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Investigations of Fluid Flow in Fractured Crystalline Rocks at the Mizunami Underground Research Laboratory

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ABSTRACT: Experimental hydrology data from the Mizunami Underground Research Laboratory in Central Japan have been used to develop a site-scale fracture model and a flow model for the study area. The discrete fracture network model was upscaled to a continuum model to be used in flow simulations. A flow model was developed centered on the research tunnel, and using a highly refined regular mesh. In this study development and utilization of the model is presented. The modeling analysis used permeability and porosity fields from the discrete fracture network model as well as a homogenous model using fixed values of permeability and porosity. The simulations were designed to reproduce hydrology of the modeling area and to predict inflow of water into the research tunnel during excavation. Modeling results were compared with the project hydrology data. Successful matching of the experimental data was obtained for simulations based on the discrete fracture network model.

1. INTRODUCTION

Characterization of the natural system is of importance to geologic disposal of nuclear waste. The Mizunami Underground Research Laboratory, located in Tono area (Central Japan), is a research facility administered by the Japan Atomic Energy Agency (JAEA). The facility provides scientific basis for the research and development of technologies needed for deep geological disposal of radioactive waste in fractured crystalline rocks. Further description of the hydrogeology of the area can be found in Iwatsuki et al., 2005 and Iwatsuki et al., 2015. Fig. 1 shows location and details of the research facility. The part of the tunnel where the modeling is based is given in Fig. 2, showing the Inclined Drift, Closure Test Drift (CTD) sections of the tunnel. The figure also shows a monitoring well (12MI33) together with monitoring locations in the well. Through the Development of Coupled Models and their Validation against Experiments (DECOVALEX19) project, a comprehensive set of fracture, hydrologic and chemical data were obtained based on experiments in a research tunnel located at 500 m depth. Development of a discrete fracture network (DFN) model is presented in a companion paper by Kalinina et al., 20018. The companion paper describes the fracture model development based on fracture data collected from the excavated areas and boreholes. The fracture data analysis produced up-scaled permeability and porosity data for flow and transport modeling. In generating the permeability and porosity fields the matrix rock was assigned a permeability of 10^{-19} m^2 and a porosity of 0.001. In this study, the focus is on flow analysis near the research tunnel using the up-scaled fracture model.

The aim of this study is to predict the amount of inflow into the research tunnel as the tunnel sections are excavated. The simulation also aims to provide pressure histories at selected monitoring locations (shown in Fig. 2) due to the excavation process. Flow simulations were conducted with PFLOTRAN (Hammond et al., 2014), an open source, state-of-the-art massively parallel subsurface flow and reactive transport code in a high-performance computing environment.

The project provided data of tunnel excavation progress, as tunnel sections are excavated is shown in Fig. 3. The figure shows excavation progress in terms of days since excavation began. The excavation data have been used in simulations of inflow into the tunnel.

The excavation progress was modeled by progressively removing material assigned as the host rock. This is equivalent to increasing the grid blocks representing the tunnel as a function of time. To get a better representation of the excavation progress, a small portion of rock material was removed at a time. Thus, the material removal was in 1 m increments for a total of 103 m tunnel length. This resulted in 103 PFLOTRAN runs applying the pressure boundary conditions assigned for the excavated area. The modeling was carried out with output of each PFLOTRAN run used as input for the next run until the complete excavation of the tunnel parts was complete. To automate the simulation process, the optimization code, DAKOTA (Adams, et al, 2017) was used as a driver to PFLOTRAN.

Simulations were carried out for a homogenous representation using the site-scale domain. These simulations are detailed in Section 2.1. Simulations were also conducted for a fracture system and are described in Section 2.2. Discussion of results and conclusions are given in Section 3.

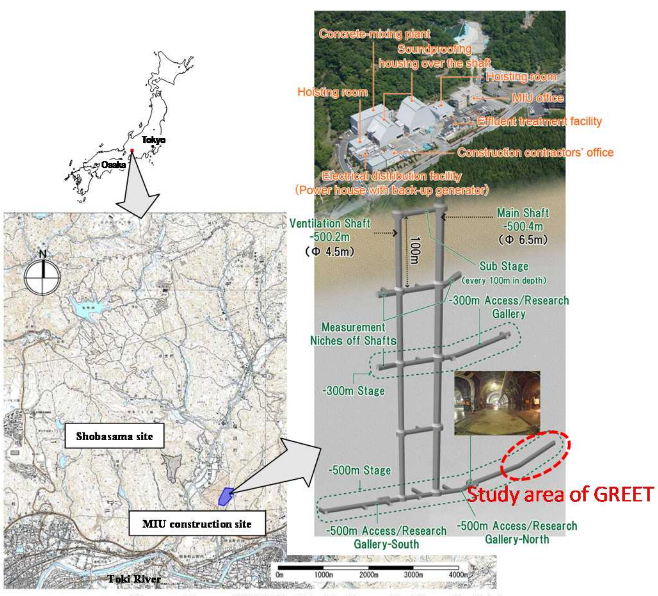

Fig. 1. Location and layout of the Mizunami Underground Research Laboratory.

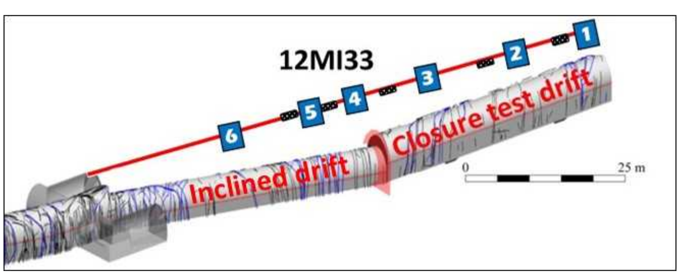

Fig. 2. Schematic diagram showing the modeled part of the tunnel and monitoring well 12MI33 with monitoring sections.

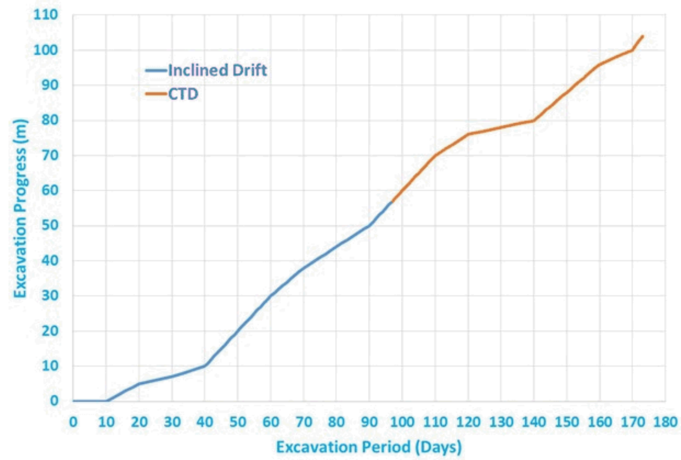

Fig. 3. Data of tunnel excavation progress.

2. MODEL SETUP

Simulations were based on a site-scale domain with a geometry of 100 m x 150 m x 100 m in the x, y and z directions, respectively. The modeling domain incorporates the Inclined Drift and the CTD sections of the tunnel with dimensions given in Table 1. The simulation domain also incorporates the monitoring sections in Well 12MI33. For the simulations, a refined Uniform (structured) grid was selected, with grid block size of 1 m x 1m x 1m for a total of 1,500,000 grid blocks.

Table 1. Dimensions of the tunnel sections

	Inclined Drift	CTD
Length (m)	57	46.5
Width (m)	4.5	5.0
Height (m)	3.5	4.5

Initial and boundary conditions were based on project specified data. Hydrostatic initial pressure conditions are represented by average head measurements of 110 EL m, based on data from monitoring wells. Top, bottom and side boundary conditions were also assigned head of 110 EL m. The excavated area was assigned a constant pressure boundary condition of 1.0 atmosphere. Head data were converted to hydrostatic pressure using the head of 110 EL m and elevation data for specific locations. Thus, the pressure at the top and bottom of the simulation domain were calculated to be 3.6 MPa and 4.6 MPa, respectively. Hydrostatic pressure boundary condition was assigned on the sides of the domain. In PFLOTRAN the domain bottom was assigned no flux boundary condition.

2.1. Homogenous System Flow Model

Simulations were first conducted for a homogenous model with reference hydraulic conductivity. For the simulations, physical properties obtained from the monitoring well 12MI33 and other sources were used. Estimated hydraulic conductivity for Toki granite is in the range of log (-8 ± 1) m/s. The homogenous simulations used a constant reference hydraulic conductivity of 10^{-8} m/s (permeability 10^{-15} m^2) and a porosity of 0.001. Initial and boundary conditions described above were applied. A steady state run was made to obtain initial pressure conditions in the model domain before the excavation progress was modeled. Simulations of excavation progress were conducted using the steady state pressure distributions and the constant pressure boundary condition inside the tunnel. The DAKOTA-PFLOTRAN system described above was used to separately model excavation progress in the Inclined Drift and the CTD. The outputs were post-processed to evaluate inflow into the tunnel and pressure history at the observation points. The flow of water into the excavated space (Inclined Drift and CTD) was predicted based on the excavation progress. Results of pressure distribution at simulation time of 173 days are shown in Fig. 4. The figure represents fluid flow into the tunnel due to the initial and boundary conditions. The fluid movement represents the assumed isotropic system. Fig. 5 shows predicted pressure vs. time at the selected monitoring points (see Fig. 2 for locations of the monitoring points). Higher pressure drawdown is predicted in Observation Section 6, which is closer to the Inclined Drift entrance. The lowest predicted pressure drawdown is in Section 1, which is close to the edge of the CTD. This is in line with expectations as the inclined tunnel was open for a longer time, and thus more inflow compared to the CTD.

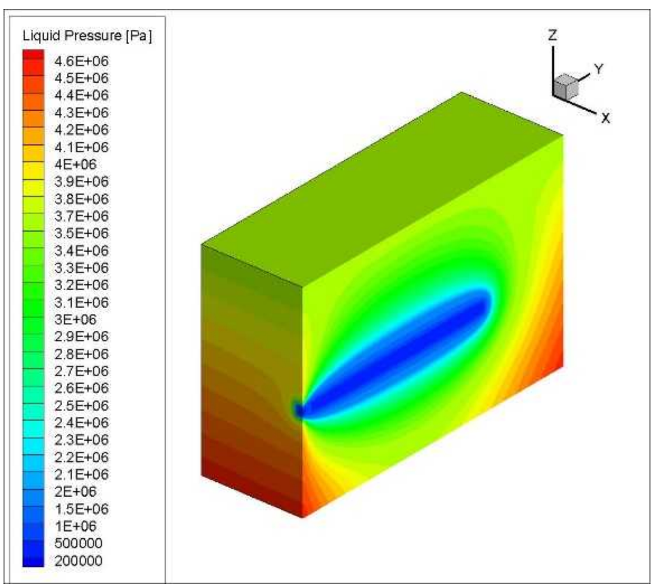

Fig. 4. Predicted pressure distribution along tunnel axis after 173 days simulation time: Homogenous Model.

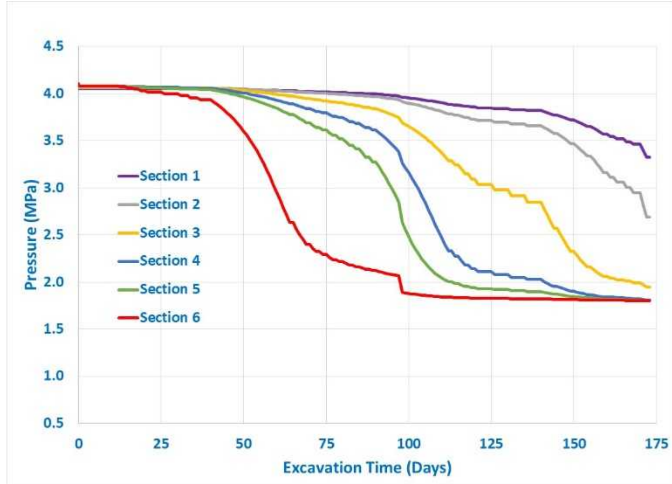

Fig. 5. Predicted pressure history at observation points in Well 12MI33 during excavation: Homogenous Model.

2.2. Fractured System Flow Model

A single realization with two fracture sets was used for simulations using the fracture model. Fig. 6 and 7 show the up-scaled permeability and porosity fields for the realization. Flow-based effective permeability was calculated using Darcy's law and liquid flux at steady state. Flow simulations were carried out using the up-scaled permeability and porosity fields to estimate the flow-based effective permeability. A pressure gradient was imposed between the west and east faces of the simulation domain. The resulting calculated effective permeability along the x-axis (perpendicular to tunnel axis) for the fracture realization was 3.27 x 10^{-16} m^2, which is about one third less than the isotropic permeability used for the homogenous model. Flow-based effective permeability values were also calculated for flow in the other directions. The complete results are shown below. The effective permeability in the vertical direction is higher than the horizontal values, indicating more flow in the vertical direction.

- Horizontal flow, perpendicular to the tunnel axis (x-axis), effective permeability: 3.27 x 10^{-16} m^2
- Horizontal flow, along the tunnel axis (y-axis), effective permeability: 1.95 x 10^{-16} m^2
- Ratio of horizontal flow effective permeability y-axis/x-axis: 0.6
- Vertical flow (z-axis), effective permeability: 5.14 x 10^{-16} m^2
- Ratio of effective permeability z-axis/x-axis: 1.6

The simulation procedure for the homogenous model described in Section 2.1, using the coupled DAKOTA-PFLOTRAN codes, were also applied to the fractured system simulation runs. Simulation results for the fractured system are shown in Figs. 8 to 10. Fig. 8 shows pressure distributions at 173 days simulation time. The pressure distribution indicates flow into the tunnel in a fractured system along the axis of the tunnel. Predictions of pressure at observation points are shown in Fig. 9. The pressure drawdown for most of the observation sections are higher than those of the homogenous model due to the increased local permeability.

The flow of water into the excavated space was also evaluated for the fractured system. The resulting predictions of inflow into the tunnel is shown in Fig. 10 together with the results for the homogenous model. Project inflow experimental data points are also included. The predicted inflow for the homogenous model matches the experimental inflow to the Inclined Drift, but over predicts the inflow to the CTD. The predicted inflow for the fracture model matches both experimental data points.

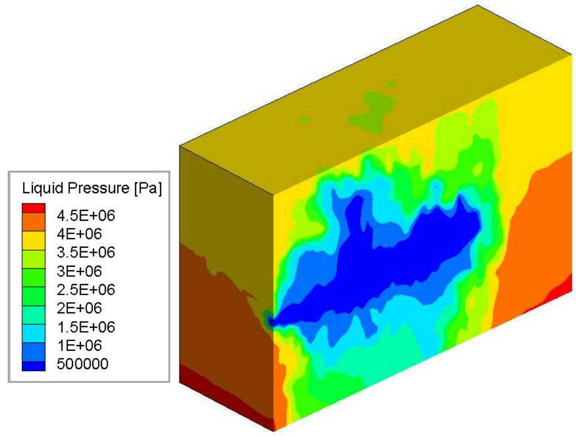

Fig. 8. Predicted pressure distribution along tunnel axis after 173 days simulation time: Fracture Model

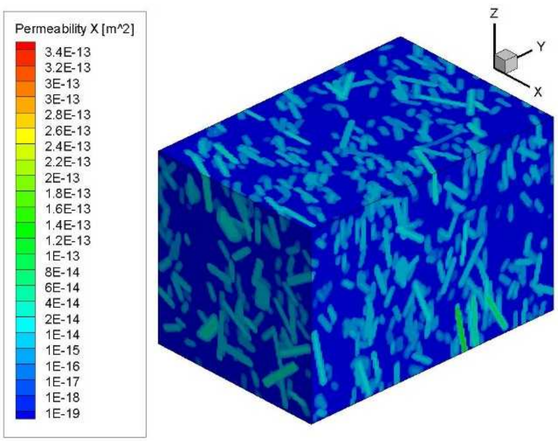

Fig. 6. Upscaled permeability: Fracture Model

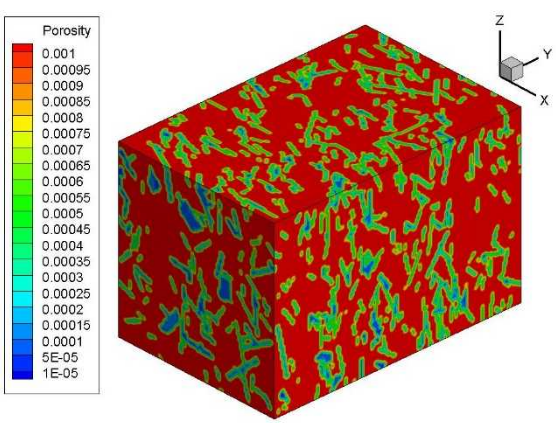

Fig. 7. Upscaled porosity: Fracture Model

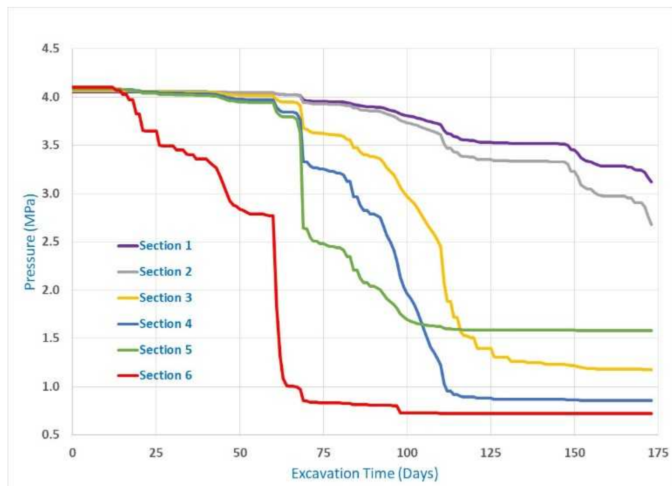

Fig. 9. Predicted pressure history at observation points in Well 12MI33 during excavation: Fracture Model.

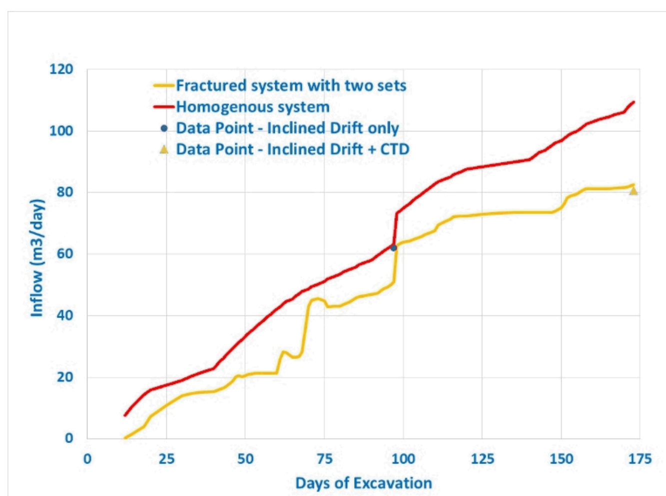

Fig. 10. Predicted inflow into Inclined Drift and CTD: Comparison of results of Homogenous and Fracture Models with experimental data.

3.0 DISCUSION OF RESULTS AND CONCLUSIONS

Preliminary modeling analysis was conducted to predict inflow of water during excavation of the Inclined Drift and CTD section of the tunnel at the Mizunami Underground Laboratory, as part of DECOVALEX19 study. The analysis looked at the use of a homogenous model with reference hydraulic conductivity, and a fracture model developed by Kalinina et al. [3]. The simulations used a site-scale domain of size 100 m x 150 m x 100 m. Boundary and initial conditions specified by the project, based on data from wells, were applied to flow simulations. Parameter data also obtained from wells were used. Data of excavation progress for the Inclined Drift and the CTD were also provided.

The modeling analysis using the homogenous model provided a simpler isotropic representation of the porous medium. However, simulation results showed uniform fluid flow and thus the model was not able to capture local hydrologic variations. The modeling analysis using the fracture model with up-scaled permeability and porosity fields allowed realistic representation of the hydrology of the fractured rock in the excavated region. The simulation results provided detailed flow analysis in a fractured system. The predicted inflow of the realization with two fracture sets matched the experimental data. The results are preliminary output for a single fracture realization. More realizations will be needed to obtain average representative output.

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