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Effect of sample size on the fluid flow through a single fractured granitoid

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ABSTRACT

Most of deep geological engineered structures, such as rock caverns, nuclear waste disposal repositories, metro rail tunnels, multi-layer underground parking, are constructed within hard crystalline rocks because of their high quality and low matrix permeability. In such rocks, fluid flows mainly through fractures. Quantification of fractures along with the behavior of the fluid flow through them, at different scales, becomes quite important. Earlier studies have revealed the influence of sample size on the confining stress–permeability relationship and it has been demonstrated that permeability of the fractured rock mass decreases with an increase in sample size. However, most of the researchers have employed numerical simulations to model fluid flow through the fracture/fracture network, or laboratory investigations on intact rock samples with diameter ranging between 38 mm and 45 cm and the diameter-to-length ratio of 1:2 using different experimental methods. Also, the confining stress, σ_3, has been considered to be less than 30 MPa and the effect of fracture roughness has been ignored. In the present study, an extension of the previous studies on “laboratory simulation of flow through single fractured granite” was conducted, in which consistent fluid flow experiments were performed on cylindrical samples of granitoids of two different sizes (38 mm and 54 mm in diameters), containing a “rough walled single fracture”. These experiments were performed under varied confining pressure ($\sigma_3 = 5$–40 MPa), fluid pressure ($f_p \leq 25$ MPa), and fracture roughness. The results indicate that a nonlinear relationship exists between the discharge, Q, and the effective confining pressure, $\sigma_{\text{eff.}}$, and Q decreases with an increase in $\sigma_{\text{eff.}}$. Also, the effects of sample size and fracture roughness do not persist when $\sigma_{\text{eff.}} \geq 20$ MPa. It is expected that such a study will be quite useful in correlating and extrapolating the laboratory scale investigations to in-situ scale and further improving theoretical/numerical models associated with fluid flow through rock masses.

1. Introduction

Investigations on the movement of fluid through rock mass and the factors that affect such movements are great concerns in geoengineering field. Constructions of deep geological engineered structures, such as rock caverns, radioactive/nuclear waste disposal repositories, metro rail tunnels, multi-layer underground parking, or exploitation of oil, natural gas, geothermal energy, mineral resources and CO_2 sequestration, are few important areas where such studies have significant roles. In general, most of these engineering activities are associated with hard or crystalline rocks, or highly consolidated sedimentary rocks, where fluid flows mainly through fractures (Walsh, 1965; Brace, 1980; Bandis et al., 1983; Zimmerman et al., 1991; Cook, 1992; Bear et al., 1993; Zimmerman and Bodvarsson, 1996; Klimczak et al., 2010), and the discharge, Q, through such fractures is much higher than that through the intact rock (Singh et al., 2015). As such, the flow capacity of the fractures is mainly governed by the flow properties of the “most prominent fracture” or the “single fracture” (Hakami and Larsson, 1996; Brown et al., 1998; Ranjith, 2010; Singh et al., 2014). In general, investigation on the behavior of fluid flow through rock mass at regional scale, i.e. in the field/in-situ condition, which consists of agglomeration of fracture(s) of variable geometry (size, shape, aperture, orientation, density and roughness), is difficult and requires in-depth knowledge of fracture systems (Illman, 2006). Also, in the deep Earth’s crust, quantification of the interconnected fractures and their in-filling

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materials, boundary condition, along with their behaviors due to change in surrounding stress conditions requires detailed geological, geophysical and geotechnical inputs. This involves huge cost, complicated instrumentations, and laborious and cumbersome test procedures, along with technical and logistical difficulties.

Therefore, investigation on the fluid flow properties of "single fracture" at different scales, under a controlled laboratory condition, becomes an excellent stepping-stone, which would assist researcher to generalize the laboratory experiments to larger scale in an enhanced approach. The scale effect on the permeability was studied by Witherspoon et al. (1980), Brace (1980, 1984), Raven and Gale (1985), Gueguen et al. (1996), Butler and Healey (1998a, 1998b), Hunt (2003), and Feng et al. (2009). Scale effects on hydraulic conductivity, *K*, under in-situ condition were studied at a granitic site at Central Spain by Guimera et al. (1995) and values of *K* were measured on the same fracture at different distances from the pumping well. Several researchers have mentioned that the scale effect on permeability is still under considerable debate, which is mainly due to the present insufficient experimental knowledge, lack of consistency in measurement and interpretation of data (Clauser, 1992; Gueguen et al., 1996; Butler and Healey, 1998a, 1998b; Zlotnik et al., 2000; Hunt, 2003; Neuman and Di Federico, 2003). Illman (2006) revealed a strong field evidence of a directional permeability scale effect from multiple cross-hole pneumatic injection tests conducted in a geologically distinct unit of unsaturated fractured tuff. It was observed that the scale effect on permeability is controlled by the connectivity of fluid-conducting fractures, which increases with the scale. Illman (2006) concluded that there is a difficulty in characterizing the permeability at multiple scales with a single or consistent method. Several researchers (Raven and Gale, 1985; Gueguen et al., 1996; Wang et al., 2002) have concluded their work by mentioning that "further work is required to investigate the behavior of fluid flow through fracture(s) at different scales in combination with quantification of fracture properties (i.e. connectivity, size, density and roughness) to provide a solid basis for normal stress-fracture flow theory". Matsuki et al. (2006) studied the size effect on aperture and permeability of synthetic fractal fractures (ranging from 0.2 m to 12.8 m) generated by a new spectral method. They mentioned that different granites are subjected to different flow and boundary conditions, and hence it is very difficult to draw firm conclusions on the relation between the size of the sample and the fracture permeability.

Few researchers (e.g. Witherspoon et al., 1979; Raven and Gale, 1985) have investigated the influence of sample size on the confining stress–permeability relationship. The effects of stress on fluid flow through single fracture or fractured rock mass have been studied mainly by numerical modeling (e.g. Tsang, 1984; Oda, 1986; Bai and Elsworth, 1994; Zhang and Sanderson, 1996; Chen and Bai, 1998; Bai et al., 1999; Pyrak-Nolte and Morris, 2000; Koyama et al., 2006; Nazridoust et al., 2006; Zhao et al., 2013; Briggs et al., 2014; Hao et al., 2015; Zou et al., 2015) or in-situ scale pumping tests (e.g. Theis, 1935; Stober, 1986; Boonstra, 1989; Krusemann and de Ridder, 1990; Genter et al., 2010; Stober and Bucher, 2015). Laboratory scale investigations are very limited (Lomize, 1951; Louis, 1969; Gangi, 1978; Witherspoon et al., 1979, 1980; Brown, 1987; Brown et al., 1998; Qian et al., 2005; Ranjith, 2010; Singh et al., 2014, 2015), or mainly focus on intact rock samples with the diameter of 38–450 mm and the diameter-to-length ratio of 1:2 (Raven and Gale, 1985; Tan et al., 2014; Selvadurai, 2015). Also, the confining stress, σ_3, has been considered to be less than 30 MPa and the effect of fracture roughness has been ignored. It can be observed from the above literature review that most of the researchers have used numerical simulation/in-situ scale testing or complicated test setups to study the behavior of fluid flow through the fractured rock mass, and have not identified the influence of fracture roughness in association with the effect of sample size on the fluid flow. In addition, investigations on fluid flow in fractured rock samples with different sizes, employing a consistent method under controlled laboratory conditions, are lacking, which is quite significant for understanding the effect of sample size on the fractured rock permeability and would assist researchers to understand the basic mechanism of fluid flow.

In this paper, an extension of the previous studies on "laboratory simulation of flow through single fractured granite" was performed, in which consistent fluid flow experiments were conducted on cylindrical granitoid sample of two different sizes (38 mm and 54 mm in diameters, with a constant diameter-to-length ratio of 1:2), containing a "rough walled single fracture". These experiments were performed under varied conditions of confining pressure ($\sigma_3 = 5$–40 MPa), fluid pressure ($f_p \leq 25$ MPa), and fracture roughness (by selecting 3 types of granitoid rocks based on their grain size) to quantify the effect of sample size in association with fracture roughness on the fluid flow through fractured rock mass. Further, fracture roughness was characterized by employing three-dimensional (3D) laser scanning technique conducted on the fracture surfaces and an attempt was made to examine the relationship between fracture aperture closure and discharge quantitatively.

2. Methodology

The experimental procedures and methodologies employed in this study to investigate the behavior of fluid flow through the granitoid samples of different sizes, comprising a single fracture, were introduced in detail in the following sections.

2.1. Sample selection and preparation

In the present study, three types of granitoid rocks were collected under in-situ conditions from an open quarry in and around Euroa-Strathbogie road, Victoria, Australia (Fig. 1). These granitoid rocks were selected based on their grain size (coarse, medium and fine grained), quality (strength and modulus) and low matrix permeability. This was done mainly to create different roughness and to ensure that the flow takes place only through the fracture but not through the matrix. The granitoid blocks were brought to the laboratory (Fig. 2) and then cylindrical rock core samples of two different sizes (38 mm and 54 mm in diameter) with the constant diameter-to-length ratio of about 1:2 were obtained, according to the recommendation of Indian Society of Rock Mechanics (ISRM). These core samples were designated as S1-CG-38, S2-MG-38, S3-FG-38 and S1-CG-54, S2-MG-54, and S3-FG-54 representing sample number, grain size (coarse, medium, and fine grained) and sample diameter, respectively. The samples' number, their geometrical details, and location coordinates in degree decimal (DD) format along with their engineering properties are presented in Table 1.

Optical properties of these granitoid samples are studied under transmitted light microscope and the photomicrographs of the samples S1-CG-38, S2-MG-38 and S3-FG-38 are depicted in Fig. 3a–c, respectively. In addition, to characterize these granitoid samples chemically, mineralogically as well as by modal count (in hand specimen and under microscope), analysis was performed based on the classification approach of the Sub-commission on the International Union of Geological Sciences (IUGS) (Streckeisen, 1974). The results are plotted on quartz-alkali feldspar-plagioclase (QAP) diagram as depicted in Fig. 4. Optical and mineralogical properties of these granitoids rocks were investigated mainly to characterize the granites, observe the variation in the grain sizes,