ANALYSIS OF INFLUENCE OF STRUCTURAL GEOLOGY AND GEOMECHANICAL IN THE BLASTING ROCKS PREDICTION*

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Resumo

Predicting rock fragmentation is essential to optimize the blasting rock operation. Fragmentation depends on many parameters, such as structural and geomechanical properties of rocky massif, blast plan geometry of detonations and properties of explosives. In this context, the objective of this work is to predict fragmentation by simulation of *Mineração Megaípe* blasting rock considering the structural and geomechanical characteristics inherent to the rocky massif formation through the Kuz-Ram methodology. The methodology consisted in the survey of the geometric properties of the visible discontinuities on the face of the bench, accomplishment of the geomechanical classification through the Rock Mass Rating (RMR) and Q systems and application of the results to prediction of the granulometric distribution of fragmentation. It was obtained as a result of the simulation that about 90% of the fragmented material should pass through the gap of the primary crusher available in the quarry, in addition to favorable results for analyzes of operational slope stability conditions.

Palavras-chave: Rock blasting; Structural geology; Geomechanical classification; Kuz-Ram methodology.

ANÁLISE DA INFLUÊNCIA DA GEOLOGIA ESTRUTURAL E GEOMECÂNICA NA PREVISÃO DO DESMONTE DE ROCHAS

Abstract

A previsão da fragmentação da rocha é essencial para otimizar a operação de desmonte de rochas. A fragmentação depende de muitos parâmetros, como propriedades estruturais e geomecânicas do maciço rochoso, geometria do plano de fogo das detonações e propriedades dos explosivos. Neste contexto, este trabalho objetivou realizar a previsão da fragmentação por simulação do desmonte de rochas da Mineração Megaípe considerando as características estruturais e geomecânicas inerentes à formação do maciço rochoso através da metodologia de Kuz-Ram. A metodologia consistiu no levantamento das propriedades geométricas das descontinuidades visíveis na face da bancada existente, realização da classificação geomecânica através dos sistemas Rock Mass Rating (RMR) e Q e aplicação dos resultados para predição da distribuição granulométrica da fragmentação. Obteve-se como resultado da simulação que cerca de 90% do material fragmentado deve passar na abertura do britador primário disponível na pedreira, além de resultados favoráveis quanto às análises de condições de estabilidade do talude operacional.

Keywords: Desmonte de rochas; Geologia estrutural; Classificação geomecânica; Metodologia de Kuz-Ram.

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1 INTRODUCTION

Process optimization is already a consolidated practice which allows to reduce costs of unitary operations and consequently of the global operation, thus seeking a greater competitiveness in the market. Mining follows the same path, absorbing different technologies from several sectors in order to improve the efficiency of their processes and reduce their costs [1].

The analysis of the resulting rock fragmentation is essential in any blasting rock operation. This importance is due to the highly influential effect of the degree and size distribution of the fragments for loading, hauling and crushing operations. Depending on the strength characteristics of the material, the breaking of the rocky massif by mechanical dismount can be expensive or impractical, and the effective detonation of the rock through explosive energy is most convenient due to the lower associated costs. The overall economy in the mining / processing operations can be optimized by managing and controlling the drilling and blasting processes, producing a suitable particle size distribution of the fragmented material [2,3,4,5,6].

Several empirical models have been developed with the aim of designing and predicting rock fragmentation, such as Kuz-Ram, using the equations proposed by Kuznetsov (1973), Cunningham (1983), Lilly (1986) and Tidman (1991) and Rosin-Rammler (1933), the JKMRC fragmentation model (2002) and the Two Component Fragmentation Model (TCM) developed by Djordjevic (1999) [7]. The basic factors that affect rock breaking can be grouped into four different categories: geotechnical parameters of the rock, such as density, hardness, presence of discontinuities; explosive parameters, such as density of the explosive and velocity of detonation; technical parameters, such as delay time interval, force and location of the initiator; and geometric parameters, such as burden, spacing, stemming lenght, etc. [8].

Rocky massifs can be defined as juxtaposed and articulated blocks of rock (rocky matrix), limited by the arrangement of discontinuity planes such as fractures, joints, faults and foliations, surfaces responsible for behavior (stability and deformability) and appearance of the massif, which have irregular geometric shapes. These discontinuity plans, due to their spatial orientations, generate a different behavior of their physical properties according to the different directions in the rocky massif, characterizing them, generally, as anisotropic [9,10,11].

The resistance, deformation and fragmentation index of the massifs depend very much on the characteristics of the rock matrix and the discontinuities, and are subject to requests that affect its stability. Thus, evaluation of potential unstable areas of a massif by surveying the geometric and mechanical characteristics of all operational slope discontinuities becomes a fundamental tool for determining the geomechanical and structural characteristics of rocky massifs in mining [12]. In addition, the knowledge of parameters such as the structure of the rock mass and the characteristics of the discontinuities is fundamental to obtain a representative geological model, providing possibilities of solutions of geotechnical problems involving the mine planning, as well as optimization of the processes inherent to the operations of mines, such as the rock blasting.

The geomechanical classification has its importance based on the need for global knowledge of the rocky massif because it includes the mechanical characterization of the material and the study of the discontinuities. One of the very widespread classification systems is the Rock Mass Rating (RMR) system proposed by Bieniawski [13], composed by the attribution of weights related to the evaluation of 6 parameters related to the mass, namely: uniaxial compressive strength, Rock Quality Designation (RQD), spacing of discontinuities, condition of discontinuities (alteration and roughness), groundwater conditions and orientation of the discontinuities in relation to the cut. Another system used is Rock Mass Quality, also known as Q classification, proposed by Barton et al. [14]. The classification methodology is the assignment of weights to each parameter of the following equation (Equation 1):

$$Q = (RQD/J_n)\ x\ (J_r/J_a)\ x\ (J_w/SRF) \qquad (1)$$

where J_n is the joint set number, J_r is the roughness index, J_a is the index of alteration, J_w is the reduction factor due to the presence of water and SRF is the Stress Reduction Factor. The quotient (RQD/J_n) provides an approximation for the block size; the relationship (J_r/J_a) provides an approximation of the shear strength between blocks; and the quotient (J_w /SRF) lists two active stress parameters [15].

The fragmentation of the massif is an aspect that assumes fundamental importance in the mining operations that follow the rock blasting and in the global operation. This subject, however, is neglected in several Brazilian mines, especially in aggregate mining. With rare exceptions, the search for solution for fragmentation is done empirically and without results control, which does not guarantee that the operations are being performed in the most efficient way [16].

The rock blasting in the mining production chain should receive a systemic approach, since the degree of fragmentation obtained directly affects the subsequent processes. This systemic approach aimed at increasing overall results includes the determination of the rocky massif properties, the modeling and simulation of the performance of each stage, simulation of the conditions to achieve global optimization, implementation of a strategy to achieve global optimization, followed by the determination of rocky massif properties in real time and “online” measurements of ore properties throughout various processes. However, the investment in research to obtain consistent results through aforementioned methodologies is high, and it is difficult for an aggregate mining enterprise to have capital for similar studies due to the low value of the ore [17].

In the state of *Pernambuco*, the aggregate mining sector for civil construction is quite expressive and essential for the movement of the regional economy. Most of the activities developed in quarries present bottlenecks in its operation, mainly due to the absence of adequate planning of unit operations considering relevant factors such as geological, mechanical and structural characteristics. Since these studies imply additional costs, even more when taking into account the low value of the products, an alternative methodology must be proposed to predict and accompany the results os the rock blasting operation. Such problems mainly consist of the absence of uniformity in the fragmentation, the generation of blocks of dimensions above the gap of the primary crusher and negative environmental impacts such as vibrations, noise and flying rocks. In this context, this work aims to predict the result of the fragmentation of rocks blasting from the rocky massif of the *Mineração Megaípe*, combining the geological and geomechanical characteristics of the massif with the prediction of the next blasting plan.

2 MATERIALS AND METHODS

The study was developed at the *Mineração Megaípe Eireli* (figure 1), located in *Jaboatão dos Guararapes*, state of *Pernambuco*, Brazil, whose economic activity is the extraction and associated processing of a rocky massif classified as granite, belonging to the Geological Formation *Borborema* Province, more specifically in the *Pernambuco-Alagoas* Land, for the production of aggregates for civil construction. The quarry is in it's initial phase of operation, having only one mining front, and its exploitation is performed through the open pit mining method by multiple benches.

Figure 1. Aerial view of the *Mineração Megaípe* pit

The methodology for the development of this study consisted basically of performing the survey of the characteristic attitudes of the workbench slope, the geomechanical classification of the rocky massif through the RMR and Q systems and the prediction of the result of the fragmentation considering the Kuz-Ram methodology [17]. For this, the operational bench (figure 2) was divided into 3 parts (right, central and left side) for easing the work and greater detailing of the parameters needed for the analysis.

Figure 2. Operational bench of *Mineração Megaípe*

The survey of the geometric properties of the discontinuities in the face of the existing operational slope in the mine comprised the collection of discontinuity attitudes (dip and dip direction) using measuring tape and Clark compass for later determination of the scanfaces in front of mining and individualization of the partition blocks. The *data* were then inserted into stereograms using the Dips stereographic projection software from Rocscience Inc. (free tryal) to obtain the spatial representation of the relationships between the geological structures of the massif and the slope attitudes, providing an analysis of the possibility of definition of the shape and size of partition blocks besides visualization of the possible types of face rupture.

For the geomechanical classification of the rock mass by means of the RMR and Q systems, work was carried out in the field and in the laboratory to identify the discontinuities present on the face of the workbench, to measure the distances between them, to verify the presence of water in the discontinuities, degree of weathering of the discontinuities and the characteristics of their roughness in order to define the necessary parameters and thus determine the weighting according to the methodologies proposed in each system [13,14]. Samples were collected to determine the uniaxial compression strength (figure 3), carried out through an ABNT / NBR 15845:2010 standardized test [18].

Figure 3. Uniaxial Compression Strength test

The parameter RQD (%) was determined in two ways: by counting the number of fractures every 1 meter, the RQD being given by equation 2 [19]:

$$RQD = 100(0{,}1\lambda + 1)e^{-0{,}1\lambda} \qquad (2)$$

where λ corresponds to the frequency of the discontinuities; and by counting the discontinuities equidistant above 10 cm, being the RQD obtained by equation 3:

$$RQD = 100\sum_{i=1}^{n}\frac{x_i}{L} \qquad (3)$$

where x_i is the spacing values greater than 0.1 m, and *n* is the number of fractures intersected by a scanline of length *L*. To determine the spacing between the discontinuities, field images were treated using the AutoCAD software version 2016, as in the example of figures 4, 5 and 6.

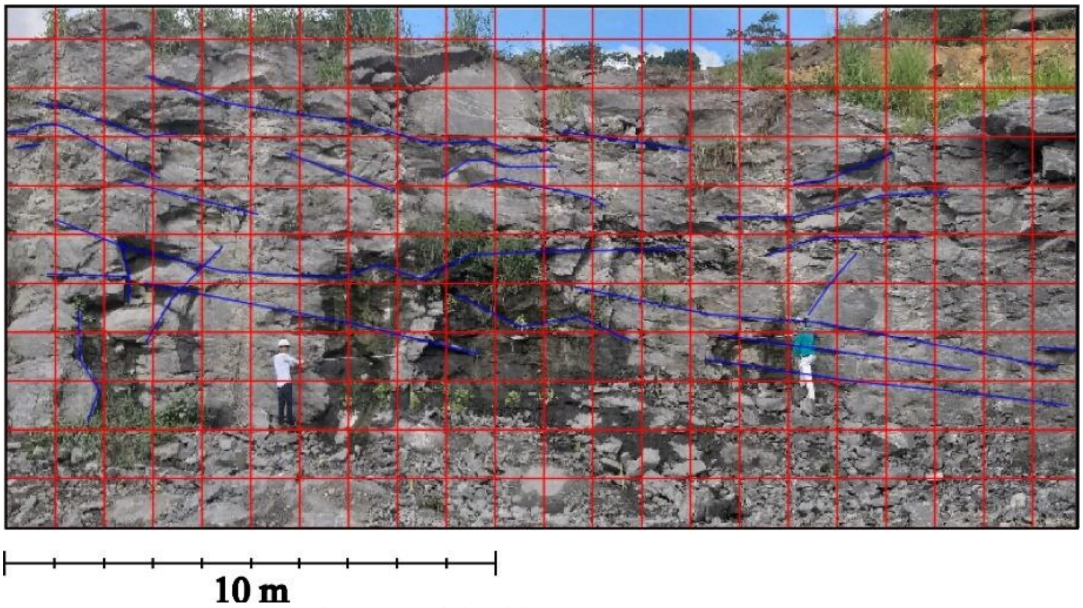


Figure 4. Right side of operational slope

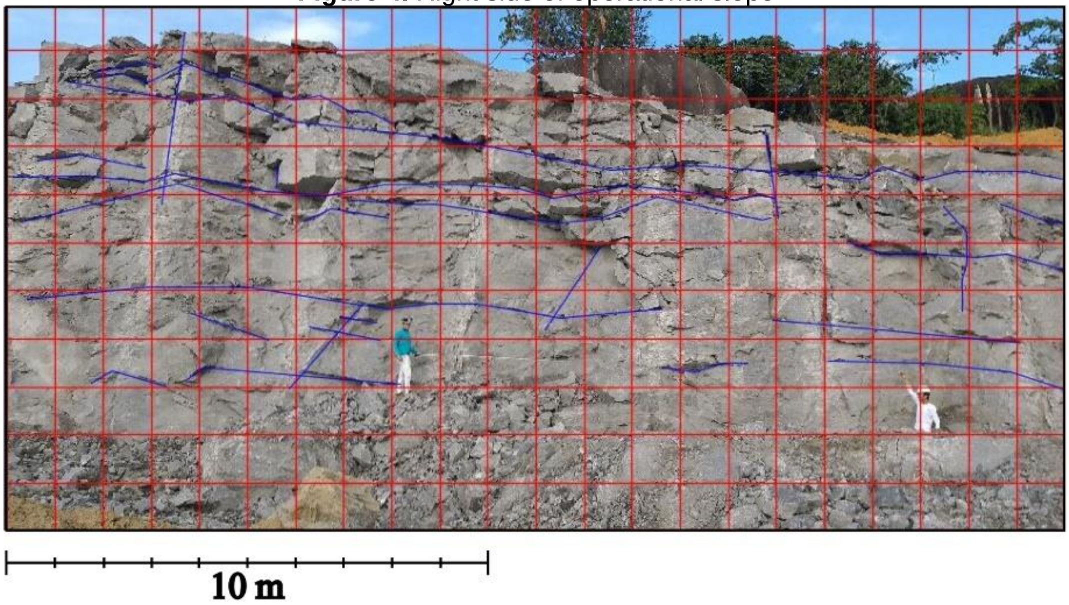


Figure 5. Central part of operational slope

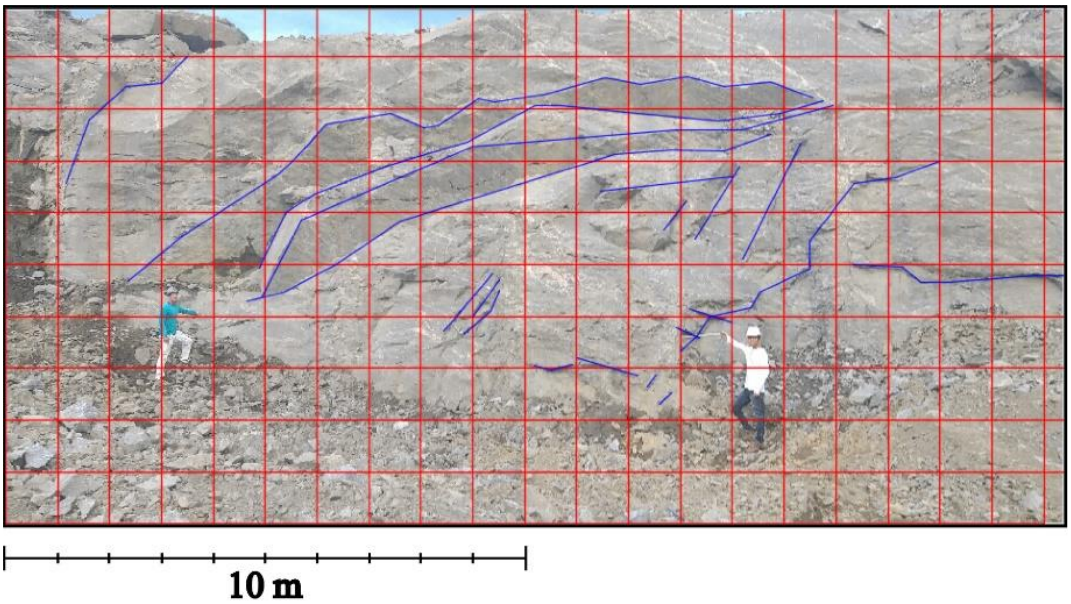
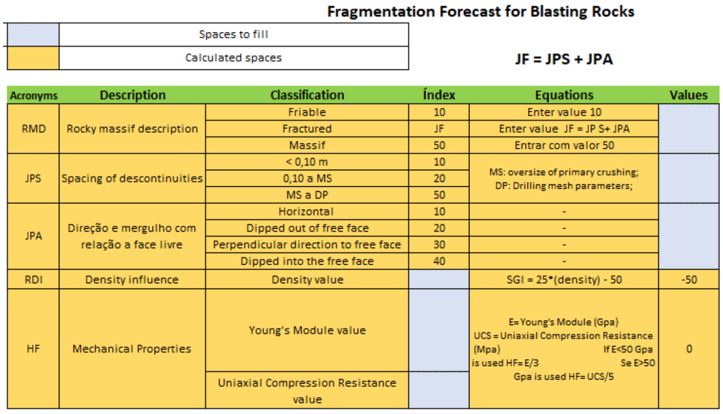


Figure 6. Left side of operational slope

The discontinuity conditions parameters, which includes Length (Persistence), Separation (Aperture), Roughness, Fill and Degree of alteration, and presence of water in the discontinuities, were determined from a classification proposed by Bieniawski [13]; for each value / characteristic assumed, a weight was considered. As in RMR determination, system Q considers weights / factors according to the characteristics of the material for each parameter analyzed [14].

Determined the structural characteristics and the geomechanical classification, the simulation of the prediction of the result of the fragmentation of rock blasting in *Mineração Megaípe* were performed using the methodology developed by Kuz-Ram [7]. In order to simplify and aid the calculations of the equations proposed by the model, a spreadsheet developed by Souza [20] in Microsoft Office Excel software was used, which is presented in the tables of figure 7.

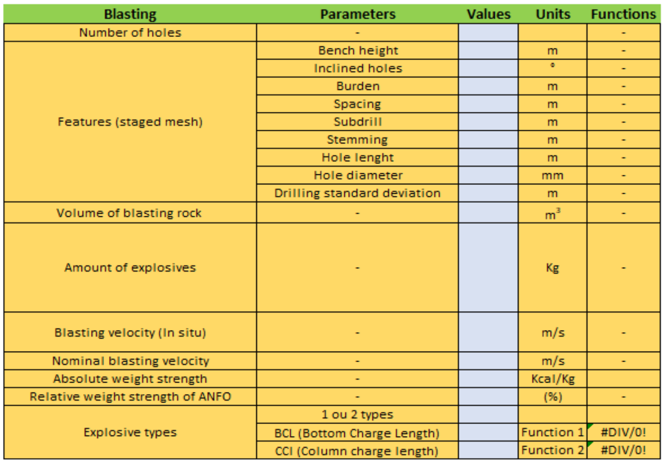


Fragmentation Forecast for Blasting Rocks

🟦	Spaces to fill
🟨	Calculated spaces

JF = JPS + JPA

Acronyms	Description	Classification	Índex	Equations	Values
RMD	Rocky massif description	Friable	10	Enter value 10	
		Fractured	JF	Enter value JF = JP S+ JPA	
		Massif	50	Entrar com valor 50	
JPS	Spacing of descontinuities	< 0,10 m	10	MS: oversize of primary crushing; DP: Drilling mesh parameters;	
		0,10 a MS	20		
		MS a DP	50		
JPA	Direção e mergulho com relação a face livre	Horizontal	10	-	
		Dipped out of free face	20	-	
		Perpendicular direction to free face	30	-	
		Dipped into the free face	40	-	
RDI	Density influence	Density value		SGI = 25*(density) - 50	-50
HF	Mechanical Properties	Young's Module value		E= Young's Module (Gpa) UCS = Uniaxial Compression Resistance (Mpa) If E<50 Gpa is used HF= E/3 Se E>50 Gpa is used HF= UCS/5	0
		Uniaxial Compression Resistance value			



Blasting	Parameters	Values	Units	Functions
Number of holes	-			-
Features (staged mesh)	Bench height		m	-
	Inclined holes		°	-
	Burden		m	-
	Spacing		m	-
	Subdrill		m	-
	Stemming		m	-
	Hole lenght		m	-
	Hole diameter		mm	-
	Drilling standard deviation		m	-
Volume of blasting rock	-		m^3	-
Amount of explosives	-		Kg	-
Blasting velocity (In situ)	-		m/s	-
Nominal blasting velocity	-		m/s	-
Absolute weight strength	-		Kcal/Kg	
Relative weight strength of ANFO	-		(%)	-
Explosive types	1 ou 2 types			
	BCL (Bottom Charge Length)		Function 1	#DIV/0!
	CCl (Column charge length)		Function 2	#DIV/0!

Figure 7. Parameters for fragmentation simulation using the Kuz-Ram methodology

From the table filling with the structural geology data, mechanical characteristics of the rock matrix, discontinuities and blast plan parameters, the model provides a theoretical result for the particle size distribution of the rock blasting operation.

3 RESULTS AND DISCUSSION

The survey of discontinuities was carried out along the entire operational slope of the quarry, making it possible to verify the repetition of the structural pattern. Figure 8 shows the preferential planes provoked by the discontinuities, confirming the presence of 3 representative families that differently influence the slope face stability, as well as the concentration of the poles of the field measurements, and Figure 9 shows the percentage distribution by area of discontinuities and the rosette diagram of the discontinuity planes, illustrating the distribution behavior of planar structures.

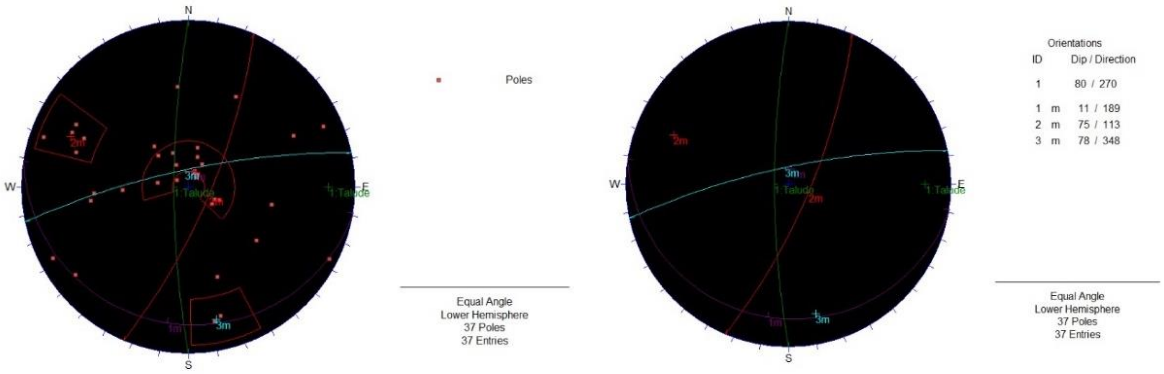


Figure 8. Concentration of discontinuity poles (left) and generated preferential planes (rigth)

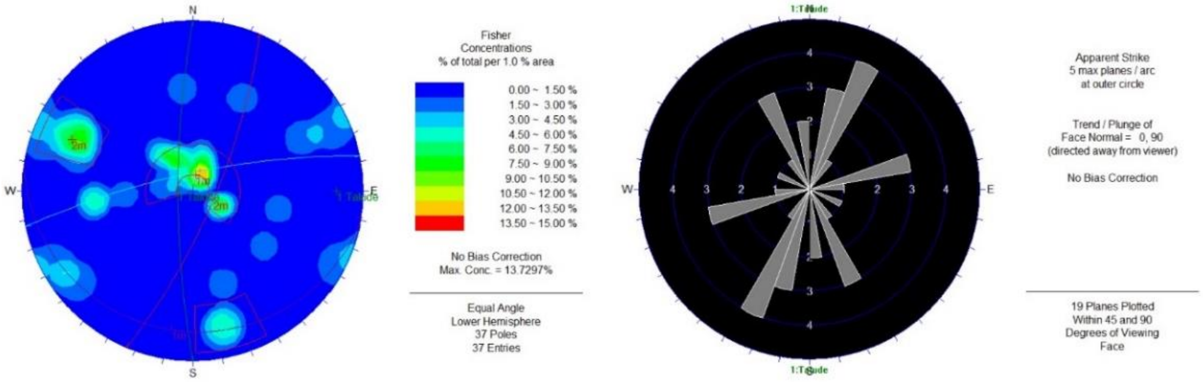


Figura 9. Fisher concentrations (left) and rosette diagram of discontinuity (right)

It was observed that the working slope, which has an average height of 12 meters, was situated in the N-S direction, dipping 80º in an easterly direction. The main discontinuity sets dips 11º to the north, 75º to the west and 78º to the south respectively. In this context, it can be affirmed, due to the absence of discontinuities with parallel or perpendicular dips that generate structures that can cause deformation (slipping, movement or rupture) through the rocky massif, that the operational slope presents favorable conditions of stability and provides security for personnel and equipment in operation. The results obtained for the geomechanical classification by the RMR system are presented in table 1.

Table 1. Geomechanical classification by the RMR system

Parameters	**Value obtained**	**Weight**
Uniaxial Compression Strength	96	7
Rock Quality Designation	99,7	20
Spacing between discontinuities	1,17	15
Condition of discontinuities	Slightly rough Slight alteration Aperture <1mm	35
Presence of water in discontinuities	Wet	10
Total		**87**

The correction factor for the RMR according to the orientation of the discontinuities is 0 (zero) [21]. According to the geotechnical significance of the RMR system, which assigns quality and geotechnical characteristics and defines the values of cohesion and the internal friction angle of the rocky massif, the value obtained from RMR includes the massif in Class I, which classifies it as rock of very good quality, with an angle of friction greater than 45º and cohesion of the rock mass greater than 400 KPa. According to an evaluation performed for several slopes, when the RMR is greater than 40, slope stability is governed by both the orientation and the resistance of the discontinuities [22]. Thus, corroborating with the results of the structural characterization, it can be affirmed that the stability of the operational bench is satisfactory. In addition, by correlating the RMR system with the SMR (Slope Mass Rating) through the methodology proposed by Romana, Serón and Montalar [22] for the evaluation of rock slope instability situations and the suggestion of stabilization techniques, the operational slope of the *Mineração Megaípe* is completely stable, without possibility of ruptures, dropping of blocks or tipping, and there is no need to apply any method of sustention (only possible removal of unstable blocks). The geomechanical classification by the Barton Q system resulted in the values presented in table 2.

Table 2. Geomechanical classification by Q system

Parameters	**Value obtained**	**Weight**
Rock Quality Designation	99,7	99,7
J_n	Three joint sets plus random	12
J_r	Rough or irregular, undulating	3,0
J_a	Slightly altered joint walls	2,0
Total		**116,7**

The parameters J_w and SRF were not evaluated by the fact that the works in the quarry are carried out in a superficial environment, and there is no need to consider the state of stresses in the massif and the influence of groundwater. Even so, the value obtained for the Q system qualifies the massif in Class II, corresponding to rocky materials with a good geomechanical standard. From this classification it was also possible to define the shape of the blocks (cubic) and their average size (8 ± 0.3), thus showing a uniformity in the subdivision of the block mass, which agrees with the classification of the rock mass in Class II with approximately equidistant blocks depending on the degree of fracturing intensity and the shape and size of the blocks.

The simulation of the prediction of fragmentation of rock blasting operation in *Mineração Megaípe* using the Kuz-Ram methodology was performed for a rock blasting on the 1N bench, and after the filling of the tables presented in figure 7 with the parameters of the blast plan (table 3) and structural and mechanical characteristics, the results of table 4 were obtained for granulometric distribution of the fragmentation. The *data* related to the blast plan were dimensioned considering the structural and geomechanical characteristics of the rock mass evaluated.

Table 3. Blast plan parameters

Parameters	Values
Number of holes	92
Bench height	12 m
Inclined holes	10º
Burden	2.5 m
Spacing	4.5 m
Subdrill	0.5 m
Stemming	1.7 m
Hole lenght	12.5 m
Hole diameter	88.9 mm
Volume of blasting rock	12,255.8 m^3
Amount of explosives	6,767.6 kg
Blasting velocity (In situ)	4,500 m/s
Nominal blasting velocity	5,000 m/s
Absolute weight strength	790 Kcal/Kg
Relative weight strength of ANFO	87%
1 ou 2 types	2
BCL (Bottom Charge Length)	6 m
CCl (Column charge length)	4 m

Table 4. Theoretical granulometric distribution of the rock blasting product

Sieve opening (cm)	Cumulative pass (%)
10	6.519252449
20	19.04393108
30	33.77446701
40	48.42101378
50	61.56872438

60	72.51275923
70	81.07984612
80	87.44115323
90	91.94744841
100	95.00553665
110	96.99985363
150	99.71080587
300	99.99999889

The primary crusher that will process the material from the rock blasting is a Metso C140 jaw crusher, which has a gap width of 140 cm and a maximum feed gap of 107 cm; however, for the purposes of effective feed gap, 80% of the maximum feed size was considered, resulting in 85.6 cm. In this context, it can be observed that, due to the results obtained for the simulation, about 90% of the total volume of rock mass has adequate granulometry to be processed by the equipment, without the need for secondary blasting. Figure 10 shows the granulometric distribution curve for the simulated rock blasting.

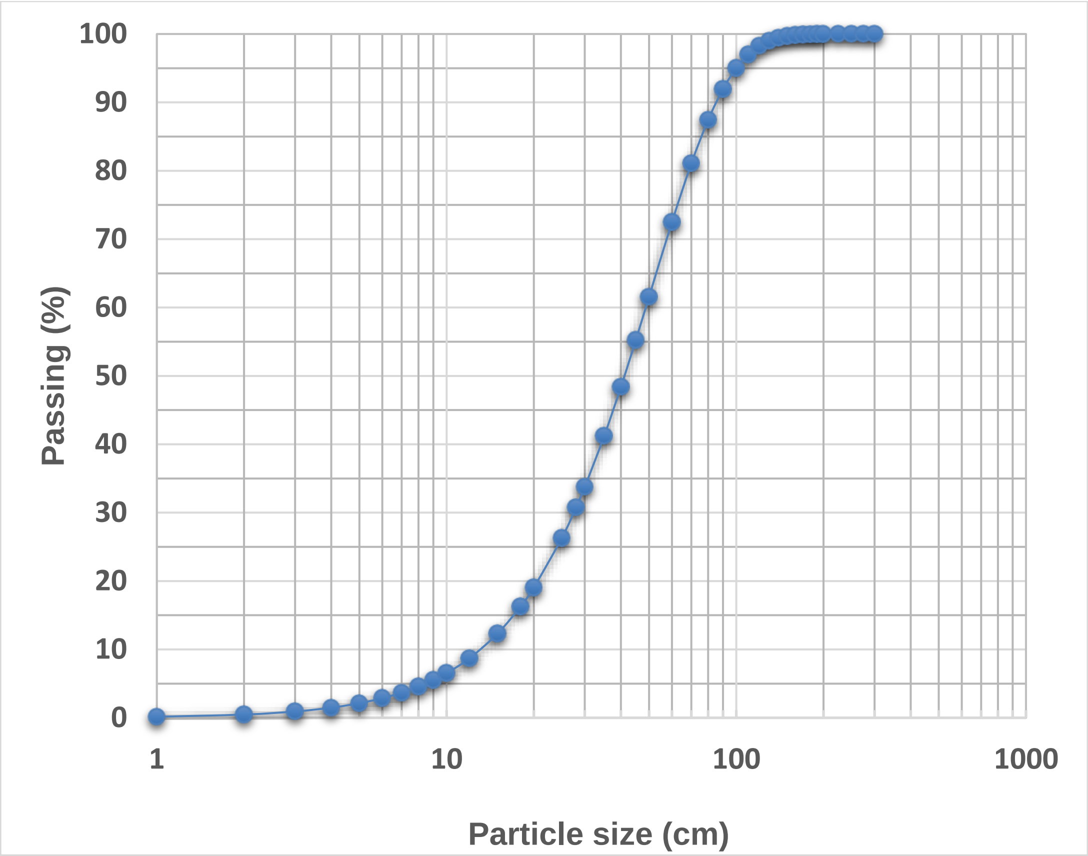


Figure 10. Granulometric distribution curve obtained for the simulation of the rock blasting

4 CONCLUSION

Considering the principles of the system approach and the mine-to-mill system, rock drilling and blasting should be dimensioned accounting the subsequent unit operations, particularly primary crushing, which directly receives the material loaded and hauled. For this reason, the mathematical modeling of rock blasting results has great importance on the planning of unit and global operations, impacting on costs, efficiency and effectiveness of mining operations.

The results of prediction of the rock blasting were satisfactory, as it was concluded that practically the whole fragmented material, about 90% of the total volume of rock, has particle size adequate to the gap of the equipment installed for primary crushing, implying in reduction of costs with reduction of the secondary blasting operation. The analysis of the particle size distribution allows to affirm that the amount of fines generated is considered satisfactory, because in the range of less than 10 cm the smaller amount of particles is obtained, which implies a relatively small material loss (about 6.5%). In addition, it can also be stated that 80% of the volume of material obtained from the fragmentation comprises the granulometries of the enterprises products, such as stone powder, 12 mm crushed stone, 19 mm crushed stone, 25 mm crushed stone and graded gravel.

The execution of this work also makes it possible to conclude that an adequate survey of the structural geology associated to the geomechanical classification of the rocky massif in the mining fronts is essential, as it envisages a greater possibility of precision in the results of the fragmentation simulation, since as a rule such characterization is performed based on an estimate of values, which does not always guarantee satisfactory results and close to the real. However, in order to obtain accurate results, the real particle size analysis must be performed in order to obtain comparative parameters and thus to verify how accurate the results of the blasting rock prediction are. The characteristics of the rock massif are, in fact, determinants for the better performance of the blasting operation, and a more detailed study of the massif would also reduce costs with loading, hauling and crushing, reducing the cycle time, consumption and wear of the spare parts, optimizing these operations and increasing the productivity of the system.

In addition to the prediction of the blasting results, the understanding of the structural and mechanical context of the rocky massif on the screen made it possible to analyze the stability conditions of the *Mineração Megaípe* quarry by evaluating the characteristics of the discontinuities and the geomechanical classification of the massif in RMR, Q and SMR systems, which make it possible to state that the rock massif can be classified as high quality rock and the slope presents favorable stability conditions without the use of any stabilization technique, which implies in safety conditions for personnel and equipment in the operation of the *Mineração Megaípe*.

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