Vadose Zone Characterization Using Ground Penetrating Radar Groundwaves

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1. Introduction

Soil water content is an important parameter for agricultural, environmental, and geotechnical applications. Accurate characterization of the soil water content can be used to optimize irrigation or to estimate travel paths and velocity for contaminants in the vadose zone. Soil water content in the vadose zone is both spatially and temporally heterogeneous, so characterizing this parameter with a limited number of point measurements is difficult. Recent research has shown that ground penetrating radar (GPR) groundwave techniques may be capable of characterizing the soil water content based upon measurements of the electromagnetic velocity with much higher resolution than is possible using point measurements. However, the efficacy of GPR groundwave techniques is limited by the uncertain groundwave penetration depth. In this project, we seek to experimentally determine the penetration depth of the GPR groundwave under controlled conditions.

2. Background

The GPR groundwave is a direct wave which travels between the transmitting and receiving antennas in the near subsurface (Figure 1). Researchers have hypothesized that the penetration depth of the groundwave is a function of antenna frequency and soil water content, but no systematic experiments have been performed to determine the penetration depth. Several theoretical methods have been used to predict the groundwave penetration depth, but these methods produce widely varying results (Du, 1996; Van Overmeeren *et al.*, 1997; Sperl, 1999).

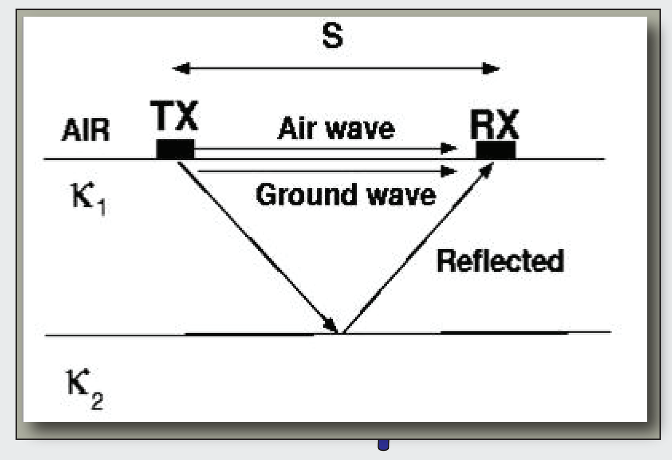

Figure 1: The GPR groundwave is a direct wave traveling in the near subsurface.

3. Data Acquisition and Analysis

This experiment investigates the groundwave penetration depth using soil layers with contrasting electromagnetic velocities within a large tank. A layer of saturated sand (with low electromagnetic velocity) was placed in the tank, and multi-frequency GPR data were acquired over this layer. Then, thin layers of dry sand (with high electromagnetic velocity) were incrementally added to the tank, and GPR data were acquired after each additional layer. The groundwave velocity was calculated for each GPR survey, and the penetration depth for each frequency was determined by noting the thickness of dry sand at which the velocity ceased to change as more dry sand was added.

3.1. Tank Preparation

The experimental tank was constructed of fiberglass to avoid metallic interference with the GPR signal. The soil used in this experiment was a medium- to well-sorted sand. To prepare the dry soil, over 7 m^3 of sand were dried in an industrial oven at 115º C for 24 hours (Figure 2). The sand was stored in airtight drums after drying. The saturated sand was prepared by placing an additional ~1.5 m^3 of sand in a large mixer and adding sufficient water to obtain a volumetric water content of 30% (Figure 3).

Figure 2: An industrial oven was used to remove moisture from the sand used in the dry soil layers.

Figure 3: A large mixer was used to ensure that the water content in the saturated sand was homogeneous.

3.2. GPR Data Acquisition

The experiment began by placing 15 cm of saturated sand in the bottom of the tank. To prevent migration of moisture from this layer, two thin plastic tarps were placed over the saturated sand and were sealed to the sides of the tank. Multi-frequency GPR data were collected over the saturated sand using antennas with central frequencies of 100-, 250-, 500-, and 1000-MHz. Three variable-offset surveys were acquired with each frequency; a common-midpoint survey was performed in the middle of the tank, and two wide angle reflection and refraction (WARR) surveys were performed, where each of the WARR surveys began at opposite ends of the tank. Next, a level 6 cm layer of dry sand was placed in the tank, and the GPR surveys were repeated as described above (Figure 4). For the remainder of the experiment, level 3 cm layers of dry sand were incrementally placed in the tank, and GPR data collection was repeated after each additional 3 cm layer. The groundwave velocity was estimated for each survey, and data collection with each GPR frequency continued until the velocity for that frequency remained constant as the depth of dry sand increased.

Figure 4: A common-midpoint survey was performed in the middle of the tank for each GPR frequency. To avoid compaction of the soil, no one entered the tank after the soil was added. Instead, the antennas were moved remotely using ropes.

3.3. Monitoring Soil Water Content

To monitor any changes in the soil water content within the tank, three 7.5 cm time domain reflectometry (TDR) probes were installed around the perimeter of the tank within each 3 cm layer of sand. The TDR probes measured the electromagnetic velocity of the sand, which can be used to estimate soil water content, once an hour. Figure 5 shows the velocity measurements from TDR probes at one station along the side of the tank. TDR probes at the other five stations have similar results, which show that the water content in the saturated sand (low velocity) remained high throughout the experiment and that no indications of moisture leaching upward into the dry sand (high velocity) were observed.

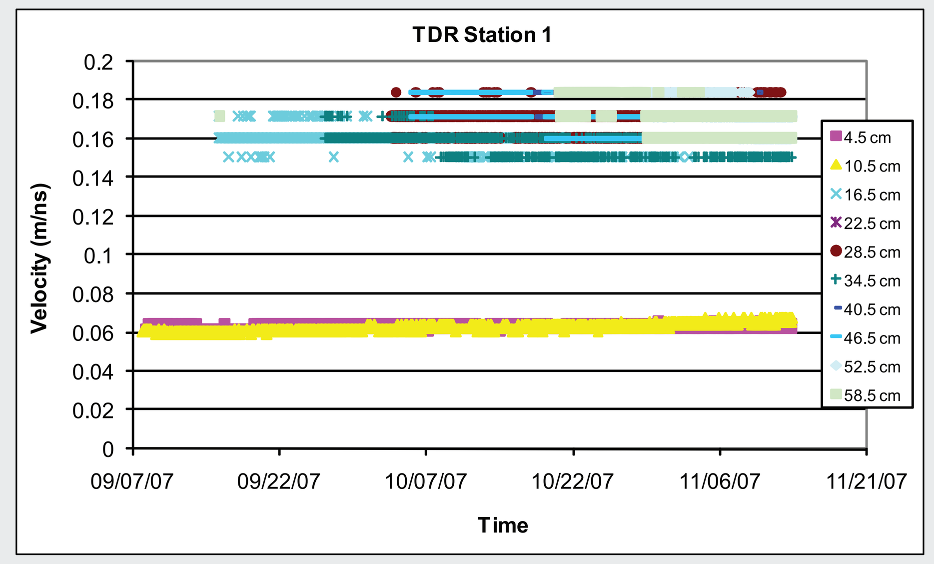

Figure 5: TDR probes were installed at six stations around the tank in 6 cm vertical increments. The TDR probes showed little change in water content in either the wet or dry layers throughout the experiment.

3.4. Data Analysis

The groundwave was identified on each GPR survey (Figure 6), and the arrival times were plotted as a function of antenna separation. Linear regression was performed to determine the groundwave velocity. The velocity was calculated for each of the three variable-offset surveys collected over each sand layer, and these velocities were averaged to obtain a single velocity estimate per frequency for each layer.

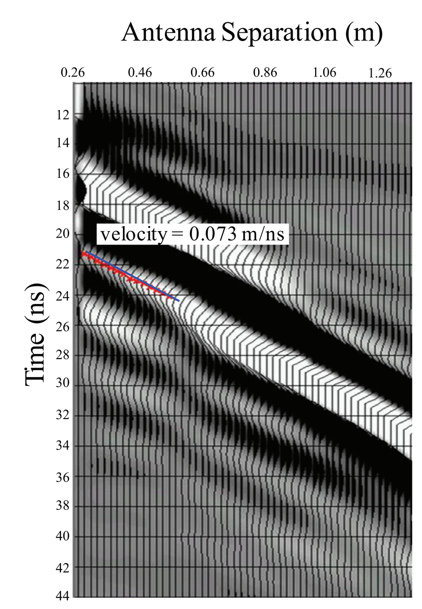

Figure 6a: 250 MHz data acquired over wet sand.

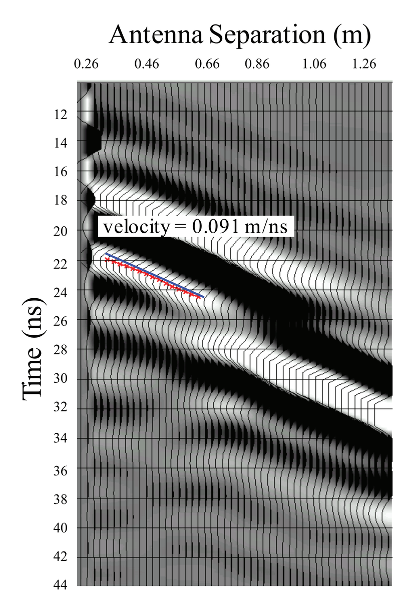

Figure 6b: 250 MHz data acquired over 6 cm of dry sand.

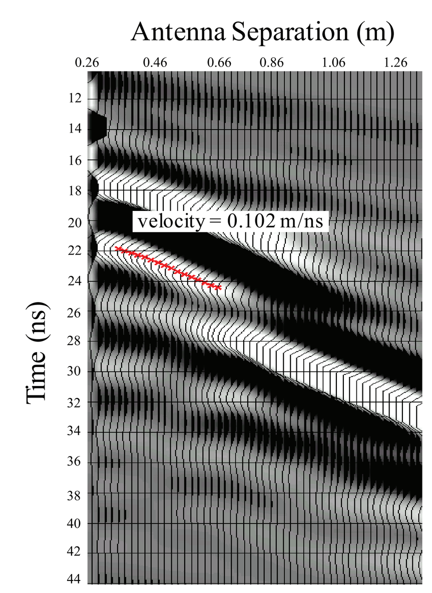

Figure 6c: 250 MHz data acquired over 9 cm of dry sand.

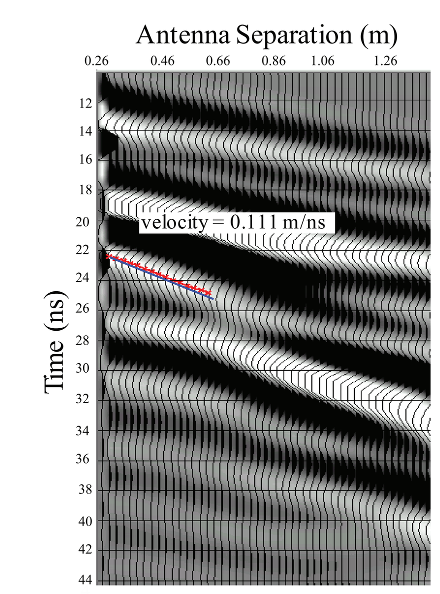

Figure 6d: 250 MHz data acquired over 12 cm of dry sand.

Figure 6: The highest amplitude trough was chosen as the groundwave pick for 250 MHz GPR data. The velocity of the groundwave increased as dry sand was added to the tank.

4. Experimental Groundwave Penetration Depths

The groundwave velocities were low for the surveys acquired over saturated sand, but the velocities increased as layers of dry sand were added (Figures 6 and 7). As the depth of dry sand increased, the portion of the groundwave passing through the wet sand decreased, and the velocity became more similar to that of dry sand. The groundwave penetration depth for each frequency was estimated by observing the depth of dry sand where the velocity ceased to change with additional sand layers. The penetration depth for each GPR frequency is given in Table 1. These results suggest that the groundwave penetration depth is frequency dependent, so multi-frequency groundwave velocity data might be used to create a vertical water content profile along a traverse. Additional experiments using wetter soils and varying soil textures are necessary to more accurately characterize the groundwave penetration depth for field-scale applications.

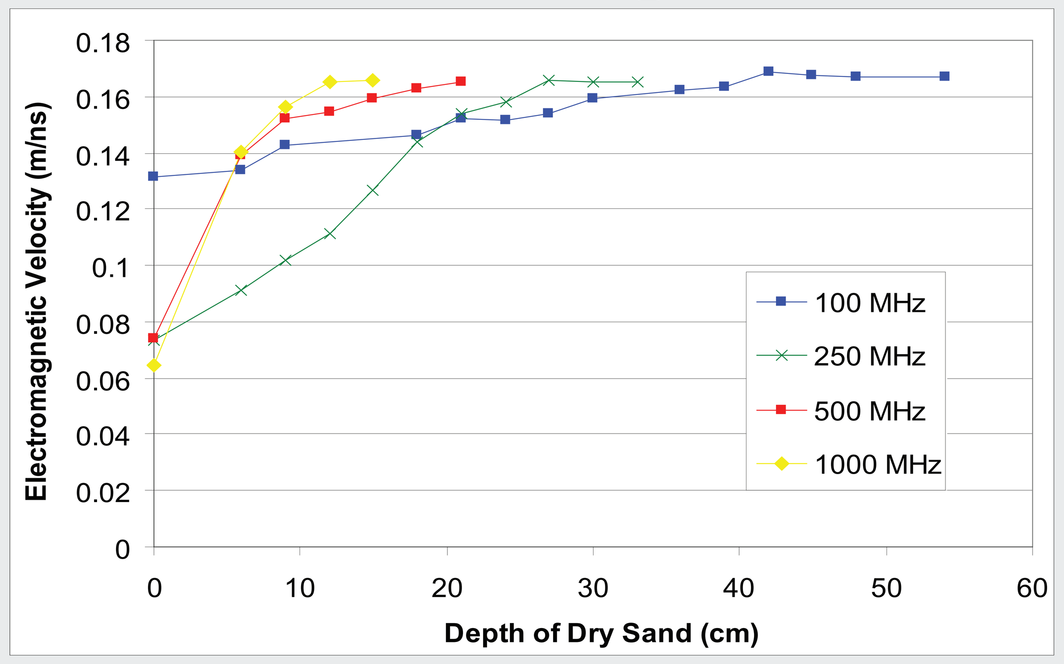

Figure 7: The groundwave penetration depth is determined by the thickness of dry sand where the velocity ceases to change as more dry sand layers are added. The penetration depth varies as a function of GPR frequency, where lower frequencies exhibit deeper penetration depths.

GPR Frequency (MHz)	Penetration Depth (cm)
100	40
250	27
500	20
1000	11

Table 1: The groundwave penetration depth for each GPR antenna frequency.

5. Acknowledgements

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6. References

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Van Overmeeren, R., S. Sariowan, and J. Gehrels, Ground penetrating radar for determining volumetric soil water content; results of comparative measurements at two test sites, J. Hydrol. 197, 316-338, 1997.