Measuring and Modeling of GPR Ground Wave Depth Penetration Under Transient Soil Moisture Conditions

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Abstract—**This study represents the first attempt to investigate the GPR direct ground wave sampling depth by comparing GPR estimated soil moisture contents with data from horizontally and vertically installed TDR probes at different depths. The GPR direct ground wave method (200 MHz centre frequency) was used to estimate the temporal soil moisture dependence during uniform irrigation and drainage. Uniform irrigation and drainage experiments were conducted in an experimental pit (2.5 x 1.0 x 0.8 m) filled with repacked sandy loam soil. The GPR moisture contents measurements were more consistent with the moisture contents from vertically installed TDR than horizontally installed TDR. An analytical solution for one-dimensional drainage of water was used to estimate the change in GPR ground wave sampling depth during drainage. The analytical solution was first fit to vertical TDR data to obtain an estimate of the soil hydraulic parameters and the GPR sampling depth was then estimated by fitting the drainage solution to the measured GPR data. The GPR direct ground wave sampling depth using the analytical solution during drainage varied from - 20 cm at high moisture content to -50 cm at the lowest moisture content**

Keywords-Ground penetrating radar; irrigation; drainage; analytical solution

I. INTRODUCTION

Soil moisture is one of the most important hydrological parameters in many field applications. Time domain reflectometry (TDR) has become the most widely accepted method over the last two decades for measuring soil moisture content. In fact, one of the major disadvantages of all traditional soil moisture estimating methods including TDR and gravimetric methods is the relatively small sample volume. Data collection has to be carried out in a reasonably large number of locations (intensive sampling) to map soil moisture distribution over a large area, which is time consuming and labour intensive.

The surface GPR method using the direct ground wave can be used to estimate the spatial variability of soil moisture in a shallow field soil [1,2,3,4,5,6]. The GPR direct ground wave method measures soil moisture very near the soil surface as in [2,4,6,7]. The GPR data for estimating soil moisture content can be collected using multiple- or single-offset methods. The GPR method for soil moisture content estimation is discussed in details by [1,5]. References [2,3,4,6,7] show that the fixed offset (FO) method using the direct ground wave is useful in soil moisture variability mapping at shallow depths over large areas. However, accurate measurements of absolute ground wave travel time and zero time calibration of the GPR instruments are essential when employing the FO method as explained in [2]. In this study, several pedon-scale experiments in a repacked sandy loam soil were conducted to measure soil moisture variability using 200 MHz GPR antennas with a fixed offset distance. The objectives of these experiments are; 1) to estimate temporal soil moisture variability under irrigation and drainage conditions using the FO method of GPR, 2) to assess the GPR direct ground wave sampling depth by comparing with vertically and horizontally installed TDR probes at different depths, 3) to analyze the change in GPR ground wave sampling depth during drainage using a quasi-analytical solution of Richard's equation for one-dimensional soil water storage.

II. MATERIALS AND METHODS

A. *Experimental Setup*

Experiments were conducted at the Cambridge Research Station of the University of Guelph, Ontario, Canada. The experimental plot was prepared by excavating a 2.5 x 1.0 x 0.8 m (LxWxD) pit and then backfilling the pit with the excavated soil sieved through a 4.0 mm sieve. During the backfilling, 1.0-m long, 3.0 mm diameter TDR probes were installed horizontally at different depths in three different lines (0 m N, 0.25 m N and 0.50 m N) from West to East as shown in Fig. 1. Vertical TDR probes of lengths 0.1 and 0.2 m were installed after the pit was backfilled (Fig. 1A and 1B).

The GPR and TDR data were collected for background soil moisture conditions and during the irrigation and drainage experiments. In all experiments, uniform irrigation was performed by applying water equally over the experimental area using a watering shower connected to a garden hose. During each GPR measurement of moisture content in the soil pit, five traces were collected with the fixed offset method and the average ground wave travel time was estimated by picking the leading edge arrival time of the ground wave at the receiver location. The ground wave velocity was calculated by dividing the fixed antenna offset by the average ground wave travel time. TDR probes were connected to a switchboard to facilitate TDR readings which were collected and analyzed manually. A Tektronix 1502C instrument was used to generate the TDR signal.

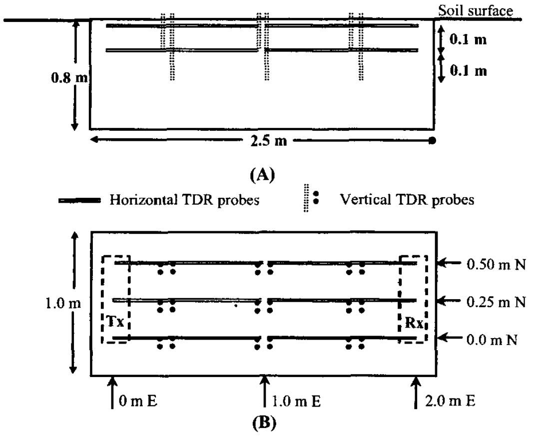

Figure 1. Schematic diagrams of the experimental pit filled with uniform sandy loam soil. (A): vertical cross section of the pit, (B): plan view of the pit. Tx: Transmitter; Rx: Receiver.

B. Estimating Soil Moisture using GPR Direct Ground Wave

The soil dielectric permittivity K_r can be calculated using the estimated soil velocity V and the velocity in free space c (c = 0.3 m/ns) as given (1). Reference [8] found a reliable empirical relationship between the soil volumetric moisture content (θ_v) and the dielectric permittivity (K_r) for a range of field soils independent of the density, texture and salt content of the soil (2).

$$K_r = (c/V)^2 \tag{1}$$

$$\theta_V = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_r - 5.5 \times 10^{-4} K_r^2 + 4.3 \times 10^{-6} K_r^3 \tag{2}$$

C. Experiment I (Uniform Irrigation)

Experiment I was conducted to observe the temporal soil moisture variability during uniform irrigation using fixed offset (1.5 m) 200 MHz GPR antennas. To evaluate the accuracy of GPR-estimated moisture contents and to measure the temporal soil moisture variability, TDR probes were installed vertically at 0-0.1 and 0-0.2 m depth ranges (Fig. 1B). Background moisture contents were measured using both GPR and TDR methods. Then, the following procedure was repeated for 1 hour and 45 minutes until water was ponded on the surface. (I) GPR antennas were removed from the site, (II) Irrigation water was applied uniformly over the experimental area for about 30-60 seconds, (III) The GPR antennas were repositioned on the experimental area at a 1.5 m offset and five traces were collected and (IV) After 4 - 5 minutes of drainage five more GPR traces were collected. During the entire irrigation period, TDR data were also collected at regular time intervals using 0.1 and 0.2 m long probes installed vertically from the soil surface.

D. Experiment II (Uniform Drainage)

The second experiment was conducted under uniform drainage condition. At the beginning of the experiment, background soil moisture data were collected using GPR and TDR. Following the background survey, the GPR antennas were removed and irrigation water was applied uniformly over the soil surface. During irrigation, the site was allowed to drain for couple of minutes. The last irrigation was carried out until water started to pond on the soil surface. Following this procedure, a field-saturated condition was achieved before starting the final drainage period.

The GPR antennas could not be positioned for about 15 minutes until the free water had drained from the soil surface. Just after the surface water drained away, the GPR antennas were positioned and kept at the same location at the same offset (1.5 m) during drainage monitoring. The GPR and TDR data were collected at a 2-minute interval throughout the drainage period of 1 hour and 10 minutes.

III. RESULTS AND DISCUSSION

A. Experiment I

Results are shown in Fig. 2 for both GPR-estimated and TDR-measured moisture content variability with time. This experiment was conducted with intermittent irrigation allowing some time for intermittent drainage. The "up and down" response of the GPR direct ground wave travel time and the estimated moisture content in Fig. 2 are due to the intermittent nature of the irrigation and drainage.

During the initial irrigation, all three-soil moisture values (GPR and two TDR depths) are very close. These initial values showed a fairly uniform moisture profile existed in the soil, with slightly higher value for the 0.2 m TDR probe compared to the other measurements. As seen in Fig. 2, moisture content increases gradually with irrigation time and the rate of increase is higher for 0.1 m TDR probe followed by the GPR and 0.2 m TDR probe. At the end of the irrigation, the GPR estimated moisture content is much closer to value measured with the 0.2 m depth TDR probe than the 0.1 m depth TDR probe. This temporal pattern again shows the tendency of GPR ground wave to couple with deeper dry layers and travel faster than the wet shallow layers during the transient irrigation [2].

B. Experiment II

The GPR-estimated moisture content was the highest (9.7%) and the 0.02 m horizontal TDR probe value was the lowest (1.5%) for background (time = zero hr) conditions (Fig.3). Data from the two vertical TDR depth ranges show essentially the same drainage pattern and both reach 15% moisture content after 1.5 hours of drainage. For the horizontal TDR probes, the 0.02 m depth compared to the 0.1 m depth shows a higher moisture content increase during irrigation and more rapid moisture content decrease during drainage, as expected (Fig.3). The soil moisture content estimated with the GPR method is always higher than measurements from both horizontal TDR depths during drainage (Fig. 3B).

When comparing the GPR data to the vertical TDR probe data, the GPR value is relatively lower at the end of irrigation, followed by the 0-0.2 m TDR probe and 0-0.1 m TDR probe

(Fig. 3A). During the initial stage of the drainage period, GPR and both TDR values are similar since the soil profile is uniformly wetted. At around 2.25 hours in the experiment (after about 0.75 hours of drainage), the difference between GPR-estimated and TDR-measured moisture contents starts to increase to a maximum of about 5 % moisture content when the experiment ended after 1.5 hours of drainage (Fig. 3A). We attribute this difference to the dependence of the GPR sampling depth on moisture content.

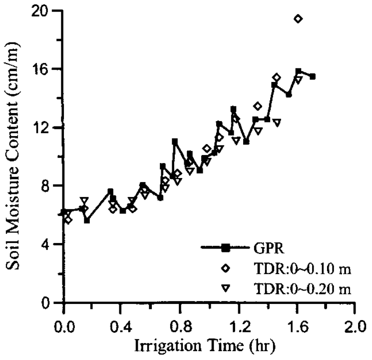

Figure 2. Comparison of soil moisture estimated with GPR using fixed offset (FO) survey mode (200 MHz) and measured using vertically installed TDR (0-0.1 and 0-0.2 m depths) during uniform irrigation.

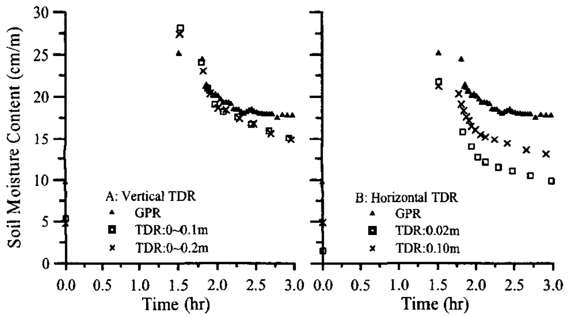

Figure 3. Temporal soil moisture variability during drainage estimated with 200 MHz GPR antennas and vertically installed TDR probes (A) at two depths (0-0.1 m and 0-0.2 m) and horizontally installed TDR probes (B) at two depths (0.02 m and 0.10 m).

The GPR-estimated moisture contents do not compare as well with data from horizontal TDR probes. GPR gives a weighted average water content similar to the vertical TDR. The weighting function for TDR is uniform with depth whereas the unknown GPR weighting function is clearly not uniform and is dependent on moisture content. Comparisons between GPR and horizontal TDR will be poor when a vertical moisture content gradient exists, as during the experimental conditions in this study.

C. Analysis of GPR and TDR data

Data for two vertical TDR depths (0-0.1 m and 0-0.2 m) and two horizontal TDR depths (0.02 m and 0.10 m) are compared (simple linear regression) with GPR-estimated moisture contents. The GPR and TDR data were not collected at exactly the same time. In order to compare the moisture content estimates from the GPR and TDR measurements at the same times all data were linearly interpolated and resampled at the appropriate time. Four regressions (GPR data set vs. four different TDR data sets) were compared statistically for the slope and the intercept. It was found that the GPR-estimated data were not statistically different with respect to 0-0.1 and 0-0.2 m vertical TDR measured values (slope = 1 and intercept = 0). Regression analyses with horizontal TDR found that GPR values were significantly different for the slope and the intercept (slope ≠ 1 and intercept ≠ 0).

Further analyses were performed to compare GPR estimated soil moisture values with TDR measured values at different depths. For this analysis, Root Mean Square Error (RMSE) values were calculated between GPR and TDR data and the smallest error is found for the lowest RMSE value between GPR and TDR depths comparisons. Estimated slope, intercept, coefficient of determination (R^2) and RMSE values for GPR estimated soil moisture data with respect to different TDR measured values are given in Table 1.

Table 1. Comparison of statistical values obtained for linear regression between GPR-estimated and TDR-measured soil moisture contents.

TDR Depths (m)	Slope	Intercept	R^2	RMSE (cm/m)
Vertical TDR:				
0 - 0.1	=1 (NS)	0 (NS)	0.91	1.58
0 - 0.2	=1 (NS)	0 (NS)	0.97	1.22
Horizontal TDR:				
0.02	≠ 1 (S)	≠ 0 (S)	0.57	5.26
0.10	≠ 1 (S)	≠ 0 (S)	0.81	3.31

RMSE: root mean square error; R^2: coefficient of determination; S: significant; NS: not significant

D. Modeling with Quasi-Analytical Solution for One-Dimensional Drainage and Estimation of the GPR Ground Wave Sampling depth Change with Drainage

Water stored in a fixed depth of soil during one-dimensional drainage was modeled employing Equation 17 of [9] for two different TDR depth ranges. For this analysis, drainage data from Experiment II was used. Parameters λ_s and K_s in equation 11 of [9] were changed (the value of C kept at 1.5) until the best fit of the approximation was found for the respective TDR data sets (Fig. 4). The predicted drainage versus time from the analytical solution of [9] using TDR depth range of 0-0.2 m as shown in Fig. 4B was adjusted by changing the value of L in the solution to match each GPR-estimated moisture contents. All other parameters in the solution, which were obtained by fitting to TDR data, were kept constant. The GPR sampling depth was estimated using 0-0.2 m TDR data since GPR data showed smaller error with 0-0.2 m TDR than 0-0.1 m TDR (Table 1).

Following this procedure, the respective GPR sampling depths were estimated as a function of time during drainage for all GPR-estimated data shown in Fig. 5. The sampling depth estimated in this way implicitly assumes that the GPR method has a uniform weighting function with depth as does the TDR. According to Fig. 5, the GPR sampling depth increased gradually with drainage time. We attribute this effect to the reduction in sampling depth that occurs with decreasing radar wavelength and higher water content that has been documented in [6,10,11].

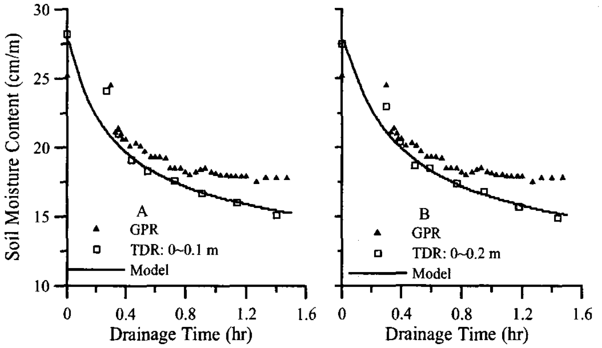

Fig. 4. Predicted curves for one-dimensional analytical model fitted to measured water content data with 0-0.1 m (A) and 0-0.2 m (B) TDR.

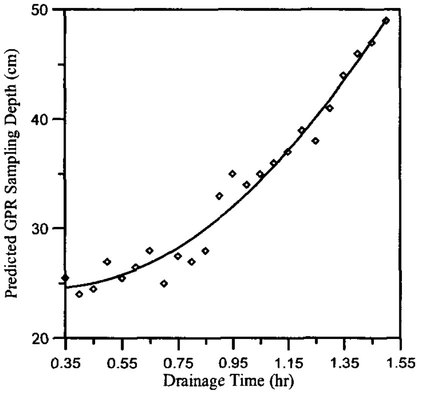

Figure 5. Variation of the predicted GPR direct ground wave sampling depth with drainage time using one-dimensional analytical drainage solution.

The correlation (R^2) and RMSE values between the analytical solution and TDR for 0-0.2 m depth found to be 0.96 and 0.72 cm/m respectively. The respective R^2 and RMSE values between the analytical solution and GPR were found to be 0.84 and 0.80 cm/m. The average, minimum and maximum GPR sampling depths predicted from the analytical solution found to be 33, 24 and 49 cm respectively. These results show that the GPR method will be a potential technique for non-destructive estimates of soil hydraulic properties such as hydraulic conductivity and α parameter over large areas for many field applications.

IV. CONCLUSIONS

Temporal variation of soil moisture contents estimated with the GPR direct ground wave (fixed offset mode) compared relatively well with TDR measured moisture contents. The horizontal TDR probes were not useful in estimating sampling depth. If a sufficient number of horizontal probes were used to determine the vertical moisture content profile then this data would contribute to a better understanding of the GPR sampling depth. The linear regression shows the GPR estimated values were well correlated with the vertical TDR probes but not with the horizontal TDR probes. An analytical solution for one-dimensional drainage was tested to estimate the GPR direct ground wave sampling depth variability during drainage. The computed sampling depth varied from 0.2 to 0.5 m over the drainage period. To obtain the best estimate of GPR ground wave sampling depth under field conditions, several horizontal TDR probe depths as well as vertical TDR probe depths (several probes perpendicular to the ray path over the same depth range) should be used. There is a possibility for non-destructive mapping of soil hydraulic properties such as hydraulic conductivity over larger areas using GPR data and analytical model.

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