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A numerical approach for assessing effects of shear on equivalent permeability and nonlinear flow characteristics of 2-D fracture networks

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ABSTRACT

Hydro-mechanical properties of rock fractures are core issues for many geoscience and geo-engineering practices. Previous experimental and numerical studies have revealed that shear processes could greatly enhance the permeability of single rock fractures, yet the shear effects on hydraulic properties of fractured rock masses have received little attention. In most previous fracture network models, single fractures are typically presumed to be formed by parallel plates and flow is presumed to obey the cubic law. However, related studies have suggested that the parallel plate model cannot realistically represent the surface characters of natural rock fractures, and the relationship between flow rate and pressure drop will no longer be linear at sufficiently large Reynolds numbers. In the present study, a numerical approach was established to assess the effects of shear on the hydraulic properties of 2-D discrete fracture networks (DFNs) in both linear and nonlinear regimes. DFNs considering fracture surface roughness and variation of aperture in space were generated using an originally developed code DFNGEN. Numerical simulations by solving Navier–Stokes equations were performed to simulate the fluid flow through these DFNs. A fracture that cuts through each model was sheared and by varying the shear and normal displacements, effects of shear on equivalent permeability and nonlinear flow characteristics of DFNs were estimated. The results show that the critical condition of quantifying the transition from a linear flow regime to a nonlinear flow regime is: $10^{-4} < J < 10^{-3}$, where J is the hydraulic gradient. When the fluid flow is in a linear regime (i.e., $J < 10^{-4}$), the relative deviation of equivalent permeability induced by shear, δ_2, is linearly correlated with J with small variations, while for fluid flow in the nonlinear regime ($J > 10^{-3}$), δ_2 is nonlinearly correlated with J. A shear process would reduce the equivalent permeability significantly in the orientation perpendicular to the sheared fracture as much as 53.86% when $J = 1$, shear displacement $D_s = 7$ mm, and normal displacement $D_n = 1$ mm. By fitting the calculated results, the mathematical expression for δ_2 is established to help choose proper governing equations when solving fluid flow problems in fracture networks.

1. Introduction

Rock fractures play an important role in the hydro-mechanical properties of tight rock masses, e.g., granite and basalt, due to their typically stronger permeability comparing with rock matrix (Koyama et al., 2008a; Blum et al., 2009). Stresses acting on a rock mass can change the aperture of single fractures involved, resulting in the change of macro permeability as well as the redistributions of local hydraulic pressure and flow field (Min and Jing, 2003; Baghbanan and Jing, 2008). The discrete fracture network (DFN) method has achieved great successes in simulating fluid flow in fractured rock masses, in which single fractures are typically presumed to be formed by parallel plates and flow is presumed to obey the cubic law, where the flow rate is linearly correlated with the pressure drop (Bear, 1972; Liu et al., 2016a; Cai et al., 2017). However, it is well known that the parallel plate model cannot realistically represent the surface characters of natural rock fractures and reflect their influences on fluid flow behavior, and the relationship between flow rate and pressure drop is not linear at

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sufficiently large Reynolds numbers (*Re*) (Zimmerman et al., 2004; Chen et al., 2015).

During the past few decades, great efforts have been devoted to investigations on the effects of stress on hydraulic properties of single fractures (e.g., Yeo et al., 1998; Esaki et al., 1999; Olsson and Barton, 2001; Auradou et al., 2005; Auradou et al., 2006; Li et al., 2008; Indraratna et al., 2015) and fracture networks (e.g., Zhang and Sanderson, 1996; Baghbanan and Jing, 2008), and on the nonlinear flow characteristics of single fractures (e.g., Zimmerman et al., 2004; Javadi et al., 2010, 2014; Xiong et al., 2011; Cherubini et al., 2012, 2013; Zhang and Nemcik, 2013; Zou et al., 2015; Wang et al., 2016), fracture intersections (e.g., Kosakowski and Berkowitz, 1999; Li et al., 2016) and fracture networks (e.g., Kolditz, 2001; Liu et al., 2016b,c). These studies have greatly improved the understanding on the influences of several important factors such as boundary stress, fracture geometry (e.g., aperture, shape of intersections, and surface roughness), Reynolds number, fracture density, and etc., on the fluid flow behavior of single fractures and fracture networks. For investigations via DFN modelling, normal stresses (confining stress) are typically imposed on the model boundaries, which mainly result in the closure of single fractures (Baghbanan and Jing, 2008). Meanwhile, past studies have revealed that the permeability change of fractures caused by shear can be several orders greater than that caused by normal stresses (Li et al., 2008). Shear displacements of rocks can either result from engineering practices such as excavations in rock masses, or from natural forces such as earthquakes. Although the shear-induced permeability change of single rock fractures has been extensively explored, studies on the effects of shear on fluid flow characteristics of DFNs have not, if any, been reported.

Since shear can significantly enhance the permeability of fractures and thereby facilitating the transition of flow from linear to nonlinear regimes, the effects of shear and the nonlinear flow behavior need to be simultaneously considered in DFNs. Recent studies have revealed that the nonlinear flow could occur for sheared fractures when the magnitude of *Re* is as low as 0.01 (Javadi et al., 2014). The nonlinear flow in rock fractures is typically described using the Forchheimer's law (Forchheimer, 1901), which can be applied over the entire range of flow rate/velocity, including $Re < < 1$. Another example of typically used equations is the Izbash's law (Izbash, 1931), although it does not have physically sensible behavior at low *Re*. The critical Reynolds number (Re_c) is a widely used parameter for identifying the onset of nonlinear flow in single fractures, which is determined when the nonlinear term or the inertial force contributes to a certain of the total pressure drop such as 10% (Zimmerman et al., 2014; Chen et al., 2015), 5% (Wang et al., 2016), and 1% (Liu et al., 2016b). However, for complex DFNs comprising a great amount of fractures, calculation of *Re* for each single fracture may become a time-consuming and technically difficult problem. Instead, the critical hydraulic gradient, which is defined as the ratio of hydraulic head difference to the DFN model side length, is utilized as a macroscopic parameter that commonly has known values in many practices on fractured rock masses (Gale, 1984; Li et al., 2016).

To efficiently address the shear effects and nonlinear flow behavior of DFNs simultaneously, in the present study, a code DFNGEN was developed to generate 2-D DFNs composed of fractures with geometries that follow well-accepted mathematical expressions. A single fracture that cuts through each DFN was artificially sheared by assigning different values of normal displacement and shear displacement. Fluid flow simulations were implemented on the original and the sheared DFNs utilizing a FVM (finite volume method) code to investigate the influences of shear on both linear and nonlinear flow behaviors of DFNs.

2. Coupled shear-flow behavior of fractures

The aperture and its evolution, which are key issues to the fluid flow characteristics of fractures, can be more significantly changed by a shear process than that by a normal loading-unloading process, due mainly to the shear induced dilation upon rough surfaces (Li et al., 2008; Koyama et al., 2008b). For originally well-mated fractures, the reduced matedness during a shear process could be another reason that alters their hydraulic properties (Xiong et al., 2011). A mechanical aperture and a hydraulic aperture were commonly utilized to quantify the aperture variations during the coupled hydro-mechanical processes. The mechanical aperture is typically defined as the mean point-to-point distance between the two walls of a fracture, and the hydraulic aperture is typically back-calculated from the pressure drop - flow rate relationship obtained from hydraulic tests or numerical simulations using the cubic law. The hydraulic aperture should be calculated at a sufficient low *Re*, because the cubic law does not hold when the fluid flow is not in the linear regime. In a shear process, the mechanical aperture of a fracture, b_m, can be estimated by (Li et al., 2008):

$$b_m = b_0 - \Delta b_n + \Delta b_s \tag{1}$$

where b_0 is the initial aperture, Δb_n is the variation of aperture during normal loading or unloading such as closure or opening, Δb_s is the variation of aperture during shear (dilation). b_0 is the aperture when no stresses are applied, which can be mainly obtained via two approaches: (1) Digitally reconstruct the surfaces of a fracture based on measured topographic data and calculate the aperture when the upper halve of the fracture can steadily 'sit' on the lower halve; (2) Use the function proposed by Bandis et al. (1983) to approximate the normal stress - normal displacement curves obtained from normal loading - unloading tests, and b_0 is obtained when a best fit is achieved. Δb_n is produced in the initial normal loading process prior to shear, which becomes 0 if the normal stress is a constant in the following shear process, i.e., shear tests under a constant normal load (CNL) boundary condition. Δb_s is the measured normal displacement (dilation) during shear, which is 0 when shear has not been applied, and may gain minus values when a shear is just initiated.

As shown in Fig. 1(a), a DFN model subjected to some newly applied stress increments (i.e., the horizontal stress $\Delta\sigma_x$ and the vertical stress $\Delta\sigma_y$) may result in the deformation of fractures in both the shear and normal directions. For a deformed single fracture, the shear stress gives rise to an incremental shear displacement Δu_s and an incremental normal displacement Δv_s due to the shear-induced dilation (see Fig. 1(b)), while the normal stress yields the compression of the fracture with a total deformation of Δv_n (see Fig. 1(c)). Note that Δv_n includes both the deformation of the fracture and the deformation of the blocks that form the fracture. The pure normal deformation of the fracture could be obtained by eliminating the deformation of the blocks with the use of elastic theories. Fig. 1(d) shows the variations of shear stress and normal displacement with $u_s = 0 \sim 18$ mm for the fractures having a JRC (joint roughness coefficient, (Barton, 1973)) value of $12 \sim 14$ under the initial normal stresses of 1 MPa (black and red curves) and 2 MPa (gray and blue curves), respectively. Fig. 1(e) shows the fracture closure subjected to normal stresses, where k_{n0} is the initial stiffness and v_{nmax} is the maximum fracture closure. With increasing the normal stress σ_n, v_n increases significantly and then gently, approaching the maximum value. These figures present the representative behaviors of rock fractures subjected to shear, which are essential for establishing some closed form solutions for hydro-mechanical behaviors of DFNs. In the present study, due to the difficulties mentioned below, a simplified form of shear behavior was applied to DFNs.

Past results revealed a three-stage evolution behavior of hydraulic aperture/transimissivity during shear processes (Xiong et al., 2011): (1) A declining stage due to minus dilation (contraction) of fractures; (2) A fast growth stage, during which the hydraulic aperture increases approximately linearly with the shear-induced dilation; (3) A gentle growth stage, where the hydraulic aperture continues to increase but at a much lower and decreasing rate. The evolutions of the total volume of voids and the geometry and distribution of single voids during shear are