Geomechanics and Engineering, *Vol. 18, No. 6 (2019) 585-594*
DOI: https://doi.org/10.12989/gae.2019.18.6.585

Enhancement of fluid flow performance through deep fractured rocks in an in-situ leaching potential mine site using discrete fracture network (DFN)

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(Received July 3, 2019, Revised August 2, 2019, Accepted August 10, 2019)

Abstract. In-situ leaching could be one of the promising mining methods to extract the minerals from deep fractured rock mass. Constrained by the low permeability at depth, however, the performance does not meet the expectation. In fact, the rock mass permeability mainly depends on the pre-existing natural fractures and therefore play a crucial role in in-situ leaching performance. More importantly, fractures have various characteristics, such as aperture, persistence, and density, which have diverse contributions to the promising method. Hence, it is necessary to study the variation of fluid rate versus fracture parameters to enhance in-situ leaching performance. Firstly, the subsurface fractures from the depth of 1500m to 2500m were mapped using the discrete fracture network (DFN) in this paper, and then the numerical model was calibrated at a particular case. On this basis, the fluid flow through fractured rock mass with various fracture characteristics was analyzed. The simulation results showed that with the increase of Fisher' K value, which determine the fracture orientation, the flow rate firstly decreased and then increased. Subsequently, as another critical factor affecting the fluid flow in natural fractures, the fracture transmissivity has a direct relationship with the flow rate. Sensitive study shows that natural fracture characteristics play a critical role in in-situ leaching performance.

Keywords: in-situ leaching; rock mass permeability; natural fracture; DFN; fracture characteristics

1. Introduction

The mines are wealth in various mineral resources, such as gold, copper, uranium, lithium, and so forth, which play a crucial role in technological development worldwide, particularly in China, India, USA, Australia, Canada, and South Africa as main supplier and consumer of minerals. However, due to the limitation of traditional technology, many resources could not be effectively exploited and utilized. Recently, some advanced techniques, such as in-situ leaching, hydraulic fracturing, acid fracturing, and microwave fracturing have been applied to fully use the mineral resources (De Silva *et al*. 2018, Hu *et al.* 2018, Kozikhin *et al.* 2018, Liu *et al.* 2018). However, the in-situ leaching has been widely used to be an alternative for, or perhaps replace, the conventional mining especially for mining the sub-economic and low-grade ore bodies due to the technical, economic and environmental benefits, and it is expected to become more potential near future (Haque and Norgate 2014, Kuhar *et al*. 2018, Martens *et al*. 2012, Petersen 2016). Meanwhile, the in-situ leaching is also facing some challenges due to the low permeability at depth. The main reason is that not all the ore bodies are naturally suitable to this mining method, for instance, it may have low permeability, and this condition will negatively reduce the in-situ leaching efficiency (Seredkin *et al*. 2016, Sinclair and Thompson 2015). To investigate the physical properties of targeted ore and fluid flow within fractured rock mass, the distribution of pre-existing natural fractures should be reconstructed through realistic methods.

Generally, there are three approaches to generate the geometrical rock fractures, namely dual porosity model (DPM), discrete fracture network (DFN) model and equivalent porous medium model (EPM) (Easton 2004). In fact, as a dual-porosity model, the ore body consists of natural fractures and matrix. Besides, the natural fractures are discretely distributed. Rock mass, therefore, can be regarded as an assemblage of intact rock blocks that are separated by discontinuities. As a consequence, the DFN model is an ideal tool to generate the distribution of natural fractures and express the behavior of fluid flow through fractured rock mass (Hyman *et al*. 2016, Medici *et al.* 2019, Rocha *et al*. 2017). Meanwhile, the DFN model is counted on a statistical characterization of the rock mass. The generation of the fracture network is based on realistic distributions of geometric parameters in a real case, including aperture, orientation, persistence, and density (Palleske 2014). However, the previous research in in-situ

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http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

leaching mainly focused on the chemical reaction between solutions and ores mineral, and few researchers were engaged in the distribution of pathways in the fractured rock mass. Worse still, although the natural fractures have various characteristics, which have different contributions to in-situ leaching, there are rare reports about the influence of natural fractures on in-situ leaching performance.

In this paper, the spatial distribution of natural fractures in fractured rock mass at depth of about 1500 m-2500 m was created using DFN model based on the boreholes data and calibrated at a particular case with measured results in Yilgarn area, Western Australia. On this basis, the fluid flow performance through deep fractured rocks was studied. Finally, the variation of flow rate versus pre-existing fracture parameters indicates the dependence of in-situ leaching performance on fracture characteristics.

2. Principle of in-situ leaching

In-situ leaching is an environment-friendly mining method, which can recover the mineral resources from the deposit without moving the rock body, as shown in Fig. 1 (Saini-Eidukat *et al*. 1993, Martens *et al*. 2012, Seredkin *et al.* 2016, Sinclair and Thompson 2015). In traditional mining, however, the rock mass is inevitably destroyed, and the waste material needs to be removed before getting valuable mineral resources (Benes *et al*. 2001). As a consequence, in-situ leaching will be one of the most promising mining methods and widely applied in the deep mining industry. Although the in-situ leaching is not a new mining method, it has received much attention and become more significant since the uranium industry developed this technology. In the new global mining, the in-situ leaching has become a central issue for mining deposits at depth (Kuhar *et al.* 2018, Taylor *et al.* 2004).

In order to extract the mineral resources by in-situ leaching, the solutions are injected into the working panel through the pipes, which are suitable for the desired ore properties. Then the fluid flow in the fractured rock mass. Meanwhile, the fluid reacts with the ore on the way of flowing. Finally, the liquid flows out from the production wells (Seredkin *et al*. 2016, Sinclair and Thompson 2015). Subsequently, the lixivium is lifted to the surface to extract the mineral resources of interest. In the production process of in-situ leaching, in short, the production wells will begin to produce the pregnant solution, containing valuable metals, after leaching process liberate them. To observe the condition of chemical solution within the system, another important monitoring well, is placed near the injection well. The overall process can be visualized through Fig. 2.

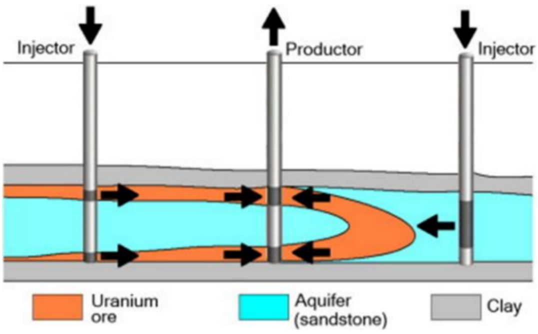


Fig. 1 In-situ leaching system (Pokalai *et al*. 2016)

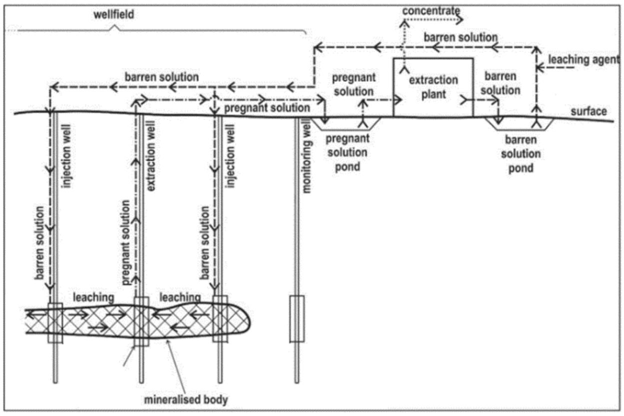
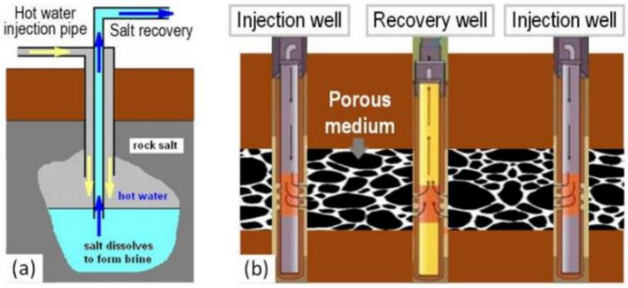
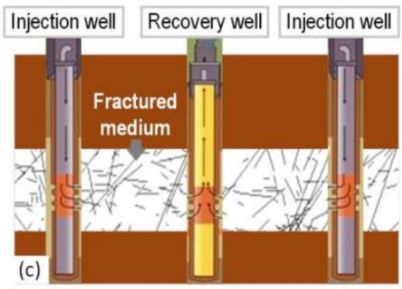


Fig. 2 The mechanism of in-situ leaching method (Seredkin *et al*. 2016)



(a) Solution mining in the past (b) Porous medium leaching in the present



(c) Fractured rock mass leaching in future

Fig. 3 In-situ leaching trend (Sharifzadeh *et al.* 2018)

Compared to the traditional mining method, in-situ leaching delivers more value and benefits, for example, low investment and operation cost, high profitability, and low environmental impact. However, as the demand for a commodity increases year by years such as copper, gold, and some other mineral resources, this method is forecast to surge shortly. However, the in-situ leaching will also deal with some challenging issues. Fig. 3 shows the trend of in-suit leaching. It is apparent that the in-situ leaching mining method first started to extract the salt by solution method (Fig. 3(a)). At present, this approach is mainly adopted in porous media, as illustrated in Fig. 3b. In the near future, however, this mining method will be widely used in the fractured rock mass (Fig. 3(c)), which has not been

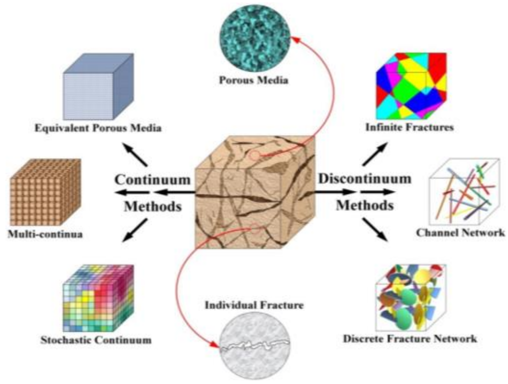


Fig. 4 Heterogeneity of fracture network approaches (Sharifzadeh and Javadi 2017)

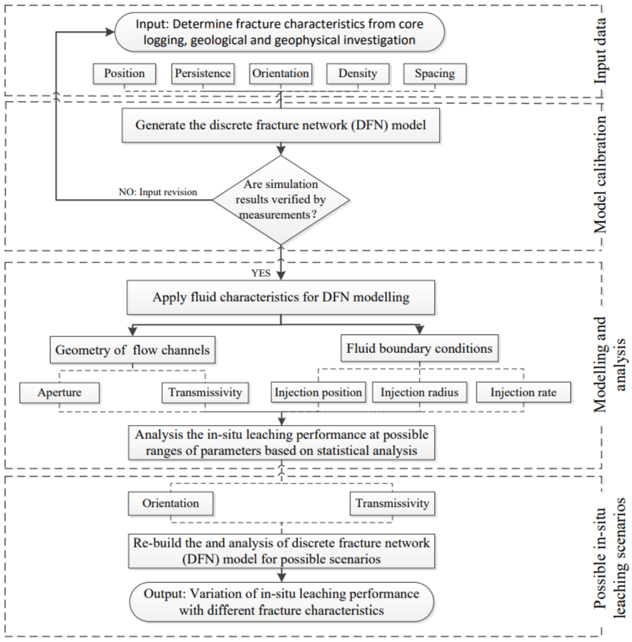


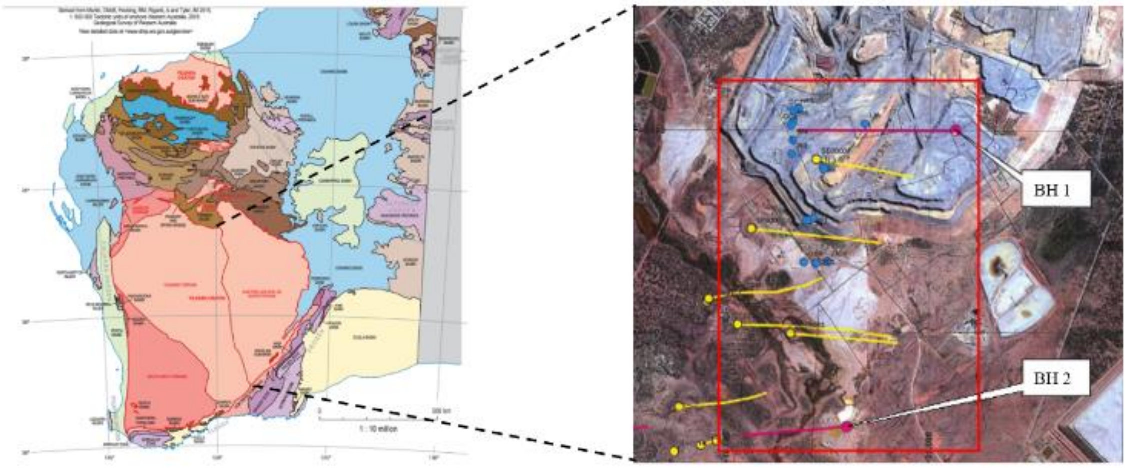
Fig. 5 Procedure for in-situ leaching simulation on pre-existing natural fractures

completely developed (Sharifzadeh *et al.* 2018). The critical parameters limiting the application of in-situ leaching in fractured rock is the low permeability of rock mass (Seredkin *et al.* 2016). It is well known that the rock mass consists of discrete fractures and matrix, and the cracks are the main channels of fluid flow. As a consequence, the pre-existing fractures are the main factor that affects the application of in-situ leaching in fractured rock mass at depth. To extend the use of in-situ leaching mining method upon hard rock deposit containing valuable metals, this paper generates the distribution of natural fractures and simulate the in-situ leaching performance through broken rock mass at depth, using the solution of numerical, statistical and probabilistic methods.

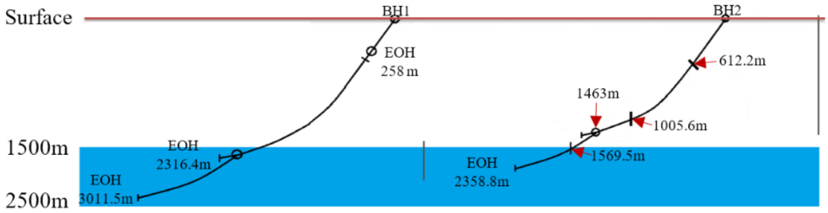
3. Discrete fracture network generation

Typically, the conventional approaches applied to generate the distribution of pre-existing natural fractures in coal and rock mass are divided into two types: continuum methods and discontinuum methods, as illustrated in Fig. 4 (AbuAisha *et al.* 2019, Ghaderi *et al.* 2018, (Sharifzadeh and Javadi 2017). As a dual-porosity media, the rock mass is composed of blocks cut by pre-existing fractures. Compared to the matrix, the natural cracks have a higher permeability, which are the main channels for the injected solution flow. As a consequence, the blocks are negligible in most case. Moreover, the fractures are discretely distributed in the rock mass. Therefore, the discrete fracture network (DFN) model could be an ideal tool to generate the spatial distribution of discrete fractures and simulate the behavior of in-situ leaching performance in the fractured rock mass (Kamali *et al.* 2018, Li *et al.* 2018).

In fact, the DFN modelling is counted on a statistical characterization. Fig. 5 shows that the procedure for in-situ leaching simulation on pre-existing natural fractures. To generate the geometrical rock mass, the fundamental natural fracture characteristics in the real case, such as aperture, persistence, orientation, density, and transmissivity, are needed. After defining the geometry of channels, the DFN model is reconstructed. To calibrate the numerical model, the simulation results are compared with the field test results. Then, injecting the solutions, the performance of

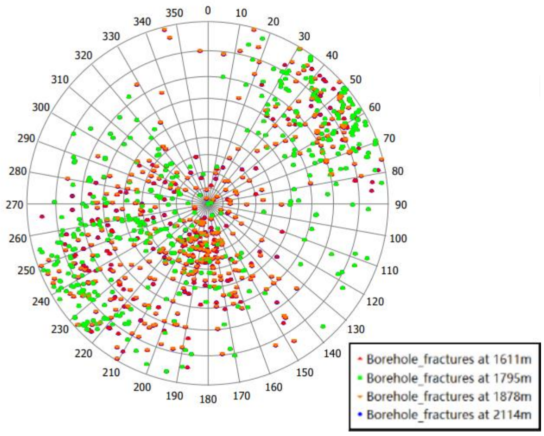


(a) Location of research area and boreholes

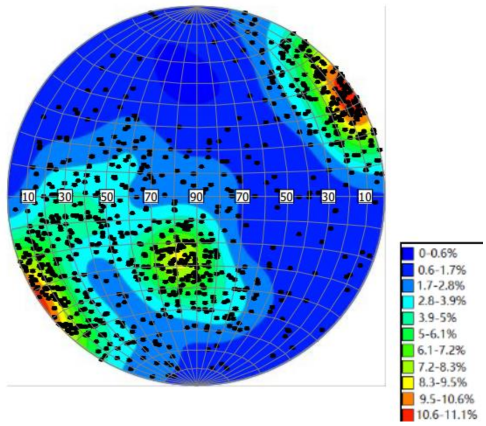


(b) Overview of drilling boreholes

Fig. 6 The on-site experiment in Yilgam area



(a) Distribution of joint orientation



(b) Contour map of joint sets

Fig. 7 The distribution of joint set

Table 1 Set identification analysis results

Fracture set	Mean pole trend	Mean pole plunge
SE set	57.149	4
NW set	231.28	14

fluid flow through pre-existing fractures could be assessed. Finally, by changing the natural fracture parameters, the variation of flow rate could be studied. Based on the results, the dependence of in-situ leaching performance on fracture characteristics is analyzed.

In order to acquire the basic natural fracture characteristics, the field experiment was conducted at Yilgarn area, Western Australia. Some boreholes, such as BH1, and BH2 were arranged in the research area, and the boreholes core logging data was extracted to investigate the distribution parameters of pre-existing fractures, as illustrated in Fig. 6(a). Based on the borehole data, basic input parameters used for DFN modelling is mapped and analyzed from core logging and geological data. According to the location, geological condition, potential mineralisation zone, drilling depth, and drilling location, some boreholes data is selected. Fig. 6(b) shows the drilling boreholes in the on-situ experiment and the sampling was completed along the whole length. Besides, it is noteworthy that only cores deeper that 1500 m were focused. Based on the basic data, the distribution of natural fractures is generated. On this basis, the in-situ leaching performance in fractured rock mass are assessed.

Fig. 7(a) shows the original distribution of joint

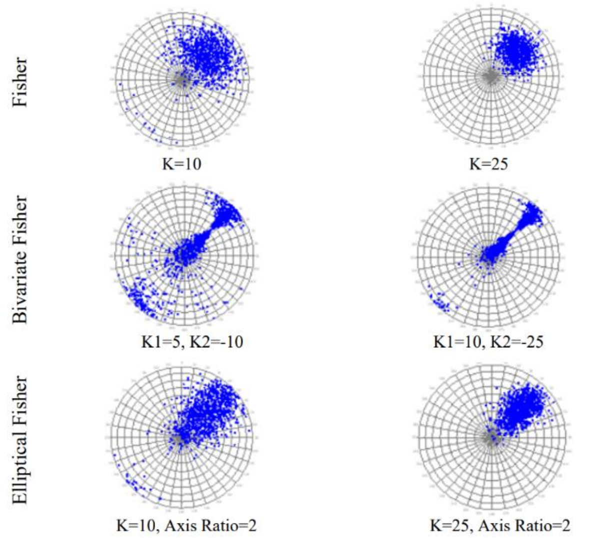
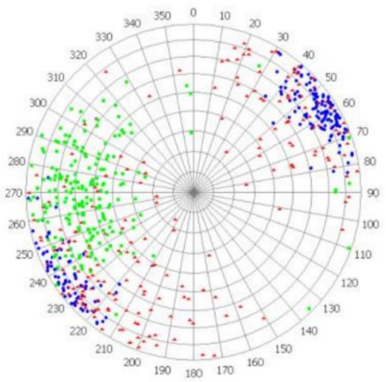
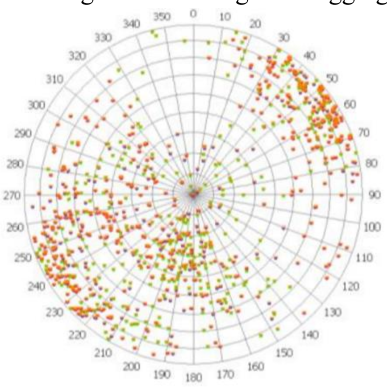


Fig. 8 Distribution of fracture orientation based on Fisher's K value



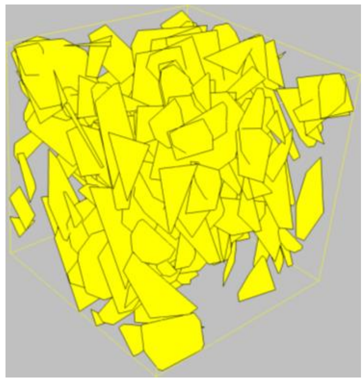
(a) Fractures generated using core logging data



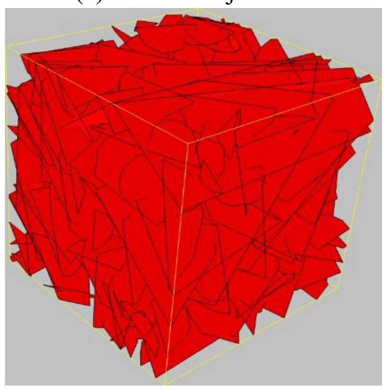
(b) Model fractures with two joint sets

Fig. 9 The calibration of DFNs modelling

orientations. Based on the boreholes data, the natural fractures are transformed into stereonet graph. Analyzing the data indicates that the joints orientations are concentrated on two clusters or domain area which are toward southeast (SE) strike and northwest (NW) strike. The probable areas of joint cluster then were to become joint set, grouping relatively similar joint orientation within a certain range. In addition, the noticeable outlook also depicts that more fractures are spotted in southwest (SW) area. In term of fractures dissemination, the southern



(a) NW strike joint set



(b) SE strike joint set

Fig. 10 Two discontinuity fracture sets generated in DFN model

hemisphere is more distributed than the SE strike joint set. Fig. 7(b) shows the spatial distribution of joint sets, which are differentiated based on the percentage. Analyzing the data indicates that there are two joint sets in the research area. The first joint set is approximately in the NE strike (highlighted by red colour). The second joint set is distinguished by the yellow-coloured area in SW direction with sub vertical orientation (close to the centre of stereonet).

Based on the above analysis, the orientation of natural fracture sets is divided into two categories: SE strike and NW strike. According to the probabilistic weights proportion of fracture orientation in each set, the distribution of fracture sets is calculated. Based on the probability statistics method, the fractures orientation obeys Fisher distribution, and the intensive degree of fractures depends on the Fisher's K value, as shown in Fig. 8. Based on the distribution of joint set generated by boreholes BH1 and BH2, the K value is 10 and orientation data is entered in the form of trend and plunge, which is listed in Table 1.

According to information on the joint set generated from the probabilistic calculation, the direction of pre-existing natural fractures in the fractured rock mass is generated, as shown in Fig. 9(b). To calibrate the DFN model, the simulation results are compared with the fractures distributed based on borehole data BH1, illustrated in Fig. 9(a). It is apparent that the simulation results exhibit a slight variation of fracture dissemination compared to the field test results. Overall, it could be confirmed that the fracture orientation generated by the two approaches are basically

Table 2 The parameters of pre-existing natural fractures used in DFN modelling

Material	Parameter	Value
Fracture set 1	Pole trend (°)	57.15
	Pole plunge (°)	4
	Radius, mean (*m*)	16.94
	Radius, standard deviation (m)	0.035
	P_{32} (m^{-1})	1.44
Fracture set 2	Pole trend (°)	231.28
	Pole plunge (°)	14
	Radius, mean (*m*)	16.24
	Radius, standard deviation (m)	0.03
	P_{32} (m^{-1})	1.21

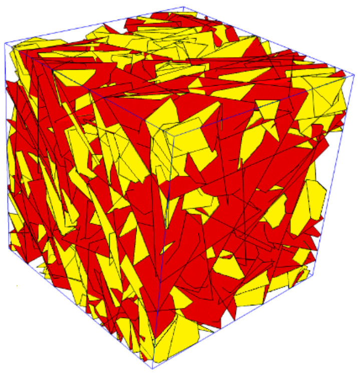


Fig. 11 Three-dimensional DFN model with two discontinuity sets

the same. On this basis, two discontinuity sets with the spatial distribution of natural fractures are generated, as shown in Fig. 10.

In addition, the natural fractures have various characteristics, such as persistence, density, aperture, and transmissivity, which could have a different contribution to generate the distribution of pre-existing natural fractures, ultimately affecting the in-situ leaching performance. However, the rock mass in the research area is impossible to be completely dismantled to obtain the complete properties of natural fracture. As a consequence, some parameters are calculated based on the stochastic methods to minimize the uncertainties.

One of the essential characteristics in DFN modelling is fracture persistence. However, it is difficult to measure the fracture size in the fractured mass directly, so the fracture persistence is calculated based on the empirical formula. Besides, the shape of natural fracture influences the calculation of crack size. Therefore, the fractures in this paper are assumed to be circular and the fracture size distribution is defined in terms of equivalent radius, which is closely related to the trace length (Karimzade *et al.* 2017). Their relationship could be expressed by Equation 1. Generally, the fracture sizes may exhibit a negative exponential, lognormal, gamma, or power law distribution (Einstein and Baecher 1983). According to the field observation, the mean trace lengths obeys a lognormal distribution. As a consequence, it is acceptable to assume that the fracture radius is distributed as the lognormal distribution.

$$R = 0.3L + s \tag{1}$$

where R is the radius of natural fracture, L is mean trace length, and s is the standard deviation.

Another fracture parameter affecting the distribution of natural fracture is the density, which describes the development of cracks in the fractured rock mass. Generally, the fracture density is divided into three types: linear density (P_{10}), areal density (P_{21}), and bulk density (P_{32}), which measures the fractures number per unit length, the fracture length per unit area, and the fracture area per unit volume (Dershowitz *et al.* 2000, Kamali *et al.* 2019). Meanwhile, fracture spacing is another essential parameter, which is the perpendicular distance of two cracks. In general, the spacing is related to fracture frequency (P_{10}), which may follow a negative exponential, lognormal or normal distribution depending on the degree of fracture saturation in the network. However, the bulk density is used to generate the DFN model.

According to the results of field measurement in Yilgarn area, Western Australia and statistical analysis, the input fracture characteristics used for DFN modelling are listed in Table 2. Based on the above analysis, a three-distributional conceptual model with the size of 50m×50m×50m is reconstructed. Fig. 11 shows the DFN model, which consists of two discontinuity sets. On this basis, the in-situ leaching performance through fractures rock mass at depth were studied.

4. In-situ leaching performance in the fractured rock mass

One of the fracture parameters that determine the flow channel geometry is the aperture. Typically, the fracture aperture is divided into the mechanical and hydraulic aperture. The former represents the physical spacing between two fractures, and the latter is the height of the flow channel. In fact, the hydraulic aperture is the main factor influencing the in-situ leaching performance in the fractured rock mass. In general, the hydraulic aperture is calculated based on the cubic law, which assumes that plates of fracture are smooth, as shown in Equation 2 (Dippenaar and Van Rooy, 2016, Dong *et al*. 2019, Hu *et al.* 2019, Medici *et al.* 2019). Besides, this approach is only suitable for studying the water flow through a single fracture. After obtaining the aperture of individual fracture within the flow channels, it is possible to investigate the distribution of hydraulic aperture in the rock mass.

$$e = \sqrt[3]{-\frac{12\mu Q}{w \cdot \nabla p}} \tag{2}$$

where e (*μm)* is the hydraulic aperture, μ (Nsm^{-2}) is the fluid viscosity, Q (m^3s^{-1}) is the flow rate, w (m) is facture width perpendicular to the flow direction, ∇p (Pam^{-1}) is the pressure gradient.

Another parameter that affects the fluid flow in DFN

Table 3 The input fluid and fracture properties used in DFNs modelling

Material	Parameter	Value
Fluid	Density (*kgm*$^{-3}$)	1000
	Compressibility (*Pa*$^{-1}$)	4.4*E*-10
	Viscosity (*Nsm*$^{-2}$)	1.0 *E*-03
	Injection rate (m^3s^{-1})	0.25
Fracture	Permeability (m^{-2})	6*E*-19
	Aperture (μm)	35
	Transmissivity (m^2 s^{-1})	3.12*E*-07

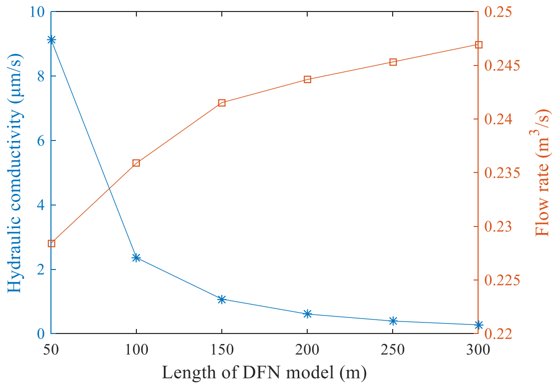


Fig. 12 Variation of hydraulic conductivity and flow rate versus DFNs model size

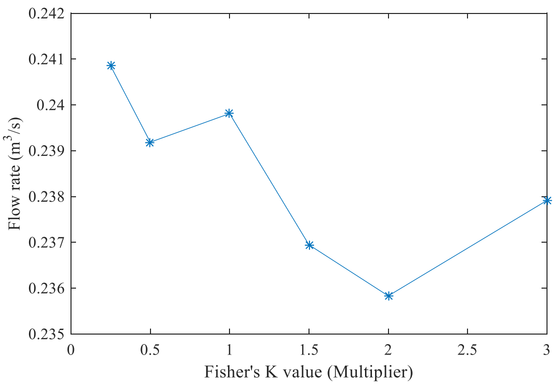


Fig. 13 Variation of flow rate versus natural fracture orientation

modelling is the fracture transmissivity. In the fractured rock mass, the transmissivity represents the ability of fracture to transfer the solution from injection path to the outlet. In fact, not all the natural fractures in the DFN model could allow the fluid flow through the cracks. Generally, the transmissivity is affected by the changed in hydraulic aperture properties, and its values could be generated by the cubic law, as follows (Easton 2004, Renshaw 1995). Investigating the transmissivity is to meet the requirements of in-situ leaching. According to the field test, the value of transmissivity is 3.12E-07 m/s with a standard deviation of 1.00E-07.

$$T = \frac{e^3 \rho g}{12\mu} \tag{3}$$

where T (m^2s^{-1}) is the fracture transmissivity, ρ is the fluid density (kgm^{-3}), g is the acceleration due to gravity (ms^{-2}).

After determining the spatial distribution of natural fractures and defining the geometry of flow channels, the fractured rock mass model with pre-existing natural fractures could be established. To assess the flow behaviour of solutions through natural cracks, the fluid properties should be applied. In order to get the accurate simulation results, all the input properties used in DFNs modelling are obtained from the field test in Yilgarn area, Western Australia, and their values are presented in Table 3.

Fig. 12 shows the variation of hydraulic conductivity and flow rate versus the domain area length. It is generally known that the distribution of natural fractures will changes with the domain region size, thereby affecting the fracture permeability and transmissivity, ultimately influencing the in-situ leaching performance. In order to produce a reliable domain region for the simulation, therefore, it is necessary to vary the domain length to assess the simulation results. Analyzing the data in Fig. 12 indicates that the bulk hydraulic conductivity has an inverse relationship with the domain region length, but the flow rate has a direct relationship. The hydraulic conductivity decreases with the increase of domain region size, but the flow rate is increased. However, with increasing the domain size after 250 m, eventually both reach a relatively stable state. Taking into account the computation, and processing limitations, and simulation time, the length of the domain region is selected to be 250 m.

Apart from the domain region size, there are various fractures parameters, which have different contributions to in-situ leaching performance in the fractured rock mass. To study the dependence of in-situ leaching on natural fracture parameters, the fluid flow through fractured rock mass with different fracture parameters are assessed. In this paper, the DFN models with fracture orientation and transmissivity variation are generated. According to the various flow rate, the influence of fracture characteristics on in-situ leaching were investigated.

5. Results and discussion on influence of fracture characteristics on in-situ leaching performance

5.1 Role of fracture orientation

Fracture orientation with respect to each other could greatly influence the fracture network and fluid flow rate. Fig. 13 shows the variation of flow rate versus natural fracture orientation. Based on the above analysis, the DFN model consists of two discontinuity sets, and the fracture orientation obey a fisher distribution. Therefore, the change of flow rate with natural direction could be studied by changing the K value, which is an indication of fracture direction. Analyzing the data in Fig. 13 indicates that with the increase of K value, the flux is firstly decreased and then increased. According to the data, it is found that the change of flow rate could be divided into two stages. When the multiplier of K value is less than 2, the flux depicts a negative correlation with the fracture orientation. With the increase of K value, however, the flow rate is increased.

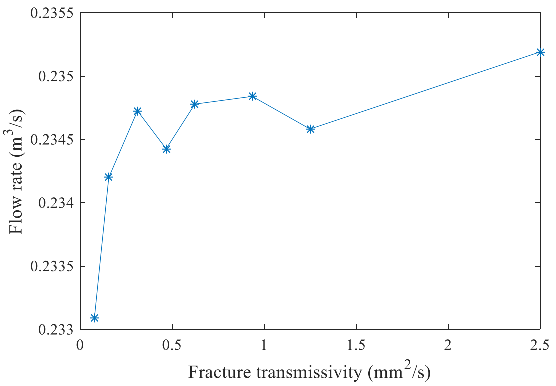


Fig. 14 Variation of flow rate versus natural fracture transmissivity

The major cause for this phenomenon may lie in that the single fractures have a wider range of orientation distribution with the increase of K value. Instead of accumulating at specific orientation, single fractures are well distributed outside the center of cluster pole. The higher K value, the more disseminated the fractures. More importantly, the intersections between fractures are also decreased. As a consequence, the flow rate is decreased. With the increase of K value, however, some isolated fractures begin to connect with others, forming the flow channels. Therefore, the flow rate is increased.

5.2 Role of fracture transmissivity on in-situ leaching performance

Individual fractures transmissivity has a dominant role on fluid flow performance in the fracture network. Fig. 14 shows the change of flow rate versus fracture transmissivity. Analyzing the data in this figure indicates that the flow rate has a direct relationship with the natural fracture transmissivity. Meanwhile, it is clear that more transmissive the fractures have, the higher flow rate will be. At some fracture transmissivity, such as 0.5, and 1.25, the flow rate is decreased with the increase of fracture transmissivity, which could be attributed to local fracture blockage. In general, the flux is increased with increasing the transmissivity. The variation of flow rate versus the natural fracture transmissivity mainly lies in that the transmissivity is affected by the changed of hydraulic aperture properties, and the aperture determines the geometry of flow channels. With the increase of transmissivity, it is easier for the lixiviant to flow into the DFN model. As a consequence, a lot of liquid is stored in the fractured model, creating a higher hydraulic pressure. Under the action of high hydraulic pressure, the majority of fluid is flowing to the outlet. Therefore, the flow rate is increased with the increase of fracture transmissivity.

6. Conclusions

In-situ leaching could be one of the promising mining methods to extract minerals from great depth, such as nickel, gold, copper, lithium, and other metal minerals. Due to technical, economic, and environmental benefits, the in-situ leaching has been widely used to be an alternative for, or perhaps replace, the conventional mining methods. Constrained by the low permeability of rock mass, however, the in-situ leaching has not been given full play to its advantages. As the main channels of fluid flow, fractures in fractured rock mass play an enormous role in the in-situ leaching performance. More importantly, the natural fracture has various characteristics, which have a different contribution to the fluid flow. Therefore, it is necessary to study the in-situ leaching performance in the fractured rock mass and its dependence on natural fracture parameters. Firstly, the natural fractures at depth of 1500m to 2500m are mapped from core logging using DFN in this paper, and then calibrated at a particular case with measured test results. Finally, the fracture orientation and transmissivity were selected to observe the dependence of fluid flow on pre-existing natural fracture characteristics. The simulation results show that with the increase of Fisher's K value, which determine the fracture orientation, the flow rate firstly decreases and then increases. The main reason is that the single fractures have a more extensive range of orientation distribution with the increase of K value, which changes the intersection between fractures. Besides, the flow rate has a direct relationship with the natural fracture transmissivity. The primary cause for this phenomenon may lie in that with the increase of transmissivity, large volume of liquid is injected and stored in the DFN model, creating high hydraulic pressure, and the flow rate is increased correspondingly.

In conclusion, this paper improves our understanding of the in-situ leaching performance in the fractured rock mass with pre-existing natural fractures and enhance the extraction of fluid earth resources.

Acknowledgments

This work was financially supported by the Fundamental Research Funds for the Central Universities (2017CXNL01). One of the authors wants to express his deepest appreciation to China Scholarship Council (CSC) for the award of Chinese Government Scholarship. The authors would also like to acknowledge the Mining Education Australia (MEA), Collaborative Research Grant Scheme (RES-SE-MEE-PM-59042).

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