OPTIMIZATION OF BLAST FRAGMENTATION BY USE OF AN ELECTRONIC INITIATION SYSTEM

Jože Kortnik[1,*], Aldijana Šehić[1], Dean Osmanović[2]
[1]University of Ljubljana, Faculty of Natural Sciences and Engineering, Department of Geotechnology, mining and environment, Aškerčeva street 12, 1000 Ljubljana, Slovenia
[2]Alpacem cement d.d, Anhovo street 1, 5210 Deskle, Slovenia
[*]Corresponding e-mail: joze.kortnik@guest.arnes.si

ABSTRACT
*The last major advance in the field of initiation systems was achieved in 1973 by the discovery of a non-electrical initiation system known as Nonel, and then in 1990 with the discovery and development of an electronic initiation system. While the use of the Nonel non-electrical initiation system has experienced a warm acceptance in practice, the Slovenian mining profession in the case of the use of an electronic initiation system remained cold, mainly due to additional necessary investment costs of blasting equipment, additional education, change in the manner of blasting and higher prices of electronic detonators. The possibility of setting any time delay and significantly more accurate monitoring of the delay time of the detonation in the case of the use of an electronic initiation system can significantly improve all mining parameters, improve the material's fragmentation, lower seismic impact and, above all, the possibility of blasting in seismically sensitive areas. Due to the reduction of negative environment impact blasting parameters, it enables more efficient extraction and thus decrease the total costs of raw minerals exploitation. When exploiting mineral resources using the drilling and blasting method, the optimal fragmentation and, indirectly, the cost of extraction depends on the choice of drilling and blasting parameters, primarily on the minimum volume of drilling work (hole diameter, stage height, length of the punching line, spacing between wells in a row and between rows, etc.), the minimum consumption of explosives (hole diameter, well lengths, plugging lengths, etc.), and the scope of measures to reduce the negative impacts of mining (seismic impact, dispersion, air blast, hazardous gases, etc.) on the environment. The dependence between mining parameters and the achieved fragmentation of the mineral resource can be established using the Kuznetsov-Ram model. The model is based on the results of empirical research written in the form of the Kuznetsov and Rosin-Rammler equations. The Kuz-Ram model was perfected by Cunningham and established a functional dependence between the fragmentation coefficient and the mining parameters, such as the diameter and length of the mine shafts, the arrangement of the mine shafts, the distance between the mine shafts in a row, the length of the punching line, the height of the floor, the deviation of the mine shafts, the length of the blasting charge, etc. The use of the Kuz-Ram model and the analysis of fragmentation with the BMX Fragmenter software allows approaching the required fragmentation already in the mining phase, thereby reducing the costs of further processing of the mineral raw material due to the reduction of the amount of crushing, reducing the wear of the crushing and screening equipment and reducing the costs of electricity consumption. The first blasting using an electronic initiation system in Slovenia was carried out in the Solkan quarry of Alpacem Cementi d.d. on 21 April 2017 at 11:13. The minefield consisted of 18 wells, in which 1,188 kg of explosives were activated and 36 E*Star electronic detonators from Austin Powder Company were used. In article will be presented the optimization of fragmentation using an electronic initiation system in the Perunk quarry, Slovenia.*
Key words*: electronic initiation sistem, fragmentation optimization, Kuz-Ram model, Perunk quarry*

1. INTRODUCTION

When exploiting mineral resources using the drilling and blasting method, the optimal fragmentation and, indirectly, the cost of extraction depends on the choice of drilling and blasting parameters, primarily on the minimum volume of drilling work (drillhole diameter, bench height, length of the burden, spacing between drillholes in a row and between rows, etc.), the minimum consumption of explosives (drillhole diameter, drillhole lengths, stemming length, etc.), and the scope of measures to reduce the negative impacts of blasting (seismic impact, fly rock, air blast, dust, noise, hazardous gases, etc.) on the environment. The dependence between blasting parameters and the achieved fragmentation of the mineral resource can be established using the Kuz-Ram fragmentation model. The model is based on the results of empirical research written in the form of the Kuznetsov and Rosin-Rammler equations. The Kuz-Ram model was perfected by Cunningham and established a functional dependence between the fragmentation coefficient and the blasting parameters, such as the diameter and length of the drillholes, the drillholes geometry, the distance between the drillholes in a row, the burden length, the bench height, the deviation of the drillholess, the explosive charge length, etc. The use of the Kuz-Ram model and the analysis of fragmentation with the BMX Fragmenter software allows approaching the required fragmentation already in the blasting phase, thereby reducing the costs of further processing of the mineral raw material due to the reduction of the amount of crushing, reducing the wear of the crushing/screening equipments and reducing the costs of electricity consumption. The use of electronic initiation systems has proven to be a good world practice in reducing the environment impact of blasting. The electronic initiation system, unlike the classic initiation systems (NONEL, electric), allows for significantly more precise control of the time delay of the activation of classic pyrotechnic detonators, achieving a more appropriate fragmentation of the rock, reducing the level of seismic and air vibrations on the environment and reducing the potential danger of fly rock. This consequently enables mining with a lower environmental impact and lower costs of mineral extraction, saving time and energy for crushing/grinding mineral raw materials, reducing maintenance costs of crushing and screening equipments. Compared to global trends, today use of electronic initiation systems in Slovenian mining industry is still low. The first company in Slovenia was Alpacem Cementi d.d. (formerly Salonit Anhovo d.d.), which introduced the electronic initiation system into regular production in the Rodež, Perunk and Solkan quarries. The first blasting using the electronic initiation system in Slovenia was carried out in the Solkan quarry on 21th April 2017 at 11:13am. The minefield consisted 18 blastholles, in which 1,188 kg of ANFO explosive were activated and 36 E*Star electronic detonators from Austin Powder Company were used.

Uncontrolled parameters:	
Geology	Characteristics of the rock mass
Discontinuity	Presence of water
Geomechanics	Physical-mechanical parameters

Controlled parameters:		
Borehole drilling:	***Charging:***	***Initiation:***
Diameter	Type of explosive	Type of detonator
Length	Explosive energy	Delay time
Sub-drilling	Charging method	Properly cleaned surface
Inclination	Charging design	No free spaces
Bench height	Charging length	Moisture
Deviation	Delay sequence	

Blasting:

Blasting results:
Fragmentation/Granulation
Dispersion of rock in a pile
Fly rock
Ground vibration/Seismic impact
Lateral and backline fractures
Noise and air shock
Unexploded explosive devices or zatajilci
Complete denial of blasting

Evaluation of blasting results:

Figure 1. Block diagram of optimization key drilling and blasting parameters [2]

2. OPTIMIZATION OF BLAST FRAGMENTATION

Drilling and blasting are the most important processes in quarry and surface mining of mineral resources, which have a direct impact on overall costs and efficiency. The key goal of both processes is to achieve optimal rock crushing, which allows easier loading, transportation and further processing of mineral resources. When operations are not carried out accurately, this usually results in higher costs and lower productivity. In quarries, a step-by-step particle size reduction method is often used, in which the mineral resource is first extracted from the deposit by mining and then crushed to the required particle sizes. By achieving optimal fragmentation already in the drilling and blasting phase, we can reduce loading, transport and crushing/grinding costs. In order for the drilling and blasting method to be as efficient as possible, it is important to achieve the most uniform particle size, which is why size measurement and analysis are essential for successful work. For mining large quantities of solid mineral resources, mechanical mining methods are still more time-consuming and less efficient. The drilling and blasting method is considered to be the fastest and most efficient reduction of particle size even in the hardest rocks. The parameters that affect the final fragmentation of the mineral raw material can be divided into two main groups [1]. The first group includes controllable factors, such as blasting planning and explosive properties. The controllable parameters can then be divided into three main areas, drilling drillholes, filling drillholes with explosives and initiation. In this case, it is possible to adjust the diameter and length of the drillholes, the geometry of the drillholes, the energy of the explosive and the time delay of initiation. The second group includes uncontrolled factors, such as the physical-mechanical and geomechanical properties of the rock. Uncontrolled parameters also include various characteristics of the rock mass (e.g. geological properties, discontinuities, the presence of water, natural fractures) that cannot be directly controlled during blasting. Figure 1 shows in the form of a block diagram the possibility of permanent optimization of the blasting process. After each blasting, an analysis of the mining results is followed, the fragmentation is assessed and the necessary new geometry to the drilling and mining parameters are determined. Such an approach allows for continuous optimization of the exploitation process, which consequently reduces costs and increases productivity.

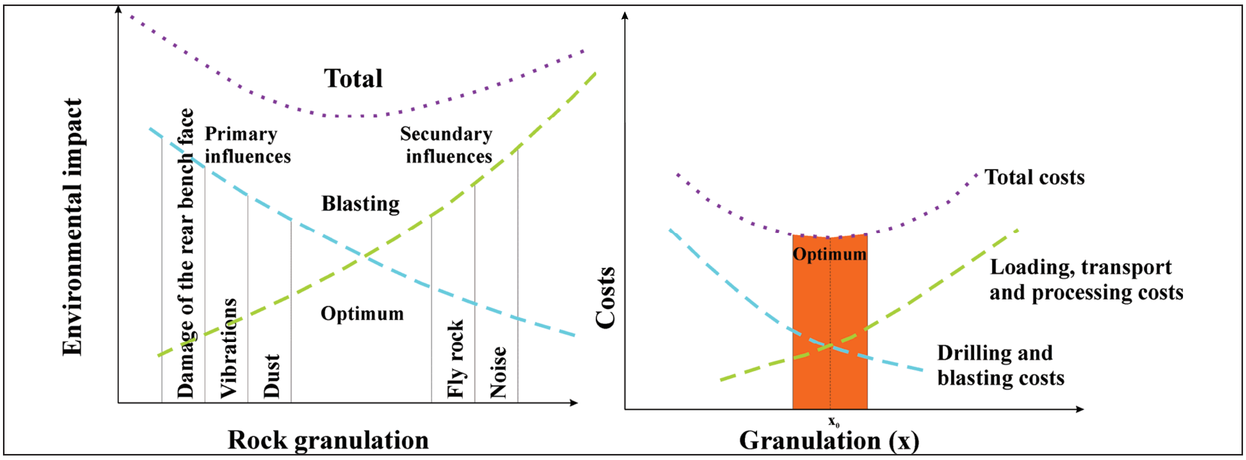

Figure 2. Fragmentation optimization by reducing the environmental impacts (left) and by reducing the costs of drilling and blasting (rigth) [3]

Figure 2. (left) shows the impact of ensuring appropriate fragmentation on the environment. Finer fragmentation mainly causes an increase in primary impacts such as vibrations, dust, etc., while coarse fragmentation increases secondary impacts such as fly rock and noise. The particle size of the extracted raw material plays a key role in further processing costs, such as crushing, screening and transportation especially in the case of technical stone. Figure 2. (right) shows the impact of ensuring the appropriate fragmentation on the total costs of the extraction process using the drilling and blasting method. The appropriate fragmentation, denoted as x_0, is the one with the lowest total costs. If the particles are too small, this increases the drilling costs and the consumption of explosives, while particles that are too large bring additional costs in screening,

transportation and further processing of the material.

3. EMPIRICAL METHODS FOR BLAST FRAGMENTATION DETERMINATION

Based on defined geometric parameters of blasting and taking into account natural laws for achieving the final fragmentation of rock by blasting, different procedures for predicting of fragmentation of blasted rock have been developed, which provide a fragmentation prediction for known geometric parameters of blasting. Such procedures are also used as a modern way of adjusting the geometry of blasting, as they allow the gradual change of individual parameters (explosive consumption and geometry) to assess the effects of their changes on the fragmentation of blasted material. Quantifying the particle size distribution of fragmented rock is very difficult and requires a direct method, such as sieve analysis, or indirectly by creating a mathematical models for the crushed rock. The direct method of sieve analysis is time-consuming. In addition, it is possible to examine the fragmentation of the rock and assess whether additional secondary blasting is necessary. Although the indirect method is accurate, it does not provide a complete analysis of fragmentation. Indirect methods are divided into two key categories: empirical modeling and mechanical modeling [3].

Among the various models for determining rock grain size, the Kuz-Ram or Kuznetsov-Cunningham-Ouchterlony (KCO) model is the most commonly used in practice due to its ease of use [6]. Empirical models are based on the assumption that to achieve a finer grain size, more powerful explosives are required. Mechanical models follow the theory of detonation physics and energy transfer and are used for specific blasting purposes. The Kuz-Ram model is considered one of the most effective methods of empirical fragmentation modeling, as it allows for simple collection of input data and establishes a direct connection between blasting design parameters and rock fragmentation [4]. The Kuz-Ram model is an empirical fragmentation model based on the Kuznetsov and Rosin-Rammler equations and the algorithm developed by Cunningham. The model allows for the determination of the uniformity coefficient in the Rosin-Rammler equation in relation to blasting parameters. The model predicts rock fragmentation and provides the result in mass percentages that achieve a certain particle size. Based on the model, the particle size distribution is estimated and the blasting parameters are adjusted to achieve optimal fragmentation. Smaller fragmentation is achieved in the case of using stronger explosives in less solid rock types and smaller drillhole diameters. More uniform fragmentation is achieved by more uniform distribution of explosive charges in the rock, with lower benches and larger drillhole spacing. Despite the widespread use of the Kuz-Ram model, there are some shortcomings in its application [4], especially regarding the consideration of geomechanical properties of the rock, the selection of power explosives, and the determination of the actual fragmentation of blasted material in the pile. The most commonly used method for estimating blasting fragmentation in pile is the modified Kuznetsov equation, which allows for a more accurate calculation of the mean particle size $\bar{x}$ regardless of used explosive. The adapted formula takes into account different types of explosives, which allows more accurate fragmentation prediction [6, 10]:

$$\bar{x} = A \cdot \left(\frac{V_{b'}}{Q_{b'}} \right)^{-0.8} \cdot Q_{b'}^{\frac{1}{6}} \cdot \left(\frac{115}{RWS} \right)^{\frac{19}{30}}, \quad \textbf{(1)}$$

where is:

$\bar{x}$ – mean particle size after blasting [m],

A – rock uniformity coefficient [ ],

$V_{b'}$ – volume of mined rock per drillhole [m^3],

$Q_{b'}$ – amount of explosive in one drillhole [kg],

RWS – explosive weight strength relative to ANFO (for ANFO ***RWS*** = 100).

The value of the rock uniformity coefficient (***A***) can be in a very wide range. In a number of practical experiments on particle size reduction by blasting, Cunningham determined an empirical equation for the rock uniformity coefficient as:

$$A = 0.06 \cdot \left(RMD + JF + RDI + HF \right) \quad \textbf{(2)}$$

where is:

RMD – cracked rock characteristic factor,
JF – rock cracking factor JF = JPS + JPA,
JPS – crack spacing factor,
JPA – crack area factor,
RDI – rock density factor $RDI = (25 \cdot \rho) - 50$,
HF – rock strength factor.

When determining the rock uniformity coefficient according to Kuznetsov ***A***, the geomechanical properties of the rock are taken into account. Key parameters include Young's modulus of elasticity (GPa) and compressive strength (MPa). Igneous rocks, such as basalt, granite and diabase, have higher values of Young's modulus, which means they are more rigid and resistant to deformation. Sedimentary rocks, such as limestone, dolomite, sandstone and shales, have lower values of Young's modulus, which means they have lower compressive strength and are less resistant to deformation. Figure 3. shows the correlation of uniaxial compressive strength and Young's modulus for sedimentary rock types.

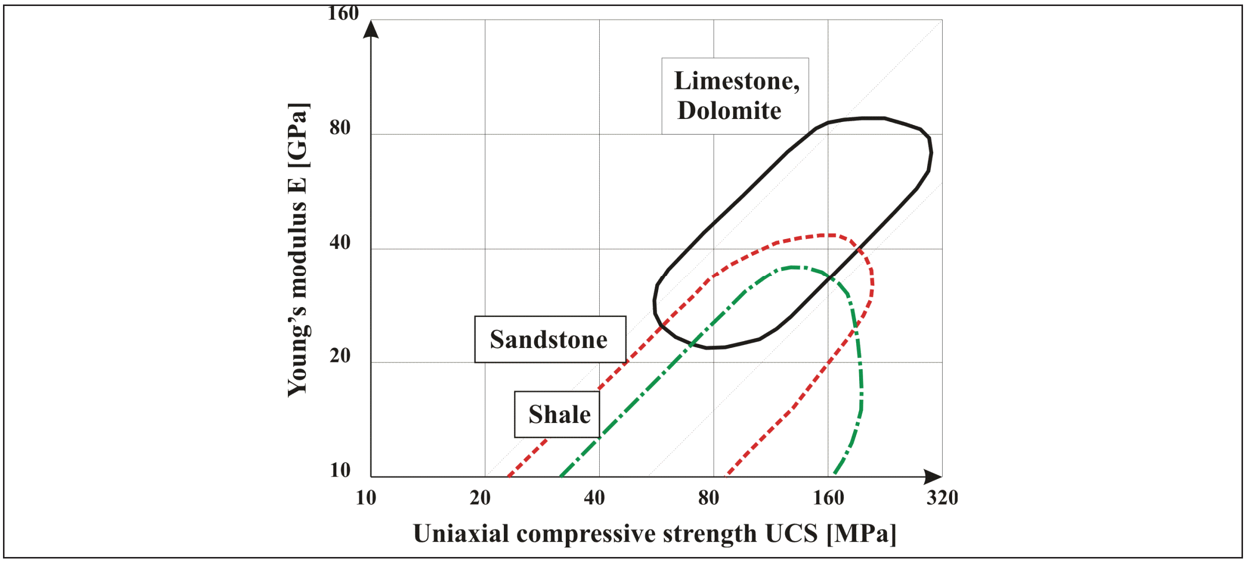

Figure 3. Correlation of uniaxial compressive strength and Young's modulus of elasticity for different types of rocks [11]

Since natural rocks are generally not homogeneous materials, a correction factor C_k also must be taken into account. In practice, the correction factor is often determined based on experience or in-situ data. Values usually range between 0.5 and 2. The equation for calculating the rock factor thus includes all key parameters and allows adaptation to different rocks.

$$A = 0.06 \cdot (RMD + RDI + HF) \cdot C_K \tag{3}$$

The fragmentation uniformity coefficient ***n*** in the Rosin-Rammler exponential equation is calculated using the Cunningham equation:

$$n = \left(2.2 - \frac{14 \cdot W}{d_b}\right) \cdot \left(\frac{1 + \frac{S}{W}}{2}\right)^{0.5} \cdot \left(1 - \frac{p}{W}\right) \cdot \left(abs\left(\frac{[l_e - l_{ep}]}{L_{sk}}\right) + 0.1\right)^{0.1} \cdot \left(\frac{L_{sk}}{H}\right) \tag{4}$$

where is:
d_b – diameter of blasting drillhole [m],
W – burden [m],
S – spacing between blastholes in row [m],
p – drillhole deviation (0.1 ÷ 0.3) [m] $p \approx d_b + (0.0 \div 0.03) \cdot H$,

l_e – length of the explosive charge in blasting drillhole [m],
l_{ep} – length of the explosive charge in the underbored part of blasting drillhole [m],
L_{sk} – total length of the explosive charge [m] $L_{sk} = l_e + l_{ep}$,
H – bench height [m].

The value of the fragmentation uniformity coefficient ***n*** is generally in the range of 0.8–1.5, usually 1.0. For values of ***n*** >1, it is usually considered that we have a more uniform fragmentation. Cunningham suggested that the value of ***n*** calculated according to the equation should be increased by 10% in the case of a regular quadrilaterals geometry of blastholes.

The fraction of mined rock particles ***R_x*** or the fraction of particle fractions larger than ***x*** in (cm) can be calculated using the Rosin-Rammler equation, which is:

$$R_x = e^{-\left(\frac{x}{x_c}\right)^n} \quad \textbf{(5)}$$

where is:
x – sieve opening [cm],
x_c – average particle size after blasting [cm] $x_c = \frac{\bar{x}}{\sqrt[n]{0.693}}$,
n – fragmentation uniformity coefficient [ ].

The modified Kuznetsov-Cunningham-Ouchterlony (KCO) model, in which the Rossin-Rammler distribution function ***n*** is replaced by the Swebrec function ***b***, is called the Kuznetsov-Cunningham-Ouchterlony (KCO) model and is written as [3]:

$$R_x = \frac{1}{\left[1 + \left(\frac{\ln \frac{x_{max}}{x}}{\ln \frac{x_{max}}{\bar{x}}}\right)^b\right]} \quad \textbf{(6)}$$

where is:
x_{max} – max. particle size [cm],
b – curve shape parameter [ ] $b = \left[2 \cdot \ln(2) \cdot \ln\left(\frac{x_{max}}{\bar{x}}\right)\right] \cdot n$.

The role of the KCO model is to improve the prediction of particle sizes from 0.05 to 50 cm and to determine the upper limit of particle size ***x_{max}***. When the particle size and fragmentation fractions do not meet the requirements, the drilling and blasting parameters are usually changed in the following relationships [6]:

- reduces the ratio ***W/d_b***,
- increases the ratio ***L_{sk}/H***,
- increases the ratio ***S/W***,
- increases the accuracy of drilling blasting drillholes.

4. BLAST FRAGMENTATION PHOTO ANALYSE

Fragmentation analysis by photography allows faster, simpler and cheaper quantitative analysis of mining results obtained with fragmentation models [5]. Taking into account various drilling and blasting parameters, we can predict the particle size in the post-mining pile. Photo analysis methods are divided into one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D). Due to the complexity of the 3D method and the insufficient accuracy of the 1D method, 2D photo analysis is most often used in practice.
The disadvantages of blasting fragmentation analysis with software is the accuracy, which depends on the facts that photos do not show the third dimension, the analysis is based only on particles visible on the top

surface of the blasted pile of material, photos may be distorted, limited resolution, meaning that particles smaller than the minimum resolution are not visible, the software misinterprets the photo, for example, when there is a strong texture or shading on the surface of particles and particles in the photo may overlap or particles may be cut off at the edges of the images.

The advantage of determining the particle size distribution by photography is that it allows comparison with the predicted fragmentation using the Kuz-Ram model. By comparing the results obtained with this method (see Figure 4.) and the predicted values, it is possible to calibrate the parameters of the Kuz-Ram model. Differences between photographic measurements and calculated values often arise from incomplete knowledge of the geological and physical-mechanical composition of the rock itself. This can be improved by adjusting the rock uniformity coefficient in the Kuz-Ram model.

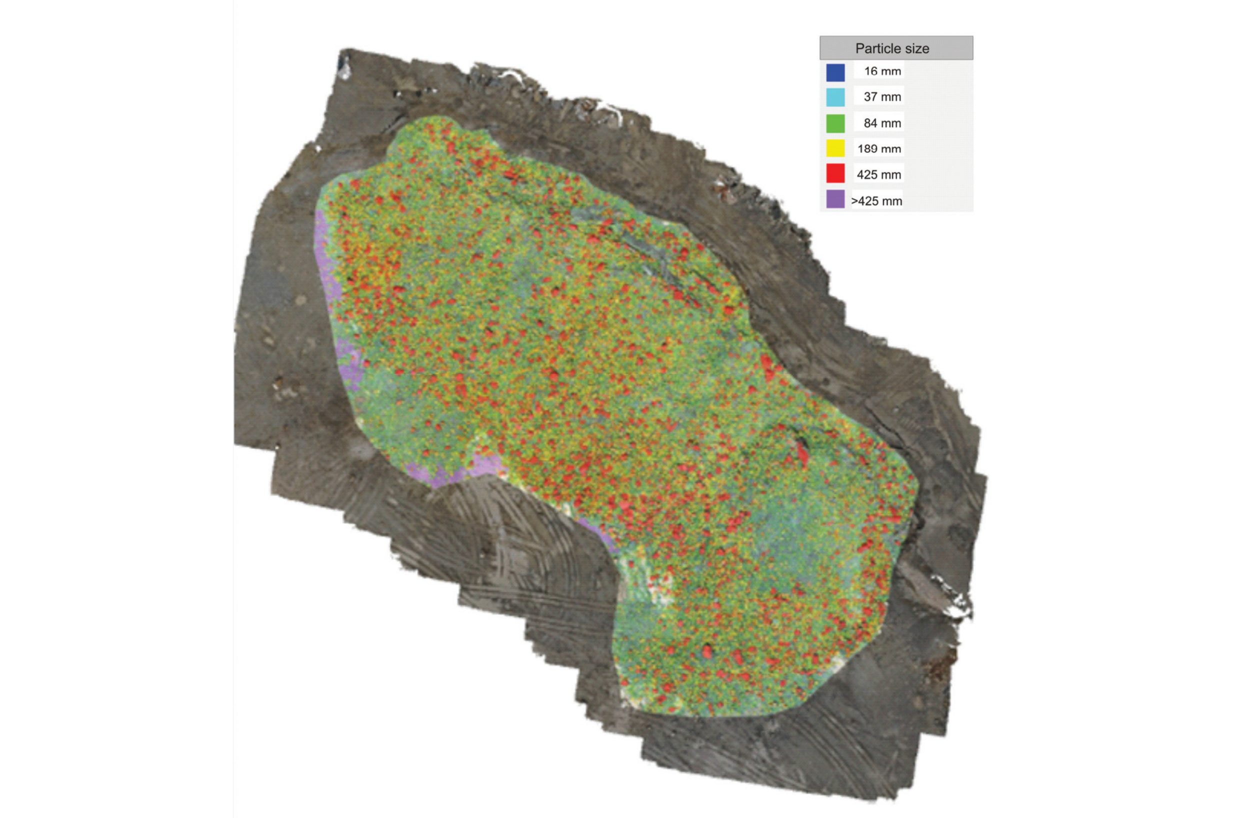

Figure 4. Results of fragmentation analysis of the pile of blasted material using BMX Fragmenter software in the Perunk quarry [3]

A range of software for blast fragmentation analysis by photography can be found on the world market, such as GoldSize, SplitEngineering, FragScan, WipFrag, Fragalyst, BMX Fragmenter, etc. [8]. In our case we used BMX Fragmenter, the results of which are given below.

5. ANALYSIS OF THE RESULTS OF IN-SITU BLAST FRAGMENTATION

In the in-situ analysis of blast fragmentation and prediction of results, based on the Kuz-Ram model, 8 blasting operations in the Perunk quarry were processed [3,7]. The BlastMetriX software tool was additionally used for blasting planning, while the analysis of the pile of mined material by photography was performed using the BMX Fragmenter software package. By means of photography of the blasted material piles, the particle size distributions were determined and the fragmentation efficiency of each blasting operation was estimated..

Table 1.: Technical properties of used explosives [3].

Blasting	Explosive						
	Emulex 1 (kg)	Emulex 2 plus (kg)	ANFO E0 (kg)	Total (kg)	RWS %	Density (g/cm³)	VoD (m/s)
1	2,499.0	550.0	2,500.0	5,549.0	94.5	1.02	4,769
2	1,543.5	475.0	3,050.0	5,068.5	96.5	0.96	4,498
3	1,151.5	400.0	1,500.0	3,051.5	95.8	1.01	4,689
4	1,396.5	350.0	1,250.0	2,996.5	94.4	1.04	4,826
5	1,176.0	300.0	1,800.0	3,276.0	95.7	0.98	4,593
6	1,274.0	350.0	2,750.0	4,374.0	96.6	0.95	4,452
7	1,886.5	375.0	1,450.0	3,711.5	93.7	1.05	4,877
8	637,0	250,0	1.475,0	2.362,0	97,1	0,95	4.455

Table 1 shows the mining and technical properties of the used explosives ANFO E0, Emulex 1 and Emulex 2 plus key parameters for selecting the appropriate explosive according to the specific requirements of the rock, such as density, relative explosive strength (RWS) and velocity of detonation (VoD). ANFO E0 (density 0.8 g/cm^3, RWS 100, VoD 3,800 m/s) is an affordable and simple explosive, suitable for less demanding geological conditions. Emulex 1 (density 1.2 g/cm^3, RWS 86, VoD 5,600 m/s) has a higher density and velocity of detonation, which improves the transfer of explosive energy through the rock mass. Emulex 2 plus (density 1.24 g/cm^3, RWS 108, VoD 5,400 m/s) has the highest density and higher power, which makes it more effective in crushing material and is suitable for more demanding geological conditions.

*Table 2.: Geological composition and calculation of the rock uniformity coefficient **A** [3].*

Blasting	Material / component	*RMD*	*JF*			*RDI*	*HF*	C_k	*A*
			JCF	*JPS*	*JPA*				
1	BP	JF	1	20	40	15	6.49	0.97	4.7
2	BP	JF	1	50	40	15	8.01	1.00	6.8
3	BP-FP	JF	1	20	40	15	4.99	0.84	4.0
4	BP-FP	JF	1	20	40	15	4.99	0.84	4.0
5	BP	JF	1	20	40	15	6.49	0.97	4.7
6	BP-FP	JF	1	20	40	15	4.99	0.84	4.0
7	BP	JF	1	20	40	15	6.49	0.97	4.7
8	BP-FP	JF	1	20	40	15	6.49	0.84	4.0

Table 2 shows the geological composition of the rock at the location of the blasting operations, indicated by abbreviations such as BP (breccia) and FP (flysch), which were mined. These combinations of materials mainly affect the way seismic waves propagate and thus the efficiency of fragmentation..

Table 3.: Predicted blast fragmentation results by Kuz-Ram model [3].

Blasting	$V_{b'}$ [m³]	*p* – blasthole deviation (m)	L_{sk} [m]	*n* - Rosin-Rammler	$\bar{x}$ [cm]	x_c [cm]
1	155	0.21	10.5	1.56	18.15	22.94
2	143	0.21	9.6	1.52	28.11	35.76
3	110	0.18	7.0	1.42	15.67	20.31
4	137	0.19	7.4	1.43	18.64	24.11
5	197	0.23	12.0	1.55	22.53	28.57
6	199	0.22	10.9	1.44	19.33	24.91
7	139	0.20	8.4	1.41	19.93	25.84
8	143	0.19	8.3	1.44	21.27	27.45

The results of the predicted fragmentation calculated with the Kuz-Ram model (Table 3) were compared with in-situ measurements of particle size distribution by in-situ photography (Table 4). We found, from Figure 5, that the Kuz-Ram model predicted the size of smaller particles (up to 20 cm) relatively accurately, which means that the blasting parameters were relatively appropriately selected for the crushing of fine fractions. For particles of size from 20 to 80 cm, minor deviations were observed, as the model often overestimated the degree of crushing. For larger particles above 80 cm, the differences were relatively small, indicating a relatively good distribution of the energy of the explosive over the rock mass. Analysis of the distribution of particles in the blasting area showed that medium-sized particles were most often collected in the central part of the mined material pile, indicating good energy transfer. Larger particles appeared more often at the edges, which is typical for all blasting. In the fifth, sixth, seventh and eighth mining runs, we observed a higher proportion of finer particles. We estimate that this is mainly due to more efficient crushing or a more heterogeneous composition of the rock mass.

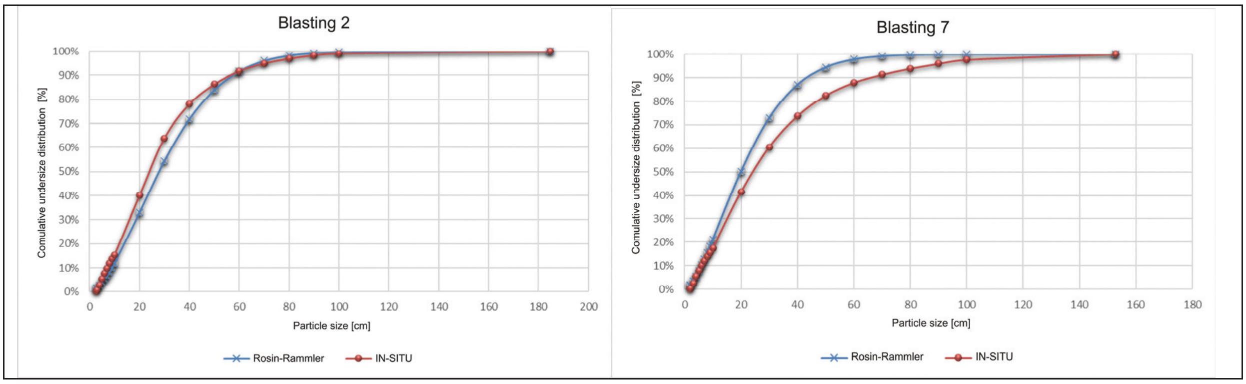

Figure 5. Results of comparison of predicted (Kuz-Ram model, blue curve) and in-situ analysis of blasted rock pile fragmentation using BMX Fragmenter software (red curve) in Perunk quarry for case of blasting 2 and blasting 7 [3].

The error analysis showed that the mean absolute error (MAE) was 3.88% and the root mean square error (RMSE) was 5.18%, which means that the Kuz-Ram model predicted the particle size relatively accurately. The best results were achieved in the second blasting, and the largest deviations were in the seventh, indicating the need for additional adjustments to better match the predictions with the actual results.

Table 4.:Blasting fragmentation results using photography of blasted material piles by Kuz-Ram and KCO model [3].

Blasting	Fragmentation (cm)					Kuz-Ram		KCO (Swebrec)		
	x_{20}	x_{50}	x_{80}	x_{90}	x_{100}	$x_{fit,50}$	n	$x_{fit,50}$	n_{eq}	b
1	8.7	18.2	34.0	46.0	150.5	18.9	1.444	18.5	1.510	7.526
2	12.8	23.5	42.1	56.5	184.7	24.5	1.586	23.9	1.660	8.048
3	7.8	17.4	32.7	45.0	208.3	17.9	1.404	17.4	1.462	8.375
4	6.9	15.7	31.4	43.9	109.8	16.3	1.305	15.8	1.365	8.019
5	6.0	15.2	30.4	41.5	169.4	15.3	1.214	15.3	1.274	4.866
6	9.4	21.5	45.2	64.2	170.7	22.3	1.214	21.7	1.271	6.840
7	11.2	24.1	46.5	66.2	152.7	24.8	1.336	24.1	1.396	7.953
8	6.7	15.0	28.3	38.6	107.7	15.3	1.362	15.1	1.426	5.951

The majority of the blasted material was of the appropriate fragmentation, and the proportion of oversized particles was within acceptable limits. Electronic detonators enabled precise coordination of the initiation of explosive charges in the minefield and a relatively even distribution of the energy transfer of the explosive over the rock mass. In the majority of the blasting, time delays of 33 ms between rows of blastholes and 77 ms between blastholes in a row were set, which enabled more uniform fragmentation and ensured lower seismic impacts on the environment. The efficiency of the blasting was mainly influenced by the geometric arrangement and inclination of the blastholes. The selected drilling schedule proved to be effective, see Table 4., as confirmed by comparisons between the Kuz-Ram model predicted and actual fragmentation by photographing and processing with the BMX Fragmenter software.

6. CONCLUSIONS

The measurement results were mostly in line with the predictions, confirming the appropriateness of the selected technical blasting parameters. However, improvements could be made for medium-sized particles, where the model predicts finer material. In the future, it would be reasonable to study the impact of types of explosives and different electronic detonator time delays on fragmentation, and to use UAV technology for photography and 3D scanning for real-time monitoring of the results. Fragmentation analysis by photography is inexpensive, does not interrupt production, and provides a good overall view of fragmentation if proper imaging techniques are used and errors caused by poor lighting conditions, the position of the imaging device in relation to the mined rock mass, and the quality of the imaging device itself are avoided. We estimate that the introduction of digitalization and automation could increase accuracy and reduce blasting costs. The findings obtained will be of great help in further optimizing blasting operations in the Rodež, Perunk and Solkan quarry, better planning and reducing the costs of secondary crushing of mineral raw materials.

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