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BLASTING DESIGN FOR OBTAINING DESIRED FRAGMENTATION

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Preliminary notes

Predictions and analyses of blasted rock mass fragmentation have increased in importance, as primary fragmentation can significantly decrease the cost of crushing and secondary breaking, on condition that the correct geometry of drilling and blasting parameters is used. The article shows the estimation of fragmentation using the "SB" program, which was created by the authors. It also shows calibration of factors given for the quarry "Očura". The resulting calibrated value of the rock enables the quality prognosis of fragmentation in further blasting works with changed drilling geometry. It also facilitates simulation in the program to optimize blasting works in order to get the desired fragmentations of the blasted rock mass.

Keywords: *fragmentation prediction, Kuz-Ram model, primary crushing, rock factor, rock factor calibration*

Određivanje bušačko-minerskih parametara za dobivanje željene fragmentacije

Prethodno priopćene

Predviđanje i analiza fragmentacije minirane stijenske mase dobiva sve veću važnost. Pravilno odabrana geometrija bušačko minerskih parametara može znatno smanjiti troškove drobljenja, odnosno sekundarnog usitnjavanja. Prikaz prognoziranja fragmentacije programom "SB", koji je izrađen od autora i kalibracija faktora stijene daje se u ovom članku za kamenolom "Očura". Dobivena kalibrirana vrijednost faktora stijene kod sljedećih miniranja omogućava kvalitetno prognoziranje fragmentacije prilikom promjene geometrije bušenja i minerskih veličina, te time simulacijom u programu omogućava optimalizaciju miniranja s ciljem dobivanja željene fragmentacije minirane stijenske mase.

Ključne riječi: *faktor stijene, kalibracija faktora stijene, Kuz-Ram model, predviđanje fragmentacije, primarno drobljenje*

1
Introduction
Uvod

The empirical prediction of expected fragmentation is in most cases carried out by using the Kuz-Ram model. By doing this, the Rosin-Rammler theory is applied. This theory, first proposed by V. M. Kuznetsov (1973), gives a reasonable description of the blasted rock fragmentation. Using this approach, one calculates a rock factor that describes the nature and geology of the rock. The uniformity index is also obtained that characterizes the explosive loading and blast pattern type and dimensions. This allows the characteristic size and size distribution to be calculated according to the Rosin-Rammler procedure. Due to the amount of too many input rock mass parameters, that are not unambiguously determined, the rock factor may also not be satisfactory and this unfavorably influences the fragmentation prediction. The later work of others, particularly that of Lilly (1986) and Cunningham (1983, 1987) was useful for improving the efficiency of that approach.

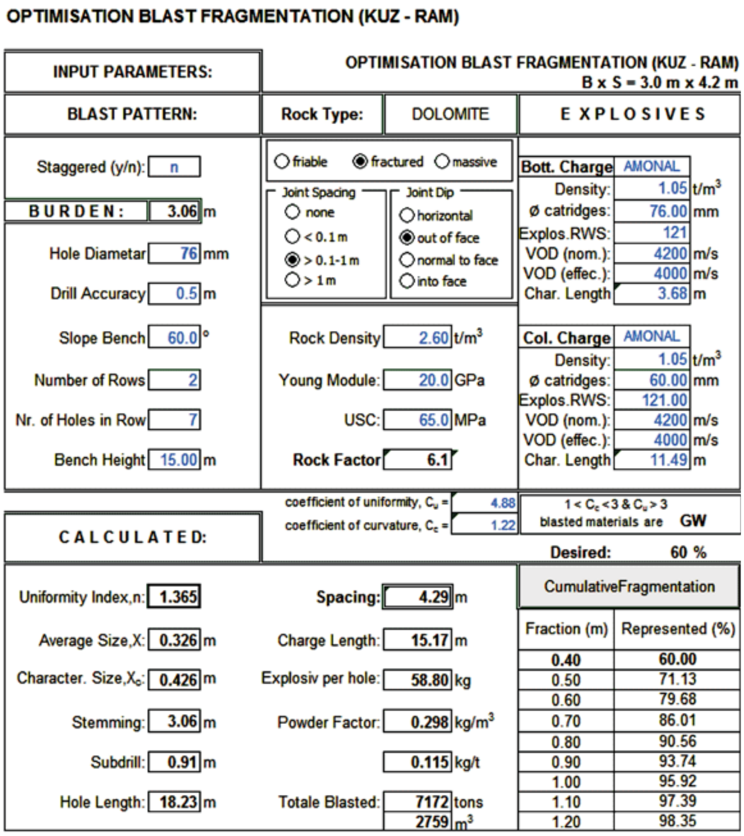
The authors have developed the program "SB" enabling the user to directly influence the blasted material size distribution by selecting a cumulative mass percentage of the required fraction size. By the required selection for the calibrated rock factor, the program computes the required drill hole pattern. The program is used for computing the drilling costs, the costs of machine crushing of larger blocks remaining after blasting and the costs of primary crushing. From the analysis of exploitation and primary processing costs it can be concluded that blasting is the cheapest method of rock fragmentation. The total costs for the required quantity of blasted material are significantly reduced by the use of smaller drill hole patterns. The costs for drilling and explosive do indeed increase in that way, but the costs of loading, transportation, crushing and grinding of the mineral are significantly smaller.

2
Field test
Terenska ispitivanja

To obtain the most beneficial costs for the whole production process, the fragmentation must be optimal. This means that the influence of the plant in the later stages of processing should be considered. Fortunately, more methods allowing prediction and estimation of the fragmentation are available today. If these methods are carefully and reasonably used, they can be very helpful to engineers in their attempting to obtain an optimum fragment distribution which will lower the total cost of the whole production process and not only that of drilling and blasting.

In the field of blasting technology the researchers are confronted with the problem of developing adequately accurate quantity indexes for determining the rock fragment size distribution in mass blasting. The difficulties are to the greatest part caused by the fact that the rock is neither homogeneous nor isotropic, the structural properties in the rock mass may, even when the rock type is the same, change from one site to another. A dominant influence on the results of blasting is exercised by the jointing system of the rock. Entry screen of blast optimization software "SB" is shown in Fig. 1.

To better understand the geological variation-quantifying problem, the blasting operations can be optimally designed, i.e. the Rock Factor correctly determined. WipJoint (WipWare Inc., 2003) is a software mapping module which enables the user to characterize and measure jointing on in-situ rock surfaces and it is used to determine the quality Rock Factor. Joint orientation and spacing has a profound influence on the blasting design. Joint mapping is essential for accurate rock quality designations and features prominently in most rock mass classifications. WipJoint will indicate the in-situ block size and it allows us to document the jointing patterns encountered and define the orientation and spacing of the



OPTIMISATION BLAST FRAGMENTATION (KUZ - RAM)

INPUT PARAMETERS:

OPTIMISATION BLAST FRAGMENTATION (KUZ - RAM)
B x S = 3.0 m x 4.2 m

BLAST PATTERN:

Staggered (y/n): n
BURDEN: 3.06 m
Hole Diametar 76 mm
Drill Accuracy 0.5 m
Slope Bench 60.0 °
Number of Rows 2
Nr. of Holes in Row 7
Bench Height 15.00 m

Rock Type: DOLOMITE

○ friable ● fractured ○ massive

Joint Spacing
○ none
○ < 0.1 m
● > 0.1-1 m
○ > 1 m

Joint Dip
○ horizontal
● out of face
○ normal to face
○ into face

Rock Density 2.60 t/m³
Young Module: 20.0 GPa
USC: 65.0 MPa
Rock Factor 6.1

EXPLOSIVES

Bott. Charge AMONAL
Density: 1.05 t/m³
ø catridges: 76.00 mm
Explos.RWS: 121
VOD (nom.): 4200 m/s
VOD (effec.): 4000 m/s
Char. Length 3.68 m

Col. Charge AMONAL
Density: 1.05 t/m³
ø catridges: 60.00 mm
Explos.RWS: 121.00
VOD (nom.): 4200 m/s
VOD (effec.): 4000 m/s
Char. Length 11.49 m

coefficient of uniformity, C_u = 4.88
coefficient of curvature, C_c = 1.22

$1 < C_c < 3$ & $C_u > 3$
blasted materials are **GW**

CALCULATED:

Desired: 60 %

Uniformity Index,n: **1.365**
Average Size,X: **0.326** m
Character. Size,X_c: **0.426** m
Stemming: **3.06** m
Subdrill: **0.91** m
Hole Length: **18.23** m

Spacing: 4.29 m
Charge Length: **15.17** m
Explosiv per hole: **58.80** kg
Powder Factor: **0.298** kg/m³
0.115 kg/t
Totale Blasted: **7172** tons
2759 m³

CumulativeFragmentation

Fraction (m)	Represented (%)
0.40	**60.00**
0.50	71.13
0.60	79.68
0.70	86.01
0.80	90.56
0.90	93.74
1.00	95.92
1.10	97.39
1.20	98.35

Figure 1 *The prediction of fragmentation using the "SB" program*
Slika 1. *Predviđanje fragmentacije programom "SB"*

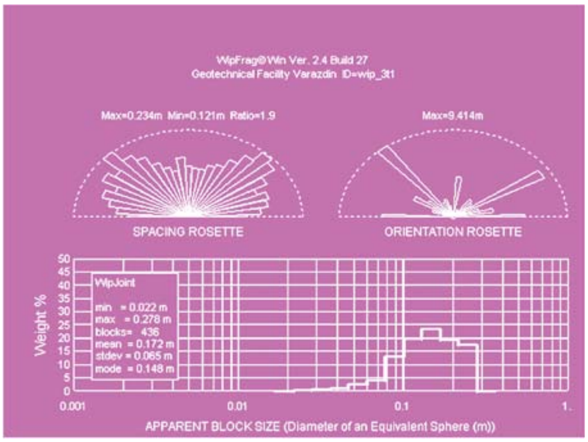


Figure 2 *WipJoint outputs*
Slika 2. *Izlazni podaci dobiveni programom WipJoint*

Figure 3 *Digitized images for analysis of distribution of blasted mass*
Slika 3. *Digitalizirana slika za analizu distribucije odminirane mase*

joints, from which one can measure more accurately the safety or blastability of the rock. WipJoint captures images from digital cameras, scanned images or video-tape playback (NTSC or PAL) and outputs all of the data onto one easy to read screen featuring spacing and orientation rosettes, as well as an 'apparent block size' graph. Fig. 2 shows the values which have been given for the typical rock mass in the quarry "Očura", near Varaždin.

These obtained values were used for the program "SB" to determine the quality Rock Factor (Fig. 1). All data used in the procedure of the evaluation of the fragment size distribution have been processed by the WipFrag (WipWare Inc., 2003) application for obtained blasted materials. WipFrag is an automated image based granulometry system that uses digital image analysis of rock photographs and video tape images to determine grain size distributions. Results can be displayed as an easy to read histogram, cumulative weight percent passing curve and sieve size. One of more digitized images from the quarry "Očura" is shown in Fig. 3.

However, in parallel with the development of computer technology photographic methods for the estimation of fragmentation develop (Compaphoto, WipFrag, Split-Engineering, GoldSize and others). These methods show that the fragmentation can be evaluated by means of a set of photographs of the blasted rock mass. On this basis, the mean fragment size and the uniformity index can be determined (Rosin-Rammler exponent n). Owing to this technology, it is possible to calibrate the Rosin-Rammler distribution, i.e. determine an exact value of the rock factor A, which in the case of bad calibration would be calibrated by one of the quoted methods. The calibrated value for A should give a realistic distribution of the blasted material in the blasting that follows.

Knowing the rock factor value (obtained by observation in the field and by laboratory investigations or calibrated in the described manner), a mean size value of the fragments (*x*) is computed (Kusnetsov, 1973) and out of it the required specific consumption of explosive. The fragment size distribution *R*(*x*) is determined by the equation Rosin-Rammler (1933) and the index of uniformity *n*, which is needed for the computation of fragment size distribution, according to the expression, that was modified by Cunningham (1987).

Cumulative distribution of digitized fragments, from Figure 3, is shown with green columns in Fig. 4. The predicted cumulative distribution of the Kuz-Ram model has been presented with blue columns (left side of image) for Rock Factor A=6,1 (Fig. 1). The distribution on the left side of Fig. 4 does not overlap, and the predicted Kuz-Ram distribution model has been re-calibrated. After this we have new calibrated value for Rock Factor, $A = 5{,}6$ (right side Fig. 4).

Calibrated value of the Rock Factor which has been given in this way, enabled optimal blast fragmentation in order to obtain the desired fragmentation of blasted rock mass. The program "SB" uses the calibrated value of the rock factor (Kuz-Ram model) when simulating blasting and computing specific consumption of energy by the primary crusher where, according to Bond's expression, the knowledge of a square opening size in sieve with 80 % of the mineral mass passing. This value is obtained from the diagram of fragment size distribution for the blasted rock. The importance of the correctly determined Rock Factor value A is shown in Fig. 5 where by the use of the program "SB", the specific consumption of explosive (in kg/m^3) and burden (*B* in m) for different diameters of the blast hole and different rock factor values are obtained. The different rock factor values were obtained by varying the joint dip only (horizontally, out of face, normal to face and into face).

The values computed in Fig. 5 relate to the same cumulative participation of the fraction to 0,4 m of 80 %, rock with joint spacing from 0,1 to 1,0 m and the coefficient of density of blast holes $m = S/B = 1{,}5$. *S* is obtained as a computed value of the burden *B* for a given blast hole diameter, increased for $m = 1{,}5$.

The significance of the rock factor *A* is seen from the values obtained in Fig. 5 or in other words, it is obvious that good knowledge of the blasted rock geology is very important for a correct determination of the rock factor. This factor is of essential importance for the Kuz-Ram model. An incorrect entering, in this particular case for the joint dip relative to the face, results in large differences in the specific consumption of explosive that are obtained, which is best seen in Fig. 5. For a correct fragmentation prediction by the Kuz-Ram model, the rock factor *A* should be well determined. The rock mass after blasting at quarry "Očura" is shown in Fig. 6.

2.1.
Control of blast fragmentation
Kontrola fragmentacija odminirane mase

The right meaning of fragmentation in the blasting process is the actual gradation of the material at the entrance to the primary crusher. As an example, let us assume that the crusher at a quarry is set up for processing the blasted material. The capacity of the crusher is 200 t/h. From the crusher, the 0,2 m size fragments are required. For this capacity the manufacturer of the crusher plant recommends, as an ideal entry material, fragments to the size of 0,3 m.

By using a computer model it is possible to design blasting that will increase the crusher capacity to e.g. 250 t/h. The capacity increment of the primary crusher can be realized by the blasting design; more than 50 % of the fragments should have sizes under 0,2 m and the remaining 50 % of fragments should satisfy the requirement of the crusher entry, i.e. the fragment sizes that do not exceed 0,3 m. These satisfy the conditions of the crushing costs as well as the technology costs of processing the blasted material mass.

The required conditions can be simulated in the "SB" program for the required cumulative fraction participation to 0,2 m of 50 %. After entering the values for bench height (15 m), explosive (AMONAL), blasthole diameter (76 mm) and rock factor $A = 5{,}6$ (calibrated value), the program computes the drill hole layout and displays the output data for the same specific explosive consumption in table form. These computed values, simulated in the program, are shown in Tab. 1. The value *m* in the table represents the coefficient of density of the blastholes, *n* is the index of uniformity and X_c is a characteristic value for the material of blasted fragments.

As it is shown in Tab. 1, characteristic value, X_c has not exceeded 0,3 m in the input material. The table also shows changes of X_c and n for different values of the burden (*B*), and spacing (*S*) for the same specific consumption ($B \times S$ = constant).

The diagram of the values of the index of uniformity (*n*) and the characteristic fragment sizes (X_c) in relation to the coefficient of density of the blastholes according to Tab. 1 is shown in the left side of Fig. 7, where the value of the Rock Factor is calibrated, A=5,6. The right side of Fig. 7 shows dependence of *n* and X_c on the coefficient density of the blastholes for the predicted Rock Factor (A=6,1) that is obtained through Kuz Ram model (Fig. 1).

From Fig. 7, we see the slight deviations between the values *n* and X_c for different *m*, which should be due to the WipJoint program that has served us for entering input data in the "SB" program. In order to predict the next desired blast fragmentation (which will be satisfactory), for the Rock Factor, the calibrated value of $A = 5{,}6$ should be taken.

The fragment size distribution is commonly determined by changing the spacing between blastholes and between rows of the blastholes.

In sound rock the dimensions in the blastholes geometry offer the best possibility for the control of the fragment size distribution. In some cases, to optimize the process, the dimensions in the blasthole layout have to be decreased. The effect of this may be an increase of the specific consumption of explosive (kg/m^3).

The saving in costs here is realized by the increased permeability through the primary and secondary crusher, increased productivity and decreased wear of the crushing, grinding and sieving equipment.

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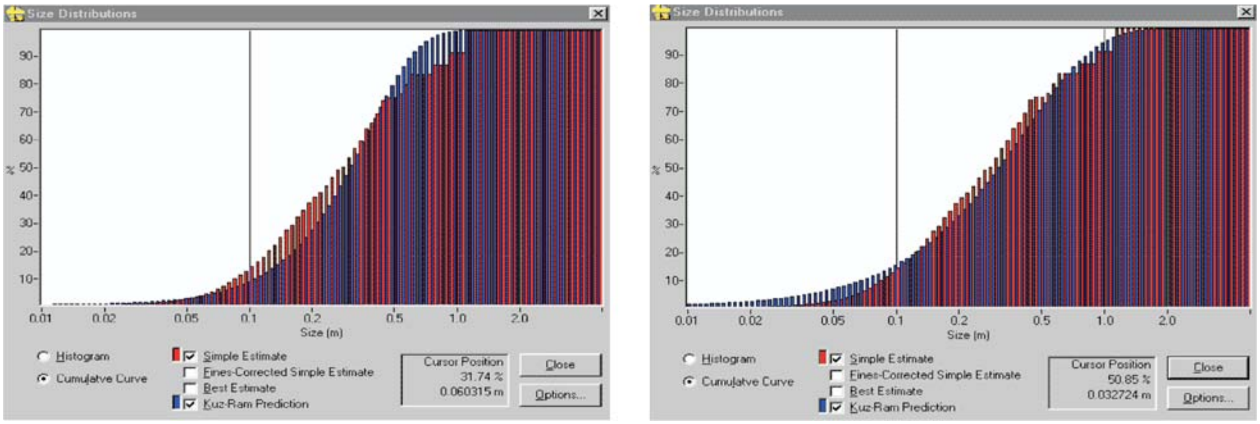

○ Histogram
● Cumulative Curve
☑ Simple Estimate
☐ Fines-Corrected Simple Estimate
☐ Best Estimate
☑ Kuz-Ram Prediction
Cursor Position
31.74 %
0.060315 m

○ Histogram
● Cumulative Curve
☑ Simple Estimate
☐ Fines-Corrected Simple Estimate
☐ Best Estimate
☑ Kuz-Ram Prediction
Cursor Position
50.85 %
0.032724 m

Figure 4 *Calibration of the predicted distributions and distributions obtained by image analysis*
Slika 4. *Kalibracija prognozirane razdiobe i razdiobe dobivene analizom slike*

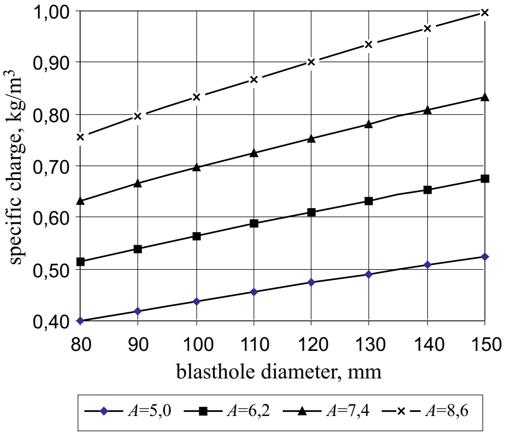

Figure 5 *Diagram of the specific explosive consumption in relation to the blast hole diameter and Rock Factor.*
Slika 5. *Dijagram ovisnosti specifične potrošnje eksploziva o promjeru minske bušotine i Faktora stijene*

Figure 6 *Blasted rock mass in quarry "Očura"*
Slika 6. *Odminirana stijenska masa (kamenolom "Očura")*

Table 1 *Calculated drilling patterns for required example*
Tablica 1. *Izračunata geometrija bušenja za traženi primjer*

Burden B / m	Spacing S / m	$B \times S$	$m=S/B$	n	X_c	Cumulative fraction participation, %			
						0,10	**0,20**	0,40	0,60
2,33	3,49	8,11	1,50	1,50	0,255	21,77	**50,00**	85,87	97,24
2,36	3,43	8,11	1,45	1,48	0,256	22,05	**50,00**	85,46	97,01
2,41	3,37	8,11	1,40	1,45	0,257	22,34	**50,00**	85,04	96,75
2,45	3,31	8,11	1,35	1,43	0,258	22,64	**50,00**	84,61	96,48
2,50	3,25	8,11	1,30	1,41	0,259	22,95	**50,00**	84,16	96,18
2,55	3,18	8,11	1,25	1,39	0,260	23,27	**50,00**	83,70	95,86
2,60	3,12	8,11	1,20	1,36	0,262	23,60	**50,00**	83,22	95,51
2,66	3,05	8,11	1,15	1,34	0,263	23,94	**50,00**	82,73	95,14
2,72	2,99	8,11	1,10	1,32	0,264	24,29	**50,00**	82,21	94,74
2,78	2,92	8,11	1,05	1,29	0,266	24,65	**50,00**	81,68	94,31
2,85	2,85	8,11	1,00	1,27	0,267	25,03	**50,00**	81,13	93,84
2,92	2,78	8,11	0,95	1,24	0,269	25,42	**50,00**	80,56	93,34
3,00	2,70	8,11	0,90	1,21	0,271	25,83	**50,00**	79,96	92,79
3,09	2,63	8,11	0,85	1,19	0,272	26,26	**50,00**	79,34	92,20
3,18	2,55	8,11	0,80	1,16	0,275	26,71	**50,00**	78,69	91,55

From Fig. 8 we can observe that the simulation of the required conditions in the program "SB" with the fraction of 0,2 m satisfies the required participation of 50 % and remains constant as the coefficient of the drill hole density increases; this of course, does not have to be the rule. The figure also shows that with the increasing of the drill hole density, the cumulative participation of the fractions above 0,2 m gradually increases and below this value gradually decreases.

3

Optimal blasting design

Optimalizacija bušačko minerskih parametara

Measuring the size distribution of the blasted rock is a complicated process due to the wide range of fragment sizes present in the rockpile. Program "SB" provides a simple and easy to use tool to obtain a measure of size distribution of

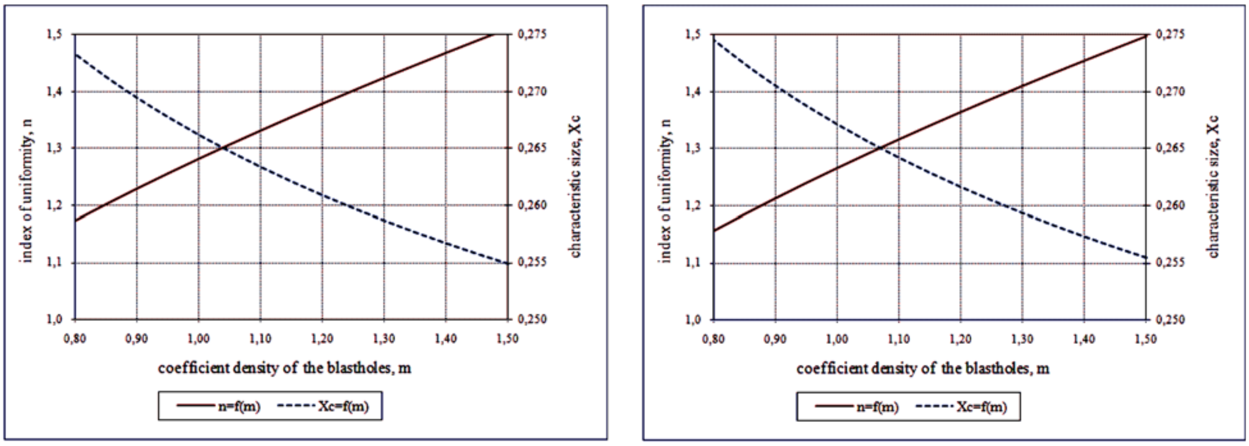

***Figure** 7 Dependence of the coefficient of uniformity (n) and the characteristic value (X_c) on the coefficient density of the blastholes (m)*
***Slika** 7. Ovisnost indeksa jednoličnosti (n) i karakteristične veličine (X_c) o koeficijentu gustoće minskih bušotina (m)*

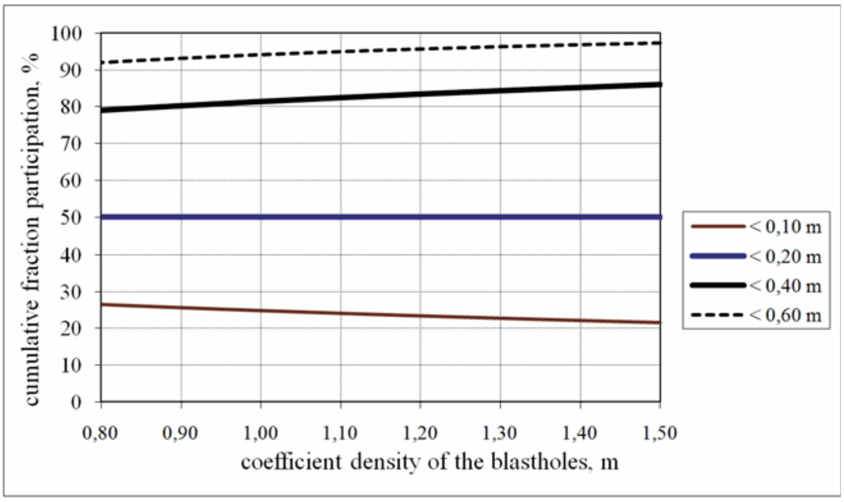

***Figure 8** Diagram of the cumulative dependence of selected fractions on the blasthole density*
***Slika 8.** Dijagram kumulativne zastupljenosti odabranih frakcija u funkciji gustoće minskih bušotina*

fragments that can be identified in photographic images.

The Kuz-Ram model for fragmentation prediction has been included in the program so that the measured fragment size distribution can be compared with the predicted size distribution and the fragmentation model parameters adjusted in the form of a calibration of the model. In this way a calibrated fragmentation prediction tool is combined with a fragmentation measurement tool which greatly improves the blast optimization cycle.

If the drilling and blasting costs are minimal, there is a great risk that the costs of the following operations may be high. The overall cost may in such a case be significantly increased. The factor, that mostly influences the operations after blasting, is the fragmentation of the blasted rock and this should be considered when computing the drilling and blasting costs.

In a quick and effective way, by varying the geometry of drilling for the required quantity of the blasted material, the program "SB" gives an analysis of costs for drilling, explosive means, subsequent crushing of the oversize blocks that have remained after blasting by the hydraulic hammer, and an analysis of the costs for primary crushing. According to the given conditions the drilling geometry is varied. In the end, a total minimum price for the specified operations is obtained.

To determine the cost price of extraction of a particular raw mineral material or crushed stone, it is not recommendable to isolate the drilling and blasting operations from the remaining operations in the operation cycle. Besides this, crushing of the oversize blocks after blasting must be considered as well as the separation of dirt from the raw mineral, loading and transport to the primary crusher (Oloffson, S.O., 1990).

3.1.
Computation of crushing costs
Izračun troškova drobljenja

One of the consequences of the bad fragmentation of the blasted rock mass is the appearance of too large blocks that cannot be tolerated with regard to the capacity of the loading and transporting equipment and to the opening size of the existing primary crusher plant. Larger blocks must subsequently be crushed by secondary blasting or a hydraulic hammer. Normally, the percentage of subsequent crushing is lowered with the increase of the blasthole density in the layout pattern or the fragmentation in the primary blasting is finer.

Represented in the "SB" program is the cost analysis of the subsequent crushing of the oversize blocks by the hydraulic hammer. To be able to compute the cost price of the subsequent crushing by hydraulic hammer, it is necessary to know the number of the oversize blocks and their participation in classes. The participation of these blocks in the interval of class 1,0 to 1,5 m can be computed by the Rosin-Rammler equation of the fragment size distribution from the following expression:

$$R_{(1,0\ \text{to}\ 1,5)} = \left[\left(1 - \mathrm{e}^{-\left[\frac{1,5}{X_\mathrm{c}}\right]^n} \right) - \left(1 - \mathrm{e}^{-\left[\frac{1,0}{X_\mathrm{c}}\right]^n} \right) \right] \cdot 100, \qquad (1)$$

where $R_{(1,0\ \text{to}\ 1,5)}$ - participation of the material of class 1,0 to 1,5 m (%), X_c - characteristic value of the blasted rock mass (m), n - index of uniformity (-).

Predicted number of the oversized blocks N_b in our case of the class 1,0 to 1,5 m , is obtained from the expression:

$$N_\mathrm{b} = \frac{0,01 \cdot W \cdot R_{(1,0\ \text{to}\ 1,5)}}{G_\mathrm{s}}, \qquad (2)$$

where W - blasted rock mass (t), G_s - weight of the characteristic block of class 1,0 to 1,5 m (t). The numbers of oversized blocks for classes 1,5 – 2,0 and 2,0 – 2,5 m are computed by analogy. If the number of the oversize blocks, the volume of the characteristic block inside of an individual class, capacity (m^3/h) and the cost of operation of the hydraulic hammer (€/h) are known, the program "SB" will compute the total cost price of crushing the oversize blocks by means of the hydraulic hammer.

The time of passing and the effect of the crusher will decrease when increasing the average fragment size.

The time loss due to the crusher blockage will be increased. At the mining location, time will be lost loading the equipment, which is used for ejecting unnecessary large fragments for secondary crushing. After in depth research on crushing rocks, lasting a number of years, Bond (1952) came to the conclusion that an average of the energy spent for a certain crushing can be obtained by the following expression:

$$W = W_i \cdot \left(\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}} \right), \qquad (3)$$

where W - specific consumption of energy (kWh/t), W_i - Bond 's work index (kWh/t), P - size of square openings in the sieve with 80 % material passing after crushing (μm), F - size of square openings in the sieve with 80 % material passing before crushing (μm).

Bond's formula is widely accepted for the computation of effectively spent work for crushing and milling in industrial companies. He elaborated a laboratory procedure to determine work index (W_i) that can be transferred to industrial conditions. This is not the case with the constants of proportionality of Rittinger and Kick. Bond's law is defined on the basis of a large number of measurements of the energy consumed by different crushing machines (crushers and grinders) and in laboratory investigations.

4
Results and discussion
Rezultati i diskusija

By altering the blasthole layout, "SB" software application, in addition to fragmentation distribution prediction, the drilling costs, explosive materials spending, crushing of oversized blocks and primary crushing costs can be analyzed. Together with drilling and explosive material spending, the costs of crushing represent a significant share in the overall production price. The costs of drilling and explosive material represent standard prices and are easily calculated whereas the consumption of crushing energy is calculated by Bond's expression. The price of crushing is obtained when the blasted mass (t) is multiplied by specific energy consumption (kWh/t) and by energy price (€/kWh). The price of crushing includes all operational costs, from the price of the crusher, amortization, maintenance, insurance and the price of electrical energy or diesel oil. Depending on the fragmentation of the blasted material, the primary crusher type (electrical energy or diesel oil), age of the crusher, etc., this value is mainly in the range between 0,20 and 0,25 €/kWh. The costs of primary crushing should always be analyzed in the process of operation, because it may greatly influence the total production costs.

The program enables us to calculate the required blasting geometry with a desired cumulative percentage up to a given fraction. For the selected fraction, a cumulative percentage is entered and the program computes the required burden and blasthole spacing that should result with the required cumulative percentage for the selected value up to the given fraction.

Fig. 9 shows a diagram obtained for a selected class of cumulative distribution fractions from 0,4 m to 60 % and consumption per ton of blasted rock mass. For set distribution the following drilling geometry is obtained, $B \times S = 3,42 \times 4,11$ and specific consumption of explosives $q = 0,275\ \mathrm{kg/m^3}$ (powder factor). The cost simulation performed by the program "SB" relates to the bench height $H = 15$ m, diameter of the blast hole ∅76 mm, blasted material quantity $Q = 7200$ t and the calibrated rock factor $A = 5,6$. For distributed fractions from 0,4 m to 80 % the program calculates the necessary drilling geometry, $B \times S = 2,7 \times 3,26$ and specific consumption $q = 0,449\ \mathrm{kg/m^3}$. For this geometry, less consumption per ton of blasted rock mass is obtained (Fig. 10). The figures show the cost simulation for the quarry "Očura". In the overall price included are the costs for drilling of the blastholes, blasting, subsequent crushing by hydraulic hammer and the cost of primary crushing (size of the crusher discharge, $d = 0,2$ m).

As shown in Fig. 9 and Fig. 10, with the increase of the layout geometry dimensions, the specific consumption of explosive decreases. This brings financial savings in drilling and blasting, but also a coarser fragmentation where the subsequent crushing and reduction in size will significantly increase the overall costs.

This larger geometry was related to larger blocks and an increased amount of energy needed for their crushing by hydraulic hammer and primary crusher. The reduction of the drilling geometry represents a significant saving for each blasting. The factor that mostly affects the after mining operations is the obtained fragmentation, which should be taken into account when running the budget costs of acquiring raw materials. If the cost of drilling and blasting is set to minimum, we get coarser fragmentation, which then significantly increases the cost of loading, transport, post-fragmentation and crushing. Cost analysis and economics of blasting is shown in Fig. 11.

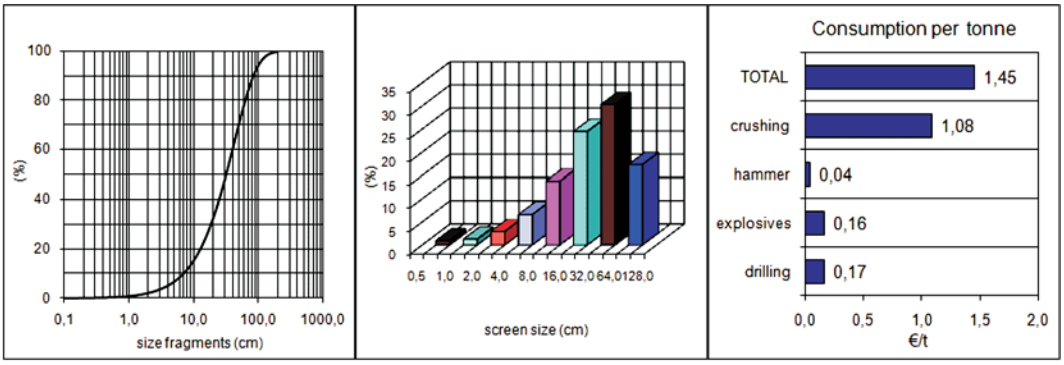

Figure 9 *Distribution of individual classes and prices for participation of the fraction to 40 cm of 60 %*
Slika 9. *Distribucija pojedinih klasa i cijene za kumulativnu zastupljenost frakcija do 40 cm od 60 %*

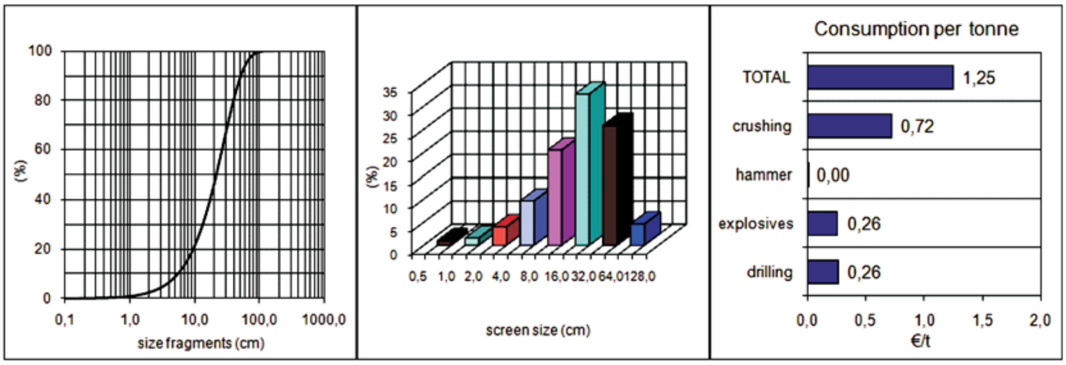

Figure 10 *Distribution of individual classes and prices for participation of the fraction to 40 cm of 80 %*
Slika 10. *Distribucija pojedinih klasa i cijene za kumulativnu zastupljenost frakcija do 40 cm od 80 %*

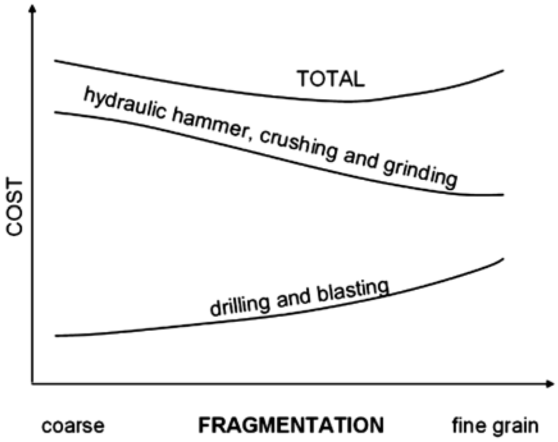

Figure 11 *Cost distribution of acquiring mineral raw materials*
Slika 11. *Analiza cijene koštanja pridobivanja mineralne sirovine*

5
Conclusion
Zaključak

The optimization of the blasting designed represents an effort to eliminate excessively big fragments or to minimize the amount of fines in the rock pile. Nevertheless, to optimize the whole production system, it is better to use blasting layout that would produce the material fragmentation required by the remaining part of the production process. The measured size distribution can be used to calibrate the Kuz-Ram fragmentation prediction model providing a site specific tool for blast optimization. This has been used to evaluate blast design options and reduce the amount of trial blasting to produce the required blast results.

The fragmentation prediction diagram and the calibration of the rock factor can be seen on the given examples of the blasting at the quarry "Očura" in the vicinity of the town of Varaždin. For presented blasting cases, a drilling cost estimate, explosive materials, crushing of large blocks by the hydraulic hammer and an analysis of the primary crushing costs were carried out.

The calibrated rock factor value can successfully be used for blasting fragmentation prediction by adjusting the blasthole pattern. Accordingly, comparison of the predicted distribution results with the distribution obtained by the analysis on the blast pile images, represents an important tool in calibration for the future predictions of fragmentation. The calibrated value is adopted in the future blasting and the participation of the fraction for different drilling geometry layouts is well predicted by the Kuz-Ram model. With regard to the cost analysis performed by the simulation in the program "SB", it may be concluded that the primary blasting design is a less expensive form of rock breaking than later mechanical crushing. To be precise, the owners of open mines and quarries are, out of ignorance, well disposed towards savings on drilling and blasting. These savings, however, will often disappear with increased costs of loading, transport, and subsequent reduction in the size of oversize blocks by hydraulic hammer and the increased costs of crushing.

The costs that will appear in the later production stages will be significantly greater than the savings in blasting and the overall costs will be greater. In most cases, dimensions and geometry of drilling need to be decreased and the process in this way optimized. The consequence of this can be an increase of the specific consumption of explosives (kg/m^3) but a significant cost reduction in the overall process. It may be also concluded that a good fragmentation after blasting is the one which most favorably influences the profitability of the whole raw mineral extraction process. To obtain the most beneficial costs of the whole production process, fragmentation achieved by blasting must be optimal. This means that the influence on the plant in the later stages of processing should be considered.

Fortunately, more methods allowing prediction and estimation of the fragmentation are available today. If these methods are carefully and reasonably used, they can be very helpful to engineers in their attempting to obtain an optimal fragment distribution which will lower the total cost of the whole production process and not only that of drilling and blasting.

Further validation of the presented material will be considered in the case study of quarry operations in Croatia. Results obtained by the "SB" program will be compared with actual costs acquired in the field to maximize the cost effectiveness in blasting projects throughout the optimization process based on the real data, instead of on theory.

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References
Litaratura

[1] Bond, F. C.; Whitney, B. B. The Work Index in Blasting, Quarterly Colorado School of Mines, 54, (1959)(July), pp. 77-82.
[2] Cunningham, C. V. B. The Kuz-Ram model for prediction of fragmentation from blasting, Lulea Fragmentation Conference, 2, (1983), pp. 439-454.
[3] Cunningham, C. V. B. Fragmentation estimations and the Kuz-Ram model – for years on. 2nd International Symposium on Rock Fragmentation in Blasting. Keystone, Colorado, USA, (1987), pp. 475-487.
[4] Kleine, T. H. Blast fragmentation measurement using GoldSize, Franklin & Katsabanis (eds), Balkema, Rotterdam, 1996.
[5] Kuznetsov V. M. The mean diameter of the fragments formed by blasting rock. Soviet Mining Science, 9, (1973), 144-148.
[6] Lilly P. A. An empirical method of assessing rock mass blastability, The Aus. IMM/IE Aust Newman Combine group, Large Open Pit Mining Conference, October 1986.
[7] Olofsson, S. O. Applied explosives technology for construction and mining, Nora Boktryckeri AB Sweden, 1990.
[8] Rosin, R.; Rammler, E. Laws governing the fineness of powered coal. J. Institute of Fuels, 7, (1933), pp. 29-36.
[9] Strelec, S. Desired Fragmentation Muckpile by Blast Optimization. Doctoral Thesis, University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, 2001.
[10] WipWare Inc., Photoanalysis System, WipFrag Calibration Manual, 2003.

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