

How to determine the appropriate methods to identify the geometry of in situ rock blocks in dimension stones

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Received: 24 February 2015 / Accepted: 18 June 2015 / Published online: 1 July 2015
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Abstract The present article reviews various methods for discontinuity and rock block survey. The variety of techniques to determine the shape and size distribution of the rock blocks were divided into index and modeling methods. The index methods calculate the average size of a rock block as a representative of the rock mass. These methods are simple, cheap and fast, but are associated with large errors because of the presence of the rock mass of rock blocks with different geometries. Hence, index methods are not recommended. In modeling techniques, discontinuity surveys try to model the rock mass realistically to determine the geometry of all blocks with different algorithms. These methods also have some defects in modeling the discontinuities and calculating the geometry of blocks. In order to perform an evaluation of all methods, six conditions were identified to determine the method for surveying rock blocks. The conditions include the ability to model random discontinuities and joint sets with specific dimensions, the inability to simulate discontinuities with statistical methods (the ability to study a discontinuity network separately), determining the geometry of all rock blocks, considering the dangling and isolated discontinuities, simplicity, and three-dimensionality. Based on the above requirements, a new approach is proposed to determine suitable methods for use in the evaluation of dimension

stones. This new methodology was applied in a limestone quarry in Joshqan, Iran, to verify the applicability of the different methods in dimension stone quarries.

Keywords Dimension stones · In situ rock blocks · Discontinuities survey · Block detection · Joshqan

Introduction

The geometry of rock blocks is one of the most important factors determining the features and behavior of the rock mass. The geometry of rock blocks including the shape and size is used in different branches of mining engineering for different purposes, such as determining the economic feasibility of dimension stone quarries (Elci and Turk 2014a; Saliu et al. 2012; Mutlutürk 2007; Sousa 2007, 2010; Turanboy 2010; Saliu and Idowu 2014), designing the blasting patterns and parameters (Wang et al. 2003; Hamdi et al. 2008; Hamdi and du Mouza 2005), determining the stability of the rock blocks (Goodman 1995; Goodman and Shi 1985; Jing and Stephansson 2007), and storage in underground and outdoor spaces (Zhang et al. 2010, 2012; Elmouttie et al. 2013).

The first step in determining the geometry of the rock blocks is to survey the existing discontinuities and assign a network of discontinuities to the rock mass in a specified range. There are various discontinuities in the rock masses including microcracks, cracks, joints, faults, rock layers, etc. (Dearman 1991; Jaeger et al. 2009). However, the most important discontinuities in the dimension stones are joints which often lead to the formation of different blocks in the rock mass. The data obtained from discontinuity surveys are the inputs of all methods for determining the geometry of the blocks and are considered as the most fundamental

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parameter in the development of the rock blocks. Therefore, the method used for joint surveying is of great importance in determining the geometry of the rock blocks. The major errors in calculating the size and shape of the rock blocks are related to the input data (discontinuities network). Thus, the methods with fewer errors should be identified and used to survey discontinuities in dimension stones.

The next step in determining the geometry of the rock blocks is to calculate the size and shape of the blocks using a specified method. The methods of assessing rock block geometry can be classified into three categories: index evaluation, image-based measurement, and modeling technique. The image-based measurement methods are usually used in measuring the size distribution of broken rock fragments by processing the 2D images taken on the surface of a rock pile (Wang et al. 2003; Maerz and Germain 1996). The two other methods are usually used in dimension stones and other materials. The presence of discontinuities in most minerals that need fragmentation for separation is often an advantage. Usually, there are three or more sets of discontinuities in the rock masses containing these materials along with a large number of random discontinuities. However, discontinuities are considered to be a disadvantage in dimension stones, because they cause rock blocks to be smaller and may result in economic loss (Demarco et al. 2011, 2013b). Therefore, there are differences between dimension stones and other minerals to consider the geometry of rock blocks, and it is important to identify the methods which have more applicability with dimension stones. In this paper, the conditions for determining an appropriate method for calculating the geometry of rock blocks are identified, and the appropriate methods will then be determined according to those conditions. This allows companies or quarry owners and engineers to become more familiar with the various methods and choose an appropriate method to study the rock blocks' geometry in quarries.

Methodology

To identify and calculate the geometry of these blocks, the discontinuities network should be determined. There are often few discontinuities in dimension stones, and they are usually random. Therefore, more accurate methods should be used to survey these discontinuities. The main methods are explained, and methods which have fewer errors in dimension stones are proposed.

The next step in dimension stone evaluation is to calculate the volume and shape of these rock blocks. Some methods try to introduce the rock mass of in situ rock blocks by considering the spacing between the

discontinuities. These methods, called Index methods, are discussed. Some other methods for determining the geometry of in situ rock blocks involve defining a discontinuity network to the rock mass, and creating a model of rock mass based on the network. The geometry of rock blocks can then be calculated by implementing computational algorithms. The algorithms calculate the geometry of rock blocks by intersecting certain planes in space. These methods are called Modeling methods. The basis and assumption of the methods are different, and they should be compared before being used. These methods, with their specifications, will be explained and compared.

In order to determine the geometry of dimension stones rock blocks, there are some essential conditions which should be considered. There are some pros and cons to using the various methods of identifying rock block geometry, which should be identified. By taking into account several conditions, a new methodology will be presented to determine the appropriate methods which provide a higher accuracy when implemented in dimension stones. The basis and assumptions of the different methods should also be studied in order to determine the appropriate methods for identifying dimension stone rock block geometry. After considering the conditions, the shortfalls of each method will be determined, and the methods will be qualitatively compared. At the end, the most optimal method with more applicability in dimension stones will be determined.

A case study—in a limestone quarry in Joshquan, Iran—is presented to better illustrate the differences between the several methods.

Best methods for discontinuity and rock blocks surveys

Methods for discontinuities surveys

Before any design study can be initiated for a particular rock mass, a field investigation is needed to collect geologic and geotechnical data on features characterizing the rock mass in order to help evaluate its future response to construction (Mahé et al. 2015). Discontinuities is one of the geotechnical rock mass properties which plays an important role in the behavior and physical, mechanical, and hydromechanical characteristics of the rock mass. Therefore, the full knowledge of discontinuities is essential. The purpose of surveying discontinuities is to fit a network of discontinuities into the rock mass. However, the rock mass is heterogeneous, meaning that complete and accurate identification of discontinuities is almost impossible. Nevertheless, over time different methods have been provided for surveying discontinuities, given the existing

equipment. A discontinuity is characterized by dip, dip direction, direction, aperture, location, outcrop, shape, and size. In addition, density and spacing are the parameters related to a set of discontinuities, which determine the network of discontinuities in a rock mass. There are many uncertainties in the survey of all parameters of discontinuities, and this may cause large errors in predicting a network of discontinuities in the rock mass. However, different methods have been developed to fit the most appropriate network of discontinuities in the rock mass. Discontinuity surveys are often performed along a line (one-dimensional), on a plane (two-dimensional) or in space (three-dimensional). Several methods for discontinuity surveys are briefly described below.

Scanline and core sampling

Scanline survey is one of the very common one-dimensional methods for indirect discontinuity surveys. Upon a section of an exposure of rock surface, a tape with length marks is fixed onto the exposure in a chosen direction. The following information is measured and recorded in sequential order: the distance to the intersection of the discontinuity with the tape (measured from the starting end of the tape), the orientation, and the trace length (or half-trace length) of the discontinuities intersected by the measuring tape (Jing and Stephansson 2007; Priest and Hudson 1981; Bonnet et al. 2001). In this method, discontinuities not intersecting the scanline are not surveyed. Moreover, this method is not applicable in inaccessible parts of the rock mass. Since only two points (intersection of each joint by scanline) are chosen to calculate discontinuity spacing, this parameter cannot be accurately calculated because the space between two joints change in different levels. Although the scanline survey is a simple and cheap method, it results in large errors in most cases. Discontinuities are surveyed by using drilling cores in a similar way. This method can only provide spacing and orientation parameters of rock mass at great depths, not the discontinuity size (Jing and Stephansson 2007).

Window mapping

Because of the limits in using the scanline technique, a window mapping technique was developed to survey discontinuities in a specific region of the rock mass. This method is a two-dimensional mapping method which provides more details of the discontinuities. In this method, a square or circular part of the rock mass with specified dimensions is selected, and the characteristics of all existing discontinuities are measured (Jing and Stephansson 2007; Dershowitz and Einstein 1988; Bonnet et al. 2001). This technique provides better estimates of the

discontinuity trace lengths and densities and, therefore, improves the reliability of the sampling data. More discontinuities are surveyed by using window mapping when compared with the scanline survey. In addition, the properties of the discontinuities in this method are more realistic than in the scanline technique (for example, the mean distance between discontinuities (spacing) is calculated). In some cases, it is impossible to access all discontinuities by using window mapping.

Image processing

One of the new methods to determine the two- and three-dimensional discontinuities is to use images taken from the rock mass (Lato et al. 2010; Mah et al. 2011; Sturzenegger and Stead 2009; Tonon and Kottenstette 2006; Van Knapen and Slob 2006). In this method, their properties can be calculated by identifying the traces and faces of the discontinuities, and the dominant joint sets are determined. Sometimes, images taken from different angles are combined together and then analyzed for a better understanding. The advantages of this method include accessing and surveying inaccessible discontinuities, low cost, and high speed.

GPR technique

Ground penetrating radar (GPR) is a modern method to survey discontinuities (fractures) in three dimensions. In this method, discontinuities in the rock mass are predicted by sending electromagnetic waves into the rock mass and analyzing data from the back waves. This method is applicable in rock masses with few fractures. As an advantage, the GPR technique identifies discontinuities at shallow depths (about 40 m). In this method, the data from different paths are combined, and the discontinuity network in the study area is determined by establishing a survey network. This procedure is mainly used to survey joints in quarries and also to assess the quality of the rock blocks (Aqeel et al. 2014; Arosio et al. 2012; Porsani et al. 2006; Seren and Acikgoz 2012; Demarco et al. 2013a).

Best option in dimension stones

Depending on the importance of the project, one or more of the above methods are selected to survey discontinuities based on the discontinuities outcrop, access to the rock mass, and the density of discontinuities. In the case of dimension quarries, if the quarry face and steps are specified, the best option to survey discontinuities is a combination of window mapping and image-processing techniques. A combination of core drilling and GPR techniques is recommended for unexcavated quarries

reserves. After a discontinuity survey, a network of discontinuities must be assigned to the rock mass. In most rock masses with a large number of discontinuities, since all discontinuities cannot be surveyed using the collected data, the statistical distribution of parameters is determined by some technique such as Monte Carlo simulation (Wang et al. 2003). The statistical methods do not define a unique network for the discontinuities, but different networks will be produced by implementing distribution functions of different parameters. The next step is to analyze the discontinuity network to determine the geometric properties of the rock mass and its blocks.

Rock blocks surveying

Index methods

One of the important geometric computations in rock mechanics is calculating the size of rock blocks. One of the general methods is to use geometric parameters (index methods). The index methods calculate an average size of a block as a representative of the rock blocks. This simple, low-cost, and fast method is used when a general understanding of the rock mass is required. Discontinuity spacing is one of the most important parameters to determine the average size of the rock blocks.

Palmström et al. has conducted many studies on index techniques and proposed various indices such as volumetric joint count (J_v), shape factor, etc. for determining the shape and size of rock blocks (Palmström 1985; 1996a, b; Palmström et al. 2001; Palmstrom 2005). Warburton developed an algorithm and software to determine the geometric properties of in situ rock blocks

considering the geometric parameters of the rock mass; in this algorithm, the joints are assumed to be parallel and infinite (Warburton 1983, 1985). Lu and Latham, Starzec and Tsang, and Smith also studied block-ability upon the geometrical parameters (Lu and Latham 1999; Starzec and Tsang 2002; Smith 2004). In the case of dimension stones, block quality designation (BQD) was proposed by Elci and Turk to measure the size of the rock blocks in the in situ quarries in Turkey in 2014 (Elci and Turk 2014a).

Table 1 shows various parameters and indices defined for calculating the average block volume of rock mass. Index methods try to determine a set of dominant discontinuities in the rock mass. In these methods, the discontinuities in the study area are considered to be infinite. However, it is essential to consider all discontinuities accurately to design the pattern of cutting plane and advance in the dimension quarries. Index methods are approximate approaches and are appropriate for preliminary studies to determine the suitability of the rock mass for excavation of the rock blocks. On the other hand, these methods are able to determine the average size of the rock blocks and are not recommended for evaluation of mineral reserves.

Modeling approaches

With advances in computers and engineering sciences, new methods were developed to determine the geometry of the rock blocks. These methods try to model the rock mass components in computers and are thus called modeling methods. Modeling approaches detect the rock blocks created by discontinuities in the rock mass, and determine

Table 1 Some indices to determine the block volume in rock mass

Dim.	Measurements	Determination of V_b or J_v	References	
3D	Joint set spacing's (S_i)	$V_b = S_1 \times S_2 \times S_3 * (\sin_{\gamma_1} \times \sin_{\gamma_2} \times \sin_{\gamma_3})$	Palmström et al. 2001	
	Joints dip (γ_i)	$V_b \approx 5S_1^2 \times S_2$		
	Number of random joints (N_r)	$V_b \approx 50S_1^3$		
	Shape factor (β)	$J_v = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \dots + \frac{N_r}{S}$		
	Block quality designation (BQD)			$V_b = \beta \times J_v^{-3} \times (\sin_{\gamma_1} \times \sin_{\gamma_2} \times \sin_{\gamma_3})^{-1}$
				$V_b = \beta \times J_v^{-3}$
		$V_b = 1.88 \times \beta \times \text{BQD}^6 \times 10^{-12}$	Elci and Turk 2014b	
2D	Joints density in an area (Na)	$J_v \approx Ka * Na$	Palmström et al. 2001	
	Weighted jointing density in an area (wJd)	$J_v \approx wJd$		
1D	Joint density along a drill core or scanline (NI)	$J_v \approx Kl * NI$	Palmström et al. 2001	
	Rock quality designation (RQD)	$J_v \approx 35 - \text{RQD}/3.3$		
	Weighted jointing density along a line (wJd)	$J_v \approx wJd$		

ka = correlation factor, which varies mainly between 1 and 2.5 with an average value $ka = 1.5$. The highest value is where the observation plane is parallel to the main joint set

kl = correlation factor, which varies between 1.25 and 6, with an average value $kl = 2$

the geometry of each set separately. In these methods, the rock blocks are modeled in two and three dimensions using various mathematical techniques and algorithms to determine the size and shape of the rock blocks. First, discontinuities are simulated and modeled in order to determine the geometry of the rock blocks. Then, a certain discontinuity network is predicted for the rock mass. Discontinuities are generally assumed as straight lines and planes in two and three dimensions, respectively.

Discontinuities modeling Rock masses are generally heterogeneous, and it is almost impossible to determine the exact discontinuities network. However, a part of the rock mass with specified dimensions is usually evaluated, and a discontinuities network is assigned to it. In the rock masses with a large number of discontinuities, it is impossible to survey all discontinuities. Therefore, the discontinuity network should be simulated considering the surveyed discontinuities. To simulate discontinuities, the probability distribution functions of discontinuity such as spacing, aperture, direction, and slope should be determined. According to Priest and Hudson, the geometry of discontinuities is not regular, and statistical methods should be employed to describe them (Priest and Hudson 1981, 1976). Attewell and Farmer, Hudson and Priest, and Einstein et al. defined discontinuities in the form of irregular and scattered two-dimensional lines to calculate the relationship between the spacing and the number of surveyed discontinuities as a negative exponential distribution. A power-law distribution function, Poisson distribution, and normal log are, respectively, proposed for discontinuity length, placement, and dimensions in various studies (Attewell and Farmer 1976; Hudson and Priest 1979; Einstein et al. 1983).

Due to the lack of sufficient information and the impossibility of surveying all discontinuities, these should be simulated to access the entire information of the rock mass (Hamdi and du Mouza 2005; Hamdi et al. 2008). For this purpose, Hamid and Mouza (2005) suggested the following steps:

- Field discontinuity measurements
- Identification of discontinuity sets
- Characterization of the geometrical parameters of each identified discontinuity set
- Three-dimensional discontinuity network modeling
- In situ block size distribution

These steps are more suitable for modeling a discontinuity network in regions with a large number of discontinuities. In the case of dimension stones in active quarries, most discontinuities can be surveyed, and thus there is no need for simulation. However, discontinuities in unexcavated reserves should be simulated.

The geometry of the rock blocks After assigning a discontinuity network to the rock mass and computer modeling, the geometry of the blocks formed by the discontinuity network should be determined. Different algorithms have been proposed for modeling and determining the geometry of the rock blocks. The main input to the algorithms is the discontinuity network. The main difference between different algorithms is the methodology and assumptions relating to the discontinuity network. These algorithms are developed in two and three dimensions, and computer software has been developed based on them. Two-dimensional algorithms consider discontinuities in the rock mass as straight lines and calculate the polygon geometries formed by these lines. The two-dimensional algorithms include those based on graph theory, matrices, directed graphs, vectors, and numerical methods (Yarahmadi et al. 2014).

Three-dimensional algorithms assume discontinuities as planes in the space where polyhedrals will be created by intersecting the planes. The main goal of these algorithms is to determine the geometry of the polyhedrals or rock blocks. Heliot proposed a three-dimensional numerical algorithm for modeling discontinuities and determining the geometric properties of the rock blocks (Heliot 1988). This algorithm assumes discontinuities with finite lengths and ignores the joint sets with infinite lengths. Goodman and Shi developed a vector-based algorithm to identify rock blocks (Goodman and Shi 1985). In this algorithm, the blocks are identified in two and three dimensions using the intersecting points. Shi examined identification of rock blocks formed by intersecting curved and straight discontinuities (Shi 1992). The proposed algorithm determines the two-dimensional blocks using directed graphs. Lin et al. proposed an algorithm based on topologic techniques to solve this problem (Lin et al. 1987). This three-dimensional algorithm can detect the rock blocks formed by the intersection of planes. Maerz and Germain used a simple computer model to determine the geometry of the rock blocks (Maerz and Germain 1992). The algorithm proposed by Jing and Stephansson examines discontinuities and the rock blocks in two and three dimensions based on numerical techniques (Jing 2000; Jing and Stephansson 1994). The last algorithm proposed by them examines the mechanical properties and fluid flow in discontinuities (Jing and Stephansson 2007). A heuristic algorithm proposed by Jafari et al. based on square matrices to identify the rock blocks in three dimensions (Jafari et al. 2013). Khishvand et al. developed this algorithm for two-dimensional problems (Khishvand et al. 2011). The proposed algorithms exclude discontinuities that do not influence the formation of rock blocks. Also, these algorithms involve many calculations. For example, the local coordinate system is used for detecting line segments created by the intersection of planes. The use of a general coordinate

system will reduce the volume of calculations and make it easier to understand. Elmouttie et al. conducted various studies in this regard (Elmouttie et al. 2010, 2013; Elmouttie and Poropat 2012). The major disadvantage is related to the assumptions made for discontinuity modeling in dimension quarries leading to substantial errors. To visualize the fragmentation of a rock body due to its segmentation by discontinuities, the software known as 3D-BlockExpert has been developed and used in some quarries in Germany (Nikolayev et al. 2007; Siegesmund et al. 2007; Mosch et al. 2011). In these studies, discontinuities are assumed to be infinite in the model, and this assumption may lead to some errors in identification of real rock blocks.

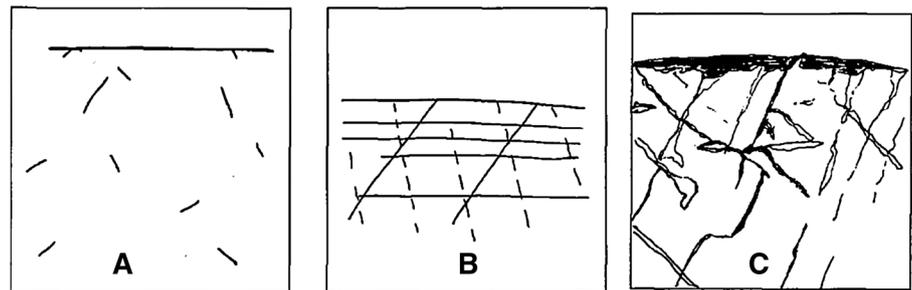
The above algorithms have advantages and disadvantages related to their assumptions. If the assumptions are much closer to reality, the proposed method will be more valid. In the methods that use geometric parameters to determine the geometry of the rock mass, the continuity

and parallel joints assumptions are the main disadvantages. In the methods that assume more realistic discontinuities, the assumptions relating to the discontinuity network and the complexity of the proposed algorithm to find the blocks are the most important parameters for evaluating the method. For example, excluding the joints not involved in the formation of the rock blocks (immature or dangling joint) is an assumption in all algorithms presented so far. In dimension quarries, this assumption causes errors in subsequent calculations.

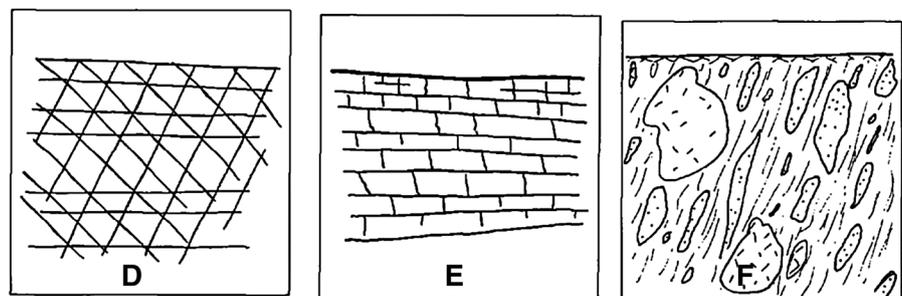
The best method to evaluated the geometry of rock blocks

Goodman divided the rock masses into 10 categories in terms of structural and mechanical properties (Goodman 1995). In this article, Goodman's classification is modified based on the particle size, and the rock masses are divided

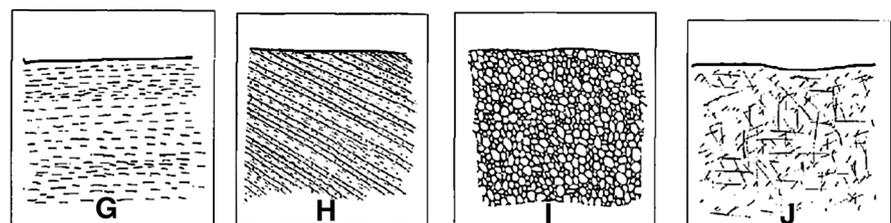
Fig. 1 Classification of various rock masses base on size of particles. **a** Joint less rock; **b** incipiently blocky rock; **c** cavernous rocks; **d** blocky rock; **e** incompletely jointed rock; **f** random mixtures; **g** squeezing or swelling rock; **h** regular mixtures; **i** highly porous rock; **f** highly fissured rock; (modified from Goodman 1995)



1) Big Average Size



2) Medium Average Size



3) Small Average Size

into three categories with small, medium, and large particles (Fig. 1). Although the joint spacing is very effective in determining the size of the rock blocks, the overall structure intended for various types of rock masses (small, medium, and large) is based on the experience.

The structural dimension stone reserves are placed in A to E categories (Fig. 1). The reserves placed in the first group (structures A, B, and C) are more profitable economically. As shown in Fig. 1, any network prediction using simulation and statistical methods incurs large errors because of the structure of discontinuity networks in Group 1 (A, B, and C). Therefore, more access to discontinuities may reduce prediction error. In addition, if the size of the modeled rock mass becomes smaller, the network will be predicted more accurately. As stated in “Methodology” section, a combination of image processing and window mapping can be used for determining the discontinuity network in the dimension quarries. Core drilling and GPR techniques are recommended for unexcavated reserves.

In previous sections, the discontinuity network modeling and the methods used for calculating the geometry (size and shape) of the rock blocks were described. The main disadvantage of the above methods when used in dimension quarries is the elimination of dangling and isolated discontinuities (discontinuities that are ineffective in the formation of rock blocks, Fig. 2). These discontinuities are excavated at later stages and form smaller rock blocks by intersecting the cutting planes. If they are not included, the determination of rock reserves will be computed with errors. Also, in designing the cutting plane these discontinuities should be considered.

According to the specificity of the dimension stones, 6 conditions have been identified for examining the suitability of the methods for calculating the geometry of rock blocks: (1) the ability to model random discontinuities and

joint sets with specific dimensions, (2) the inability to simulate discontinuities with statistical methods (the ability to study a discontinuity network separately), (3) determining the geometry of all rock blocks, (4) taking into consideration the dangling and isolated discontinuities, (5) simplicity, and (6) three-dimensionality. The suitable procedure for evaluating the proposed methods is to review the assumptions, calculations, and their validation through practical examples. So, different methods have been evaluated based on the assumptions and the presented algorithm basis, and a case study was used to verify the comparison. Under the aforementioned conditions, the proposed algorithms and methods were evaluated, and their usability in dimension stones was investigated. Using qualitative variables is very common in classifications and comparisons. Five qualitative variables (very low, low, medium, high, and very high) were used to determine the applicability of the methods in dimension stones. Table 2 shows the description of the levels based on the shortfalls of the 6 mentioned conditions.

Table 3 shows various methods proposed over the years in the fields of application and the applicability of these methods for dimension stones. The shortages are listed in the applicability column.

According to Table 3, the methods proposed by Goodman and Shi (1985), Jafari et al. (2013), Jing and Stephansson (1994, 2007), and Elmouttie et al. (2010, 2013), Elmouttie and Poropat (2012) have minimum shortfalls and outperform other methods for dimension stones. The algorithms presented by Goodman and Shi (1985) and Jafari et al. (2013) cover all the conditions, except taking into consideration the dangling and isolated discontinuities. The method presented by Jafari et al. (2013) provided more algorithm details and are easy to understand. Elmouttie et al. (2010, 2013), Elmouttie and Poropat (2012) algorithms also cover the conditions but the method is very difficult.



Fig. 2 Dangling and isolated discontinuities in a step face in Joshaqan quarry

A case study

In order to verify the results obtained and presented in the Table 3, a part of rock mass body in the Joshaqan quarry was selected as a case study. The quarry is located 110 km northwest of Isfahan near the village of Joshaqan in the

Table 2 Description of the qualitative levels based on the conditions

Level	Description
Very low	If the method doesn't cover any condition
Low	If the method doesn't cover 3 conditions simultaneously
Medium	If the method doesn't cover conditions 1 or 2
High	If the method doesn't cover condition 4 and/or 5
Very high	If the method covers all the conditions

Table 3 Summary of some researches in in situ blocks' geometry and their applicability in dimension stones

Method no.	Researcher	Field of study	Method basis	Applicability in dimension stones (and shortages)
1	Palmström (1985, 2005)	General	Geometrical parameter	Low (1, 3, 4)
2	Warburton (1983)	General	Geometrical parameter	Low (1, 3, 4)
3	Lin et al. (1987)	General	Topologic techniques	Medium (1, 4)
4	Heliot (1988)	Block stability	Numerical systems	Medium (1, 4)
5	Shi (1992)	General	Directed graphs	Low (4, 5, 6)
6	Jing and Stephansson (1994, 2007)	General	Numerical techniques	High (4, 5)
7	Goodman and Shi (1985)	Block stability	Vector method	High (4)
8	Lu (2002)	General	Topologic techniques	Medium (1, 4)
9	Wang et al. (2003)	Block caving	Numerical techniques	Medium (2, 4)
10	Lu and Latham (1999)	General	Numerical techniques	Medium (2, 4)
11	Latham et al. (2006)	Breakwaters armourstone	Numerical techniques	Medium (2, 4)
12	Sousa (2007)	Granite stones	Geometrical parameter	Low (1, 3, 4)
13	Mutlutürk (2007)	Dimension stones	Principles of solid geometry	Low (1, 2, 4)
14	Turanboy and Ulker (2008)	General	Numerical techniques	Medium (1, 4)
15	Yu et al. (2009)	Underground spaces	Numerical techniques	Low (1, 4, 5)
16	Turanboy (2010)	General	Geometric approaches	Medium (1, 4)
17	Zhang et al. (al. 2010, 2012)	Underground spaces	Mesh gridding technique	Low (2, 4, 5)
18	Elmouttie et al. (2010, 2013; Elmouttie and Poropat 2012)	General	Numerical techniques	High (4, 5)
19	Saliu et al. (2012)	Dimension stones	Geometrical parameters	Low (1, 3, 4)
20	Jafari et al. (2013)	General	Square matrices	High (4)
21	Stavropoulou (2014)	General	Geometrical parameters	Low (1, 3, 4)
22	Elci and Turk (2014a, b)	Dimension stones	Geometrical parameters	Low (1, 3, 4)
23	Siegesmund et al. (2007)	Dimension stones	Numerical techniques	Medium (1, 4)

(1) The ability to model random discontinuities and joint sets with specific dimensions, (2) inability to simulate discontinuities with statistical methods (the ability to study a discontinuity network separately), (3) determining the geometry of all rock blocks, (4) considering the dangling and isolated discontinuities, (5) simplicity and (6) three-dimensionality

Isfahan province, Iran. Figure 3 shows the location of the quarry in the map of Iran. Limestone in this quarry formed during the Oligocene–Miocene periods. The intact rock has a uniform white color with low density of fossils and 50–80 MPa compressive strength (GSI 2015). Also, tectonics activities had low effects on the rock mass body, and there are only some stochastic joints with few faults which caused large rock blocks in the rock mass body. The rock blocks are extracted with diamond wire cutting method in 3 faces (Northern, Eastern and Southern) in the quarry. A part of the third step (bench) in the southern face, which contained some different types of joints, was selected for the study. The dimensions of this part were 24-m length, 7.5-m height, and 3-m width. All of the observed joints in the selected part were mapped with the combination of scanline and image-processing techniques. Figure 4 shows the southern face of the quarry and selected part of the third step with observed (traced) joints on it. The dip, the dip

direction, and the observed length of the joints were measured and are presented in Table 4.

The joints were assumed to be consistent in the width direction (north–south) in the studied part. The joints network and the rock blocks formed by them were simulated by MATLAB (Fig. 5).

As shown in the Figs. 4 and 5, there are six joints which create five rock blocks (B1, B2, B3, B4, and B5) in the studied part. The volumes of rock blocks calculated as: $V1 = 68.6$, $V2 = 147.4$, $V3 = 28.6$, $V4 = 31.4$, and $V5 = 264 \text{ m}^3$. According to these results, the methods mentioned in Table 3 were compared and are presented in Table 5.

Some methods in Table 3 cannot be used in the selected part because of the input data needed to apply the method. Some other methods were also compared. The index methods can only determine the average size of the rock blocks (i.e., method No. 1), so these methods have low



Fig. 3 Location of Joshaqan quarry in Iran map (Modified from GNI 2007)

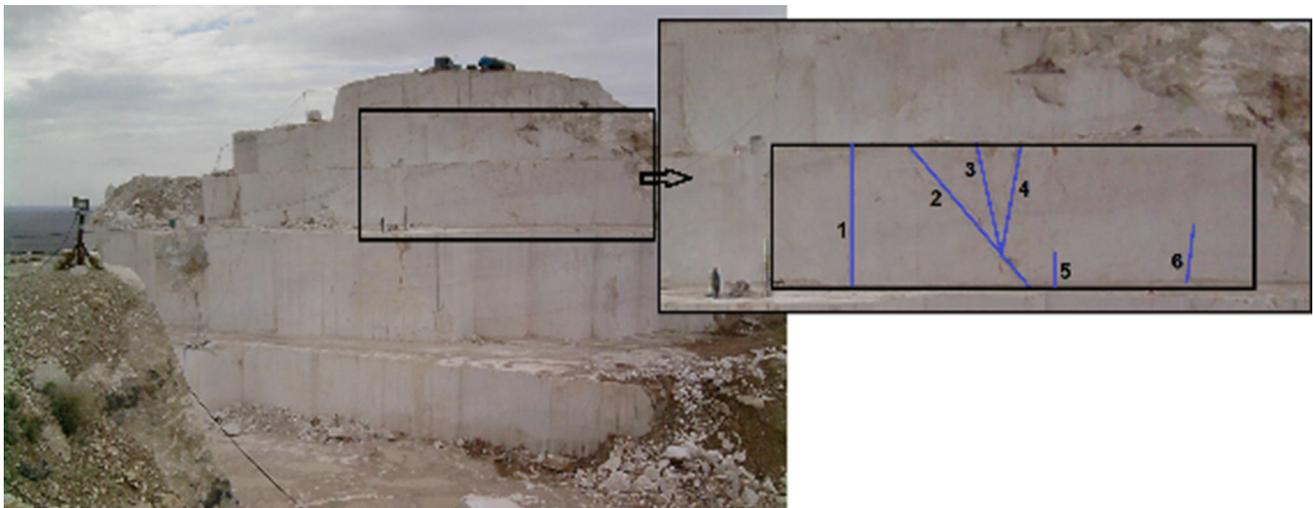


Fig. 4 Southern face of Joshaqan quarry and the selected part with joints network

applicability to use in dimension stones. The methods with medium level can only use the infinite joints for the detection of blocks, so these methods can not detect all the blocks (i.e., B1, B2, and B6 (B3 + B4 + B5) in the case

study). High level methods detect all blocks but they can not detect the defective rock blocks (i.e., B5 in the case study). However, high level methods are preferred for use in large scale block detection in dimension stone quarries.

Conclusion

Various methods for discontinuity surveys were investigated to determine the geometric properties of dimension rock blocks. A combination of window mapping and image

processing was suggested for dimension stones in active quarries. Core drilling and GPR techniques were recommended for unexcavated reserves. Thereafter, the methods proposed for calculating the size and the geometry of the rock blocks were divided into index and modeling techniques. Index methods are simple, cheap, and fast, but their results are not valid for dimension stones because the average values are reported for the rock blocks. However, these methods are used when a general understanding of the rock mass is required or where sets of discontinuities are just arranged. Modeling techniques predict the discontinuity network in the rock mass by using different assumptions and mathematical principles, and calculate the size and shape of the rock blocks separately.

The methods used for rock block survey were evaluated according their applicability in dimension stones studies, considering six conditions. The algorithm used in

Table 4 The specifications of the joints in the selected part

Observed length (m)	Dip direction (degree)	Dip (degree)	Dis. No.
7.5	302	90	1
9.6	270	63	2
5.7	270	76	3
5.6	72	82	4
2.8	270	90	5
3.7	270	79	6

Fig. 5 **a** The joints network in the studied part. **b** The rock blocks created by the joints network

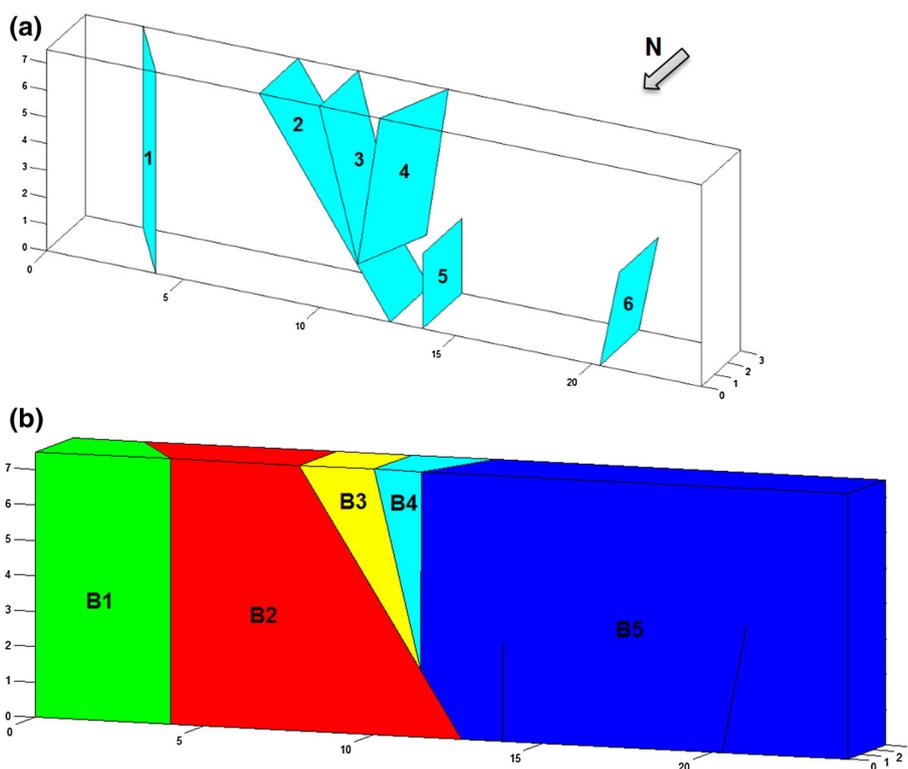


Table 5 Observation from the methods mentioned in Table 3

Level	Description	Blocks average size (m ³)	No. of detected blocks	Method No.
Very high	B5 is a defective rock block	108	5	Real
Low	Only the average of the rock blocks can be calculated	67.7	1	1
Medium	B1, B2, B6 (B3 + B4 + B5) can be detected in the rock mass body.	108	3	3, 4, 5, 8, 14, 16, 23
High	B5 detected as a complete rock block.	108	5	6, 7, 18, 20

dimension stones should be able to model random discontinuities and joint sets with specified dimensions. It should not simulate discontinuities only by statistical methods. The method used to determine the geometry of all blocks should be three-dimensional and include dangling and isolated discontinuities. Under the above conditions, the methods proposed so far were evaluated. The methods proposed by Goodman and Shi (Goodman and Shi 1985), Jafari et al. (2013) and Elmoultie (2010, 2013; Elmoultie and Poropat 2012) were introduced to be used for dimension stones. In a case study application, these methods proved to be the best options and to better illustrate the differences between the several methods.

Conflict of interest The authors declare that they have no conflict of interest.

References

- Aqeel A, Anderson N, Maerz N (2014) Mapping subvertical discontinuities in rock cuts using a 400-MHz ground penetrating radar antenna. *Arab J Geosci* 7(5):2093–2105
- Arosio D, Munda S, Zanzi L (2012) Quality control of stone blocks during quarrying activities. In: 2012 14th international conference on ground penetrating radar (GPR). IEEE, p 822–826
- Attewell PB, Farmer IW (1976) Principles of engineering geology. Chapman and Hall, London
- Bonnet E, Bour O, Odling NE, Davy P, Main I, Cowie P, Berkowitz B (2001) Scaling of fracture systems in geological media. *Rev Geophys* 39(3):347–383
- Dearman W (1991) Engineering geological mapping. Butterworth-Heinemann, Oxford
- Demarco MM, Oyhantçabal P, Stein K-J, Siegesmund S (2011) Black dimensional stones: geology, technical properties and deposit characterization of the dolerites from Uruguay. *Environ Earth Sci* 63(7–8):1879–1909
- Demarco MM, Oyhantçabal P, Stein K-J, Siegesmund S (2013a) Dolomitic slates from Uruguay: petrophysical and petromechanical characterization and deposit evaluation. *Environ Earth Sci* 69(4):1361–1395
- Demarco MM, Oyhantçabal P, Stein K-J, Siegesmund S (2013b) Granitic dimensional stones in Uruguay: evaluation and assessment of potential resources. *Environ Earth Sci* 69(4):1397–1438
- Dershowitz W, Einstein H (1988) Characterizing rock joint geometry with joint system models. *Rock Mech Rock Eng* 21(1):21–51
- Einstein H, Veneziano D, Baecher G, O'reilly K (1983) The effect of discontinuity persistence on rock slope stability. *Int J Rock Mech Min Sci Geomech Abstr* 20:227–236
- Elci H, Turk N (2014a) Block volume estimation from the discontinuity spacing measurements of mesozoic limestone quarries, Karaburun Peninsula, Turkey. *Sci World J* 2014:1–10. doi:10.1155/2014/363572
- Elci H, Turk N (2014b) Rock mass block quality designation for marble production. *Int J Rock Mech Min Sci* 69:26–30
- Elmoultie M, Poropat G (2012) A method to estimate in situ block size distribution. *Rock Mech Rock Eng* 45(3):401–407
- Elmoultie M, Poropat G, Krähenbühl G (2010) Polyhedral modelling of rock mass structure. *Int J Rock Mech Min Sci* 47(4):544–552
- Elmoultie M, Krähenbühl G, Poropat G (2013) Robust algorithms for polyhedral modelling of fractured rock mass structure. *Comput Geotech* 53:83–94
- GNI (2007) Geoscience news and information. Iran Map-Iran Satellite Image. <http://www.geology.com/world/iran-satellite-image.shtml>. Accessed Jan 2015
- Goodman RE (1995) Block theory and its application. *Geotechnique* 45:383–423
- Goodman RE, Shi G-H (1985) Block theory and its application to rock engineering. Englewood Cliffs, Prentice-Hall, pp 9–98
- GSI (2015) Geological survey of Iran. Report on exploration of Kashan region (in persian). <http://www.gsi.ir>. Accessed Jan 2015
- Hamdi E, du Mouza J (2005) A methodology for rock mass characterisation and classification to improve blast results. *Int J Rock Mech Min Sci* 42(2):177–194
- Hamdi E, Romdhane NB, du Mouza J, Le Cleac'h JM (2008) Fragmentation energy in rock blasting. *Geotech Geol Eng* 26(2):133–146
- Heliot D (1988) Generating a blocky rock mass. *Int J Rock Mech Mining Sci Geomech Abstr* 25(3):127–138
- Hudson J, Priest S (1979) Discontinuities and rock mass geometry. *Int J Rock Mech Mining Sci Geomech Abstr* 16(6):339–362
- Jaeger JC, Cook NG, Zimmerman R (2009) Fundamentals of rock mechanics. Wiley, Oxford
- Jafari A, Khishvand M, Rahami H (2013) Developing an algorithm for reconstruction blocky systems in discontinuous media: three-dimensional analysis. *Int J Numer Anal Methods Geomech* 37(7):661–684
- Jing L (2000) Block system construction for three-dimensional discrete element models of fractured rocks. *Int J Rock Mech Min Sci* 37(4):645–659
- Jing L, Stephansson O (1994) Topological identification of block assemblages for jointed rock masses. *Int J Rock Mech Min Sci Geomech Abstr* 31(2):163–172
- Jing L, Stephansson O (2007) Fundamentals of discrete element methods for rock engineering: theory and applications: theory and applications, vol 85. Elsevier, Amsterdam, pp 199–232
- Khishvand M, Jafari A, Rahami H (2011) Developing an algorithm for reconstruction of blocky systems in discontinuous media: two-dimensional analysis. *Geomech Geoeng* 6(3):171–183
- Latham J-P, Van Meulen J, Dupray S (2006) Prediction of in situ block size distributions with reference to armourstone for breakwaters. *Eng Geol* 86(1):18–36
- Lato MJ, Diederichs MS, Hutchinson DJ (2010) Bias correction for view-limited Lidar scanning of rock outcrops for structural characterization. *Rock Mech Rock Eng* 43(5):615–628
- Lin D, Fairhurst C, Starfield A (1987) Geometrical identification of three-dimensional rock block systems using topological techniques. *Int J Rock Mech Min Sci Geomech Abstr* 24(6):331–338
- Lu J (2002) Systematic identification of polyhedral rock blocks with arbitrary joints and faults. *Comput Geotech* 29(1):49–72
- Lu P, Latham J-P (1999) Developments in the assessment of in situ block size distributions of rock masses. *Rock Mech Rock Eng* 32(1):29–49
- Maerz N, Germain P (1992) Block size determination around underground openings using simulations based on scanline mapping. Preprints of the international society for rock mechanics conference on fractured and jointed Rock Masses, Lake Tahoe, Nevada Berkeley
- Maerz NH, Germain P (1996) Block size determination around underground openings using simulations. Proceedings of the FRAGBLAST 5 workshop on measurement of blast fragmentation, Montreal, Quebec, Canada, p 215–223
- Mah J, Samson C, McKinnon SD (2011) 3D laser imaging for joint orientation analysis. *Int J Rock Mech Min Sci* 48(6):932–941
- Mahé S, Gasc-Barbier M, Soliva R (2015) Joint set intensity estimation: comparison between investigation modes. *Bull Eng Geol Environ* 74(1):171–180. doi:10.1007/s10064-014-0572-1

- Mosch S, Nikolayev D, Ewiak O, Siegesmund S (2011) Optimized extraction of dimension stone blocks. *Environ Earth Sci* 63(7–8):1911–1924
- Mutlutürk M (2007) Determining the amount of marketable blocks of dimensional stone before actual extraction. *J Min Sci* 43(1):67–72
- Nikolayev D, Siegesmund S, Mosch S, Hoffmann A (2007) Modell-based prediction of unfractured rock masses [Computergestützte Modellierung zur Erfassung ungestörter Gesteinsbereiche]. *Z dtsh Ges Geowiss* 158(3):483–490
- Palmström A (2005) Measurements of and correlations between block size and rock quality designation (RQD). *Tunn Undergr Space Technol* 20(4):362–377
- Palmström A (1985) Application of the volumetric joint count as a measure of rock mass jointing. *Proceedings international symposium on fundamentals of rock joints*. Björkliden, p 103–111
- Palmström A (1996a) Characterizing rock masses by the R_{Mi} for use in practical rock engineering, part 2: some practical applications of the rock mass index (R_{Mi}). *Tunn Undergr Space Technol* 11(3):287–303
- Palmström A (1996b) Characterizing rock masses by the R_{Mi} for use in practical rock engineering. Part 1: The development of the Rock Mass index (R_{Mi}). *Tunn Undergr Space Technol* 11(2):175–188
- Palmström A, Sharma VI, Saxena K (2001) *In-situ characterization of rocks*. AA Balkema Publishers, Exton
- Porsani JL, Sauck WA, Júnior AO (2006) GPR for mapping fractures and as a guide for the extraction of ornamental granite from a quarry: a case study from southern Brazil. *J Appl Geophys* 58(3):177–187
- Priest S, Hudson J (1976) Discontinuity spacings in rock. *Int J Rock Mech Min Sci Geomech Abstr* 13(5):135–148
- Priest S, Hudson J (1981) Estimation of discontinuity spacing and trace length using scanline surveys. *Int J Rock Mech Min Sci Geomech Abstr* 18(3):183–197
- Q-c Yu, Ohnishi Y, G-f Xue, Chen D (2009) A generalized procedure to identify three-dimensional rock blocks around complex excavations. *Int J Numer Anal Methods Geomech* 33(3):355–375
- Saliu MA, Idowu KA (2014) Investigating the effect of fracture on rock fragmentation efficiency: a case study of Kopec Granite Quarries, South Western, Nigeria. *J Earth Sci Geotech Eng* 4(4):53–69
- Saliu MA, Muriana OB, Olayinka HJ (2012) Modified volumetric joint count to check for suitability of granite outcrops for dimension stone production. *J Eng Sci Technol* 7(5):646–660
- Seren A, Acikgoz AD (2012) Imaging fractures in a massive limestone with ground penetrating radar, Haymana, Turkey. *Sci Res Essays* 7(40):3368–3381
- Shi G-H (1992) Discontinuous deformation analysis: a new numerical model for the statics and dynamics of deformable block structures. *Eng Comput* 9(2):157–168
- Siegesmund S, Nikolayev D, Hoffmann A, Mosch S (2007) 3D-block-expert. *Naturstein* 5(2007):102–107
- Smith J (2004) Determining the size and shape of blocks from linear sampling for geotechnical rock mass classification and assessment. *J Struct Geol* 26(6):1317–1339
- Sousa LM (2007) Granite fracture index to check suitability of granite outcrops for quarrying. *Eng Geol* 92(3):146–159
- Sousa L (2010) Evaluation of joints in granitic outcrops for dimension stone exploitation. *Q J Eng Geol Hydrogeol* 43(1):85–94
- Starzec P, Tsang C-F (2002) Use of fracture-intersection density for predicting the volume of unstable blocks in underground openings. *Int J Rock Mech Min Sci* 39(6):807–813
- Stavropoulou M (2014) Discontinuity frequency and block volume distribution in rock masses. *Int J Rock Mech Min Sci* 65:62–74
- Sturzenegger M, Stead D (2009) Close-range terrestrial digital photogrammetry and terrestrial laser scanning for discontinuity characterization on rock cuts. *Eng Geol* 106(3):163–182
- Tonon F, Kottenstette J (2006) Laser and photogrammetric methods for rock face characterization. Report on a workshop held in Golden, Colorado
- Turanboy A (2010) A geometric approach for natural rock blocks in engineering structures. *Comput Geosci* 14(4):565–577
- Turanboy A, Ulker E (2008) LIP-RM: an attempt at 3D visualization of in situ rock mass structures. *Comput Geosci* 12(2):181–192
- Van Knapen B, Slob S (2006) Identification and characterisation of rock mass discontinuity sets using 3D laser scanning. *IAEG 2006 Geological Society of London Paper* 438
- Wang L, Yamashita S, Sugimoto F, Pan C, Tan G (2003) A methodology for predicting the in situ size and shape distribution of rock blocks. *Rock Mech Rock Eng* 36(2):121–142
- Warburton P (1983) Applications of a new computer model for reconstructing blocky rock geometry—analysing single block stability and identifying keystones. 5th ISRM Congress
- Warburton P (1985) A computer program for reconstructing blocky rock geometry and analyzing single block stability. *Comput Geosci* 11(6):707–712
- Yarahmadi R, Bagherpour R, Kakaie R, Mirzaie NH, Yari M (2014) Development of 2D computer program to determine geometry of rock mass blocks. *Int J Min Sci Technol* 24(2):191–194
- Zhang Y, Xiao M, Chen J (2010) A new methodology for block identification and its application in a large scale underground cavern complex. *Tunn Undergr Space Technol* 25(2):168–180
- Zhang Y, Xiao M, Ding X, Wu A (2012) Improvement of methodology for block identification using mesh gridding technique. *Tunn Undergr Space Technol* 30:217–229