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Estimation of In-Situ Block Size Distribution in Jointed Rock Masses using Combined Photogrammetry and Discrete Fracture Network

Mohammad Ghaedi Ghalini[1], Mojtaba Bahaaddini[2,3*] and Mohammad Amiri Hossaini[4]

1- Department of Mining Engineering, Higher Education Complex of Zarand, Zarand, Iran
2- School of Mining Engineering, College of Engineering, University of Tehran, Tehran, Iran
3- Shahid Bahonar University of Kerman, Kerman, Iran
4- Mining and Geology Researches Department, Golgohar Mining and Industrial Company, Sirjan, Iran

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Abstract

Estimation of the in-situ block size is known as a key parameter in the characterization of the mechanical properties of rock masses. As the in-situ block size cannot be measured directly, several simplified methods have been developed, where the intrinsic variability of the geometrical features of discontinuities are commonly neglected. This work aims to estimate the in-situ block size distribution (IBSD) using the combined photogrammetry and discrete fracture network (DFN) approaches. To this end, four blasting benches in the Golgohar iron mine No. 1, Sirjan, Iran, are considered as the case studies of this research work. The slope faces are surveyed using the photogrammetry method. Then 3D images are prepared from the generated digital terrain models, and the geometrical characteristics of discontinuities are surveyed. The measured geometrical parameters are statistically analysed, and the joint intensity, the statistical distribution of the orientation, and the fracture trace length are determined. The DFN models are generated, and IBSD for each slope face is determined using the multi-dimensional spacing method. In order to evaluate the validity of the generated DFN models, the geological strength index (GSI) as well as the stereographic distribution of discontinuities in the DFN models are compared against the field measurements. A good agreement has been found between the results of the DFN models and the filed measurements. The results of this work show that the combined photogrammetry and DFN techniques provide a robust, safe, and time-efficient methodology for the estimation of IBSD.

1. Introduction

The increase in the human need for ore minerals and the progress of open-pit mines to extract deep reserves have pushed the mining companies to optimize their mining operations from different aspects. Collection of high-quality data and employing advanced measurement techniques are now vital to optimize mine extraction as well as improving safety condition.

Determination of the geometrical structures and mechanical properties of rock masses is of great importance in the mine design, drilling and blasting operations, as well as the stability analysis in open-pit mines. The common methods for measurement of the geometrical properties of jointed rock masses involve data collection from boreholes, outcrop exposures, and surface or underground excavation faces. These conventional techniques are manual, time-consuming, disruptive to mine operations, and expose the staff to hazardous conditions. The collected data, especially in open-pit mines, are also expose to several limitations due to difficulties of the physical access to rock exposures. The recent developments in unmanned techniques such as photogrammetry and laser scanning have provided an opportunity for a high-quality, fast, real-time, and safe data acquisition as well as an efficient monitoring of the mining process [1, 2].

Corresponding author: m.bahaaddini@ut.ac.ir (M. Bahaaddini).

The intersection of discontinuities in a jointed rock mass results in the generation of individual rock blocks. Due to the stochastic nature of size, spacing, and orientation of discontinuities, a range of block sizes are generated, which is represented as the in-situ block size distribution (IBSD). IBSD is a key parameter in the rock engineering projects from different aspects such as rock mass classification, excavation and support design in the underground activities, stability analysis, drilling and blasting operations, and hydro-geological analyses [3]. The number of joint sets, persistency, fracture frequency, and orientation has been well understood as the effective parameters on the block sizes.

As our information about the internal structure of discontinuities in jointed rock masses is limited, the in-situ block size cannot be determined directly. A number of studies have been undertaken in the previous studies in order to estimate IBSD. Da Gama [4] has developed a computer simulation algorithm to measure the block sizes based on the filed measurement of persistent discontinuities. Stewart [5] has reported a simulation result of the IBSD estimation in a molybdenum mine using a computer program. In this study, the statistical parameters of discontinuities were used in the Monte Carlo simulation based on the surveyed data from scanline mapping. Xu and Cojean [6] have developed a model for simulation of the rock mass granulometry, and an advancement was made in considering the connectivity of rock joints. Kleine and Villaescusa [7] have developed a rock mass model that takes into account the finite extension, location, and orientation of discontinuities. However, they have assumed that the intact blocks of a specific size occur with the same frequency of the measured discontinuity spacing. Wang and his co-workers [8-10] have developed two techniques, namely equation and dissection methods, and both methods have been implemented in computer codes. In the equation method, the empirical equations were employed to relate IBSD to the mean spacing and mean orientation of three principal sets of discontinuities. Wang *et al.* [10], based on the block theory proposed by Goodman and Shi [11], have developed an algorithm to determine the sizes and shapes of the blocks generated by persistent planes within the boundary block. Dershowitz and Herda [12], by considering the finite size of discontinuities, have devised a 3D stochastic simulation procedure in order to generate a discrete fracture network (DFN) model. The validity of this model was checked in an iterative process to meet the trace length statistics of the measured data. Maerz and Germain [13] have developed a software package to measure IBSD, which was limited to three persistent joint sets.

An analytical method has been suggested by Lu and Latham [14] to study the effect of spacing distribution on the IBSD, while their analysis was limited to three sets of persistent joints. The most widely used analytical equation for determination of block sizes refers to Palmstrom [15], where the equivalent block volume V_b is measured by the spacing S and intersection angle γ of three joint sets:

$$V_b = \frac{S_1.S_2.S_3}{\sin\gamma_1 \sin\gamma_2 \sin\gamma_3} \quad (1)$$

Cai *et al.* [16] have investigated the effect of joint persistency p on the block volume, revising Eq. (1) into the following form:

$$V_b = \frac{S_1.S_2.S_3}{\sqrt[3]{p_1 p_2 p_3}\sin\gamma_1 \sin\gamma_2 \sin\gamma_3} \quad (2)$$

Jern [17], based on the dimensional analysis, has developed an analytical method for estimation of IBSD. Latham *et al.* [18], by reviewing the previously developed methods for estimation of IBSD, have shown that the Wang's equation method and the Palmstrom's weighted joint density can provide a practical basis for prediction of IBSD. Kim *et al.* [19] have statistically analysed the effect of joint orientation, spacing, and persistency on the bock sizes using distinct element codes. Elmouttie and Poropat [20] have developed a DFN model based on the Monte Carlo simulations of the joints combined with a polyhedral modeler to predict IBSD. Elmo *et al.* [21] have evaluated the ability of the DFN models for estimation of the equivalent rock mass properties for continuum modelling, showing that this approach can improve the predictability of the geo-mechanical simulations and the empirical rock mass classification systems. Miyoshi *et al.* [22] have developed a new approach for estimation of the geological strength index (GSI) for spatially variable rock masses using a stochastic representation of the 3D fracture networks and block size analysis. Stavropoulou and Xiroudakis [23], by considering the finite persistence of three rock joint sets, have presented a close-form cumulative block volume proportion function based on the fracture frequency of drill cores.

A review of the previous studies clearly shows that the simulation of the stochastic nature of the finite size fractures as well as the limitations of the conventional techniques for geometrical characterization of rock joints are the two main challenges existing for estimation of IBSD. The recent developments in the photogrammetry technique have provided an opportunity for a fast and cost-efficient digitisation of the rock surface exposures. In the photogrammetry techniques, the 3D spatial data can be measured from two or more 2D images taken from the same scene. The application of photogrammetry in the engineering problems had been limited in the past due to the special difficulties for automatic extraction of the 3D data, limitation of the computation systems, and problems of the film-based cameras. These limitations have been largely resolved in the recent years by the enhanced development of digital cameras and the emergence of high-speed computers [24]. This technique is now successfully employed in different large-scale mining and civil related projects such as 3D spatial modelling in the open-pit mines [25, 26], rock slope characterisation [27-30], structural mapping [31], tunnel-face mapping and underground mining performance [32-35], measuring the surface roughness of rock joints [36-38], as well as monitoring the strain rate and displacement in the geotechnical physical modelling projects such as soil slopes [39, 40].

Simulation of the jointed rock mass using deterministic joint geometrical parameters can lead to both over- and under-conservative designs and neglect the inherent variability in the joint parameters [41]. DFN modelling is a stochastic approach for simulation of the fracture systems in a rock mass, which captures the inherent rock mass structural variability. In order to generate a DFN model, distribution of the geometrical properties of discontinuities is required to be collected. The quantity of the collected data is vital as the DFN model incorporates in the variability of the data [42, 43]. A high-quality input data ensures that a DFN model is representative of the field observations, and it is a reliable model for further rock mechanics analyses.

This work aims to develop a method for estimation of the in-situ block size distribution using the combined photogrammetry and DFN methods. Four blasting, the benches in the Golgohar iron mine No. 1, located in Sirjan, Iran, were considered as the case studies. The slope face of these benches was surveyed using the photogrammetry techniques. The collected image data was processed using the photogrammetry technique in order to generate the point clouds and digital terrain models (DTMs). The geometrical characteristics of joints were measured, and the statistical analyses were carried out in order to determine the probability distribution functions. Then the DFN models were generated, and the in-situ block sizes for each blasting bench were measured. In order to investigate the validity of the generated DFN models, the results obtained were compared against the field measurements.

2. Photogrammetry

The field measurements of this work were carried out at the Golgohar iron mine No.1. The Golgohar mine is located in the Kerman province, Iran, 55 km south-west of Sirjan, and 325 km north-east of Shiraz, between the 55°15'40"E and 55°22'33"E longitudes and the 29°03'10"N and 29°07'04"N latitudes, 1740 m altitude above the sea level. This mine contains six anomalies with approximately 1135 million tonnes of iron ore [44]. The selected benches of this work were located in the main anomaly in the iron ores at different locations of the open-pit mine.

Photogrammetry was carried out at four benches having 15 m height, in the magnetite iron ore. An essential step before taking the pictures is the camera and lens calibration (interior orientation), which is carried out in order to prevent 3D image distortion. In the calibration process, the coordinate of points in the images can be determined with the accuracy of up to one tenth of a pixel, while the distortion may lead that the apparent locations being shifted internally dozen of pixels [45]. The calibration parameters are the focal length (C), radial lens distortion (K_1, K_2, K_3, K_4), principal point offset in the x and y directions (X_p, Y_p), decentring distortion (P_1, P_2), and scaling factors (B_1 and B_2). A Canon 5DMKII0244 mark II camera was used in this work. The camera calibration was carried out using the 3DM CalibCam software (for more details, the readers are referred to 3DM Analyst Manual [45]). Then a few control points (at least 3 points) were surveyed on the slope using the total station camera to scale the model, as shown in Figure 1. The relative-only points were then automatically generated by the 3DM CalibCam in order to determine the relationship between the camera positions in the 3D space. The common points were then identified in each pair of images to project the rays into the scene, followed by the determination of the 3D coordinates of the captured points. The 3D images of the slope faces were then generated (Figure 1), and these images were used for joint surveying.

Figure 1. Generated 3D image of bench face (location of control points is shown by red circles).

In order to measure the geometrical characteristics of the rock joints, the 3DM Analyst software was used. In order to measure the joint orientations, 3 points were manually selected on the joint surface, and the representative planes passing through these points were created. The trace length of the rock joints was also measured using the size of the representative circles. A typical surveyed rock joints on the slope face is shown in Figure 2.

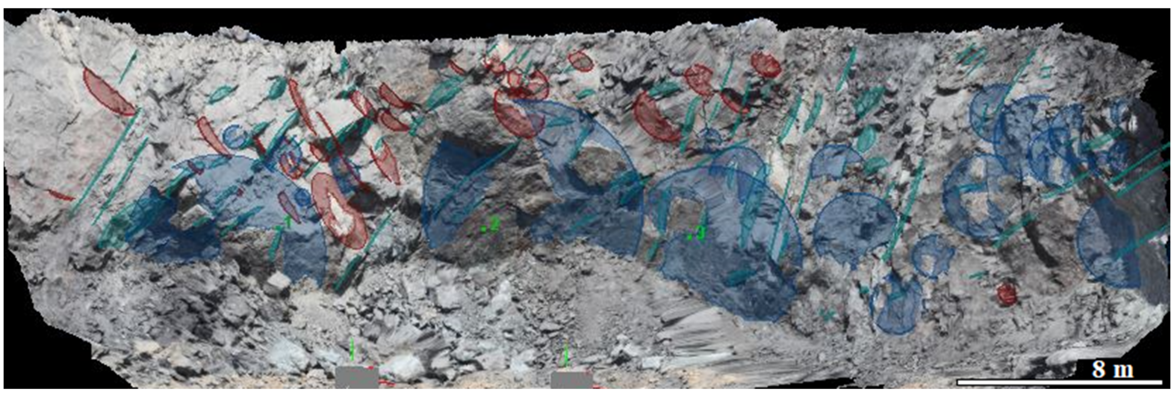

Figure 2. Measurement of joint geometrical characteristics using 3D images.

3. Discrete fracture network (DFN) model

The required parameters for generation of the DFN models includes the number of joint sets, statistical parameters of the orientation, trace length for each joint set, and fracture intensity. The surveyed dip and dip direction of each joint set was imported into the Dips software. Then the number of joint sets were identified based on the pole clusters on the stereogram, and the corresponding dip, dip direction, and statistical parameter of the Fisher constant were determined for each joint set. These parameters are summarized in Table 1.

Table 1. Measured orientation parameters of joint sets for each slope face.

Slope face	Joint set	Dip	Dip direction	Fisher constant
15-417	1	54	203	33.53
	2	71	352	34.64
	3	78	106	229.03
15-408W	1	72	199	13.99
	2	14	251	16.22
	3	84	6	41.15
15-411	1	46	172	12.87
	2	77	57	28.49
	3	63	289	38.96
15-408E	1	65	209	33.96
	2	13	204	37.48
	3	80	116	18.65

The statistical parameters of the fracture trace length were determined using the Minitab software, as shown in Figure 3. The most appropriate statistical distribution was selected amongst different distribution types, which provides the highest significance level. The statistical parameters of the fracture trace lengths are summarized in Table 2.

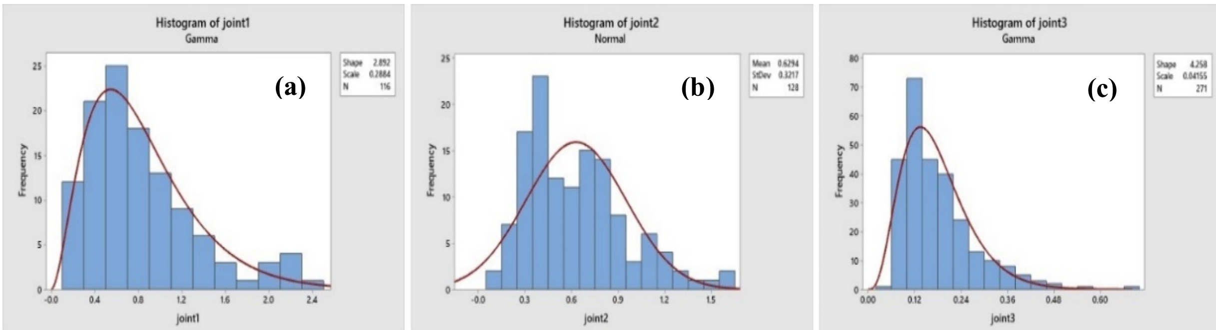

Figure 3. Statistical distributions of fracture trace length for slope ID 15-408E a) first joint set b) second joint set c) third joint set.

Table 2. Statistical parameters of fracture trace lengths.

Slope face	Joint set	Type of distribution	Parameter
15-417	1	Normal	Mean = 0.82, SD = 0.26
	2	Normal	Mean = 0.69, SD = 0.29
	3	Gamma	Shape = 4.56, scale = 0.69
15-408W	1	Gamma	Shape = 2.35, scale = 0.14
	2	Gamma	Shape = 2.86, scale = 0.12
	3	Gamma	Shape = 4.82, scale = 0/06
15-411	1	Exponential	Mean = 0.68
	2	Normal	Mean = 0.72, SD = 0.35
	3	Exponential	Mean = 1.387
15-408E	1	Gamma	Shape = 2.89, scale = 0.29
	2	Normal	Mean = 0.63, SD = 0.32
	3	Gamma	Shape = 4.258, scale = 0.04

The fracture intensity was measured by dividing the sum of the trace lengths by the area of the studied surface (P_{21}). For generation of the 3D DFN models, the fractures area per block volume (P_{32}) is required, which cannot be measured directly. Therefore, the proportionality relation between P_{32} and P_{21} was used, where P_{32} in the DFN models were changed in the iterative process to reproduce the measured P_{21} [22]. By determination of the input parameters, the DFN model for each slope face was generated. A typical generated DFN model is shown in Figure 4.

4. Estimation of in-situ block size distribution

The in-situ block size distribution was determined for each case study using the multi-dimensional spacing (MDS) method. In this method, several points are randomly selected in the generated DFN model. For each point, the lines in three specified directions are generated, and the location of the fractures intersecting each line is recorded. From the recorded lengths between the fractures, the spacing frequency distribution is measured in three directions. The frequency distribution of the block volumes is then created by multiplying the spacing probability distributions using the Monte Carlo sampling technique [46]. The predicted mean block volume and the size distribution of the in-situ blocks are shown in Table 3 and Figure 5, respectively.

Table 3. Predicted mean block volume using DFN model.

Slope face	15-417	15-408W	15-411	15-408E
Mean block size (m^3)	0.08	0.31	0.09	0.15

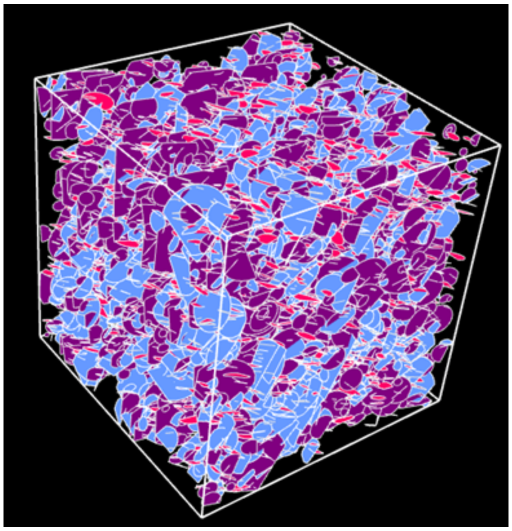

Figure 4. A generated DFN model.

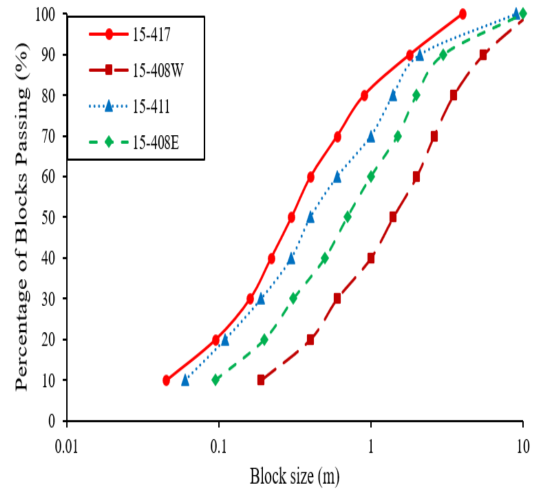

Figure 5. Predicted in-situ block size using DFN model.

5. Validation study

As the input data for generation of the DFN models were obtained using the statistical analysis of the joint survey of the slope faces, and the 3D DFN models were also created through a statistical process, it is important to investigate the validity of the generated models. To this end, the generated DFN models were compared against the field measurements.

Two approaches were employed for the validation study. First, the scattering of discontinuities in stereograms for the generated DFN models were compared against the filed measurements. The results of this comparison are shown in Figure 6. The same patterns were observed in the simulated DNF models compared to the field measurements, and the comparison showed a good agreement between them. The second approach for the validation study involves comparing the measured GSI in the generated DFN models against the filed measurements. For each slope face, the GSI value was measured in the field. GSI was estimated in the DFN models using the average block volume V_b and the joint surface conditions J_C as [15]:

$$GSI=\frac{26.5 + 8.79\, Ln\, J_c + 0.9\, Ln\, V_b}{1 + 0.0151\, Ln\, J_c - 0.0253\, Ln\, V_b} \quad (3)$$

The measured and estimated GSI values for each slope face are presented in Table 4. The difference in the estimated GSI values is less than 10% in all the studied benches. Therefore, both the estimated GSI values and the stereogram presentations of discontinuities in the DFN models are in good agreement with the field measurements, and it can be concluded that the DFN models provide a 3D simulation of discontinuities with a high accuracy and validity.

Table 4. Comparison of GSI values from field measurements and DFN models.

Slope face	Geological strength index (GSI)	
	Field measurement	DFN model
15-417	54.23	58.23
15-408W	51.51	57.01
15-411	54.06	55.4
15-408E	58.67	60.14

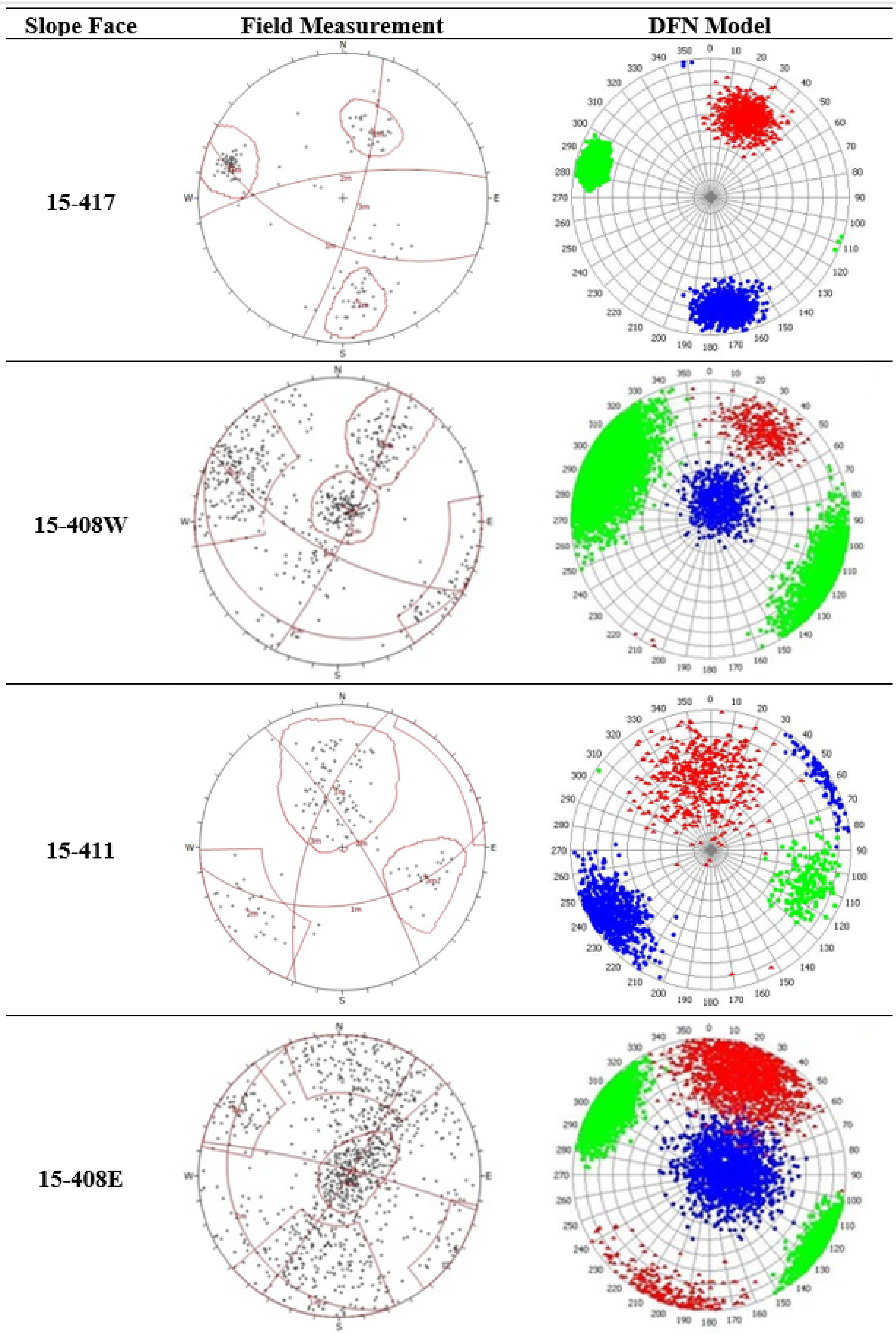

Figure 6. Comparison of pole distributions of discontinuities from filed measurements and DFN models.

6. Conclusions

In this work, the combined photogrammetry and DFN techniques was suggested as an efficient and robust technical tool for estimation of IBSD in the jointed rock masses. Four blasting benches in the Golgohar iron mine were selected as the case studies of this research work. The photogrammetry technique was employed to survey the slope faces, and the geometrical characteristics of discontinuities were measured from the generated (3D) images. This methodology was found as a high-quality, time-efficient, and safe technique compared to the common manual approaches for discontinuity surveying. The DFN models were then generated using the statistical parameters that were determined through the statistical analysis of joint surveys. IBSDs were determined from the DFN models using the multi-dimensional spacing analysis. IBSD is a key parameter in the stability analysis of the slope faces as well as the drilling and blasting performance. In order to investigate the validity of the DFN models, the stereographic distribution of the fractures as well as the estimated GSI values in the DFN models were compared against the filed measurements for each slope face, and good agreements were found.

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تخمین توزیع ابعادی بلوک برجا در توده سنگ با استفاده از تلفیق فتوگرامتری و شبکه شکستگی مجزا

محمد قائدی قالینی[۱]، مجتبی بهاالدینی[۲،۳]* و محمد امیری حسینی[۴]

۱- بخش مهندسی معدن، مجتمع آموزش عالی زرند، زرند، ایران

۲- دانشکده مهندسی معدن، دانشکدگان فنی، دانشگاه تهران، تهران، ایران

۳- بخش مهندسی معدن، دانشکده فنی و مهندسی، دانشگاه شهید باهنر کرمان، کرمان، ایران

۴- مرکز تحقیقات معدن و زمین‌شناسی، شرکت معدنی و صنعتی گل گهر، سیرجان، ایران

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* نویسنده مسئول مکاتبات: m.bahaaddini@ut.ac.ir

چکیده:

تخمین اندازه بلوک برجا به عنوان یک پارامتر کلیدی در توصیف خواص مکانیکی توده سنگ شناخته می‌شود. از آنجا که اندازه بلوک برجا بصورت مستقیم قابل اندازه‌گیری نمی‌باشد، چندین روش ساده برای این منظور ارائه شده است که در آن ماهیت ذاتی متغیر خواص هندسی ناپیوستگی‌ها غالباً نادیده گرفته شده است. هدف از این تحقیق، تخمین توزیع ابعادی بلوک برجا با تلفیق روش‌های فتوگرامتری و شبکه شکستگی مجزا (DFN) می‌باشد. برای این منظور، چهار پله انفجاری در معدن شماره یک گل گهر سیرجان به عنوان موارد مطالعاتی در نظر گرفته شده است. سطح دیواره این پله‌ها با استفاده از روش فتوگرامتری برداشت شد و سپس تصاویر سه بعدی از مدل رقومی تهیه و در ادامه خواص هندسی ناپیوستگی‌ها برداشت گردید. خواص هندسی برداشت شده مورد تجزیه و تحلیل آماری قرار گرفته و شدت درزه‌داری، توزیع آماری جهت‌داری و طول رخنمون تعیین گردید. سپس مدل‌های DFN ساخته شد و توزیع ابعادی بلوک برجا برای هر سینه‌کار با استفاده از روش فاصله‌داری چند بعدی تعیین گردید. برای ارزیابی اعتبار مدل‌های DFN ساخته شده، شاخص مقاومت زمین‌شناسی (GSI) و توزیع استریوگرافیک ناپیوستگی‌ها در مدل‌های DFN با برداشت‌های صحرایی مقایسه شد و انطباق مناسبی بین نتایج مشاهده گردید. نتایج این مطالعه نشان می‌دهد که تلفیق روش‌های فتوگرامتری و DFN می‌تواند روشی کارآ با صرفه زمانی و ایمنی بالا برای تخمین توزیع ابعادی بلوک برجا فراهم نماید.

کلمات کلیدی: توده سنگ درزه‌دار، اندازه بلوک برجا، فتوگرامتری، شبکه شکستگی مجزا، معدن سنگ آهن گل گهر.