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Research Paper

Optimization of Blast Parameters based on Geo-mechanical Properties of Rock to Prevent Creation of Toes and Boulders in Mine Benches

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Abstract: Toe and boulder due to blasts in the open pit mines reduce the production efficiency and increase extraction costs. In this study, these phenomena were reduced to correct the blast parameters of the ore blocks in the Sirjan Golgohar-2 Mine. For this purpose, the values of seven effective parameters including, an average of depth holes, burden, sub-drilling, powder factor, spacing, rock quality designation, and blastability index were collected for 19 blasting blocks in the studied mine. In this research, the values of Geo-mechanical properties of rock mass were obtained by the photogrammetric method and discontinuity set extractor software. Subsequently, the experimental models were created to predict the volume of boulder and toe relative to the volume of blasting block by nonlinear multiple regression. The predicted ability related to each of the created models by statistical indicators was investigated, and it was determined that the polynomial model to product boulder and the exponential model for toe are more accurate with 94.43 and 98.13 coefficients of determination respectively. Then, the minimization process of these phenomena was performed to access optimal values of controllable parameters and their coefficients in each of the created two models simultaneously by the combinational algorithm of Particle Swarm Optimization-Genetic algorithm. Finally, to evaluate the predicted ability of two optimized models, four blasts based on the optimized information were performed on the mine. The results showed that the models predicted the volume of boulder and toe relative to the block volume with the Root Mean Square Error 0.47 and 0.08 respectively.

Keywords: Boulder, Toe, Photogrammetry, Discontinuity Set Extractor software, Particle Swarm Optimization-Genetic algorithm.

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INTRODUCTION

Usually, after blasting in open mines, a series of adverse effects such as boulder production and toe remaining are created which reduce the efficiency of excavator, loader, and crushing machines; increase the consumption of explosives, and generally increase drilling and blasting costs. Several parameters and factors are influential on the quality and efficiency of drilling and blasting operations, including boulder production and toe remaining , which can generally be divided into two categories of uncontrollable parameters including the properties of discontinuity and fractures in rock masses; and physical and mechanical properties of rocks; and controllable parameters such as blast hole geometry [1-5]. The aim of this study was to prevent boulder and toe production due to blasting in the Gol-Gohar Iron Ore Mine No. 2. This was done based on two characteristics of rock mass including, Rock Quality Designation (RQD) and Blastability Index of rock (BI), related to 19 blast blocks by modifying the geometry of blast holes including burden (B), spacing (S), powder factor (PF), sub-drilling (SD) and the mean height of hole (MHL). For this purpose, the photogrammetry method and AgiSoft MetaShape 3D software were used to withdraw and analyze the discontinuity status in the blasting blocks. Also, the data of 19 blasting blocks and the ratio of the volume related to the produced Toe and Boulder to the volume of blast blocks were calculated by field measurements, surveying operations of bench floor level and photogrammetry was performed using photos taken from boulders and analyzed in AgiSoft MetaShape software (Table 1). Then, using measured values related to seven influential parameters and two effective parameters for 19 explosive blocks, first, several different nonlinear models with SPSS software were created to predict the ratio of boulder volume and production toe to explosive block volume. Then, based on the statistical indicators of the modeling, the two models were selected and in the first stage, the values of each of the geometric parameters of the blast holes and in the second stage the coefficients related to each of the seven influential parameters were optimized by the combined algorithm of the particle-genetic swarm in the specified numerical intervals. Finally, the prediction accuracy of the optimized models was evaluated by a four-test dataset.

Table 1. Statistical values of the collected parameters related to the 19 blast blocks

Parameter	Powder factor (kg/ton)	Burden (m)	Spacing (m)	Mean height hole (m)	Sub-drilling (m)	PB (%)	PT (%)
Maximum	0.51	4.97	5.72	17.73	1.33	20.92	86.94
Minimum	0.11	2.12	2.96	9.78	-4.82	0.9	0
Average	0.22	2.93	4.04	14.51	-1.62	5.38	22.7
Std.v	0.11	0.59	0.56	2.16	1.47	5.38	22.93

METHOD

In this study, to perform the modeling, first, it was necessary to determine the physical and mechanical properties of the requirement rocks and the characteristics of the discontinuities in the rock mass of explosive blocks harvested in the study mine using laboratory results and photogrammetry method [6-8]. Then the sensitivity of the parameters affected by the changes of each of the seven effective parameters is examined.

Short range photogrammetry and determination of discontinuity properties

To use the photogrammetry method, a number of photos were taken from the surface of the benchwork related to each explosive block. Then, in order to analyze the photos to determine the spacing, continuity and number of lineament or discontinuity sets and to plot polar density diagrams, Rose diagrams and pole Stereonet map of discontinuity planes DSE and Dips V.7 software were used. After determining the discontinuity properties of the rocks in each of the 19 blast blocks harvested using the equations (1-4) and a modified table of blast ability index [9], the values of RQD and BI for each of the mentioned blocks were calculated, respectively (Table 2).

$$RQD = 100 \cdot \exp(-t \cdot \lambda) \cdot (t \cdot \lambda + 1) \tag{1}$$

$$\lambda = \sum \frac{1}{(s_i / \cos(a_i))} \tag{2}$$

$$J_V = \frac{1}{S_1} + \frac{1}{S_2} + \cdots + \frac{1}{S_n} \tag{3}$$

$$RQD = 115 - 3.3 \cdot J_v \tag{4}$$

Table 2. Statistical values of the BI and RQD of the 19 blast blocks

No.	Factor	Minimum	Maximum	Average	Std.v
1	Blastability Index	48.3	79.22	69.76	6.67
2	Rock Quality Designation (Percent)	20.20	87.80	51.98	24.26

Sensitivity analysis of parameters

For sensitivity analysis, the cosine field method (CAM) was used. The results of sensitivity analysis in this study showed that the most effective input parameters on the volume of boulder and toe ratio to the block volume are powder factor (%79) and sub-drilling (%94), respectively.

Multivariate nonlinear regression analysis

In this research, to achieve optimal relationships between two influential variables and seven effective parameters, several nonlinear models such as polynomials with correct coefficients, second-order polynomials, power, exponential, and inverse were created by SPSS software based on 19 data series harvested from the studied mine. After creating the desired models, statistical indicators such as coefficient of determination, root-mean-square deviation, Mean Absolute Percentage Error, and performance index were calculated based on the predicted and measured values of the boulder and toe volume relative to the total volume of each of the 19 explosive blocks harvested. Based on the calculated indices, second-order polynomial and exponential models (Equations 5 and 6) were selected as the most suitable models for predicting boulder and toe volume ratio to block volume, respectively (Table 3).

$$\begin{aligned} PT &= 162.07 - 34.9Exp(0.25B) + 0.71Exp(0.77S) + 4.76Exp(-0.16MHL) + 5.25Exp(-0.61SD) + 1.84Exp(0.03RQD) \\ &- 14.39Exp(0.02BI) - 50.79Exp(0.61PF) \end{aligned} \tag{5}$$

$$\begin{aligned} PB &= -842.78 + (0.12B - 28.03)^2 + (2.31S - 8.14)^2 + (0.49MHL - 7.01)^2 + (-0.56SD - 1.35)^2 + (-0.06RQD + 3.55)^2 \\ &+ (-0.01BI + 8.64)^2 + (12.35PF - 2.2)^2 \end{aligned} \tag{6}$$

Table 3. Evaluation indexes of the created models to calculate the volume of Toe and Boulder ratio to block volume

Model	R^2		RMSE		MAPE		VAF	
	Boulder	Toe	Boulder	Toe	Boulder	Toe	Boulder	Toe
Second- order polynomials	94.43	97.13	1.24	3.78	46.15	94.41	94.42	97.12
Exponential	88.60	98.13	1.85	3.05	59.89	56.96	87.52	98.13

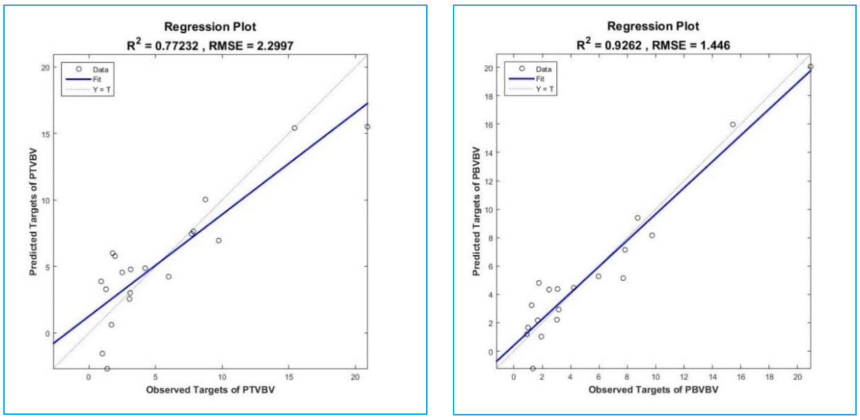
Optimization of influential parameters and related coefficients in selected models

To minimize the volume of toe and boulder produced by explosions compared to the total volume of the explosive block, it was tried to optimize the values of controllable parameters in two selected models at the specified intervals at the same time. Therefore, among the seven factors affecting the second-order polynomial models and exponential values of five explosive factors using genetic-particle swarm hybrid algorithm code in the used intervals related to each parameter in the studied mine were optimized. In the second step of optimization, the coefficients of variables in each of the two selected predictive models were separately optimized in specified intervals (Table 4).

Table 4. Optimized coefficients of equation 5 (a1 to a15) and equation 6 (b1 to b15)

Parameter		Powder factor (kg/ton)		Burden (m)		Spacing (m)		Mean height hole (m)		Sub-drilling (m)	
Value		0.2		2.7		4.08		16.99		0.48	
Coefficient	value	Coefficient	value	Coefficient	value	Coefficient	value	Coefficient	value	Coefficient	value
a_1	28.95	a_6	306.04	a_{11}	-0.17	b_1	-996.86	b_6	0.47	b_{11}	12.24
a_2	73.34	a_7	-0.44	a_{12}	999.9	b_2	0.12	b_7	-6.78	b_{12}	0.04
a_3	-0.14	a_8	4.1	a_{13}	-0.07	b_3	-29.47	b_8	-0.69	b_{13}	-1.23
a_4	999.9	a_9	0.43	a_{14}	-93.63	b_4	-2.25	b_9	-1.19	b_{14}	-12.31

After optimizing the coefficients of variables in the models, their predictive accuracy was plotted by drawing regression diagrams based on a comparison between the predicted and measured values of produced boulder and toe volume about the blast block volume of 19 data series (Figure 1). The values of statistical indicators obtained in each diagram showed that the process of optimizing coefficients in selected models could reduce the prediction error of boulder volume ratio and production toe to block volume due to blasting.



(A) **(B)**

Figure 1. Regression plots between measured and predicted values **A:** boulder, **B:** toe

Models validation

To evaluate the efficiency of quadratic polynomial models and selective exponential with optimized coefficients of variables, the data of the four blasts done in the studied mine were used as test data. After replacing the amounts of blast parameters implemented in the four test explosions, the values of boulder and toe volume ratio to the block volume were predicted by a quadratic polynomial and exponential with optimized coefficients, respectively. Then, after each blast and transporting the crushed material compartments, the volume of the produced boulders and the remaining toe were measured using photogrammetry and survey tools, respectively, and the volume ratio of each was calculated to the total volume of the blasted block. The plotted sensitivity analysis diagrams between the predicted and measured values of boulder volume ratio and toe to blasting block volume related to four test explosions showed low error in prediction of 0.08 and 0.47, respectively (Figure 2).

CONCLUSIONS

In this study, we tried to minimize the amount of the occurrence of two phenomena of toe and boulder produced by explosions in the Gol-Gohar Iron Ore Mine No. 2 using seven input factors including two characteristics of rock mass and five factors of blast design. Therefore, the values related to seven input parameters and two output parameters were calculated or measured using field harvesting, survey operations,

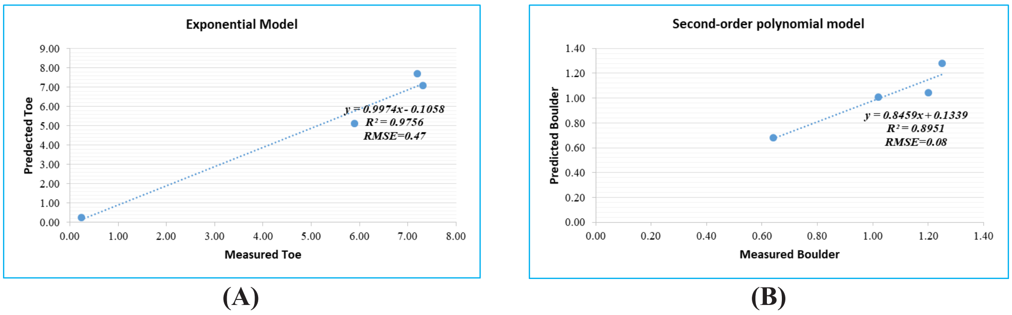


Figure 2. Correlation plots between measured and predicted values of the test dataset **A:** boulder, **B:** toe

photogrammetry method and related software. After the most suitable nonlinear regression models were selected among the types of created models by the SPSS software, the values of blast design parameters were optimized in the selected models by the combined Particle swarm - Genetic algorithm. Thus, it was found that the optimized values of MHL, SD and B have the highest difference in 19 series of collected data, respectively. In other words, by designing and implementing the mean height of blast holes correctly, the occurrence of toe and boulder due to blast in the studied mine will be greatly reduced.

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