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New Concept Discrete Fracture Network Model Simulator, GeoFlow, and Three Dimensional Channeling Flow in Fracture Network

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ABSTRACT

Discrete fracture network (DFN) model simulations, where a fracture network can have a natural heterogeneity, is one of the most effective approaches in fluid flow analyses for naturally fractured and enhanced geothermal reservoirs. In the DFN model simulations, fractures are modeled by a pair of parallel smooth plates although real fractures have rough surfaces. Numerous field and laboratory observations have suggested that fluid flow through a fracture occurred in specific channels (channeling flow) due to a heterogeneous aperture distribution formed by the rough surfaces that are partially in contact with each other under a subsurface compressive stress field. The conventional DFN model simulations therefore give us a serious concern about the reality. To address this concern, we have developed a new concept DFN model simulator, GeoFlow, in which fractures can have heterogeneous aperture distributions. Three dimensional fluid flow simulations were performed for a simple fracture network by both the conventional and the new DFN modeling simulations. In the conventional DFN model simulation, fractures have no aperture distribution, and fluid flow in the fracture plane was therefore quite uniform, which was conflict with the filed observations. On the other hand, GeoFlow clearly showed formation of preferential flow paths in each fracture plane, developing three dimensional preferential flow paths in the fracture network.

1. INTRODUCTION

Fluid flows through rock fractures in the Earth's crust have been a subject of interest for some time because rock fractures usually have much greater permeability than the rock matrix. Rock fractures are therefore recognized as the predominant pathways of resources and hazardous materials such as groundwater, oil/gas, geothermal fluids, and the high –level nuclear wastes. The fluid flow properties of rock fractures have been investigated with respect to the geological disposal of the high-level nuclear wastes. As a result, our understanding of the subsurface flow system has been greatly improved and has been applied to the development of geothermal and oil/gas fractured reservoirs. Recently, the prediction of flow and transport phenomena through rock fractures based on a precise modeling of the flow system in a fractured rock mass with natural heterogeneities has become increasingly important because recent environmental and energy problems require urgent solutions using underground space based on the safe and effective development of reservoirs. A modeling with a natural heterogeneity of a fracture network has been established by the Discrete Fracture Network (DFN) modeling technique [Benke and Painter, 2003; Darcel et al., 2003; Park and Lee, 2003; Min et al., 2004; Botros et al., 2008].

In the conventional DFN modeling, rock fractures have been described by parallel smooth plates. However, field and laboratory studies have suggested that fluid flow through a rock fracture is far from the fluid flow through parallel smooth plates, due to channeling flow in a heterogeneous aperture distribution by rough surfaces [Cacas et al., 1990; Abelin et al., 1991; Dverstorp et al., 1992; Carmeliet et al., 2004; Johnson et al., 2006; Rowland et al., 2008; Watanabe et al., 2008; Nemoto et al., 2009; Watanabe et al., 2009]. When channeling flow occurs in a single fracture of granite, the area where flowing fluid exists is expected only 5-20% at confining pressures of up to 100 MPa, with various features in the preferential flow paths [Watanabe et al, 2009].

The parallel plate concept the DFN model simulation therefore gives us a serious concern about the reality. Applications of the DFN model simulation in developments of naturally fractured reservoir or the enhanced geothermal reservoirs can result in misunderstanding of fluid flow in the reservoirs. To address this concern, we have developed a new concept DFN model simulator, GeoFlow, in which fractures can have heterogeneous aperture distributions. The present paper describes GeoFlow and case-study simulation results for fluid flow through a three dimensional fracture network. The results shows formation of three dimensional preferential flow paths, which cannot be addressed with the conventional DFN model simulators, and the results suggest that the three dimensional channeling flow should be addressed for effective developments of geothermal reservoirs.

2. GEOFLOW AND FLUID FLOW SIMULATION

GeoFlow is a kind of 3-D DFN model simulator, and has the following features: i) Fractures have 2-D aperture distributions; ii) Fracture distributions in a 3-D space are given by assigning center coordinates, strikes and dips of generated fractures; iii) Fluid injection and production through wells can be simulated.

The present version of GeoFlow can simulate steady state flow of incompressible and viscous fluid in a fracture network by using a Local Cubic Law (LCL)-based fluid flow model [Brown, 1987; Mourzenko et al., 1995; Zimmerman and Bodvarsson, 1996; Ge, 1997; Oron and Berkowitz, 1998; Yeo et al., 1998; Pyrak-Nolte and Morris, 2000; Brush and Thomson, 2003; Konzuk and Kueper, 2004; Watanabe et al., 2008; Nemoto et al., 2009; Watanabe et al., 2009]. In a 3-D space (rock matrix) with a x-y-z coordinate system, fractures with 2-D aperture distributions, $a(i, j)$, are allocated by assigning their center coordinates, strikes and dips (Fig. 1). The 3-D space is divided into L x M x N grids to determine permeabilities at grid-grid interfaces since the Darcy flow is calculated at these interfaces based on the following equation:

$$\frac{\partial}{\partial x}\left(Ak\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial x}\left(Ak\frac{\partial P}{\partial y}\right)+\frac{\partial}{\partial x}\left(Ak\frac{\partial P}{\partial z}\right)=0, \quad (1)$$

where A is the cross-sectional area where fluid flows, k is the permeability, and P is the fluid pressure. With the LCL, Ak in the equation (1) is described as:

$$Ak=\sum_{n=1}^{N}A_{f,n}k_{f,n}+A_m k_m=\sum_{n=1}^{N}\frac{w_{f,n}a_{j,n}^{3}}{12}+A_m k_m, \quad (2)$$

where $A_{f,n}$ and A_m are the areas of nth fracture and the rock matrix at a grid-grid interface, $k_{f,n}$ and k_m are the permeabilities of the nth fracture and the rock matrix (10^{-19} m^2 in the present study), and $w_{f,n}$ and $a_{f,n}$ are the width and the aperture of the nth fracture. Consequently, the permeability at the grid-grid interface with fractures depends on both the fracture and the matrix permeabilities, whereas the permeability at the interface with no fracture depends only on the matrix permeability (Fig. 2). With this permeability calculation, it is possible to obtain results that reflect the heterogeneities of both the fracture and aperture distributions. The equation (1) is solved by a finite difference method at given boundary conditions.

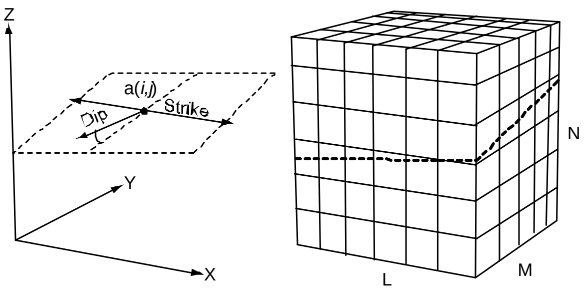

Fig. 1: The generation of a fracture (shown by the dashed lines) in the 3-D space (a) and the grid system (b).

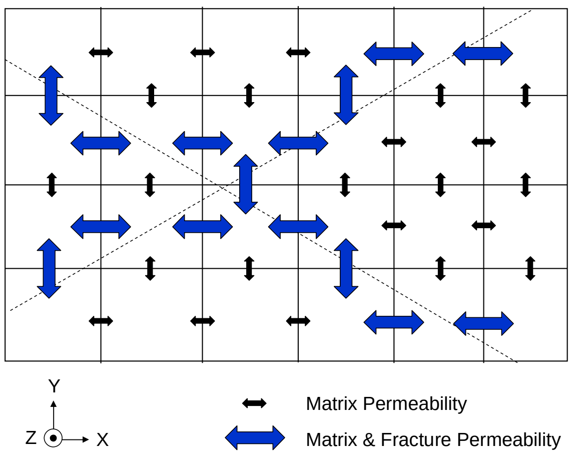

Fig. 2: The permeabilities at the grid-grid interfaces. The dashed lines show fractures.

Fig. 3 shows a comparison of fluid flow simulation results, for an aperture distribution of the tensile fracture in granite (Fig. 3a), by the 2-D simulator used in Watanabe et al. [2008] (Fig. 3b) and GeoFlow (Fig. 3c), where the aperture distribution had been determined by Watanabe et al. [2008]. The two different simulators provided identical flow rate distributions, which showed formation of preferential flow paths. It was therefore demonstrated that GeoFlow could simulate previously observed channeling flow in rock fractures. In the present study, fluid flow through a simple fracture network, which consisted of two fractures intersecting each other, was analyzed by both the conventional DFN and GeoFlow simulations, to examine formation of three dimensional preferential flow paths and limitations of the conventional DFN model simulations.

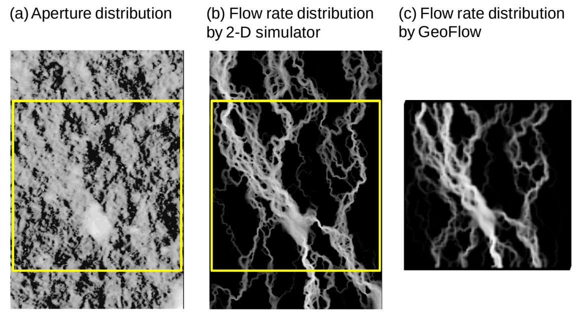

Fig. 3: The flow rate distributions for the aperture distribution of the single tensile fracture in granite (a) by the 2-D simulator (b) and GeoFlow (c). Note that the aperture distribution within the yellow square in (a) was used in the GeoFlow simulation, and flow rate distribution within the yellow square in (b) is comparable to the flow rate distribution in (c). The magnitudes of the aperture and the flow rate are shown by gray scale.

3. RESULTS AND DISCUSSION

Fig. 4 shows the fluid flow simulation result for two fractures (A and B) intersecting each other, with the conventional DFN model. The fractures A and B have the same unique aperture (hydraulic aperture). Fig. 4a shows homogeneous permeability distributions in the fracture planes due to the parallel smooth plate model with the unique aperture. With the boundary conditions of unidirectional flow in the direction parallel to the red axis, fluid first flowed through only the fracture A, and then flowed through both the fractures A and B after the intersection. Fig. 4b shows the flow rate distribution corresponding to the permeability distribution. No formation of preferential flow path was confirmed in the fracture planes, and similar flow rates were observed between the fractures A and B after the intersection.

On the other hand, fluid flow through the same fracture network was quite different when the fractures had aperture distributions. Fig. 5 shows the fluid flow simulation result for the two fractures with the aperture distributions. The fracture A and B have the same aperture distribution determined by Watanabe et al. [2008]. Additionally, the aperture distribution provides the same fracture permeability (hydraulic aperture) as that of the aforementioned parallel smooth plate model fractures. Except for the aperture distribution, simulation conditions for this result were the same with those for the result shown in Fig. 4. Fig. 5a shows heterogeneous permeability distributions in the fracture planes by the aperture distribution. Fig. 5b shows the flow rate for the permeability distribution, which was quite different compared with Fig. 4b. Fluid flow was highly localized in specific preferential flow paths in each fracture plane. The flow paths in each fracture plane connected at the intersection, developed 3-D preferential flow paths in the fracture network. Flow rates after the intersection were dramatically different between the fractures A and B. Most fluid flowed through the fracture A after the intersection, which was entirely different from the result by the conventional DFN model simulator. This result suggested that the conventional DFN model simulation could provide results that were entirely different from the realities in both macroscopic and microscopic scales.

Fig. 6 shows the fluid flow simulation result when fracture B was moved by parallel shift along the fracture plane. Because the part of fracture B before the intersection did not contribute to the fluid flow due to the boundary conditions, the result shows flow path changes due to the change of the aperture distribution after the intersection, which may occur in hydraulic stimulation of a geothermal reservoir. With the change of the aperture distribution (Fig. 6a), drastic changes of the preferential flow paths in fractures A and B were observed particularly after the intersection (Fig. 6b). In contrast to Fig 5b, fracture B had significant contribution to the fluid flow. Additionally, different preferential flow paths were observed in fracture A after the intersection. The conventional DFN model simulation, which focused only on permeability (hydraulic aperture) changes of fractures, could not provide insights concerning such drastic changes of preferential flow paths in a geothermal reservoir.

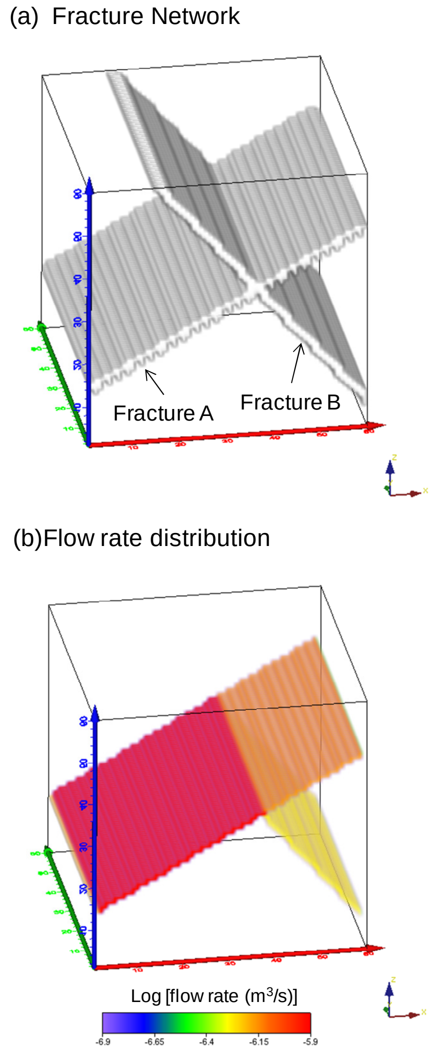

Fig. 4: The fracture network with the homogeneous permeability distribution (a) and the flow rate distribution (b) by the conventional DFN model simulation.

4. CONCLUSIONS

The present study provided a new concept DFN model simulator, GeoFlow, which can be utilized in the analyses of fluid flow in naturally fractured and enhanced geothermal reservoirs. In contrast to the conventional DFN model simulators, GeoFlow enables us to perform three dimensional fluid flow simulations for fracture networks with heterogeneous aperture distributions. By using GeoFlow, it is possible to take into account channeling flow that has been observed by numerous previous fields and laboratory studies. The present results suggested that 3-D channeling flow could occur in geothermal reservoirs, and the conventional DFN model simulation could provide results that were entirely different from the realities in both macroscopic and microscopic scales.

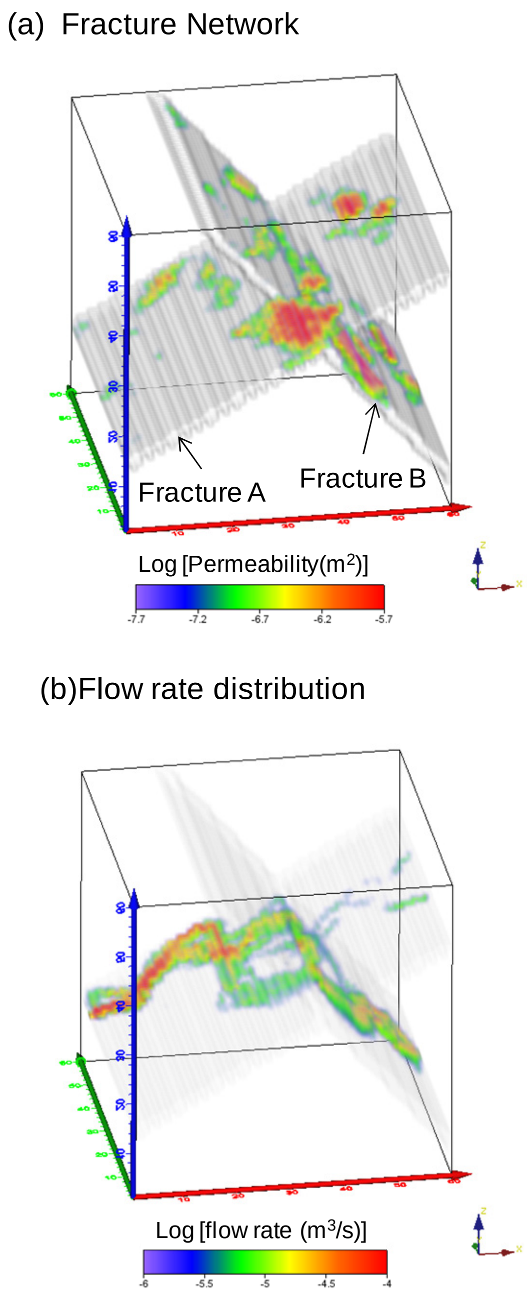

Fig. 5: The fracture network with the heterogeneous permeability distribution (a) and the flow rate distribution (b) by the GeoFlow simulation.

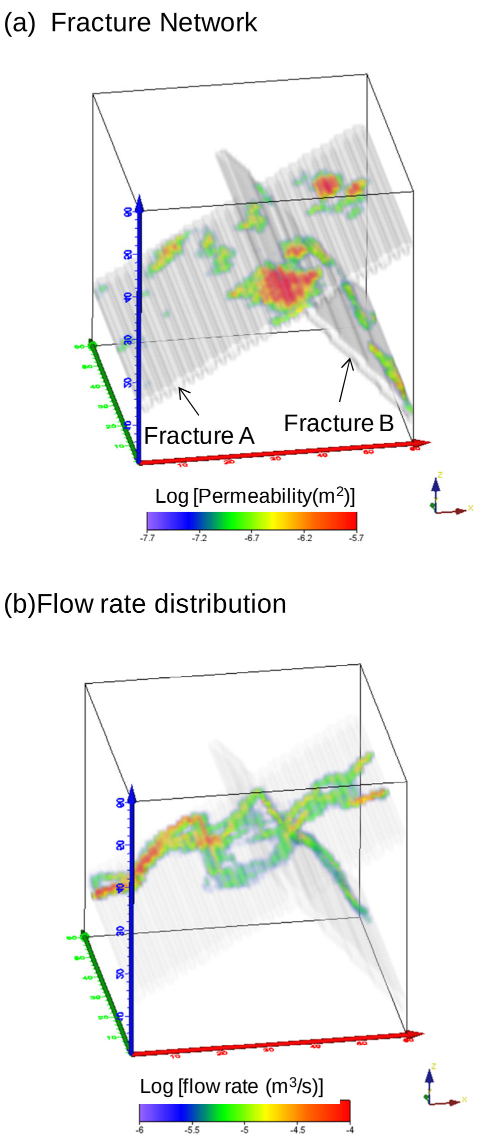

Fig. 6: The fracture network with the heterogeneous permeability distribution (a) and the flow rate distribution (b), after the parallel shift of the fracture B (a), by the GeoFlow simulation.

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