Modelling the hydro-mechanical behaviour of a 3D rough-walled rock joint

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ABSTRACT: The geometrical morphology of single rock joints considerably impacts the hydromechanical behaviour of fractured rock mass. Although the influences of various geometrical parameters on flow behaviour have been well-studied, only a few previous studies explored the interactions of shear-flow processes in evaluating flow behaviour through a rock fracture. This paper presents numerical simulations for coupled shear-flow processes in single rock fractures based on an improved hydro-mechanical model. The model considers the evolution of the contact area ratio based on Grasselli's criterion as well as the variable aperture distributions during shearing, and the associated effects on the flow behaviour. The proposed model is then numerically incorporated into the discrete element code 3DEC to conduct shear-flow test simulations, thereby demonstrating the performance of the model. A number of shear-flow tests are performed on single rock fractures. The simulation results are verified by comparison with experimental results, and an acceptable agreement is achieved.

Keywords: Rock joint, Numerical simulation, Contact area, Aperture distribution, Shear-flow coupled.

1 INTRODUCTION

The rock joints weaken the strength of rock mass and provide major flow channels for fluid flow. Therefore, the understanding of the hydro-mechanical behaviour of a single rock joint has become a primary issue for fractured rock masses, and has aroused more and more concerns for ensuring the safety and economic performance of engineering applications.

Many fluid flow models have been proposed based on the well-known cubic law, incorporating various geometrical parameters (Y. Zhang & Chai, 2020). Aperture irregularity is one of the most sensitive factors for water flow through rock joints. Several studies (Renshaw, 1995; Xiong et al., 2011; Zimmerman & Bodvarsson, 1996) have incorporated aperture distributions into their equations. However, the effect of changes in aperture distribution during shearing was always overlooked. The contact of rock joints is another critical factor influencing the hydro-mechanical behaviour of rock joints, as fluid tends to flow through a rough joint along connected channels while bypassing the contact obstacles with tortuosity. Previous studies predominantly focused on characterizing joint roughness or aperture changes based on 2D joint profiles, while only a few works have attempted to quantify the effect of contact area based on 3D joint surfaces (Walsh, 1981; Yeo, 2001; Zimmerman et al., 1992). Moreover, contact area changes induced by shearing and the associated impact on flow behaviour are often ignored.

The numerical method become a powerful tool for reproducing the outcomes of theoretical and experimental investigations (Inc, 2016; L. Zhang et al., 2018), as it can effectively address the difficulties inherent in solving complex boundary and geometric conditions. By incorporating various shear-flow models in finite or discrete element code, numerical simulations can be conducted overcoming the challenges associated with conducting lab tests on large-scale fractures and complex fluid flow behaviours, as well as collecting the resulting information regarding the fracture evolutions, thereby performing hydraulic analysis in many practical cases.

Summarily, even though numerous previous studies have been carried out focusing on the fluid flow through single rock joints, the interactions of the shear flow process in assessing flow behaviour through a rock fracture are still complex that require further studies. In this paper, numerical simulations are performed for investigating coupled shear-flow processes in single rock fractures based on an improved hydro-mechanical model. The evolutions of contact area and aperture distributions induced by shear are implicitly considered. A series of shear-flow tests are conducted on two artificial joint samples to validate the model. The correlations of the numerical results with experimental data show a good performance of the numerical model.

2 IMPROVED HYDRO-MECHANICAL MODEL

2.1 Mechanical behaviour

The mechanical behaviour of a single rock joint has been numerously studied over the decades. In this paper, the commonly used Barton-Bandis model (Barton et al., 1985) is adopted for mechanical behaviour analysis, since it is simple and can be easily upscaled to field scale.

According to the Barton-Bandis model, in the post-peak stage, the mobilised JRC (JRC_{mob}) is used to describe asperity degradation. The joint model is expressed as:

$$\tau = \sigma_n \tan\left[\phi_r + JRC_{mob} \cdot \log\left(\frac{JCS}{\sigma_n}\right)\right] \tag{1}$$

The dilation can be calculated by:

$$\Delta\delta_n = \Delta\delta_s \tan\left(\frac{1}{M} JRC_{mob} \cdot \log\left(\frac{JCS}{\sigma_n}\right)\right) \tag{2}$$

where M is a damage coefficient, the value of which for this study is determined by direct shear tests.

The evolution of contact area during shearing is obtained based on Grasselli's criterion (Grasselli et al., 2002), which proposes a 3D morphology characterisation approach. The approach expresses the variation of the actual contact area A_{θ^*} as a function of the apparent dip angle θ^* of the surface along the shear direction, as:

$$A_{\theta^*} = A_0 \left(\frac{\theta^*_{max} - \theta^*}{\theta^*_{max}}\right)^C \tag{3}$$

where A_0 and θ^*_{max} are the maximum possible contact area and the maximum apparent dip angle in the shear direction, respectively. C is a fitting parameter.

The concept of the threshold inclination angle is introduced, which is equivalent to the threshold apparent dip angle θ^*_{cr} for Grasselli's criterion. Based on the Barton-Bandis model, the threshold inclination angle, which mobilised during shear, is expressed as:

$$i_{mob} = JRC_{mob} \cdot \log\left(\frac{JCS}{\sigma_n}\right) \tag{4}$$

Combining Eqs. (3) and (4), the mobilised contact area ratio c_{mob} is calculated as:

$$c_{mob} = A_0 \left(\frac{\theta^*_{max} - i_{mob}}{\theta^*_{max}}\right)^C \tag{5}$$

2.2 *Hydraulic behaviour*

The complexity of water flowing through rock joints mainly arises from the irregularity of aperture distributions and the tortuosity of the flow path due to contact areas, as demonstrated in Figure 1.

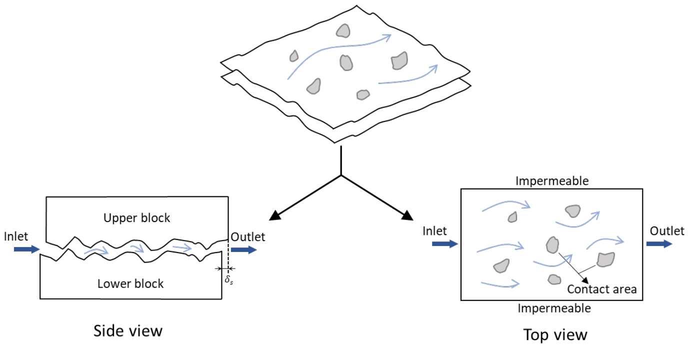


Figure 1. Schematic representation of water flow through a natural rough rock joint.

An improved equation, which considers the reduction of flow rate by aperture irregularities and contact obstacles by incorporating aperture correction term f_{aper} and contact correction term f_{cont}, respectively, is utilised to describe the hydraulic behaviour of a single rock joint, given by:

$$e_h^3 = e_m^3 \left(1 - 1.0\frac{\sigma_{e\_mob}}{e_m}\right)(1 - \frac{1}{A_0} c_{mob}) \tag{6}$$

where e_h is the hydraulic aperture, e_m is the mean mechanical aperture, obtained from initial apertures and dilations during shearing, and σ_{e_mob} is the standard deviation of the mean mechanical aperture, which will mobilise during shearing and be calculated using a computational procedure.

3 NUMERICAL IMPLEMENTATION

The simulation of shear-flow tests is performed using the three-dimensional distinct element code, 3DEC. The numerical model is established at the same size as the experimental samples for later validation, as shown in Figure 2.

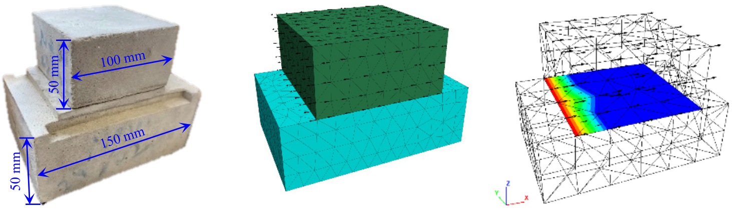


Figure 2. Samples for experimental and numerical tests.

The hydro-mechanical model is incorporated in 3DEC using the built-in programming language, FISH. Figure 3 shows a flow chart for the numerical implementation of the proposed model.

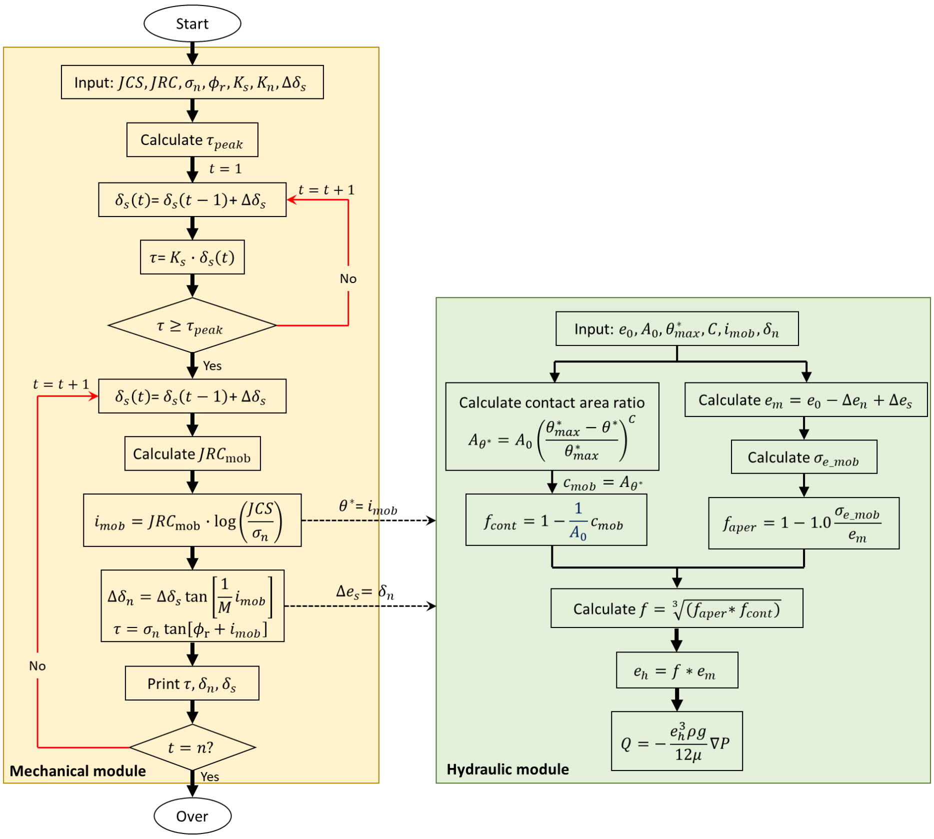


Figure 3. Flowchart for the numerical implementation of the proposed model.

4 MODEL VALIDATION

4.1 *Shear-flow experiments*

Two types of artificial fractures (labelled as J1 and J2) were used in tests, as shown in Figure 4. The geometrical properties of the two fracture surfaces are listed in Table 1.

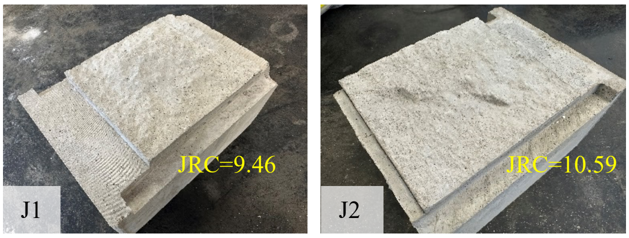


Figure 4. Two types of rock joint replicas for testing.

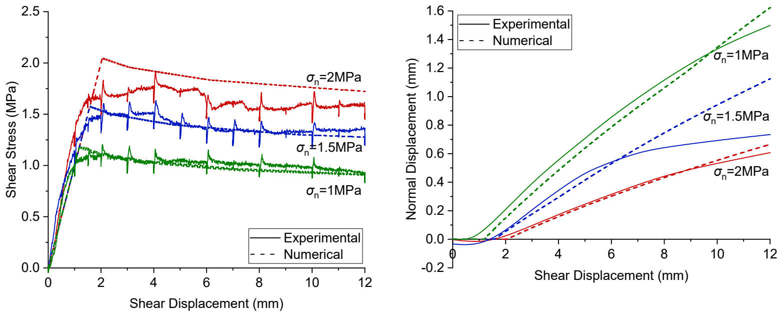
A laboratory shear-flow apparatus was adopted to conduct shear-flow tests under constant normal loads σ_n (1 MPa, 1.5 MPa and 2 MPa) and low inlet pressure from 5 kPa to 40 kPa. For each joint surface under each normal stress, about eight hydraulic tests with various pressure gradients at about seven different shear displacements d (ranging from 0 mm to 12 mm) were carried out. The flow rate was recorded, and the pressure drop was calculated from the differential pressure of the water inlet and outlet.

Table 1. Geometrical properties of two fracture surfaces based on Grasselli's criterion.

Fracture No.	θ^*_{max} (°)	A_0	C	JRC
J1	59.5637	0.4362	6.3407	9.46
J2	79.6584	0.4492	8.1013	10.59

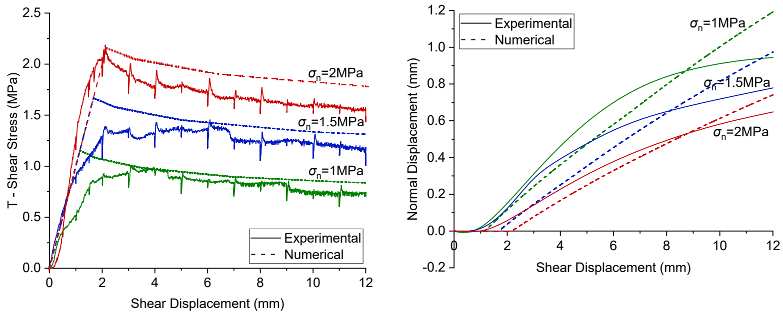
4.2 Model validation

Figure 5 shows the mechanical behaviours of two joints under different normal loads, including the evolution of shear stress and dilation with shear displacement. The comparison between the curves obtained from numerical simulations and lab tests indicates that the model agrees fairly well with the lab results, with the exception of slight drops observed at larger shear displacement in some of the experimental curves. These deviations may be attributed to fracture surface damage.



(a) J1, shear stress versus shear displacement curves

(b) J1, dilation curves

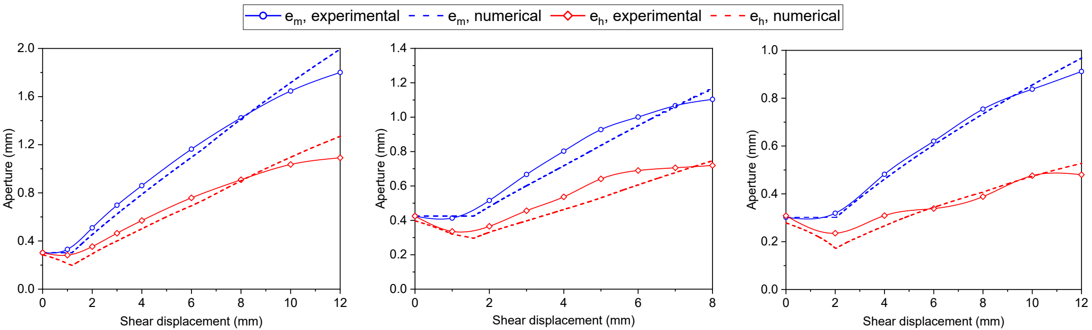


(c) J2, shear stress versus shear displacement curves

(d) J2, dilation curves

Figure 5. Mechanical behaviours of fractures J1 and J2 in coupled shear-flow tests.

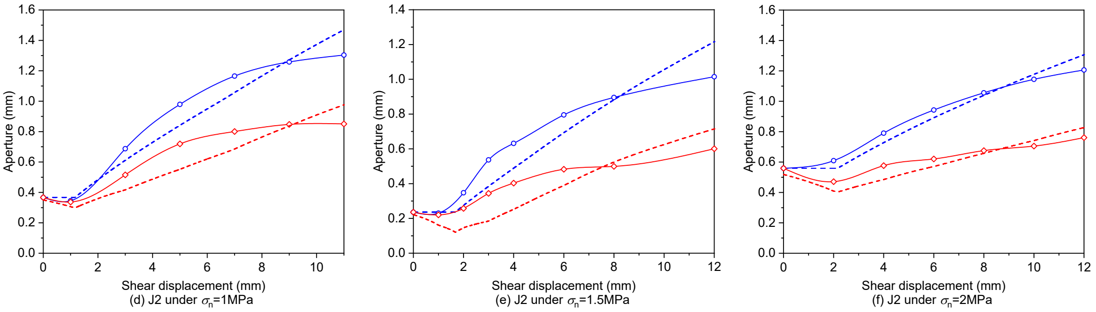
The experimentally measured e_m is calculated from dilations, while the measured e_h is back calculated with cubic law. Figure 6 demonstrates the correlation between the numerically implemented improved model for estimating the hydraulic conductivity of a single rock joint with the experimental results.



(a) J1 under σ_n=1MPa

(b) J1 under σ_n=1.5MPa

(c) J1 under σ_n=2MPa



(d) J2 under σ_n=1MPa (e) J2 under σ_n=1.5MPa (f) J2 under σ_n=2MPa

Figure 6. Hydraulic behaviours of fractures J1 and J2 in coupled shear-flow tests.

The simulation results exhibit an acceptable agreement with the experimental outcomes, thus attesting to the effectiveness of the numerical model.

5 CONCLUSIONS

In this paper, an improved hydro-mechanical model was numerically implemented in 3DEC to investigate the coupled shear-flow processes of single rock joints. The model implicitly considered the evolution of aperture distributions and contact area ratio during shearing. A series of shear-flow tests were conducted on artificial joint samples under constant normal loads to validate the numerical model. Correlations between numerical and experimental results show good overall agreements in both shear and flow behaviours, indicating that the numerical model with a proper hydro-mechanical constitutive model has the potential to accurately evaluate the shear-flow coupled behaviour of rock joints. The numerical model can then be upscaled to field level to perform hydraulic analysis in various practical cases.

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