Study on Water Diffusion in the Subsurface by Cross-hole Radar

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Abstract

Borehole radar is a geophysical survey method that is applied to several fields. We applied borehole radar to monitoring of subsurface water diffusion. It is important not only to estimate the geological structure in the subsurface but also measure the quantity of ground water. We used cross borehole measurement technique and acquired travel time across several paths. Based on the change of the travel time, we analyzed the diffusion of subsurface water. Then, based on a fluid migration model, we could model the movement of ground water even from insufficient spatial sampled data.

Keywords : Cross-hole radar Water diffusion Piston model

1. Introduction

The monitoring of ground water level, which helps us to set an irrigation plan, is conducted recently. It is related to water containing capability of the subsurface. A flood and a drought can be expected using the subsurface hydraulic characteristics with precipitation information. Acquiring the subsurface hydraulic characteristic, there are several methods like TDR (Time Domain Reflectometer) and Tensiometer used to measure volumetric moisture content. However these methods restrict those application ranges within 1 m.

Borehole radar is conducted on deep-site surveillance, because the transmitting and receiving antennas can exist in deep-site through borehole. Compared with surface-based GPR (Ground Penetrating Radar) which has the same measurement mechanism as borehole radar, its surveillance capability is limited to several meters in depth.

Many papers, related to the monitoring of ground water level, were published [1], [2]. However these papers proposed a measurement result elicited by ZOP (Zero-Offset Profiling) of which transmitting and receiving antennas were coincided with a depth position during those vertical movements. It renders the stability of received signals to be reduced, because fluctuation of antenna position during those vertical movements affects a travel time of received signal. Proposed borehole radar measurement with fluid migration model can be estimated position and velocity of ground water level.

2. Measurement system and configuration

2.1 Measurement system

Measurement setup is shown in Fig. 1. Measurement consists of single transmitting antenna and three vertically positioned receiving antennas. Thus travel times of zero-offset path and inclined paths are acquired at a fixed position. Electric permittivity derived from travel time of received signal with known distance between antennas. Then volumetric moisture content can be estimated using Topp’s equation [3]. Acquiring travel time of received signal, an operating frequency of measurement system (20 MHz ~ 400 MHz) is selected by composition of the subsurface materials, because an attenuation of transmission media is drastically increased in proportion to frequency increment. Although operating frequency band must be as low as possible, measurement system must have wide frequency bandwidth. It should be required to improve a time resolution which can discriminate multiple-path waves.

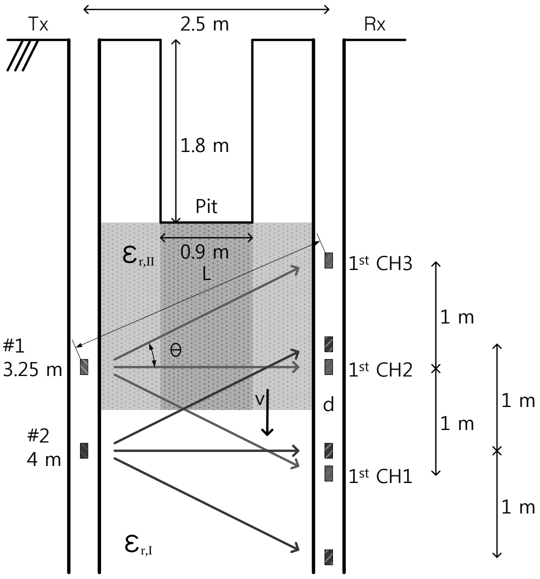


Figure 1: Setup of cross borehole radar measurement.

2.2 **Measurement configuration**

Water is selected a tap water which has relatively low salinity. Thus electrical conductivity of injected water is estimated to have a low value. Artificial increment of water salinity is achieved by an insertion of additional agent like sodium chloride into flowing water. However artificial control of water salinity is not conducted, because electrical conductivity of migrated water is not deterministically related to volumetric moisture content.

When water is poured into a pit, its flow rate per unit area is expressed as

$$C = \frac{Q}{A} = \frac{1.65\ m^3/h}{1.62\ m^2} = 1085\ mm/h \tag{1}$$

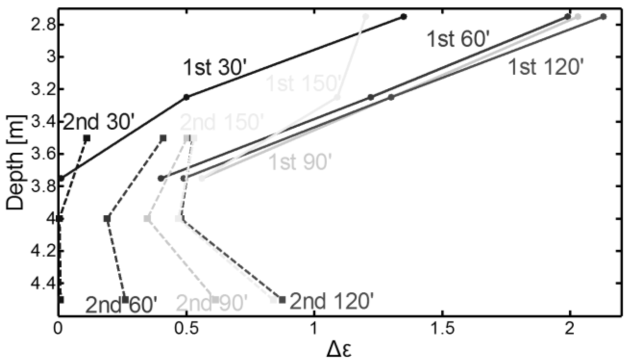
where Q is volumetric flow rate of injected water, A is an area of pit.

Water injection is continued 90 minutes, thus amount of total injected water is 2475 L. This experiment condition is not existence in nature. However it will help to acquire equilibrium water content which indicates a balanced flow state.

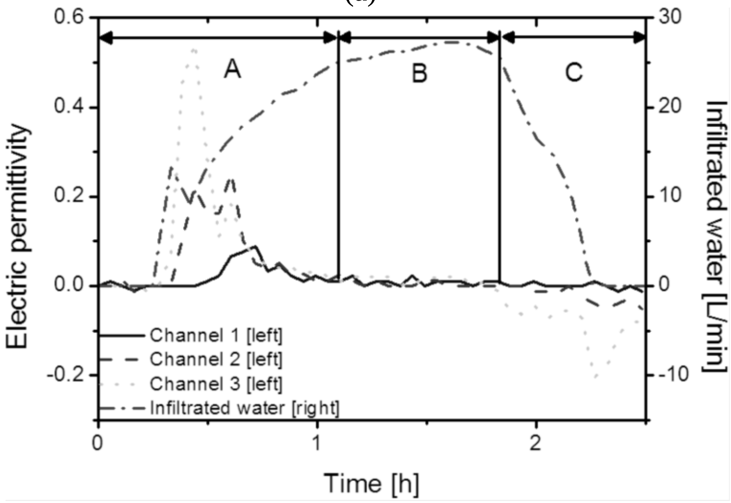
3. Experiment result

Comparing permittivity profiles with time acquired from data of 1st and 2nd experiments in Fig. 2(a), not only the channel 1 of 1st experiment with 3.75 m depth but also the channel 3 of 2nd experiment with 3.5 m have almost the same electric permittivity values. At that time, injected water at the 1st experiment is almost drained during a day. And the reproducibility of measurement and the continuity of layer are satisfied.

Net infiltrated the subsurface water is acquired to subtract remained water in a pit from injected water into a pit, because a thin sand layer with low hydraulic permeability on the surface may disturb water infiltration. Injected water is 27.5 L/min during 90 minutes, and contained water is estimated. Using these values, differential infiltrated water is acquired in Fig. 2(b). And explaining physical phenomenon of water infiltration in the subsurface, travel time is expressed as differential value. This value helps us to quantify equilibrium water content corresponding to inflow of water indirectly. When differential infiltrated water is increased, variation of electric permittivity is also increased in A of Fig. 2(b). Considering the positions of propagating wave path, variation start times correspond to closeness of antenna position to the surface. However differential infiltrated water is over 25 L/min, there is no variation of electric permittivity in B of Fig. 2(b). It means that 25 L/min inflow rate makes the subsurface to be a quasi-saturation which is a balanced flow state in the specified area. At that reason, when inflow rate falls down under 25 L/min, quasi-saturation does not maintain. Thus variation of electric permittivity is decreased in C of Fig. 2(b). Borehole radar can detect a quasi-saturation of transmission media through variation of electric permittivity.



(a)



(b)

(a) Differential permittivity profile (b) Permittivity with infiltrated water rate.
Figure 2: Time varying profiles.

4. Fluid migration model

The piston model approximates the fluid migration formation as a rectangle shape which moves straightly down, as shown in Fig. 1. At that time, subsurface is designed as homogeneous media which has the same electric permittivity, but has different hydraulic conductivity with depth [4]. Water infiltrated region has electric permittivity which is larger than the value of subsurface. Thus variation of travel time of each propagating wave path is affected by position and movement velocity of water front [5]. Relation between travel time and depth of water front are expressed as

$$T_p = \frac{1}{c}\left[\sqrt{\varepsilon_{r,I}}\left(L - d \cdot csc(\theta)\right) + \sqrt{\varepsilon_{r,II}} d \cdot csc(\theta)\right] \tag{2}$$

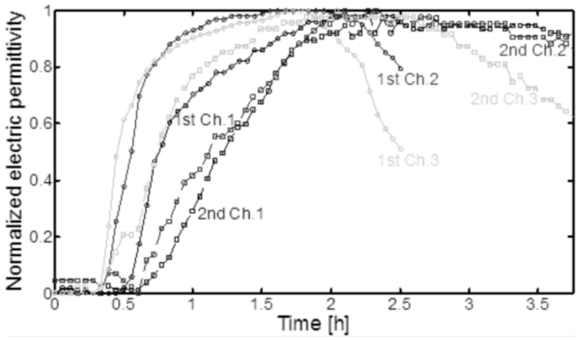
$$d \cdot csc(\theta) \leq L \tag{3}$$

where d is the depth of water front, c is the velocity of light, $\varepsilon_{r,I}$ is the electric permittivity of initial region, L is the length of propagating wave path, θ is the incline angle of propagating wave path, and $\varepsilon_{r,II}$ is the electric permittivity of infiltrated region.

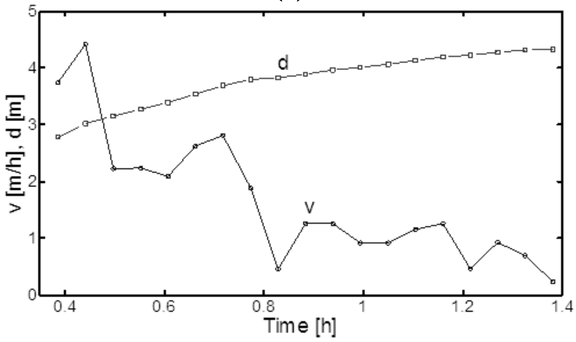
Deriving the depth of water front d from the given equations, electric permittivity of each region must be decided. However electric permittivities of initial and quasi-saturation state with depth are different. At that reason, the fluctuation of electric permittivity is normalized as initial and quasi-saturation state are set 0 and 1, respectively, in Fig. 3(a). The depth of water front d is calculated by (2) and (3) with experiment data. At that time, channel 2 is assumed to have the incline angle of propagating wave path, because its d value is expressed as step function in the calculation.
Based on these values, the movement velocity of water front is derived as

$$v_{water}(\tau) = \frac{d}{d\tau} d(\tau) \tag{4}$$

where τ is the actual time.



(a)



(b)

(a) Differential permittivity profile (b) Estimated water front depth and velocity.

Figure 3: Estimation of water front velocity.

At that time, envelop infiltration velocity is acquired by selecting the maximum value of each time in Fig. 3(b). Comparing boreholes distance (2.5 m) and pit width (0.9 m), infiltrated region affects a part of propagating wave path calculated by the ratio between boreholes distance and pit width. Water front depth is expressed in Fig. 3(b).

5. Conclusion

Proposed borehole radar measurement with fluid migration model can estimate quasi-saturation and equilibrium moisture contents of the subsurface acquired by the net infiltrated subsurface water and measured travel times. Many parameters are approximated and ignored and number of acquired signal is restricted by fixed antenna position and limited measurement time. Although these conditions, position and velocity of ground water level can be acquired.

References

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Acknowledgments

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