



Optimization Charge Scheme for Multi-row Ring Blasting Design Adopting Equilateral Triangle Layout Based on Modified Harries' Mathematical Model from a Fragmentation Perspective: A Case Study

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Abstract. To eliminate undesired phenomena such as brow damage and excessive fines owing to the energy concentration on the collar of the ring, a fragment simulation using a charge scheme optimization algorithm is proposed based on modified Harries model in this article. First, the traversal algorithm for an arrangement of regular holes (holes charged to the collar) is proposed based on the analysis of the current interval charge design method in ring blasting. Second, a new developed mathematical model based on Harries model is introduced to predict the fragment size of the column charge using the superposition method. Then, the optimization criteria based on the calculated blasted fragment matrix are discussed. Finally, a case study is introduced to illustrate the usage and optimization procedure of the program. Ten trial blastings were conducted in the Tonglvshan copper mine to verify the feasibility and effectiveness of the optimization algorithm. The findings reveal that the probability of brow damage was reduced efficiently.

Keywords: Ring blasting · Charge scheme optimization · Fragmentation matrix · Harries' mathematical model

1 Introduction

Fan-pattern holes are widely used in many mining methods owing to economical advances in stoping and high drilling efficiency. Meanwhile, the planned spacing diminishes as it nears the collar; the explosive charge in the sector is always uneven compared to the parallel holes, which may lead to undesired phenomena including hanging roofs, brow damage or over crushing. Moreover, in the design of the underground mine blast, it is common to use double powder factor to ensure fine breakage in the limited space available (Darling 2011). Thus, it is important to prevent adverse phenomena caused by the concentration of energy, especially in the lower part of the ring, by improving the quality of the blasting design and optimizing the charge structure.

Many researchers have proposed solutions to these problems. To achieve better use of the explosive energy, Hagen (1987) suggested drilling holes in a fan-pattern based on a reoriented equilateral triangle. Zhang (2011, 2014) suggested decoupling the charge (using cartridge charges in the lower parts of the holes) or moving primers to the toe of holes to reduce tensile stress in the eyebrow region. These modifications can effectively reduce the overcrush effect near the brow due to the concentration of explosive energy. However, a reasonable scheme for the charging and stemming length (as shown in Figs. 1 and 2) is a basic requirement for ring blasting design whenever the mentioned measurements are applied. Therefore, it is necessary to discuss the method used to develop an optimal charge scheme for fan-pattern holes, especially in the region near the brow.

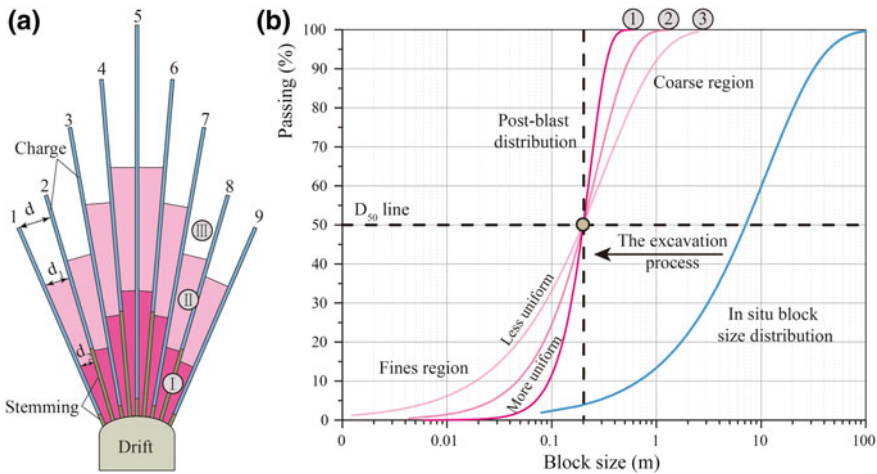


Fig. 1. The influence of the charge scheme on the block size distribution in ring blasting.

The final blasting effect is mainly influenced by two factors. The first is the basic blasting condition, including rock properties, the structure of the rock mass and free face, etc. The second is the design aspect, which covers the drilling pattern, charge structure, explosive properties and detonation method (Scott et al. 2006; Saharan et al. 2006). The design parameters should change in concert with the variation of the initial conditions and should be synchronized with them for a better blasting effect. For mass blasting in underground production, some initial conditions, such as the rock condition and the free face vary notably along the blasting area, which makes it difficult for the engineers to ensure that the design parameters exactly match the given conditions. A mathematical model or simulation tool is needed that can provide a rationale for designers to adjust the design parameters accurately based on the results of numerical simulations.

There are several mature mathematical models of blasting that have been used in the field. For blasting mechanics and process simulation, there are the fracture mechanics blasting model proposed by Margolin and Adams (1982), the KUS damage

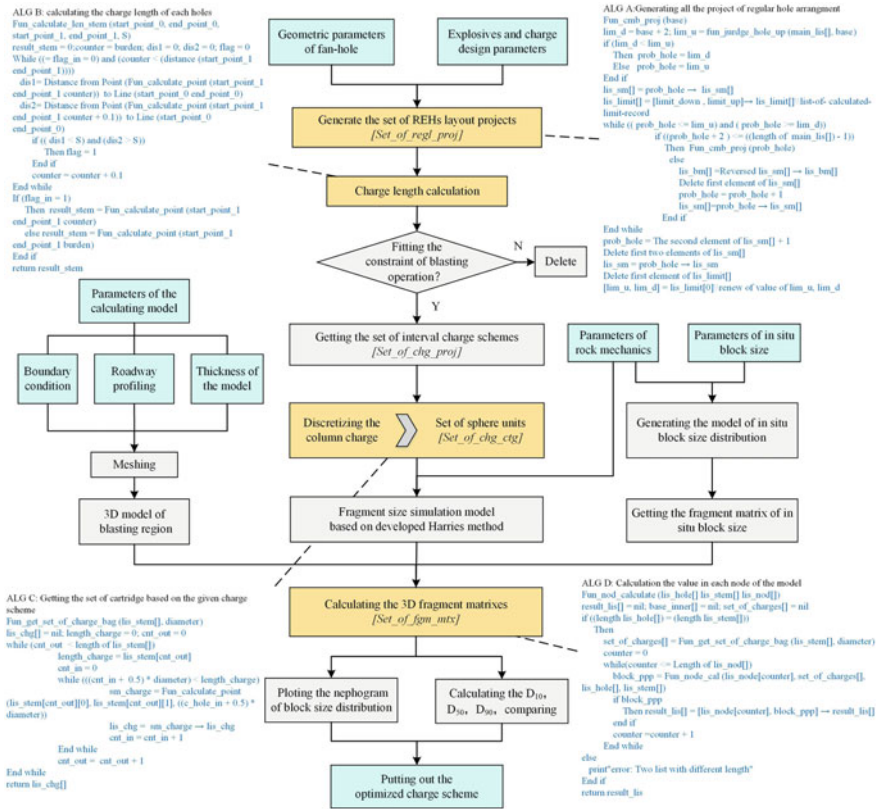


Fig. 2. System flowchart and partial code of the algorithm for the proposed method.

model proposed by Taylor et al. (1986), the PPV damage model (Holmberg 1979; Blair 1999) and the BLAST-CODE model proposed by Qu et al. (2002). For fragment prediction, the Harries model (1983, 1990) can simulate the development of cracks and the fragment size generated by a sphere cartridge. Morin and Ficarazzo (2006) proposed a working form of the Kuz-Ram fragment prediction model based on Monte Carlo simulations. There is a hybrid finite-discrete element model proposed by An et al. (2017) that can simulate the rock crushing, block casting and muck pile profile. However, most mature software products are aimed at the computer-aided design of the layout of the drill-holes, muck pile profile prediction and the prediction of the block size distribution in an open pit mine (Chung et al. 1991; Carter 1992; Liu et al. 2014). There are also many geological data management software packages and cartography systems used in underground mines. However, the functionality of the computer-aided design tools that meet the specific demands of complex mining operations is limited.

This article introduces a new algorithm for calculating the optimal fan-hole charge scheme. First, the current design method for determining the fan-hole charge scheme and its deficiencies are discussed in the context of the rock-crushing mechanism for ring blasting. Second, the methodology of the proposed algorithm is introduced in

detail. Then, a case study of the Tonglvshan copper mine is presented and the two different charge scheme projects, one manually developed and the other designed by a program, are compared. Finally, more blasting data were acquired during on-site observation, and production data were also collected to verify the effectiveness of the optimization algorithm.

2 Problem Description

The process of the excavation by blasting described from the fragmentation aspect is illustrated in Fig. 1. The in situ block size distribution is been changed into the post blasting fragment distribution. There are three different post blasting curves in the Figure, where the curve 1 has the most uniform distributed fragment, the curve 3 is the worst. The different quality of the three blasting curves can be influenced by three aspects (Saharan 2006): the rock condition, the explosive and charge design, and the boundary condition. In the underground ring blasting operation, the charge scheme design may cast a significant impact on the blasting effect in light of the limited boundary condition and the layout of fan-pattern drill-hole. As mentioned above, the explosive energy concentration usually occurred at the collar of the ring. Thus, as we can imagine that the resource of fine particles in the fines region in the Fig. 1 is located in the brow of the ring. Besides the fines ore, the brow damage and the back damage are also result from the unreasonable explosive distribution in the centre or the brow of the ring to a much extent (Darling 2011).

The current design method of the ring blasting is kind of randomness and uncertainty (Wang et al. 2017). First, dividing the drill-holes in the ring into several groups, where there are at least three holes in each holes. The holes located on the boundary of each groups are charged to the collar, which means the length of stem is equal to the minimum permitted stem length. Hereinafter refer to as REH (regular hole). Second, the charge length of the other holes in the groups are determined by the maximum spacing principle ensuring that the time delay between holes would not be influenced (Darling 2011). The stem length of these holes are always longer than the minimum permitted stem length. Hereinafter refer to as IRH (irregular hole).

The charge scheme is mainly determined by the arrangement of the REHs. However, it is kind of subjective and random. There are two contrary idea about the arrangement of the REHs:

1. The location of the two adjacent REHs should be arranged as close as possible, ensuring the ample crushing effect by a higher the powder factor.
2. The explosives in the collar of ring should be reduces, thus the spacing of the REHs should be located as far as possible.

Actually, the most of designers' principle is in between these two rules mentioned above, influenced by their experience and the specific condition of different mine.

Besides the interior effect of charge length between different holes in the same ring, the mutual influence of the charge scheme in each rings should also be considered. The reorientated equilateral triangle arrangement of drilling holes between rings can eliminate the adverse effect due to the uneven distribution of holes (Hagen 1987).

However, the charge schemes of two adjacent rings are different. The spatial distribution of explosive must have a significant impact on the holistic blasting effect.

So, these three principles should be considered in charge scheme design for the multi-ring blasting with triangle arranged fan-pattern holes:

1. The charge distribution should keep in step with the variation of the rock condition in different blasting region.
2. The arrangement of REHs in each ring should be optimized.
3. The mutual influence between rings should be considered, the charge scheme design should be optimized according to the geometric parameters of holes in adjacent rings. In underground mining operations, the rock condition, boundary conditions and free surface profile varies considerably with each blasting case, even in the same stope. Using only one type of charge scheme as is current practice is not reasonable. Determining the specific condition of each ring and calculating different charge schemes manually places too much of a workload on the blast designer. Thus, faced with complex and mutable geologic conditions, the issue of how to calculate an optimal charge scheme efficiently will be discussed in this article.

3 Methodology

According to the previous discussion, the issue is concerned with three key points. First, there are many feasible charge schemes that meet the requirements of current basic charge rules for ring blasting. Second, to figure out which one is the most suitable, rational evaluation criteria are needed that can describe each project quantitatively. Third, for the applicability and operability of the design method, the method must not only deal with the complex and mutable geological condition in underground mining but also must not require too much manual work for the designers.

In this article, a computer-aided design and optimization method is proposed; the program is implemented using AutoCAD on a Visual LISP platform. Figure 2 shows the major steps to establish a computer-aided ring blasting design and simulation system. The detailed steps are given as follows.

Step 1. Generate all the possible REH arrangement projects in each rings based on input drill-hole parameters. Then, filter the results using the primary demands of the blasting operation and other customer constraints provided by the designer, and calculate the set of all the feasible REH arrangement projects by traversal algorithm (Wang et al. 2017). Calculate the charge length of IRHs, and acquire the set of all feasible charge schemes. Finally, combining all the projects between two adjacent rings in the minimum calculated unit.

Step 2. Based on the geometric conditions of the blasting area and the accuracy required, generate a 3D meshed model of the blasting region.

Step 3. Calculate the blasted block size value at each node of the 3D model based on the modified Harries mathematical model (Wang et al. 2017) and the in situ block size distribution. Then, acquire the 3D blasted block size value matrices of each feasible charge scheme.

Step 4. Calculate several indexes of each block size matrix to evaluate the quality of each charge scheme. The two key evaluation index of the block size distribution D_{50} and $D_{90} - D_{10}$ are adopted which can be used to measure the centralization and the fluctuation range of the size value. A fragment size nephogram in the 3D blasting model can also be drawn for further analysis to compare the blasting performance of each project.

4 Case Study

4.1 Background and Calculation Model

The Tonglvshan copper mine is located in Daye Hubei Province, producing 800 thousand tons of ore per year, using sublevel stoping as the major mining method. The stopes are laid perpendicular to the trend of the ore body. The length of each stope is equal to the thickness of the vein. The width of each stope is 8.0 m. The height of each level is about 40.0 m. There are three sublevels (with a height of around 13.0 m) in each level. For blasting operations, the diameter of a drill-hole is 64 mm. The space between each ring is 1.6 m in lateral blasting area. The drill-hole toe spacing is 1.9 m, and the minimum permitted stem length at the collar of a drill-hole is 1.2 m.

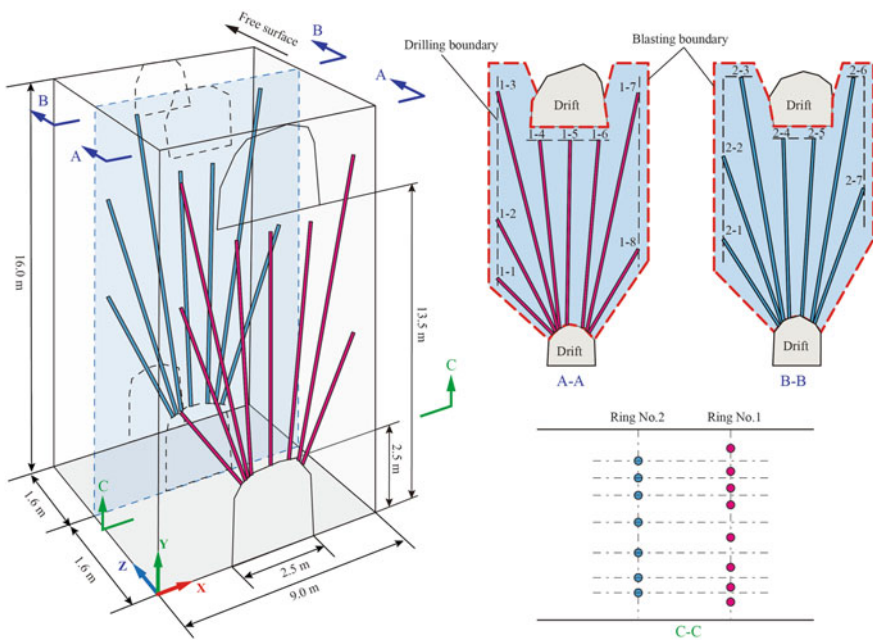


Fig. 3. Geometric properties of the calculated model.

The 9225# room stope at the -450 m level was selected as the trial stope. The geometric properties of the blasting model are illustrated in Fig. 3. The drill-hole parameters, explosive parameters and rock mass properties are given in Tables 1 and 2.

Table 1. Geometric parameters of the fan-holes in the model

Borehole (No.)	Depth (m)	Angle (degree)
1-1	4.5	45
1-2	7.2	63
1-3	13.9	76
1-4	11	84
1-5	10.7	89
1-6	10.9	85
1-7	13.8	78
1-8	5.5	59
2-1	5.9	57
2-2	10	71
2-3	13.5	81
2-4	10.4	88
2-5	10.3	86
2-6	13.3	81
2-7	8.2	70

4.2 Multi-scheme Optimization

Inputting the rock parameters, charge parameters and geometric information of drill-holes, the program put out nine projects for ring No. 1, nine projects for ring No. 2. The result of all the projects are given in Tables 3 and 4. Finally, there are 81 kinds of projects generated in this unit of rings after combination.

Then, the final fragment matrixes of all the combination are calculated. And the two key index of the fragment distribution are calculated. The result is shown in Fig. 4.

Among all the projects whose D_{50} located in the reasonable fluctuate range. The project marked in the figure has the minimum $D_{90} - D_{10}$. Thus, it is determined as the optimal charge project for the two adjacent rings in the unit.

5 Discussion

The optimized project (Hereafter Project A) adopts the charge scheme 2# for ring No. 1, 1# for ring No. 2 according to the program. The specific charge parameters of the charge scheme can be found in Tables 3 and 4. In comparison with the previous blasting design data in the Tonglvshan mine, there is a combination similar with the charge scheme, which the designers were accustomed to use in former blasting operation. Adopting charge scheme 7# for ring No. 1, 9# for ring No. 2. Thus, it is necessary to compare the two charge schemes, Project A and B, the optimal charge scheme and the manually designed scheme.

First, the nephogram of fragment size can be drawn according to the final blasted fragment matrix of each project. The fragment size in the blasting region of Project A and B is shown in Figs. 5 and 6. Figure 5a is the fragment in the whole calculated region, Fig. 5b–e are the fragment nephograms of Project A, starting at the plan

Table 2. Parameters referenced in the paper

Parameters		Value
<i>Rock properties</i>		
ν^*	Poisson's ratio	0.25
ρ^*	Density	3.3 g/cm ³
C_P^*	Longitudinal wave velocity	5200 m/s
T^*	Dynamic ultimate tensile strain of rock	2.0e-4
D_{50situ}^*	Mean value of in situ block size distribution	1.0 m
ε	The tangential strain at the wall of hole	
n	Number of cracks	
λ	Block size value	m
$\lambda_0(i, j, k)$	Fragment matrix of in situ block size	
$\lambda_1(i, j, k)$	Fragment matrix of blasting block size	
$\lambda_{fnt}(i, j, k)$	Fragment matrix of the final blasted block size	
<i>Explosive parameters</i>		
ρ_1^*	Density	1.1 g/cm ³
P^*	Pressure of explosion	7500 MPa
K^*	Adiabatic index	2.0
<i>Borehole properties and charge parameters</i>		
b^*	Radius	0.032 m
d^*	Toe spacing of drill-hole	1.9 m
B^*	The minimum permitted stem length	1.2 m
S^*	Influence radius of column charge	0.95 m
$(D_{50min}, D_{50max})^*$	Fluctuation range of reasonable mean size of fragment	(0.15 m, 0.25 m)
D_{10}	Sieve size of 10% passing value	m
D_{50}	Sieve size of 50% passing value (mean value)	m
D_{90}	Sieve size of 90% passing value	m
$*$	Meshing scale	0.1 m
(μ, θ, h)	Cylindrical coordinates of the calculated point	

Parameters marked with * represent the input parameters in the calculation.

$z = 0$ m, there are five sectors spacing 0.8 m parallel to the ring. Figure 6a is the fragment distribution in the whole calculated model. Figure 6b–e are the nephograms of the optimized charge scheme (Project B). For Project A, the distribution of REHs is more dispersed compared with that of Project B; the explosives are also uniformly distributed in the brow of the ring. This result can be clearly reflected in the fragment size nephogram of the plan $z = 0$ m, seen in Figs. 5b and 6b, and of $z = 0.8$ m, seen in Figs. 5c and 6c. After optimization, fines in the brow of the ring were notably reduced. The optimization has a positive effect on the brow protection and the improvement of the fragment size distribution.

Then, ranking the elements of the final fragment matrix by the size value, the proportion of elements at series size levels raising at a given increment was calculated. Then, the fragment distribution was generated by fitting with the Rosin-Rammler

Table 3. Charge schemes of the ring No. 1 calculated by the program

Charge scheme	Charge length for each holes (m)								
	1-1	1-2	1-3	1-4	1-5	1-6	1-7	1-8	Total
1#	3.3*	3.7	12.7*	5.1	8.3	5.5	12.6*	2.9	54.1
2#	3.3*	4.7	8.0	9.8*	6.4	5.5	12.6*	2.9	53.2
3#	1.9	6.0*	8.0	9.8*	6.4	5.5	12.6*	2.9	53.1
4#	3.3*	4.7	11.5	6.5	9.5*	5.6	12.6*	2.9	56.6
5#	1.9	6.0*	10.4	6.5	9.5*	5.5	12.6*	2.9	55.3
6#	3.3*	3.7	12.7*	5.1	9.5*	5.5	12.6*	2.9	55.3
7#	3.3*	3.7	12.7*	5.1	8.3	9.7*	8.3	4.3*	55.4
8#	3.3*	4.7	8.0	9.8*	6.4	9.7*	8.3	4.3*	54.5
9#	1.9	6.0*	8.0	9.8*	6.4	9.7*	8.3	4.3*	54.4

Holes marked * represent that they are REHs in the specific charge scheme.

Table 4. Charge schemes of the ring No. 2 calculated by the program

Charge scheme	Charge length for each holes (m)							
	2-1	2-2	2-3	2-4	2-5	2-6	2-7	Total
1#	2.6	8.8*	8.9	8.0	6.6	12.1*	3.9	50.9
2#	4.7*	5.4	12.3*	5.3	6.6	12.1*	3.9	50.3
3#	4.7*	6.8	8.3	9.2*	6.6	12.1*	3.9	51.6
4#	2.6	8.8*	8.3	9.2*	6.6	12.1*	3.9	51.5
5#	4.7*	6.8	8.3	9.2*	7.9	9.1	7.0*	53
6#	2.6	8.8*	8.3	9.2*	7.9	9.1	7.0*	52.9
7#	4.7*	6.8	11.1	7.9	9.1*	9.1	7.0*	55.7
8#	2.6	8.8*	9.0	7.9	9.1*	9.1	7.0*	53.5
9#	4.7*	5.4	12.3*	5.3	9.1*	9.1	7.0*	52.9

Holes marked * represent that they are REHs in the specific charge scheme.

model. The fragment size distributions of the two projects are shown in Fig. 7. It can be clearly observed that the fines of Project A were reduced. Although the D_{50} value is increased, the fragment distribution was more concentrated compared with Project B.

Brow damage and undesired fragment quality are frequently seen adverse phenomena in the Tonglvshan copper mine. To justify the validity of the optimization program, further tests were conducted. The results using the computer-designed method and manually designed method were compared, after carrying out 10 blastings using the optimization method. Among the 10 times the computer designed blasting was performed, brow damage appeared 1 times and no bulk appeared. According to the production data in the Tonglvshan mine, the average rate of brow damage or back damage is higher than 30% in previous production, which indicate that the possibility of brow damage can be efficiently reduced due to the more reasonable charge structure. Figure 8a shows the broken brow at the end of the tunnel in 9312# room stope Sublevel No. 3 at the -485 m level; Fig. 8b is a photo of bulk in a blasting case carried out in 9312# room stope Sublevel No. 2 at the -485 m level.

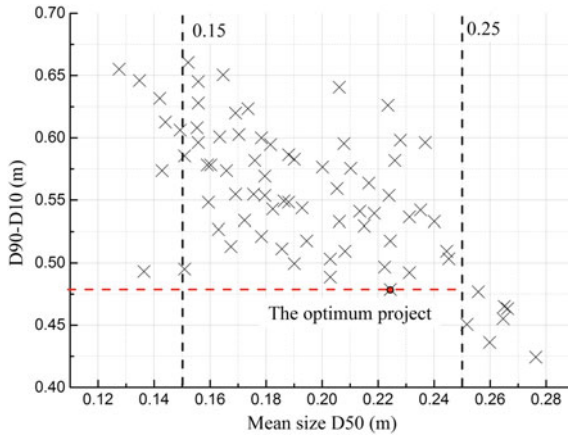


Fig. 4. Results of the evaluation index of the nine feasible charge schemes.

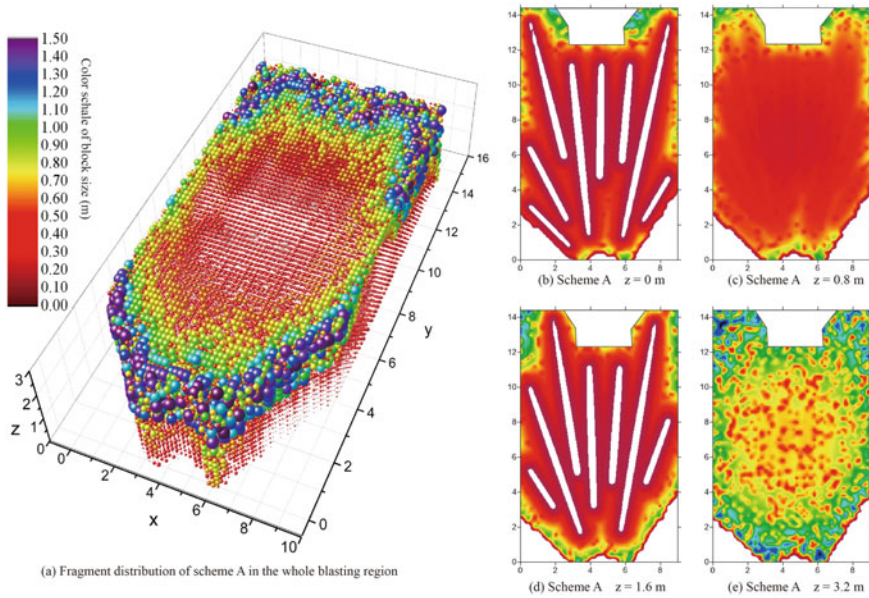


Fig. 5. The nephograms of fragment size in blasting region of the charge schemes A.

The linear superposition method is adopted in the modified Harries model, which considers the linear accumulated effect of sphere units to substitute for the effect of blasting of column charges. However, linear superposition may have some deficiencies (Blair 2008). Thus, to obtain a more rational result regarding the damage effect of column charges based on Harries' model, the algorithm needs to be further improved to find a suitable non-linear superposition function to describe the accumulated damage due to rock blasting. Moreover, delayed initiation is always used in ring blasting to

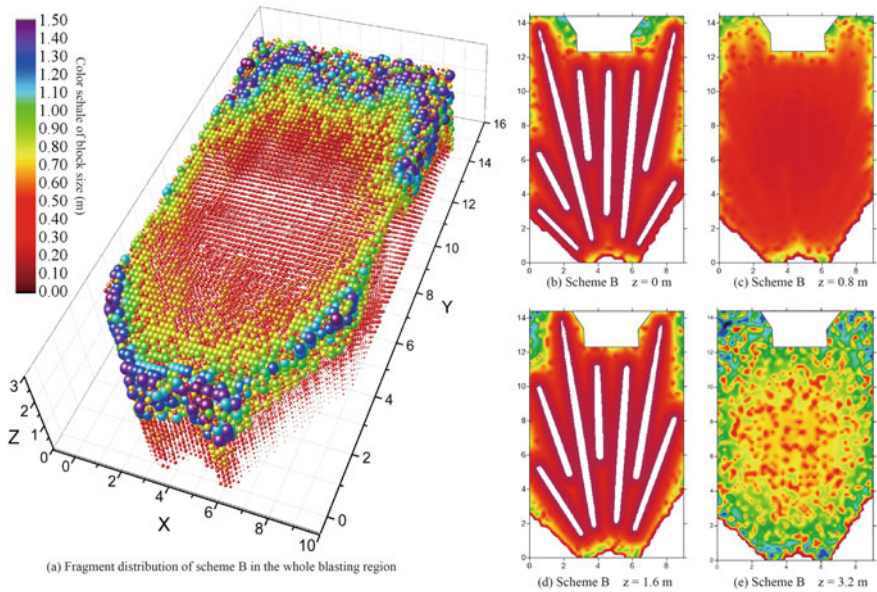


Fig. 6. The nephograms of fragment size in blasting region of the charge schemes B.

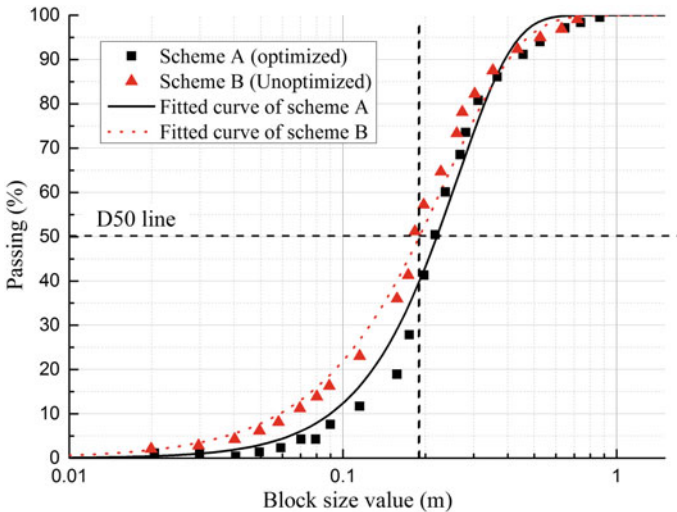


Fig. 7. Comparison of the blasted fragment distribution of the two charge schemes, A and B.

reduce vibration and improve the utilization of energy in the stress wave. However, the delay time is not a major variable controlling fragmentation (Blair 2009). Some small-scale tests (Johansson and Ouchterlony 2013) and numerical simulations (Schill and Sjöberg 2012; Yi et al. 2012) also show that the short delay has no significant impact on fragmentation. The program should achieve a more uniform distributed

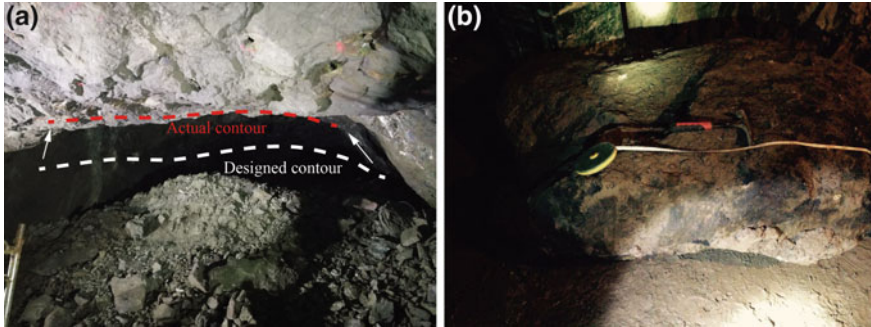


Fig. 8. Photograph of brow damage and bulk in the field.

charge scheme according to the predicted blasted fragment distribution. Thus, the time effect is not considered in the modified Harried model.

6 Conclusion

To achieve the optimum charge scheme at the collar of the ring in ring blasting, a new computer-aided design and fragment simulation optimization program is proposed based on the modified Harries model. By inputting the geometry information of the fan-holes, rock mass properties, explosive parameters and boundary conditions, all the feasible charge schemes and the final blasted fragment matrix of each project can be calculated. The optimum charge scheme can be selected by comparing some key indexes of the fragment matrix and analysing the fragment nephogram of the blasting region. To verify the feasibility of the optimization program, some field blasting tests were conducted in the Tonglvshan copper mine. The following conclusions were reached:

1. By comparing the simulation results of the two charge schemes that were designed manually and via the optimization program, it was found that the optimization program can reduce the explosive concentration on the brow of the ring and that the theoretical fragment distribution can also be improved.
2. In 10 field tests, there is only one time brow damage occurred, where the average rate of brow damage is higher than 30%. This result indicates the optimization program can positively affect brow protection and can improve the quality of the blasting distribution. However, more trial blasting needs to be conducted to verify the reliability and the feasibility of the optimization method.
3. The algorithm proposed in this article is intended to acquire a more uniform distributed charge scheme and to reduce the explosive concentration at the brow ring. The time effect should be further considered about the modified Harries model to obtain a more precise result from the simulation regarding the blasting process and fragment prediction.

Acknowledgements. This research is partially supported by the National Key Research and Development Program (Grant No. 2017YFC0602902) of China, the Shenghua Lieying Program of Central South University (Principle Investigator: Dr. Jian Zhou), and the Fundamental Research Funds for the Central Universities of Central South University (Grant No. 2017zzts567).

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