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Research article

Comparison of Infinite Fracture Model (IFM) and Discrete Fracture Network (DFN) for Estimating the Volume of In-Situ Blocks in Dimension Stone Mines with a Focus on UAV Photogrammetry

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Abstract

The dimension stone extraction industry serves as a vital economic sector in numerous countries, particularly in Iran, necessitating the implementation of innovative and efficient methods to optimize extraction processes and manage mineral resources. This paper focuses on the application of digital photogrammetry techniques and drone technology in the extraction and modeling of dimension stone quarries, specifically examining the Josheghan marble mine located in Isfahan Province. The study emphasizes the significance of identifying and analyzing fractures as key factors in enhancing the quality of extracted blocks, illustrating how modern methodologies can lead to optimized extraction processes and increased profitability for quarries. The research is based on two principal hypotheses: the Infinite Fracture Model (IFM) and the Discrete Fracture Network (DFN) model. The IFM posits that fractures extend indefinitely within the rock mass, a premise that may lead to inaccurate estimations of block volumes. In contrast, the DFN model provides more precise estimations of block volumes and quality by accounting for the complexities of geological structures and the presence of hidden fractures. To achieve accurate information regarding fractures and the structural characteristics of the mine, several procedures were undertaken in this research. Following the initial survey, seven scanlines, each 22 meters in length, were established at various locations within the mine to gather detailed data on fracture intensity and related features. The results indicate that effective management of dimension stone resources is contingent upon a thorough understanding of geological conditions and precise modeling of discontinuities within the rock mass. The use of advanced techniques such as digital photogrammetry and drone technology can significantly enhance extraction efficiency, ultimately contributing to the sustainable development of the dimension stone industry. The parameters P10 and P32 in this study were utilized as the primary criteria for analyzing discontinuities. Using specialized software, 70 Discrete Fracture Network (DFN) models were generated and calculated separately based on the values of P32. These models were employed to simulate the behavior of rock blocks and estimate their volumes in the selected quacontrast face. Ultimately, based on the data obtained from the conducted surveys, ten distinct DFN models were created for the entire area of the mine. These models were designed based on information related to hidden fractures and the structural complexities of the rock, facilitating more accurate estimations of the volumes of extracted blocks. The results indicate that the DFN model, by taking into account the real complexities present in the geological structure, provides more precise estimates of expected block volumes. This research clearly demonstrates that the application of modern photogrammetry methods and DFN modeling can enhance the extraction process of dimension stones. The insights gained from the analysis of discontinuities and modeling not only contribute to a better understanding of the geological structure of the mine but also lead to more effective managerial and economic decision-making in the field of mineral resource extraction. These findings could be particularly beneficial for dimension stone quarries in Iran, which face various challenges and could aid in sustainable development and optimization of mineral resources.

1. INTRODUCTION

In recent years, the integration of advanced technologies within the mining sector, particularly in the extraction of dimension stones, has ascended to a paramount priority. Among these technologies, the deployment of drones and digital photogrammetry has been recognized as highly effective instruments for the acquisition of geological data and the modeling of rock mass characteristics [1,2]. Digital photogrammetry enables the generation of precise three-dimensional models, significantly enhancing the geological data collection process; as a result, its application is experiencing rapid expansion in the mining industry[3]. A plethora of studies have been conducted on the utilization of drones in mining operations. Notably, research by Cress et al. has introduced innovative and practical methodologies for implementing unmanned aerial systems in geological investigations across the United States. Their work underscores the multifaceted applications of this technology, including its efficacy in monitoring mine conditions and assessing tailings management [4].

In this context, Li and Choi examined the trends and applications of drone technology in the mining industry, specifically detailing the use of this technology for topographical surveys [5]. Vahedi et al. conducted a comprehensive review of extensive studies on the use of drone technology as an efficient tool for the design and extraction of both open-pit and underground mines. This paper emphasizes the importance of digital photogrammetry in the collection and modeling of geological features, addresses the challenges of gathering geotechnical data in inaccessible areas, and discusses recent advancements in obstacle detection systems, which enhance the accuracy and speed of surveying [6]. In dimension stone quarries, factors such as stone color, dimensions, and the integrity of the stone significantly influence the marketability of the stones. Therefore, determining the optimal extraction direction to achieve the maximum yield of blocks is essential [7, 8].

Dimension stone deposits comprise both intact rock and networks of discontinuities, with joints recognized as the most significant type of discontinuity. The production of dimension stones involves three primary stages: exploration, extraction, and processing[9]. A key objective during the exploration phase is to assess the productivity of dimension stone reserves. Conducting surveys of discontinuities is a critical step in achieving this goal[10]. Due to geological heterogeneity, discontinuity surveys often result in inaccuracies. However, focusing on smaller sections of the rock mass and employing precise mapping techniques can help reduce these errors [11]. Among the various discontinuity survey methods for dimension stone reserves, techniques such as window mapping and image processing are recommended for operational quarries, while methods like core drilling and geophysical surveys are suggested for unexploited reserves. Following a discontinuity survey, determining the geometry of in situ blocks is essential for evaluating block productivity. A critical piece of information that quarry owners require is the quantity of extractable and profitable stone blocks, commonly referred to as the quarry yield. Notably, joint systems are vital in providing reliable insights into both the quantity and quality of in-situ blocks [12, 13]. The extraction process of stone blocks is constrained by the patterns of fracturing, the density, and spacing of these fractures, as well as the thickness of the bedding planes, particularly in stratified deposits. During the exploration phase, the evaluation of fractures is essential as it directly influences the productivity of a dimension stone reserve [14].

Accurate measurement and analysis of the distribution of discontinuities are crucial for predicting the sizes and shapes of the extracted blocks. The final dimensions and quality of these blocks are affected by multiple factors, including microcracks, fissures, bedding planes, joints, and faults. Some of these issues may only become apparent during the processing phase when the slabs fail under high pressure. The orientation of fractures identified within a quarry typically correlates with nearby regional fault zones [15]. First-order fractures are generally found alongside lower-order fractures that are oriented perpendicularly to them. It is important to note, however, that fractures can occur irregularly and may vary significantly between different quarries. They may not always align with regional fault zones, which can influence both the shape and volume of the in-situ blocks. Therefore, not only are large-scale surveys essential for the development of a deposit, but detailed small-scale surveys within the quarries are also necessary. Additionally, it is important to assess how the patterns and density of fractures change with depth, as proximity to faults can have a significant impact. One often overlooked aspect during the analysis of joint spacing is the distribution of the data, which typically follows a log-normal distribution.

Consequently, the mean value may not serve as the most accurate representation of the "average" distance or block volume; instead, a more robust approach would be to utilize the median value. By employing median values, the results about block size and quarry yield will yield more conservative estimates that more accurately reflect actual conditions. This methodological shift enhances the reliability of the data and provides a clearer understanding of the variability inherent in quarry operations [16-20].

This research investigates the extraction of dimension stones, focusing specifically on the Josheghan marble mine. It examines the modeling of discontinuities and their impact on the quality of extracted blocks. Utilizing advanced techniques in digital photogrammetry and Discrete Fracture Network (DFN) modeling, this study addresses gaps in existing literature, providing enhanced accuracy in estimating block volumes and the characteristics of discontinuities. The novelty of this research lies in the integration of sophisticated imaging methods with rigorous geological analyses. Notably, the estimation of hidden fractures and their influence on the optimal cutting angle and direction in quarry faces is presented as a significant and innovative aspect of this study. This approach particularly contributes to resolving the issue of assuming infinite length for fractures, a premise that often fails to yield accurate estimates of the volumes of existing fragments. In contrast, the DFN model, by accounting for the real complexities inherent in the geological structure and the discontinuities, facilitates more precise volume estimations for blocks. The findings of this research have the potential to inform better decision-making regarding extraction and mineral resource management, serving as a model for future investigations in the dimension stone mining sector. Consequently, the results can aid in the development of managerial and economic strategies within this industry, optimizing extraction processes and enhancing the profitability of quarries.

2. CASE STUDY: JOSHEGHAN MARBLE MINE

The dimension stone extraction industry is one of the most significant economic sectors in many countries. In Iran, dimension stone quarries play an important role in the national economy. Isfahan Province, due to its numerous high-quality dimension stone mines, is considered a key area in this field. Given its geographical position and existing infrastructure, this province has become a major center for mining activities, which can significantly contribute to regional economic development. In this study, the marble mine located in Josheghan, Isfahan Province, was selected for conducting flight planning and capturing images for three-dimensional modeling. This mine is located 110 kilometers northwest of Isfahan city, near Josheghan, and discontinuity is a critical controlling factor in the block extraction process at this site. These characteristics make the Josheghan mine a suitable candidate for scientific and research studies. Fig. 1 and Fig. 2 illustrate the geographical location of the mine and provide an overview of the mine's geometry, respectively.

Fig. 1. Location of Josheghan Mine.

Fig. 2. Overview of Mine Geometry.

3. METHODOLOGY

3.1. UAV Photogrammetry And Discontinuity Mapping

Several methodologies exist for comprehending and identifying the conditions of discontinuities relevant to engineers and specialists in the field. These methodologies include the scanline method, laser scanning, and photogrammetry. Among these techniques, photogrammetry offers several advantages over the previously mentioned methods, including faster execution, quicker accessibility, and lower costs. Additionally, photogrammetry facilitates the acquisition of a greater volume of data regarding the status of the rock mass. One of the most significant challenges confronting the dimension stone extraction industry is the accurate surveying of discontinuities and understanding their orientations. This issue is particularly critical due to its direct impact on the marketability of the blocks extracted from quarries. Discontinuities can influence both the stability of quarry walls and the quality of the extracted blocks. Therefore, a precise understanding of the characteristics of these discontinuities, such as their dip, orientation, and spacing, is essential. Photogrammetry serves as a valuable technique for understanding the orientation of discontinuities in dimension stone quarries. This method utilizes digital imagery and specialized software to conduct a thorough examination of the geological features of the rock mass. By leveraging these advanced imaging techniques, researchers and practitioners can gain deeper insights into the structural complexities of the rock, which is vital for optimizing extraction processes and improving the quality of the dimension stone produced. In this methodology, digital images of the quarry surface are initially captured. These images are subsequently processed using specialized photogrammetry software, such as Sirovision. The software employs advanced algorithms to model points and rock blocks within the software environment, and it is also capable of calculating key discontinuity characteristics, including dip, orientation, and spacing. To construct a three-dimensional model of the Josheghan marble mine utilizing drone imagery, the DJI Mini 3 drone was selected for imaging purposes. This drone features a flight endurance of 38 minutes with a standard battery and 51 minutes with an extended battery, alongside a maximum imaging tilt angle of 41 degrees. Additionally, it offers a 12-megapixel imaging resolution and supports 4K video recording. A total of 93 images were captured from the Josheghan mine during two flight missions, with an overlap of 85%. These images were instrumental in generating the final three-dimensional model. The imaging sequence during these missions was meticulously designed to optimize the final model's quality for the extraction of discontinuities. The geometric model was constructed using Agisoft software, resulting in an output comprising 22 million meshes and 94 million dense point clouds. Fig. 3 and Fig. 4 illustrate the network of captured images, while Fig. 5 presents the final three-dimensional model derived from these images.

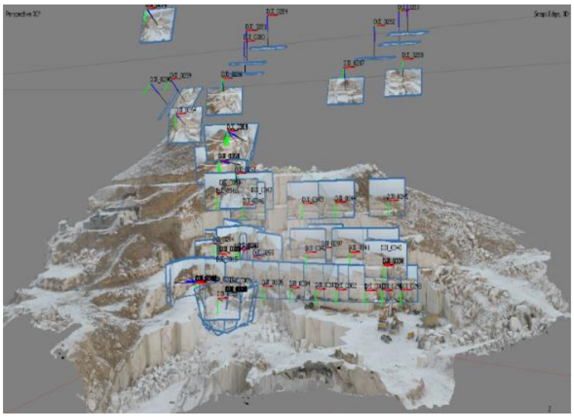


Fig. 3. Network and Captured Images.

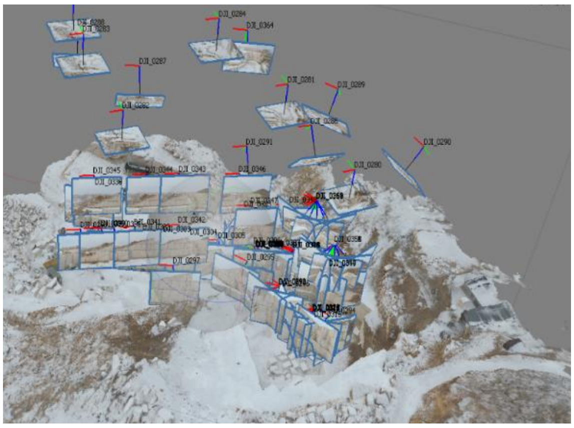


Fig. 4. Imaging Networks in the Flight Missions Conducted at the Josheghan Mine.

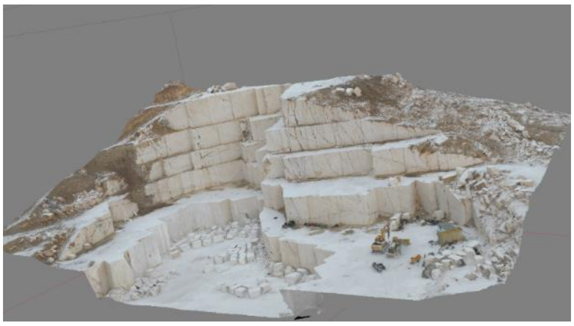
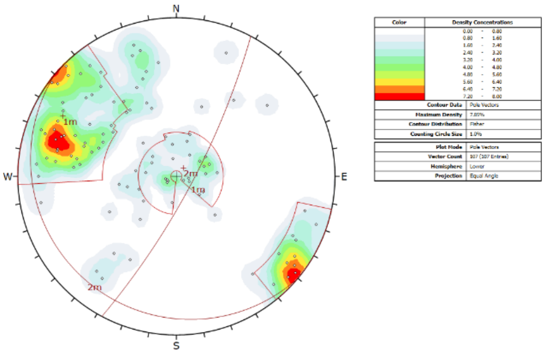


Fig. 5. Final Three-Dimensional Model Constructed from the Josheghan Mine.

Following the construction of the three-dimensional model, discontinuities present in the mine were identified using Datamine Sirovision software, resulting in the detailed characterization of over 190 discontinuities. Given that the model incorporates global coordinates embedded in each image, it ensures accurate scaling; thus, the final output reflects the precise locations of each discontinuity with their actual positions on the ground. By geo-referencing the model, it became possible to access areas of the mine that are otherwise difficult to reach. Consequently, all discontinuities in the mine were documented during this process, capturing their characteristics—such as dip, dip direction, length, spatial position, and spacing—with high precision. Furthermore, using the visual features of the aforementioned software, the discontinuities were categorized. Importantly, one of the outputs from the discontinuity identification process is compatible with Dips software. After mapping the discontinuities in Sirovision, the results were imported into Dips for further analysis, rather than utilizing the built-in discontinuity analysis module of Sirovision. Subsequently, the identified discontinuities were *16*nalysed and categorized within Dips, from which the parameters of these categories were extracted. The study revealed that the mine exhibits two distinct sets of discontinuities oriented in a northeast-southwest direction. Figs. 6, 7, and 8 display the identified discontinuities in the mine, along with the output of the stereonet and the rose diagram generated from this analysis.

Fig. 6. Discontinuity Survey of Over 190 Fractures in the Josheghan Marble Mine.

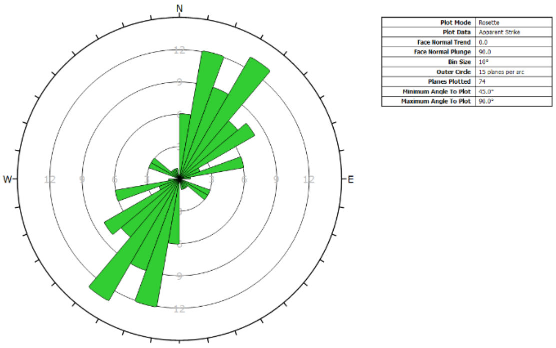


Color	Density Concentrations
	0.00 - 0.80
	0.80 - 1.60
	1.60 - 2.40
	2.40 - 3.20
	3.20 - 4.00
	4.00 - 4.80
	4.80 - 5.60
	5.60 - 6.40
	6.40 - 7.20
	7.20 - 8.00

Contour Data	Pole Vectors
Maximum Density	7.85%
Contour Distribution	Fisher
Counting Circle Size	1.0%

Plot Mode	Pole Vectors
Vector Count	107 (107 Entries)
Hemisphere	Lower
Projection	Equal Angle

Fig. 7. Stereonet Output of Identified Discontinuities.



Plot Mode	Rosette
Plot Data	Apparent Strike
Face Normal Trend	0.0
Face Normal Plunge	90.0
Bin Size	10°
Outer Circle	15 planes per arc
Planes Plotted	74
Minimum Angle To Plot	45.0°
Maximum Angle To Plot	90.0°

Fig. 8. Rose Diagram of Extracted Discontinuities.

3.2. Hypothesis Of Infinite Fractures Model (IFM)

In this study, two distinct hypotheses were employed to evaluate the volume of anticipated blocks in the quarry face of the Josheghan marble mine. The first hypothesis regarded the existing discontinuities within the quarry as continuous, modeling them as Infinite Fracture Models (IFM). Conversely, the second hypothesis adopted a Discrete Fracture Network (DFN) approach to estimate the discontinuities present in the rock and to analyze their impact on the volume of expected fragments in the quarry face. Under the IFM scenario, a geometric model of the Josheghan marble mine was constructed, and a working bench was selected on the eastern side of the mine. The orientation of the existing discontinuities on this bench was extracted using Sirovision software. Subsequently, the software 3DEC was employed to estimate the volume of the fragments formed by the identified discontinuities on the quarry face. Fig. 9 highlights the location of the selected bench on the eastern side of the mine, indicated in red, while Figs. 10 and 11 illustrate the fragments generated from the intersections of the identified discontinuities and their arrangement on the quarry face. Additionally, Table 1. provides information on the orientation of the discontinuities present on the specified quarry face.

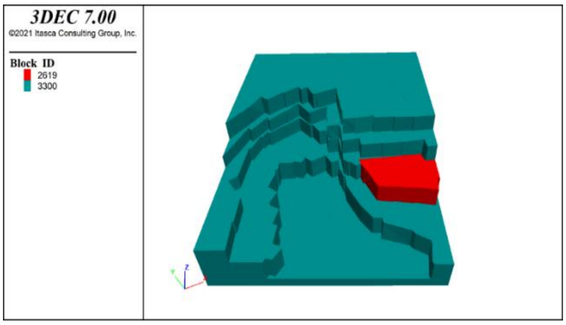


Fig. 9. Selected Bench for Study in the Eastern Section of the Mine.

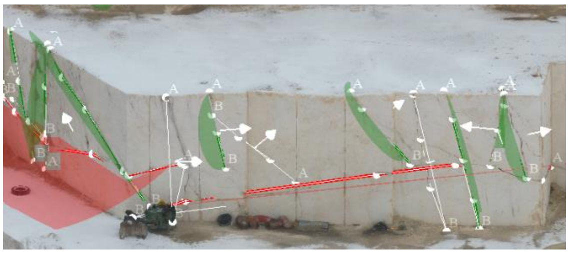


Fig. 10. a) Extraction of Discontinuities on the Selected Quarry Face.

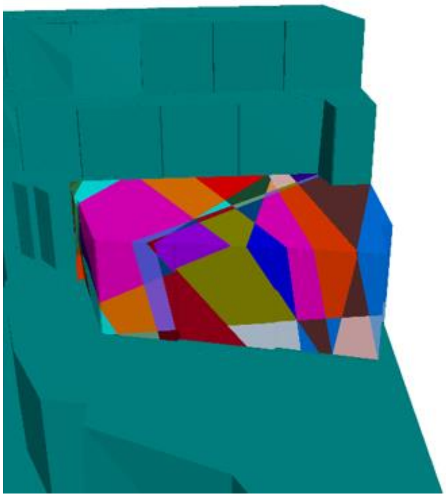


Fig. 10. b) Application of Extracted Discontinuities with the IFM.

Table 1. Orientation Information of Extracted Discontinuities on the Eastern Quarry Face

id	DIP (°)	Dip Direction(°)	centroid (X)	centroid (Y)	centroid (Z)	Length (m)	end to end (m)
1	19.2	9.1	17.403	-37.363	2285.618	26.584	31.865
2	55.4	109.7	4.068	-26.113	2288.284	13.801	13.899
3	77.7	160.3	6.193	-32.574	2287.404	7.622	8.081
4	78.9	120	3.598	-17.494	2287.834	8.114	8.119
5	28.9	265.4	4.29	-23.619	2286.326	17.306	19.095
6	89.3	135.5	3.918	-20.09	2287.439	7.894	7.91
7	32.5	134.6	3.625	-17.551	2286.706	5.287	5.326
8	77.8	144.4	8.753	-33.327	2289.216	4.845	4.851
9	48.9	159.6	10.718	-34.415	2288.102	6.725	6.741
10	81.6	90	19.94	-39.659	2287.262	8.807	8.982
11	73.7	131.3	24.613	-42.233	2288.965	5.674	5.792
12	79.7	284.9	23.67	-41.709	2289.433	4.597	4.6
13	77	107.5	21.85	-40.585	2287.459	8.929	8.987
14	51.6	124.9	17.201	-37.847	2289.827	5.821	5.868

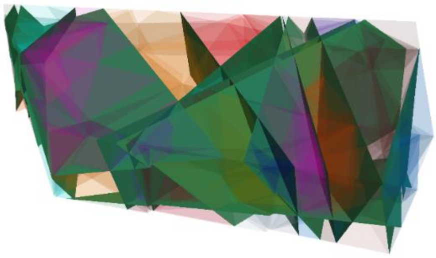


Fig. 11. Arrangement of Discontinuities on the Quarry Face Under the IFM Assumption.

3.3. Discrete Fracture Network (DFN) Generation

Following the collection of fracture data, a graphical representation was created using Sirovision software, enabling the implementation of various scanlines throughout the entire mining area. The data obtained from these scanlines were subsequently separated from the broader dataset and utilized for the determination of P_{10} values. In line with the previously described methodology, a total of seven scanlines, each extending 22 meters in length, were strategically positioned at different locations within the mine. The data gathered from these scanlines were employed to assess the intensity of fracturing. By isolating the fractures associated with each category present along each scanline, the fracturing intensity was determined. Fig. 12 provides a visual representation of the established scanlines within the mining site.

Fig. 12. The domain of Existing Scanlines in the Mine.

The statistical parameters of fractures and the linear intensity derived from the photogrammetric process, obtained using Easy Fit and Sirovision software, are presented in Table 2. According to this table, two categories of fractures with a power distribution function were sampled from the mining site. After implementing various scanlines, the linear intensity values for fracture categories one and two were determined to be 0.157 and 0.075, respectively. Additionally, this table illustrates the statistical parameter values for each fracture category.

Table 2. Data Related to the Fracture Categories Sampled from the Josheghan Mine

JSET	Dip	DD	size-limit	P_{32}	P_{10}	PDF		
						orientation	size	position
						FISHER	POWER-LAW	---------
1	78	118	3.66 - 13.8	0.159	0.157	k=17.44	a=1.47	uniform
2	8	220	6.257 - 45.526	0.292	0.075	k=18.56	a=1.01	uniform

Given that the production of discrete fracture networks (DFNs) using the P_{32} condition is significantly more accurate than generating DFNs based on the P_{10} condition, a total of 30 networks for each fracture category were produced using the established P_{10} value along with the derived distribution functions, utilizing the 3DEC software. In total, 60 discrete fracture networks were generated with varying random numbers, resulting in P_{32} values of 0.159 and 0.292 for the first and second fracture categories, respectively. In the subsequent phase, leveraging these values, 10 discrete fracture networks were created for the entire mining area. After constructing several DFN models, a working step was selected on the eastern side of the mine to assess the expected volume of fragments in this step. This assessment is conducted based on the DFN hypothesis, which aims to consider the hidden fractures present within the rock and their impact on rock block stability. As illustrated in Fig. 13, which shows the specified step in the eastern section of the mine after applying DFN number 1, it can be concluded that considering various probabilities for the existence of hidden fractures within the rock allows for the estimation of the expected quantity and volume of blocks when employing the DFN method. Additionally, Figs. 14 and 15 depict the specified step under the application of DFNs 2 and 3, respectively. The differences in the formation and volume of blocks across different DFNs indicate the consideration of various scenarios to achieve a reliable estimation of block stability prior to the excavation of the working face, thereby optimizing the economic calculations of the mine.

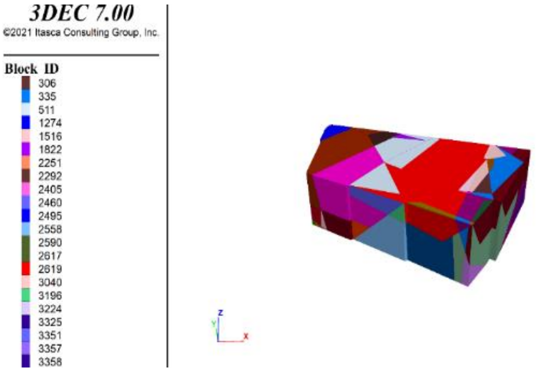


Fig. 13. Status of Fragments After the Application of DFN 1.

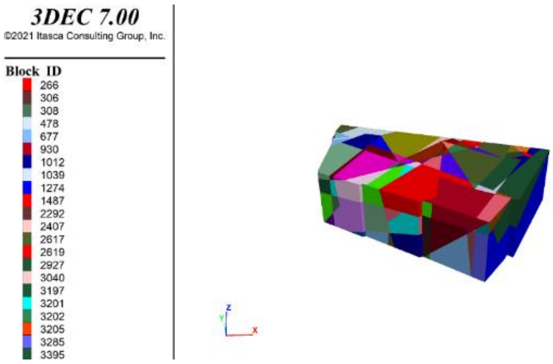


Fig. 14. Status of Fragments After the Application of DFN 2.

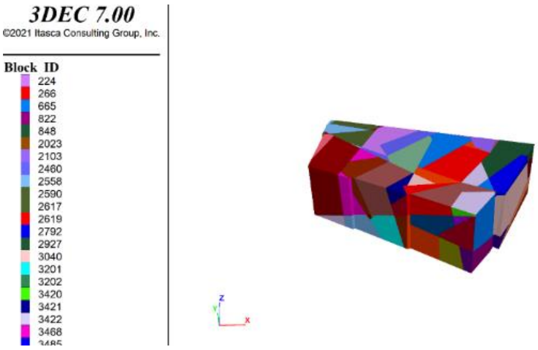


Fig. 15. Status of Fragments After the Application of DFN 3.

The distribution of block volumes across different DFNs provides a reliable estimate of the formation of blocks present in the specified working face. Therefore, analyzing the volume of blocks formed in the working face while considering the estimation of hidden fractures within the rock using the DFN method represents a superior approach for determining the expected volume of blocks in dimension stone mining operations. Fig. 16 illustrates a comparison of the number of blocks formed in ten DFNs against the number of blocks formed under the assumption of infinite fracture lengths. Additionally, Fig. 17 compares the average volume of expected fragments along with their average standard deviation. These figures demonstrate that, by employing the DFN method, not only has the volume of fragments increased, but their standard deviation has also significantly decreased. A reduction in the standard deviation of fragment volumes indicates a higher homogeneity among the extracted blocks. This improvement can enhance the quality of the extracted blocks and ultimately lead to increased sales and profitability.

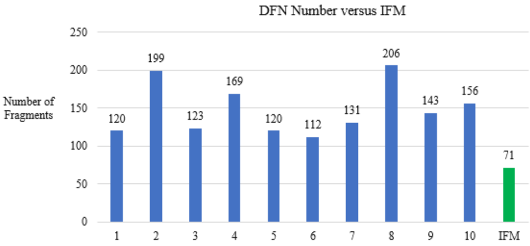


Fig. 16. Expected Number of Blocks in All Fracture Networks and the IFM State.

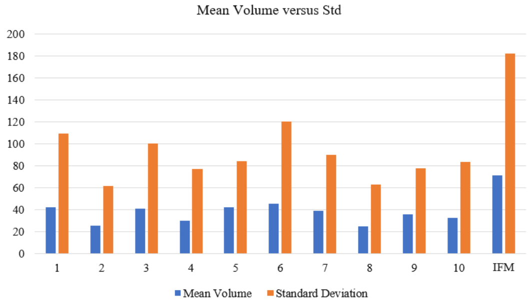


Fig. 17. Average Volume and Standard Deviation of Fragments.

The analysis of the cumulative distribution of block volumes in the Discrete Fracture Network (DFN) and Infinite Fracture Model (IFM) reveals significant differences in their ability to estimate large volumes. As shown in Fig. 18, the cumulative distribution of block volumes derived from DFN simulations is distinct from that of blocks generated by the IFM. The IFM model shows limitations in its capacity to identify and estimate blocks with substantial volumes, resulting in less accurate volume estimates compared to the DFN model. The convergence of various fracture networks supports the possibility of very large blocks existing within the ore body. This suggests considerable variability in block sizes, which the DFN model captures more effectively. According to the results, approximately 80 percent of the blocks estimated in the IFM scenario have volumes of less than 10 cubic meters. This observation not only highlights the shortcomings of the IFM model in estimating larger volumes but also indicates its inability to recognize larger blocks, leading to less valuable estimates when compared to those from the DFN model. Furthermore, the differences in block volume estimates between the two models can be accounted for by considering the standard deviation. Standard deviation, as a statistical measure of the dispersion of data around the mean, emphasizes the DFN model's capability to recognize the diversity and range of block sizes. Overall, these findings clearly indicate that the DFN model is a more effective tool for analyzing block distributions than the IFM model. Therefore, selecting an appropriate modeling approach in geological and engineering studies is crucial, as inaccurate results can significantly impact subsequent decision-making and analyses.

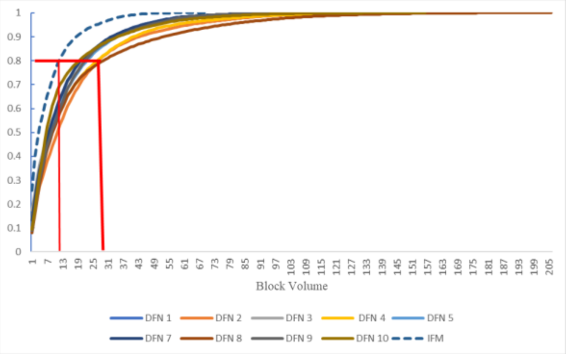


Fig. 18. Cumulative Distribution of Various DFN Models and the IFM State.

4. Conclusion

This research presents a comprehensive analysis of the Josheghan marble mine in Isfahan Province, focusing on the integration of modern photogrammetric techniques and detailed fracture analysis to enhance the extraction of dimension stones. The study leverages cutting-edge tools, including the DJI Mini 3 drone and specialized software, to create an accurate three-dimensional model of the mine. This model provides critical insights into the geological characteristics and fracturing patterns of the site. The principal results of the study are outlined as follows:

- Comparison of Models: The research contrasts the Infinite Fracture Model (IFM) with the Discrete Fracture Network (DFN) model, showing that the DFN model yields more accurate block volume estimates by accounting for hidden fractures and geological complexities.
- Enhanced Accuracy in Volume Estimation: The DFN model's effectiveness is illustrated by Figs. 16 and 17, which demonstrate significant differences in the number and average volumes of blocks extracted compared to the IFM model. Notably, the DFN model results in a larger number of blocks, suggesting a more precise volume estimation across different working faces.
- Optimization of Extraction Processes: The study highlights the role of DFN modeling in improving the decision-making process for mineral resource management, leading to more efficient and cost-effective mining operations.
- Quantitative Improvements: Detailed analyses provided in Fig. 17 show that the DFN model facilitates more accurate

estimations of block volumes and reduces the variability in block size, which are critical factors for reducing operational costs and enhancing mining efficiency.

The findings from this study clearly indicate that adopting advanced methodologies such as photogrammetry and DFN modeling can significantly improve the extraction processes in dimension stone mining. These methodologies not only provide a deeper understanding of the geological structure of the mine but also support more effective managerial and economic decisions in the sector. Particularly for dimension stone mines in Iran, which encounter numerous challenges, these insights are invaluable for promoting sustainable development and optimizing resource utilization. This research exemplifies how technological advancements can transform traditional industries and lead to greater economic and environmental benefits.

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