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# NUMERICAL SIMULATION AND PARAMETER ESTIMATION USING BOREHOLE FLOWMETER LOGGING IN LOW PERMEABILITY ROCKS

Kazumasa Ito, Naoto Takeno, Yoji Seki, Kazuki Naito, Yoshio Watanabe

AIST, Research Center for Deep Geological Environment
1-1-1 Higashi
Tsukuba, Ibaraki, 305-8567, Japan
e-mail: kazumasa-ito@aist.go.jp

## ABSTRACT

Hydraulic properties of low permeability rocks are indispensable to construct a three dimensional rock property model for the performance assessment or safety estimation of the underground nuclear waste disposal. However, the efficient and accurate estimation of hydraulic properties of low permeability rocks is difficult with the in-situ borehole hydraulic tests, such as injection test or slug test.

The borehole flowmeter logging is a useful method to estimate a magnitude of seepage or inflow between borehole and surrounding rocks. However, because of the low sensitivity of conventional flowmeter logging and the lack of the numerical analyses to estimate hydraulic properties, the observation results were usually used for a qualitative estimation of the relative magnitude of the permeability of fractures across the borehole.

The authors improved the heat-pulse type borehole flowmeter up to 0.03cm/s in detection limit, and applied it to an actual field investigation. The site scale numerical model was constructed from the geologic survey, and basic hydraulic properties were estimated from the hydraulic test and matching of piezometric pressure in boreholes.

In order to simulate the vertical flow velocity along an open borehole in the natural site scale groundwater flow system, the authors developed hybrid RZ2D and rectangular mesh construction program for TOUGH2, and applied it to the site scale model. In this paper, the results of the numerical simulations are compared to the measured velocity profile for the more detailed estimation of hydraulic properties along a borehole.

## INTRODUCTION

It is often difficult to estimate hydraulic properties in low permeability rocks directly from well test data, because of the low injection or drainage rate. In order to estimate the hydraulic properties in low permeability rocks, Tsang et. al..(1990), Tsang and Doughty (2003) developed the fluid electric conductivity (FEC) logging method. However, since the FEC logging requires the total substitution of borehole water to deionezed water, the preparation of FEC logging may cause the long-term disturbance to the chemical condition around the borehole.

On the other hand, borehole flowmeter logging is a cont effective, passive measurement of water flow velocity along a borehole. In the conventional borehole flowmeter logging, the sensitivities of tools were low, and the quantitative estimation of hydraulic properties from the obtained velocity profile was difficult.

In this paper, the authors improved a heat-pulse type flowmeter, and applied it to an actual test site. The authors also constructed the hydrogeological model of this site to reconstruct the pressure distribution using TOUGH2. For the validation of the numerical model, the authors developed the hybrid RZ2D-recutangular mesh system along the borehole and simulated the borehole flowmeter logging just after the completion of the drilling.

## SITE DESCRIPTION AND THE NUMERICAL MODEL

### Geology of The Test Site

The test site (Kanamaru site) is located in the mountainous area of the northeast part of Japan. Geology of the test site mainly consists of late Cretaceous granite and Tertiary sedimentary rocks. The unconformity boundary between granite and sedimentary rock is clastics of the base granite. Below the unconformity boundary, several meters thick of the granite is strongly weathered and contains many fractures. In this site, 9 shallow boreholes up to 50m were excavated for the hydraulic tests, periodic pressure monitoring and groundwater sampling.

### Three-dimensional Numerical Model

Digital Elevation Model and geological information were collected into the geological information system and the numerical model for TOUGH2-EOS3 isothermal module was constructed. Figure 1 shows the topography of the test site, the area for numerical model, and the location of the boreholes.

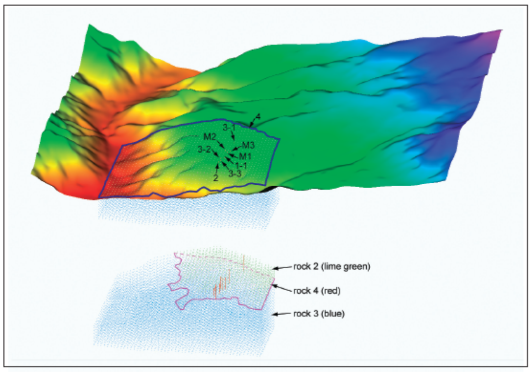


*Figure 1. Topography of the test site, the area for numerical modeling, and borehole locations.*

Three-dimensional numerical mesh system was constructed by using WinGridder (Pan et al., 2001). The distribution of the hydrogeological materials in the model is shown in Figure 2.

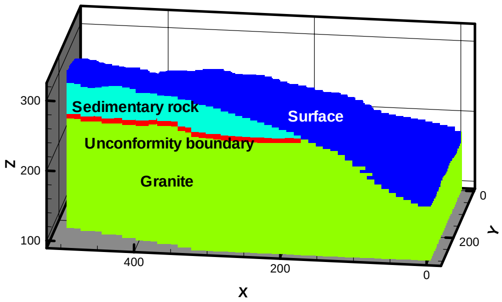


*Figure 2. Hydrogeological material distribution in the three-dimensional model constructed from the geological information system.*

The upper boundary of the model was assigned as the constant rate condition from the estimated recharge rate. The bottom and side boundaries except northern boundary were assigned as the no-flow boundary. The northern, high elevation boundary was the fixed pressure boundary with the measured hydraulic head in the borehole close to the boundary.

The results of hydraulic pressure monitoring showed that at the center of the test site, the hydraulic head in the deep granite is lower than the hydraulic head in the shallow zone. The unconformity boundary layer in Figure 2 was set as a low permeability layer to reconstruct the hydraulic head profile of along the borehole.

The calculated pressure and liquid saturation distribution is shown in Figure 3.

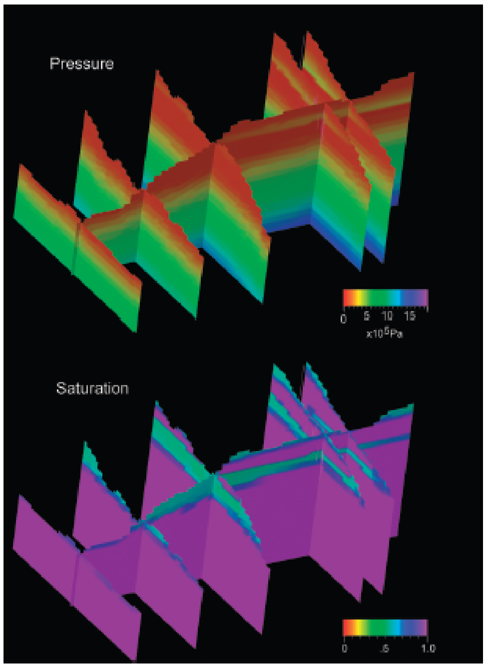


*Figure 3. The calculated distribution of hydraulic pressure and liquid saturation. The upper figure is the pressure distribution and the lower is the saturation. This figure shows that the unsaturated zone is constructed below the low permeability unconformity layer.*

Pressure distribution and liquid saturation distribution shown in Figure 3 do not completely reproduce the pressure profile obtained in the monitoring. However, the relative pressure decrease is reproduced. The hydraulic properties of each rock is shown in Table 1.

*Table 1. Hydraulic properties used in the simulation*

| Rock Type | Permeability ($m^2$) | Porosity |
|---|---|---|
| Sedimentary rock | $3.6\times10^{-14}$ | 0.05 |
| Unconformity boundary | $8.5\times10^{-17}$ | 0.05 |
| Granite | $2.5\times10^{-14}$ | 0.05 |

## BOREHOLE FLOWMETER LOGGING

### Method

The authors applied the borehole flowmeter logging (Dudgeon et al, 1975) to the borehole 3-3 in Figure 1, which is located at the center of the test site (Seki et al., 2005). Borehole flowmeter logging was carried out sixteen days after the drilling had been finished. The heat-pulse type borehole flowmeter was applied to measure water velocity along the borehole with 1m intervals.

The detection limit of the conventional heat-pulse type is 0.15cm/s. However, in the borehole, because of the low permeability of rocks, the vertical velocity was lower than the limit. Small packer was installed in the sensor unit of the flowmeter to reduce cross section of flow in the sensor. After the improvement, the detection limit of the flowmeter was improved up to 0.03cm/s.

### Result

Figure 4 shows the natural velocity profile obtained in the flowmeter logging (Seki et al., 2005).

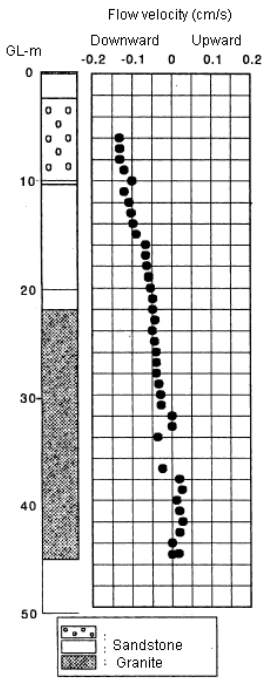


*Figure 4. Measured vertical water velocity profile in borehole 3-3. The measuring interval is 1m.*

From this result, it was shown that the dominant flow within the borehole is downward flow, and the down ward water velocity decreased with the increase of depth. The water inflow from the shallow unsaturated zone was not observed. Besides the genral trend of the velocity profile, there are several inflection points that represent the seepage or inflow zones. Among these zones, the water inflow at the shallowest zone: from the water table to GL-6m, shows the largest inflow rate.

## NUMERICAL MODEL FOR BOREHOLE FLOWMETER LOGGING

### Mesh Structure

In a simulation of conventional well tests like slug test or pumping test, the wellbore and reservoir simulation is usually carried out separately as was discussed in Murray and Gunn (1993). This tabular approach to the dynamic change of flowing bottomhole pressure was incorporated in TOUGH2 (Pruess et al., 1999).

However, this approach cannot be applied to the simulation of borehole flowmeter logging because it doesn't consider the flow within a borehole. A simulation with normal large size mesh is inappropriate because the simulation result is affected by the disturbance caused by a large high permeability zone.

In order to simulate the borehole flowmeter logging, the authors constructed the hybrid mesh construction program with rectangular and RZ2D mesh system. Figure 5 illustrates the mesh system for this model.

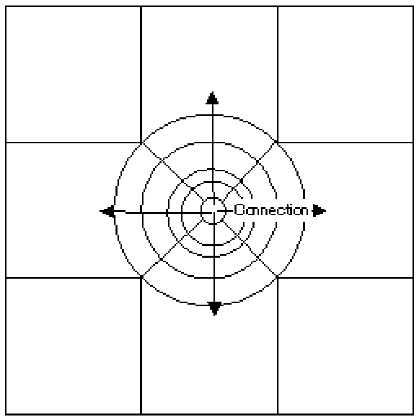


*Figure 5. An illustration of rectangular-RZ2D hybrid mesh system. The meshes including wellbore are refined like RZ2D meshes.*

In order to model the flow within/around the borehole, the vertical column of original rectangular meshes, which include the borehole, were refined like RZ2D mesh system. Element volumes, nodal distances, and interfacial areas were calculated according to the geometry. The element volumes and the nodal distances of the adjacent rectangular elements were reduced according to the geometry.

## Hydraulic Property of Wellbore Elements

To estimate the vertical water velocity along borehole with the hybrid model described above, it is important to assign appropriate permeability value to the borehole elements. If the wall of the borehole can be assumed smooth tube, and the flow through the borehole can be assumes as the laminar flow, the pseudo permeability value can be calculated from Navier-Stokes equation as below (de Marsily1986).

$$k' = \frac{r^2}{8} \quad (1).$$

In this case, from the actual borehole radius (0.043m), the calculated pseudo permeability is $2.3\times10^{-4}$ $m^2$. However, the actual borehole wall is rough, the appropriate pseudo permeability should be smaller than this value. The existence of local high permeability causes the instability and error in numerical simulation. In this study, variation of the borehole permeability was set between $1.0\times10^{-7}$ $m^2$ and $1.0\times10^{-10}$ $m^2$.

## SIMULATION RESULTS

Vertical velocity profiles from numerical simulations with various borehole permeabilities are shown in Figure 6.

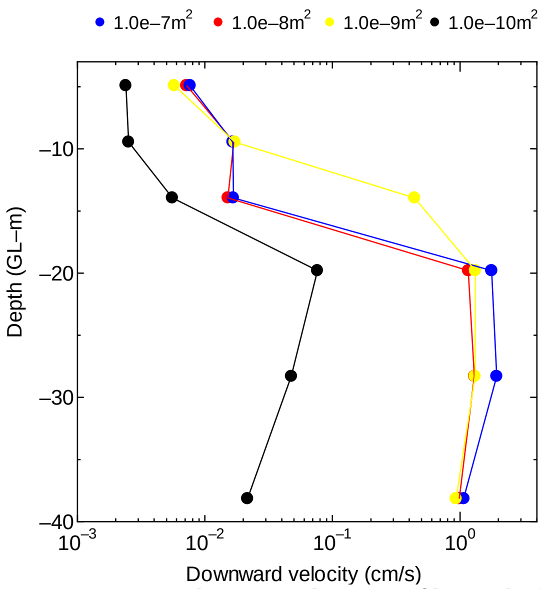


*Figure 6. Vertical water velocity profiles with the variation of the borehole permeability assignment.*

From these results, if the borehole permeability is assigned higher than $1.0\times10^{-9}$ $m^2$: about five orders of magnitude higher than permeability of surrounding rocks, pressure profiles do not show the significant difference in any borehole permeabilities.

In the general trend of the results, all connections between adjacent borehole elements show the downward flow. The downward water velocity is small down to GL–20m, below GL–20m, downward velocity increase rapidly about two orders of magnitude, and slightly decrease along the borehole.

The downward velocity values from the case with borehole permeability higher than $1.0\times10^{-9}$ $m^2$ is about two orders of magnitude higher than the measured velocities.

## DISCUSSION

### Trend of Velocity Profile

Comparing the measured and calculated velocity profile, downward water flow was observed in the most zones in both results, and the velocity decrease along the borehole was observed in both result.

However, in the shallow zone, the measured profile showed high downward velocity, while small velocities were observed in the numerical simulations. Since the unsaturated zone exists just above the shallowest point in the measured result, there was no downward water flow above the shallowest point. The downward flow in the measured result was caused by a thin high permeability zone just below the water table, which was not imported into the numerical model.

### Comparison to the Measured Profile

#### *Sensitivity of the permeability of granite*

The downward velocity in the zone deeper than GL-20m of the calculated results with borehole permeability higher than $1.0\times10^{-9}$ $m^2$ are about two orders of magnitude higher than the measured velocity profile.
Since the recharge boundary condition from the surface is fixed, and the regional groundwater flow reached close to the steady-state condition, the downward velocity value is determined by the permeability.

In this study, the authors carried out sensitivity studies of the permeability of granite to the velocity profile.

The permeability of the borehole was set as $1.0\times10^{-8}$ $m^2$, according to the results shown above and the stability of numerical simulation. Figure 7 shows the result of sensitivity studies.

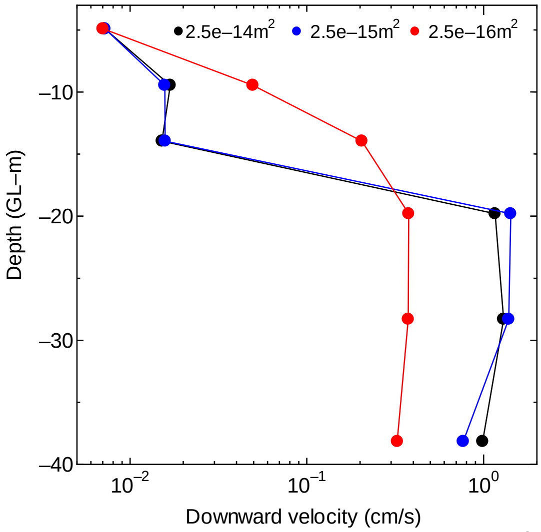


*Figure 7. Vertical downward velocity profiles calculated from the variation of the permeability of granite. The permeability in the original model is 2.5e-14 $m^2$.*

The change of permeability in one order of magnitude in granite does not have the significant influence to the vertical velocity profile. However, if the permeability of the granite is two orders of magnitude lower than the original model, the contrast of inflow between unconformity layer and granite becomes smaller, and the downward velocity shows the gradual change along the borehole.

### *Consideration of whole area permeability*

The measured velocity in the granite was less than 0.1cm/s. On the other hand, the calculated velocity is one order of magnitude higher than the measured one. In this model, the permeability of whole area could be estimated higher than the actual value.

Therefore, the authors carried out two more cases of numerical simulation with permeability modification factor of 0.1 and 0.01. In this cases, the permeability of the borehole was fixed as the original value.

Figure 8 shows the result of simulations with the variation of permeability modification factor applied to the rocks.

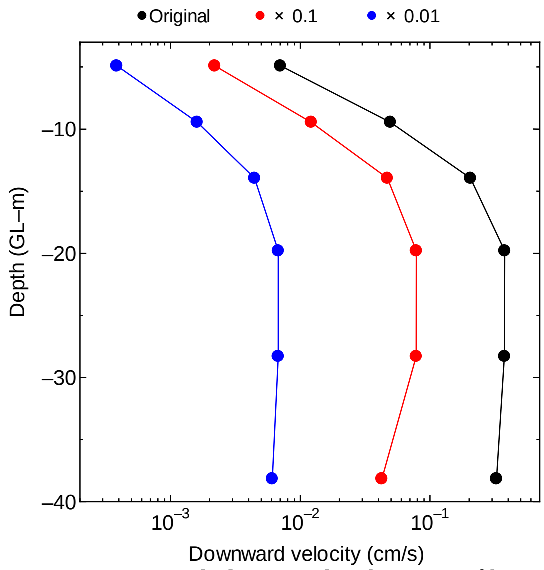


*Figure 8. Vertical downward velocity profile with permeability modification to the whole rocks. The measured vertical velocity is in the order of $1.0\times10^{-2}$ cm/s.*

In these cases, the permeability modification factor 0.1 shows the similar velocity values in granite. In this simulation, permeabilities of whole rocks were changed with the same factor. However, even in these simulations, velocity values in the shallow zones could not be reproduced.

## RESULT

In this study, the borehole flowmeter logging has been directly simulated with the rectangular-RZ2D hybrid mesh system. According to some sensitivity studies, the permeability of granite could be estimated with the appropriate settings of borehole permeability and the comparison of the velocity profile in the granite zone between measured and calculated results.

However, the velocity profile in the shallow zone remained unmatched in the numerical model. In order to reproduce the whole velocity profile, the numerical model should be refined in vertical discretization, and set the weathered high permeability layer.

In order to estimate the permeability with borehole flowmeter logging accurately, the repetitive measurement with different water table in borehole by pumping is necessary. In this study, the authors had only the result in the natural water table condition, the determination of permeability for whole rocks were difficult.

The other way to determine the permeability is the numerical inversion. In this case the direct use of velocity as the observation value is possible, but the pressure distribution and/or total recharge rate with fixed water table should also be used as the observation data.

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