Comparison Analysis of Muck Pile Fragmentation Obtained Through the Photogrammetry Method and Based on the Kuz-Ram Empirical Model

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Abstract

This paper presents an evaluation of muck pile fragmentation based on the Kuz-Ram empirical model. Furthermore, a comparison of the cumulative size distribution curves obtained from the photogrammetry analysis and based on the Kuz-Ram model was made. Size distribution was performed based on the Kuz-Ram model and further validated in the O-Pitblast software. It was established that the algorithm applied in O-Pitblast software was not modified. The difference between empirical results and in-situ analysis could be explained by, inter alia, the subjective assumption of the RMD index value.

Keywords: blasting works, muck pile fragmentation, Split Desktop 2.0, Kuz-Ram, O-Pitblast

Introduction

Muck pile fragmentation by blasting is the subject of numerous studies. This is due to the impact of defragmentation on the costs of drilling works, the process of loading and hauling of the rock material and the selection of equipment for processing (Mackenzie 1966), (Bozic 1998), (Morin and Ficarazzo 2006), (Sanchidrian et al. 2007), (Bahrami and Monjezi 2011), (Faramarzi et al. 2013). In addition, Morin and Ficarazzo (2006) stated that in the case of opencast mining, mechanical processing of the rock mass is more costly than similar works performed with explosives. As reported by Cunningham (2005), determining the optimum fragmentation not only streamlines the extraction process but also leads to minimising losses resulting, inter alia, from the possibility of limiting the percentage of the finest fraction (below 4 mm).

Muck pile fragmentation is determined through the use empirical modelling (to better estimate the fraction with a low grain diameter) and mechanical modelling (applying the basics of detonation physics and passing the energy generated through the explosive transformation through the rock mass on the basis of the well-established strength parameters of the rocky matrix) (Cunningham 2005). As stated by Jahani and Taji (2015), the major empirical models include: the Dnis and Gam (1970), Larson, Kuznetsov (1973), SveDeFo (1974), Kuz-Ram (1983), modifications of the Kuz-Ram model (1987), Kou and Rustan (1993), CZM, TCM (1999), CK (2003), KCO (2005) and Gheibi et al. model (2009).

However, it should be noted that the attempts at estimating muck pile fragmentation are carried out mainly on the basis of the Kuz-Ram model or the modified Kuz-Ram model (Badroddin et al. 2012), (Ghaeini et al. 2017), (Mohammadi and Barati 2018). The theoretical basis of the Kuz-Ram model was discussed in detail in studies by Cunningham (1983 and 1987). Morin and Ficarazzo (2006) applied the Monte Carlo analysis on the basis of the Kuz-Ram model in order to estimate output, and Mohammadi and Barati (2018) modified the Kuz-Ram model to use it in the blasting works carried out during tunnelling.

It should be noted that the development of IT systems has made it possible to apply state-of-the-art statistical modelling (Bahrami et. al. 2011), (Shams et al. 2015). Monjezi et al. (2010) used muck pile fragmentation modelling on the basis of artificial neural networks for the Sarcheshmeh copper mine. Using the CAM (Cosine Amplitude Method) sensitivity analysis they concluded that the time delay, the number of series in the blasting pattern, charge weight per delay, the powder factor and the ratio between the burden and the spacing have the greatest impact on the degree of fragmentation. Research carried out by Monjezi et al. (2010) was continued by Shams et al. (2015), who in their fragmentation modelling made use of the FIS (Fuzzy Inference System) and the MRA (Multiple Regression Analysis). On the basis of the obtained coefficients of determination, RMSE and VAF and data from the Sarcheshmeh copper mine they concluded that the FIS model provides a better compliance of the modelled fragmentation with the data from in-situ measurement. Bahrami et. al. (2011) applied a four-level neural network in their modelling. Through the sensitivity analysis they determined the main parameters, partially consistent with the results (Monjezi et al. 2010). Hasanipanah et al. (2018) and Mojtahedi et al. (2018) suggested the use of the hybrid method employing respectively the ANFIS (Adaptive Neuro-Fuzzy Inference System) in combination with the PSO (Particle Swarm Optimization) algorithm and the ANFIS with the FA (Firefly Algorithm), while Enayatollahi et al. (2014) compared the potentials of the results obtained through neural networks with various regression models.

The assessment of fragmentation, i.e. the possibility of verifying the modelled results, can be made for in-situ measurements with the use of, inter alia, the indirect method based on the photogrammetric analysis. The very use of the photogrammetric method in underground and opencast mines was discussed by Biessikirski et al. (2016a), Biessikirski et al. (2016b), Biessikirski et al. (2017) and Mustafin et al. (2017).

The objective of the article is to present the Kuz-Ram model and to verify it by comparing it with the results obtained on the basis of the photogrammetric method.

The theoretical basis of empirical models

The possibility of estimating muck pile fragmentation can be established on the basis of empirical correlations. The general form of the equation for the average grain size (D_{50}) is presented in equation 1.

$$x_{50} = C \cdot D \cdot E \cdot F \qquad (1)$$

where:
x_{50} – average grain size, cm,
C – statistical constant,
D – coefficient for the strength parameters of the rock mass,
E – coefficient specifying the geometrical parameters of the designed series,
F – coefficient specifying the properties of the explosive.

Ghaeini et al. (2017) state that the empirical correlation, regardless of the model, consists of two parts: first determining the average grain size (D50) or (D80) and second responsible for the statistical distribution.

One of the first broadly applied models among the developed solutions was Larsson's model – equation 2 (Jimeno et al. 1995), (Bakhtavar et al. 2015).

$$x_{50} = s' \cdot e^{\left(0,58 \cdot \ln B - 0,145 \cdot \ln\left(\frac{a}{z}\right) - 1,18 \cdot \ln\left(\frac{q}{c}\right)^{-0,82}\right)} \qquad (2)$$

where:
s' – blastability index (coefficient specifying the impact of the rock mass structure on the result of blasting works) (Chatziangelou and Christaras 2013),
Z – burden, m,
a – spacing, m,
q – powder factor, kg/m^3 ,
c – constant arising from the rock mass properties.

In the SveDeFo model (equation 3) rock mass properties and geometrical parameters of blast holes (inter alia, the length of the blast hole)

$$x_{50} = s' \cdot \left(1 + 4,67 \cdot \left(\frac{T}{L}\right)^{2,5}\right) \cdot e^{\left(0,29 \cdot \ln Z^2 \cdot \sqrt{\frac{a}{1,25}} - 1,18 \cdot \ln\left(\frac{q}{c}\right)^{-0,82}\right)} \qquad (3)$$

where:
T – stemming length, m.
L – length of the borehole, m,
a – spacing, m,
q – powder factor, kg/m^3 ,
c – constant arising from the rock mass properties,
Z – burden, m.

Kou and Rustan (1993) used in-situ measurements to develop correlation 4, on the basis of which it is possible to estimate muck pile fragmentation for a specific type of material with an accuracy of up to ±0.15% (Bakhtavar et al. 2015). However, as Monjezi (2009) stated, models developed for data obtained from in-situ measurements in specific mining and geological conditions have local applications, as results obtained for other mines are subject to statistical error.

$$x_{50} = 0,01 \frac{({}_r \cdot C_p)^{0,6} \cdot \left(\frac{S}{B}\right)^{0,5} \cdot B^{0,2}}{\left(\frac{L}{H}\right)^{0,7} \cdot D^{0,4} \cdot q_t} \qquad (4)$$

where:
γ_r – specific density of the rock, kg/m^3 ,
C_p – longitudinal wave propagation velocity (P), m/s,
D – explosive material's detonation velocity, m/s,
L – total length of the explosive charge in the blast hole, m
q_t – powder factor including charge weight in the subdrill, kg/m^3 .

The Kuz-Ram model

One of the models most frequently used for estimating muck pile fragmentation is the Kuz-Ram model developed by Cunningham (Shams et al. 2015), (Adebola et al. 2016). The Kuz-Ram model was conceived from three equations: the Kuznetsov (equation 5), Rosin-Rammler (equation 6), and uniformity equation (equation 7) (Cunningham 2005). The Kuznetsov equation was revised by Cunningham with the so-called blastability index. The use of the Rosin-Rammler equation enabled the statistical distribution of grain size.

$$x_m = A \cdot q^{-0,8} \cdot Q^{1/6} \cdot \left(\frac{115}{RWS}\right)^{19/20} \qquad (5)$$

where:
A – rock factor (depending on the hardness and structure, from 0.8 to 22), derived from equation 8,
q – powder factor, kg/m^3 ,
Q – total charge weight per hole, kg,
RWS – weight strength relative to ANFO.

$$R_x = \exp \cdot \left(-0,693 \cdot \left(\frac{x}{x_m}\right)^N\right) \qquad (6)$$

where:
x – grain size, mm,
x_m – characteristic grain size, mm,
N – uniformity index (usually within the range between 0.7 and 2.0).

The impact of blasting works parameters on the degree of fragmentation was accounted for in the form of a uniformity index (N), as in equation 7 (Adebola et al. 2016), (Bakhtavar et al. 2015), (Cunningham 2005).

$$N = \left(2,2 - \frac{14 \cdot B}{d}\right) \cdot \sqrt{\left(\frac{1 + \frac{a}{Z}}{2}\right)} \cdot \left(1 - \frac{W}{Z}\right) \cdot \left(\frac{|BCL - CCL|}{L}\right) + 0,1)^{0,1} \cdot \frac{L}{H} \qquad (7)$$

where:
Z – burden, m,
a – spacing, m,
d – hole diameter, mm,
W – standard deviation of drilling precision, m,
L – charge length,
BCL – bottom charge length, m,
CCL – column charge length, m,
H – bench height, m.

Tab. 1. Joint Condition Factor (Cunningham 2005)
Tab. 1.Wartość wskaźnika spękań JCF (Cunningham 2005)

Parameter	Coefficient value
Tight joints	1
Relaxed joints	1.5
Gouge-filled joints	2

Tab. 2. Joint Plane Spacing (Cunningham 2005)
Tab. 2. Wartość wskaźnika JPS (Cunningham 2005)

Distance between cracks (JF)	Coefficient value
JF <0,1	10
JF =0.1÷0.3	20
JF =0.3÷0.95·P	80
JF > P	80

Tab. 3. Joint Plane Angle (Zou 2017)
Tab. 3. Wartość wskaźnika JPA (Zou 2017)

Joint Rock Factor	Coefficient value
Dip out of face	40
Strike out of face	30
Dip into face	20

The impact of geology on muck pile fragmentation is defined by the following coefficients: A (equation 8), RMD , RDI (equation 9), HF (equation 10).

$$A = 0,06 \cdot (RMD + RDI + HF) \tag{8}$$

where:
RMD is Rock Mass Description, indicating the geological structure of the rock mass
RDI is Rock Density Influence, as in equation 9,
HF is Hardness Factor, see equation 10.

The influence of the RMD coefficient is assigned on the basis of rock mass fragmentation. A highly fragmented, powdery/ friable rock mass is assigned a score of 10, while a rock mass with few cracks (distance between boreholes lower than the distance between the joints) the RMD coefficient value is 50 (Cunningham, 2005).

The rock mass density coefficient is determined with equation 9, into which the specific density of the rock mass, γ_r in t·m^{-3}, is substituted.

$$RDI = 25 \cdot \gamma_r - 50 \tag{9}$$

The hardness factor (HF) is derived from equation 10 or equation 11 depending on the value of Young's modulus (Y).

$$HF = \frac{Y}{3} \, when \; Y < 50 \tag{10}$$

$$HF = \frac{UCS}{5} \, when \; Y < 50 \tag{11}$$

where:
Y – Young's modulus, GPa,
UCS – Unconfined Compressive Strength, MPa.

In the case of vertical joints at the working level (Cunningham, 2005) the JF (Joint Rock Factor) is recommended, as in equation 12:

$$JF = (JCF \cdot JPS) + JPA \tag{12}$$

where:
JF – Joint Rock Factor,
JCF – Joint Condition Factor – Table 1,
JPS – Joint Plane Spacing, Table 2,
JPA - Joint Plane Angle, Table 3.

The JPS value is determined as a reduced pattern (P), defined according to the equation 13.

$$P = (Z \cdot a)^{0,5} \tag{13}$$

where:
P – reduce pattern index,
Z – burden, m,
a – spacing, m,

As provided by Spathis (2004) and Cunningham (2005), the Kuz-Ram model is one of the most frequently used models for estimating muck pile fragmentation. Only recently, depending on the blasting technology (opencast and underground mines, tunnelling) and on the level of adjustment of changing geological conditions, some coefficients have been modified (Faramarzi et al. 2013), (Mohammadi and Barati 2018).

Cunningham (2005) claimed that in the case of empirical models an increase in energy generated by the detonation of the explosive material impacts on the degree of fragmentation (lower grain size) for the entire pile. As stated by Cunningham (2005), the assumption is accurate, but not necessarily applicable to in situ conditions. Cunningham (2005), Faramarzi et al, (2013), and Mohammadi and Barati (2018) pointed to such factors as the properties of the rock mass (strength parameters and degree of cracking), blasting parameters (the number of

Tab. 4. Blasting parameters and calculated rock mass parameters
Tab. 4. Rzeczywiste parametry robót strzałowych oraz wyznaczone parametry masywu skalnego

Parameter	Value
Number of blast holes, n	6
a	3 m
Z	3 m
H	10 m
d	105 mm
q	0.43 kg/m^3
Max. charge in the borehole, Q_c	41 kg
Max. charge per delay Q_z	24 kg
Subdrill, L_p	1 m
γ_r	2850 kg/dm^3
RMD	50
Y	110 GPa

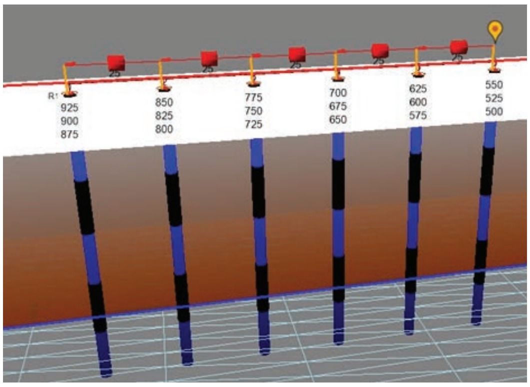

Fig. 1. The blasting series designed in the O-Pitblast software
Rys. 1. Zaprojektowana w programie O-Pitblast seria strzałowa

Tab. 5. Output size distribution based on the Kuz-Ram model and Split Desktop 2.0
Tab. 5. Procentowy udział frakcji na podstawie modelu Kuz-Ram i Split Desktop 2.0

Grain size; mm	**Output size distribution, %**	**Output size distribution, %**
	The Kuz-Ram model	**Split Desktop 2.0**
4.0	0.79	13.78
5.5	1.09	15.47
7.8	1.54	17.28
11.0	2.17	17.24
16.0	3.15	22.09
22.0	4.32	25.18
31.0	6.08	29.14
44.0	8.60	33.98
63.0	12.25	39.44
88.0	17.00	44.60
125.0	23.92	48.70
250.0	46.28	61.98
500.0	86.30	77.24
750.0	95.48	85.39
1000.0	96.38	89.83
2000.0	99.98	95.69
4000.0	100.00	100.00

Fig. 1. The blasting series designed in the O-Pitblast software
Rys. 1. Zaprojektowana w programie O-Pitblast seria strzałowa

Grain size; mm	Output's size distribution, %
	O-Pitblast
0	0.0
93	10.0
142	20.0
185	30.0
226	40.0
269	50.0
315	60.0
368	70.0
433	80.0
475	85.0
530	90.0
615	95.0
2000	100.0

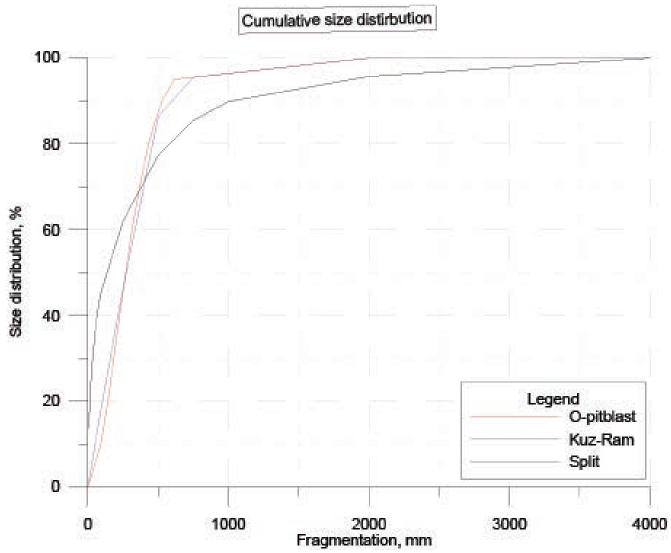

Fig. 2. Cumulative size distribution curves depending on the type of analysis
Rys. 2. Krzywe składu ziarnowego w zależności od rodzaju analizy

series, the number of holes in a series, time delay, precision which depends on the initiation system, stemming type and the ratio between the height of the bench to the length of the stemming and subdrill) as well as the properties of the explosive material (detonation velocity) must be known in order to precisely determine fragmentation.

Measurement methodology

Output size distribution was calculated with the use of the theoretical Kuz-Ram model; see equation 5÷7. The results were verified with the dedicated computer software O-Pitblast and with the photogrammetric analysis. O-Pitblast was used to design a blasting series (Fig. 1) and muck pile fragmentation was estimated with the analytical module. A comparison of the obtained cumulative grain size distribution curve (based on the theoretical model and correlations applied in the O-Pitblast software module) enabled a verification of the algorithm used in the software (checking for possible additional modifications of the formula). Table 4 presents the actual parameters on which the blasting works were based and the rock mass parameters were determined.

The photogrammetric analysis was performed on the basis of data from blasting works carried out in an opencast dolomite mine. The mine is located in the Małopolskie Province. The measurement methodology and the detailed results of the photogrammetric analysis are presented in the studies by Biessikirski et al. (2016a and 2016b). The photogrammetric analysis was performed for the output directly after the blasting works and for a partially extracted output in the Split Desktop 2.0 software. The obtained results were averaged and formulated in Table 5, Table 6, and Fig. 2. Output size distribution was specified on the basis of the Kuz-Ram model and presented in Table 4, Table 5, and Fig. 2.

Results

Based on the comparison of the shape of the cumulative size distribution curves determined with the use of the Kuz-Ram model (Fig. 2, the blue line) and with O-Pitblast (Fig. 2, the red line) it was found to be almost identical. For the Kuz-Ram model, the highest calculated size range was 2000-4000 mm, and for the O-Pitblast software the range was 650-2000 mm, see Table 6. This difference could be due to the inclusion of the charge structure by the software (a three-part charge), which is not the case for the theoretical Kuz-Ram model (a division into an upper and lower charge only). The shape of the curves obtained for the Kuz-Ram model and on derived from the same model in the O-Pitblast software shows that no additional modifications of the algorithm were carried out. A common practice in the algorithm's modification is their application only to specific mining and geological conditions. Comparing the obtained values for the theoretical models with photogrammetric analysis data (Fig. 2, the black line) a substantial difference was recorded, especially for the size ranges 4-125 mm and 750-1000 mm. The difference reached around 28.0%. This could have resulted from the calculated rock mass coefficient, for which RMD is defined on the basis of inspecting the rock mass and experience.

Conclusions

The article discusses the methodology for predicting muck pile fragmentation using the Kuz-Ram model and compares the determined theoretical values (equations 5÷7, the O-Pitblast software) with the data obtained from the performed photogrammetric analyses.

The achieved shape of the cumulative size distribution curve calculated with the theoretical model (the Kuz-Ram equation) and with the analytical module of the computer software shows that the Kuz-Ram algorithm was not subjected to additional modifications. Minor differences result from a better reflection of the charge structure in the software as compared to the Kuz-Ram equation. In addition, as stated by the software's producer, a higher precision can be obtained for modelling the blasting grid on the basis of a scan of the wall. Due to the lack of an actual scan, the model was designed for a perfectly even sidewall, which further facilitated a comparison of the results from the software with those from the Kuz-Ram equation. It could be expected that the impact of sidewall shape and the actual geometric parameters of the blast holes could contribute to a greater similarity between the output size distribution calculated in the software module and the results determined on the basis of photogrammetric analysis. For verification purposes, further analyses could be performed in the future.

Differences in size distributions for theoretical values and those derived from photogrammetric analyses can result not only from not taking into consideration the actual mining conditions but also from the adopted RMD parameter. This parameter is determined subjectively, solely based on experience and site inspection.

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Analiza porównawcza fragmentacji urobku wyznaczonej na podstawie metody fotogrametryczną oraz modelu Kuz-Ram

artykule przedstawiono teoretyczne podstawy wyznaczania przewidywanej fragmentacji urobku oparciu model Kuz-Ram. Dodatkowo, wykonano porównanie krzywych składu ziarnowego uzyskanych na podstawie metody fotogrametrycznej oraz modelu Kuz-Ram. Procentowy udział frakcji dla charakterystycznych wielkości ziarna wyznaczono na podstawie równania Kuz-Ram, zaś dodatkową weryfikację przeprowadzono programie O-Pitblast, przy użyciu modułu analitycznego bazującego na analizowanym modelu fragmentacji. Na podstawie przeprowadzonych badań stwierdzono brak wprowadzenia modyfikacji do algorytmu programu O-Pitblast. Uzyskane różnice procentowego udziału frakcji wyznaczonej na podstawie obliczeń teoretycznych, oraz badań in-situ, można tłumaczyć m.in. subiektywnym przyjęciem współczynnika RMD.

Słowa klucze: roboty strzałowe, fragmentacja urobku, Split Desktop 2.0, Kuz-Ram, O-Pitblast