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Numerical study on the shear-flow behavior and transport process in rough rock fractures

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A B S T R A C T

This paper presents a systematic research for understanding mechanical shearing effects on the fluid flow and the solute transport behavior of rough fractures through a numerical simulation approach. The aperture fields were modeled based on a real rock fracture geometry and the normal displacement obtained from the shear-flow test. The fluid flow through the rough fracture under shear was simulated using a finite element code that solves the Reynolds equation, and the transport behavior through the rough fracture under shear was simulated calculating the advection–dispersion equation. The results show that the fracture apertures increase as the shear displacement increases, with a few major flow channels detected through the fracture. The shear-induced flow channels increase both flow connectivity and transport connectivity, which accelerate the movement of solutes in a particular direction and lead to early breakthrough of the contaminants. Adsorption, acting as a retardation term, has a decisive influence on the transport process. These results can give a basic knowledge of the hydromechanical and solute transport progress through fracture, and will be helpful to safety assessment for high-level radioactive waste disposal facilities.

1. Introduction

Groundwater circulation and contaminant migration in rock fractures have attracted substantial attention for the development and utilization of deep underground spaces such as landfill reservoirs, geothermal energy plants, and radioactive waste repositories [1–3]. The excavations of these engineering works modify the stress field and induce deformations of the pre-existing joints in the rock mass, which alter the fluid flow and solute transport. While an increase in normal loading tends to close the fracture, shear displacement may open fractures due to dilation and result in significant channeling effect, which would increase its permeability and accelerate the migration of solutes in a particular direction [4–7]. This has a significant impact on radioactive waste repositories in fractured rocks, since their performance is mainly based on the knowledge of waste transport paths and travel times.

Many efforts have been made to analyze the characteristic of fluid flow and solute transport processes in rock fracture [8–12]. The shear-flow test in fractured rocks is of great importance to understand and quantify the behavior of fluid flow

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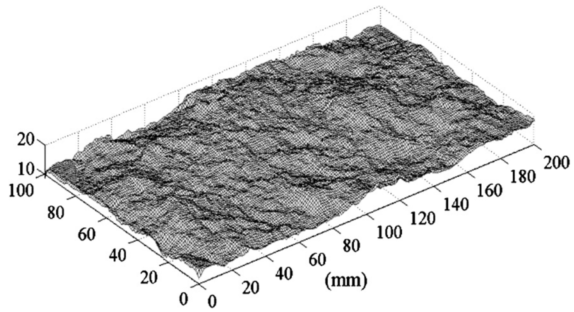

Fig. 1. Three-dimensional surface topographies of the sample.

and solute transport. Saito et al. [13] conducted a series of permeability shear tests on the specimens made artificially, and concluded that, during the shear process, the fracture tends to be more heterogeneous and permeable. Similar conclusions were obtained by Esaki et al. [14], who showed that transmissivity increases rapidly during shearing, by about 1.2 to 1.6 orders of magnitude within the first 5 mm of shear displacement, and Chen et al. [15], who highlighted the need for considering surface roughness and tortuosity when estimating the hydraulic characteristics during shearing. These studies investigated the permeability anisotropy and quantified the evolutions of hydraulic aperture based on hydromechanical shear experiments. Unfortunately, during the progress of the experiment, direct measurements and visualizations of transmissivity and flow paths inside the tested fracture specimens are generally not possible, especially during shearing. Therefore, many researchers [16–20] resorted to numerical simulations to overcome some of these drawbacks. In their studies, however, to avoid solving ill-formed matrix equations in simulations, very small aperture values were assigned to the contact spots. Thus, there still exist some artificial flows, despite small in magnitude, inside the contact areas. To address this question, Koyama et al. [21] proposed a special algorithm to treat the contact areas as zero-aperture elements, which could produce more accurate flow field and make possible continued simulations of solute transport. These findings are not only important for a more physical understanding of the coupled shear-flow behavior, but also of great help to simulate the solute transport process in fractured rocks in a more realistic fashion.

The process of mass transport through rock fractures includes many different mechanisms, such as advection, hydrodynamic dispersion, sorption reaction, and matrix diffusion [22]. Since the 1960s, many numerical simulations, analytical studies, or laboratory experiments have been performed to study contaminant transport behaviors in rock fractures [23–25]. Numerical simulation methods for solute transport in rough fractures for various initial and boundary conditions have been widely used to consider the transport mechanisms mentioned above. Among them, transport simulation with stochastic aperture for a single fracture was conducted by Wendland and Himmelsbach [26], and the results were compared with those of a laboratory experiment. Additionally, many solutions in analytical forms for different boundary conditions were also proposed [27,28]. Although these studies have considered many processes, mechanisms, and factors, they neglected the effect of shearing on the transport process in rough fractures.

Overall, the shear flow behavior and solute transport in rough factures have been widely investigated independently. However, the effects of shear on solute transport have not been extensively studied. In the present study, the effects of mechanical shearing on fluid flow and solute transport were studied by numerical modeling. The study is divided into three steps: the first one is a basic study of fracture aperture distributions and their evolution during shearing, combined with measured surface topographical data, and shear dilations obtained from a laboratory test. In the second step, based on the aperture evolution pattern drawn from the first step, the study was extended to investigate the effect of shear-induced channels on transmissivity and flow anisotropy, considering the natural roughness of the fracture surface, which was incorporated into the simulation model by assignation of spatially variable apertures to fracture elements. The third step added solute transport processes to the fluid flow field, including both non-sorbing and sorbing species, so that the impact of shear stress on transport properties can be evaluated. Artificial rough rock fractures were used to model the flow and transport with a numerically simulated shearing process under constant normal stress. The hydromechanical process and mass transport behavior were discussed based on the simulation results.

2. Estimation of aperture and transmissivity during shearing

The rough fracture specimen and experimental results by Xiong et al. [29] were used in this study to simulate more realistically the shearing process. The artificial fracture specimen J3 used in the experiment is 200 mm in length, 100 mm in width, and 100 mm in height, and is composed of upper and lower halves. The upper and lower surfaces of a fracture were supposed to be fully mated, thus the initial contact ratio was very close to 1.0. The surface of the specimen was measured by using a three-dimensional laser scanning profilometer system to build the geometrical models as shown in Fig. 1. The fracture has a very rough surface with plenty of small asperities, of which JRC ranges 17–18 [29]. Once the specimens were set in the shear box, the lower half was fixed, and the upper half can move in vertical and horizontal directions without rotating during shearing. The relation between the normal displacement and the shear displacement

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