RGNZ/MGPB

Geological investigations and production planning by identification of the discontinuities and rock mass blocks in dimension stone quarries: a case study

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 553.5
DOI: 10.17794/rgn.2024.2.7

Original scientific paper

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Abstract

The dimension stone industry faces a significant environmental challenge due to the large amount of waste produced during the production process. About 51.3% of the materials extracted from dimension stone quarries worldwide end up as quarry waste. The presence of discontinuities and fractures primarily causes this waste. However, by examining the characteristics of these discontinuities and fractures and identifying in-situ blocks of the rock mass, it is possible to reduce the amount of waste produced during dimension stone quarrying. This study focuses on an abandoned quarry bench of the Lashotor quarries complex in the Isfahan Province, Iran. Due to high waste production, the quarry bench was left unused. The study aimed to identify the in-situ blocks of the quarry bench by examining the characteristics of the rock mass's discontinuities and fractures. The authors used a modified algorithm to identify and grade all the quarry bench blocks based on the target market. The study revealed that some blocks in the abandoned quarry bench could be supplied to the target market, and the bench has the potential for block extraction. The algorithm's modification based on the shape factor of blocks is an important innovation that increases the accuracy of block determination compared to previous methods. Overall, this algorithm can be used as a decision-making tool in extracting or not extracting the quarry bench of dimension stone quarries and implementing an optimal cutting pattern to reduce waste production.

Keywords:

dimension stone; discontinuities modelling; rock fractures; geological investigations; waste production

1. Introduction

Dimension stone and ornamental stone are titles for natural stones that are extracted from quarries using special methods and used with standard dimensions and shapes for various decorative and construction purposes (**ASTM, 2020**). The final success of a natural stone as a dimension stone in the market depends firstly on its appearance and secondly on the possibility of the economic production of blocks with the appropriate dimensions. So, in addition to its decorative aspect, it provides the possibility of producing the final product in the required dimensions (**Carvalho et al., 2008**). Therefore, a suitable dimension stone block is a block with the appropriate dimensions and appearance, along with minimum physical and mechanical properties (such as strength, ability in processing, resistance to physical and chemical weathering, etc.) (**Ashmole, 2004**). The dimension stone production process is divided into three parts: exploration, quarrying, and processing. The goal in dimension stone quarrying is to produce blocks with the maximum possible dimensions, which are transferred to the processing plant. In the processing plant, according to the final goal of product and market demand, the blocks are cut into large or small stone slabs with standard dimensions and thicknesses (**Bianco and Blengini, 2019; Jalalian et al., 2021**).

In recent years, due to the expansion of urbanization and construction, as well as the increase in the production of stone products, the production of dimension stones in the main producing countries is increasing, and investors in the quarry and processing plant sectors are seeking ways to reduce costs and improve efficiency (**Hosseini et al., 2019**). **Figure 1** shows the top ten leading countries in dimension stone production.

One of the main factors affecting the profitability of the dimension stone industry is the amount of waste production. The wastes produced in the dimension stone production process are divided into two parts: wastes from the quarrying operation and wastes from the processing operation. The wastes of the quarrying operation include unshaped and broken blocks and rubble, and the wastes of the processing operation including crushed slabs, sawdust, and sludge (**Careddu, 2019**; **Jalalian et al., 2021**).

According to the statistics published in 2021 in the field of dimension stones, out of the total materials extracted from dimension stone quarries, which was about 318 million tons, approximately 163 million tons

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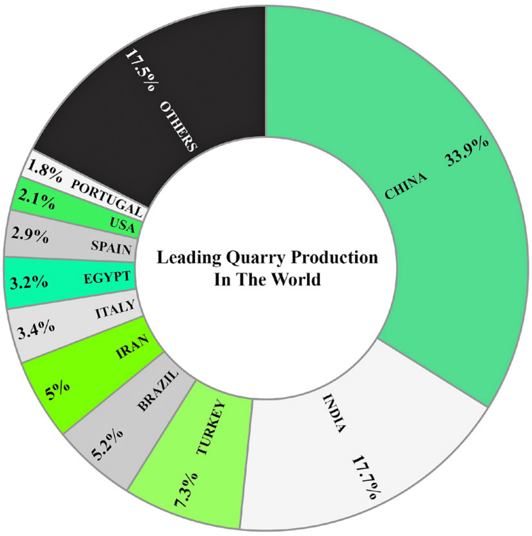

Figure 1: Ten leading countries in dimension stone production (based on information from **Montani (2021)**)

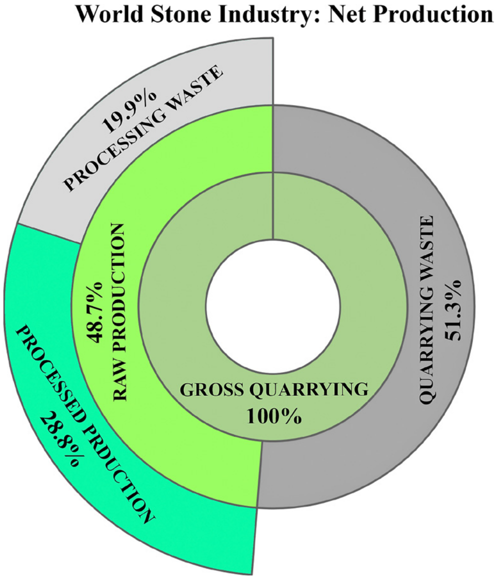

Figure 2: The amount of products and wastes in the dimension stone production process (based on information from **Montani (2021)**)

(51.3%) were turned into wastes during the quarrying operation, and from the remaining 155 million tons, which were transferred to the processing plant, about 63.5 million tons (19.9%) were turned into waste during the processing operation (**Montani, 2021**). **Figure 2** shows the amount of waste during the dimension stone production process.

As shown in **Figure 2**, about 71.2% of all materials extracted from dimension stone quarries have been turned into waste, a significant part of which is the waste during quarrying (about 51.3%). The main factor of waste production in dimension stone quarrying is the existence of discontinuities and fractures. The existence of discontinuities and fractures in the rock mass reduces the dimensions of the extracted blocks and increases the waste production (**Jalalian et al., 2021; Rasti et al., 2021**). As the published information shows, it can be concluded that the main part of waste production is quarrying. The methods for dimension stone quarrying are diamond wire cutting, chainsaw, cutting disc, flame jet, blasting methods, etc. Currently, most quarries use the diamond wire cutting method for extraction. The diamond wire cutting method has some disadvantages, such as the high risk of hazards. In contrast, the chainsaw machine cutting method offers increased safety, better quality of extracted stone block, and ease of work (**Bustillo Revuelta, 2021, Mikaeil et al., 2021, Samarakoon et al., 2023**). Generally, dimension stone quarrying involves risks such as wire cut failures, workloads, rockfalls, driving accidents, falls of mining vehicles and staff from the bench, electrical shock, and fire (**Esmaeilzadeh et al., 2022**). **Figure 3** shows the dimension stone quarrying and how discontinuities and fractures affect waste production.

In recent years, many studies have been carried out to identify discontinuities and fractures in dimension stone quarries and use this information to optimize the cutting pattern to reduce waste production and increase productivity. In 2009, Ulker et al. used a new method to maximize the number of cubic blocks in dimension stone quarries. They stated that factors such as rock type, rock fractures, and quarrying method have a direct effect on quarrying efficiency. In the used method, by considering the fractures and discontinuities, and by 3D modelling of fractures based on the geometric characteristics of discontinuities and techniques, such as tree structure and genetic algorithm, the optimization of dimension stone quarries was done (**Ülker and Turanboy, 2009**). In 2011, Mosch et al. used a new approach called 3D-BlockExpert to optimize the extraction of dimension stone blocks. They optimized the quarrying operation by considering the effect of the orientation of the discontinuities and fractures on the shape and size of the blocks. This method can be a powerful tool in planning the quarrying of dimension stones (**Mosch et al., 2011**). Also, Elmouttie et al. developed a method to estimate the size distribution of in-situ blocks in the quarry based on Monte Carlo simulation. This method has a more realistic prediction than previous block size estimation methods (**Elmouttie and Poropat, 2012**). In 2013, Arriba et al. used a new algorithm to optimize the cutting of the in-situ blocks. They stated that by choosing the right cutting direction for the in-situ blocks, it is possible to significantly reduce the mining costs and the environmental effects. In this study, to optimize quarrying efficiency, numerical methods were used to calculate the appropriate quarrying direction, and the results included the presentation of cutting parameters and the quarrying direction. This method presents the results graphically (**Fernández-de Arriba et al., 2013**). In 2014, Yarahmadi et al. used a 2D algorithm for determining the geometry and number of the blocks in the rock mass (**Yarah-**

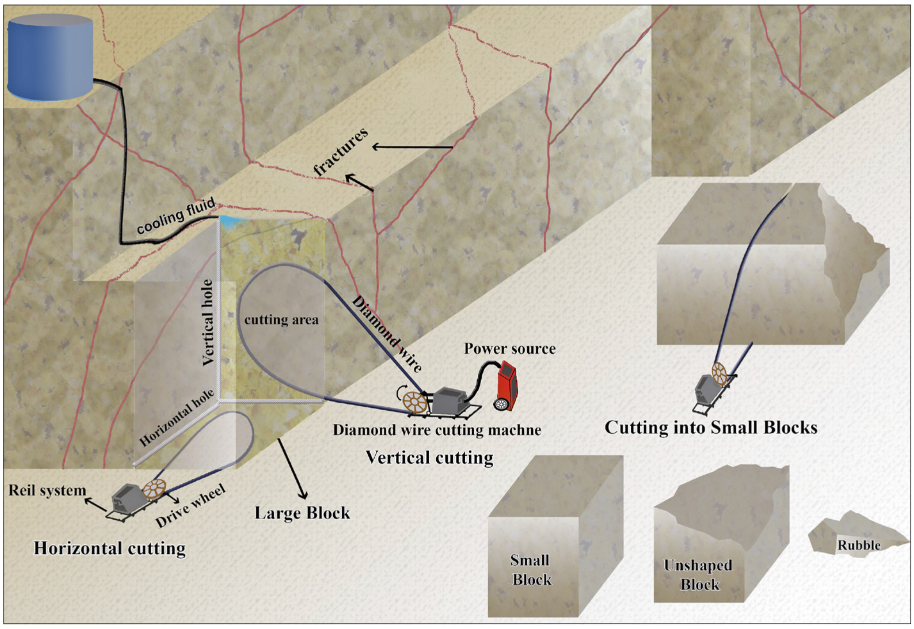

Figure 3: A view of the quarrying operation (**Jalalian et al., 2023**)

madi et al., 2014). Also, in 2018, Yarahmadi et al. used an algorithm called the 3D-QuarryOptimizer to determine the geometry of in-situ blocks in dimension stone quarries and optimize quarrying based on the quality classification of blocks. On a large scale, the optimization approach in this study was used to increase quarry productivity and examine the quarrying direction. In smaller scales, this approach is used to determine the optimal cutting pattern of the quarry bench (**Yarahmadi et al., 2018**). In 2017 and 2020, Elkarmoty et al. used a 3D algorithm to find the optimal cutting direction in dimension stone quarries to maximize the block recovery rate. This algorithm was provided by a software called BlockCutOpt and was applied to two case studies. The results, while presenting the design of the cutting network (by optimizing the number of blocks without breakage), showed that the optimal cutting direction of the blocks could be different vertically and horizontally (**Elkarmoty et al., 2017; Elkarmoty et al., 2020**). The main goal in dimension stone quarrying is to extract blocks with the maximum possible dimensions without discontinuities and fractures. One of the main solutions for the production of these blocks is to collect information from the fractures and discontinuities of the quarry bench and to calculate the geometry of the blocks enclosed between the discontinuities (**Jalalian et al., 2021**). In this paper, to achieve this goal, a case study was evaluated in one of Iran's quarries named Lashotor Quarries complex (Pietra gray marble) in the Isfahan Province. Firstly, the characteristics of discontinuities and fractures of the selected quarry bench were determined. Then, using these specifications, three-dimensional modelling of the desired quarry bench was done. In the following, according to the intersection of discontinuity planes and quarry bench surfaces, the formed blocks were identified. Then, the identified blocks were graded according to the geological conditions of the mine as well as the target market, and the desired quarry bench was evaluated according to its block extraction capability.

2. Methodology

2.1. Basic algorithm

There are a variety of techniques and algorithms to determine the shape and size distribution of the rock

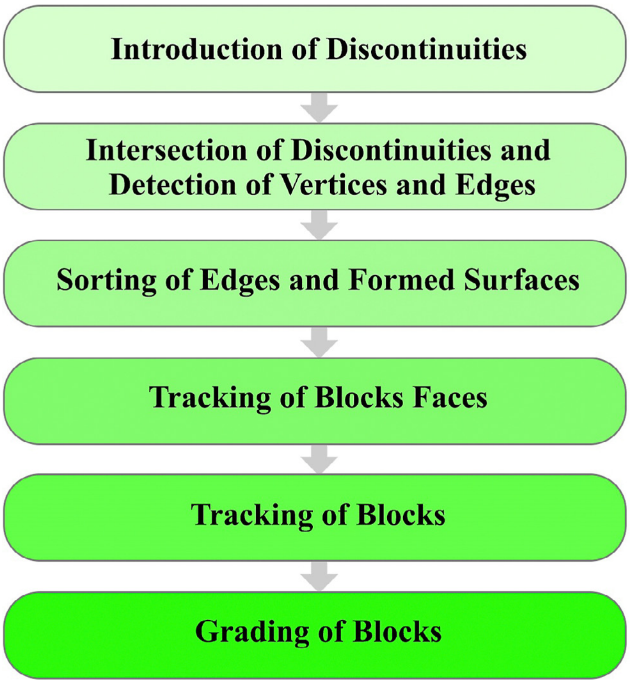

Figure 4: Block identification and grading steps in the selected basic algorithm (**Yarahmadi et al., 2018**)

blocks (**Yarahmadi et al., 2015**). Among the algorithms for calculating the geometry of in-situ blocks in the rock mass, the algorithm developed by Yarahmadi et al. was chosen as the basic algorithm. This algorithm has several advantages. It can model both complete and incomplete discontinuities, determine the geometry of all blocks in their original positions, perform 3D modelling, and grade the identified blocks. The algorithm works by first considering the discontinuities as planes and intersecting them. Then, it identifies and sorts the edges and vertices. Next, it tracks the blocks and their faces, and finally, it grades the identified blocks. The grading of the identified blocks in this algorithm is based on two parameters, their volume and shape. The larger the volume of the traced block and the more similar its shape is to a representative rectangular block (RRB), the better the grade of that block (**Yarahmadi et al., 2018**). The steps of the basic algorithm are briefly shown in **Figure 4**.

2.2. *Modification of the algorithm*

As mentioned, in the selected basic algorithm, the grading of the blocks is obtained by multiplying the two parameters of volume and shape of the block. in other words, after tracking the blocks, the volume of each block is calculated. Once the volume has been determined, the shape factor of each block is then calculated. This shape factor takes into account the unique dimensions and characteristics of each block and is an important factor in the accurate analysis of the blocks. Through this process, a comprehensive understanding of each block's properties can be obtained. The block shape factor of each block is a number between 0 and 1, which changes according to the similarity of an irregularly shaped block to a representative rectangular block (RRB). The block shape factor of each block is calculated from **Equation 1**:

$$BSF_i = \frac{A_{RRB}}{A_{bi} + \sum \min A_{f>6}} = \frac{(2k + 2l + 2kl) \times (\frac{v_{bi}}{kl})^{2/3}}{A_{bi} + \sum A_{fj}} \quad (1)$$

where BSF_i is the block shape factor of the ith block, A_{RRB} is the surface area of a representative rectangular block (RRB), and Abi is the surface area of the ith block. For blocks with more than six faces, $\sum A_{fj}$ is the sum of the faces area except for its six larger faces, k and l are the ratios of two bigger dimensions of RRB to the smallest dimension, and V_{bi} is the volume of the ith block. BSF is a coefficient between 0 and 1 that shows how much the *i*th block is like the RRB.

After calculating the volume and shape of the block, the useful volume of the block is calculated from **Equation 2**:

$$UV_{bi} = BSF_i \times V_{bi} \quad (2)$$

where UV_{bi} is the useful volume of the ith block, BSF_i is the block shape factor of the ith block and V_{bi} is the volume of the ith block.

If UV_{bi} is higher, the block is placed in a better grade. However, in special situations, we may encounter blocks that have a very high volume, but their block shape factor shows a low number. Even so, the multiplying of these two parameters is such that blocks are placed in high grades. For example, in the studied area (Lashotor quarries complex), due to the geological conditions and different stratification, we are faced with blocks that have a large length and width but a small height. In other words, the layering with low spacing of this area leads to the production of blocks that are low in height. Examples of these blocks are shown in **Figure 5**.

Figure 5: Examples of the formation of blocks with low height in Lashotor quarries complex

As shown in **Figure 5**, the blocks have a high volume due to their large length and width despite their low shape factor. As a result, a high number for the useful volume of the blocks is obtained, which describes the block with a high value. If, from the point of view of the target market, these blocks are considered waste and have no economic value. In this situation, it is better to use only the block shape factor parameter for the grading of the blocks instead of multiplying two parameters of the volume and shape of each block. Therefore, in this study, the block shape factor was used for the grading of the blocks.

3. Case study

The evaluation of in-situ blocks using the mentioned algorithm was carried out in an abandoned quarry bench in the Lashotor quarries complex (Pietra gray marble) as a case study. The Lashotor quarries complex is a quarrying complex with more than 65 active dimension stone quarries. These quarries are located 20 kilometers south of Isfahan, Iran. The area of Lashotor quarries is in the Sanandaj-Sirjan zone based on structural divisions. The complex is located between the two faults of Kolah Ghazi and Baharestan, which is the most obvious lithological sequence in the region, related to the Cretaceous

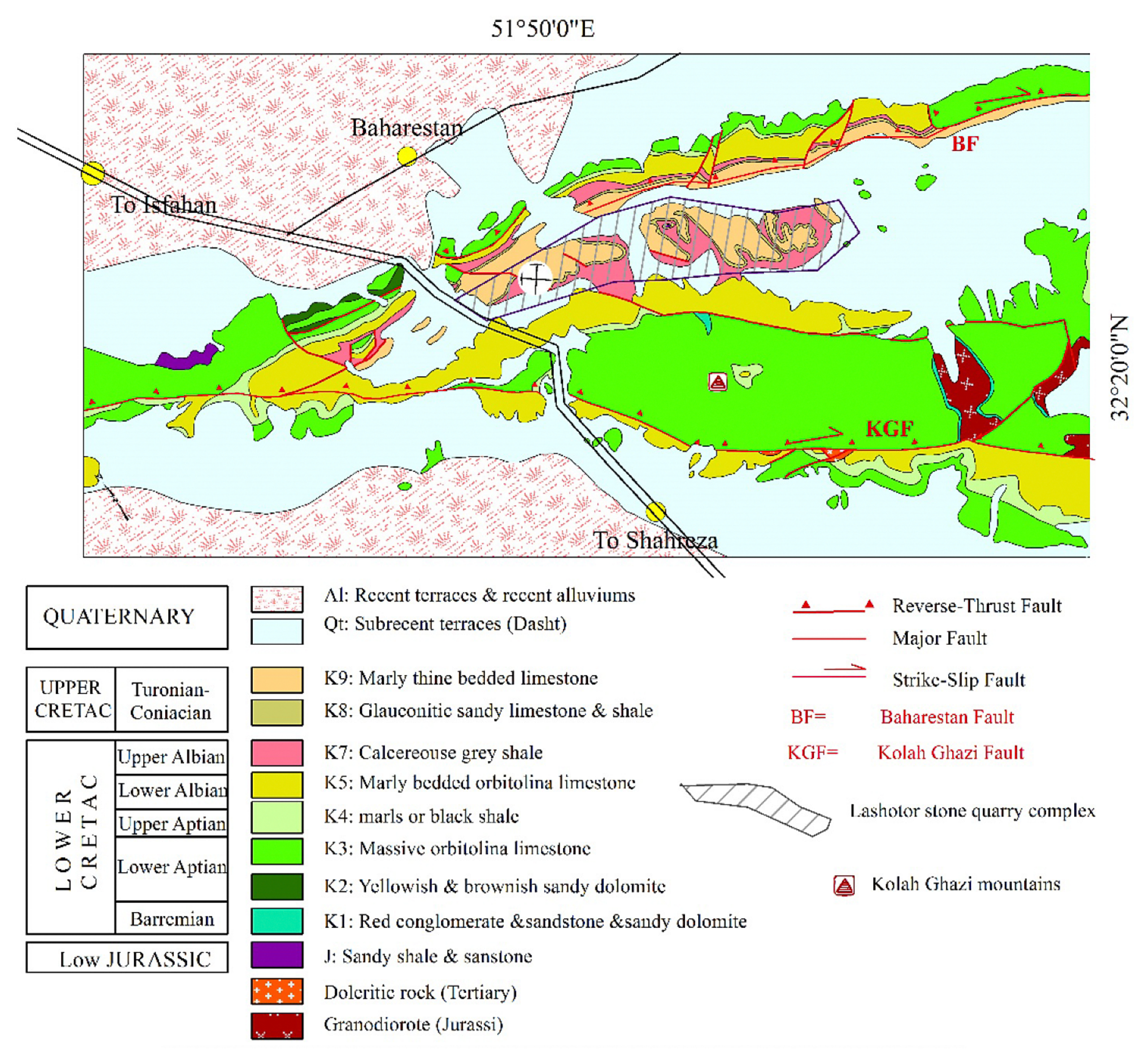

Figure 6: Geological map of the Lashotor quarries complex (**Tanzadeh et al. 2020**)

period. The geological map of the studied area and the location of the Lashotor quarries complex are shown in **Figure 6**.

The product of these quarries is marble blocks with gray to black colour (named pietra gray marble). The conventional method of quarrying in these quarries is the diamond wire-cutting method, which has been used since 1985 and is still used in 90% of dimension stone quarries today (**Özçelik et al., 2002; Servet et al., 2014**). The advantages of this method include high cutting speed, more production efficiency, and increased block production (**Khoshouei et al., 2020**). **Figure 7** shows a quarry bench being quarried by diamond wire-cutting machines.

One of the main problems in the Lashotor region is a large amount of waste during the quarrying operation, which, as previously mentioned, the main factor of its production is the presence of discontinuities and fractures in the rock mass and lack of attention to geological studies before the quarrying operation (identification of

Figure 7: A view of a quarry bench in the Lashotor quarries complex

Figure 8: A view of waste production in the Lashotor quarries complex

Figure 9: A view of the studied quarry bench

existing discontinuities and fractures). **Figure 8** shows a view of the production wastes in this area.

To understand the conditions of the quarry bench before the quarrying operation, an abandoned quarry bench was considered in one of the quarries in this area (see **Figure 9**).

To understand the jointing system and also to identify the blocks enclosed by the discontinuities and fractures of the rock mass, in the beginning, an area of the quarry bench with a length of 15 meters, a height of 4 meters, and an extraction depth of 2 meters was considered, and the information related to discontinuities and fractures in this area were collected from the quarry bench using the scan line and the cell mapping methods. In other words, in the scan line method, first, a line of 15 meters in length was considered along the quarry bench, and the characteristics of the discontinuities intersecting with the considered line were identified (see **Figure 10a**). Next, the window mapping method was used due to the limitations of the line scan method in identifying other discontinuities in the quarry bench. In this method, first, a window with dimensions of 15 meters in length and 4 meters in height was considered, and the characteristics of the discontinuities in this window were identified (see **Figure 10b**). Finally, according to the data required in the used algorithm, the characteristics of all discontinuities, including dip, dip direction of joint type (complete or incomplete), coordi-

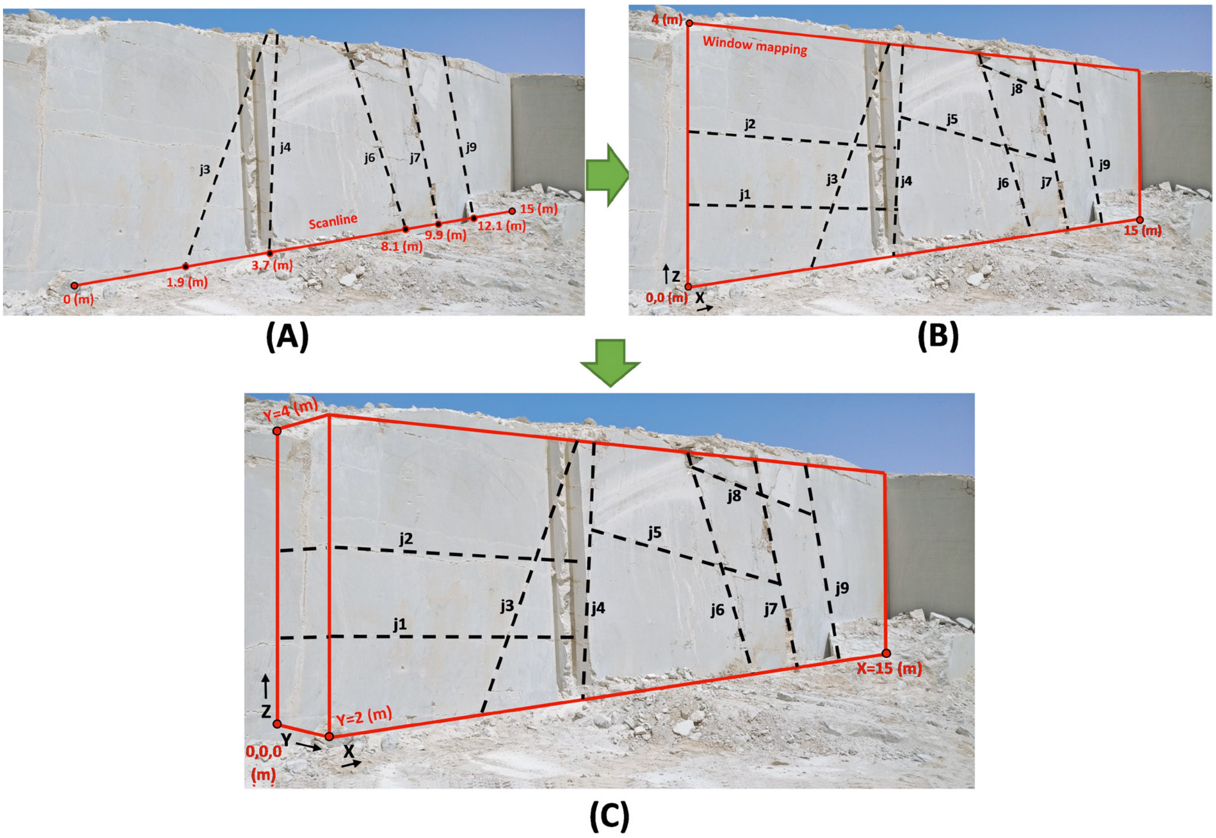

Figure 10: A view of the identified discontinuities in the studied quarry bench; (a): scan line method; (b): window mapping method; (c) 3D mapping method.

Table 1: Characteristics of identified discontinuities

Joint number	Joint type	Dip (degree)	Dip direction (degree)	Coordinates of a point			Radius
				X	Y	Z	
1	incomplete	2	0	2	2	1	2.5
2	incomplete	2	0	2	2	2	2.5
3	complete	68	210	2	1.9	0	-
4	complete	85	225	2	3.7	0	-
5	incomplete	8	0	1	7.5	2	2
6	complete	78	302	2	8.1	0	-
7	complete	80	310	2	9.9	0	-
8	incomplete	8	0	1	9.5	3	2
9	complete	75	25	2	12.1	0	-

Table 2: Information obtained from the blocks formed in the studied quarry bench

Block number	Block volume (m^3)	Block shape factor	Block Grade
B1	5.53	0.962	'Grade 2'
B2	6.31	0.938	'Grade 2'
B3	15.08	0.99	'Grade 1'
B4	3.67	0.924	'Grade 2'
B5	0.38	0.793	'Waste'
B6	2.97	0.949	'Waste'
B7	0.03	0.77	'Waste'
B8	3.13	0.847	'Waste'
B9	0.31	0.891	'Waste'
B10	0.46	0.858	'Waste'
B11	1.12	0.977	'Waste'
B12	0.19	0.826	'Waste'
B13	0.47	0.942	'Waste'
B14	8.89	0.889	'Grade 3'
B15	5.19	0.905	'Grade 3'
B16	2.76	0.855	'Waste'
B17	8.37	0.895	'Grade 3'
B18	22.16	0.876	'Grade 3'
B19	24.20	0.95	'Grade 2'
B20	6.39	0.84	'Grade 4'
B21	2.53	0.855	'Waste

nates of a point of discontinuity, and also the radius of incomplete discontinuities in three-dimensional space, were determined (see **Figure 10c**).

Also, the characteristics of identified discontinuities in the studied quarry bench are shown in **Table 1.**

4. Results and discussion

The information related to the studied quarry bench, as well as the characteristics of identified discontinuities, were given as primary input information to the modified algorithm, and the algorithm was implemented on it. In modelling, discontinuities are considered as planes in space according to their characteristics. Complete discontinuities are assumed as disks with unlimited diameter and incomplete discontinuities are assumed as disks with a certain diameter. Disks are considered as plates in space and their intersection is determined. Then, according to the intersection lines, the edges of the faces of the blocks are traced and according to the edges, the faces of the blocks are identified. Finally, the blocks are traced and their volume and shape are determined. According to the information obtained from the quarry experts of this region, as well as the target market of the product and limitation, the best dimensions of the final blocks or RRB are 2 × 2 × 3 m, blocks with a shape factor greater than 0.97 as block grade 1, between 0.92 and 0.97 as block grade 2, between 0.85 and 0.92 as block grade 3 and less of 0.85 was considered as grade 4 block. Also, blocks whose volume is less than 3.5 m^3 and whose shape factor is less than 0.95 were considered waste. The information in **Table 2** was obtained from the blocks formed as the output of the programmed algorithm.

The 3D modelling of the in-situ blocks formed by the intersection of discontinuities and the limited area of the studied quarry bench is obtained according to **Figures 11** and **12**.

The view of the identified in-situ blocks in the studied quarry bench is shown in **Figure 13**.

Also, the number of in-situ blocks and volume percentage of each grade in the studied quarry bench are shown in **Figure 14**.

As shown in **Figure 14**, the studied quarry bench can extract some blocks with top grades and high-volume percentages to be supplied to the market. For example, the total number of grade 1 and grade 2 blocks is five blocks, which is about 46% of the total volume of the quarry bench, which is a significant amount. 3D modelling and grading of quarry bench blocks can be used as a decision tool in extracting or not extracting a quarry bench, as well as it can be used as a tool to implement optimal cutting patterns and reduce waste production.

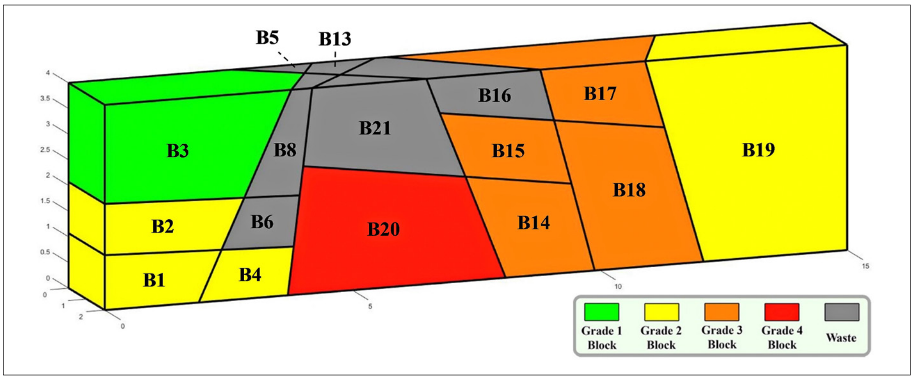

Figure 11: 3D modelling of the in-situ blocks formed in the studied quarry bench

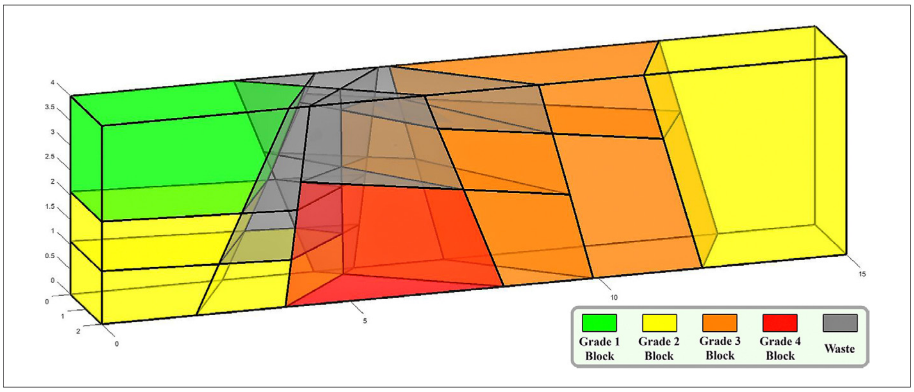

Figure 12: 3D modelling of the in-situ blocks formed in the studied quarry bench (glass mode)

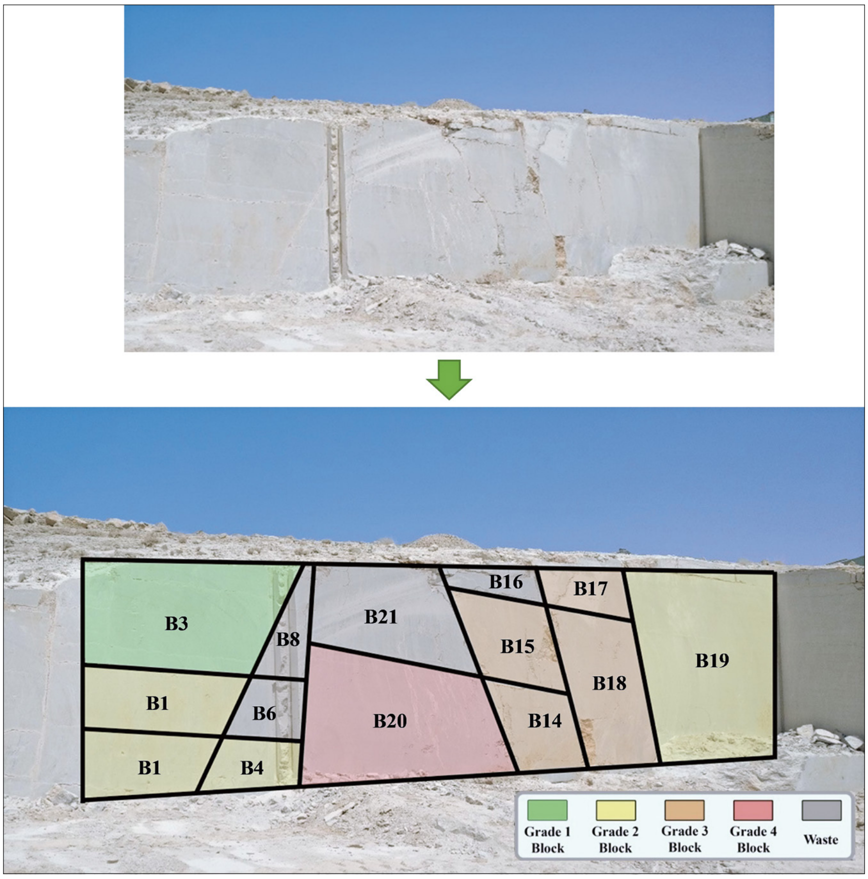

Figure 13: The view of the identified in-situ blocks in the studied quarry bench

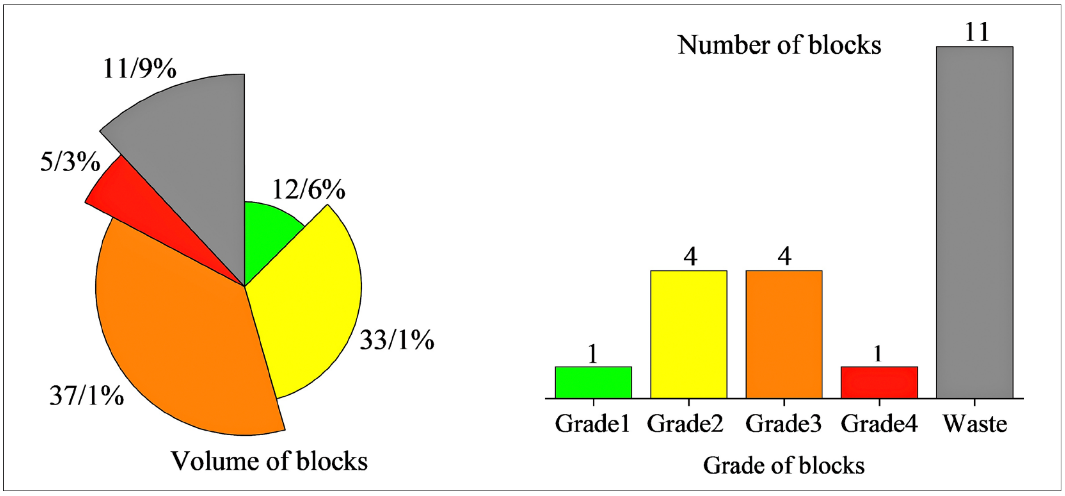

Figure 14: the number of in-situ blocks and volume percentage of each grade

One of the limitations of the implementation of this algorithm is that each type of dimension stone has a block-grade classification based on the following factors:

- The value or price of the dimension stone
- Structural discontinuities and minimum block dimensions that can be extracted.
- Limitations imposed by the type and size of quarrying equipment.
- Quarrying method and technology used in the dimension stone production chain (from extraction to stone processing).

Based on these cases, it is recommended that before implementing the discontinuity modelling algorithm in any dimension stone quarry, a thorough analysis of the area should be conducted. This analysis should include a decision on the valuation of the stone blocks, as well as updating the algorithm elements accordingly.

In the future of this research, one of the activities that can be performed is the application of modern and advanced techniques for the initial detection and identification of rock discontinuities. This can be achieved using ground-penetrating radar and new methods. The use of these techniques can lead to a faster and more accurate process of detecting and recording discontinuities, thereby reducing human errors in the process.

5. Conclusion

One of the most important environmental challenges of the dimension stone industry is unsuitable exploitation and a significant amount of waste production during quarrying operations. About 71.2% of all materials extracted from dimension stone quarries have turned into wastes, most of which are related to the quarrying operations. Paying attention to the characteristics of discontinuities and fractures and identifying the geometry of the in-situ blocks surrounded by them in the rock mass, can be used as a suitable tool for making decisions in dimension stone quarrying. In this paper, a quarry bench in one of Iran's dimension stone quarries in the Lashotor area of Isfahan was considered as a case study, and the characteristics of discontinuities and fractures were identified. Then, using the modified algorithm by the authors, the characteristics of discontinuities and fractures, as well as the operational parameters of the quarry as input to the algorithm, all the blocks in the rock mass were identified, and their volume and shape were determined and according to the target market, they were graded. According to the results, it can be concluded that the abandoned quarry bench contains some blocks that can be supplied to the target market, and it can be used as a quarry bench with the potential for block extraction. This method can be used as a tool to decide whether or not to extract the quarry bench of dimension stone quarries and in the continuation of the quarrying, can be used as a tool to implement the optimal cutting pattern to reduce waste production.

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SAŽETAK

Geološka istraživanja i planiranje proizvodnje identifikacijom diskontinuiteta i blokova stijenske mase u kamenolomima arhitektonsko-građevnoga kamena: studija slučaja

Industrija arhitektonsko-građevnoga kamena suočava se sa znatnim ekološkim izazovom zbog velike količine otpada proizvedenoga tijekom procesa eksploatacije. Oko 51,3 % materijala izvađenih iz kamenoloma arhitektonsko-građevnoga kamena diljem svijeta završi kao otpad. Tu vrstu otpada ponajviše uzrokuje prisutnost diskontinuiteta i lomova. Međutim, ispitivanjem karakteristika diskontinuiteta i lomova te terenskim identificiranjem blokova stijenske mase moguće je smanjiti količinu otpada proizvedenoga tijekom eksploatacije kamena. Ova je studija usredotočena na napuštenu kosinu kamenoloma Lashotor u pokrajini Isfahan u Iranu. Zbog velike količine otpada kosina u kamenolomu ostala je neiskorištena. Cilj je ove studije identificirati blokove kamenoloma na licu mjesta ispitivanjem karakteristika diskontinuiteta i lomova stijenske mase. Autori su se koristili modificiranim algoritmom za identifikaciju i ocjenjivanje svih kamenolomskih blokova na temelju zahtjeva tržišta. Studija je otkrila da bi se neki blokovi u napuštenome kamenolomu mogli isporučivati ciljnom tržištu te da ležište ima potencijal za vađenje preostalih blokova. Modifikacija algoritma temeljena na faktoru oblika blokova važna je inovacija koja povećava točnost određivanja blokova u usporedbi s prethodnim metodama. Taj se algoritam može primjenjivati kao alat kod odlučivanja treba li vaditi ili ne vaditi na kosinama arhitektonsko-građevnoga kamenoloma te kod primjene optimalnoga obrasca rezanja za smanjenje otpada.

Ključne riječi:
arhitektonsko-građevni kamen, modeliranje diskontinuiteta, lomovi stijena, geološka istraživanja, proizvodnja otpada

Author's contribution

Mohammad Hossein Jalalian (1) (PhD student in mining engineering, Isfahan University of Technology): provided algorithm modification, field data collecting, algorithm implementation, and presentation of the results. **Raheb Bagherpour (2)** (Professor at the Department of Mining Engineering, Isfahan University of Technology) provided the main idea and editing of the paper. **Mehrbod Khoshouei (3)** (PhD student in mining engineering, Isfahan University of Technology): provided the literature part of the manuscript and data analysis.