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Uncertainty reduction of hydrologic models using data from surface-based investigation

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SUMMARY

Geohydrologic model uncertainties include permeability, boundary, and initial conditions as well as the conceptual model it is based on. We present some examples of using information other than pressure data to constrain a geohydrologic model of the Horonobe area in Hokkaido, Japan. The initial model was constructed using information from surface geology and a few boreholes. Inversion analysis of pressure data implied the existence of a low-permeability cap rock. We then used river flow data and temperature data from a hot spring as a basis for estimating the recharge flux, which suggested that the overall permeability of the modeled area could be one order of magnitude larger than that of the base model. Next, we simulated a saltwater washout process and compared the simulated salinity distribution with the salinity data from a borehole. We found that a better match to the salinity data is obtained if the increase in permeability is taken up by a localized fault zone rather than uniformly by the entire model. A smaller-scale match to the temperature, pressure, and density profiles from two boreholes indicated that there was a low-permeability fault in between the two boreholes. The present study demonstrates that pressure data alone are insufficient to calibrate a model, and that additional observations are needed to accurately represent a site.

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1. Introduction

It is very difficult to characterize a large body of heterogeneous rock sufficiently, and to build a reliable groundwater flow model, particularly when the rock is fractured, which is most often the case. Available hydrological data are often limited and insufficient, both spatially and temporally. It is extremely challenging to scale-up detailed small-scale (tens of meters) measurements and to predict and verify large-scale (over several km) behavior. Unless there is an underlying known property that extends over scales, measurements conducted at a certain scale can only be used to describe the processes at the same scale. Some geostatistical tools may be used to predict the range of the model outcome. However, the more heterogeneous the rock is, the larger the uncertainty becomes.

Building a geohydrologic model of a large area involves many uncertainties from various sources, from the conceptual model to the input parameters. Model uncertainties include material parameters such as permeability and porosity. Often overlooked are boundary conditions and initial conditions. The most important element of a reliable model is the correct conceptual understanding of the geohydrologic processes within the area, which comes only after a long progression of model building, with much trial and error. Although model uncertainties originating from different modeling approaches have been addressed (e.g., Ijiri et al., 2009), uncertainty studies applied to actual field sites are limited. Most numerical models have implicit limitations that may lead to uncertainties that are inconspicuous and are seldom discussed. Many numerical models do not consider all the physical processes involved, which may or may not be necessary. A complete thermal, hydrological, mechanical, and chemical (THMC) simulation is very challenging and a subject of intense research at present. There are multiple reasons for this, including the difficulty in estimating the initial conditions and specifying the constitutive equations (such as the porosity–permeability relationship) that are applicable at a practical scale, in addition to the scarcity of relevant data such as the material properties and other *in situ* parameters.

The conditions at the outer boundaries of numerical models need to be specified all around, although they are usually impossible or impractical to measure. Therefore, they are often cho-

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sen for the convenience of modeling. The surface boundary conditions are often set to be a constant flux condition. Observations that can be made in the field are often severely limited in type, space, and time. One quantity that can be relatively easily observed is pressure, which can involve uncertainties of its own, such as gauge drift and borehole short-circuiting due to packer leak. To measure pressure at depth, we need to drill deep boreholes, which is very expensive. As a consequence, only a limited number of boreholes are drilled. Furthermore, the locations where boreholes can be drilled are often limited for reasons such as physical accessibility.

Ideally, tests should be designed to directly stress the system at the scale of interest, so that the observed response is the result of the averaging of the inherent properties up to that scale. However, this is difficult if the scale is over a kilometer or more. Moreover, in a very active tectonic environment like that of Japan, faults exist ubiquitously, which greatly affect the hydrology around their vicinity. Correct characterization of large faults is crucial in building a reliable geohydrologic model. Illman et al. (2009) successfully applied transient hydraulic tomography to large-scale (~1 km scale) cross-hole pumping tests to estimate the properties of fractured granite.

Large-scale groundwater flow models are typically calibrated to the steady-state pressure head data. An inversion scheme can be used to search for optimum parameters. However, we rarely have enough head data, and furthermore, head data alone are not sufficient for building a reliable model. Therefore, it is very important to utilize all available relevant data to constrain model uncertainties. In this paper, we show a progressive model improvement, in which information other than pressure data, such as temperature and salinity data, are used to constrain a hydrologic model to help reduce uncertainties in the conceptualization of a large heterogeneous rock formation, using the data from the Horonobe Underground Research Laboratory in Japan during the ground-surface-based initial investigation phase.

2. Horonobe site

The Japan Atomic Energy Agency (JAEA) is constructing an underground research laboratory (URL) in Horonobe Cho, Hokkaido (Fig. 1), to study physical and chemical processes deep underground and to develop technologies that may be applied to future geologic disposal of high-level radioactive waste elsewhere in Japan (Yamasaki et al., 2004; Ota et al., 2007). The formations of main interest, Koetoi and Wakkanai Formation are Neogene siliceous sedimentary rocks. Transecting the URL area is the Omagari Fault, an eastern dipping reverse fault with a left-lateral strike-slip component. Another fault of perhaps similar origin, the Nukanan Fault exists to the east of the Omagari Fault. A brief description of the lithology can be found in Table 1. At the Horonobe URL, 11 deep boreholes (HDB-1 to HDB-11) have been drilled, with depths ranging from 470 m to 1020 m (Fig. 2). After various investigations, loggings, and pressure tests were conducted, each borehole was isolated by packers into several intervals, and the pressure was monitored.

3. Geohydrologic model

Groundwater in the Horobobe area in general is expected to flow from the higher hills in the east to the Japan Sea in the west. Based on the information obtained from early boreholes, geologic, and geophysical surveys, Imai et al. (2002) constructed a hydrogeologic model of the Horonobe area with updated fault geometry. They concluded that there are large uncertainties with the permeability and the recharge rate and showed that the salinity data may be useful to constrain a model. The original mesh of Imai et al.'s model was in a finite element model (FEM) format, which was converted to that of integrated finite difference (IFDM) for simulations using TOUGH2 (Pruess et al., 1999). Fig. 3 shows the geohydrological model used for the simulations. The total number of elements is 7,8000 with varying sizes from 50 m to 500 m that are classified into 11 material types. Based on borehole tests and core analyses the groundwater flow is thought to be mainly through fractures. We assume that an equivalent continuum can be used to represent the large-scale groundwater flow in the area. Heads observed in the boreholes show an increase with depth (Kurikami et al., 2008a,b), which can be caused by several sources, including the topography, geostatic load or gas generation. As shown in Fig. 2, most boreholes are in the proximity of the Omagari Fault. The initial version of the Imai et al. model shown in Fig. 3 failed to reproduce the observed head data: particularly the high heads observed in the Koetoi formation as shown in Fig. 4.

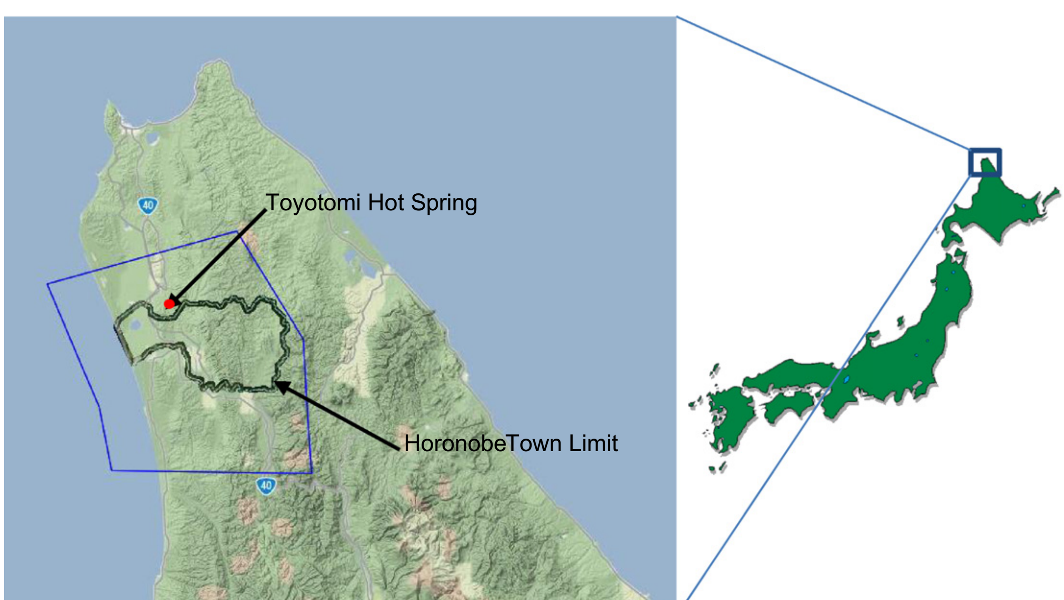

Fig. 1. Location of Horonobe Town in Hokkaido, Japan. Also shown is Toyotomi Hot Spring. The blue polygon denotes the model footprint shown in Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)