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Equivalent discrete fracture networks for modelling fluid flow in highly fractured rock mass

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ABSTRACT

Fracture flow is the dominant flow in many cases in a fractured rock mass, which behaves more heterogeneous, anisotropic and irregular than porous flow because of the complexity of the fracture networks. Rock mass with fracture networks is commonly represented by homogenized continuous models to reduce the impractical computational complexity. In this paper, a density-reduced equivalent discrete fracture network (E-DFN) method is proposed to simplify the original highly dense target DFN (T-DFN) models. An equivalent permeability factor is derived for the fracture sets in the simplified E-DFN models. A number of T-DFNs with different fracture patterns are stochastically generated and fluid flow is simulated in both T-DFN and corresponding E-DFN to test the effectiveness of the proposed method. Results show the permeability similarity of the two DFN systems and high accuracy of the proposed E-DFN method. The proposed method takes the advantage of permeability similarity of DFN systems, and it significantly reduces the computational complexity and cost while the characteristics of the fluid flow such as heterogeneity, irregularity, and discontinuity in highly fractured rock mass are well retained. Because of the statistical equivalence of the two DFN systems, Monte Carlo simulations can be used to optimize the equivalent permeability factor and to achieve more accurate and reliable results.

1. Introduction

Natural rock masses contain discontinuities in different scales, densities, and distributions, which have significant influences on fluid flow and mass transport in the rock mass. Discontinuities are of different types, such as faults, joints, fissures, and cracks. They are all referred by a general term of “fracture”. The permeability of fractures can be orders of magnitude higher than the matrix rock blocks; therefore, fracture networks usually act as the dominant flow conduits in rocks (Berkowitz, 2002; Neuman, 2005). In addition, the distribution of fracture networks can be very complex in the natural environment, which makes fluid flow heterogeneous and anisotropic in highly fractured rock masses.

Different numerical strategies have been proposed to treat fractures properly, among which the continuum based models (Oda, 1986; Pan et al., 2010; Samardzioska and Popov, 2005; Warren and Root, 1963) have been widely used because of their convenience in handling fractures. Fractured rock mass is simplified either as the classical single continuum representing the homogenized features of both fractures and matrix blocks, or a dual continuum (Pruess, 1985; Warren and Root, 1963; Wu and Pruess, 1988) that consists of two overlapping media with contrasted hydraulic properties representing the fracture networks and the matrix rocks respectively. The continuous approaches are usually based on the concept of Representative Elementary Volume (REV), which assumes the existence of a threshold size, over which the mean hydraulic property of the fractured rock mass stabilizes (Long et al., 1982). Continuum models with equivalent properties are efficient for large-scale numerical simulations. However, REVs do not always exist in naturally fractured rocks (Neuman, 2005). The homogenization of individual fracture properties into a constant one also over-neglects the important geometrical characteristics of fracture networks (Liu et al., 1998; Reeves et al., 2013). As in a natural geological material, fractures are highly random and heterogeneous in size, shape, spacing, and aperture (Gillespie et al., 1993; Odling et al., 1999). The inherent uniformity assumption of the continuous models has large discrepancies with the naturally fractured rocks.

Discrete models are thus developed to simulate each individual fracture explicitly, thereby reducing the abstractions in continuum models. They generally fall into two categories depending on whether the permeability of matrix rocks is considered, namely the Discrete

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Fracture Network (DFN) models (Baghbanan and Jing, 2007; de Dreuzy et al., 2012), which neglect the contribution of matrix flow, and the hybrid models (Hoteit and Firoozabadi, 2006; Karimi-Fard et al., 2004; Noorishad and Mehran, 1982; Ren et al., 2017a,b), which account the matrix flow together with fractures flow. Besides, there is a wide range of methods being proposed to handling fractures. For the problems of crack propagation and fluid-structure interaction (FSI), meshless methods (Rabczuk et al., 2010) have been successfully implemented to handle complex FSI due to fracture. Fracture propagation simulations also have been studied by using meshless methods with level sets (Zhuang et al., 2012), dual-horizon peridynamics (Ren et al., 2016b,c), cracking particles (Rabczuk and Belytschko, 2004), screened Poisson equation with local remeshing (Areias et al., 2016), nonlinear semi-concurrent multiscale method (Zhu et al., 2016), and multi-scale computational homogenization method for Hydraulic fracture problems (Zhuang et al., 2017).

DFN models only concern fluid flow in a fracture network, so they are valid for rocks with relatively low permeability in the matrix. They normally idealize fractures as 2D discrete polygonal planes distributed in 3D spaces (1D line segments in 2D domains) with individual hydraulic properties. Therefore, they contain more detailed information and are more realistic. Moreover, it is able to inspect the influence of individual fracture parameters on flow using DFN models. However, the exact geometries and detailed hydraulic properties of individual fractures in fractured rock masses are sometimes unavailable. The practical method of using DFN models is to generate stochastic realizations with data collected from site investigations (Chesnaux et al., 2009; Mauldon et al., 2001). One disadvantage of DFN models is the high density of fractures, which is one of the main reasons limiting their applications in practice. The excessively huge amount of fractures in a model make numerical simulations impractical (Leung and Zimmerman, 2012). The burdensome simulation tasks can be exacerbated when the Monte Carlo method is adopted, which is sometimes necessary to reduce the uncertainties caused by the stochastic DFN models.

In this paper, a density-reduced equivalent DFN (E-DFN) modelling method is proposed. First, the similarity of fracture networks in directional permeability is investigated. Then, the concept of the E-DFN modelling method is proposed based on the permeability similarity to the target DFN (T-DFN), and the equivalent permeability factors are derived for the E-DFN. Numerical experiments with fracture networks of different distributions are further carried out to verify the effectiveness of the proposed method. E-DFN models have much fewer fractures than the original fracture networks, but they have the equivalent permeability in space. The E-DFN method is within the frame of discrete methods; therefore, it well retains the heterogeneity and discontinuity of fractured rock masses. Monte Carlo simulations are able to be conducted using E-DFN models due to their relatively low computational complexity, thus to fully utilize the available statistical fracture data.

2. Numerical method – the pipe network method

In this study, 2D fractured rock masses are investigated. For hard rocks, the permeability of rock matrix can be neglected compared to the permeability of the fracture networks. Therefore, fluid flow in 2D fractured hard rocks is simulated as flow in fracture networks consisting of 1D fractures. The pipe network method (Priest, 1993; Ren et al., 2015; Ren et al., 2016a) is used to simulate fluid flow in 2D DFN models, which treats fractures as flow pipes. Mass conservation is applied at each intersection nodes. For static single-phase flow, the node mass conservation equation in node i is

$$\sum_{j=j_1}^{j_m} q_{fp(i,j)} = S_i \tag{1}$$

where $q_{fp(i,j)}$ is the fracture flow rate in the pipe segment $fp(i,j)$ defined by nodes $i$and j. $j_1 \ldots j_m$ denote all nodes connecting to the node i. S_i is a fluid source term.

For low-velocity laminar flow, the "cubic law" is applied to calculate the flow rate in fractures,

$$q_f = \frac{a^3}{12\mu l}\Delta p \tag{2}$$

Here, Δp is the pressure difference between two nodes. a and l are hydraulic aperture and length of fractures, respectively. μ is the dynamic viscosity of the fluid. By substituting Eq. (2) into Eq. (1), the mass conservation equation can be written as

$$\sum_{j=j_1}^{j_m} \frac{a_{ij}{}^3}{12\mu l_{ij}}(p_i - p_j) = S_i \tag{3}$$

The pressure of each node is calculated by solving Eq. (3) with specific boundary conditions, and the flow rate of each fracture is calculated by Eq. (2). The convenience and accuracy of pipe network method in simulating flow in fracture networks have been verified by Ren et al. (2015). The following numerical experiments are simulated by using the pipe network method.

Table 1
Statistical parameters of fractures in case 1.

Fracture set	Inclination angle θ (degree)	Length (m)	Aperture (mm)	Quantity ratio of fractures
I	30–2[a] (normal)	2–0.5 (normal)	0.05	2:1
II	130–3 (normal)	3–0.5 (normal)	0.08	

[a] The parameters are presented in the form of: mean value – standard deviation.

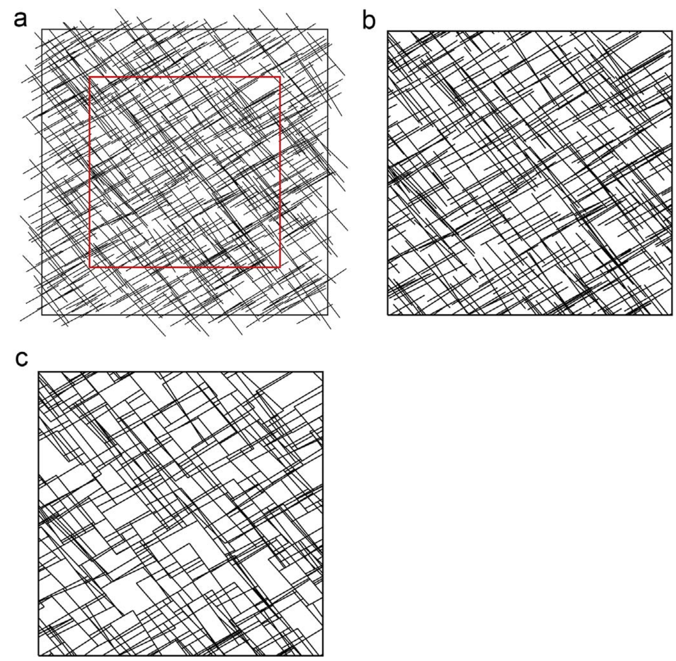

Fig. 1. The generation of a numerical model.

3. Permeability similarity of fracture networks and equivalent permeability factors

3.1. The permeability similarity

The permeability of fracture networks has been studied by a number of researchers both analytically and numerically (Baghbanan and Jing,