Assessment of block size distribution in fractured rock mass and its influence on rock mass mechanical behavior

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ABSTRACT
The response of rock mass to engineering activities related to environment greatly depends on the scale of rock mass. Therefore, the scale dependency of rock mechanical behavior under different rock mass conditions is investigated in this research. As a crucial parameter, the volume of the block provides a fundamental understanding to define the rock mass condition and possible mechanical response. In this paper, at first, a systematic approach to calculate the block size distribution (BSD) based on the natural fracture parameters using most suitable distribution functions was established with the R language. Then, the rock mass parameters were extracted from core mapping in the depth of 1500 m–2000 m and the BSD was presented in a similar manner to soil particle size distribution. Finally, the rock mass behavior under different block sizes was investigated. The results showed that $V_{b25} = 3.4 \text{ dm}^3$, $V_{b50} = 6.4 \text{ dm}^3$, and $V_{b75} = 11.2 \text{ dm}^3$, which were the average percentages to represent the BSD. In the research area, therefore, the fractured rock mass was dominated by minor blocks. Besides, the variation of rock mass deformation vs BSD showed that the fractured rock mass was aggravated with the decrease in the block size. The results will enhance the effect of BSD on rock mass mechanical properties.

I. INTRODUCTION

In underground mining, the rock mass will undergo various types of behavior, which eventually leads to the destruction of the environment, such as plant destruction, surface subsidence, and groundwater pollution. The rock mass behavior is closely related to the rock mass integrity and mechanical properties. Squeezing, moving, and deforming are examples of this behavior, which eventually leads to the ground collapse (Das et al., 2019; Zhang et al., 2019). The variety of rock mass movement requires different assessments or calculation methods for a proper design that can be relied on to cover the actual case (Song et al., 2018; Wu et al., 2020). Typically, the empirical methods, i.e., the rock mass classification systems, are used to describe the rock mass integrity and behavior, which is dominated by block falls. Currently, the classification is divided into RQD, RMR, RMI, Q, and GSI (Ming and Peter, 2006; Rehman et al., 2018; Taherkhani and Doostmohammadi, 2015; and Zheng et al., 2018). However, these classifications have some limitations, not suitable in some cases, and may even cause severe consequences in underground activities (Kim et al., 2007; Stavropoulou, 2014). The main reason lies in that these methods only consider one or several attributes and use a single number to represent the rock mass integrity and mechanical properties. Besides, there are also some rocks that have the same value of classification, but have different rock behaviors. That is, the geological properties are the same, but geotechnical properties are different. It is obvious that more systematic investigations regarding the rock mass classification and mechanical properties are required. In fact, the block size
plays a crucial role in assessing the rock mass behavior and its distribution is an important indicator in underground mining (Hardy et al., 1997; Katherine et al., 2006). The naturally fractured rock mass could be regarded as an assemblage of intact blocks separated by discontinuous fractures (Karimzade et al., 2017; Kim et al., 2007). As a consequence, the shapes of blocks are delineated by natural fracture characteristics, as shown in Fig. 1. As the grains of a fractured rock mass, the blocks indicate the degrees of fracture, rock mass integrity, and rock mechanical characteristics. Therefore, it is necessary to study the subsurface block size and its distribution in the rock mass. Currently, the block size is usually calculated by empirical equations. However, the results are monotonous, which is not accurate enough to describe the distribution of the block size in the fractured rock mass.

In this paper, the natural fractures used to calculate the block size distribution (BSD) were mapped at a particular case in Yilgarn area, Western Australia. Then the volume of blocks and its distribution were calculated using the R language. Meanwhile, the results were calibrated with the on-site results. Finally, some numerical modeling of underground excavations with different BSD were performed and discussed. This research will enhance the awareness of the dependence of rock mass mechanical properties and its movement on the block size.

II. INFLUENCE OF FRACTURE CHARACTERISTICS ON BSD

Typically, the BSD in naturally fractured rock mass is delineated by the fracture characteristics. The main reason is that the rock mass consists of fractures and matrix, and the blocks are generated by the intact rock cut by fractures (Bertrand et al., 2017; Yao et al., 2019). However, natural fractures have various characteristics based...
on different geological conditions, which have different effects on BSD. Therefore, to calculate the volume of blocks and their distribution, the spatial distribution of natural fractures should be generated. To reconstruct the natural fractures, an appropriate medium model should be selected. Typically, the conventional approaches applied to generate the distribution of pre-existing natural fractures in rock mass are divided into two types: continuum methods and discontinuum methods (AbuAisha et al., 2019; Ghaderi et al., 2018; Sharifzadeh and Javadi, 2017; and Yazdani et al., 2012). However, the natural fractures are randomly and discontinuously distributed in the rock mass, causing various rock lumps in the rock mass. As a consequence, the volume of the block and its distribution are different. Therefore, this paper suggests, based on the considerations above, to use the discrete fracture network (DFN) to simulate the distribution of natural fractures and calculate the block size and its distribution. On this basis, the influence of the block size on rock mass integrity and mechanical properties are assessed.

Figure 2(a) shows the shape of blocks in the DFN model. In general, the spatial distribution of the blocks consists of three discontinuous joint sets. With the increase in discontinuous joint sets, however, the BSD will change obviously and the volume of blocks will decrease. Therefore, the block size is an expression of volumetric joint density, which is an important parameter of rock mass quality. However, the natural fractures have various characteristics, which could influence the volume of blocks and their distribution, as shown in Fig. 2(b).

Therefore, the BSD mainly depends on the fracture parameters, such as joint set orientation, joint spacing, joint sets number, and persistence, illustrated in Fig. 3. Based on the statistical distribution of fracture parameters, the algorithm written in the
R language, which is a programming language for statistical computing and graphics supported by the R Foundation for Statistical Computing, has been produced to calculate the volume of blocks and its distribution. Besides, this language is widely used among statisticians and data miners for developing statistical software and data analysis. The output results will show the block size and its distribution.

Figure 4 shows the basic procedure for calculating the block size and its influence on rock mechanical properties. To generate the geometrical rock mass, therefore, the fundamental natural fracture characteristics in the real case, such as location, persistence, orientation, and density, are needed. However, these parameters in fractured rock mass at depth cannot be completely extracted. Actually, the characteristics of the natural fractures obey the probability distribution. Therefore, the distribution of fracture parameters is assessed based on the boreholes’ data. According to the DFN model, the spatial distribution of fractured rock mass is reconstructed. To calibrate the numerical model, the simulation results are compared with the field test results. Then, the block size and its distribution are calculated using the R language. Finally, rock behavior during

![FIG. 5. Estimated location of boreholes in the research area.](image-url)
underground mining with different block sizes could be studied. Based on the results, the influence of the block size on rock mechanical property is analyzed.

In order to obtain the fracture parameters, a field experiment was conducted at Yilgarn area, Western Australia, illustrated in Fig. 5. Some boreholes were arranged in the research area, and the boreholes core logging data were extracted to investigate the distribution parameters of pre-existing fractures. Based on the borehole data, basic input fracture parameters used for the calculation of the block size are mapped and analyzed from core logging and geological data.

III. MEASUREMENTS OF FRATURES CHARACTERISTICS

Natural fractures have various characteristics that affect the distribution of fractures, such as location, orientation, persistence, and density. In order to rebuild the fractured rock mass model, the basic parameters are needed based on the on-field experiment. Figure 6 shows the measure of fracture characteristics based on boreholes, whose orientations are perpendicular to the ground, illustrated in Fig. 6(d). In this paper, the photos of the core are taken after being processed. Based on the scale ratio on the core photo, the fracture parameters can be directly measured, as shown in Figs. 6(a) and 6(b). In the natural fractured rock mass, the fractures are randomly and discontinuously distributed. However, it is impossible to obtain all parameters in the fractured rock mass at depth. As a consequence, the probability distribution is used to reconstruct the spatial distributions of natural fractures. The DFN model is a mathematical representation of natural fracture characteristics. After obtaining the basic parameters of natural fractures, the spatial fracture distribution model is rebuilt through the DFN model, as illustrated in Fig. 6(c).

As an essential component of blocks, fracture orientation represents the direction of the joint rock surface. In this paper, the fracture orientation is calculated based on the core data. Based on the boreholes data, the natural fractures are transformed into a stereonet graph, as shown in Fig. 7. It is apparent that the joint orientations are concentrated on three clusters, which are differentiated based on the percentage. Meanwhile, the domain area is the original distribution of joint orientations. Based on the distribution of clusters, fracture orientations are calculated. According to the measurement results, three joint sets are created in the study region based on the information of the joint set generated from the probabilistic calculation, and their values are listed in Table I.

One of the essential characteristics in DFN modeling is fracture persistence, which expresses the fracture extent and is one of the most challenging properties to measure the fractured mass directly. Only by completely dismantling a given coal and rock mass, could it

| Fracture parameter | Value   |
|--------------------|---------|
| Joint set 1        | $60 \pm 5$ | $160 \pm 8$ |
| Joint set 2        | $26 \pm 4$ | $126 \pm 3$ |
| Joint set 3        | $3 \pm 2$  | $270 \pm 6$  |
| Joint set 1 and 2  | $40$      |
| Joint set 2 and 3  | $24$      |
| Joint set 3 and 1  | $60$      |
| Joint set 1        | $1m$      |
| Joint set 2        | $0.5m$    |
| Joint set 3        | $0.9m$    |
be possible to trace and to measure the complete area of each fracture. In most cases, fracture persistence is calculated based on the empirical formula. Besides, the shapes of natural fractures could be divided into discs and polygons. However, the polygonal fractures have a more complex geometry. As a consequence, the circular fractures are selected in this paper to study the fracture distribution. Meanwhile, the fracture size is defined in terms of equivalent radius, which is closely related to the trace length (Karimzade et al., 2017). Their relationship could be expressed as follows:

\[ R = 0.3L + S, \]  

where \( R \) is the radius of natural fracture, \( L \) is mean trace length, and \( S \) is the standard deviation.

Another critical fracture parameter affecting the distribution of blocks in the fractured rock mass is the spacing, which is the perpendicular distance of two joints. Spacing is one of the essential parameters of a joint set, which describes the development of natural fractures and has a direct effect on slope stability and the block size. Generally, the fracture spacing is characterized by density in DFN modeling, which is divided into three types: linear density (\( P_{10} \)), areal density (\( P_{21} \)), and bulk density (\( P_{32} \)), meaning the fracture numbers per unit length, the fracture length per unit area, and the fracture area per unit volume (Dershowitz et al., 2000). Figure 8 shows the distribution of fracture spacing in the research area. Analyzing the data indicates that the spacing follows a lognormal distribution model. Although the parameters of probability distribution function change with fracture joint sets, the overall trend of the curves is consistent.

According to the results of field measurement in Yilgarn area, Western Australia, and statistical analysis, the basic input fracture characteristics used for DFN modeling are listed in Table I. On this basis, the volume of blocks in fractured rock mass at depth and its distribution were calculated.

### IV. CALCULATION OF THE BLOCK SIZE

According to the geometry, the volume of blocks in fractured rock mass could be calculated as follows (Cai et al., 2004):

\[ V_b = \frac{s_1s_2s_3}{\sin \gamma_1 \sin \gamma_2 \sin \gamma_3 \sqrt{p_1p_2p_3}}, \]  

where \( V_b \) is the block size, \( s \) is fracture spacing, \( \gamma \) is the angle of joint sets, and \( p \) is the persistence of joint.

Due to the discontinuity of fracture joints, however, the equivalent continuous joint spacing must be found to use the equation below. Considering the little effect of short joint on the stability of the cavern, the combined persistence factor \( P_i \) is defined as follows:

\[ P_i = \begin{cases} L, & l_i < L, \\ 1, & l_i \geq L, \end{cases} \]  

where \( l_i \) is the cumulative joint length of joint set \( i \) and \( L \) is the characteristic length of the rock mass.

According to the results of measuring in the field, the basic fracture parameters used to calculate the BSD are list in Table II. Then the algorithm code written in the R language is produced to calculate the block size. On this basis, the distribution of the block size is assessed.

### V. DISTRIBUTION OF BSD IN THE ROCK MASS

Figure 9 shows the volume of the block size and its distribution in the naturally fractured rock mass. Typically, the best way to characterize the block size relies on the average \( V_{B25} \), \( V_{B50} \), and \( V_{B75} \), describing the volume of blocks accounting for 20%, 50%, and 70%, respectively. Analyzing the data indicates that \( V_{B25} = 3.4 \text{ dm}^3 \), \( V_{B50} = 6.4 \text{ dm}^3 \), and \( V_{B75} = 11.2 \text{ dm}^3 \). Therefore, the volume of blocks in this research area is quite

### TABLE II. Input data of fracture characteristics for calculating the block size.

| Input parameter | Joint set 1 | Joint set 2 | Joint set 3 |
|-----------------|-------------|-------------|-------------|
| Angle           | 40          | 24          | 60          |
| Persistence factor | 1          | 0.5         | 0.9         |
small, which indicates the high development of natural fractures in the fractured rock mass. For rock mass conditions, however, the results show that the study area has a heavily jointed rock mass. Therefore, the stability of this rock mass is unstable for excavation. In addition, the rock mass has very good fracture networks, which will be the most suitable for the \textit{in situ} leaching mining method.

To study the variation of the block size with natural fracture parameters in the research area, this paper removes some small natural fractures and then calculates the distribution of the block volume using the R language. The results are illustrated in Fig. 10. Analyzing the data shows that the block size increases with the increase in the removal of natural fracture persistence, and the magnitude of the growth gradually increases. The main reason for this phenomenon is the spacing of natural fractures, which increases with the removal of some small fractures. As a consequence, the volume of blocks is increased. Meanwhile, the overall distribution of the block size with all scenarios in the fractured rock mass is consistent.

\section*{VI. ROLE OF BSD IN ROCK MASS MECHANICAL BEHAVIOR}

Based on the above analysis, there are various types of rock mass behaviors during underground mining based on mechanical characteristics. The main reason is that the grains of the different rock mass, i.e., blocks, vary greatly in size and shape. Therefore, the block size plays a crucial role in rock mass behavior. According to Hoek–Brown criterion, the strength could be calculated as follows:

$$\sigma_{CM} = \sigma_C \sqrt{S},$$

where $\sigma_{CM}$ is the maximum failure strength, $\sigma_C$ is the tensile strength, and $S$ is the characteristic parameter of a rock mass. Based
on the different block sizes, the parameter could be calculated as follows (Palmstrom, 2005):

\[ S = \begin{cases} e^{\frac{RMR-100}{9}} \\ e^{\frac{GSI-100}{9}} \end{cases} \]

(5)

where RMR and GSI are the rock mass classifications, respectively.

Based on the above analysis, the mechanical properties of rock mass change with block sizes, resulting in various types of behaviors. Figure 11 shows the deformation of rock mass during excavation. It is apparent that the extent of damage in the sections is different, which indicates that the block size plays an important role in the deformation of rock mass during underground activities.

In order to analyze the influence of the block size on rock mass mechanical characteristics and behavior, the spatial distribution of rock mass with natural fractures is rebuilt using the DFN model, as shown in Fig. 12(a). The size of the basic model is 50 * 50 * 8 m$^3$. On this basis, a tunnel with a radius of 6 m is excavated. According to the field experiment, the mechanical characteristics of natural fractures are listed in Table III, and the initial stress applied to the model is shown in Fig. 12(b).

### TABLE III. Input data of fracture mechanical

| Material     | Parameter          | Value  |
|--------------|--------------------|--------|
| Rock mass    | Density (kg m$^{-3}$) | 2200   |
|              | Poisson            | 0.25   |
|              | Young modulus (GPa)| 6.9    |
|              | Shear modulus (GPa)| 2.7    |
|              | Friction (deg)     | 35     |
|              | Bulk (GPa)         | 4.6    |

VII. RESULTS AND DISCUSSION

Figure 13 shows the deformation of fractured rock mass during underground activities. Analyzing the data indicates that the maximum displacement of the rock mass is 8.22 cm. According to the on-site monitoring, the displacement of the rock mass in underground mining is 7.6, which is consistent with the simulation results and proves the reliability of the simulation method, thus laying a good foundation for analyzing the influence of the block size on rock mass deformation.

Figure 14 shows the various types of rock mass behavior and mechanical properties with different block sizes. Based on the above analyses, the volume of the blocks mainly depends on fracture spacing. As a consequence, the fractured rock mass with different fracture densities is rebuilt, and the various types of rock mass deformations are assessed. Analyzing the data indicates that the deformation of the rock mass is 1.97 cm when the fracture density is 0.35 m$^{-1}$. However, when the density increases to 0.1 m$^{-1}$, the maximum displacement is 8.73. It is apparent that the deformation degree increases with the natural fracture density. However, the block size has a negative relationship with the fracture density. Therefore, the maximum displacement increases with the decrease in the block size. The main reason for this phenomenon is that the...
integrity and mechanical properties of rock mass decreases with the decrease in the block size.

VIII. CONCLUSIONS

Rock mass has various types of behaviors during underground activities, which has a close relationship with the rock mass integrity and mechanical properties. Typically, the rock mass deformation is assessed based on the empirical methods, i.e., the rock mass classification systems. Actually, the block size distribution could be a better indicator in assessing the rock mass mechanical properties and behavior. In this paper, therefore, the blocks were generated with the pre-existing natural fractures using the DFN model, and the subsurface fractures from the depth of 1500 m–2500 m were mapped from core logging. Using the R language, the volume of blocks and their distribution were studied. The results show that the volume of the block in the study area is small, indicating that naturally fractured rock mass is heavily jointed. As a consequence, the stability of rock mass in this research area is unstable for excavation. Besides, the variation of rock mass behavior with different block sizes shows that the deformation degree increases with the decrease in the block size, which indicates that the rock mass mechanical properties are decreased correspondingly.

This paper improves our understanding of the dependence of rock mass mechanical properties and its movement on the block size.

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