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# Optimizing the blast fragmentation quality of discontinuous rock mass: Case study of Jebel Bouzegza Open-Cast Mine, North Algeria

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**Abstract**

**Purpose.** The research aims to investigate the impact of discontinuity characteristics, including dip direction, dip and joint spacing, on the size distribution of blasted fragments in mines and quarries. The accuracy of blasting results is essential for efficient operations, and understanding these factors can enhance blast fragmentation outcomes.

**Methods.** We conducted our research at the Jebel Bouzegza C01 aggregate quarry, analyzing eight blast benches. To determine fragment sizes, we employed image processing tools to calculate P50, P80, and Pmax sizes. Additionally, we used the Kuz Ram model to predict the average size ($X_{50}$) and the percentage of oversize fragments (Pmax). The determination coefficient ($R^2$) is calculated for both methods to assess their correlations with dip direction.

**Findings.** Our analysis revealed significant findings related to the impact of discontinuity characteristics on fragment size distribution. The dip direction exhibits the strongest correlation of Pmax size when using Split Desktop and $X_{50}$, as well as Pmax% with the Kuz Ram model. Joint spacing also plays a role in influencing blast fragmentation outcomes, although its effect depends on the infill materials.

**Originality.** This research contributes to the understanding of factors affecting blast fragmentation outcomes. The research focuses on dip direction, dip and joint spacing characteristics, and adds to existing knowledge in this field.

**Practical implications.** The findings of this research have practical implications for mines and quarries, offering valuable guidance for site investigations and optimization of blasting practices. By assessing properties such as dip direction and joint spacing, blasting operations can be enhanced to achieve more efficient and accurate results.

***Keywords:*** *blasting, fragment size distribution, discontinuity characteristics, dip direction, joint spacing*

## 1. Introduction

Efficient mining operations are of paramount importance in the mining industry to minimize production costs and optimize mining processes [1]-[7]. The initial step in rock crushing is blasting, followed by the subsequent milling process [8], [9]. The effectiveness of blasting operation depends on achieving the desired fragment size, which directly affects the productivity of mining operations. The size of fragmented rocks significantly affects processes such as loading, hauling, crushing, and grinding of mined materials [10], [11]. Rock fragmentation is influenced by a combination of controllable and uncontrollable variables [12], [13]. Controllable variables include blast design parameters and explosive properties, while uncontrollable variables encompass physico-mechanical properties, geological structure, water presence, and discontinuities [14]. It is essential to consider these variables when planning blasting operation to achieve optimal fragmentation outcomes. This provides an opportunity to reduce costs and increase productivity in mining operations.

Understanding the characteristics and distribution of discontinuities is critical for optimizing blasting operations and improving the efficiency of mining processes. Discontinuities, including faults, joints, shear zones, and bedding planes, can have a significant impact on rock fragmentation, blast energy, and the distribution of blast results [15], [16]. To explore the connection between discontinuities and the distribution of fragment sizes, extensive research has been carried out globally, encompassing various methodologies such as cinematic analysis, analytical modeling and numerical simulations. This research aims to provide a comprehensive understanding of how the presence and characteristics of discontinuities influence the resulting fragment sizes after blasting. The orientation of discontinuities is a key factor in determining specific charge values, while the size of the crushing zone surrounding the borehole is important for closed, open, or filled joints [17]. It has been observed that the filling material within joints can also influence rock mass fragmentation, with harder filling materials generating more fine frag-

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ments compared to weaker filling materials [18], [19]. Thus, considering the filling material within the joints and increasing the average distance between the joint sets and bedding planes are crucial for achieving improved breakage after blasting. By understanding the effects of discontinuities, mining operations can reduce production costs, optimize mining processes, and enhance productivity [20], [21]. Previous studies, such as those conducted by Akbari [22] and Souza et al. [23], have demonstrated the significance of discontinuities in optimizing mining processes, highlighting their influence on blast energy and the distribution of blast results.

To enhance our understanding of the impact of discontinuities on mining operations and rock fragmentation, a significant number of laboratory and field studies have been conducted. These studies have provided valuable insight into how discontinuities can influence rock fragmentation by affecting gas escape and reducing blast energy. The location of joints has emerged as a crucial factor, as laboratory research has shown that it can greatly influence fragmentation mechanics [24]-[27]. Field experiments have also contributed to our understanding of discontinuities and their effects on rock fragmentation. For example, the type of filling material used in joints has been found to impact the fragmentation process, with harder materials generating finer fragments compared to weaker ones [28]. The orientation of discontinuities is another critical aspect, as the specific charge values are lowest when the orientation is parallel to the blast face [29]. Researchers suggest that increasing the average distance between joint sets and bedding can lead to improved breakage after blasting [8]. Additionally, the size of the crush zone around the borehole is an essential consideration for mining companies when dealing with closed, open, or filled joints [30]-[33]. Therefore, understanding the characteristics and location of discontinuities is vital for optimizing blasting operations and improving the efficiency of mining processes. By taking these factors into account, mining companies can reduce production costs, optimize their operations, and minimize their environmental impact.

Mining engineers are constantly looking for ways to assess the effectiveness of their blasting operations, particularly with regard to rock fragmentation. Two widely used methods are employed for this purpose: the direct method and the indirect method. The direct method involves physical analysis of rock fragments through techniques such as screen analysis and boundary counting. This approach provides direct measurements of the fragment sizes and shapes. However, it can be time-consuming and costly to perform, requiring extensive manual labour and equipment. On the other hand, the indirect method relies on capturing photos of fragmented rock and analysing them using image processing software such as Wipfrag, Split Desktop, and Fragalyst. This method offers a faster and more cost-effective alternative for assessing rock fragmentation. Using image analysis algorithms, the software can accurately determine the size distribution and shape characteristics of fragments based on the captured images. The indirect method holds several advantages, including its ability to rapidly process large amounts of data and its potential for automation, reducing human errors. Additionally, it simplifies data storage and exchange compared to physical handling of rock fragments in the direct method. In the context of blasting in open-cast mines, the indirect method has proven to be a valuable tool for mining engineers in evaluating rock fragmentation. Its speed and cost-effectiveness make it particularly advantageous for large-scale operations, where efficient and timely analysis of fragmentation outcomes is crucial for optimizing mining processes and minimizing production costs. In the field of mining engineering, predicting the size distribution of blasted rock is essential for optimizing various mining processes. Empirical models have been developed to estimate size distributions by considering blast design parameters and rock properties. Among these models, the Kuz-Ram model, also known as the Kuznetsov-Rammler model, has become widespread [34]. This model was independently developed by Russian mining engineers Nikolay Vasilievich Kuznetsov and Ernst Rammler in the early 20th century [35].

The Kuz-Ram model serves to estimate the particle size distribution in a comminuted material, which undergoes crushing or grinding to break down into smaller pieces. It assumes that the particles exhibit varying sizes that adhere to a log-normal distribution, where the size distribution can be represented by a normal distribution in logarithmic space. This model finds applications in assessing particle size distribution in diverse mining processes including grinding, crushing, and milling. It aids in the design and optimization of crushing and grinding circuits and facilitates achieving the desired particle size distributions. One notable advantage of the Kuz-Ram model is its simplicity, as it requires only a few input parameters. These parameters can be readily obtained from standard laboratory tests or from plant data, making it a convenient tool for practical applications. The model provides crucial information about the particle size distribution, including the average size, the spread of the distribution, and proportion of fine particles. Such information proves valuable for process design, optimization and control. Despite its limitations, the Kuz-Ram model assumes a specific mathematical form for the particle size distribution, which may not be suitable for all comminution processes or materials. It may not accurately represent the behaviour of particle size distribution in the case of very fine or very coarse particles [36]. These ranges require careful consideration, as the mathematical function employed by the model might not be appropriate in such cases.

This research focuses on exploring the impact of discontinuity characteristics on blast fragmentation outcomes in open-cast mines. The researchers aim to investigate how various parameters related to discontinuities influence the fragmentation outcomes. To achieve this, the main families of discontinuities and their specific characteristics are identified at the Bouzegza C01 quarry, specifically on three benches. To evaluate the blast fragmentation outcomes, the researchers use digital image processing techniques and the Kuz-Ram model. This allows them to accurately assess the size distribution and other relevant properties of the fragmented rocks.

The investigation encompasses a total of eight blasts conducted at the quarry. By analyzing the obtained data, the researchers examine the influence of discontinuity parameters on the quality of blast fragmentation at the quarry. This analysis aims to provide insight into the relationship between discontinuity characteristics and resulting fragmentation outcomes. The findings of this research contribute to a better understanding of the factors impacting blast fragmentation and can potentially inform strategies for improving blasting operations in open-cast mines.

## 2. Study area

The research is conducted at the Jebel Bouzegza C01 quarry, which is operated by Cosider Company and located in Kherrouba, in the province of Boumerdes, northern region of Algeria (Fig. 1). This quarry is a significant producer of aggregates and primarily consists of limestone deposits from the Upper Jurassic era. The limestone formations form a massive rock mass, with a Middle Eocene limestone summit. Within this mass, various joint sets and discontinuities intersect the calcareous formations (Fig. 2).

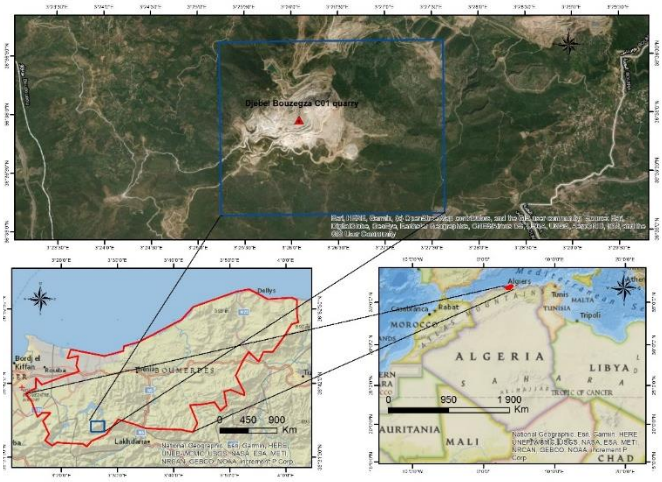

*Figure 1. Location of the Jebel Bouzegza C01 quarry*

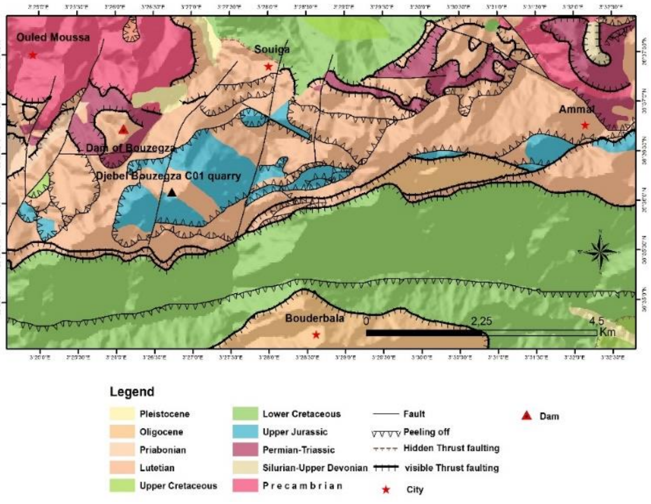

*Figure 2. Geology of the Jebel Bouzegza Massif*

The Jebel Bouzegza unit, known for its substantial stratigraphic sequences, exhibits a more complete profile compared to the Koudia Tichat unit, especially with respect to Mesozoic formations. By examining the lithostratigraphic columns and their arrangement, the unit can be divided into two distinct subunits. The northern subunit is characterized by thick Sinemurian limestone masses that exhibit internal platform facies at the base, featuring poor and low-diversity fauna. In the top, these facies transition to pelagic conditions with relatively greater depth, culminating in the formation of tidal channels. Detrital and secondary quartz are commonly present in this series. The detrital Eo-Oligocene layer consists primarily of coarse conglomerates, reaching a thickness of 350 m.

Conversely, the southern subunit is distinguished by the presence of Upper Lias-Dogger-Malm sediments deposited in an open marine environment. The depth increases towards the Malm, exhibiting ammonite facies (Kimmeridgian) and calpionelle facies (Upper Portlandian-Valanginian). The middle-upper Cretaceous layer is significantly reduced and displays homogeneous but intermittent facies. Sedimentation in a deep environment, rich in pelagic fauna (globotruncanids), characterizes this layer. Additionally, there is a Paleocene sandstone-carbonate layer with microcodia, indicating a change in sedimentation compared to the upper Cretaceous. The Eo-Oligocene molassic layer is particularly extensive and discordant with the underlying formations, sedimenting on a marine slope in its upper part (Slump facies). Alongside with the Senonian carbonate (Campanian marl-limestone), the lithostratigraphic series of this ridge includes a unit of thick detrital Eo-Oligocene layer (500 m). The study of the lithostratigraphic series of this ridge unit reveals two noteworthy characteristics. Firstly, it represents the median unit of the Djurdjura region, and secondly, it extends from the median-external units of Djurdjura. These geological details provide essential contextual information for the study conducted at the Jebel Bouzegza C01 quarry, enabling a comprehensive understanding of the geological setting in which the research is carried out.

## 3. Materials and methods

### 3.1. The Kuz-Ram model

The Kuz-Ram model is an empirical model widely employed in mining engineering to estimate the average fragment size ($X_{50}$) and the uniformity index ($n$) resulting during bench blasting. This model is among several existing models used to predict blast fragmentation. The calculation for $X_{50}$ is determined by Equation (1):

$$X_{50} = A \cdot Q^{1/6} \cdot \frac{\left(\frac{115}{E}\right)^{19/30}}{q^{0.8}}. \qquad (1)$$

The Kuz-Ram model offers a formula to estimate the average size of rock fragments ($X_{50}$, cm) formed during bench blasting. It incorporates various parameters, including the rock factor A, the quantity of TNT explosive used in the blast hole ($Q$, kg), the relative weight strength of the explosive ($E$, a percentage relative to ANFO), 115 (representing the RWS of TNT), and powder factor ($q$, cm). By inputting these parameters into the equation, the value of $X_{50}$ can be calculated.

The formula to calculate the uniformity index ($n$) is presented as follows:

$$n = \left(2.2 - 14\frac{B}{d}\right) \cdot \left(1 - \frac{W}{B}\right) \cdot \left(1 + \frac{(S/B) - 1}{2}\right) \cdot \frac{L}{H}. \qquad (2)$$

The Kuz-Ram model necessitates an accurate determination of the rock factor "$A$", which relies on the quality and density of the rock mass. The equation for predicting the uniformity index ($n$) takes into consideration several factors, including the blast hole diameter ($d$, mm), burden ($B$, m), spacing ($S$, m), the standard deviation of drilling accuracy ($W$, m), charge length ($L$, m), and bench height ($H$, m). Hence, a proper assessment of the rock factor is vital for the precise application of the Kuz-Ram model in predicting blast fragmentation.

Cunningham [37] introduced a new definition of the rock factor A by incorporating the rock discontinuity, density, and hardness using the Lilly blastability index:

$$A = 0.06 \cdot \left( RMD + JF + RDI + HF \right). \tag{3}$$

The Equation (3) encompasses the rock factor, including the rock mass description (*RMD*), joint factor (*JF*), rock density influence (*RDI*), and hardness factor (*HF*) (Table 1).

***Table 1. Factors influencing the rock factor in the Kuz-Ram model***

| | | |
|---|---|---|
| *RMD* | Rock mass description | 10 for rock powdery or friable<br>*JF* for vertical joints<br>50 for massive rock |
| *JF* | Joint factor | *JF* = *JPS* + *JPA* |
| *JPS* | Joint plane spacing | 10 if ($Sj$ < 0.1 m)<br>20 if (0.1 < $Sj$ < 0.3)<br>30 if (0.3 < $Sj$ < 95% $x_0$)<br>50 if ($Sj > x_0$) |
| *JPA* | Joint angle parts | 20 for dip out of face<br>30 for strike perpendicular to face<br>40 for dip into face |
| *RDI* | Rock density influence | $RDI = 25\rho - 50$ |
| *HF* | Hardness factor | $E$/3 for $E$ < 50 GPa<br>$\sigma_c$/5 for $E$ > 50 GPa |

Determining the rock factor ($A$) in the Kuz-Ram model involves considering various factors, including rock density ($\rho$, t/m$^3$), the defined oversize ($x_0$, m), rock Young's modulus ($E$, GPa), and uniaxial compressive strength ($\sigma_c$, MPa). Typically, medium-hard rocks are assigned a rock factor ($A$) value of 7, while hard and highly fissured rocks are assigned a value of 10, and very hard and weakly fissured rocks are assigned a value of 13. However, additional factors such as joint condition, spacing and hardness can influence the value of factor $A$. As a result, the revised rock factor $A'$ can range from 1.7 to 21, expanding the previously assumed range of 7 to 13. The calculation of the uniformity index (n) is based on the Equation (4):

$$n = \left( 2.2 - 14\frac{B}{d} \right) \cdot \left( 1 - \frac{W}{B} \right) \cdot \sqrt{\frac{1 + S/B}{2}} \cdot abs \times \\ \times \left( \frac{L_b - L_c}{L_{tot}} + 0.1 \right)^{0.1} \cdot \frac{L_{tot}}{H}, \tag{4}$$

where:

$L_b$ and $L_c$ denote the bottom and column charge lengths, respectively (m);

$L_{tot} = L_b + L_c$.

Recent studies by Cardu, & Calzamiglia [38], and Yilmaz [39] used the Kuz-Ram model to estimate blast fragmentation in the field of mining engineering. The model popularity stems from its simplicity and effectiveness in providing accurate predictions of blast fragmentation with minimal input data. However, it is important to acknowledge the limitations of the model, such as its assumption of a homogeneous blast and the omission of geological and geotechnical variations that can impact fragmentation. Despite these limitations, the Kuz-Ram model remains a valuable tool in the mining industry for estimating blast fragmentation.

### 3.2. Analysis of fragmentation using digital image processing techniques

To analyze blast fragmentation, this research uses digital image processing techniques in Split-Desktop software based on a gray-scale analysis of rock fragments developed by the University of Arizona [40], [41]. The procedure involves ope-ning and scaling the image, determining the image scale, applying manual delineation for enhanced precision, analyzing fragment sizes, and displaying the size distribution results in a diagram format. It is important to note that accurate evaluation of fragment size using Split-Desktop requires at least one (or two) reference dimensions, with their diameters being perpendicular to the optical axis of the image. The muckpile images obtained from the blasting are processed using the Split-Desktop software and the results are generated by combining all the graphs [42]. The use of digital image processing techniques such as Split-Desktop provides a reliable and accurate method for evaluating blast fragmentation.

### 3.3. Blast design parameters for bench blasting

The blasting operations at the Jebel Bouzegza C01 quarry are conducted with specific blast design parameters. These parameters include hole drilling diameter of 89 mm, a bench height of 13 m, and a stemming length of 1.0 m. The burden and spacing values are set at 3.5 and 3.0 m, respectively. For the blasting process, ANFO and TEMEX II are used as primary explosives, with a charge length of 9.0 m and a specific explosive charge of 0.38 kg/m$^3$.

In order to achieve the desired fragment size, which is limited to a maximum size of 1000 mm based on the capabilities of the quarry loading, hauling and crusher opening equipment, fragmentation analysis is performed using digital image processing techniques using Split-Desktop software [43]. It is important to note that accurate fragment size evaluation using Split-Desktop requires at least one or two reference dimensions that are perpendicular to the optical axis of the image.

The blast design parameters applied at the Jebel Bouzegza C01 quarry are carefully optimized to attain the desired fragmentation size, while prioritizing the safety of personnel and equipment.

### 3.4. Mapping discontinuities using measurement techniques

Rock masses are composed of rock material as well as discontinuities such as faults, joints and fractures, which significantly influence the mechanical behaviour of the rock mass. To characterize these discontinuities, a traditional Scanline method is used, which involves line mapping measurement and compass measurements. This method allows the determination of various discontinuity properties, including the number of joint sets, dip direction, joint dip statistics, joint spacing, frequency, and filling. By drawing intersections of joints and scanlines on the high walls of the bench, the orientation and dip angles of the joints are measured.

The joint spacing is determined by measuring the distance between discontinuities along a measurement line, while the frequency is the reciprocal of the joint spacing for each measurement. To assess the characteristics of the main discontinuity families, the measured data of dip direction and dip are processed using a projection stereographic program [44], [45]. In this research, three benches are selected for measuring discontinuity properties, including dip direction, dip, joint spacing, and frequency, along eight blast surfaces ranging from 35 to 65 m in length. A total of 437 discontinuities are measured: 83 discontinuities for blast 1, 46 for blast 2, 54 for blast 3, 62 for blast 4, 48 for blast 5, 39 for blast 6, 58 for blast 7, and 47 for blast 8.

A methodological flowchart depicting the step-by-step process used in this research is illustrated in Figure 3.

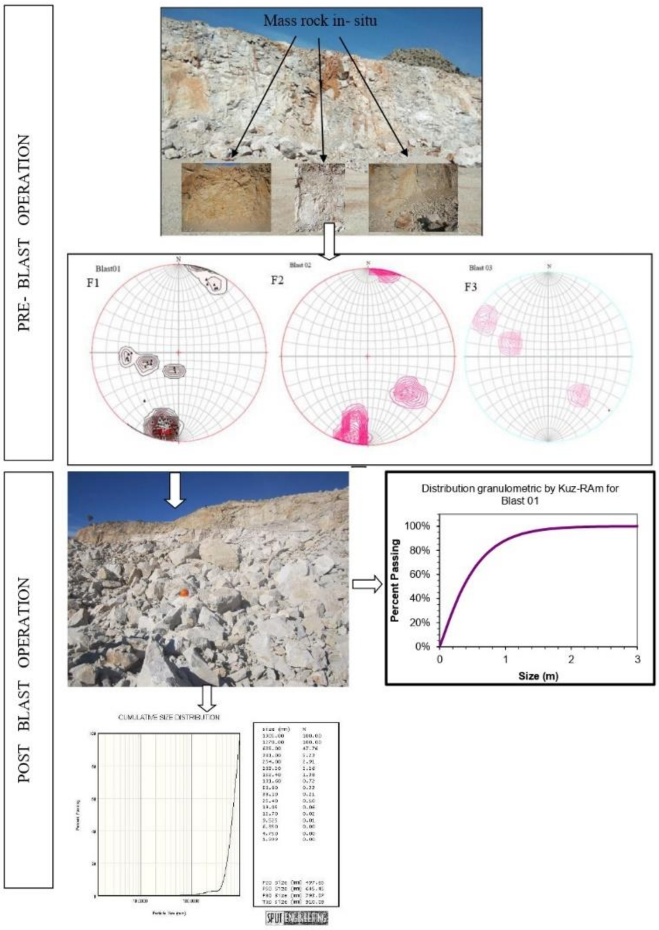

*Figure 3. Flowchart for the methods applied at the Jebel Bouzegza C01 quarry*

The flowchart shows the multi-stage methodology implemented to characterize rock mass properties and evaluate blasting performance at the Jebel Bouzegza C01 quarry. The work incorporates both pre-blasting and post-blasting analyses to obtain a comprehensive understanding of the geological factors influencing fragmentation outcomes.

The pre-blasting stage involves detailed field mapping and discontinuity surveys to determine the orientation and characteristics of structural weaknesses within the rock mass. Numerous fractures with variable dip direction, dip and spacing parameters are observed and systematically recorded. Stereonet program is used to classify fractures into three predominant discontinuity sets based on orientation. Understanding these structural patterns through quantitative discontinuity data collection is imperative for blast design and controlled fragmentation.

Post-blasting stage includes image-based fragmentation assessment. High-resolution images of the post-blast muckpile are processed using conventional image segmentation techniques to determine fragments size distribution. This objective fragmentation analysis allows evaluation of comminution efficiency versus predicted outcomes. The Kuz-Ram model is used to predict granulometric curve based on the input blast design and rock mass parameters obtained during pre-blast mapping. This multi-stage methodology, integrating both discontinuity domain analysis and quantitative post-blast metrics, provides mining engineers with insight into geological influences on fragmentation and aids in the design, monitoring and optimization of future quarry production blasting performance. A systematic approach supports continuous improvement of extraction processes.

## 4. Results and discussion

In order to evaluate the influence of dip direction, dip, and joint spacing on the quality of fragmentation in blasted rocks at the Jebel Bouzegza C01 Quarry, a total of eight blasts have been chosen for analysis. These blasts, designated as Blast 1, Blast 2, and Blast 3 at the 810 m bench, Blast 4, Blast 5, Blast 6, and Blast 7 at the 820 m bench, and Blast 8 at the 870 m bench, are specifically selected to represent different locations within the quarry. By examining these eight blasts, we aim to understand how variations in dip direction, dip angle, and joint spacing contribute to the resulting fragmentation quality. This investigation will provide valuable insight into rock mass behavior and assist in optimizing future blasting operations at the quarry.

### 4.1. Analysis of discontinuity characteristics at the Jebel Bouzegza C01 quarry

The measured data of dip direction and dip are processed using a stereographic program, allowing us to identify three primary families of discontinuities. Family 1, characterized by a dip direction ranging from 20 to 30° and a dip ranging from 60 to 70°, includes Blast 1, Blast 4, and Blast 5. Family 2, with a dip direction between 90 and 100° and a dip ranging from 30 to 40°, comprises Blast 2 and Blast 7. Lastly, Family 3, with a dip direction ranging from 350 to 360° and a dip ranging from 70 to 80°, includes Blast 3, Blast 6, and Blast 8.

Furthermore, based on the analysis of joint spacing, we have identified two distinct classes. Class 1, characterized by joint spacing (*Sj*) greater than 0.5 m, includes Blast 1, Blast 3, Blast 4, and Blast 7. On the other hand, Class 2, featuring joint spacing (*Sj*) less than 0.5 m, includes Blast 2, Blast 5, Blast 6, and Blast 8 (Table 2).

To identify discontinuities associated with opened joints and fractures filled with clay or calcite materials, the line mapping method is used. These findings provide valuable insight into the nature of discontinuities present in the rock mass, allowing us to better understand their influence on blast fragmentation and optimize blasting strategies accordingly.

*Table 2. Characteristics of Discontinuities at the Jebel Bouzegza C01 Quarry*

| Bench / Charact | Bench 810 m | | | Bench 820 m | | | | Bench 870 m |
|---|---|---|---|---|---|---|---|---|
| N° of Blast | Blast 1 | Blast 2 | Blast 3 | Blast 4 | Blast 5 | Blast 6 | Blast 7 | Blast 8 |
| Dip direction (°) | 22.1 | 356.5 | 98.6 | 22.0 | 23.5 | 352.6 | 95.3 | 356.5 |
| Dip (°) | 63.4 | 73.9 | 38.6 | 66.0 | 68.6 | 71.8 | 35.7 | 73.9 |
| Length (*L*, m) | 60.5 | 61.2 | 60.1 | 50.2 | 47.8 | 54.6 | 54.0 | 42.0 |
| Joint spacing (*Sj*, m) | 0.625 | 0.212 | 0.714 | 0.513 | 0.374 | 0.227 | 0.889 | 0.318 |
| Frequency (*Fr*, $m^{-1}$) | 1.601 | 4.719 | 1.400 | 1.951 | 2.672 | 4.400 | 1.125 | 3.146 |

### 4.2. Analysis of fragmentation in blasted rocks using split desktop image processing

The blast fragmentation images are analyzed using Split Desktop software to assess the fragment size distribution after blasting operations. The obtained results, depicting the outcomes of this analysis for eight blasts executed at the Jebel Bouzegza C01 quarry, are presented comprehensively in Table 3. In this evaluation, we focus on determining the percentage of fragments passing through three distinct sizes: $P_{50}$ (representing the size at which 50% of fragments pass), $P_{80}$ (representing the size at which 80% of fragments pass), and $P_{max}$ (representing the maximum size observed). By examining these fragmentation parameters, we gain essential insight into the effectiveness and efficiency of blasting operations, as they reflect the distribution and size characteristics of the resulting fragments. The presented data in Table 3 will contribute significantly to our understanding of the fragmentation patterns achieved at the Jebel Bouzegza C01 quarry, facilitating further analysis and optimization of blasting techniques.

***Table 3. Fragmentation analysis results using Split Desktop image processing software at the Jebel Bouzegza C01 quarry***

| Pass fragments | Blast 1 | Blast 2 | Blast 3 | Blast 4 | Blast 5 | Blast 6 | Blast 7 | Blast 8 |
|---|---|---|---|---|---|---|---|---|
| $P_{50}$ (mm) | 615.10 | 428.54 | 751.32 | 638.55 | 529.12 | 476.87 | 709.66 | 503.78 |
| $P_{80}$ (mm) | 803.82 | 596.73 | 1002.69 | 842.00 | 675.32 | 629.24 | 890.22 | 668.44 |
| $P_{max}$ (mm) | 953.53 | 729.94 | 1225.22 | 1003.17 | 791.56 | 788.56 | 1033.78 | 798.6 |

### 4.3. Effect of parameters on blast fragmentation

This research aims to investigate the influence of joint properties on blast fragmentation quality through the use of Split Desktop image processing for eight blasts. Percentage pass values for $P_{50}$, $P_{80}$, and $P_{max}$ are examined and the findings are graphically presented in (Figs. 4, 5), highlighting the impact of dip direction and dip on fragment size. The analysis has revealed notable variations in fragment size among the blasts. Blast 1, Blast 3, Blast 4, and Blast 7 exhibit larger fragments compared to Blast 2, Blast 5, Blast 6, and Blast 8. This discrepancy can be attributed to the heterogeneous nature of the rock mass and the influence of fractures on blast fragmentation.

The angle formed between the dip direction of each discontinuity family and the blast surface is as a significant factor influencing the size of blasted rocks. Notably, when the angle reaches 90°, signifying that the discontinuities are perpendicular to the blast surface, larger fragment sizes are observed. These findings underscore the importance of considering the orientation and spatial arrangement of discontinuities when assessing blast fragmentation outcomes.

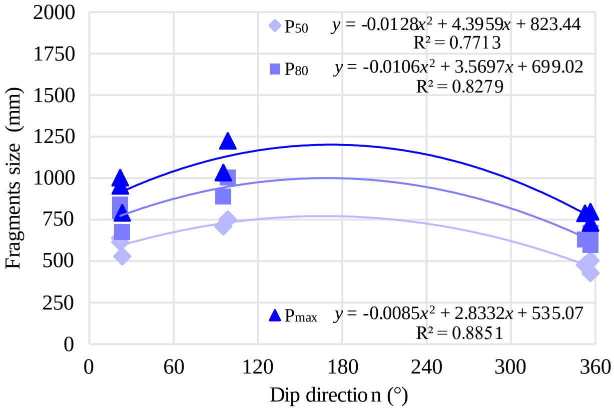

***Figure 4. The effect of dip direction on blast fragmentation at the Jebel Bouzegza C01 quarry***

Furthermore, the research examines the effect of joint spacing on blasted rock, and the results are illustrated in Figure 6. A clear relationship is observed between joint spacing and fragment size, with an increase in joint spacing leading to larger fragment sizes for $P_{50}$, $P_{80}$, and $P_{max}$. It is worth noting that all $P_{50}$ fragment sizes are below 800 mm, and when joint spacing is less than 0.5 m, the fragment sizes for $P_{50}$, $P_{80}$, and $P_{max}$ are below 800 mm.

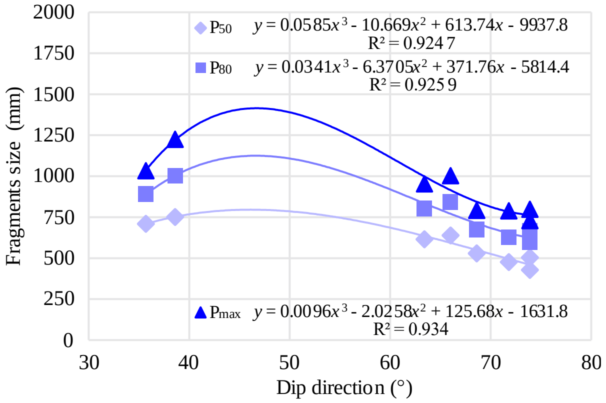

***Figure 5. The effect of dip on blast fragmentation at the Jebel Bouzegza C01 quarry***

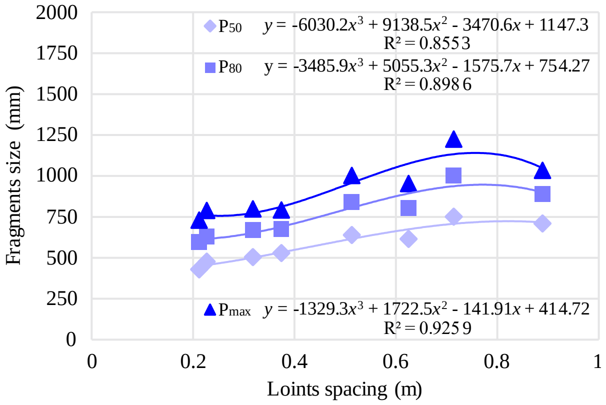

***Figure 6. The effect of joint spacing on blast fragmentation at the Jebel Bouzegza C01 Quarry***

However, when joint spacing exceeds 0.5 m, Blast 3, Blast 4, and Blast 7 exhibit $P_{max}$ fragment sizes exceeding 1000 mm, which is considered to be oversized fragments.

To identify a quantitative relationship between the properties of discontinuities and fragment size, the determination coefficient $R^2$ is calculated. For dip direction, the $R^2$ values are 0.771, 0.827, and 0.885 for $P_{50}$, $P_{80}$, and $P_{max}$, respectively. Similarly, for dip, the $R^2$ values are 0.924, 0.925, and 0.934 for $P_{50}$, $P_{80}$, and $P_{max}$, respectively. Additionally, the $R^2$ values for joint spacing are 0.855, 0.898, and 0.925 for $P_{50}$, $P_{80}$, and $P_{max}$, respectively. Notably, the best-fitting model is observed between discontinuity properties and the fragment size $P_{max}$, suggesting a stronger relationship between these variables. These findings provide valuable insight into the influence of joint properties on blast fragmentation outcomes and contribute to a deeper understanding of the interaction between discontinuity characteristics and fragment size. The determination of $R^2$ values further enhances the robustness of the analysis by demonstrating the significance of the examined factors in predicting and explaining variations in fragment size.

### 4.4. Application of the Kuz-Ram model for fragmentation analysis

In order to accurately predict the size distribution of fragmentation using the Kuz-Ram model, comprehensive data regarding the geological and geomechanical properties of the rock mass, as well as the blast design parameters, have been collected. The predicted fragmentation outcomes using the Kuz-Ram model for the eight blasts conducted at the Jebel Bouzegza C01 quarry are presented in Table 4. This table provides valuable information on various fragmentation parameters, including average fragment size ($X_{50}$), blastability index ($n$), percentage of oversize fragments (larger than 100 cm), and percentage of fragments within the desired range (10 to 100 cm).

Analysis of these results enables a comprehensive assessment of the effectiveness of the blasting operations in achieving the desired fragmentation outcomes. The average fragment size ($X_{50}$) provides insight into the central tendency of the fragmentation distribution, while the blastability index ($n$) offers a measure to assess the uniformity of the fragmentation.

***Table 4. Predicted fragmentation outcomes using the Kuz-Ram model in the study area***

| Blast<br>Charact | Blast 1 | Blast 2 | Blast 3 | Blast 4 | Blast 5 | Blast 6 | Blast 7 | Blast 8 |
|---|---|---|---|---|---|---|---|---|
| Blast ability index ($n$) | 7.7026 | 8.3346 | 8.4915 | 7.6618 | 7.7222 | 8.6029 | 8.316 | 8.5764 |
| Average size ($X_{50}$, cm) | 36.0 | 39.0 | 40.0 | 36.0 | 36.0 | 41.0 | 39.0 | 40.0 |
| Percentage of oversize ($P_{\max}$, %) | 11.7 | 14.0 | 14.9 | 11.5 | 11.7 | 15.0 | 13.9 | 14.9 |
| % in the range | 87.1 | 84.9 | 84.3 | 87.2 | 87.0 | 83.9 | 84.9 | 84.0 |

The percentage of oversize fragments highlights the extent to which larger fragments are produced, which can impact downstream operations such as loading and crushing. Conversely, the percentage of fragments within the desired range indicates the effectiveness of blasting in producing fragments suitable for efficient handling and processing.

By examining these parameters, we can evaluate the performance of each blast and identify any deviations from the desired fragmentation outcomes. These findings can be valuable for optimizing future blasting operations and enhancing overall productivity and efficiency in open-cast mining.

### 4.5. The influence of dip direction on fragmentation

The quality of fragmentation in blasting operations is of paramount importance in mining and is influenced by various factors. The Kuz-Ram predictive model is widely used to assess fragmentation quality and Figure 7 provides visual representations of how different parameters influence fragmentation outcomes. Specifically, Figure 7a, b highlights the influence of dip direction, while Figure 7c, d depicts the effect of dip angle. Furthermore, Figure 7e, f reveals the impact of joint spacing on fragmentation quality.

When analyzing the results, it has been noted that the average blast fragmentation size ranges from 36.0 to 41.0 cm. Notably, Blast 3, Blast 6, and Blast 8 exhibit the highest average size and the largest percentage of oversize fragments. These blasts are associated with Family 2 and Family 3 of discontinuities, indicating that the properties of these discontinuities significantly influence the fragmentation quality. In contrast, Blast 1, Blast 4, and Blast 5 show an average size of 36.0cm and an oversize percentage of 11.7%, and they are associated with Family 1 of discontinuities.

To further assess the relationship between fragmentation quality and the different parameters, the determination coefficient $R^2$ is calculated. The $R^2$ values for dip direction are 0.928 for the average size ($X_{50}$) and 0.943 for the percentage of oversize fragments ($P_{\max}$ %). Regarding dip angle, $R^2$ values of 0.724 for $X_{50}$ and 0.817 for $P_{\max}$ % can be obtained. For the joint spacing, $R^2$ values of 0.451 for $X_{50}$ and 0.501 for $P_{\max}$ % can be found. These $R^2$ values indicate the strength of the relationship between the parameters and fragmentation quality. Notably, the best agreement is observed for the relationship between dip direction and the average size ($X_{50}$), as well as the percentage of oversize fragments ($P_{\max}$ %), suggesting that dip direction has a significant impact on fragmentation quality. However, the relationship between joint spacing and fragmentation quality is not consistent with other parameters, implying that additional factors may influence fragmentation outcomes. Overall, these findings can assist mining operations in optimizing their blasting parameters and enhancing fragmentation quality.

### 4.6. Impact of joint spacing on fragmentation degree

The role of rock mass properties in improving blast fragmentation quality has been widely recognized. However, in order to gain deeper insight into the degree of fragmentation, the study explores the impact of joint spacing. By simulating the average size ($X_{50}$) using the Kuz-Ram model and analyzing the average size ($P_{50}$) as a result of image processing, valuable findings have been obtained (Table 5 and Fig. 8).

***Table 5. Joint spacing simulation results for $X_{50}$ and $P_{50}$ at the Jebel Bouzegza C01 Quarry***

| Bench | N° Blast | Spacing joint (cm) | $X_{50}$ (cm) | $P_{50}$ (cm) |
|---|---|---|---|---|
| 810 m | B 1 | 62.46 | 36.00 | 61.51 |
| | B 2 | 21.19 | 39.00 | 42.85 |
| | B 3 | 71.41 | 40.00 | 75.13 |
| 820 m | B 4 | 51.26 | 36.00 | 63.86 |
| | B 5 | 37.42 | 36.00 | 52.91 |
| | B 6 | 22.73 | 41.00 | 47.69 |
| | B 7 | 88.87 | 39.00 | 70.97 |
| 870 m | B 8 | 31.79 | 40.00 | 50.38 |

During the research, it has been observed that the joint spacing values in Blast 3, Blast 4, and Blast 5 are higher than the average size ($P_{50}$), whereas the largest joint spacing values are in Blast 1 and Blast 7. This observation indicates that the rock mass size in situ decreases after the blasting process due to the effective use of blast energy without any gas leakage in the fractures.

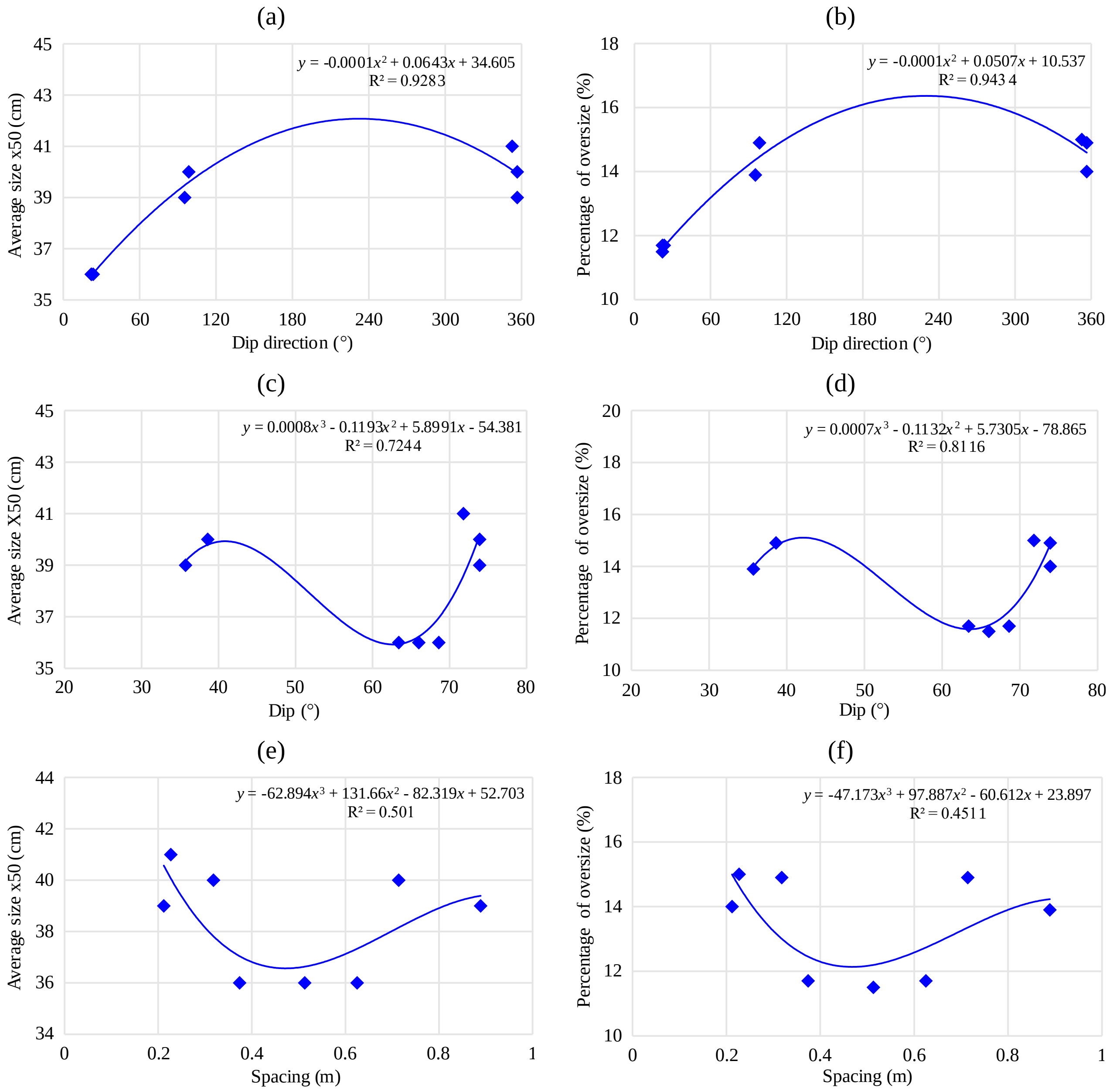

***Figure 7. The influence of dip direction on fragmentation: (a) effect of dip direction on $X_{50}$; (b) effect of dip direction on $P_{max}$ %; (c) effect of dip on $X_{50}$; (d) effect of dip on $P_{max}$ %; (e) effect of spacing on $X_{50}$; (f) effect of spacing on $P_{max}$ %***

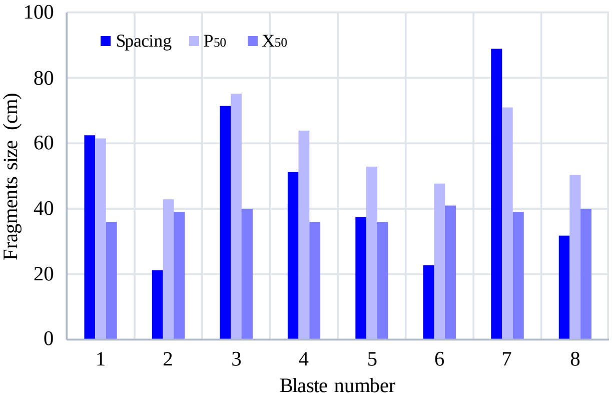

***Figure 8. Joint spacing simulation histogram for $X_{50}$ and $P_{50}$***

Additionally, when the joint spacing is less than 32 cm in Blast 2, Blast 6, and Blast 8, it has been noticed that the average size ($X_{50}$) and average size ($P_{50}$) values are larger than the joint spacing. This suggests that the results in these blasts could be attributed to the similar mineralogical composition of the infilling materials within the joints and the limestone rock. In the bench blasts, the infilling materials in the discontinuities primarily consist of calcite and aragonite materials.

In our future research, we plan to combine additional natural factors, such as geology and rock structures, with human-made factors, including existing excavations and infrastructure within the rock mass. This will help exploit inherent weaknesses to achieve improved blast fragmentation performance. A multi-disciplinary approach incorporating geophysics, petrology, and hydrology data will provide a more holistic understanding of rock mass characteristics, including genesis, mechanical behavior under stress and rheological properties under dynamically loading during blasting. The main goal is to gain deeper insight into how both natural features and anthropic additions to the rock mass influence blasting outcomes. These effects could potentially be enhanced by optimizing blast designs considering the integrated geotechnical, geological, and hydrogeological conditions. A broader rock mass characterization using diverse data sources will assist engineers in better predicting and controlling fragmentation, thereby enhancing the operational and economic results of future blasting operations [46]-[53].

## 5. Conclusions and recommendations

The production of desired-size fragments is a crucial requirement in mining, and achieving this goal requires a comprehensive understanding of rock characteristics. This research assesses the impact of dip direction, dip, and joint spacing on blast fragmentation at the Jebel Bouzegza C01 quarry. The results demonstrate that the smallest fragment sizes are associated with specific families of discontinuities. Joint spacing is found to increase fragment size, as indicated by the determination coefficient ($R^2$) values. The dip direction shows the strongest correlation with the average size ($X_{50}$) and the percentage of oversize fragments. However, the Kuz-Ram model is not directly related to discontinuity characteristics.

Based on the findings obtained, several recommendations can be made to improve the blast fragmentation in mining operations. It is recommended to thoroughly assess the rock mass characteristics, consider dip direction, dip, and joint spacing during planning, select appropriate blasting methods and explosives, and regularly monitor the results to make necessary adjustments. Implementing these recommendations can enhance blast fragmentation quality, reduce the need for secondary breakage, and increase productivity.

Furthermore, future research can explore additional rock mass properties, investigate alternative blasting techniques and explosives, develop advanced imaging technologies for rock mass assessment, and study the environmental impact of blasting operations. These research directions have the potential to further improve blasting efficiency and minimize environmental impacts.

In conclusion, this research provides valuable insight for optimizing blasting operations at the quarries and mining sites. It also lays the foundation for future research in the field aiming to enhance blast fragmentation and overall productivity in the mining industry.

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## Оптимізація якості роздроблення вибухом переривчастої гірської маси: тематичне дослідження на прикладі відкритого рудника Джебель Бузегза, Північний Алжир

К. Бедрі, М. Оулд Хамоу, М. Філалі, Р. Хаджі, Х. Таіб

**Мета.** Вивчення впливу характеристик несплошності, включаючи напрямок падіння, саме падіння та відстань між тріщинами, на розподіл підірваних вибухом фрагментів за розміром у шахтах і кар'єрах для уточнення ефективної технології підривних робіт та розуміння впливових факторів покращення роздроблення.

**Методика.** Дослідження проведено на кар'єрі Джебель-Бузегза C01 з видобування осадового каменю, де було проаналізовано вісім підірваних уступів. Для визначення розмірів фрагментів використовували інструменти обробки зображень для розрахунку розмірів P50, P80 та $P_{max}$. Крім того, застосовано модель Куз-Рама для прогнозування середнього розміру ($X_{50}$) та відсотка фрагментів збільшеного розміру ($P_{max}$). Коефіцієнт детермінації ($R^2$) розрахований для обох методів, щоб оцінити їхні кореляції з напрямком падіння.

**Результати.** Виявлено важливі аспекти, що пов'язані з впливом характеристик несплошності на розподіл фрагментів за розміром. Визначено, що напрямок падіння демонструє найсильнішу кореляцію розміру $P_{max}$ при використанні Split Desktop і $X_{50}$, $P_{max}$ %, а також з моделлю Куз-Рама. Встановлено, що відстань між тріщинами відіграє певну роль, впливаючи на результати роздроблення вибухом, хоча її вплив залежить від матеріалів наповнювача.

**Наукова новизна.** Дослідження сприяє розумінню чинників, що впливають на результати роздроблення вибухом, та зосереджено на характеристиках напряму падіння, самому падінні й відстані між тріщинами, а також доповнює наявні знання у цій галузі.

**Практична значимість.** Результати цього дослідження мають практичне значення для шахт і кар'єрів, пропонуючи цінні рекомендації для вивчення об'єктів та оптимізації методів підривних робіт. Оцінюючи такі властивості як напрямок падіння й відстань між тріщинами, підривні роботи можна вдосконалити для досягнення більш ефективних і точних результатів.

***Ключові слова:*** *підривання, розподіл фрагментів за розміром, характеристики несплошності, напрямок падіння, відстань між тріщинами*