Flow simulation in digital rough fractures by considering anisotropic roughness and geometrical combinations

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ABSTRACT: Anisotropic flow behavior in rock fractures is playing an important role in resource exploitation and engineering. To better understand the relation between flow behavior and geometrical features of fractures, digital fractures with 3 roughness were generated based on the spectral method. Simulation was conducted on 3 constant velocity inlets. From the results, flow behavior in 4 fracture pairs all show anisotropy in opposite directions. Different flow behaviors of the walls swapped fracture pairs indicate the influence of normal vectors of fracture asperities. Ratios of the roughness parameter *M* between upper and lower fracture walls are correlated to flow pressure gradient.

Keywords: Rock fracture, flow simulation, anisotropy, pressure gradient, roughness.

1 INTRODUCTION

Flow behavior can not be ignored in underground resource exploitation (oil, water, geothermal resources, and so on) and radioactive waste disposal (Lin & Takahashi 1999, Takahashi et al. 2015, Yin et al. 2020). Many research and practices have shown that flow behavior is greatly affected by geometrical features of fractures, which include the roughness of fractures.

Hitherto, *JRC* (Barton & Choubey 1977), *D* (Carr & Warriner 1989), and Z_2 (Tse & Cruden 1979) are popular roughness indexes in the field of fracture flow. However, these indexes are unable to display anisotropy in opposite directions (Bao et al. 2020). There are only few research focusing on the influence of anisotropic roughness in opposite directions on the fracture flow.

As a factor of fracture geometry, effects of the combination of the fracture pairs are rarely seen. In particular, how the flow behavior be like if the upper and lower fracture walls swapped without changing the morphology of fracture pairs. It can be helpful to reveal a reasonable way to describe the effects of fracture geometry on the fracture flow.

In this research, digital fracture surfaces with different roughness were generated by the spectral method. With the model constructed, water-flow simulations on constant velocity inlet were implemented under the premise of ignoring the fracture deformation. Results show the influence of anisotropic roughness on the fractures with various geometrical combinations.

2 PREPARATION OF THE FLOW SIMULATION

Traditionally, research on rock fracture will start with gathering fracture samples in the field. However, it is not always easy to collect ideal samples. To lower the difficulties and the cost of the field collecting work, computational methods, such as the spectral method (Brown 1995) and the successive random addition (SRA) (Ye et al. 2015), are currently used instead to generate fracture surface for subsequent research.

Computational methods also have the advantages in controlling the geometry of fracture, so that only focusing on interested geometrical factors that may affect the flow behavior can be realized. Given its obvious advantages, the spectral method of the research by Brown (1995). Generated surfaces with three different roughness (F1, F2, and F3) are shown in Figure 1. A larger value of *D* means a rougher surface.

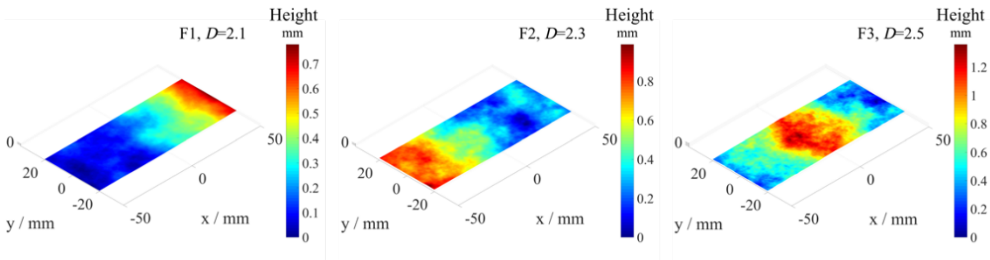

Figure 1. Generated rough surfaces with three different roughness.

From Figure 1, with the increase of the fractal dimension (*D*), the surface becomes rougher and shows larger asperities. F1, F2, and F3 will be applied to construct 3D models with different combinations of the fracture pairs. Heights of the pairs are shown in the colormap of Figure 2.

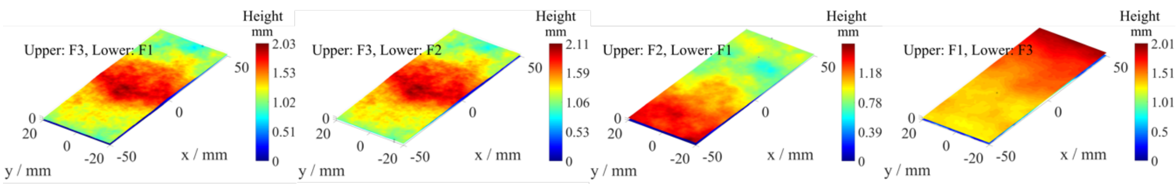

Figure 2. Fracture pairs with different combinations of F1, F2, and F3.

To further investigate the combinatorial effect of roughness, the case where F1 exchanges position with the F3 is also considered (Figure 2). Real aperture distribution of 4 mismatched pairs that are single-point contacted but ignoring sliding and deformation are shown in Figure 3.

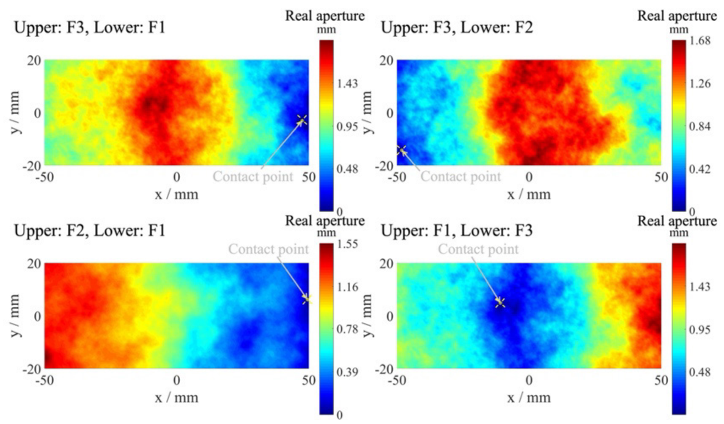

Figure 3. Distribution of the real apertures corresponding to F1, F2, and F3.

Generated digital surfaces were imported to 3ds MAX for adding thickness, adjusting normal vectors and transferring to solids. As a format widely acceptable in simulation process, STL files were exported from the modeling software for subsequent simulation.

3 FLOW SIMULATION SETUP

Constructed 3D models were imported to the FLUENT panel (Figure 4) in ANSYS for flow simulation. The solved pressure distributions were obtained using the second-order scheme. Properties of the liquid water flow include a density of ρ = 998.2 kg/m^3 and a viscosity of μ = 0.001003 kg/m·s. Constant velocity inlets (Tabel 1) were set to the fracture models, and a pressure outlet was set to the another end of the fracture where it is exposed to atmospheric pressure. It assumed that there was no slip between upper and lower fracture pairs.

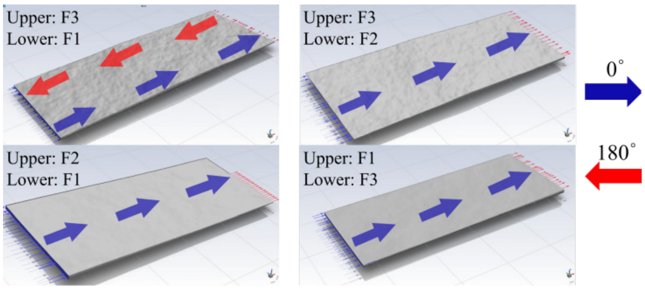

Figure 4. Models input in ANSYS-FLUENT.

Table 1. Simulations setup.

Pair No.	Dir. (°)	Inlet velocity (m/s)
F3$_U$-F1$_L$	0, 180	0.01, 0.1, 0.2
F3$_U$-F2$_L$	0	
F2$_U$-F1$_L$	0	
F1$_U$-F3$_L$	0	

To distinguish the upper and lower fracture walls, subscripts of letters U and L were applied. For example, the No. F3$_U$-F1$_L$ denotes the fracture pair with F3 as the upper wall and F1 as the lower wall. As shown in Figure 4 and Table 1, only the F3$_U$-F1$_L$ model was simulated with the flow along 0° and 180° (F3$_U$-F1$_{L0}$ and F3$_U$-F1$_{L180}$), others were along only 0°.

4 RESULT AND ANALYSIS

According to the simulation results shown in Figures 5-6, solved pressures display anisotropic characteristics even if they are the same fracture pair. Solved pressure values of the model F3$_U$-F1$_{L0}$ are generally larger than that of model F3$_U$-F1$_{L180}$. It was caused by the relative positions between velocity inlet and the small-aperture region (Figure 3). Therefore, anisotropy in opposite directions may also be cause for concern.

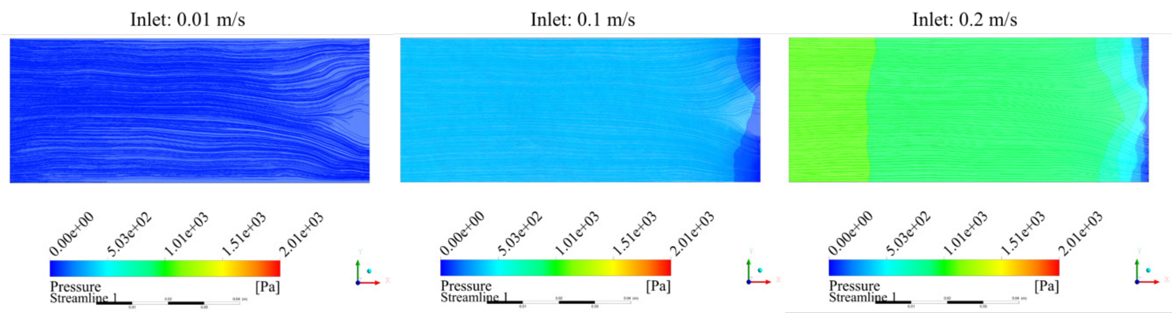

Figure 5. Pressure traces under different inlet velocities (Taking F3$_U$-F1$_{L0}$ as an example).

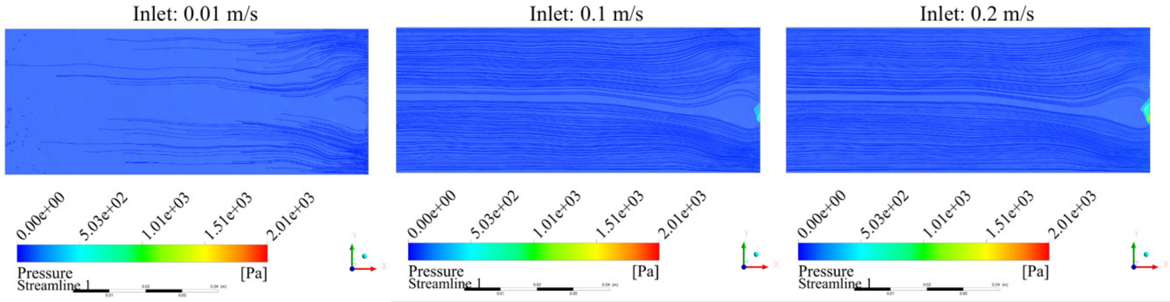

Figure 6. Pressure traces of $F3_U$-$F1_{L180}$ under different inlet velocities.

By comparing the solved pressure of models $F3_U$-$F1_{L0}$ (Figure 5) with $F1_U$-$F3_L$ (Figure 7), difference can also be seen clearly. Even if the inherent morphology of the F1 and F3 did not change, the flow path and pressure distribution vary dramatically. A possible reason of this phenomenon is the variation of the normal vectors of fracture pairs (Figure 8). After swapping the upper and lower walls, angles between the normal vectors of asperities and inlet-flow direction vary. Therefore, roughness should be described by anisotropic parameters instead to distinguish the difference of fracture walls in opposite directions.

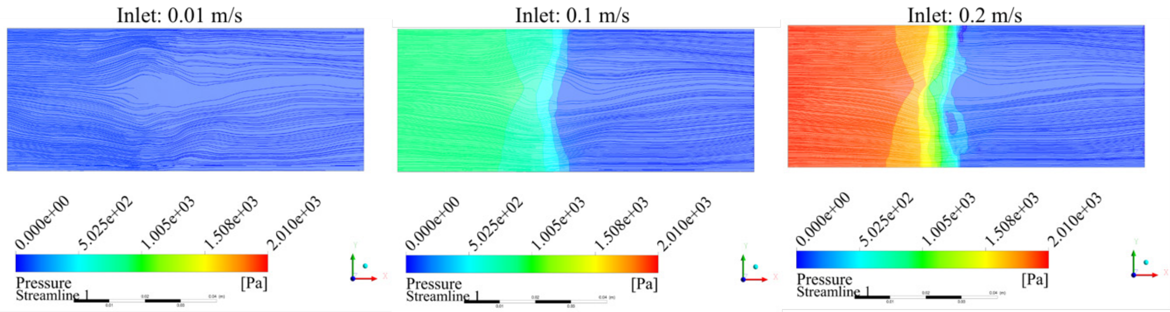

Figure 7. Pressure traces of $F1_U$-$F3_L$ along 0° direction under different inlet velocities.

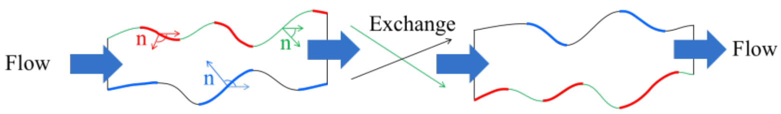

Figure 8. Explanation of the difference when the upper and lower walls are swapped.

Based on solved pressures and preset velocity on the inlet, pressure gradient between inlet and outlet (∇P) and the volumetric flow rate (Q) were calculated by considering the fracture lengths and areas of inlet. The relation between pressure gradient and flow rate is shown in Figure 9.

$$\nabla P = AQ + BQ^2 \quad (1)$$

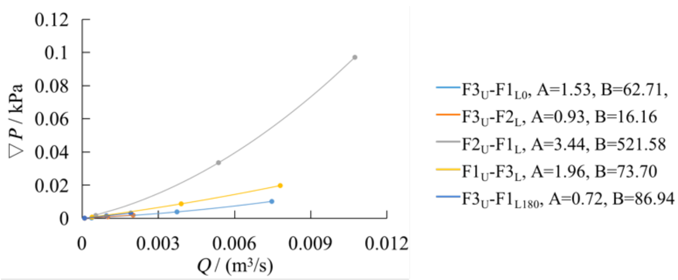

Figure 9. Relations between volumetric flow rates and pressure gradients.

From Figure 9, generally, pressure gradients have quadratic relations, namely Equation (1). This relation shows that flow in the simulation obeys the Forchheimer equation that is widely used to quantitatively describe the nonlinear flow behavior in fractures (Xiong et al. 2022). Moreover, it can be seen that the differential behaviors of $F3_U$-$F1_{L0}$ and $F3_U$-$F1_{L180}$, which again shows the anisotropic flow behavior in opposite directions.

To investigate the relation between anisotropic roughness and flow properties in fractures, the index for describing roughness needed to be quoted. A new roughness parameter (*M*) presented by Bao et al. (2020) was therefore applied herein to analyze the anisotropic roughness instead of fractal dimension (*D*), which was utilized to generate the digital fractures but can not express anisotropy in opposite directions. The ratios (R_M) between the *M* values of upper walls to the lower ones (R_M=M_{upper} / M_{lower}) were used to describe the roughness of the mismatched 4 fracture pairs. Therefore, a relation between R_M and ∇P can be obtained below (Figure 10).

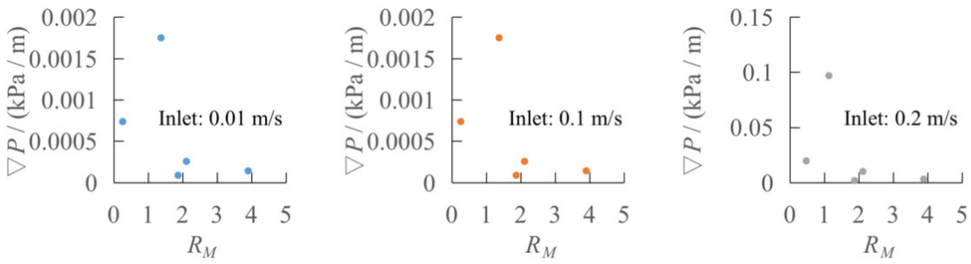

Figure 10. Relation between ratio of *M* (R_M) values and pressure gradient (∇P).

As shown in Figure 10, with the increase of ratio of *M*, the pressure gradient increases first and then decreases. The drastic high pressure gradients occurred around the R_M value of 1.35.

5 CONCLUSIONS

(1) Flow behavior shows anisotropy even in opposite directions, valid roughness parameters should be used to express this anisotropy.
(2) Solved pressures will be changed when upper and lower walls swapped due to the variation of normal vectors of asperities.
(3) Pressure gradient of the flow is quite large when ratios of the roughness parameter *M* between upper and lower fracture walls are around 1.35.

ACKNOWLEDGEMENTS

This study was financial supported by JST SPRING of Kyoto University (Grant Number JPMJSP2110).

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