International Journal of Rock Mechanics & Mining Sciences 87 (2016) 29–38

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

The role of fracture surface roughness in macroscopic fluid flow and heat transfer in fractured rocks

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ARTICLE INFO

Article history:
Received 12 November 2015
Received in revised form
13 April 2016
Accepted 9 May 2016
Available online 21 May 2016

Keywords:
Rock fracture
Surface roughness
Fluid flow
Heat transfer
Discrete fracture network model

ABSTRACT

Rock fractures are major conduits for fluid flow in fractured rocks, and the convective heat transfer between rock fracture surfaces and circulating fluid is a critical issue in heat recovery in fractured rocks. It has been demonstrated that fracture surface roughness has a significant influence on the mechanical, hydraulic, thermal and transport behavior of single fractures. This study aimed to assess the effects of local surface roughness of fractures on fluid flow and heat transfer processes at the macroscopic scale of fracture networks. Two distributions of Joint Roughness Coefficient (JRC) were determined based on the JRC data in Oskarshamn/Forsmark, Sweden and Bakhtiary, Iran. Two empirical models relating hydraulic apertures to mechanical apertures were considered. A total of ninety-one realizations that considered different JRC distributions and empirical models of mechanical-hydraulic apertures were studied. The results show that fracture surface roughness can affect the fluid flow and heat transfer processes in fracture networks to various extents, mainly depending on the empirical models of mechanical-hydraulic apertures. In other words, the role of fracture surface roughness in macroscopic fluid flow and heat transfer in fractured rocks is critical, when using a model of mechanical-hydraulic apertures that predicts significant reduced hydraulic apertures. Discrete fracture networks models with the normal distribution of JRC are less permeable than those with the lognormal distribution of JRC, using the fitting parameters of in-situ JRC data.

1. Introduction

A rock fracture consists of two rough surfaces that are in contact with each other at some locations, but separated at others. Roughness refers to the local departures from planarity,[1] and a number of parameters have been proposed to characterize the fracture surface roughness, e.g., Joint Roughness Coefficient (*JRC*),[2] Z_2,[3] the ratio of standard deviation (σ_E) of the varying aperture over mechanical aperture (E) (σ_E/E),[4] and fractal dimension.[5] Grasselli and his co-workers proposed a mathematical expression of $\theta^*_{\max}/(C+1)$ to parameterize fracture surface roughness, which can be used for three-dimensional surface topography[1] or two-dimensional profiles.[6] The regressive relationships between these roughness parameters have also been extensively investigated .[6–10]

Fractures in rock masses have a controlling influence on the mechanical behavior of rock masses, since they provide planes of weakness on which further displacement can more readily occur. Fractures also often provide major conduits through which groundwater can flow. It has been demonstrated that fracture surface roughness has a significant influence on the mechanical, hydraulic, thermal and transport behavior of single fractures.[11] Discrete fracture network (DFN) models have been widely used to simulate the coupled thermal-hydrological-mechanical-chemical (THMC) processes on the field scale of fractured rock mass that contains a large number of fractures. However, most of the previous numerical studies assumed identical hydraulic and mechanical apertures in DFN models for simplicity. In other words, a fracture network consisting of rough fractures is usually simplified as an idealized fracture network where individual fractures are smooth and parallel walled, without properly considering the reduced hydraulic apertures due to roughness (Fig. 1). Up to now, it still remains poorly understood that how the reduced hydraulic apertures in local fractures affect the macroscopic fluid flow and heat transfer in complex fracture systems.[12–14]

The main objective of this study is to examine the role of fracture surface roughness in coupled fluid flow and heat transfer in fractured rocks, because an accurate understanding of fluid flow and heat transfer through fracture networks in rocks is a critical

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http://dx.doi.org/10.1016/j.ijrmms.2016.05.006
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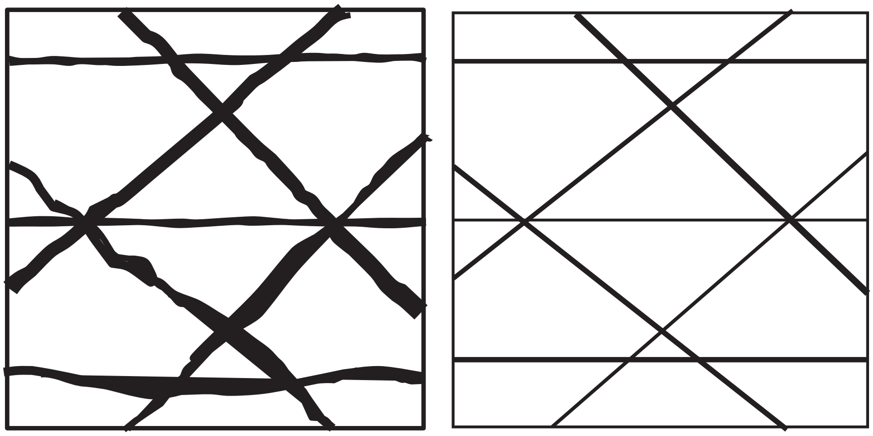

Fig. 1. A rock fracture network (left, varying apertures in each single fracture) and an idealized discrete fracture network model (right, smooth and parallel walled fractures). Line thickness represents magnitudes of fracture apertures.

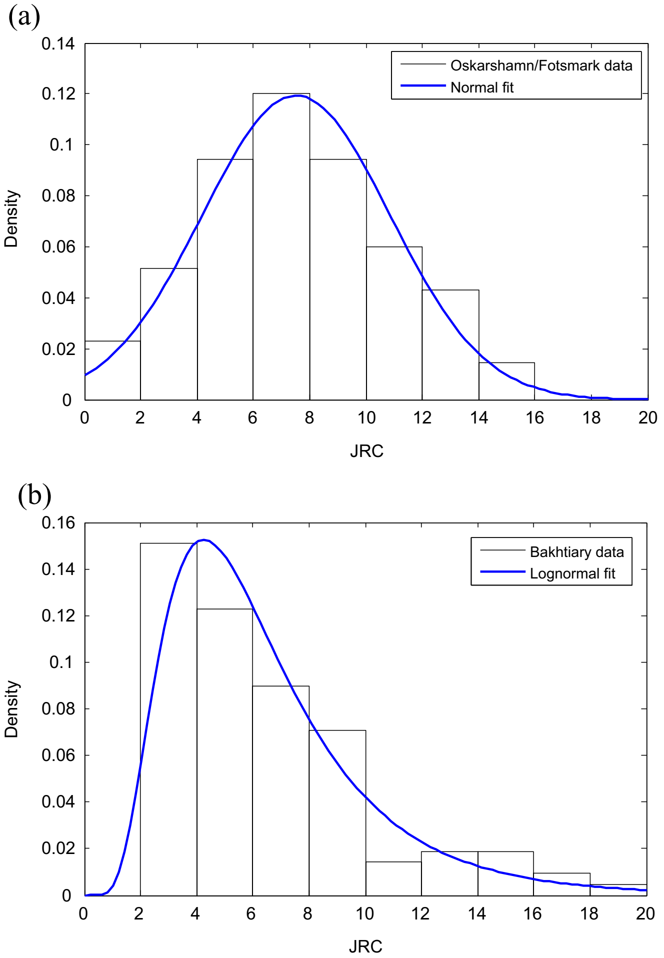

Fig. 2. Observed and modeled distributions of fracture roughness coefficient (JRC) in rock mass. (a) Normal distribution for the Oskarshamn/Forsmark data.[17] (b) Lognormal distribution for the Bakhtiary data.[18]

Table 1.
Best-fit parameters of JRC distributions in rock mass.

Site	JRC distribution	Parameters	
		μ	σ
Oskarshamn/Forsmark, Sweden[17]	Normal distribution	7.5	3.3
Bakhtiary dam, Iran[18]	Lognormal distribution	1.7	0.5

issue in many applications, such as underground nuclear waste repositories, CO_2 sequestration, and enhanced geothermal systems. In a complex fracture network, surface roughness varies within different fractures, but there has not been a reported statistical distribution that can describe the roughness distribution in fracture networks. For this reason, we reviewed two published sets of fracture surface roughness data in order to derive a general statistical distribution of surface roughness in fracture networks. The influences of surface roughness of individual fractures on the macroscopic fluid flow and heat transfer in complex fracture networks were numerically studied.

2. Distribution of fracture surface roughness

Since *JRC* was proposed together with the empirical criterion of joint shear strength by Barton,[15] a number of studies have been devoted to accurately and objectively measure the values of *JRC* based on the ten standard profiles.[9,16] However, the directly related question of *JRC* distribution in a field seems to have attracted very little attention, mainly due to the insufficient in-situ data. Two databases were reported in the recent studies: (1) Asadollahi [17] reviewed a series of site investigation reports published by Swedish Nuclear Fuel and Waste Management Co. (SKB, www.skb.com) that included direct shear tests on 175 rock fracture samples collected in Oskarshamn and Forsmark, Sweden, and back-calculated the *JRC* values based on Barton's failure criterion[15]; (2) Sanei et al.[18] conducted direct shear tests on 106 rock fracture/bedding plane samples collected at the Bakhtiary dam site, Iran, as well as three in-situ direct shear tests on bedding planes at the same site, and estimated the *JRC* values based on the values of fractal dimension. With these two available databases, we attempted to answer the question whether a common statistical distribution that can describe the *JRC*/roughness distribution in fracture systems exists.

The chi-square goodness-of-fit tests were applied to examine the appropriate statistical distributions of *JRC*/roughness in fracture networks. For the chi-square goodness-of-fit computation, the data are divided into k bins and the test statistic (χ^2) is of the form

$$\chi^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \tag{1}$$

where O_i and E_i are the observed and expected frequency for the ith bin, respectively. The expected frequency for the ith bin can be calculated by