



Assessing vertical soil moisture dynamics using multi-frequency GPR common-midpoint soundings

Colby M. Steelman^{a,b,*}, Anthony L. Endres^a

^a Department of Earth and Environmental Sciences, University of Waterloo, 200 University Avenue West, Waterloo, ON, Canada N2L 3G1

^b School of Engineering, University of Guelph, 20 Stone Road East, Guelph, ON, Canada N1G 2W1

ARTICLE INFO

Article history:

Received 10 October 2011

Received in revised form 15 February 2012

Accepted 21 February 2012

Available online 26 February 2012

This manuscript was handled by Philippe Baveye, Editor-in-Chief, with the assistance of Xunhong Chen, Associate Editor

Keywords:

Soil moisture

Ground-penetrating radar

Seasonal moisture dynamics

Vadose zone

Common-midpoint sounding

Multi-frequency

SUMMARY

Soil moisture measurement techniques are of utmost importance to vadose zone hydrologists. Surface hydrogeophysical methods, such as ground-penetrating radar (GPR), have the capacity to provide field-scale soil moisture information across a range of depth scales. This paper presents an extensive field study using multi-frequency (i.e., 225 MHz, 450 MHz, 900 MHz) GPR common-midpoint (CMP) soundings to monitor a complete annual cycle of soil moisture conditions at three distinct sites. We examine the use of normal-moveout (NMO) velocity analysis applied to CMP data for monitoring highly dynamic vertical soil moisture conditions in a mid-latitude climate consisting of wetting/drying and freeze/thaw cycles with varying degrees of magnitude and vertical velocity gradient. NMO velocity analysis is used to construct interval-velocity-depth models at a fixed location collected every 1–4 weeks. These time-lapse models are combined to construct temporal interval-velocity fields, which are converted into soil moisture content using an appropriate petrophysical relationship. Using these moisture fields, we were able to characterize the vertical distribution and dynamics of soil moisture in the shallow vadose zone. Although the use of multiple antenna frequencies provided varying investigation depths and vertical resolving capabilities, optimal characterization of soil moisture conditions was obtained with high-frequency 900 MHz antennas. The integration of direct ground wave and NMO velocity data from a single CMP sounding allowed us to better refine the shallow soil moisture profile and underlying vadose zone conditions during seasonal wetting, drying and freezing cycles. This study demonstrates the capacity of GPR to characterize vertical moisture dynamics, and highlights the importance of collecting high-resolution data along the air–soil interface to resolve the water content profile from the surface down to the deeper vadose zone conditions.

© 2012 Elsevier B.V. All rights reserved.

1. Introduction

Soil water content is a fundamental component in the prediction of hydrological state variables (e.g., soil moisture fields, soil water storage), soil hydraulic properties (e.g., hydraulic conductivity function, water retention curve) and hydraulic fluxes (e.g., infiltration, redistribution, drainage) at both the field and catchment scale. Numerous studies have demonstrated the value of soil moisture data to the characterization of vadose zone hydrology; recent reviews on this topic have been published by Vereecken et al. (2008) and Robinson et al. (2008). The vadose zone is also a fundamental component of the climate system because it governs plant transpiration and photosynthesis, and acts as a storage component for water and energy (Seneviratne et al., 2010). Moisture conditions are also important for the characterization of seasonal freeze

and thaw cycles (Luo et al., 2003), and hence the evaluation of overland flow potential (Nyberg et al., 2001), melt water recharge (Bayard et al., 2005) and soil thermal conductivity. Freeze and thaw processes also play an important role in the evolution of soil functioning (i.e., changes in soil physical properties, microorganisms, carbon and nutrient dynamics) (Henry, 2007). Techniques that provide in situ estimates of soil moisture distribution are fundamental to hydrologic studies.

Conventional moisture monitoring techniques such as gravimetric sampling, thermal neutron probes and time-domain reflectometry (TDR) provide highly localized information and are generally invasive; further, these methods are not well suited for efficient acquisition of spatial data. Alternately, remote sensing imagery has low spatial resolution and lacks the depth of investigation necessary to estimate vertical hydraulic fluxes. Hence, surface hydrogeophysical methods are increasingly recognized (e.g., Vereecken et al., 2008; Robinson et al., 2008) as an important source of soil moisture information at the field scale due to their sampling volume (i.e., dm³–m³ scale), non-invasive nature, good depth of

* Corresponding author. Tel.: +1 519 824 4120x56263.

E-mail addresses: cmsteelm@uwaterloo.ca, csteelma@uoguelph.ca (C.M. Steelman).

investigation (1–10 m) and high resolving power. In particular, ground-penetrating radar (GPR) techniques have been proven to be very useful for monitoring vadose zone soil water content at the field scale (Huisman et al., 2003). While GPR data are dependent on the same electromagnetic (EM) properties that govern TDR response, its larger sampling volume and non-invasive nature makes it much less affected by measurement errors associated with macropores (e.g., root and worm holes) and air gaps along sensors that may impact TDR measurements (Robinson et al., 2003).

Two important requirements of vadose zone hydrology are the vertical soil moisture distribution within the vadose zone and the nature of its coupling with soil moisture variations at the surface (Vereecken et al., 2008); this information is needed to quantify moisture storage, estimate groundwater recharge, and quantify exchange of water and energy between the soil and atmosphere. A technique for obtaining information about the vertical moisture profile from surface GPR measurements utilizes the normal-move-out (NMO) velocity analysis of the offset distance–traveltime relationship for subsurface reflection events in common-midpoint (CMP) data. The results of NMO velocity analysis are subsequently used to determine the interval velocities of layers in the subsurface. NMO velocity analysis and interval velocity determination were originally developed for application to seismic reflection data and have been extensively analyzed in the literature (e.g., Taner and Koehler, 1969; Shah and Levin, 1973; Castle, 1994; Yilmaz, 2001). Recently, their application to GPR data for obtaining subsurface EM wave velocity information has been examined in a number of papers (e.g., Tillard and Dubois, 1995; Jacob and Hermance, 2004; Becht et al., 2006; Barrett et al., 2007; Booth et al., 2010).

Studies by Greaves et al. (1996), Garambois et al. (2002) and Turesson (2006) have applied NMO velocity analysis and interval velocity determination to GPR CMP data to characterize the spatial distribution of soil moisture in the vadose zone. However, these studies lack the temporal component necessary to critically examine the ability of this approach to monitor over a range of annual conditions the vertical soil moisture distribution within the vadose zone and the nature of its coupling with very shallow soil moisture variations.

To address this point, we have undertaken an extensive field study to examine the use of NMO velocity analysis applied to CMP data for monitoring vertical soil moisture variations over a complete annual cycle of soil conditions (i.e., dry summer, wet spring and autumn, frozen winter soil conditions) typical of mid-latitude climates; as a result, our data set covers a wide range of in situ vertical velocity conditions in terms of magnitude and gradient. By collecting multi-frequency (i.e., 225 MHz, 450 MHz and 900 MHz) data sets at three sites with different soil textures (i.e., sand, sandy loam and silt loam), we will examine the effects of the trade-off between resolving power and depth of penetration inherent in GPR surveys. Our ability to obtain reliable interval velocity measurements from NMO analysis will also be assessed. Further, the fact that these data yield information at discrete depth intervals in the shallow vadose zone enables us to evaluate the nature of the coupling between surface and deeper moisture conditions.

2. NMO velocity analysis and interval velocity determination

Surface GPR techniques use a transmitting antenna positioned on the surface (i.e., air-ground interface) that radiates short pulses of EM waves commonly in the bandwidth between 10 MHz and 1 GHz. These propagating EM fields respond to changes in material electrical properties which are recorded by a receiving antenna also located on the surface. For non-magnetic low-loss soils, the propagation velocity (v) of EM waves within GPR bandwidth primarily depends on the relative permittivity (κ) (i.e., the effective

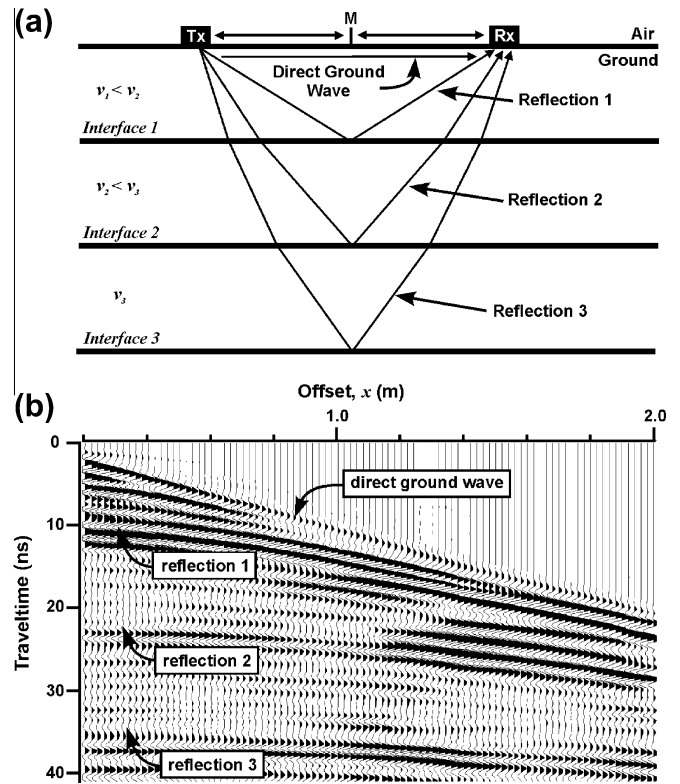


Fig. 1. (a) Schematic CMP survey illustrating multiple reflection events and (b) corresponding CMP sounding.

permittivity of the bulk material ε relative to the free space permittivity, ε_0). This relationship is defined by the equation

$$v = \frac{c}{\sqrt{\kappa}}, \quad (1)$$

where c is the EM velocity in free space (0.2998 m/ns). Within this bandwidth, the relative permittivity of liquid water ($\kappa_w = 78$ –88) contrasts strongly with other common components of the soil system (i.e., mineral soil grains $\kappa_s = 4$ –6 and air $\kappa_a = 1$), as well as ice ($\kappa_i = 3.2$) (Cassidy, 2009). This relative permittivity contrast provides the basis for estimating liquid volumetric water content using EM wave velocity measurements.

CMP surveys systematically separate a transmitting and receiving antenna about a fixed midpoint (M) position (Fig. 1a), which results in a separation of coherent events in the wavefield (e.g., direct waves and reflections) (Fig. 1b). This separation allows the extraction of subsurface EM wave velocity information from the various events through the analysis of their respective traveltime–offset distance relationships. Direct ground waves (DGW) possess a linear traveltime–offset relationship in CMP data such that the velocity is obtained from a line-fitting procedure (Steelman and Endres, 2010). The traveltime–offset relationship for the reflections in CMP data is more complicated and requires a different analysis technique.

Let us consider the reflection event from the N th interface in a horizontally layered subsurface (Fig. 2) where the N th layer has a thickness and interval velocity h_N and v_N , respectively. The relationship between the antenna offset distance x and the corresponding two-way traveltime $t_x(N)$ for this event can be expressed in terms of the following power series expansion (Yilmaz, 2001):

$$[t_x(N)]^2 = C_0(N) + C_1(N)x^2 + \sum_{i=2}^{\infty} C_i(N)x^{2i}, \quad (2)$$

where $C_0(N) = [t_0(N)]^2$, $C_1(N) = 1/[V_{RMS}(N)]^2$ and $C_i(N)$ are functions that depend on layer thicknesses and interval velocities. The normal

Download English Version:

<https://daneshyari.com/en/article/4577026>

Download Persian Version:

<https://daneshyari.com/article/4577026>

[Daneshyari.com](https://daneshyari.com)