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Possible ways of optimizing blasting operations using O-Pitblast software
Możliwość optymalizacji parametrów robót strzałowych z zastosowaniem oprogramowania O-Pitblast

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Abstract*: Blasting is one method of mining solid rock masses. The operation parameters, i.e. burden, blast hole and row spacing, stemming length, subdrilling length or explosive charge mass per single delay and total explosive charge mass per series, must be determined. The determined parameters can be optimized taking into account both technical and economic performance, using a dedicated software with an optimization module. The article presents different ways of improving and optimizing blasting operation parameters using O-Pitblast software and the effects of these improvements on planned blasting operations.*

Streszczenie: *Roboty strzałowe są jednym ze sposobów urabiania skał zwięzłych. W celu wykonania takich prac należy zaprojektować ich parametry tj. zabiór, odległość pomiędzy otworami strzałowymi i pomiędzy szeregami otworów, długość otworów strzałowych, długość przybitki, długość przewiertu czy masy ładunków materiałów wybuchowych przypadających na jedno opóźnienie oraz masę ładunku całkowitego odpalanego w serii. Wyznaczone parametry można zoptymalizować pod kątem technicznym i ekonomicznym, przy pomocy dedykowanych programów komputerowych, posiadających moduł optymalizacji. W niniejszym artykule zaprezentowano schemat postępowania w celu poprawy (optymalizacji) parametrów robót strzałowych z wykorzystaniem oprogramowania O-Pitblast, oraz efekty, jakie z tego wynikają dla zaprojektowanych robót strzałowych.*

Keywords: *open-cast mining, blasting operation design, O-Pitblast, optimization*
Słowa kluczowe: górnictwo *odkrywkowe, projektowanie robót strzałowych, O-Pitblast, optymalizacja*

Symbols and abbreviations

B	blast hole inclination angle [°]
C	explosive mass per 1 m of blast hole [kg/m]
c	blastability [kg/m^3]
c_o	corrected blastability [kg/m^3]
d	blast hole diameter [m]
d_{MW}	explosive charge diameter [m]
f	blast hole limiting factor [-]

H	bench height [m]
L	blast hole length [m]
l_k	volume of a 1 m long blast hole [kg/m]
l_p	stemming length [m]
l_{MW}	explosive length in the blast hole [m]
m	relative blast hole spacing [m]
Q_z	explosive charge mass per single delay [kg]
Q_c	total explosive charge mass per series [kg]
q	powder factor [kg/m^3]
RQD	rock quality designation (degree of fracture in a rock mass)
s_{MW}	explosive specific gravity [N/m^3]
Z_d	bottom burden [m]
Z_g	top burden [m]
Z_m	maximum burden [m]
Z_o	calculated burden [m]
Z_p	practical burden [m]
α	free face inclination angle [°]
ρ_{MW}	explosive density [kg/m^3]
ρ_s	rock mass density [kg/m^3]

1. Introduction

Open-cast mining is the most cost-effective and efficient method of solid rock mining, however, it is a high-risk operation due to the use of explosive charges in the rock mass [1]. To protect the mine's infrastructure, machines and immediate vicinity from the effects of detonation in the blast hole, the blasting operation parameters must be designed correctly with those factors not directly related with the parameters of the mined deposit, *e.g.* protected areas, being considered. The defined parameters of blasting operations include the following:
– design burden,
– blast hole spacing,
– blast hole row spacing,
– stemming length,
– subdrilling length,
– powder factor,
– blast hole length,
– inclination angle and diameter.

Correctly selected values allow the detonation energy to be used effectively to mine the deposit while limiting side effects, *e.g.* para-seismic shocks, airborne shock wave, rock fragment scatter, undercutting or non-uniform size distribution of the run-of-mine. The results of blasting operations, apart from the geological and mining conditions, can be affected by [2-6]:
– explosive type,
– charge shape and structure,
– stemming,
– initiation point, and
– blast delay.

The problems related with the design and optimization of blasting operations have been discussed in many research studies. Studies [2, 7-11] include empirical formulas and guidelines for designing blasting operations under different mining conditions. The results of these studies are used both in Poland [2, 7] and worldwide [8-11] in the preliminary design of blasting operations for specific local geological conditions and in preparing blasting documentation for use in mining, construction and engineering.

The process of blasting operation optimization is usually focused on minimizing the costs of the operations [5, 6, 12-15]. However, lowering unit cost does not always translate into reduced production costs of the end product, *e.g.* grit. The second group of optimization processes involves observation of the entire production process of a given product, and based on these observations, selecting the blasting operation parameters. In this case, it involves optimizing the run-of-mine size distribution curve [12, 13, 16]. The unit cost of blasting operations may be higher but will contribute to a lower cost of the end product.

The third group of optimization processes is related to the effects of blasting operations. In this case, the costs are the least important factor, the main goal is the carrying out of blasting operations in a safe manner and transferring the costs of obtaining a given end product to the later production stages. To optimize the process, advanced predictive tools are used, including Artificial Neural Networks (ANN), Support Vector Machines (SVM) or Genetic Algorithm (GA) [17-21].

It shoold be noted that optimization of one factor may affect other factors, *e.g.* reducing the blasting operation costs may increase its effects on the surrounding area. Specialist companies providing blasting services usually use optimization software, although commercial software is available for purchase by individual mining companies. Obtaining correct data requires knowledge of the relationships between the blasting operation parameters and the optimization algorithms in the software. To illustrate the scale of the problem, this article presents different empirical relationships in determining one of the parameters of blasting operations, namely, the burden. The article also presents *O-Pitblast* software, and based on actual data from one of the mines (free face scan and actual blast hole array) a module to optimize blasting operations, reduce costs and obtain a specified distribution size in the run-of-mine.

2. Empirical determination of the burden

To determine the geometric parameters of blasting operations, different formulas presented in other studies [2, 7-11] can be used. The burden, in accordance with the definition in literature [9] is the *„smallest distance from the centre of the explosive charge to the nearest free face of the blasted rock mass"*. The burden can be classified as the:

– top burden,
– bottom burden,
– design burden, or
– spatial burden.

A correctly designed burden guarantees the highest efficiency of rock mass mining. An insufficient burden may cause excessive run-of-mine diminution and in the worst case, a large scattering of rock fragments. A large distance between the blast hole axis and the nearest free face may result in high resistance, intensive shocks, may affect output, cause further fractures and in the worst case, yield no output. To reduce undesirable blasting effects, the burden must be determined precisely throughout the entire length of the blast hole, paying particular attention to the top and bottom part of the blast hole and in places with overhangs or voids in the outcrop. The bottom part of a blast hole shows higher mining resistance than the top part, and an incorrect burden may result in undercutting and excessing para-seismic shocks [2, 7, 22].

In [2], Korzeniowski and Onderka included the most common formulas, supported by experimental research, used to calculate burden size. If the free face and the hole are vertical, the relationship can be expressed as:

$$Z_o = \sqrt{\frac{l_k \cdot (L - l_p)}{q \cdot m \cdot H}} \quad (1)$$

If the face is inclined and the blast hole is vertical, the authors [2] introduced a correction (Equation 2) for the bottom burden:

$$Z_d = Z_o + H \cdot \mathrm{ctg}\alpha \quad (2)$$

If the blast hole and the free face are inclined and parallel, they recommend Equation 3 to determine the burden and Equation 4 to determine the design burden allowing for a constant of proportionality (k) of 31 to 44, for ρ_{MW} = 900 kg/m^3 and q = 0.3-0.6 kg/m^3.

$$Z_d = Z_g = \frac{Z_o}{\sin\alpha} \tag{3}$$

$$Z_o = k \cdot d \cdot 1000 \tag{4}$$

If the free face and the blast hole are inclined, the burden can be defined using Equation 5 [2]:

$$Z_d = Z_g + H(\mathrm{ctg}\alpha - \mathrm{ctg}\beta) \tag{5}$$

Study [23] shows the relationship between the burden and volume of the blast hole and the amount of explosive required to mine 1 m^3 of rock mass:

$$Z_o = \sqrt{\frac{0.785 \cdot d^2 \cdot \rho_{MW} \cdot l_{\mathrm{MW}}}{m \cdot H \cdot q}} \tag{6}$$

The calculated burden ensures that reliable blasting results are guaranteed by the explosive charge filling the blast hole.
If the explosive factor is not known, the burden can be calculated using the following relationship [2]:

$$Z_o = 53 \cdot k_t \cdot d \cdot \sqrt{\frac{\rho_{MW}}{\rho_s}} \tag{7}$$

Constant k_t depends on the type of rock mass subjected to blasting operations (Table 1).

Table 1. Constant k_t depends on the type of rock mass [2]

Rock mass type	**Constant k_t**
Monolithic and large solid rocks with the divisibility higher than the distance between charges	0.90
Rocks divided with fissures into blocks, narrow, cemented fissures	0.95
Fissured rocks, voids in fissures filled with softer rocks and rubble	1.00
Heavily fissured rocks, small blocks, free fissures in any direction	1.05
Heavily fissured rocks, weakened zones in the bottom section of the bench	1.10

Foreign literature also includes many relationships used to determine the burden. In the 20th century, over 50 years, many equations were proposed to define this parameter, using different factors. The researchers based their studies both on laboratory and *in-situ* test results. Gustafsson [8] presented the relationship (Equation 8) between burden and blast hole diameter in accordance with Langefor's methodology:

$$Z_o = 45 \cdot d \tag{8}$$

In-situ research showed that a 45-fold increase of the burden should not be exceeded, except for blasting operations in weakened rock mass and when loosening rock mass [2]. The Swedish researcher also included a relationship (9) defining the practical burden, allowing for deviation of the blast hole.

$$Z_p = 45 \cdot d - (0.05 + 0.03 \cdot H) \tag{9}$$

In 1978, Langefors and Kihlström determined the Equation 10, which defines the maximum burden necessary to obtain the required fragmentation of the run-of-mine. It includes the key factors affecting burden size, *i.e.* properties of the explosive used, geometric blast parameters and blastability (c) – a factor characterizing the mass of explosive required to mine 1 m^3 of the rock mass. The authors emphasize that the equation applies to holes with diameters of 0.003 to 0.089 m. For diameters above 0.089 m, the maximum burden will deviate from the actual value, since no hole deviation is considered [24, 25].

$$Z_m = 0.958 \cdot \mathrm{d} \cdot \sqrt{\frac{\rho_{MW} \cdot s_{MW}}{c_o \cdot f \cdot \left(\frac{a}{Zo}\right)}} \qquad (10)$$

In 1995, Pal Roy [25] presented a comprehensive equation for the burden. It allows for a detailed qualitative description of the rock mass quality (RQD), details of the explosive charge structure, energetic medium properties, *e.g.* loading concentration in the hole or powder factor and the geometric free face properties. Equation 11 is as follows:

$$Z_o = \mathrm{L} \cdot \frac{d_{MW}}{d} \cdot \frac{5.93}{RQD} + 0.37 \cdot \left[\frac{C}{q}\right]^{0.5} \qquad (11)$$

The presented equations are not the only ones available in literature which define the burden size. They show that the key factors affecting burden size are the properties and structure of the rock mass, the properties of the explosive and the structure of the charge in the blast hole. The geometrical parameters, including:

- bench height,
- face inclination angle,
- blast hole diameter, and
- stemming length,

affect the final distance from the blast hole axis to the free front. Considering the number of factors, burden is one of the most important parameters in designing blasting operations. This does not mean that other parameters can be underestimated and that their correct calculation and determination can be omitted from blasting operations. In practice, the burden is never constant and always differs between blast holes, and even within a single blast hole at different depths. It is determined individually for every blast hole based on the free face scan and blast hole probing [26].

Choosing the correct empirical formulas to determine the parameters of blasting is a complex process, dependent on many different factors. These range from, the mining system used, working geometry, limitations in explosive charge use or the effects of blasting operations on the surrounding area, to the properties of the mined rock mass, nature of deposition and the hydrogeological conditions in the deposit, through to the characteristics of the explosives and detonators used.

The situation is similar for the empirical determination of other geometric parameters of blasting operations – several different formulas are available in national and international literature. When using a specific relationship to determine a specific parameter, *e.g.* burden, the widest range of factors affecting its value must be allowed for in order to reduce the risk of error. In this way, each designed parameter will correlate well with the *in-situ* mining and geological conditions, reducing the risk of undesirable effects of blasting.

3. Design and optimization of blasting operations using O-Pitblast software

O-Pitblast software is a comprehensive tool for designing blasting operations and predicting the outcome, using the actual topographic models of the working. Based on actual data, including slope profile and parameters, the free front view available at the design stage is similar to the actual conditions (Fig. 1).

O-Pitblast calculates the parameters based on input data for the rock mass, type and parameters of the explosives and other equipment used in the design (base charges, in-hole detonators, surface connectors). The software enables the total costs of the modelled blasting operations to be estimated by entering the unit price of explosives, detonators or blast hole drilling.

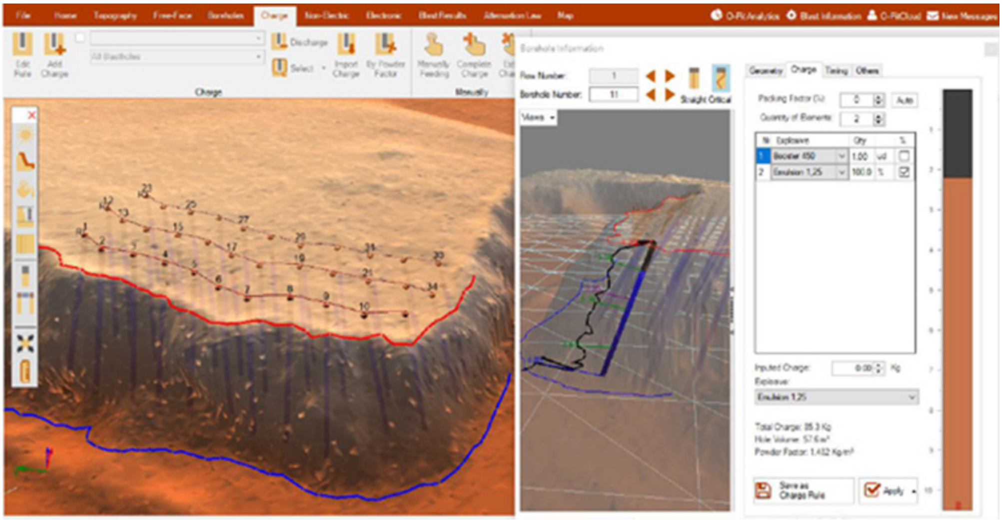


Figure 1. Example dialog box in O-Pitblast software

The presented optimization process is based on 2 blasting series; the data were obtained from a single limestone mine. The optimization process included the price of blasting equipment based on the information available on the manufacturer's website [27], converted to PLN. In addition to the costs of blasting operations, the cost of drilling a 1 m long blast hole was used (20 PLN for a 95 mm diameter hole). Blasting operation and blasting equipment parameters were selected, based on guidelines in blasting documentation developed and used in the mine (Table 2).

Table 2. Parameters of the designed series

Designed parameter	Unit	Series No. 1	Series No. 2
Bench height	[m]	19-20.5	11-15.5
Hole diameter	[m]	0.095	0.095
Design burden	[m]	3.8	3.55
Top burden	[m]	4.0	3.75
Blast hole spacing	[m]	4.2	3.9
Row spacing	[m]	4.0	3.55
Subdrilling length	[m]	1.2	1.2
Stemming length	[m]	3.8	3.55
No. of blast holes	[pcs.]	30	28
No. of rows	[pcs.]	2	2
Maximum explosive charge Q_z	[kg]	161.7	117.0
Maximum explosive charge Q_c	[kg]	4589.5	2618.7
Permissible explosive charge Q_z	[kg]	193.0	120.0
Permissible explosive charge Q_c	[kg]	5492.0	3406.0

Figure 2 shows an example of size distribution of the design burden (Series no. 2). Green shows the burden closest to the design burden (within a given tolerance, *e.g.* 20%), blue shows the burden above the tolerance, and red shows where the burden is below the tolerance, creating potential for high scatter.

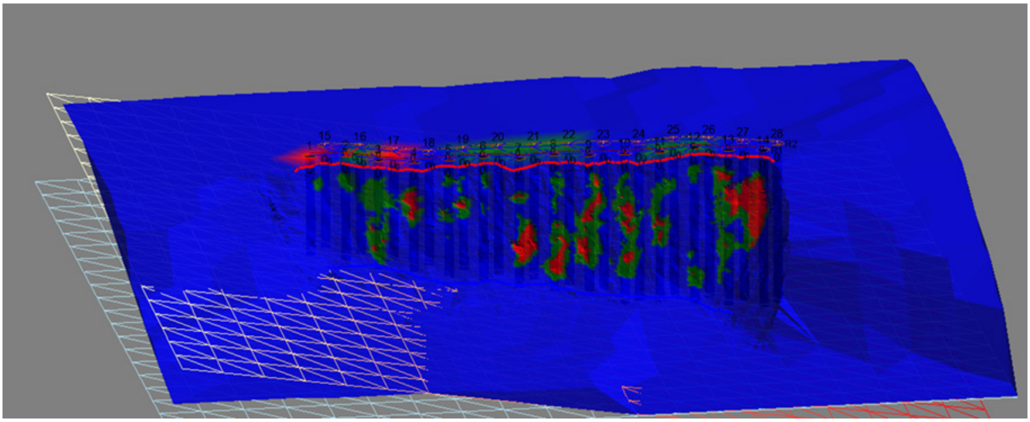


Figure 2. The burden size distribution for Series No. 2

The burden size distribution provides data of a proposed blast hole pattern in accordance with blasting documentation guidelines. It clearly shows that the blast hole pattern allowing only for the distance from the free face edge (standard *in-situ* procedure), will affect burden size distribution (numerous fragments marked red). Table 3 show the summary of lasting operations for both series after allowing for the data entered into the software.

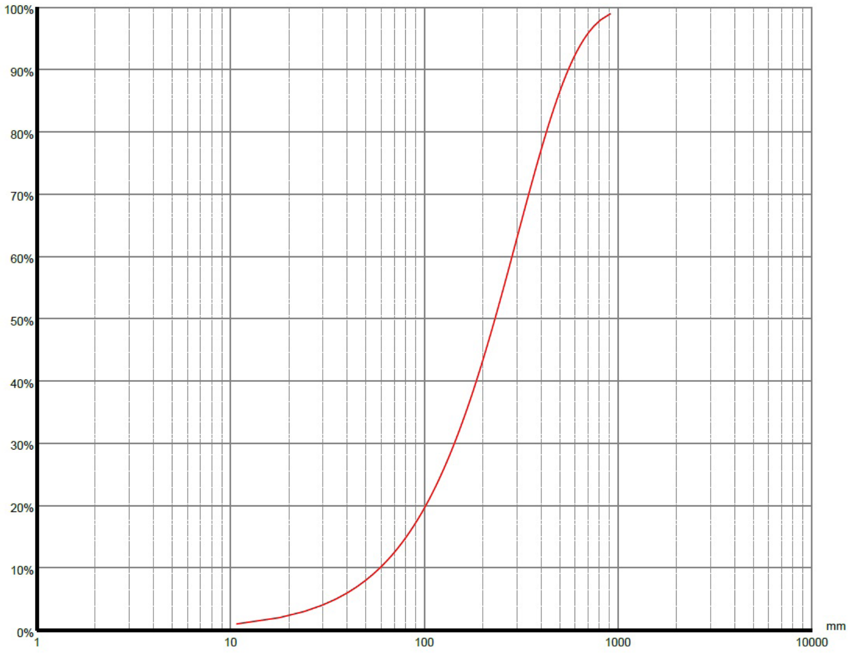
Table. 3. Parameters for both series before optimization

Parameter	Unit	After optimization	
		Series No. 1	Series No. 2
Bench high	[m]	20.18	12.24
Total of holes	[pcs.]	30	28
Drilled	[m]	677.03	420.65
Design burden	[m]	3.80	3.55
Average stemming	[m]	3.80	3.55
Volume*	[m³]	10,725	5,459
Mass of rock	[Mg]	29,815.7	15,174.7
Specific drilling	[m/m³]	0.063	0.077
Design spacing	[m]	4.20	3.90
Total stemming volume	[m³]	0.81	0.70
Powder factor	[kg/m³]	0.428	0.480
	[kg/Mg]	0.154	0.173
Rock density	[g/cm³]	2,780	2,780
Design volume	[m³]	10,231	5,359
Average stemming volume	[m³]	0.027	0.025

* – volume based on the hole's length

Determining the effects of blasting operations, analysis of costs and size distribution, tamping of explosives and instrumenting with auxiliary equipment in accordance with the blasting documentation, can be simulated. Figure 3 shows the predicted size distribution for this type of blasting operation. The software predicts size distribution based on the Kuz-Ram model [28, 29]. Both graphs shows similar size distribution for each grain size distribution range. The content of the fine fraction is higher for Series No. 2. The data, presented in Table 4, can be used to summarize the costs of drilling and blasting operations for both series.

Series No. 1



Series No. 2

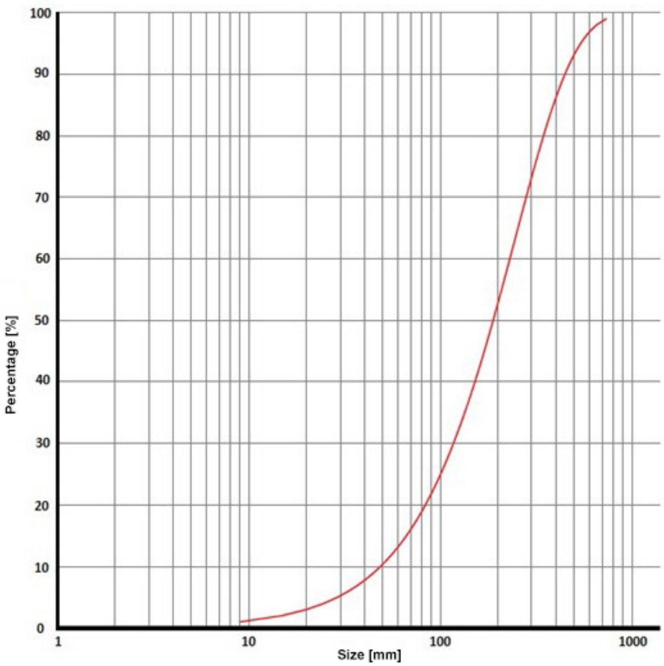


Figure 3. Predicted run-of-mine size distribution curve before optimization

Table 4. Simulation costs before optimization

Cost	Value – Series No. 1 [PLN]	Value – Series No. 2 [PLN]
Explosive material	29,074.10	16,742.96
Initiating means	1,887.93	1,598.00
Blast hole drilling	9,048.52	5,622.05
Total for the drilling-blasting operations	40,010.52	23,963.03
Converted to per tonne of run-of-mine	1.35	1.57

O-Pitblast software includes an optimization module for improving blasting operation parameters in order to ensure cost efficiency that changes the geometric parameters of blasting operations and the predicted rock mass size distribution. The optimization is based on the conjugate gradient method which, in this case, is used to solve the optimization process, without constraints [30]. This improvement aims to reduce the unit cost of blasting operations. To create a uniform optimization process with predictions based on data from the blasting documentation, the size of oversized blocks was set at 500 mm for both series. The parameters of the blasting changed as a result of the optimization process, see Table 5. Figures 4 and 5 show the dialogue boxes of the optimization software before and after optimization, respectively, and Tables 2-6 show the list of parameters. A red cross indicates that the parameter is not consistent with the assumptions.

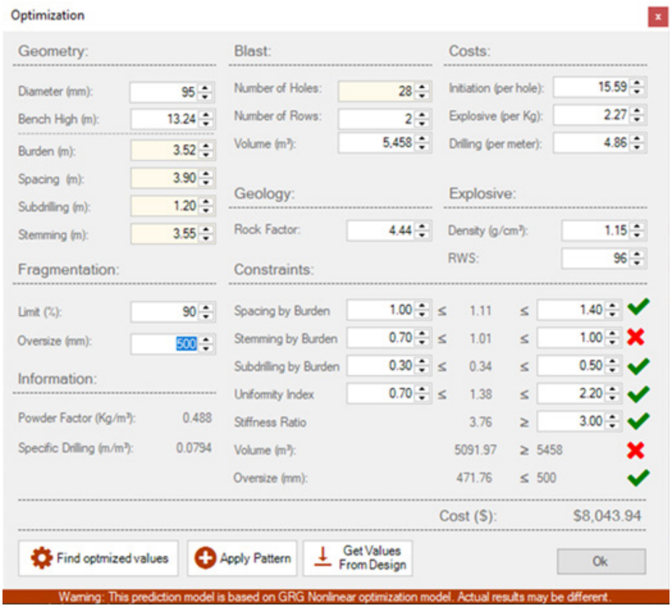


Figure 4. Dialog box with blasting parameters before optimization

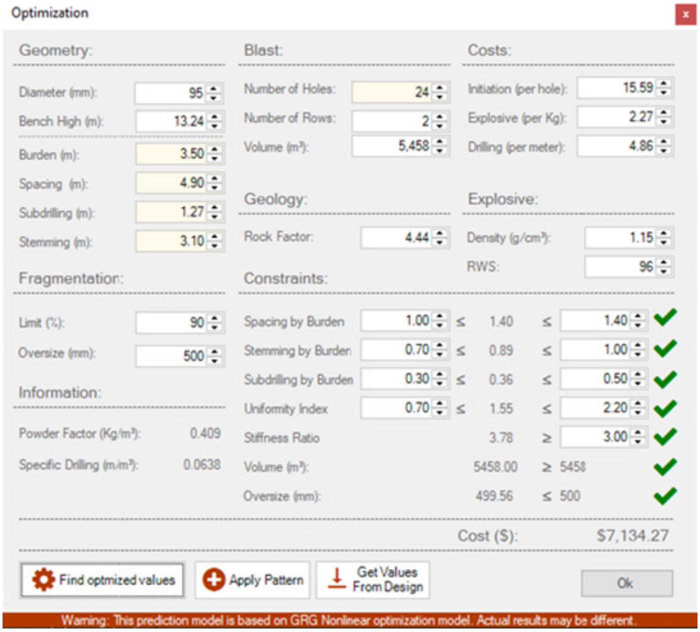


Figure 5. Dialog box with blasting parameters after optimization

Table 5. The parameters of the designed series after optimization

Designed parameter	Unit	Series No. 1	Series No. 2
Bench height	[m]	19-20.5	11-15.5
Hole diameter	[m]	0.095	0.095
Top burden	[m]	3.49	3.50
Blast hole spacing	[m]	4.89	4.50
Row spacing	[m]	3.49	3.50
Subdrilling length	[m]	1.06	1.27
Stemming length	[m]	3.22	3.10
No. of blast holes	[pcs.]	31	24
No. of rows	[pcs.]	2	2
Maximum explosive charge Q_z	[kg]	175.2	119.5
Maximum explosive charge Q_c	[kg]	4797.5	2287.7
Permissible explosive charge Q_z	[kg]	193.0	120.0
Permissible explosive charge Q_c	[kg]	5492.0	3406.0

Figure 6 shows the burden distribution after optimization for Series No. 2. The average burden changed slightly (from the design burden – 3.55 to 3.5 m), which is insignificant under the *in-situ* conditions. A key factor is the change in burden in hole No. 2 area, where it is moved back and its inclination angle is corrected to limit the area below the tolerances. The optimization process did not eliminated those areas. The distance between the blast holes changed from 3.90 to 4.50 m. Average row spacing, similar to the burden, changed slightly from 3.55 to 3.50 m. The changes resulted in a change of length of the explosive charge column in the blast hole by the slight elongation of subdrilling from 1.2 to 1.27 m (insignificant under the *in-situ* conditions) and reducing the stemming length from a design value of 3.55 to 3.10 m. The maximum explosive charge for a single millisecond delay increased from 117.0 to 119.5 kg, and the total explosive charge was reduced from 2618.7 to 2287.7 kg.

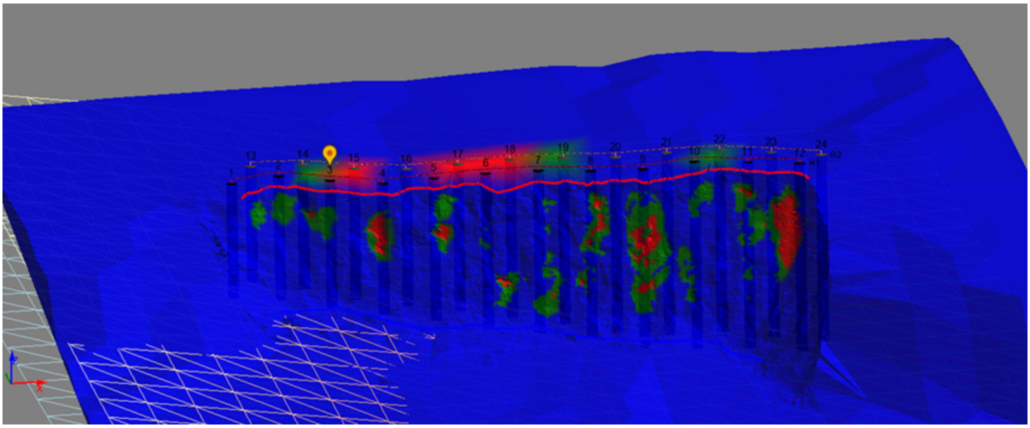


Figure 6. Burden distribution for Series No. 2 after optimization

Table 6 shows a summary of the blasting operations for both series, based on the data in Table 4, *i.e.* after optimization. Comparing the results before optimization (Table 3) with those after (Table 6), Series No. 2 in particular shows an increased run-of-mine after the blasting (from 5,459 to 5,614 m³), with a simultaneous reduction of the powder factor (from 0.49 to 0.41 kg/m³) as a result of increasing the spacing between the blast holes in the row. For Series No. 1, the changes are minor, however, an improvement can be observed.

Table. 6. Parameters for both series after optimization

Parameter	Unit	After optimization	
		Series No. 1	Series No. 2
Bench high	[m]	20.20	13.10
Total of holes	[pcs.]	31	24
Drilled	[m]	688.46	355.09
Design burden	[m]	3.49	3.50
Average stemming	[m]	3.22	3.10
Volume*	[m³]	11 284	5,614
Mass of rock	[Mg]	31,368.3	15,607.4
Specific drilling	[m/m³]	0.061	0.063
Design spacing	[m]	4.89	4.90
Total stemming volume	[m³]	0.71	0.53
Powder factor	[kg/m³]	0.425	0.407
	[kg/Mg]	0.153	0.147
Rock density	[g/cm³]	2,780	2,780
Design volume	[m³]	11,176	5,575
Average stemming volume	[m³]	0.023	0.022

** – volume based on the hole's length*

Figure 7 shows the estimated size distribution after optimization. The grain size d_{90} after optimization of Series No. 1 parameters was reduced from 554 to 487 mm. There is a significant improvement in the run-of-mine comminution. For Series No. 2, the grain size d_{90} was increased from 448 to 476 mm. The run-of-mine after optimization of blasting parameters includes larger size fractions. Both optimization processes resulted in a more uniform distribution of each fraction, and in one case – reduced the larger fraction content, and in the other – reduced the smaller fraction content.

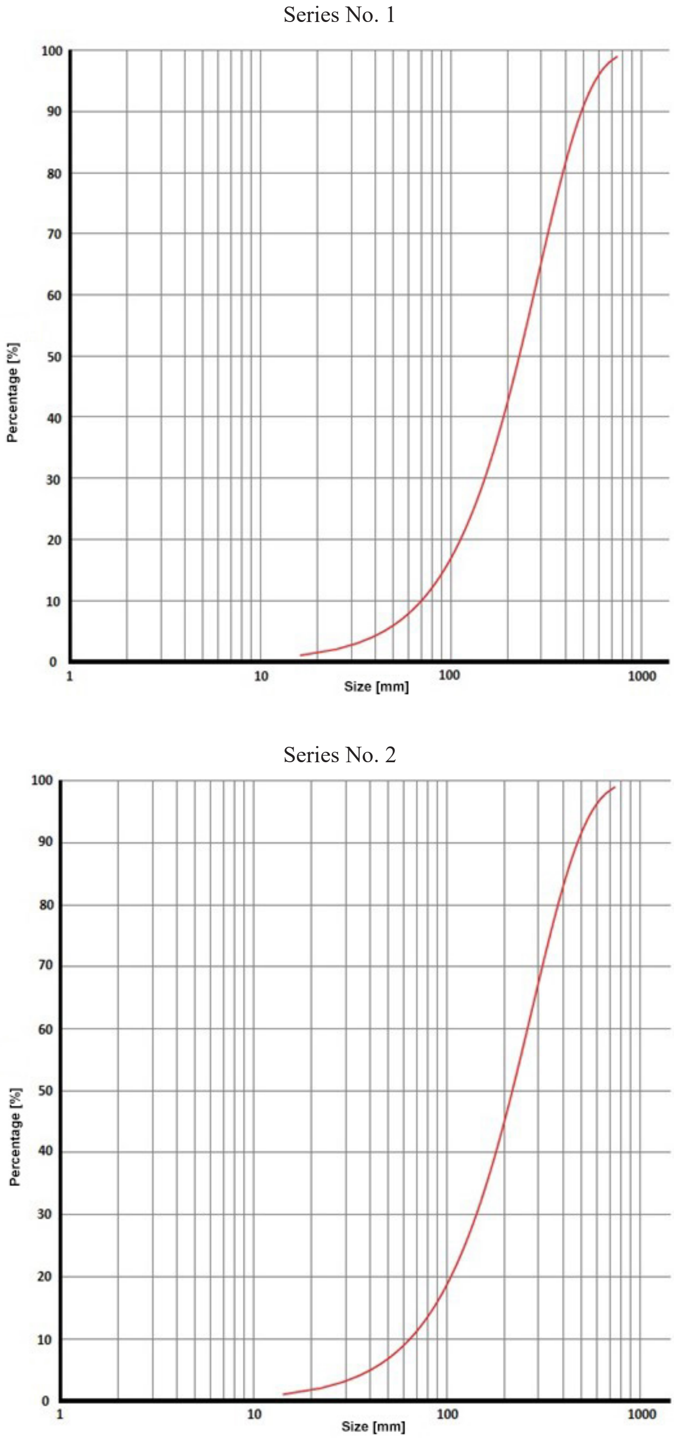


Figure 7. Predicted run-of-mine size distribution after optimization

The final stage of optimization is the verification of the blasting costs. Table 7 shows the results after optimization.

Table 7. Simulation costs after optimization

Cost	Value – Series No. 1 [PLN]	Value – Series No. 2 [PLN]
MW	30,386.70	14,619.94
Initiating means	1,951.84	1,383.75
Blast hole drilling	9,201.28	4,745.81
Total for the drilling-blasting operations	41,539.82	20,749.49
Converted to a tonne of run-of-mine	1.32	1.32

Compared to the costs shown in Table 4, blasting operation costs for Series No. 1 seemingly increase due to the fact that the optimization process added another blast hole. This increased the blasting operation costs, but the final comparison of unit cost shows a slight reduction in the unit cost of the run-of-mine (1 Mg) after optimization (from 1.35 to 1.32 PLN/Mg). For Series No. 2 the predicted blasting costs dropped significantly by reducing the number of blast holes for the same volume of rock mass, reducing the unit cost from 1.57 to 1.32 PLN/Mg.

4. Summary

The design of blasting operations is a complex process, dependent on several key factors, *e.g.* the mining system, geological properties of the deposit and the nature of deposition, hydrogeological conditions of the rock mass, type and properties of the explosives used or the location of protected areas in the locality. A properly designed blast series requires a detailed analysis of *in-situ* conditions. The parameters are determined for specific mining and geological conditions allowing for the widest spectrum of factors which may affect their values. Using the available empirical equations, found both in national and international literature, and the actual geological and mining conditions in a given mine, the best fitting formula can be selected and used to calculate a specific parameter of the blasting operation.

The analysis of the optimization processes of the O-Pitblast software, shows notable benefits in both cases. Both the number of blast holes and their pattern were modified, leading to a change in volume of the mined rock mass. For Series No. 2, the number of blast holes was reduced from 28 to 24, and the volume of the mined rock mass changed by 3% with a simultaneous increase in powder factor of 16%. For Series No. 1, the number of blast holes was reduced by 1 with the run-of-mine volume reduced by 5% and the predicted powder factor reduced by 1%. The analysis of the size distribution shows that both optimization processes resulted in a more uniform distribution of each fraction, and in one case reduced the larger fraction content (Series No. 1) and in the other reduced the smaller fraction content (Series No. 2). All the modifications affected the estimated costs of the blasting. For Series No. 1, even though the optimization increased the costs, the result was satisfactory due to a slight reduction in the estimated unit cost of 2%. For Series No. 2, the estimated unit cost reduction was significant at 16%. In both cases, the estimated unit costs of the blasting operations were reduced.

Blasting is a high risk operation, and geological conditions are not constant within the deposit. The designed parameters will not be ideal and suitable for the entire heading. A blasting engineer planning a blasting must demonstrate experience to avoid undesirable effects and hazard to the surrounding area. No software should replace the experience of designers and blasting engineers – it should only aid the design process.

The simulation process, for obvious reasons, has not been verified under *in-situ* conditions, since it is not possible to carry out 2 blasting operations under the exact same mining and geological conditions. However, the process shows that the blast hole pattern parameters (burden, blast hole and row spacing) and the blast hole parameters (explosive charge column length, stemming length, inclination angle, azimuth), may affect the results of the blasting operation.

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