Estimating water content of unsaturated sandy soils by GPR during a drainage experiment

M. H. Zhang¹, ², M. Bano¹, X. Feng³, N. Lesparre¹, J. F. Girard¹, O. Razakarisoa¹, B. Belfort¹, F. Lehmann¹ and P. Friedmann¹

¹ School and Observatory of Earth Sciences (EOST), University of Strasbourg, Strasbourg, France
² College of Geo-exploration science and Technology, Jilin University, Changchun, PRC
E-mail: minghe.zhang@unistra.fr

Abstract. This study shows how to estimate water content of unsaturated sandy soils from ground-penetrating radar (GPR) data acquired during water drainage experiment. Using the Topp equation, water content can be converted to dielectric permittivity. Afterwards, based on 1D forward modeling method a GPR synthetic trace is generated. Finally, a trial-and-error match of modeled and observed GPR traces was performed to estimate the optimum set of parameters characterizing the materials composing the soil. According to the comparison of the modeling signal and the real signal, we go back to update the water content. Repeating the procedure until the modeling signal fits the real signal very well. We used this procedure to obtain the evolution of water content of unsaturated sandy soils. The method is presented on drainage experiment carried out on unsaturated sandy soil of a large-controlled experimental site. In order to follow the change of the water level, we measured GPR profiles at different times and picked up four GPR profiles, then the same trace (No. 700) were picked up on each GPR profile and estimated the water content from each signal.

1. Introduction

Soil water content is a key factor in many fields like agriculture, construction, soil erosion control, hydrology, water resource management and earth system modeling. In recent years, geophysical methods have played an important role in water content measurement because many of them are noninvasive and easy to use. Commonly used hydro-geophysical methods are electrical resistivity measurements [23][9] and electromagnetic methods [20][1][15].

Among the geophysical methods, GPR has been known as an accurate method to measure water content variations in soils [11][16][2][8] because the GPR wave velocity is highly sensitive to the change in soil water content. Different techniques are available for monitoring water content in soils by using GPR. Binley et al. [5] and Kowalsky et al. [14] used tomography imaging between boreholes during infiltration experiments. Many advanced techniques have been proposed in literature. Lunt et al. [17] used two-way travel time variations from a reflector at a known depth to monitor water content variation with time. Multi-offset GPR survey techniques like Common Mid Points (CMP) orWide-Angle Reflection-Refraction (WARR), were carried out to monitor water content in field or lab-scale experiments [6] [18] Coupled inversions were investigated by Hinell et al. [10] and Busch et al. [7]. Three-dimensional and four-dimensional investigations are now applied much more widely [22][3].
This paper focuses on the use of GPR as a tool for monitoring the change of water level during drainage in an unsaturated soil.

2. Drainage experiment

Figure 1 shows the experimental setup and a photograph of the large controlled site [12]. The length of the site is 24 m. We used a MALA RAMAC system with 500 MHz and 800 MHz antenna. The GPR system was set to acquire a trace for each 0.02 m. We started to measure the profile at 8 h 30 min and stopped at 17 h during a drainage experiment; the level of water table is moving down from 0.484 m depth at 8 h 30 min to 0.938 m depth at 17 h. In the morning, we measured the same GPR profiles by using 500 MHz and 800 MHz antenna alternately for each half hour. In the afternoon, we measured by using 500 MHz and 800 MHz antenna alternately for each one hour. However, in this paper, we mainly analyze the results measured by 500 MHz antenna and just select four profiles at different times. The length for each profile is also 24 m. For all the GPR field data, we did some processing like DC filter and shift with 20 samples. The processed real profiles at different times were shown in Figure 2.

Figure 1b presents a longitudinal section of the flow reservoir which is composed by three kind of medium. Under the experiment area, there are three layers. The porosity of the first layer is 43 % and the thickness is 0.5 m. The porosity of the second layer is 40 % and the thickness is 2.0 m. For the final layer, the porosity is 38 % and the thickness is 0.5 m.

3. Algorithm

This algorithm is divided into four basic steps:

1. We measured GPR profiles at different times and picked up four profiles. Then the same traces are picked up from each profile. These four signals are the real signals at the same place, however at the different times.

2. Petrophysical relationships

   We use the Topp equation [21], which relates the relative dielectric permittivity to the water content. The Topp equation as follow:
   \[
   \kappa = 3.03 + 9.39\theta + 146\theta^2 - 76.7\theta^3
   \]
   where \( \kappa \) is the relative dielectric permittivity and \( \theta \) is the water content.

3. Electromagnetic Modeling

   We realize the 1D forward modeling (Bano, 2004) of the data according to the equation (2) as follows:
   \[
   E(\omega) = \sum_{i=1}^{n} R_i G_i E_0(\omega) \exp\{-i\omega T_i\} \exp\{-\sum_{i=1}^{n} \alpha_i [T_i - T_{i-1}]\},
   \]
   where \( T_i = 2 \sum_{i=1}^{n} [Z_i - Z_{i-1}] / V_i \) is the two way travel-time inside the layer, \( R_i \) is the reflection coefficient, \( n \) is the number of layers. The geometrical spreading term is:
   \[
   G(T) = \frac{1}{\sum_{i=1}^{n} V_r [T_i - T_{i-1}]} \quad \text{and} \quad \alpha = \frac{\omega}{2Q}
   \]
where $c = 0.3 \text{ m/ns}$ is the free-space velocity of electromagnetic waves, $\kappa$ and $Q$ are the dielectric constant and the quality factor of each layer, respectively. The theoretical GPR trace in time (calculated for a range of sets of parameters) is obtained by transforming back the spectrum of equation (2).

4. Estimation of water content

We compare the forward modeling GPR signal with the real GPR signal picked up from the real GPR profile and backing to update the water content. Then, we repeat the update until the forward modeling GPR signal fits well with the real GPR signal. Finally, the best fit gives an estimation of the water content and we also compare our results with the water content field measurement achieved with a Sentek sensors [19].

Figure 2. Processed real GPR profiles. The levels of water table are 0.484 m (8 h 30 min), 0.744 m (10 h 30 min), 0.836 m (12 h 30 min) and 0.938 m (16 h).

4. Results and Discussion

In order to perform the forward modeling we picked up the wavelet from the first arrival of the real trace by applying a Blackman filter with $t_1 = 3.5 \text{ ns}$ and $t_2 = 7.0 \text{ ns}$ (see Figure 3). The Blackman taper, wavelet and the frequency spectrum of wavelet are presented in Figure 3.

Figure 4 shows the comparison of the forward modeling GPR signals with the real GPR signals observed at different times.
Figure 3. Blackman taper, wavelet and frequency spectrum

Figure 4. Comparison of modeling signals and real signals for four different times with different positions of water level. The levels of water table are 0.484 m (8 h 30 min), 0.744 m (10 h 30 min), 0.836 m (12 h 30 min) and 0.938 m (16 h).

Figure 5 shows the evolution of water content estimated with our algorithm and from the GPR data acquired at different times corresponding to different levels of the water table. The green dot lines show the estimation results of the water content by GPR data. The red dot lines are the water content measured by Sentek Sensors. From Figure 5, we notice that when the level of the water table is going down, the water content becomes smaller, especially in the boundary of two layers at 0.5 m depth. The estimated water content curves (in green) show the similar trend as the in-situ measured water content curves (in red).
Figure 5. Water content at four different times with different positions of water level. The levels of water table are 0.484m (8h 30min), 0.744m (10h 30min), 0.836m (12h 30min) and 0.938m (16h).

Figure 6. The 800 MHz GPR profile, the wavelet picked from the real trace (No. 700) and its spectrum, the comparison between real (in blue) and modeled trace (in red) and the estimation of water content (in green) compared to the water content measured in-situ (in red).

Figure 6 shows the results of the GPR profile measured by using 800 MHz antenna at 15h, the level of the water table is at about 0.915 m. The comparison between real (in blue) and modeled trace (in red) is pretty good. Additionally, the comparison of the water content estimated by using the 800 MHz (at 15h) antenna and 500 MHz antenna (at 16h, see Figure 5) shows a similar trend.

5. Conclusions

A water table fluctuation experiment has been carried out in a 24 m x 12 m x 3 m flow tank filled with different soil layers. GPR profiles have been done during the drainage of the basin and this article presents a methodology to estimate water content in a non-intrusive way. The results presented in this paper show that the GPR method is a good technique for estimating the water content and monitoring
the water level which were showed by experiments in an unsaturated soil. In the future, we will apply the inversion algorithm to realize the comparison between real and synthetic traces automatically by calculating the minimum of RMS error.

Acknowledgement
M. H. Zhang is supported by China Scholarship Council (CSC) during 2018-2019.

References
[1] Akbar M, Kenimer A, Searcy S and Tobert H 2005 Soil water estimation using electromagnetic induction *Transactions of the American Society of Agricultural Engineers*, **48**, 129-135
[2] Annan A P 2005 GPR methods for hydrogeological studies: Hydrogeophysics 185-213
[3] Allroggen N, van Schaik L, M B and Tronicke J 2015 4D ground-penetrating radar during a plot scale dye tracer experiment *Journal of Applied Geophysics* **118** 139–144
[4] Bano M 2004 Modeling of GPR waves for lossy media obeying a complex power law of frequency for dielectric permittivity *Geophysical Prospecting* **52** 11-26.
[5] Binley A P, Winship R, Middleton R, Pokar M and West J 2001 High-resolution characterization of vadose zone dynamics using cross-borehole radar *Water Resources Research* **37** 2639-2652
[6] Bradford J 2006 Applying reflection tomography in the post-migration domain to multi-fold *Ground-Penetrating Radar Geophysics* **71** K1-K7
[7] Busch S, Weihermüller L, Huisman J A, Steelman C M, Endres A L, Vereecken H and van der Kruk J 2013 Coupled hydrogeophysical inversion of time-lapse surface GPR data to estimate hydraulic properties of a layered subsurface *Water Resources Research* **49** 8480–8494
[8] Doolittle J, Jenkinson B, Hopkins D, Ulmer M and Tuttle W 2006 Hydropedological investigations with Ground-Penetrating Radar (GPR): Estimating water-table depths and local ground-water flow pattern in areas of coarse-textured soils *Geoderma* **131** 317-329
[9] Goyal V, Gupta P, Seth S, and Singh V 2006 Estimation of temporal changes in soil moisture using resistivity method *Hydrological Processes* **10** 1147-1154
[10] Himnell A C, Ferré T P A, Vrugt J A, Huisman J A, Moysay S, Rings J and Kowalsky M B 2010 Improved extraction of hydrologic information from geophysical data through coupled hydrogeophysical inversion *Water Resources Research* **46** W00D40
[11] Huisman J, Hubbard S, Redman J and Annan A 2003 Measuring soil water content with Ground-Penetrating Radar *Vadose Zone Journa** 2** 476-491
[12] Jellali S, Muntzer P, Razakarisaona O and Schäfer G 2001 Large Scale Experiment on Transport of Trichloroethylene in a Controlled Aquifer *Transport in Porous Media* **44** 145-163
[13] Klotzsche A, Jonard F, Looms M C, van der Kruk J and Huisman J A 2018 Measuring soil water content with ground penetrating radar A decade of progress *Vadose Zone Journal* **17** 180052
[14] Kowalsky M, Finsterle S, Peterson J, Hubbard S, Rubin Y, Majer,E, Ward A and Gee G 2005 Estimation of field-scale soil hydraulic and dielectric parameters through joint inversion of GPR and hydrological data *Water Resources Research* **41** W11245
[15] Léger E, Saintenoy A and Coquet Y 2014 Hydrodynamic parameters of asandy soil determined by ground-penetrating radar inside a single ringinfiltrometer *Water Resources Research* **50** 5459–5474
[16] Loeffler O and M Bano 2004 GPR measurements in a controlled vadose zone *Influence of the water content* **3** 1082–1092
[17] Lunt I, Hubbard S, and Rubin Y 2005 Soil moisture content estimation using Ground-Penetrating Radar reflection data *Journal of Hydrology* **307** 254-269
[18] Mangel A R, Moysay S M J, Ryan J C and Tarbutton J A 2012 Multi-offset ground-penetrating radar imaging of a lab-scale infiltration test *Hydrology & Earth System Sciences* **16** 4009–4022
[19] Sentek 2001 Calibration for sentek soil moisture sensors *Sentek Pty Ltd* 60p
[20] Sheets K V and Hendrickx J M 1995 Non invasive soil water content measurement using
electromagnetic induction *Water Resources Research* **31** 2401-2409

[21] Topp G C, Davis J L and Annan A P 1980 Electromagnetic determination of soil water content Measurements in coaxial transmission lines *Water Resources Research* **16** 574–582

[22] Truss S, Grasmueck M, Vega S and Viggiano D A 2007 Imaging rainfall drainage within the Miami oolitic limestone using high-resolution time-lapse ground-penetrating radar *Water Resources Research* **43** W03405

[23] Zhou Q, Shimada J and Sato A 2001 Three-dimensional spatial and temporal monitoring of soil water content using electrical resistivity tomography *Water Resources Research* **37** 273-285