 450 MHz center frequency antenna with a 200 V transmitter. The radar data was collected with a Toshiba computer using a 386 processor. A sampling rate of 100 ps with 16 stacks per trace and time windows of 50 and 70 ns was used.

In order to determine the correlation between dielectric constant and water content for the TDR, a field trench was dug to a depth of 1.5 m so that soil samples could be taken and water contents determined throughout the summer at various locations of the profile. The TDR probe was inserted 14.5 cm into the soil and a TDR length measurement was taken. Using this length measurement and the known length measurement from pure water, a dielectric constant for the soil was found. Soil samples were taken with 100-cm^3 rings at the location of the TDR measurement after the probe was taken out. The volumetric water contents were then found by the standard oven-drying technique. Although correlation equations relating a soil's water content to its dielectric constant already exist (Whalley, 1993; Topp et al., 1980), this correlation was performed on the field soils at this site to eliminate possible error introduced from using an equation formulated under different conditions.

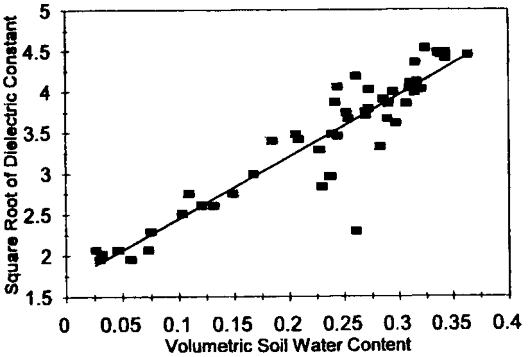

Fig. 2. Time-domain reflectometry moisture calibration showing line of best fit.

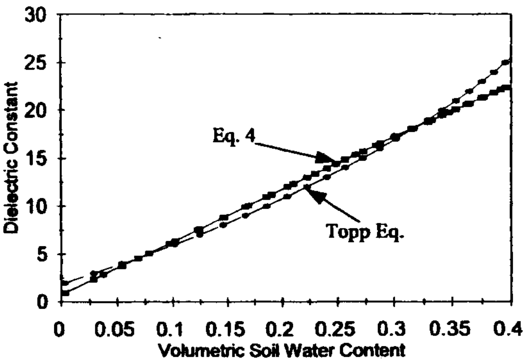

Fig. 3. A comparison between the Topp equation (Eq. [3]) and Eq. [4].

Apparent dielectric constants were also determined with the GPR using two methods. First, GPR transects were taken where known coarse sand lenses would produce reflections. These GPR transects resulted in plots of two-way travel to the coarse sand layer (Fig. 1). Auger holes were then made and soil samples taken so that water contents could be found. By analyzing soil texture and water contents, depths to the coarse layers (the GPR wave reflectors) were determined so that average EM velocities could be found from the measured EM wave travel times. These velocities were then converted to dielectric constants.

Average EM wave velocities with GPR were also found with the CMP method approximately 20 m from the trench used for the TDR measurements. The CMP method involves separating the GPR transmitter and receiver by known distance increments (in our case 5-cm increments) and taking a reading of two-way travel time to a common reflector at each separation. The subsequent radar image is then analyzed and a velocity of the EM wave is found using the Pythagorean theorem. This velocity can be converted to a dielectric constant as described in Boll et al. (1996). Common midpoints were taken above coarse sand reflectors during the summer and fall. These CMPs yielded velocities to coarse sand lenses below the surface. Auger holes were made at CMP sites to determine average soil water contents to the coarse sand lenses.

Results and Discussion

To obtain the two constants in Eq. [1] for TDR, the measured water contents were linearly regressed against the square root of the dielectric constants calculated with Eq. [3]. The regression was performed on 52 soil

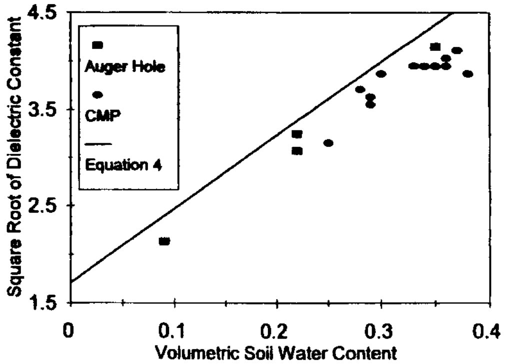

Fig. 4. Equation [4] moisture predictions based on ground-penetrating radar (GPR) dielectrics using the common midpoint (CMP) method compared with auger hole moisture samples.

samples taken from the trench mentioned above; a reasonable fit was found, $R^2 = 0.92$, for a range of water contents normally found in the field during the growing season ($\theta = 0.15$–0.40; Fig. 2). Regression produced a calibration equation of

$$\varepsilon_a^{0.5} = 7.62\theta + 1.71 \quad [4]$$

The experimental constants for the conversion of TDR to water content found through this calibration agree well with those determined by Whalley (1993), who calculated, for a sandy loam soil, a slope of 8.028 and an intercept of 1.618, compared with 7.62 and 1.71, respectively. To further check the accuracy, Eq. [4] is compared with Topp's equation (Eq. [2]) in Fig. 3. A good agreement exists between both except in the highest range where a maximum divergence of 0.03 m^3/m^3 is seen in water content prediction.

Next, we determined if the TDR-derived equation (Eq. [4]) can be used for GPR at this field site. The data points in Fig. 4 are the square root of observed values of GPR dielectric constants (Eq. [3]) and water contents found from soil cores. Data points show dielectric constants found using both the auger hole method and the CMP method. The solid line in Fig. 4 is based on Eq. [4]. Regardless of the method used to measure the water content (auger hole or CMP method), Eq. [4] consistently underpredicts the water contents found in the field, with an average underprediction of 0.05 m^3/m^3. Note, however, that the observed data and the predicted line have approximately the same slope, indicating that only the intercept is different for TDR and GPR. Two possible causes for the deviation of the intercept between TDR and GPR are the frequencies used by both instruments and the zero time shift of the GPR.

The dielectric constant is actually a misnomer, because it is dependent on frequency. Thus, both instruments, which use different frequency ranges, could actually measure a different dielectric constant. White and Zegelin (1995) show convincingly, however, that if there is any difference, it is very small. Thus, frequency effects are probably not the most prevalent factor in the discrepancy seen in Fig. 4.

Another factor that could cause the errors seen in Fig. 4 is the zero time shift of the GPR. Because of the high velocity of the EM wave that the GPR emits, there is some uncertainty in the zero point setting on any GPR trace at the factory calibration. In standard GPR field applications, the zero-time shift is relatively unimportant in finding or indicating the presence of subsurface anomalies. In this case, though, the zero-time shift may cause difficulty in determining the exact velocity of the EM wave.

If we correct Eq. [4] for *y* axis intercept in Fig. 4, we can then formulate a GPR calibration equation relating dielectric constants to soil moisture:

$$\varepsilon_a^{0.5} = 7.62\theta + 1.35 \quad [5]$$

This equation is based on the GPR data obtained in this experiment and is consistent with theoretical prediction.

Conclusions

Time-domain reflectometry is an established water measurement method that has been used to find in situ water contents in the field by utilizing a guided EM wave to measure the soil's dielectric constant. Ground-penetrating radar, which employs an unguided EM wave, shows great promise in the future for nondestructive soil water sensing. Some advantages of GPR are that it can measure larger volumes of soil than the TDR and can be utilized without disturbing the soil. Disadvantages include that automatic measurements are not possible because every instrument might have to be calibrated first and that it is prone to failure in soils with high clay contents and high salinity contents.

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