Borehole radar monitoring of infiltration processes in a vadose zone

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Abstract: Ground-penetrating radar (GPR) is an effectiveness tool for imaging spatial distribution of hydrogeologic parameters. An artificial groundwater recharge test has been conducted in Nagaoka City in Japan, and time-lapse crosshole GPR data were collected to monitor infiltration processes in a vadose zone. Since radiowave velocities in a vadose zone are largely controlled by variations in water content, the increase in traveltimes is interpreted as an increase in saturation in the test zone. We use a finite-difference time-domain method in two-dimensional cylindrical coordinates to simulate field results. Numerical modeling successfully reproduces the major feature of velocity changes in the filtration process.

Keywords: GPR, crosshole, vadose zone, time-lapse, FDTD

1. INTRODUCTION

Ground-penetrating radar (GPR) is a technique of imaging the subsurface at high resolution. A short radar pulse in the frequency band 10 – 1000 MHz is introduced into the ground. In high resistive rocks (> 100 ohm-m), the propagation velocity of the radar pulse is mainly controlled by the dielectric constant (relative permittivity, ε_r) of the subsurface. Water has a dielectric constant of 80, whereas in most dry geological materials the dielectric constant is in the range 4 – 10. Consequently, the water content of materials exerts a strong influence on the propagation of radar pulse.

Near-surface, environmental investigations often require monitoring of the spatial distribution of water content and identification of preferential fluid flow paths. GPR has proven to be a powerful tool for hydrogeological characterization (Reynolds, 1997). Since the radiowave velocity is highly correlated with water content in the subsurface, the technique is commonly used to detect differences in porosity in a saturated zone, and differences in soil water retention and thus grain size in a vadose zone.

In 2002, an artificial groundwater recharge test was carried out in Nagaoka City, Japan. We use borehole radar to monitor infiltration processes in a vadose zone. Water contents of soils can be estimated by the dielectric constant obtained from first arrival times of GPR pulses. Time-lapse crosshole measurements were made to collect zero-offset radargrams. To simulate GPR wavefields and to evaluate hydraulic parameters in a vadose zone, we employ a finite-difference time-domain (FDTD) solution of Maxwell's equations in two-dimensional (2D) cylindrical coordinates.

2. FIELD TEST

An artificial groundwater recharge test has been conducted in Nagaoka City in Niigata Prefecture, Japan (Kuroda et al., 2006). In this test, borehole radar measurements were made for monitoring infiltration processes in a vadose zone, which is the area of unsaturated soil from the surface to the groundwater table. Figure 1 shows a schematic diagram explaining the spatial arrangement of an infiltration pit and boreholes. The top 2-m surface soil consists of loam, and the subsoil is gravel. The water table is located at about 10 m below the surface.

A 2 m × 2 m square of wooden water tank is set in the surface layer and its bottom, at which groundwater is recharged into the soil, is located at -2.3 m from the surface. A total volume of water was set to 2 m^3 (2 m × 2 m × 0.5 m). It took about 40 minutes for all groundwater flowed off into the soil from the tank. Two boreholes are located on either side of the tank. The lengths of boreholes *T* and *R* are 11 m and 5.7 m, respectively. The distance between the two boreholes is 3.58 m. The boreholes are PVC cased, and its diameter is 7 cm. All GPR data were collected by a GSSI SIR10 system with borehole antennas at a dominant frequency of 110 MHz. The transmitter and receiver antennas were placed in boreholes *T* and *R*, respectively. In this test, instead of using time-consuming multi-offset gathering, we collected radargrams with repetitive zero-offset gathering (ZOG). GPR measurements were made every 0.1 m from -2.3 m and -5.0 m, it took about 2 minutes to collect a zero-offset gather (ZOG) of radargrams.

Figure 2 shows radargrams observed during the infiltration test. First arrival times are about 36 – 38 ns in the initial state (Figure 2a), while 42 – 44 ns in the final state (Figure 2c), which is consider to be fully saturated. In the intermediate case of 51 – 53 minutes after the infiltration, at depths of lower than -4 m, the first arrival times are not changed from the initial state. In the zone upper than -4 m, however, we can find delayed first arrival times; shallower the depth, slower the time. The increase in traveltimes is interpreted to be caused by increased wetting of a vadose zone. In the zone between -3.5 m and -4 m, first arrival times are rapidly changed with depth. This may be due to a gradually change of water saturation or refractions.

Figure 3 shows vertical profiles of all first arrival times measured in the test. In the illustration, the volumetric water content at a depth was estimated as follows. First, the traveltime is transformed into velocity (v), v in the soil calculated by $v = d/t$, assuming a straight ray path, where d is the distance between the boreholes, and t is the travel time. Next, apparent dielectric constant K_a is obtained by

$$K_a = (c/v)^2, \tag{1}$$

where c is the EM velocity in free space. Finally, volumetric water content can be estimated by substituting K_a into Topp's equation (Topp et al., 1980). Note that radar measurements at depths upper than -2.8 m are not reliable. From Figure 3, we can find the progress of filtration with time.

3. NUMERICAL MODELING

Next, we make FDTD modeling in 2D cylindrical coordinates to reproduce field results and to obtain hydraulic parameters. We employ the modeling scheme developed by Jang et al. (2007) to model EM fields radiated from a transmitter antenna in a borehole.

To simulate field results, we use a FD grid consisting of 370 × 600 cells, each of which is 1 cm × 1 cm. We consider a simple two-layer model whose dielectric constants of $13\varepsilon_0$ and $9\varepsilon_0$.

Gaussian pulses with $t_0 = 2$ ns and $\tau = 4$ ns are transmitted every 0.1 m from 1 m above to 1 m below the layer boundary.

Figure 4 shows normalized electric fields at a point of 3.6 m horizontally from the centre of a 1 m transmitter antenna. All radar traces are normalized by their maximum amplitudes for easier comparison. In the illustration, first arrival times are defined as the way used in the field data (Figure 2)). The EM velocity of the upper region, where the medium of dielectric constant has 13, is about 5 ns slower than that of the lower region, where the medium of dielectric constant has 9. When the transmitter and receiver antennas are both close to the layer interface, the first-arriving energy can travel as a refracted wave along the interface. Clear refractions are confirmed at depths from 0.5 m to 0.0 m. This modeling result is well fitted to the field data shown in Figure 3b, and thus successfully reproduces the major feature of field results. In addition, the velocity change at between depths of -3.5 m and -4 m can be explained by refracted traveltimes.

4. CONCLUSIONS

We performed time-lapse borehole radar monitoring to clarify infiltration processes in a vadose zone. ZOG of radar data were acquired in the artificial groundwater recharge test. The infiltration process is clearly observed as a variation of EM-wave velocities. The hydraulic parameter of soil is evaluated from field data. The EM-wave velocity can be transformed into dielectric constants, which are further converted to water content. The radar responses in a vadose zone are largely controlled by variations in water saturation. An increase in traveltimes can be interpreted as an increase in water saturation in the test zone. We used a FDTD solution of Maxwell's equations in cylindrical coordinates to explain the field results. The modeling approach successfully reproduces the major feature of velocity changes during the infilteration process.

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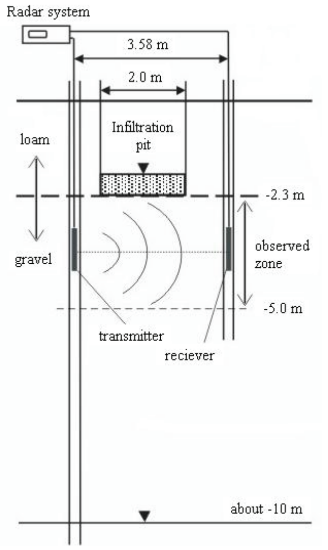
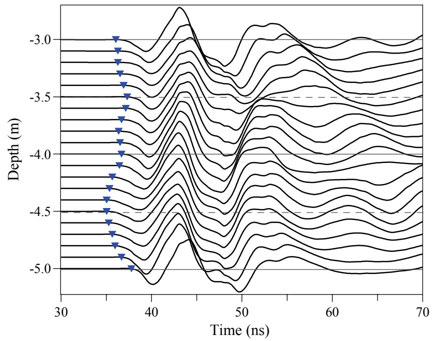
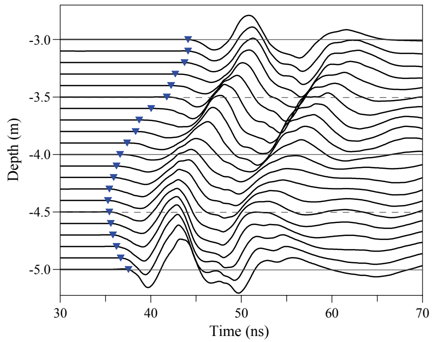


Fig. 1. Schematic of an artificial groundwater recharge test in a vadose zone.

(a) Initial



(b) 51 ~ 53 min.



(c) 105 ~ 107 min.

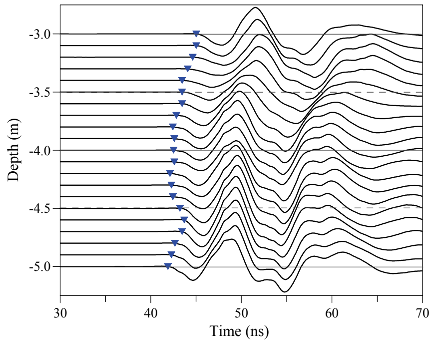


Fig. 2. Radargrams observed during the infiltration test: (a) before infiltration, (b) about 52 minutes after infiltration, and (c) about 106 minutes after infiltration. Triangles show first arrival times.

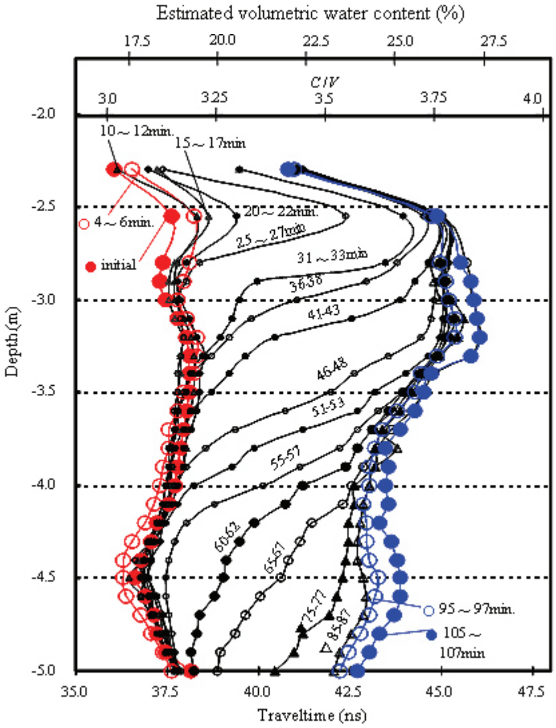


Fig. 3. Profile of traveltimes and water contents changes in the test zone obtained by cross-hole radar measurements.

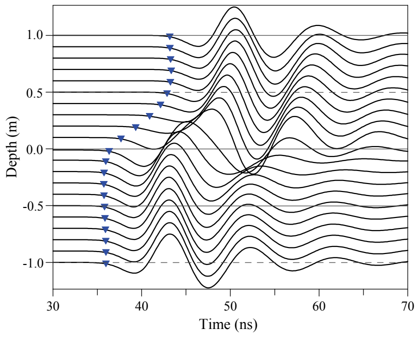


Fig. 4. Radargrams observed at a point of 3.6 m horizontally from the centre of a 1 m transmitter antenna located in an air-filled borehole with a diameter of 7 cm. The model contains a horizontal interface across which the dielectric constant varies from $13\varepsilon_0$ to $9\varepsilon_0$. Triangles show first arrival times.