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Laboratory investigation of nonlinear flow characteristics in rough fractures during shear process

Guan Rong, Jie Yang *, Long Cheng, Chuangbing Zhou

[a] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, Hubei 430072, China
[b] Key Laboratory of Rock Mechanics in Hydraulic Structural Engineering, Ministry of Education, Wuhan University, Wuhan, Hubei 430072, China

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ABSTRACT

To understand the influence of shear behavior on the transporting properties of fluid through a single fracture, splitting fractures were made in the laboratory and shear flow tests were carried out under constant normal load conditions. The applied normal stress is in the range of 0.5–3.0 MPa. Before the physical test, the fracture's morphology is measured for identification of the roughness. At each shear step, we performed 5–8 high precise hydraulic tests with different hydraulic gradient. The relationship between pressure gradient and volume flow rate demonstrates to be nonlinear and fits very well with Forchheimer's and Izbash's laws. The linear and nonlinear coefficients in Forchheimer's law are quite sensitive to shear deformation (closure or dilation), experienced 1–2 and 1–3 orders of magnitude reduction during shear, respectively. An empirical equation is proposed to quantify the relationship between linear coefficient and nonlinear coefficient based on the experimental observations. The two coefficients in Izbash's law are quantified. The m value is in the range between 1.06 and 1.41 and the λ value experiences a reduction of 1–2 orders of magnitude during shear. In addition, the studied critical Reynolds number exhibits a decreasing and increasing variation corresponding to shear contraction and shear dilation of rock fracture. For all the cases in this study, the critical Reynolds number ranges between 1.5 and 13.0.

1. Introduction

Fluid flow in fractured rock masses exists in many engineering activities, such as reservoir storage, liquid waste disposal, contaminant containment, oil and natural gas production and geosequestration of greenhouse gasses. Most of these problems are associated with hard or crystalline rock where fluid flow is mainly dominated by the fracture networks. Understanding the fluid flow characteristics of rock fractures is very important to ensure the performance and safety of these engineering activities. However, the processes of fluid flow through fracture networks are complex. Thus, numerous studies focused on single rough fractures (Tsang, 1984; Zimmerman and Bodvarsson, 1996; Yeo et al., 1998; Konzuk and Kueper, 2004; Qian et al., 2011) or rock joints (Barton et al., 1985; Brown, 1987; Gentier et al., 1997; Esaki et al., 1999; Ranjith and Darlington, 2007) had been conducted, which is the fundamental element of realistic model of fluid flow in fracture networks. Even though widely studied in the past decades, the fracture flow characteristics still remain not fully understood.

Single fluid flow in rock fracture obeys the basic law of fluid dynamics. Navier-Stokes (NS) equations, as the governing equations, can well describe the motion of fluid through a single rock fracture (Zimmerman and Bodvarsson, 1996). However, solving the NS equations in real rock fracture is very difficult, not only because of the complexity of the nonlinear partial differential equations, but also because irregular geometry of rock fracture (Brush and Thomson, 2003). To circumvent the problem, the fluid flow through a single fracture was regarded as laminar flow between two parallel plates in earlier studies. According to the model, the NS equations can be simplified to the well-known cubic law (Snow, 1969). In the model, the flow rate is proportional to the cubic power of the separation between the plates. However, the real fracture surfaces are rough and two surfaces may not completely match each other. This causes deviations from the result obtained by the cubic law (Hakami and Larsson, 1996; Yeo and Ge, 2001; Lee et al., 2014). With this in view, the total volume flow rate Q [$L^3 T^{-1}$] and the pressure gradient ∇P [$ML^{-1} T^{-2}$] were utilized in the cubic law to obtain a hydraulic aperture e_h [L] for rough fracture. For fluid flow through a single fracture with a width of w

* Corresponding author at: State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, Hubei 430072, China.
E-mail address: rock_whu@163.com (J. Yang).

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[L], the hydraulic aperture is commonly written as (Brown 1987; Zimmerman and Bodvarsson, 1996; Chen et al., 2015)

$$Q = -\frac{we_h^3}{12\mu}\nabla P \tag{1}$$

where μ [$ML^{-1}T^{-1}$] is the viscosity coefficient of the fluid.

The linearity of Darcy law has been validated in low fluid rated laminar flow (Witherspoon et al., 1980). Recently, nonlinear flow regimes in rock fracture have been extensively investigated (Zimmerman et al., 2004; Qian et al., 2005; Zhang and Nemcik, 2013; Zhou et al., 2015). Two equations, namely Forchheimer's and Izbash's laws, were used to macroscopically describe nonlinearity behavior of the flow in rock fractures (Zhang and Nemcik, 2013). For the case of one-dimensional flow, these equations read, respectively:

$$-\nabla P = aQ + bQ^2 \tag{2a}$$

$$a = \frac{\mu}{kA_h} = \frac{12\mu}{we_h^3} \tag{2b}$$

$$-\nabla P = \lambda Q^m \tag{3}$$

where a [$ML^{-5}T^{-1}$] and b [ML^{-8}] are the coefficients, representing viscous and inertial effect, respectively; λ and m are empirical coefficients; k [L^2] is the intrinsic permeability defined as $e_h^2/12$; ρ [ML^{-3}] and A_h [L^2] are the fluid density and assumed cross-sectional area, respectively. Even though the two equations can well describe correlation between the ∇P and Q, the mechanisms that trigger nonlinearity in a rough rock fracture is still not completely understood. Zimmerman and Bodvarsson (1996) have mentioned at first that roughness and contact areas, making the flow path tortuosity, might cause non-negligible inertial force losses. These features may contribute to the occurrence of non-linear flow in rock fractures. Similar conclusions were also drawn from the experiment and numerical works by different investigators (Zimmerman et al., 2004; Qian et al., 2005; Javadi et al., 2010; Lee et al., 2014; Tzelepis et al., 2015; Li et al., 2016). It has been observed that flow regime will transient from linear Darcy law to nonlinear flow with increase of Reynolds number (Schrauf and Evans, 1986; Wang and Davis, 1996; Zoorabadi et al., 2015; Chen et al., 2015). The critical Reynolds number, Re_c, characterized the onset of nonlinear flow becomes a key threshold value in the fracture flow. Zimmerman and Yeo (2000) mathematical analyzed the flow in rough walled rock fracture based on NS equations, suggesting that the upper limit on critical Reynolds number is about 15. This conclusion is in accordance with many experimental findings that reported by Durham and Bonner (1994), Zimmerman et al., (2004) and Ranjith and Darlington (2007). Recently, Javadi et al. (2014) experimentally investigated the variation of critical Reynolds numbers in the shear process. It indicated that the critical Reynolds numbers varied from 0.001 to 25 as the shear displacement increased from 0 to 20 mm, although most of the existing work has revealed a transition from linearity to nonlinearity when the value of the Reynolds number is around 10. One possible explanation of these discrepancy problems could be the different geometrical characteristics of the fracture.

Many factors may influence the hydraulic phenomena of a single fracture, including the fluid properties, geometry of the fluent aperture (aperture characteristics in the fluent direction by considering the flow in rock fracture is anisotropic) and the applied fluid pressure at the fracture boundary. The geometry of the fluent aperture in the fractures is governed by the geological history and stress field (Olsson and Barton, 2001). As described above, most of the previous researches are focused on the flow characterizations of matched rock fractures. However, rock fracture may subject to shear during its course of history, such as disturbance caused by earthquake and excavation. The shear behavior will change the geometrical characteristics of the fluent aperture including the void space between two surfaces, the contact areas distribution and the gouge materials in the fracture (Archambault et al., 1997; Gentier et al., 1997; Auradou et al., 2005, 2006; Matsuki et al., 2010). The void spaces between the opposite surfaces may decrease or increase when a rock fracture is subjected to the normal or shear loads (Li et al., 2008; Kulatilake et al., 2008; Xia et al., 2014). As a result, the hydraulic properties of fractures often vary significantly during shear (Lee and Cho, 2002). In the past decades, variation of the permeability in the process of shear has commonly been studied (Barton et al., 1985; Chen et al., 2000; Xiong et al., 2011). However, limited researches investigated the influence of shear process on the flow regimes of fracture, particularly, the nonlinear flow characteristics.

Therefore the purpose of the present study is to experimentally investigate nonlinear flow in a single fracture during shear. In the present research, a simple and effective sealing technique of shear flow test is reported. High precision hydraulic tests were conducted at different shear steps and the applied water head ranges from 0 to 23 m. Based on the test results, nonlinear flow characteristics are analyzed in terms of the morphology and mechanical behavior of fractures during shear flow experiments.

2. Specimens preparation and roughness measurement

In this study, granite fractures were selected as the testing materials, for its low permeability of the rock matrix. The studied granite is collected from the Dabieshan of Anhui province, China. It has a medium grain which mainly composes of k-feldspar, quartz and black micas. The rock shows a little degree of weathering. Its aspect is white, gray and mixed with some yellow particles. The uniaxial compressive strength (UCS) of the rock is 130.0 MPa. Intact rock blocks were cut to cuboid specimens with the approximate sizes of 197 × 100 × 100 mm. To create a fracture in the middle of the rock sample, a setup similar to Brazilian technique equipment was developed. The setup consisted of a pair of V-shaped wedges. After the rock sample was consolidated between the two V-shaped wedges, and then the normal load is applied to create the tensile fracture. The fractures are numbered from A1 to A6. More details of the fracture preparation processes are available in Yang et al. (2016).

The flow properties, deformability and strength of rock fracture depend very much on the surface roughness of fracture. Therefore, accurate quantification of roughness is important in studying the hydro-mechanical properties of fractures. A three-dimensional (3D) morphology scanner system is utilized to measure the fracture surfaces' topography. The 3D morphology scanner is made up of a charge coupled device (CCD) displacement sensor, a two-dimensional (2D) moving platform, and a data acquisition software. Roughness profiles of the six fracture samples were measured with an interval of 0.2 mm. Details about 3D morphology scanner can be found in Hou et al. (2016). Based on the scanned point clouds, the fracture surfaces of the six specimens were digitized (see Fig. 1). To quantify the roughness of the fracture, three profiles were extracted from each fracture by dividing the fracture surface into three equally-spaced lines which is along the shear direction. The joint roughness coefficient (JRC) is estimated according to the following equations (Tse and Cruden, 1979):

$$\mathrm{JRC} = 32.2 + 32.47\log Z_2 \tag{4a}$$

$$Z_2 = \left[\frac{1}{(n-1)(\Delta x)^2}\sum_{i=1}^{n-1}(z_{i+1} - z_i)^2\right]^{\frac{1}{2}} \tag{4b}$$