

熱解析による水理モデルの境界条件の検討 Constraining Hydrologic Models Using Thermal Analysis

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Abstract

Starting with regional geographic, geologic, hydrologic, geophysical, and meteorological data for the Tono area in Gifu, Japan, we develop a numerical model to simulate subsurface flow and transport in a 4 km by 6 km by 3 km thick fractured granite rock mass overlain by sedimentary layers. Individual fractures are not modeled explicitly. Rather, continuum permeability and porosity distributions are assigned stochastically, based on well-test data and fracture density measurements. The primary goal of the study is to simulate steady-state groundwater flow through the site, then calculate travel times to the model boundaries from specified monitoring points. The lateral boundaries of the model follow topographic features such as ridgelines and rivers. Assigning lateral boundary conditions is a major point of uncertainty in model construction. We evaluate two models with opposing boundary conditions: mostly closed and mostly open boundaries. The two models show vastly different spatial distributions of groundwater flow, so we would like to find a means of choosing the more realistic model. Surface recharge is much larger for the closed model, but field recharge data are of too limited spatial extent to provide a definitive model constraint. Temperature profiles in 16 boreholes show consistent trends with conduction-dominated (linear) temperature profiles below depths of about 300 m. The open and closed models predict strongly different temperature versus depth profiles; with the closed model showing a strong convective signature produced by widespread surface recharge effects to the depth. The open model shows more linear temperature profiles, better agreeing with measurements from the field. Based on this data we can eliminate from consideration the closed model, at least in its present form in which surface recharge penetrates deep into the model.

Key words: thermal analysis, fractured rock, groundwater flow and transport

1. Introduction

The present work is a part of the site characterization study for Mizunami Underground Research Laboratory being conducted by Japan Nuclear Cycle Development Institute. One element of the study is to examine the uncertainties for evaluating groundwater flow by comparing multiple modeling approaches (Oyamada and Ikeda, 1999; Sawada, et al., 2001; Doughty and Karasaki, 2001; Sawada et al., 2003). In the present paper, we outline thermal analyses using the model discussed in Doughty and Karasaki.

Starting with regional geographic, geologic, hydrologic, geophysical, and meteorological data, we develop an effective continuum model to simulate subsurface flow and transport in a 4 km by 6 km by 3 km thick fractured granite rock mass overlain by sedimentary layers. Individual fractures are not modeled explicitly. Rather, continuum permeability and porosity distributions are assigned stochastically, based on hydraulic conductivities determined from well-test data and fracture density measurements. Large-scale features such as lithologic layering and major fault zones are assigned deterministically. The bulk of the model is composed of granitic rocks, with mean hydraulic conductivity and porosity of about 10^{-7} m/s and $3.7 \cdot 10^{-4}$, respectively.

One of the difficulties in constructing a groundwater model is the selection of the lateral boundary conditions. We examine two models with opposing boundary conditions at the lateral boundaries that coincide with ridgelines or other natural groundwater divides. One model has mostly closed lateral boundaries. Constant head boundaries are applied only in two places where rivers intersect the model boundary: the entire southern boundary of the model, which is coincident with a stretch of the Toki River, and over a short low-elevation section along the NE boundary of the model, where a seasonal creek flows. The other model has mostly open lateral boundaries, except under the Toki River at the southern

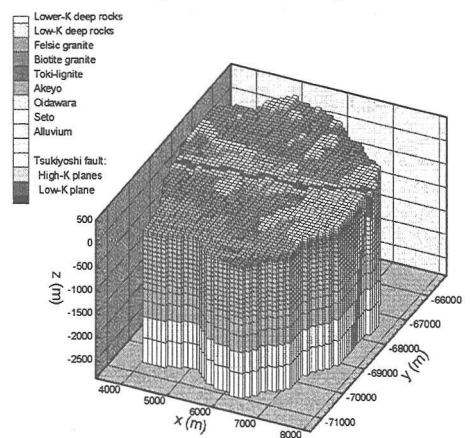


Figure 1. Perspective view of the new base case model.

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boundary of the model. The top layer of the model at the Toki River is a constant head boundary, but the underlying layers are closed. At all open boundaries, head is set equal to ground surface elevation.

Other model boundary conditions are set as follows. The top boundary of the model is a constant-head boundary, with the head value set equal to the ground surface elevation (that is, the water table is coincident with the ground surface, eliminating consideration of the vadose zone). With such a boundary condition, water flows into or out of the model according to local head differences. Water flowing in is interpreted as infiltration or recharge whereas water flowing out is interpreted as spring discharge or the conversion of groundwater to surface water in rivers and creeks. The bottom boundary of the model is closed. Moreover, the mean permeability of the lowest three layers of the model gradually decreases, to represent the closing of fractures with increased lithologic stress, and to provide a gradual transition to the closed boundary.

The Tsukiyoshi Fault, a major east-west sub-vertical fault that passes through the center of the model, is assumed to have a sandwich structure with a low-conductivity plane surrounded by high-conductivity planes on either side (Figure 1). The low-conductivity plane has a mean conductivity ten times lower than the bulk fractured rock (based on field data), and the high- conductivity planes have a mean conductivity ten times higher than the bulk fractured rock (no quantitative data available, but well-test observations by Takeuchi et al. (2001) suggest a high conductivity zone adjacent to the fault). All three fault planes use normal distributions from which to draw hydraulic conductivities. No other faults are included in the model.

2. Steady State Flow and Transport

Steady state isothermal flow and transport simulations are conducted using the two models described above. Table 1 summarizes the water budgets for the open and closed boundary models. For the open model, water enters along the east, north, and west sides of the model and mainly exits the model through the surface. For the closed model, water infiltrates through the surface, moves down through the model, and mainly exits at the southern Toki River boundary. There are both upward and downward flows through the top surface boundary for both models and the spatial flow distributions are similar for the two models, being generally controlled by surface topography. However, given the additional lateral inflow present in the open model, surface inflows tend to be smaller and surface outflows tend to be larger compared to the closed model. This effect is so strong that the net surface flow is in the opposite direction for the open and closed models.

Table 1. Water budgets for the open and closed versions of the new base case. Flow rates (kg/s) into the model are positive.

	Surface	Toki River	North Side	East and West Sides
Open Model	-99	-5	27	77
Closed Model	63	-55	-8	0

Observed surface recharge data is only available for a small fraction of the 4 km by 6 km model. This data shows recharge into the model most years, with an average value in the range of 100 to 200 mm/yr. The average closed model recharge rate of 63 kg/s corresponds to 106 mm/yr, which certainly appears more consistent with the field data than the open model, which shows discharge rather than recharge. However, observed water budget data comparing precipitation, stream flow, and recharge may relate primarily to shallow subsurface flow that is localized in the sedimentary rocks overlying the granitic basement. The model's coarse vertical discretization near the surface (50 m) makes it difficult to accurately model such flows. Therefore, we cannot eliminate the open model from consideration solely based on its worse prediction of surface recharge data.

3. Thermal Analyses

Groundwater flow simulations are often done assuming isothermal flow. However, as can be seen in Figure 2, the water viscosity is a function of temperature and thus can affect the flow significantly at depth. At a depth of 3 km, where the bottom of the model lies, the viscosity of water is one third of that at the surface. Therefore, we conduct thermal analyses to assess the error made by doing isothermal simulations of steady-state flow fields and the accompanying tracer transport. Furthermore, we want to

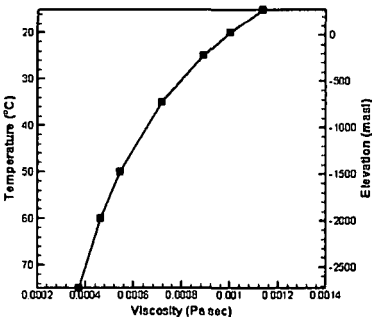


Figure 2. Viscosity as a function of temperature. The elevations shown on the right y-axis are calculated from temperature assuming a surface temperature of 15°C and a temperature gradient of 2°C per 100 m.

determine whether or not borehole temperature profiles provide any information on regional or local hydrology that can help us better constrain our models.

3.1 Temperature profile data

Temperature versus depth profiles have been measured in 24 wells in the Tono area. Of these, 16 extend over 200 m below the ground surface, making them amenable to an analysis of the basin-scale interplay between conductive and convective heat flow. In 6 wells, temperature measurements were repeated several months or years later, allowing an assessment of transient effects and instrument reliability. Assuming constant thermal conductivity, purely conductive profiles are linear, so any curve or kink in an observed T vs. z profile should represent fluid flow of some sort. However, it is worth noting the following points regarding interpretation of borehole temperature observations: (1) Thermal conductivity can vary with rock type. Thus, a conductive T vs. z profile can show a kink at a sharp lithological boundary. (2) Depending on well completion techniques, fluid flow may occur in the borehole that is not representative of fluid flow in the surrounding rock. We expect that generally, the convective signatures of such flows will not be long lasting in space or time, because there is ample opportunity for heat transfer from the borehole to the surrounding rock to damp them out. However, borehole temperature measurements provide extremely sparse information in both space and time, making it generally quite difficult to distinguish local or transient events from global or steady ones a priori. This makes numerical simulation a valuable tool. If we cannot reproduce a given temperature fluctuation with any steady-state balance of fluid flow and conduction, chances are the observation represents a borehole effect or an instrument error.

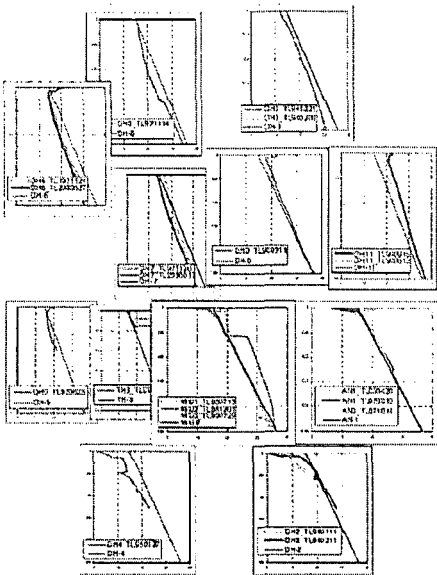


Figure 3. Observed temperature profiles. Plot location on the page is meant to roughly mimic well location in space. A conductive profile representing 2°C per 100 m is shown for reference on each plot.

Figure 3 shows all the observed temperature profiles. Each well or group of closely spaced wells is shown in a separate plot. The locations of the individual plots on the page roughly represent the wells' locations in space. Based on the analysis of surface flow, we expect that in the northern, higher elevation portion of the model, downward fluid flow prevails, whereas in the southern, lower elevation portion of the model, upward fluid flow prevails. Although there is a great deal of variability among the temperature profiles shown in Figure 3, this flow pattern is generally supported. Ignoring sharply changing temperatures in the upper 10-20 m, wells that suggest evidence of downward fluid flow are MIU-3, DH-5, DH-6, DH-7, DH-8 (above 700 m), and one of the two DH-11 profiles. Wells that suggest upward flow are MIU-2, AN-1, DH-2, and DH-3. Localized temperature peaks, such as those shown for wells MIU-1, DH-2, DH-4, and DH-9 suggest horizontal flow across the borehole.

3.2 3-D uncoupled thermal and flow analysis

Based on the borehole temperature profiles, the simplest approximation for thermal behavior is a constant temperature gradient of about 2°C per 100 m. In our model we assign this linear temperature variation as an initial condition and hold it fixed during the subsequent simulation of steady-state flow. We refer to this procedure as an uncoupled thermal and flow analysis.

As temperature increases with depth, both density ρ and viscosity μ of water decrease. Because the viscosity decrease is much greater, hydraulic conductivity $K = \rho g k / \mu$ increases with depth (if intrinsic permeability k is constant).

Table 2. Water budgets for realization 1 of the open and closed versions of the new base case, for various thermal approaches.

Open Model	Surface	Toki River	North Side	East and West Sides
Isothermal	-119	-7	26	100
Uncoupled thermal and flow	-124	-7	30	101
Coupled thermal and flow	-139	-11	32	118
Closed Model	Surface	Toki River	NE Valley	
Isothermal	65	-57	-8	0
Uncoupled thermal and flow	79	-71	-8	0
Coupled thermal and flow	68	-60	-7	0

Isothermal models that are restricted to constant values of ρ and μ could thus account for increasing temperatures by assigning increasing values of K with depth. The dependence of μ on T , shown in Figure 2, is nonlinear, with larger changes for larger T values.

Steady-state flow and transport simulations were done using a constant surface temperature of 15°C and a fixed temperature gradient of 2°C per 100 m, for the open and closed models. Water budgets are compared to the corresponding isothermal (20°C) cases in Table 2, which also shows coupled analyses results that are discussed in the next section. The differences are modest, but more flow moves through the model for the non-uniform temperature cases, a reflection of the higher average temperature (45°C compared to 20°C) producing a lower average viscosity (0.0006 Pa sec compared to 0.001 Pa sec).

Comparison between the uncoupled case and the isothermal case shows that the overall pattern of the stream traces is little changed by the addition of a non-uniform temperature. The stream traces for the closed model tend to be deeper than those for the open model, hence they encounter higher temperatures: the average temperature along the stream traces is 27°C for the open model and 36°C for the closed model.

Table 3 compares the particle transport modeling results for the uncoupled thermal and flow models to those of the isothermal models. The travel time decrease for the closed model is larger than that for the open model, reflecting the higher temperatures encountered by the stream traces. Overall, the differences between uncoupled and isothermal models are small, indicating that doing an uncoupled thermal analysis does not add much value compared to the previous isothermal analyses. Whether or not a fully coupled thermal analysis is valuable is addressed below.

3.3 3-D coupled thermal and flow analysis

For the fully coupled thermal and flow analysis, we specify the same linear initial temperature distribution as for the uncoupled analysis, but allow the both the temperature and head distributions to change as the system evolves to a steady state.

Table 2 compares the water budgets for the fully coupled, uncoupled, and isothermal approaches. Differences among the different thermal approaches are small compared to differences between the open and closed boundary conditions.

The steady-state temperature distributions and stream traces are shown in Figure 4 for the open and closed models. The temperature distributions differ markedly from the initial linear temperature distribution that represents a purely conductive temperature regime, implying that convective transport accompanying fluid flow is significant. Comparing stream traces and temperature distributions illustrates how convection occurs. For the open model, flow is mainly up and out of the southern half of the model, and the temperature distribution reflects this by showing higher temperatures at shallow depths resulting from the upward flow of deeper, hotter water. For the closed model, flow is mainly down through the model surface, and the temperature distribution shows greatly lowered temperatures over most of the model resulting from the infiltration of cool surface

Table 3. Performance measures for realization 1 of the open and closed versions of the new base case, for various thermal approaches. Numbers shown are averages over 24 stream traces.

	Path length (m)	Travel time (yr)	Average Temperature (°C)	Velocity (m/yr)
Open Model				
Isothermal	1897	3.6	20	528
Uncoupled thermal and flow	1886	2.9	27	643
Coupled thermal and flow	1888	2.7	32	704
Closed Model				
Isothermal	2910	8.3	20	351
Uncoupled thermal and flow	3218	6.0	36	532
Coupled thermal and flow	3067	9.2	18	334

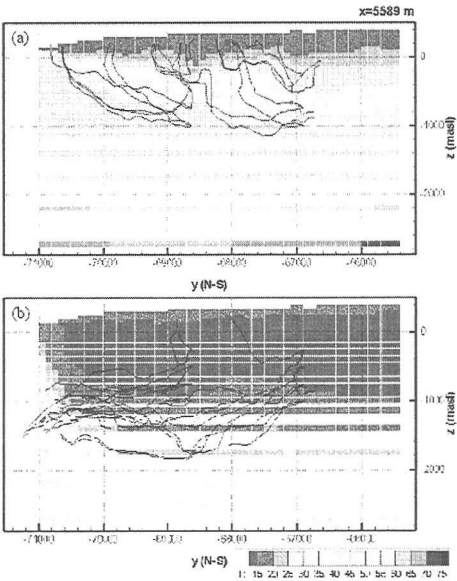


Figure 4. All stream traces leaving the 24 monitoring points projected onto a vertical cross-section near the center of the model, (a) open model and (b) closed model. The steady-state temperature distribution on the cross-section is also shown.

water.

Table 3 compares average performance measures for one realization of the coupled thermal models with the corresponding realization for the uncoupled thermal and flow models and the isothermal flow models. The open model measures do not change much between uncoupled and coupled models: path length is essentially the same and travel time decreases from 2.9 to 2.7 years. The closed model measures change a little more: path lengths are a little shorter but travel time increases from 6.0 years for the uncoupled model to 9.2 years for the coupled model, indicating a much slower average velocity. This velocity decline is due to the much cooler temperatures present in the coupled model, with their correspondingly higher viscosities. In terms of predicting performance measures, the tentative conclusion from the previous section that the isothermal models are adequate remains valid.

Figure 5 shows temperature versus depth profiles extracted from the steady-state 3-D model results. Compared to the field observations shown in Figure 3, it is clear that the open model is much better than the closed model at capturing the character of the field data. This is a significant finding, because isothermal steady-state and transient modeling results did not produce distinct results that could be compared to field data, precluding us from picking a preferred model.

One important caveat about the model is worth mentioning. The open lateral boundary conditions maintain the initial linear temperature and head profiles. That is, they consider a conductive temperature profile and hydrostatic pressures. This would be a good choice if we felt that it were justified based on the topography and regional hydrology, which is probably not the case for the present studies. A better approach would be to use the present results as the first step in an iterative process. We could assign steady-state temperature and head values representing convection (from an appropriate location near the middle of the model) at the lateral boundaries for a second simulation. This process could be repeated until the resulting temperature and head distribution did not change significantly. Another alternative would be to create a much larger model, so the lateral boundaries do not come into play.

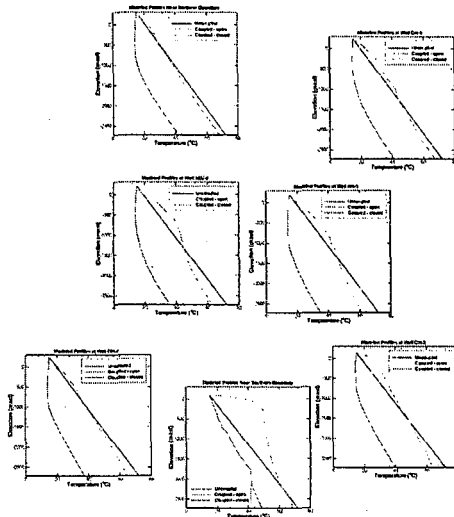


Figure 5. T vs. z profiles extracted from the 3-D models. Plot location on the page is meant to roughly mimic well location in space.

4. Conclusions

We have two versions of the model with opposing boundary conditions: one with mainly open lateral boundaries and the other with mainly closed lateral boundaries. Although they produce relatively similar performance measures for both steady-state flow (path length and travel time for stream traces leaving monitoring points) and transient flow (pressure changes at observation wells during a long-term pump test), they predict quite different overall groundwater flow patterns. We would like to use observed data to decide which model is a better representation of reality. Three types of analyses were conducted: steady-state isothermal flow, transient isothermal flow (not shown), and steady-state non-isothermal flow.

For steady-state isothermal flow, the only observed data with which to compare is surface recharge data. The closed model compares better with this data, showing net surface recharge rather than the net surface discharge predicted by the open model. However, the observed data does not provide good coverage of the model as a whole, and may relate more to shallow hydrology within the sedimentary rocks than to large-scale groundwater flow through the deeper granitic basement. We believe that steady-state isothermal analysis cannot be used to pick a preferred model.

For transient isothermal flow (well-test analysis of the long-term pump test), pressure changes at observation locations close to the pumping well are not very sensitive to the lateral boundary conditions. Pressure responses closer to the model boundaries are so small that differences reflecting the different boundaries probably would not be observable under real field conditions. Therefore, we believe that pressure-transient analysis cannot discriminate between the two models either.

In contrast, for steady-state fully coupled thermal and flow analysis, the two models predict strongly different temperature versus depth profiles, and numerous measurements from the field agree better with the open model. We believe that based on this data we can eliminate from consideration the closed model with its large infiltration rates that produce widespread deep recharge. Deep recharge of cool surface water creates temperature profiles strongly at odds with observed profiles.

A model with closed lateral boundaries would be possible if recharge were confined to shallow sediments and did not penetrate very far into the granitic basement. Given the sparse surface recharge data, which suggests that net surface recharge is in fact more likely than net surface discharge, such a model could be an improvement over the current open model. One possible way to achieve such a groundwater flow pattern would be to significantly increase the permeabilities of the sedimentary rocks above those of the granitic rocks. Then surface infiltration would flow vertically in the sedimentary rocks, then sub-horizontally, down-gradient (mainly from northwest to southeast) at the interface between the sedimentary rocks and the underlying granite. Very few measurements of the hydrologic properties of the sedimentary rocks are currently available, and it would therefore be worthwhile to conduct further field tests to try to better ascertain their characteristics.

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