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Technical note

Estimation of permeability of 3-D discrete fracture networks: An alternative possibility based on trace map analysis

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ABSTRACT

The permeability of 3-D discrete fracture networks (DFNs) is estimated based on the geometrical parameters of 3-D model and permeability of its 2-D trace maps. This is achieved by the analysis of 84 3-D DFN models and 672 2-D DFN models that are cut from 3-D ones. The relationships between permeability of 3-D model and parameters such as fracture density, fracture length exponent of 3-D models and permeability of 2-D cut planes were analyzed. A multi-variable regression function was proposed for predicting 3-D fracture network permeability. The results show that the dimensionless equivalent permeability of 3-D fracture networks increases with the increasing fracture density following linear relationship. For the fracture networks with the fracture length exponent $a = 2.0$, the fracture network that carries flow is mainly consisted of several long fractures; whereas the fracture network connectivity is dominated by a large amount of relatively small fractures when $a = 4.5$. The permeability of 2-D DFN models that are cut from an original 3-D one underestimates the permeability of 3-D DFNs by approximately 10.45–80.92%. The regression function estimates the evolution of permeability of 3-D DFNs with a wide range of fracture density from 0.025 to 0.125 m^{-3}, and the predicted results agree with that calculated using Lang's method. The proposed model provides a simple method to approximate permeability of 3-D fracture networks using parameters that can be easily obtained from analysis on outcrop trace maps of fractured rock masses.

1. Introduction

In fractured rock masses with negligibly low matrix permeability, the hydraulic response of the fracture networks is of special importance for understanding the overall flow and transport properties since the main flow paths are governed by connected fractures (Neuman, 2005; Cai et al., 2010). Natural fractured media usually displays a strong hydraulic complexity coming from the internal topography of fractures (i.e., geometry of the void spaces within a single fracture) (Brown, 1987; Tsang and Tsang, 1989; De Dreuzy et al., 2001; Konzuk and Kueper, 2004; Zhang et al., 2015; Li et al., 2016) and from their arrangement in complex networks (i.e., geometry of the fracture backbone) (Bour and Davy, 1997; De Dreuzy et al., 2000; Zhang and Yin, 2014; Liu et al., 2016a). The 3-D fracture networks have the outstanding advances of describing the orientation, connectivity, and permeability tensor of real fractured rock masses. A literature survey shows that study of 3-D fracture network in term of geometrical modeling and their hydraulic properties is of growing popularity. According to the Web of Science Core Collection, the number of papers related to 3-D fracture networks has increased over the past twenty years from 12 per year (in 1996) to about 86 per year (in 2016). Whereas, direct calculation of fluid flow through 3-D fracture networks is usually a time-consuming work due to a large number of meshes performed on each fracture plane and seems to be unavailable for fracture networks whose fracture density is so high that beyond the capability of the present computers (Berkowitz, 2002; Berrone et al., 2014; Liu et al., 2016a). Therefore, such analysis is commonly reduced to a 2-D problem (Darcel et al., 2003a; Min and Jing, 2003; Min et al., 2004; Baghbanan and Jing, 2008; Nick et al., 2011; Leung and Zimmerman, 2012; Lang et al., 2014).

The 2-D fracture network model, which is a cut plane of the 3-D fracture network, is constructed using the geometric properties of outcrops of fractured rock masses. It cannot capture the real geometric properties (i.e., orientation in the out-of-plane direction) of 3-D fracture

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networks inside rock masses. Many researches have verified that directly using 2-D fracture network permeability to approximate 3-D fracture network permeability would induce significant errors in both the magnitude and direction (Min et al., 2004; Lang et al., 2014; Huang et al., 2016). However, it is still appealing to predict permeability of fractured rock masses using 2-D fracture networks for many engineers and geologists working in hydrology-related fields, because the characterization of 2-D fracture networks allows for the usage of outcrop trace maps and significantly reduces the computational cost compared with 3-D calculation (Berkowitz, 2002; Darcel et al., 2003b; Zhang, 2015a; Liu et al., 2016a). Therefore, the difference between permeabilities calculated using 2-D and 3-D fracture networks should be understood, and it would be useful to predict 3-D fracture network permeability using 2-D models, while maintaining the accuracy of predicted permeability (Liu et al., 2016b).

Many efforts have been devoted to relate the characteristics of 3-D fracture networks with the 2-D ones. Balberg et al. (1984) derived the average excluded area and the average excluded volume associated with 2-D and 3-D randomly oriented fractures. Darcel et al. (2003b) assessed the stereological rules for fractal fracture networks and derived a stereological function that extrapolates the parameters of the 3-D length distribution from their measurements on 2-D fracture networks. Zhao et al. (2015) developed correlations between the 3-D fractal dimension of fracture surfaces and the fractal parameter of fracture trajectory in a 2-D profile. However, these studies are restricted to the analysis of geometrical configurations and involve no fluid flow calculation. As for fluid flow through 3-D fracture networks, the permeability that is an essential parameter for describing flow characteristic is usually predicted using the geometric properties of fracture networks. Mourzenko et al. (2011) obtained an expression of the permeability of isotropic fracture networks, which involves coefficients determined by numerical fits for specific fracture shapes, and the obtained expressions were extended to anisotropic fracture networks with the orientations following Fisher distributions. Ebigbo et al. (2016) predicted the permeability of inclusion-based effective medium models using several geometric properties, containing the aspect ratio of the spheroidal fracture and the ratio between matrix and fracture permeability. To the best of our knowledge, the only formulation to approximate permeability of 3-D models with correlation to 2-D models is proposed by Lang et al. (2014), in which the permeability is approximated in terms of the permeability of cut planes whose dimensionless density is the same with that of the original 3-D model. However, the dimensionless density of 3-D model is commonly larger than that of its cut planes; therefore, in their study, the 2-D cut planes were abstracted from other denser 3-D models, rather than from itself. This will increase the difficulty for permeability estimation of 3-D fractured rock masses, because it cannot be directly predicted using the permeability of corresponding 2-D outcrops.

In the present study, the geological characteristics of 3-D discrete fracture networks (DFNs) are firstly analyzed, and then an originally developed code is used to calculate flow through both 3-D and 2-D fracture networks based on a series of 3-D DFNs and their 2-D cut planes. The influences of geometrical parameters of fractures on equivalent permeability of 3-D networks are quantified, and a multiple regression function is proposed to predict the permeability of 3-D DFNs with respect to the permeability of its 2-D trace maps. Finally, the validity of the proposed predictive model of permeability for 3-D fracture networks is verified by comparisons with previous works.

2. Geological features of 3-D DFNs

Natural fractures have a broad range of scales varying from microscopic to regional scales, e.g. microcracks, joints, large scale joints and joint networks (Klimczak et al., 2010; Zhang, 2015b). It is usually difficult to perfectly represent the real 3-D fracture networks, since only geometrical data coming from either 1-D scan lines or boreholes or 2-D outcrops are available. The DFN approach has been widely used to mimic natural fractures, whose characteristics such as fracture length and orientation follow some given probability distributions. The fracture shape is generally modeled by circles, ellipse or polygons of varying aspect ratios (Long et al., 1985; Cacas et al., 1990; Bogdanov et al., 2003). In this study, all the fractures are assumed to be circular disks, with the center location and fracture orientation uniformly and randomly distributed. The fracture apertures are all set to be 1 mm, therefore aperture heterogeneity is not considered. Under these simplifications, fracture density and fracture length distribution are two most critical features that control hydraulic properties of DFNs. Fracture density ρ of 3-D fracture network is defined as the number of fracture centers per unit volume. The fracture length, which is represented by the diameter of disk, is usually broadly-ranged and exhibits no characteristic length scales. The length distribution of fractures is assumed following a power-law function, written as:

$$n(l) = \alpha \cdot l^{-a} \tag{1}$$

where α is the proportionality coefficient, a is the fracture length exponent varying generally between 2.0 and 4.5, and l is the fracture length defined between l_{min} and l_{max}, which are the lower and upper bounds of the fracture lengths, respectively.

Fracture characteristics have a critical influence on the fracture network topology. A series of fracture networks with fracture lengths following power-law distribution are generated. The detailed parameters are tabulated in Table 1. Fig. 1(a)–(g) illustrate nine of the 3-D DFNs with different fracture densities and fracture length exponents. From top to bottom, ρ increases from 0.010 to 0.125 m^{-3}, corresponding to the number of fractures increasing from 80 to 1000. The fracture length exponent a is assigned to be 2.0, 3.0 and 4.0 from left to right, respectively. For a smaller a, the network structure is dominated by a few longer fractures. As a increases, the proportion of smaller fractures increases and the structure is gradually dominated by the smaller fractures. This phenomenon is relatively obvious for the DFNs with a smaller ρ such as ρ = 0.010 m^{-3}. With a relatively lager ρ, for example ρ = 0.125 m^{-3}, a fracture plane trends to be intersected by more adjacent fractures. Since all fractures are assigned a same aperture, the denser fracture would lead to a higher degree of connectivity and thereby a larger permeability.

3. Flow simulations in the fracture networks

3.1. Flow model in 3-D fracture networks

Fluid flow through fractures is generally governed by the nonlinear Navier-Stokes equations. However, solving Navier-Stokes equations needs sophisticated computing techniques and is time-consuming that is unavailable for characterizing flow through complex fracture networks (Liu et al., 2016a). For fractures that have smooth surfaces and fluids that have a low flow velocity, the Navier-Stokes equations are commonly reduced to the Reynolds equation, written as (Min et al., 2004; Liu et al., 2016b):

$$\frac{\partial}{\partial x}\left(\frac{\rho g e^3}{12\mu}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\rho g e^3}{12\mu}\frac{\partial h}{\partial y}\right) = 0 \tag{2}$$

Table 1
Parameters used for the generation of 3-D DFNs.

Parameter	Distribution	Value
Model size (m)		$L = 20$
Positions	Uniform	
Orientations	Uniform	
Fracture length (m)	Power law	$2.0 \le a \le 4.5$
Fracture density (m^{-3})		$0.01 \le \rho$ 0.125