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Transient pulse test and morphological analysis of single rock fractures

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ABSTRACT

Transient pulse tests were performed on single rock fractures at different confining pressures. A new data analysis method based on polynomial fitting was introduced to investigate the relationship between flow velocity and hydraulic gradient. 3D laser scanning was used to quantify the morphological changes of the fracture surface after the transient pulse test or under the hydro-mechanical coupling effect. The results show that the flow velocity versus hydraulic gradient data gradient shows a nonlinear relationship at very low hydraulic, possibly due to strong solid-water interaction, but becomes approximately linear after the hydraulic gradient is high enough. The permeability of a single fracture is sensitive to the confining pressure. As the confining pressure increases, the permeability first remarkably decreases when the confining pressure is lower than a certain value and then decreases at a much lower speed when the confining pressure is higher than that value. Both mechanical and hydraulic apertures decrease at a decreasing rate with the increase in confining pressure. The effect of fracture roughness on the permeability is related to the magnitude of the confining pressure. Rougher fractures have lower permeability at low confining pressures; but the opposite can be true when the confining pressure is high enough. Roughness is no longer critical to permeability when the confining pressure is over a certain value.

1. Introduction

The hydro-mechanical behavior of single rock fractures is fundamental to the hydro-mechanical analysis of fractured rock masses.[1–5] Many studies have been conducted on the various aspects of water flow through rock fractures. The experimental studies have shown that the hydro-mechanical behavior of a fracture is affected by different factors, including the geometry of the fracture, the interconnection of voids/fractures, the fracture in-filling material, the roughness of the fracture, the fluid pressure, and the confining pressure.[3–12] As widely accepted, fractures with higher roughness and small aperture tend to have lower conductivity. Moreover, the change in water pressure or confining stress leads to change of the fracture aperture and thus the flow characteristics.[13–19] However, because the water flow through a fracture is affected by a large number of factors, there is no unique relationship between fracture properties and water flow that can be applied to all rock fractures.[20–22] For example, Witherspoon et al.[23] reported that Darcy flow could be used even in the case of rough or irregular fracture surfaces at low water pressure and/or Reynolds number. However, at high water pressure and/or Reynolds number, the water flow through a fracture cannot be modeled using the conventional Darcy flow because of the development of a turbulent/nonlinear flow.[24–26]

The water flow through rock fractures is dominated by the morphology of the fracture. So it is important to quantitatively characterize the geometric properties of fractures. In the past decades, numerous models and parameters have been put forward to characterize fractures,[4,7,27] including the methods to quantify fracture surface roughness.[27–31] Much research has been conducted to investigate the effect of morphology on the hydro-mechanical behavior of single rock fractures.[32–34]

Permeability measurements can be performed either at a steady state or a non-steady state (transient pulse method). The steady state method consists of applying a constant pressure gradient to a specimen and measuring the resulted flow rate. The transient pulse method is based on the analysis of the decay of a small step change of pressure imposed at one end of a specimen. This method, pioneered by Brace et al.[35] is appropriate for low- permeability materials and has been used to evaluate the permeability of different geo-materials.[36–42] In recent years, several attempts have been made at measuring the

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permeability of rock fractures using the transient pulse method. For example, Siriwardane et al.[43] measured the permeability of coal containing a single fracture using the transient pulse method. Bajaalah[44] applied the transient pulse method to determine the matrix and fracture permeability of a fractured core. The solutions to the transient pulse method were derived by Brace[35] (simplified solution) and Hsieh et al.[36] (exact solution) based on the assumption of Darcy flow. Although the exact solution considers both the permeability and the specific storage, most investigators still use the simplified solution because of its simplicity.[37,38,40]

Although many researchers have studied the hydro-mechanical behavior of rock fractures experimentally and numerically,[6–8,10,12,16,18–20,26,30,55–57] the studies have mainly focused on experimentally examining the hydro-mechanical behavior of rock fractures using a steady-state rather than a transient pulse method. Moreover, the previous studies have mainly focused on the effect of morphology on the permeability of rock fractures, but hardly investigated the quantitative changes of the morphological characteristics of fractures caused by the hydro-mechanical coupling. Therefore, in the present study, transient pulse tests were performed on cylindrical specimens containing a single fracture at different confining pressures. A new data analysis method different from the existing simplified and exact solutions[35,36] was introduced to investigate the relationship between flow velocity and hydraulic gradient. In addition, 3D laser scanning was performed on the fracture surfaces before and after the transient pulse test to quantitatively characterize the morphological changes. This study could further enhance the understanding of the hydro-mechanical behavior of single rock fractures and the morphological changes of fractures due to the hydro-mechanical coupling.

2. Test method

2.1. Specimen preparation

Intact cylindrical specimens of 50 mm diameter were cored from limestone blocks obtained from an underground roadway construction site at the Meitanba Coal Mining Area located in south China. The specimens were cut into lengths of 152 mm, ground to approximately 150 mm following ASTM D4543,[45] and then oven dried for 24 h. The limestone has a density of 2.61 g/cm^3, a porosity of 8.5%, an UCS and a tensile strength of 44.8 MPa and 4.78 MPa, respectively, and an elastic modulus and a Poisson's ratio of 20.1 GPa and 0.23, respectively.

A setup as shown in Fig. 1(a) was developed to produce a single vertical fracture running along the length of the core, which was 150 mm in length and 50 mm in diameter. The setup consisted of two 6 mm diameter hardened steel rods attached to the top and bottom platens of a rock-testing machine. The specimen was placed between the two hardened steel rods to ensure that the rods made contact along the specimen length. Subsequently, the loading was applied perpendicular to the specimen length using the rock-testing machine at a slow loading rate of 200 N/s until a single fracture in the specimen was developed. In this way, the rock core was separated into two cylindrical halves. The obtained fracture surfaces by the splitting test were rough. The fracture surfaces with dimensions of length L and width W for specimens SR1, SR2 and SR3 are shown in Fig. 1(b)–(d), respectively. It is noted that although the steel rods caused damages to the surface of the specimens during loading, the damages were very small due to the high hardness of the rock. In addition, an intact cylindrical specimen was also prepared as a control.

2.2. Measurement of morphological parameters

A Talysurf CLI (2000) morphology instrument was employed to scan the fracture surface.[27,28] The morphology instrument consists of a range of platforms and gauges offering rapid non-contact 3D measurements, simple calibration, and powerful Talymap analysis. The height of a surface point was deduced by sensing the position of a laser spot on the surface. The resolution is 0.5 μm in the z-direction, and the scan spacing can be 0.5 μm in both the x- and y-directions. In the test, each half of the rock specimen was placed on the laser scanner table. Data collection and analysis were automatically completed by the Talymap analysis software. Each spot had corresponding x, y and z coordinate values, with z being the vertical height above the reference plane. The so-called reference plane is the plane that gives the minimum sum of the squares of the distances of points (x, y) from it. A number of statistical parameters were selected to quantify the morphology, as described below.

2.2.1. Height parameters [4,27,28]

The maximum peak height S_p is the height between the highest peak and reference plane:

$$S_p = \max(S_{p1}, S_{p2}, \ldots, S_{pn}) \tag{1}$$

where S_{pi} (i=1,2, ..., n) is the height between the ith peak and the reference plane; and n is the number of peaks. The maximum depth of valleys S_d is the depth between the reference plane and the deepest valley:

$$S_d = \max(S_{d1}, S_{d2}, \ldots, S_{dn}) \tag{2}$$

where S_{di} (i=1,2, ..., n) is the depth between the ith valley and the reference plane; and n is the number of valleys. The maximum absolute height S_h is the vertical distance between the highest peak and the deepest valley, i.e.

$$S_h = S_p + S_d \tag{3}$$

The arithmetic mean height S_m is a parameter representing the mean surface roughness:

$$S_m = \frac{1}{B}\iint_B |z(x, y)| dxdy \tag{4}$$

where $z(x, y)$ is the height of the fracture surface at location (x, y); and B is the horizontal definition area or the area of the rough surface projected onto the horizontal plane. The root-mean-square (RMS) deviation of the surface S_q is the standard deviation of the height distribution:

$$S_q = \sqrt{\frac{1}{B}\iint_B z^2(x, y) dxdy} \tag{5}$$

The skewness of the height distribution S_s is used to quantify the symmetry of the height distribution of the fracture surface. A zero S_s indicates that the height distribution is symmetrical. A negative S_s indicates that the fracture surface has many deep and fine valleys. However, a positive S_s indicates a fracture surface with numerous peaks.

$$S_s = \frac{\int_{-\infty}^{\infty} z^3 \varphi(z) dz}{S_q^3} \tag{6}$$

where φ(z) is a probability density function for the height distribution $z(x, y)$.

The kurtosis of the height distribution S_k is used to quantify the flatness of the height distribution and indicates the concentration degree of the height distribution. When $S_k < 3$, the height distribution is platykurtic and scattered. When S_k=3, the height distribution is a normal distribution. When $S_k > 3$, the height distribution is leptokurtic and concentrated.

$$S_k = \frac{\int_{-\infty}^{\infty} z^4 \varphi(z) dz}{S_q^4} \tag{7}$$