Application of GPR ground wave for mapping of spatiotemporal variations in the surface moisture content at a natural field site

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Abstract

In the present study GPR ground wave (GW) was used to monitor the spatial distribution of surface moisture content at a natural Kanto loam site. To map the soil moisture variations, measurements were conducted on a regular interval of 2~3 days per week. Results revealed that ground wave data were sensitive to the upper surface soil conditions as well as seasonal variations. Significant increase in the moisture content values were observed a day after a precipitation event. However, moisture content increase was non-uniform over the entire area; the probable cause of the variations might be associated with soil hydraulic properties (e.g. hydraulic conductivity, water retention characteristics), and/or topography of the site. The GW sampling depth obtained by taking one quarter of wavelength (Pallavi, 2009) was found more reliable with the reference measurements. The GW sampling depth was found to be between 0.06 ~ 0.07 m at this site. The study shows that the GPR GW can be used as a principal tool for large scale spatiotemporal monitoring in non-invasive and rapid mode with high resolution and provides quality data with known sampling volume at a field scale.

Key Words

Ground penetrating radar (GPR), Ground wave (GW), GW sampling depth, moisture content, precipitation

Introduction

The near surface moisture content is a key parameter for soil/water conservation, irrigational and agricultural management. In general, surface moisture content is highly variable in space and still is difficult to characterize on a consistent and spatially comprehensive basis at a field scale. The measurement of spatial variation of moisture content at the field scale is thus important. The conventional method (TDRs, cores, neutron probes) provide the essential information, but are limited to a specific point location. Applications of GPR have shown promise for moisture content estimation at the field scale during last two decades (Grote *et al*., 2003; Huisman *et al*., 2003). The ground wave (GW) of GPR provides a means to monitor large areas relatively fast, non-invasively, and cost-effectively with good resolution data quality. The most important character of the GPR method is that it estimates the moisture content in absence of shallow reflectors in the subsoil (Van Overmeeren *et al*., 1997). However, the sampling depth of the GW is not well defined, and this uncertainty limits its application for large-scale monitoring. Therefore, the specific aim of the presented study was to monitor the seasonal variations in the spatial distribution of the moisture content.

Methods

Basics of ground wave of GPR

Ground penetrating radar is a geophysical technique that uses high frequency (MHz ~ GHz) electromagnetic energy to probe the subsurface. Energy is emitted from the GPR transmitter as a spherical wave, and some of this energy travels along the air-ground interface in the near subsurface toward the receiver. This energy creates a boundary wave that is referred to as the direct wave (air and ground wave). The first strong signal

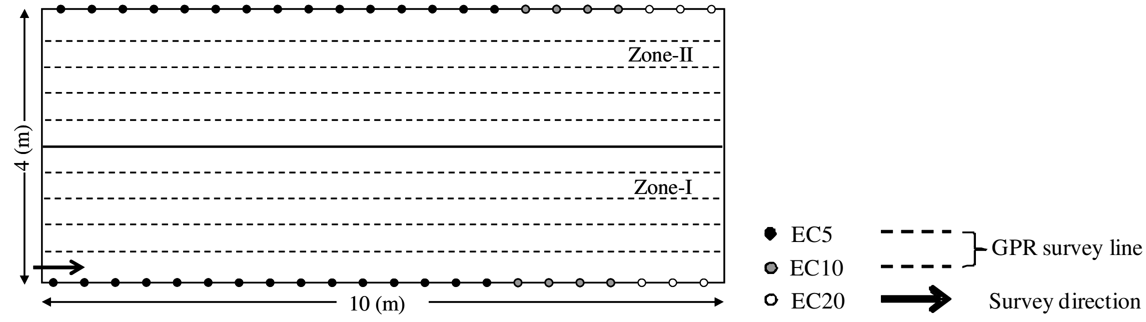

Figure 1. Schematic diagram of study site with GPR transects, sensor position and zone divisions (I: 0 ~ 2 m, vegetation, and II: 2-4 m, bare soil)

usually represents airwave (AW), which travels directly from the transmitter to the receiver through air at the speed of the electromagnetic wave in vacuum. GW is the part of the radiated energy that travels between the transmitter and receiver along the soil surface. The propagation velocity of GW (v_{gw}) depends on the dielectric constant of the soil K_{soil}, the moisture content θ, the soil texture etc. The velocity (v_{gw}) is calculated by dividing the antenna separation (S) by the GWTT (ground wave travel time: t_{gw}), e.g. $v_{gw} = (S/t_{gw})$. The dielectric constant K is then calculated by following equation, $K = (c/v_{gw})^2$ (Davis and Annan, 1989), where c is the speed of the EM wave in a vacuum (3×10^8 m s^{-1}). The volumetric water content is obtained from K using Topp's equation (Topp *et al.*, 1980). Two different GW depth models proposed by van Overmeeren *et al.* (1997), $[0.5(\lambda \times S)^{0.5}]$ and Pallavi *et al.* (2009) $[0.25 \times \lambda]$ are used for depth estimation. The wavelength λ is calculated by ($\lambda = v_{gw}/f$), where f is the central frequency of GPR and v_{gw} is the GW velocity.

Equipment and analysis

A pulseEKKO PRO 250 system (Sensors and Software, Canada) with 250 MHz central frequency antenna was used in this study. Radar signals were processed and analyzed by the EKKO view deluxe software. Simple processing was applied to the data, consisting of dewow filter to remove the background noise and AGC gain to distinguish the ground, refracted, and reflected waves at larger separations. Soil moisture sensors (ECHO sensors by Decagon Devices, Inc.) were also used for soil moisture and dielectric constant measurements.

Field site

An intensive study area of 10 m by 4 m in Field Science Centre of Tokyo University of Agriculture and Technology, Japan was used for measurements of moisture content variations of near surface soils pre- and post-precipitation. The schematic diagram of the study site is depicted in Figure 1. The whole area was divided into two zones, with and without vegetation, with 10 equidistant parallel transects for the GPR measurement. Along the boundary in x-direction, soil moisture sensors were also installed, where the black circles (EC5) represent the 5-cm-long sensors, gray circles (EC10) represent 10-cm-long sensors, and the open circles (EC20) represent 20-cm-long sensors, respectively. Vegetation was allowed to grow on the Zone-I, while Zone-II was cleaned weekly to maintain a bare soil surface during the research campaign.

Survey method

Measurements were conducted using both common-offset (CO) and common-midpoint (CMP) methods for moisture content mapping and velocity estimation. The CO profile provides the detailed information of the imaged area (e.g. surface-subsurface moisture content distribution, buried anomaly position, stratigraphical information etc.). However, in this study, our main concern was to monitor the behaviour of direct ground wave in relation to changes in surface soil moisture contents.

Results and discussions

CMP surveys were first conducted for velocity profile estimation. Measurements were performed along the central lines of the both zones (3rd and 8th line), with a step size of 0.10 m. In both surveys, ground waves were clearly recognized between antenna separations of 0.38 to 0.98 m. At larger separations, interference between shallow reflections and ground waves were observed. One of the CMP profiles (along transect 3) is given in Figure 2, where the AW and GW velocities were obtained by taking the inverse of linear slope of position-travel time plot. The estimated AW and GW velocity was 0.29, and 0.067 m ns^{-1} respectively.

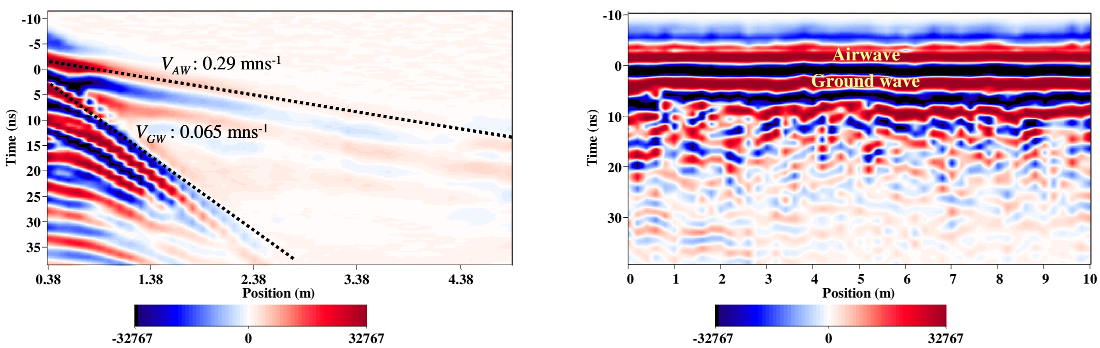

Figure 2. (a)CMP profile with AW and GW velocity and (b) unprocessed CO profile showing the AW and GW pick (same picking process for GW is used in all data analysis).

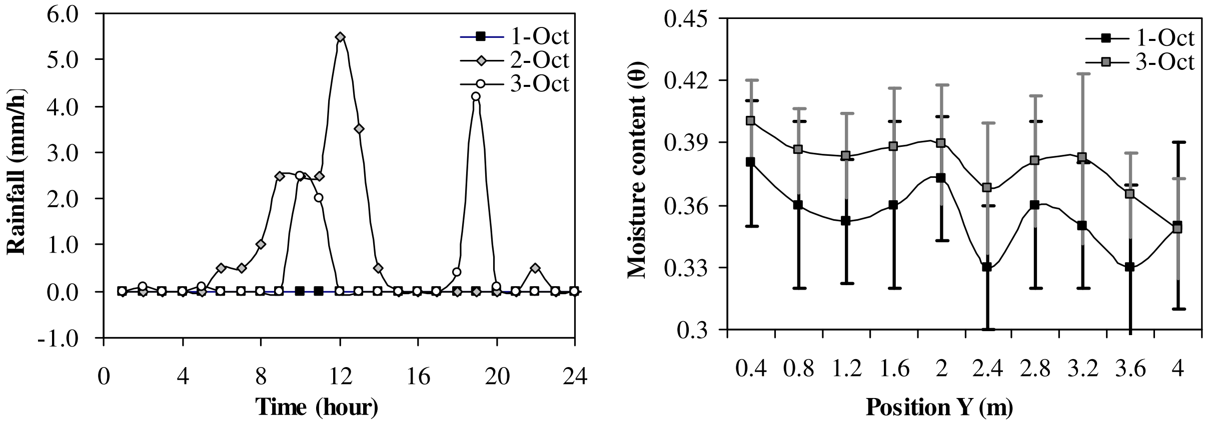

Figure 3. (a) Hourly rainfall intensity on the study site from Oct. 1st to 3rd, 2009 and (b) averaged moisture content along each survey lines on Oct. 1st and Oct. 3rd based on GW information.

The automatic velocity extraction from CMP profile also showed the GW velocity of 0.067 m ns^{-1} respectively. Similar response was observed in the second CMP survey (along transect 8), where the GW velocity by taking the inverse of linear slope was 0.061 m ns^{-1} and from the automatic velocity extraction was 0.067 m ns^{-1} respectively. CMP surveys were also used as a reference for true AW and GW picks from the CO profile and selection of an optimal antenna separation for the CO survey. After careful inspection of all CMP data and the results of semblance analysis, an antenna separation of 0.40 m was selected for CO survey. Data was collected 2-3 times a week during the monitoring experiment. The AW was selected as first maximum amplitude and GW as the second maximum value. A similar picking process was applied during all data acquisition campaigns. Soil heterogeneity, shallow reflections, and high and weak reflections zones were clearly observed from the profiles. In this paper, we focus only on two results that were collected pre- and post-precipitation; October 1st and October 3rd in 2009, respectively. The rainfall intensity during these data acquisitions is given in Figure 3a. During both campaigns, CO profiles were collected along each transect with a step size of 0.4 m, time window of 50 ns, sampling rate of 0.4 ns and eight stacks per trace. This survey resulted in ten CO profiles over the entire area in each campaign, five in bare soils and five in vegetated soils. Figure 2b shows one of the CO profiles collected during the first campaign.

Analysis of travel times of GW was performed to assess near-surface variations in space and time. The arrival times of the air and ground waves picked from the CO data were compensated for time-zero starting delays. The calibrated travel times were converted into velocities and velocity values were then converted into dielectric constants and finally Topp's equation (Topp, 1980) was used for moisture content estimation. Comparison of GPR and sensor data along Transect 1, GPR estimated moisture content values showed similar trend until 6.5 m where 5-cm-long sensors were installed, while the information based on 10-cm and 20-cm sensors (from 6.4 m to 10 m) underestimates the moisture content. The estimated depth of influence of GW based on two depth models for the GW velocities of 0.06, 0.065 and 0.07 mns^{-1} was; (a) van Overmeeren *et al.* (1997): 0.12 m to 0.14 m, and (b) Pallavi *et al.* (2009): 0.06 m to 0.07 m respectively. Model (b) was found more consistent with the obtained moisture content estimates. The similarities between 5-cm-long sensors and GPR data showed that GPR can provide spatially dense and potentially valuable information about the surface moisture content variations at rapid pace in non-invasive manner at our study site. In addition, inaccuracy in data picking for GWTT and difference in sampling volume, especially the depth of influence of GPR ground wave and the soil moisture sensors can not be ignored in this comparison. Using the same approach, moisture content distributions were mapped one day after precipitation. An impact of precipitation was observed on the surface moisture content. Figure 3(b) shows the averaged moisture content along all survey lines during pre- (Oct.-1st) and post (Oct-3rd) precipitation campaigns. A significant increase in the moisture content was observed. Extending the investigated ground wave analysis into two-dimensional space, Figure 4 illustrates the spatial variation is the near surface moisture content over the entire study area. Figure 4a represents the data collected during the Oct.-1st, while Figure 4b represents the data obtained one day after precipitation (Oct. -3rd). The moisture content shows significant increase in the post precipitation campaign. Figure 4c shows the changes in the moisture content after precipitation. The moisture content change was not uniform over the study area. A probable cause might be related to the soil hydraulic properties and/or topography of the site. In summary, the present study signifies the potential of ground wave for spatial mapping of surface moisture content at the field scale.

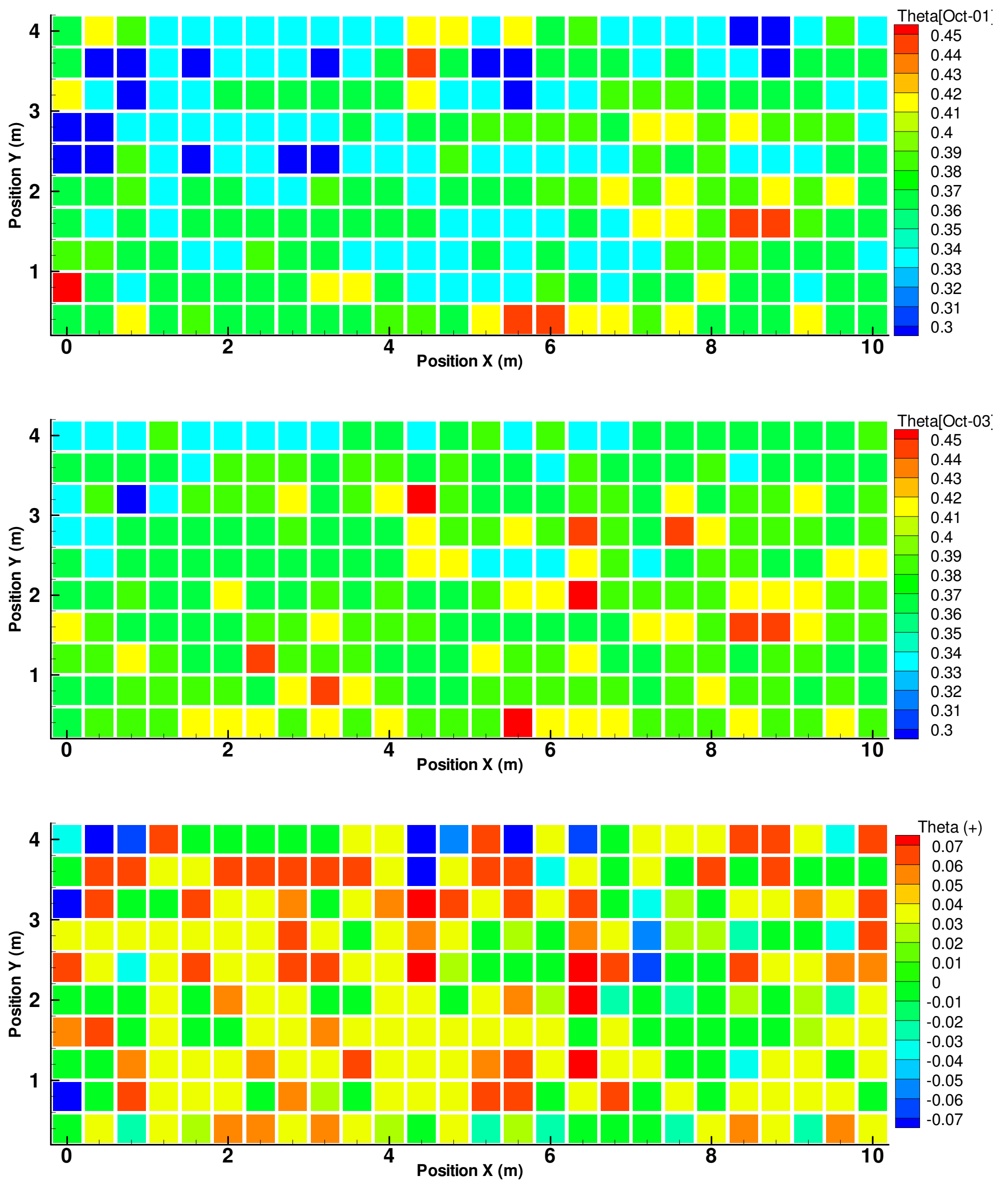

Figure 4. Spatial variations of moisture content (θ) maps obtained using GPR ground waves, (a) on fine sunny day (Oct.- 1st), (b) a day after precipitation (Oct.-3rd) in 2009, and (c) Change in moisture content after precipitation over the entire area.

Additionally, it was also verified that the GW depth can also be measured with GPR information only. Experimentally, it was observed that GW can image the seasonal variations of surface moisture content with high resolution and known sampling volume.

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