The relationship between permeability and geometric properties of 2-D fracture networks

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1. Introduction

Estimation of equivalent permeability of fractured rock masses plays an important role in assessing the safety of many engineering applications, such as underground nuclear waste repositories, geothermal energy development and oil storages[1-2]. Recent studies have shown that the equivalent permeability of a discrete fracture network (DFN) is significantly related with the geometric properties of discontinuities, such as fracture length, density, aperture and orientation. However, the empirical expressions for such correlations have not been completely established. In this study, the geometric parameters for generating DFNs were considered based on a great number of fracture network models, and an empirical expression was proposed to link the permeability and geometric properties of 2-D DFNs.

2. Research method and fracture network models

In this study, numerical simulation was performed to calculate the flow rate of each fracture network model. Distilled water was used as fluid with a density of 998.2 kg/m^3 and a dynamic viscosity of 0.001 Pa·sec at a room temperature of 20°. Non-compressible Newtonian fluid was adopted as fluid model in this study.

To quantify the permeability of DFNs, the equivalent permeability (K) was adopted as a main variable. This study aims to establish DFN models based on the Monte Carlo method, and analyze the influences of fracture length and orientation on the variation of permeability. The fluid flowing in fractures was assumed to obey the cubic law. For each model, only the horizontal flow was conducted with a constant horizontal hydraulic gradient of 10 kPa/m, while the vertical boundary was impermeable, as shown in Fig. 1. Taking into account the gravity term, K could be back-calculated using the following equation.

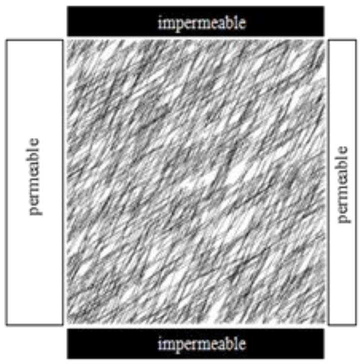

Fig.1 DFN and boundary conditions

$$Q = A\frac{K}{\mu}\frac{\partial P}{\partial L} \quad (1)$$

where Q is the flow rate, A is the cross-sectional area, μ is the dynamic viscosity, L is the fracture length, and P is the hydraulic pressure.

To avoid the influence of boundaries and to consider the scale effect, the DFN models with the lengths from 50 m to 400 m were truncated from the larger DFN models with a length of 500 m. The fundamental parameters for generating DFNs are shown in Table 1. When analyzing one parameter, the other parameters were fixed. Fracture length was enlarged to 2L and 3L, and the orientation of fractures varied from -30° to 30°, while the random range of fracture length was changed to 20%, 50% and 100%. There were totally eight geometric conditions simulated in this research.

Table 1 Parameters for generating fracture networks.

Parameters	Distribution types	Intermediate value	Random range
Length	lognormal distribution	50 m	10%
		70 m	10%
Orientation	normal distribution	60°	10%
		30°	10%
Center point	random	400 m×400 m	
Aperture	constant	0.1 mm	

To signify the geometric properties of fracture networks, d_m (length of fracture per square meter), d_{in} (number of fracture intersection at the boundary per meter) and C_r (connectivity) were defined to represent geometric properties of rock masses. d_m depicts density of fractures in a rock mass, d_{in} illustrates boundary condition, and C_r represents connectivity of fracture networks that is the radio of number of segments to the number of intersections.

3. Results and discussions

Flow rate (Q) could be obtained from the simulation processes and K could be calculated by using Eq. (1). d_m, d_{in} and C_r are statistical data in model analysis. According to the simulation results, the relationships between K and the geometric variables are shown in Fig. 2. It is found that K increases with the increment of d_m, d_{in} and C_r, following linear relationships (see Eqs. (2) ~ (4)). When the values of the geometric parameters are small, the value of K varies within a large dispersion, and gradually convergences to the best fitted curves when the values of the geometric parameters become large. The reason is that when fracture density is small, the location of fractures is more significantly influenced by the randomly distributed fracture center points, comparing with that with a larger fracture density, where the effects of randomness would decrease. This phenomenon is more obvious in the relationships between K and d_m, d_{in}. On the contrary, the correlation between K and C_r is more stable in the whole range.

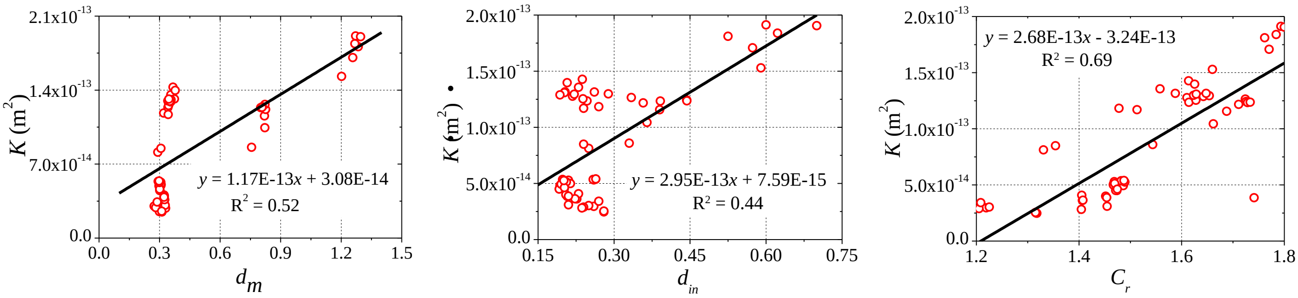

Fig.2 Relationships between K and d_m, d_{in} and C_r.

$$K = 1.17\text{E-}13\ d_m + 3.08\text{E-}14 \qquad (2)$$

$$K = 2.95\text{E-}13\ d_{in} + 7.59\text{E-}15 \qquad (3)$$

$$K = 2.68\text{E-}13\ C_r - 3.24\text{E-}13 \qquad (4)$$

To establish a mathematical expression between K and these parameters, a multi-variable regression algorithm was adopted. d_m, d_{in} and C_r are three independent variables, and K is the only dependent variable. The best-fitted expression is as follows:

$$K = 1.00\text{E-}14\ d_m + 6.12\text{E-}14\ d_{in} + 3.27\text{E-}13\ C_r - 4.47\text{E-}13 \qquad (5)$$

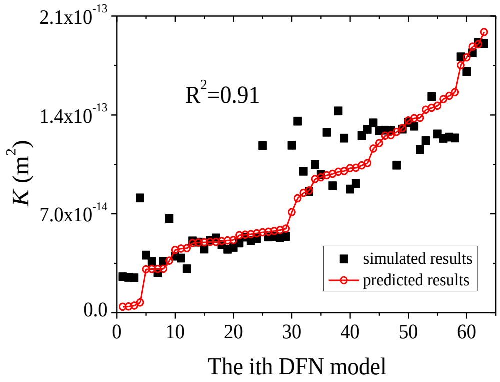

Fig. 3 Comparison of the predicted and calculated results.

According to the fitted parameters before the variables, C_r has the greatest impact on the variation of K, followed by d_{in} and d_m. C_r represents the connectivity of fractures in the rock mass, which influences the flow path and the volume of the fluid. The comparison of Eq. (5) and the simulation results based on 63 DFN models is shown in Fig. 3. The correlation coefficient R^2 is greater than 0.90, indicating that Eq. (5) has good performance to estimate the equivalent permeability of fractured rock masses.

4. Conclusions

In this study, a series of discrete fracture network models were established and simulated to study the relationship of permeability and geometric properties of 2-D fracture networks. The relationships between K and d_m, d_{in}, C_r are summarized, respectively. The empirical expressions were proposed to link permeability and geometric properties of 2-D fracture networks. The results show that K increases with the increment of d_m, d_{in} and C_r, which represent the geometric properties of fractured rock masses. C_r has the greatest impact on the variations of K, followed by d_{in} and d_m. The proposed empirical expressions can be utilized to predict the equivalent permeability of the fractured rock masses.

References

1. Baghbanan A, Jing L: Hydraulic properties of fractured rock masses with correlated fracture length and aperture, International Journal of Rock Mechanics and Mining Sciences, 2007, 44(5): 704-719.

2. Liu R, Jiang Y, Li B, Wang X: A fractal model for charactering fluid flow in fractured rock masses on randomly distributed rock fracture networks, Computers and Geotechnics, 2015, 65: 45-55.