Fragment Size Distribution of Blasted Rock Mass

Jasmin Jug 1, Stjepan Strelec 1, Mario Gazdek 1, Boris Kavur 1

1 University of Zagreb, Faculty of Geotechnical Engineering, Hallerova aleja 7, 42000 Varaždin, Croatia
jasmin.jug@gfv.hr

Abstract. Rock mass is a heterogeneous material, and the heterogeneity of rock causes sizes distribution of fragmented rocks in blasting. Prediction of blasted rock mass fragmentation has a significant role in the overall economics of open cast mines. Blasting as primary fragmentation can significantly decrease the cost of loading, transport, crushing and milling operations. Blast fragmentation chiefly depends on the specific blast design (geometry of blast holes drilling, the quantity and class of explosive, the blasting form, the timing and partition, etc.) and on the properties of the rock mass (including the uniaxial compressive strength, the rock mass elastic Young modulus, the rock discontinuity characteristics and the rock density). Prediction and processing of blasting results researchers can accomplish by a variety of existing software’s and models, one of them is the Kuz-Ram model, which is possibly the most widely used approach to estimating fragmentation from blasting. This paper shows the estimation of fragmentation using the "SB" program, which was created by the authors. Mentioned program includes the Kuz-Ram model. Models of fragmentation are confirmed and calibrated by comparing the estimated fragmentation with actual post-blast fragmentation from image processing techniques. In this study, the Kuz-Ram fragmentation model has been used for an open-pit limestone quarry in Dalmatia, southern Croatia. The resulting calibrated value of the rock factor enables the quality prognosis of fragmentation in further blasting works, with changed drilling geometry and blast design parameters. It also facilitates simulation in the program to optimize blasting works and get the desired fragmentations of the blasted rock mass.

1. Introduction
The objective of a blasting engineer in a mine is to generate a suitable muck pile having a suitable size distribution of the rock that can be efficiently loaded, transported and milled [1]. The blasting operation affects all the other mentioned activities, and the ultimate goal is to achieve the lowest costs of exploitation and processing. The empirical prediction of an expected size distribution of blasted rock mass is in most cases carried out by using the Kuz-Ram model. This model is an empirical fragmentation model that combines rock properties, explosive properties and design variables. Kuz-Ram model is based on the Kuznetsov [2] and Rosin-Rammler [3] equations modified by Cunningham [4, 5]. Using that approach a rock factor and the uniformity index are determined. Rock factor characterizes the rock properties and the uniformity index characterizes the drill and blast design parameters. Prediction of blasted rock mass fragmentation is possible as the final result. Bellow are three key Equations 1, 2, and 3 [4, 5 and 6].

The adapted Kuznetsov equation:

\[ x_m = A \cdot K^{0.8} \cdot Q^{1/6} \cdot \left(\frac{115}{RWS}\right)^{19/20} \] (1)
, where $x_m$ is the mean particle size in centimeters, $A$ is a rock factor (varying between 0.8 and 22), $K$ is the powder factor in kilograms of explosive per cubic meter of rock, $Q$ is mass of explosive in the hole in kilograms and $RWS$ is weight strength relative to ANFO (ammonium nitrate fuel oil).

The adapted Rosin-Rammler equation:

$$R_x = \exp \left[-0.693 \cdot \left(\frac{x}{x_m}\right)^n\right]$$

where $R_x$ is the mass fraction retained on screen opening $x$ and $n$ is the uniformity index (usually between 0.7 and 2).

The uniformity equation:

$$n = \left(2.2 - \frac{14\cdot B}{d}\right) \cdot \sqrt{\left(\frac{1+S/B}{2}\right) \cdot \left(1 - \frac{W}{B}\right) \cdot \left(\frac{BCL-CCL}{L}\right) + 0.1} \cdot \left(\frac{L}{H}\right)^{0.1}$$

where $B$ is burden in meters, $S$ is spacing between holes in meters, $d$ is hole diameter in millimeters, $W$ is standard deviation of drilling precision in meters, $L$ is charge length in meters, $BCL$ is bottom charge length in meters, $CCL$ is column charge length in meters and $H$ is bench height in meters.

The authors of this paper have developed "SB" program which includes the Kuz-Ram model. The program was first tested for predictions and analyses of blasted rock mass fragmentation for the quarry "Očura" [7]. The "SB" program enabling the user to directly influence on 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 necessary drill hole pattern. Moreover, it enables economic analysis like the drilling costs, costs of crushing oversized blocks remained after blasting with a hydraulic hammer and primary processing costs. Entry screen of blast optimization software "SB" is shown in Figure 1.

2. Research method and field works

From the introductory chapter, it is apparent that fragmentation of blasted rock mass depends upon two groups of variables: drill and blast design parameters that can be controlled and optimized rock mass properties which cannot be controlled. The reason is in the fact that the rock is neither homogeneous nor isotropic. A dominant influence on the results of blasting is exercised by the jointing system of the rock mass.

In this research study, field tests have been carried out in limestone quarry called "Vrsi" in Dalmatia. To quality determine the rock factor joint orientation and spacing are considered using WipJoint software [8], which enables the user to characterize and measure jointing on in-situ rock surfaces. WipJoint determines the size of blocks in situ, allows researchers to detect jointing patterns and determine their orientation and spacing. By processing a digital image of rock surface, the user gets a spacing rosette, orientation rosette and apparent block size graph.

Fragmentation characteristics such as mean fragment size, uniformity index and characteristic size were calculated by using digital images in an image analysis system called Wipfrag software [8]. These features were determined in the same way by [7], [9], [10] and other researchers. Results of the analysis can be displayed as a histogram and cumulative size curve. The results of image analysis are corrected concerning the fines less than the average maximum fines size [11]. So the value of the rock factor is immediately corrected, with calibration of the Kuz-Ram model by comparing the cumulative distribution of digitized fragments of blasted rock mass from the image and the predicted cumulative distribution of the Kuz-Ram model.

A mean size value of the fragments was calculated according to Equation 1, the fragment size distribution is determined by the Equation 2 and the index of uniformity according to Equation 3. The required conditions are then simulated in the "SB" program for the required cumulative fraction
participation to 0.4 m of 80%. After entering the values for bench height, explosive properties, blast hole diameter and calibrated rock factor value, the program has calculated the drill hole layout and displayed the output data for the same specific explosive consumption in table form. At the end, program gave an analysis of costs for drilling, explosive means, a subsequent crushing of the oversize blocks that have remained after blasting by the hydraulic hammer, and an analysis of the costs for primary crushing.

The costs of drilling and explosive material represent regular prices and are easily calculated whereas the consumption of crushing energy is calculated by Equation 4 [12]. The price of crushing is obtained when the blasted mass in tons is multiplied by specific energy consumption in kilowatt-hours per ton and by energy price in Euros per kilowatt-hour. 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 [7].

The Bond's equation:

$$W = W_i \cdot \left( \frac{10}{P} - \frac{10}{P'} \right)$$

where $W$ is a specific consumption of energy in kilowatt-hours per ton, $W_i$ is Bond's work index in kilowatt-hours per ton, $P$ is size of square openings in the sieve with 80% material passing after

| INPUT PARAMETERS | OPTIMISATION BLAST FRAGMENTATION (KUZ - RAM) |
|------------------|---------------------------------------------|
| Bench Height: 15.00 m |
| Number of Rows: 22 |
| Slope Bench: 75.0° |
| Drill Accuracy: 0.4 m |
| Hole Diameter: 76 mm |
| Joint Spacing: none |
| Joint Dip: horizontal |
| Joint Type: none |
| Drill Pattern: Staggered |

| Rock Type: | LIMESTONE | EXPLOSIVES |
|------------|-----------|------------|
| Density: 1.50 t/m³ |
| Prom. patro.: 70.00 mm |
| Explos.RWS: 145 |
| VOD (nom.): 6000 m/s |
| VOD (effici.): 5900 m/s |
| Char. Length: 0.10 m |
| Young's Modul: 45.0 GPa |
| UCS: 158.0 MPa |
| Rock Density: 2.65 t/m³ |
| Col. Charge: CROEX t/m³ |
| Prom. patro.: 76.00 mm |
| Explos.RWS: 99.99 |
| VOD (nom.): 2500 m/s |
| VOD (effici.): 2300 m/s |
| Char. Length: 13.50 m |

| C A L C U L A T E D | Desired: 80% |
|--------------------|--------------|
| Uniformity Index, $n$: 1.382 |
| Average Size, $X$: 0.217 m |
| Character. Size, $X'$: 0.283 m |
| Stemming: 2.84 m |
| Subdrill: 0.91 m |
| Hole Length: 16.44 m |
| Spacing: 4.3 m |
| Charge Length: 13.60 m |
| Explosives per hole: 62.08 kg |
| Powder Factor: 0.341 kg/m³ |
| 0.129 kg/t |
| Hole Blasted: 10601 tona |
| Total Blasted: 4000 m³ |

Figure 1. The prediction of fragmentation using the "SB" program – entry screen.
crushing in micrometers and $F$ is size of square openings in the sieve with 80% material passing before crushing in micrometers.

### 3. Results and discussions

Using WipJoint software on the example of a quarry "Vrsi" is determined that joint spacing is in the range of 0.1 to 1.0 m, a joint dip is horizontal and rock mass is characterized as friable. The values of uniaxial compressive strength (UCS = 158 MPa) and Young's modulus ($E = 45$ GPa) were determined in a rock mechanics laboratory (personal contact). The input parameters of the rock mass are entered in the middle column of the entry screen of the "SB" program, as can be seen in Figure 1.

Cumulative distribution of digitized fragments concerning the fines less than the average maximum fines size is shown with green columns in Figure 2. The predicted cumulative distribution of the Kuz-Ram model has been presented with blue columns (left side of Figure 2) for rock factor $A = 4.0$. The distribution on the left side of Figure 2 does not overlap, and the predicted Kuz-Ram distribution model has been corrected. After that step new calibrated value for rock factor was obtained, $A = 3.8$ (right side of Figure 2).

![Figure 2. Calibration of the predicted distributions and distributions obtained by image analysis.](image)

Calibrated value of the Rock Factor enabled optimal blast fragmentation to obtain the desired fragmentation of blasted rock mass. The "SB" program uses the calibrated value of the rock factor when simulating blasting and computing specific consumption of energy by the primary crusher where, according to Equation 4, the knowledge of a square opening size in a sieve with 80% of the mineral mass passing. The importance of the correctly determined rock factor value $A$ is shown in Figure 3, using the "SB" program, the specific consumption of explosive in kilograms per cubic meter and burden in meters for different diameters of the blast hole and different rock factor values are obtained. The different rock factor values were achieved by varying the joint dip (horizontally, out of the face, normal to face and into the face). The values computed in Figure 3 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 meter and the coefficient of the 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 required conditions are simulated in the "SB" program for the required cumulative fraction participation to 0.4 m of 80%. After entering the values for bench height ($H = 15$ m), explosive (VITEZIT and CROEX), blast hole diameter ($d = 76$ mm) and rock factor $A = 3.8$ (calibrated value), the program computes the drill hole layout and displays the output data for the same specific explosive consumption in table form. These calculated values, simulated in the program, are shown in Table 1.
The value $m$ in the table represents the coefficient of the density of the blast holes, $n$ is the index of uniformity and $X_c$ is a characteristic value for the material of blasted fragments. Table 1 shows changes of $X_c$ and $n$ for different values of the burden and spacing for the same specific consumption ($B \times S = constant$).

![Figure 3](image)

**Figure 3.** Diagram of the specific explosive consumption in relation to the blast hole diameter and rock factor

**Table 1.** Calculated drilling patterns for required example

| Burden, $B$ (meter) | Spacing, $S$ (meter) | $B \times S$ | Coefficient of density of blast holes, $m$ | Index of uniformity, $n$ | Characteristic value for the material, $X_c$ | Cumulative fraction participation (%) |
|---------------------|----------------------|-------------|----------------------------------------|------------------|------------------------------------------|----------------------------------------|
| 2.84                | 4.26                 | 12.12       | 1.50                                   | 1.37             | 0.284                                    | 79.76                                  | 98.39                                  |
| 2.89                | 4.19                 | 12.12       | 1.45                                   | 1.35             | 0.285                                    | 79.34                                  | 98.20                                  |
| 2.94                | 4.12                 | 12.12       | 1.40                                   | 1.33             | 0.287                                    | 78.91                                  | 97.99                                  |
| 3.00                | 4.05                 | 12.12       | 1.35                                   | 1.31             | 0.288                                    | 78.48                                  | 97.75                                  |
| 3.05                | 3.97                 | 12.12       | 1.30                                   | 1.28             | 0.289                                    | 78.03                                  | 97.50                                  |
| 3.11                | 3.89                 | 12.12       | 1.25                                   | 1.26             | 0.291                                    | 77.57                                  | 97.21                                  |
| 3.18                | 3.81                 | 12.12       | 1.20                                   | 1.24             | 0.292                                    | 77.09                                  | 96.90                                  |
| 3.25                | 3.73                 | 12.12       | 1.15                                   | 1.21             | 0.294                                    | 76.60                                  | 96.56                                  |
| 3.32                | 3.65                 | 12.12       | 1.10                                   | 1.19             | 0.296                                    | 76.10                                  | 96.18                                  |
| 3.40                | 3.57                 | 12.12       | 1.05                                   | 1.16             | 0.298                                    | 75.58                                  | 95.76                                  |
| 3.48                | 3.48                 | 12.12       | 1.00                                   | 1.14             | 0.300                                    | 75.04                                  | 95.29                                  |
| 3.57                | 3.39                 | 12.12       | 0.95                                   | 1.11             | 0.302                                    | 74.48                                  | 94.78                                  |
| 3.67                | 3.30                 | 12.12       | 0.90                                   | 1.09             | 0.305                                    | 73.90                                  | 94.22                                  |
| 3.78                | 3.21                 | 12.12       | 0.85                                   | 1.06             | 0.308                                    | 73.30                                  | 93.59                                  |
| 3.89                | 3.11                 | 12.12       | 0.80                                   | 1.03             | 0.311                                    | 72.67                                  | 92.90                                  |

The left side of Figure 4 shows the relationship between the coefficient of the density of the blast holes, according to Table 1, and the index of uniformity as well as the characteristic fragment sizes for $A = 3.8$. Dependence of $n$ and $X_c$ on the coefficient density of the blast holes for the predicted rock
factor ($A = 4.0$) is shown on the right side of Figure 4. From Figure 4, there are the slight deviations between the values $n$ and $X_c$ for different $m$, which is probably a consequence of the use image analysis system that served for entering input data in the "SB" program. To predict the next desired blast fragmentation, for the rock factor should be taken the calibrated value ($A = 3.8$).

The fragment size distribution is commonly determined by changing the spacing between blast holes and between rows of the blast holes through the "SB" program. Figure 5 shows the cumulative dependence of some fractions on the blast hole density. With increasing of the blast holes density, the cumulative participation of the fractions above 0.2 m gradually increases and below this value gradually decreases.

![Figure 4. Dependence of the coefficient of uniformity $n$ and the characteristic value $X_c$ on the coefficient density of the blast holes $m$](image1)

![Figure 5. Diagram of the cumulative dependence of selected fractions on the blast hole density](image2)

The application of "SB" program enables users economic analysis. To calculate the required blasting geometry user select fraction and cumulative percentage, while the program computes the required burden and blast hole spacing. To determine the cost price of exploitation of a particular raw mineral material or crushed rock, it is not recommendable to isolate the drilling and blasting operations from the remaining processes in the operation cycle. If the drilling and blasting costs are minimal, there is a high risk that the expenses of the following operations may be high. Together with drilling and explosive material spending, the costs of crushing represent a significant share in the overall production price. In a quick and efficient way, by varying the geometry of blast hole drilling for the required quantity of the blasted material, the "SB" program analyze the drilling costs, explosive materials spending, crushing of oversized blocks and primary crushing costs.
The costs of drilling and explosive material represent standard prices from the market. The consumption of crushing energy is calculated by Equation 4. The price of crushing is obtained when the blasted rock mass (in tons) is multiplied by specific energy consumption (in kilowatt-hours per ton) and by energy price (in Euros per kilowatt-hour). The price of crushing includes all operational costs (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 power or diesel oil), the age of the crusher, etc., according to the author's experience, this value is mainly in the range between 0.20 and 0.25 €/kWh.

Figure 6 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, $B \times S = 3.5 \times 5.3$ m and specific consumption of explosives $q = 0.209$ kg/m³ (powder factor). The cost simulation performed by the "SB" program relates to the bench height $H = 15$ m, the diameter of the blast hole $d = 76$ mm, blasted material quantity $Q = 10600$ t and the calibrated rock factor $A = 3.8$. For distributed fractions from 0.4 m to 80 % the program calculates the necessary drilling geometry, $B \times S = 2.8 \times 4.3$ m and specific consumption $q = 0.341$ kg/m³. For this geometry, less consumption per ton of blasted rock mass is obtained (Figure 7). The figures show the cost simulation for the quarry "Vrsi". In the overall price included are the costs for drilling of the blast holes, blasting, subsequent crushing by hydraulic hammer and the cost of primary crushing.

Comparison of Figures 6 and 7 shows that larger drilling 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, coarser fragmentation is gained, which then significantly increases the cost of loading, transport, post fragmentation and crushing.

![Figure 6](image-url)

**Figure 6.** Distribution of individual classes and prices for fraction participation to 40 cm of 60%.

![Figure 7](image-url)

**Figure 7.** Distribution of individual classes and prices for fraction participation to 40 cm of 80%.
4. Conclusion

In this research, the size distribution of rock fragmentation for the quarry "Vrsi" was predicted by Kuz–Ram model. It was ascertained that the Kuz–Ram model is simple in terms of the ease of garnering input data, and in its direct linkage between blast design and rock breaking result. The most important function of Kuz–Ram is to guide the blasting engineer in thinking through the effect of various parameters when attempting to improve blasting effects [6].

Discontinuity characteristics of the blast surfaces are considered using the WipJoint software. Fragmentation degrees occurring as a result of blasting in performed blasting test were determined by using Wipfrag image processing method and Kuz-Ram estimation model. These obtained values were used for the "SB" program to determine the calibrated rock factor value, which can be successfully used for blasting fragmentation prediction by adjusting the blast hole pattern. It can be concluded that "SB" program provides a simple and easy to use tool to obtain a measure of the size distribution of fragments that can be identified in photographic images.

In simulations conducted with "SB" program, the fragment size distribution is commonly determined by changing the drilling geometry. The dimensions in the blast hole geometry offer the best possibility for the control of the particle size distribution.

The cost analyzes performed by "SB" program have shown that blasting is the cheapest rock crushing method. In some cases, to optimize the process, the dimensions in the blast hole layout have to be decreased. The effect of this may be an increase in the specific consumption of explosive. 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. It may also be concluded that a real fragmentation after blasting is the one which most favorably influences the profitability of the whole raw mineral exploitation process.

It was found that the uncontrollable parameters such as joints and fractures have significant influence on rock factor value. For future work, the calibration of rock factor value should be carried out first and foremost by collecting detailed data on the rock for different lithology within the quarry. Except for UCS value, elastic modulus and rock density, the analysis should include other parameters that describe the rock mass, like the Geologic Strength Index (GSI). This value well describes the rock mass properties and experienced researchers can easily determine it. In line with this thinking, it is necessary to amend and improve the "SB" program.

References
[1] S. P. Singh, R. Narendrula, D. Duffy, “Influence of blasted muck on the productivity of the loading equipment”, Proceedings of the 3rd EFEE Conference on Explosives and Blasting, pp. 347-353, 2005.
[2] V. M. Kuznetsov, “The Mean Diameter of the Fragments Formed by Blasting Rock”, Soviet Mining Science, vol. 9 (2), pp. 144-148, 1973.
[3] P. Rosin, E. Rammler, “The laws governing the fineness of powdered coal”, J. Inst. Fuel, vol. 7, pp. 29-36, 1933.
[4] C. V. B. Cunningham, “The Kuz-Ram Model for the Prediction of Fragmentation from Blasting”, Proceedings of the International Symposium on Rock Fragmentation and Blasting, Lulea, August 22–26, pp. 439-454, 1983.
[5] C. V. B. Cunningham, “Fragmentation Estimations and the Kuz-Ram Model – Four Years on”, Proceedings of the Second International Symposium on Rock Fragmentation by Blasting, Keystone, August 23–26, pp. 475-487, 1987.
[6] C. V. B. Cunningham, “The Kuz-Ram Model-20 years on”, Brighton Conference Proceedings, pp. 201-210, 2005.
[7] S. Strelec, M. Gazdek, J. Mesec, “Blasting design for obtaining desired fragmentation”, Technical Gazette, vol. 18 (1), pp. 79-86, 2011.
[8] WipWare Inc. Photoanalysis System, “WipFrag and WipJoint Calibration Manual”, 2003.
[9] A. Tosun, G. Konak, T. Toprak, D. Karakus, A. H. Onur, “Development of the Kuz-Ram model
to blasting in a limestone quarry”, Archives of Mining Sciences, vol. 59 (2), pp. 477-488, 2014.

[10] P. K. Singh, M. P. Roy, R. K. Paswan, Md. Sarim, S. Kumar, R. Ranjan Jha, “Rock fragmentation control in opencast blasting”, Journal of Rock Mechanics and Geotechnical Engineering, vol. 8, pp. 225-237, 2016.

[11] H. C. Sang, N. Masaaki, Y. Masaaki, K. Katsuhiko, “Fragment Size Distribution in Blasting”, Materials Transactions, Vol. 44 (5), pp. 951-956, 2003.

[12] F. C. Bond, B. B. Whitney, “The Work Index in Blasting”, Quarterly Colorado School of Mines, vol. 54, pp. 77-82, 1959.