Quasi 3D Image Construction of Infiltration Processes in the Vadose Zone by Combining Inter Borehole Radar Data and Numerical Simulation of Water Flow in Soils

Seiichiro Kuroda(1), Hirotaka Saito(2), Takehiko Okuyama(1) Mutsuoka Takeuchi(1), Jiri Šimínek (2) and Martinus TH. Van Genuchten (3)

(1) National Institute for Rural Engineering, Japan. (2) University of California, Riverside, USA. (3) G.E. Brown Jr. Salinity Laboratory, USDA, ARS, Riverside, CA.

ABSTRACT

A study to clarify the hydrological processes in the vadose zone by using a time-laps geophysical methodology has been performed. Recently, estimation of soil hydraulic parameters, such as the hydraulic conductivity, using geophysics data has increasingly received attention. We report the study characterizing hydraulic parameters of the vadose zone using inter borehole radar data obtained from artificial ground water recharge test at the infiltration pit. A numerical study was carried out to obtain inversely the hydraulic parameters, such as soil water retention curve model parameters and hydraulic conductivity function using HYDRUS-2D. The forward simulation of soil water flow using obtained parameters could be used to construct the quasi 3D image of water flow in the vadose zone.

KEY WORDS: Ground Penetrating Radar (GPR), cross-borehole radar, soil hydrology, vadose zone, parameterization

INTRODUCTION

Recently many studies have tried to characterize the hydrological processes by monitoring time-laps geophysical methodologies. Inter-borehole radar, which has an advantage in quantitatively estimating water contents in a variety of spatial resolutions, has been one of the most useful geophysical tools for analyzing hydrological processes, especially in the vadose zone (Hubbard, et al., 1997; Parkin, et al., 2000; Binley, et al., 2001; Rucker and Ferré, 2003). Recently the soil hydraulic properties were theoretically estimated from borehole GPR data (Rucker and Ferré, 2003).

This paper presents the study characterizing hydraulic parameters of the vadose zone using inter borehole radar data obtained from artificial ground water recharge test at the infiltration pit. A numerical study was carried out to obtain inversely the hydraulic parameters, such as soil water retention curve model parameters and hydraulic conductivity function using HYDRUS-2D. The forward simulation of soil water flow using obtained parameters could be used to construct the quasi 3D image of water flow in the vadose zone.

FIELD TEST DATA

Inter-borehole radar data to characterize hydraulic parameters in the vadose zone were obtained by monitoring the artificial groundwater recharge test conducted in Nagaoka City in Niigata Prefecture, Japan. Figure 1(a) shows the schematics of the test site and the spatial arrangement of the infiltration pit and boreholes. The top 2-m surface soil was loam, and the subsoil was gravel. The water table was located about 10 m below the surface. The infiltration pit was a 2 × 2 m square and its bottom, at which infiltration into the soil occurred, was located at 2.3 m from the surface (z=–2.3 m). Two boreholes were located on opposite sides of the pit. While the length of the borehole T (Fig. 1(a)) was 11 m, the borehole R was only 5.7 m long because of an unexpected machine trouble at the field. The distance between the two boreholes was 3.58 m. The target ponding depth in the infiltration pit was set at 50 cm. It took about 40 min for the ponding depth to reach its target value.

All ground penetrating radar data were collected by a GSSI SIR10 system with borehole antennae at the dominant frequency 110 MHz. The transmitter was placed in T borehole, while the receiver antenna was placed in R borehole (Fig. 1(a)).

In this test, instead of using time-consuming multi-offset gathering (MOG) and tomography analysis, repetitive zero-offset gathering (ZOG) was adopted as the main measurement methodology because we were particularly interested in vertical water flow. Rapid water migration into the gravel layer was expected on the basis of hydraulic conductivity data obtained by a series of pumping tests. ZOG measurements were made at z=–2.3 and –2.55 m, and at every 0.1-m between z=–2.8 and –5.0 m.

The volumetric water content at each measurement depth was estimated as follows. First, the propagation velocity of the electromagnetic wave V in the soil was calculated by $V = D/t$, assuming ray-path linearity, where $D$ is the distance between the boreholes, and $t$ is the travel time between the two boreholes measured with ZOG. Next, the apparent dielectric constant $K_a$ was obtained by the following equation:

$$K_a = (C/V)^2,$$

where $C$ is the electromagnetic velocity in free space. Finally, volumetric water content was estimated by substituting the calculated $K_a$ value into Topp's equation (Topp et al., 1980).
Figure 1(b) shows the vertical profile of traveltimes (or calculated water contents) and their change with time. Wetting front movement and the infiltration process in the vadose zone are clearly observed. As can be seen, the initial water content in the upper zone (around 2.5-3.5m depth) is greater than the lower zone (around 4.5m depth). The spatial distribution of the final water content (105-107 min.) has a similar trend. This difference is therefore due to the difference in hydraulic characteristics of soils: the soil in the upper layer has finer texture higher water retentivity compared to the soil in the lower layer, resulting higher initial water contents. On the other hand, because the finer and less permeable upper layer limits the amount of infiltration, the lower layer with higher permeability is kept unsaturated and at a low volumetric water content. Such a feature suggested that it is not appropriate to consider a uniform vadose zone. The characterization of hydraulic properties in the next chapter was conducted in consideration of the feature mentioned above.

**SIMULATION OF SOIL WATER FLOW IN THE VADOSE ZONE AND CHARACTERIZATION OF HYDRAULIC PROPERTIES**

Simulation of water flow in the vadose zone and its parameterization were conducted using HYDRUS-2D (Simunek, et al., 1999). It was based on the Darcy-Richard’s equation. The water movement around the infiltration pit was assumed axisymmetric and was simulated within cylindrical 2 dimensional coordinates. The pore size distribution model of Mualem (1976) was used to predict the unsaturated hydraulic conductivity function, $K(h)$, from the saturated hydraulic conductivity $K_s$ and the van Genuchten’s (1980) model parameters of the soil water retention curve

$$\theta(h) = \begin{cases} \theta_i + \frac{\theta_s - \theta_i}{[1 + (zh)^m]^n} & h < 0 \\ \theta_i & h \geq 0 \end{cases}$$

where

$$K(h) = K_s S_e \left[1 - \left(1 - S_e^{1/m} \right)^m \right]^2$$

$m=1-1/n$, $n>1$
and θ(h) is soil water retention curve, which describes the functional relationship between the volumetric water content θ at a pressure head h.

The simulation zone is simply divided into two regions above and below the 3.5m depth, following the feature described in the previous section (Table 1). The initial volumetric water content θ₀ was 0.19 in the upper region and 0.18 in the lower region, referring to the measurement value. The same values for θ₁ and θ₂ were used for both regions. Other parameters, α, n, and saturated soil hydraulic conductivity Kₛ were inversely obtained using the Levenberg-Marquardt nonlinear minimization method (details can be found in Simunek et al., 1999).

Fig.2 shows the breakthrough curves of water content measured by inter-borehole radar at 5 depths and their fitting curves using estimated parameters listed in Table 1. Fitting curves reproduce the observed values and the feature of soil water flow described in the previous section well.

Fig.3 shows the simulated quasi 3D (cylindrical 2D) water flow in the vadose zone under the infiltration pit using parameters obtained. It only shows the right hand side of the axis. Although the original data were obtained by zero offset profiling of inter-borehole radar, the fusion with numerical simulation of water flow enables a creation of a quasi-3D dynamic image of water infiltration processes.

CONCLUSIONS

The simulation of water flow in soils based on the Darcy-Richards equation and the van Genuchten model has flexibility in estimating hydraulic properties by fitting to the actual field data of inter-borehole radar. The hydraulic parameters inversely obtained using the nonlinear least-squares approach enable to describe the infiltration process into the vadose zone from the artificial ground water recharge pit observed by inter-borehole radar. The hydraulic parameters obtained enable to create a quasi 3D dynamic image of the infiltration process.

In the future, the radiation pattern, the propagation path, and the resolution of the electromagnetic wave must be considered.

REFERENCES


Table 1: Parameters for vadose zone water flow simulation

<table>
<thead>
<tr>
<th>Zone</th>
<th>Depth ( \sim )</th>
<th>( \theta_{ini} )</th>
<th>( \theta_i )</th>
<th>( \theta_s )</th>
<th>( \alpha )</th>
<th>( n )</th>
<th>( K_s )</th>
<th>( l )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region1</td>
<td>3.5m</td>
<td>0.19</td>
<td>0.178</td>
<td>0.282</td>
<td>5.33</td>
<td>4.44</td>
<td>6.12E-05</td>
<td>0.5</td>
</tr>
<tr>
<td>Region2</td>
<td>3.5m</td>
<td>0.19</td>
<td>0.18</td>
<td>0.36</td>
<td>4.85</td>
<td>2.78</td>
<td>4.07E-04</td>
<td></td>
</tr>
</tbody>
</table>

\( \theta_{ini} \): Volumetric water content in the initial condition
Italic figures were parameters given by inversion

Figure 2: Comparison between simulation results and GPR data

Figure 3: Infiltration image by vadose zone simulation based on GPR data fitting