

STUDYING THE EFFECT OF MEDIATE AIR-DECK LENGTH BETWEEN EXPLOSIVE CHARGES IN A BOREHOLE ON THE EFFECTIVENESS OF ROCK-BREAKING

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ABSTRACT: The air-deck blasting technique has been commonly applied in construction and mining to crush and break rock masses or minerals. There have not been any theories accurately calculating parameters of blasting plans with air-decking, and effectiveness evaluation methods for blasting in practice, though. Hence, based on analyzing the theory of air-deck blasting, this paper establishes and carries out experiments on consecutive explosive charges and air-deck models with the condition that the distance between explosive charges varies. The resulting data is the rock particle size ratio. Using Excel software along with the least squared method to establish the experimental dependence of the average particle size of stones on the relative length of the mediate air gap between explosive charges in a borehole. The results show that an optimum value of this relative length always exists, assuring the best quality crushing, corresponding to the minimum average size of stones.

Keywords: Blasting, air-deck blasting, rock fragmentation, blasting control.

1. Introduction

Improving the quality of rock breaking by blasting is a regular and continuous task in rock excavation works in construction or mining. Up to now, controlling the quality of rock breaking has included basic blasting techniques and technologies such as: differential blasting technology, compression environmental blasting technology [1, 6, 7, 8, 9, 10], changing parameters and structures of the explosive charge [1, 2, 3, 4, 5, 9], changing parameters of stemming quality [1, 9, 19],... Research in this direction usually inherits theoretical research results on the mechanic physical nature of rock blasting [16]. On that basis, technical or technological solutions are proposed and proven through experimentation. This research direction is vibrant and diverse, aiming

to satisfy different explosive conditions, even for each excavation or mineral exploitation project condition, to control and improve the rock-breaking quality of blasting plans.

The solution to change the structure of explosive charges in the blasting hole, typically the solution with air-decking, has been researched by many scientists around the world such as F. A. Baum, N. V. Mennhikov, A. N. Khanucaev, L. N. Martrenko [1, 12, 13, 14]. M. G. Novojilov, M. F. Drukovani proposed a method to determine the length of the air gap between two fractional explosive charges in the blasting hole based on calculating the impact time value and the relatively uniform pressure distribution in the borehole [1, 14]. However, this method is difficult to apply in practice.

Although the air-deck blasting method has been applied quite commonly in rock breaking, until now there has not been a complete theoretical model to calculate the characteristic parameters for the air-deck blasting. In practice, when applying air-deck blasting technology, there are two methods of adjusting the set of structural parameters of fractional explosive charges to control the rock fragmentation to the optimal zone, including: Adjusting the air gap length between two fractional explosive charges in the borehole when the volume of the explosive charges is fixed; Adjusting the volume of fractional explosive charges while keeping the air gap length. Of these two adjustment methods, the former is more commonly applied. However, up to now, there has not been any theoretical or experimental research on the relationship between the distance between fractional explosive charges in a blasting hole and rock fragmentation. Therefore, analyzing the theoretical basis of air-deck blasting and establishing an experimental research model to clarify the relationship between the distance between fractional explosive charges and rock fragmentation is one meaningful research direction.

2. Analyze the theoretical basis for the effective effects of air-deck blasting

The shape of the explosive energy field surrounding the explosive charge is closely related to the shape of the explosive charge and its structure, (see Figure 1). When blasting in a borehole with continuous explosive charges, the surrounding medium, especially in the lower area, often causes rock to be broken up more than necessary. Meanwhile, the upper part of the borehole (part of stemming materials) has many oversized rocks, see figure 1a. The reason for this uneven rock breaking is that the explosive energy field is concentrated in the

lower region. To overcome this problem, it is necessary to use the air-deck blasting solution to ensure a reasonable distribution of the surrounding explosive energy field along the wall of the borehole (Figure 1b).

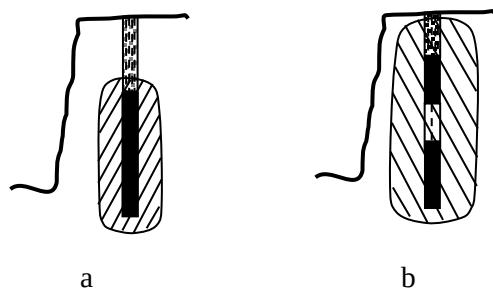


Figure 1. The modified breaking area when air-decking
a- continuous explosive charges; b- air-deck blasting

After detonating a continuous explosive charges, it will create extremely high explosive pressure, crushing the rock and soil close to the explosivs. Excessive crushing is not only unnecessary for the requirements of rock destruction, but is a source of large amounts of dust flying into the air, affecting the ecological environment. Research results in the laboratory of A. N. Khanucaep have proven that the crushing zone close to the explosive charge is about 2 times of its radius. Although this volume is much smaller than the destruction and cracking zone, it consumes a the energy ratio is as large as (60-75) % of the explosive energy due to crushing and plastic deformation of the environment [1, 13]. Therefore, using air-deck blasting will reduce the explosion pressure in the borehole, and at the same time prolong the explosion effect time, thereby reducing the size of the crushing zone and increasing the efficiency of rock crushing, (Figure 2). Controlling the change in value and distribution of explosion pressure along the borehole wall also means controlling the change of the explosion stress wave field propagating in the rock environment.

The structure of the air-deck blasting in a borehole has the effect of increasing the length and area of the borehole wall, which is directly exposed to the pressure of the explosive products. This also leads to an increase in the energy transfer coefficient into the rock environment, residtributing the explosive energy and the stress wave fields around the borehole. Thereby changing the effectiveness of breaking rock and soil.

To simplify the comparison of changes in stress wave parameters, using the F. A. Baum method with the assumption that the fractional explosive charges is considered as a continuous explosive charges with a smaller density, corresponding to a larger height, and the radial expansion around the borehole is vanished. Then, the study of the variation of explosive pressure in a borehole with the continuous explosive charges or air-deck explosive charges follows the law of the expansion of strong explosive gases in the adiabatic process of the form [1, 18, 19]:

$$p \cdot V^\gamma = \text{const} \quad (1)$$

When $p > p_c$ so $\gamma = \gamma_1 = 3$, and when $p < p_c$ so $\gamma = \gamma_2 = 7/5$, whereas the value of critical pressure $p_c \approx 2 \cdot 10^3 \text{ kG/cm}^2$ [19].

Firstly, the average pressure of explosion in a borehole is calculated as follows:

$$p_k \cdot V_k^\gamma = p_0 \cdot V_0^\gamma$$

$$\text{After transformation:} \quad \frac{p_k}{p_0} = \left(\frac{V_0}{V_k} \right)^\gamma \quad p_k = \frac{1}{\left(1 + \frac{L_k}{L_t} \right)^\gamma} p_0 \quad (2)$$

$$\text{Or} \quad L_k = \left[\left(\frac{p_0}{p_k} \right)^{\frac{1}{\gamma}} - 1 \right] \cdot L_t \quad (3)$$

Where: p_0, p_k - initial average blasting pressure in a borehole corresponding to a continuous explosive charges case and an air-deck case, respectively; V_0, V_k - the volume of explosive charges chamber corresponding to a continuous explosive charges case and an air-deck case, respectively; L_t - the total length of explosive charges in a borehole; L_k - the length of air gap between two explosive charges.

Hence, choosing the value of superscript γ depends on the value of blasting pressure in a borehole, the blasting pressure in a borehole depends on the ratio between the air gap length and the total length of explosive charges in a stemmed borehole.

Investigating the variation of blasting pressure in a borehole for TNT explosive charges with $p_0 = 226377 \text{ kG/cm}^2$ [1]. The formula (3) is applied to determine the ratio between the length of the air gap and the total length of

explosive charges (L_k/L_t), corresponding to the average blasting pressure in a borehole equals the critical pressure ($2,10^3 \text{ kG/cm}^2$), is approximately 3,84. According to Machenko, with the buried explosions of conventional boreholes in open-pit mines, the ratio L_k/L_t is less than 0,35 in different types of rocks [1]. On the other hand, when blasting through normal rock layers, the length of stemming material is smaller than the length of the explosive charges, meaning that $L_{kk}/L_t < 1$, so during the time the stemming material moves in the borehole, the expansion law of the strong explosive gas only occurs corresponding to 1st period with exponential index $\gamma = \gamma_1 = 3$. Then formulas (2) and (3) can be expressed as:

$$p_k = \frac{1}{\left(1 + \frac{L_k}{L_t}\right)^3} p_0 \quad (4)$$

$$L_{kk} = \left[\left(\frac{p_0}{p_k} \right)^{\frac{1}{3}} - 1 \right] \cdot L_t \quad (5)$$

The law equation (4) or (5) is reflected in Figure 2. Analysis of Figure 2 shows that the relative level of blasting pressure reduction in borehole depends on the ratio of the air-deck length and the length of the explosive charges.

Thus, the process of moving stemming material in the borehole and the pressure of the blasting products on the borehole wall will be calculated as follows:

$$p_k \cdot V_k^3 = p_x \cdot V_x^3$$

After transformation:

$$\begin{aligned} \frac{p_x}{p_k} &= \left(\frac{V_k}{V_x} \right)^3 \\ p_x &= \frac{1}{\left(1 + \frac{x}{L_t + L_k}\right)^3} p_k \end{aligned} \quad (6)$$

$$p_x = \frac{1}{\left(1 + \frac{x}{L_t + L_k}\right)^3} \cdot \frac{1}{\left(1 + \frac{L_k}{L_t}\right)^3} p_0 \quad (6')$$

Where: p_x - The average blasting pressure in a borehole when the stemming materials move for a distance of x ; V_x - The volume of a borehole containing blasting products when the stemming materials move for a distance of x .

Formula (6') allows us to illustrate Figure 3 about the average pressure distribution of blasting products along the borehole wall, corresponding to the change of air-deck length between two explosive charges.

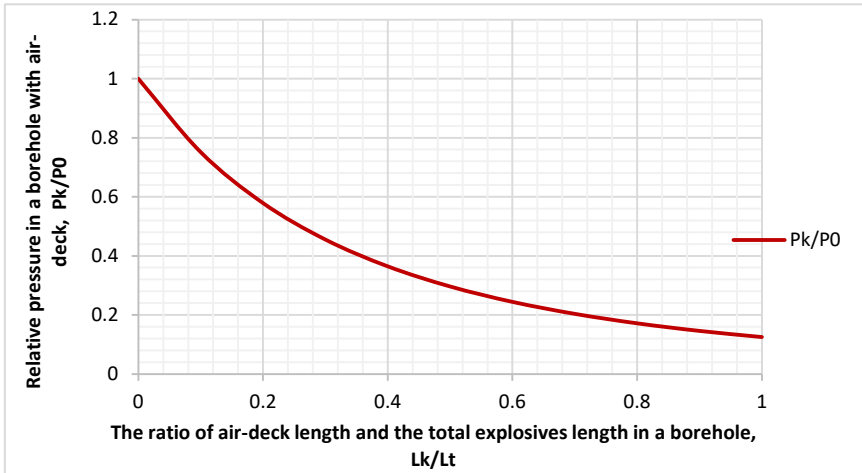


Figure 2. The dependence of the relative pressure of blasting products in a borehole on the ratio between air gap length and the total length of explosive charges

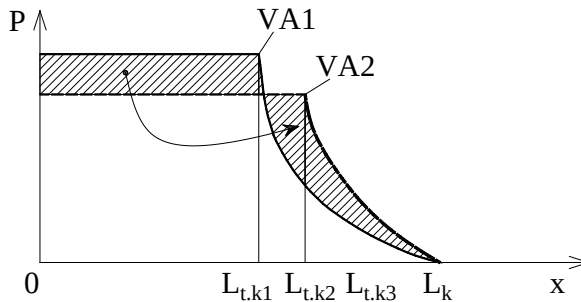


Figure 3. The average pressure distribution of blasting products on the borehole wall, based on the length of air-deck between two explosive charges (VA1, VA2- 2 plans corresponding to air-deck lengths $L_{t.k1}$ and $L_{t.k2}$, $L_{t.k1} < L_{t.k2}$; the cross-hatched area illustrates the rearrangement of the blasting impulse from VA1 to VA2)

Analysis of equations (2), (6') and Figure 3 shows that changing the structure of the explosive charges from continuous to air-deck has the effect of reducing the blast pressure and increasing the time of effective duration of blasting impact on rock and soil, this reduces the unnecessary crushing effect in the vicinity of the explosive charges, leading to more uniformly rock breaking. When the

length of the air-deck is equal to the length of the explosive charges, the explosive pressure in the borehole is reduced by 8 times, and the density of the blasting product is reduced by 2 times compared to the case of using continuous explosive charges.

When using statistical methods to study rock fragmentation by blasting, people are not interested in the actual nature of the dynamic crushing process but only consider the initial and final results of the destruction process [10, 11]. The environmental state and explosive charges distribution in the rock mass corresponding to the blasting pressure distribution in the borehole is considered the initial state of the environment. The final state of the environment is the particle size distribution after an explosion. Currently, there is no theoretical model that can establish the relationship between the influence of the air-deck length on rock fragmentation. Therefore, to clarify the above statements, it is necessary to conduct experimental research on the models.

3. Experimental research

3.1. Selection of the experimental model

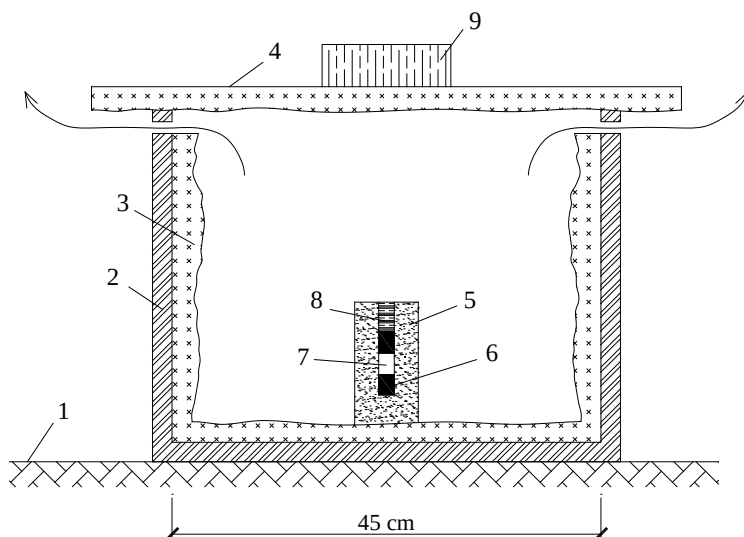


Figure 4. The diagram of experimental model

1. Surface; 2. Chamber made of steel with a thickness of 1mm; 3. Carton damping layer;
4. Carton cover; 5. Experimental samples made of cement mortar; 6. Explosive charges;
7. Air-deck; 8. Paper stemming; 9. Wood bar; 10. Blasting products exhaust through open holes.

The experimental model chosen is a cylindrical solid material sample with a diameter of 100 mm and a height of 250 mm, with a 9 mm diameter drill hole in the middle of the sample (Figure 5a). The drill hole is used to bury small cylindrical explosive charges into the sample cavity. After arranging the explosive amount with air segment structure into the drill hole in the middle of the sample, stuff paper screws and place the sample in the explosion chamber (Figure 4). After detonating, the destroyed samples are collected to measure and analyze experimental data, see Figures 5b, 5c, 5d.

The components characteristics of the experimental model are as follows:

- The samples are made of cement mortar with the ratio of cement to fine sand ($\leq 0,05$ mm), corresponding to (1:1), denoted as model M1, and the ratio of cement to fine sand equals (1:4) denoted as model M2. Sample type M1 has a compressive strength ranging from (3,1-3,6) Mpa and sound wave speed ranges from (2100-2600) m/s, while sample type M2 has a compressive strength ranging from (14,9-15,7) Mpa and sound wave speed fluctuates in the range (3200-4000) m/s. Model materials of this type are inherited from commonly used methods in the laboratory [2, 3, 5, 15, 17].

- Explosive charges: using small explosive charges with a mass of 1 g equivalent to TNT prepared at the factory. The explosive charge has the same principle as an electric detonator, but the bottom of the detonator is flat with an aluminum shell, a diameter of 7,1 mm, and a length of 46 cm (the length of explosive is 31 mm).

- Chamber for explosion: the chamber has a shape of cylindrical, made of steel, has a damping cushion layer of carton, and has explosion exhaust holes. This carton layer is to eliminate the additional impact of crushing the samples when exploding due to impact on the chamber wall. The dimensions, shape, and structure of this chamber are described in Figure 4.

- Detonator: MFB - 200 electrical detonator made from China.

3.2. Measurement method collecting experimental data

Using a 10 kg - 1 g electronic scale to measure the mass of the sample before explosion and the mass of particle sizes of the sample on the sieves after explosion. Using a 9-level Vietnamese standard sieve set with diameters of (50; 40; 30; 20; 10; 5; 2.5; 1.25) mm (Figure 5c).

4. Content and experimental results

Experimental content as follows:

- For sample M1, arranging 02 explosive charges above with a total explosive mass of 2 grams changing the length of the air-deck between two explosive charges (a) to 0 mm, 60 mm, 90 mm, 100 mm, 140 mm, 180 mm, respectively. 3 experiments are conducted in each case, and then the data is obtained for analysis. The total number of blasting samples is 18;

- For sample M2, similar to sample M1 except in the case that the length of the air-deck is 90 mm. The total number of blasting samples is 15.

The measured result after an explosion is the mass of each group of particle size corresponding to the size of the two adjacent sieves for each sample. Then, the average particle size (D_{av}) is calculated as the following formula [1, 9, 15]:



a



c



b



d

Figure 5. Experiments on laboratory
*Examples before blasting; b) Examples after blasting in a chamber; c) Sieves;
d) Scales for groups of particle size*

$$D_{av} = \frac{\sum \gamma_i \cdot d_i}{100} \quad (7)$$

γ_i - ratio of the i^{th} particle size, %;

d_i - average size of the i^{th} particle, mm.

Calculating the average particle size from the experimental data sets allows us to draw Table 1.

Table 1. The average particle size D_{tb} after an explosions for each sample

Code	The length of air-deck		The average particle size after explosions of M1 samples, D_{av}	Code	The average particle size after explosions of M2 samples, D_{av}
	Absolute length, L_k (mm)	Relative length, L_k/L_t			
M1.1	0	0	30.9	M2.1	21.1
M1.2	0	0	31.5	M2.2	17.3
M1.3	0	0	30.7	M2.3	21.6
M1.4	60	0.8	24.0	M2.4	9.3
M1.5	60	0.8	25.7	M2.5	10.4
M1.6	60	0.8	24.5	M2.6	9.6
M1.7	90	1.1	22.0	-	-
M1.8	90	1.1	22.9	-	-
M1.9	90	1.1	22.4	-	-
M1.10	100	1.3	20.1	M2.7	8.4
M1.11	100	1.3	21.4	M2.8	8.0
M1.12	100	1.3	20.9	M2.9	8.7
M1.13	140	1.8	22.2	M2.10	5.6
M1.14	140	1.8	22.0	M2.11	7.0
M1.15	140	1.8	22.5	M2.12	5.7
M1.16	180	2.3	23.1	M2.13	7.6
M1.17	180	2.3	23.2	M2.14	7.5
M1.18	180	2.3	23.3	M2.15	7.5

Note: The relative length of air-deck is the ratio of air-deck length to the total length of explosive charges.

5. Experimental results analysis, and practical application proposal

To establish experimental laws and the influence of the air-deck length between explosive charges to rock fragmentation, it is necessary to establish an experimental relationship between the average particle size of the sample after

Studying the effect of mediate air-deck length between explosive charges in a borehole on the effectiveness of rock-breaking

an explosion and the air-deck length between explosive charges. From the results of Table 3, using Excel software to establish empirical laws of the dependence between the average particle size of the sample after an explosion and the air-deck length is reflected in Figure 9 and the quadratic form of regression equation as follows:

$$D_{av} = f\left(\frac{L_k}{L_t}\right) = a \left(\frac{L_k}{L_t}\right)^2 + b \frac{L_k}{L_t} + c \quad (8)$$

Where: a, b, c - are the parameters of the quadratic regression equation, characterizing the strength of experimental samples. These parameters are shown in Table 2 below

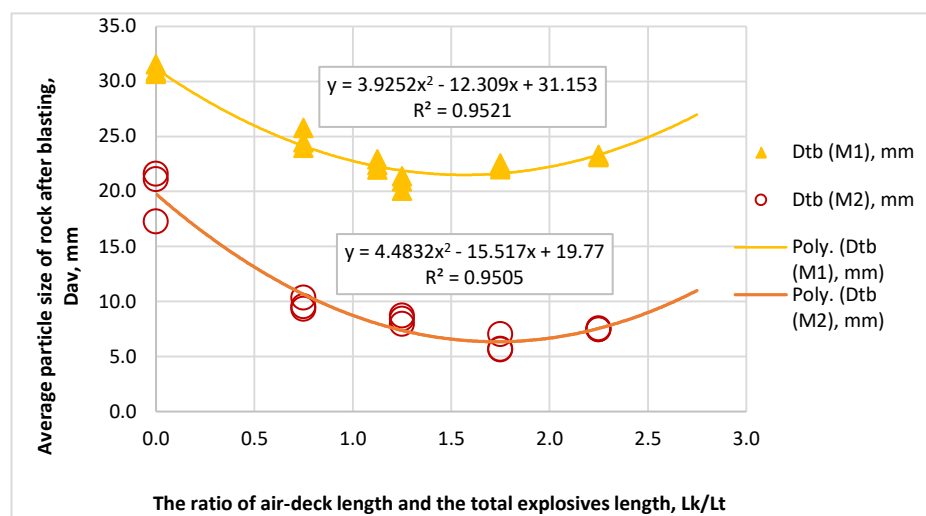


Figure 9. The dependence of the average particle size after an explosion Dtb on the air-deck length, for M1 and M2 samples.

Table 2. Parameters of the quadratic regression equation

Sample type	a	b	c	Coefficient of determination, R^2
M1	3,9252	-12,309	31,153	0,9521
M2	4,4832	-15,517	19,77	0,9505

Analyzing the results shown in Figure 9 and the regression equation (7) shows that, if the relative air-deck length between the explosive charges (L_k/L_t) is increased to a critical value, the average particle size after an explosion will

decrease to a minimum value. Then, if the relative air-deck length L_k/L_t kept to increase, the average particle size after an explosion will grow again.

Because the total mass of explosive charges is constant, so the optimal relative air-deck length (L_k/L_t) obtains the best rock fragmentation, meaning that the average particle size reaches a minimum value. When it comes to mathematics, the value of optimal relative air-deck length is determined as the condition that the first derivative of function $f(\frac{L_k}{L_t})$ for (L_k/L_t) vanishes:

$$\frac{\partial D_{av}}{\partial \frac{L_k}{L_t}} = \frac{\partial f}{\partial \frac{L_k}{L_t}} = 0 \quad (9)$$

The solution of (8) is the optimal relative air-deck length between explosive charges (L_k/L_t) as follows:

$$\left(\frac{L_k}{L_t}\right)_{op} = \frac{-b}{2a} \quad (10)$$

Substituting two coefficients a and b in Table 2 into expression (10) to obtain the optimal relative air-deck length between the explosive charges, which is approximately equal to 1.57 for the sample type M1 and 1.73 for the M2 model. The average particle size of the smallest rock is determined as follows:

$$D_{av.min} = f\left(\frac{L_k}{L_t}\right)_{op} = a\left(\frac{L_k}{L_t}\right)_{op}^2 + b\left(\frac{L_k}{L_t}\right)_{op} + c \quad (11)$$

Substituting (10) into (11) obtains:

$$D_{av.min} = -\frac{b^2}{4a} + c \quad (11')$$

Substituting a , b , c from Table 2 into expression (11') obtains: $D_{av.min} \approx 21,5$ for sample type M1 and $D_{av.min} \approx 6,5$ for sample type M2.

Two types of samples have different durability, but share the same powder factor value of 1,019 kg/m. Therefore, it can be seen from the graph in Figure 9 that at the same powder factor, the higher the materials' durability (Model M1), the smaller the rock fragmentation, meaning that the average particle size is larger. In contrast, the lower the materials' durability (Model M2), the greater the rock fragmentation, meaning that the average particle size is smaller.

6. Conclusion and recommendation

When the total explosive mass and the total explosive length in the borehole are fixed, the air-deck length affects the intensity and average blasting pressure distribution along the borehole wall. The longer the air-deck length between two explosive charges, the lower the average blasting pressure value in the borehole, but the length of the borehole wall directly affected by the initial average blasting pressure increases. Hence, it changes the rock fragmentation characteristics of each borehole. The results of blasting experiments by samples proves that when increasing the air-deck length from 0 (corresponding to the continuous explosive charge) to a critical value (equal to 1,57 for model M1 and 1,73 for sample M2), then the average particle size after an explosion reduces to the smallest value (equal to 21,5 for sample M1 and 6,5 for sample M2). Then, if the air-deck length is increased beyond the critical value, the average particle size after an explosion will increase. The results emphasize that using the air-deck method with reasonable parameters of explosive charges in the borehole will improve the quality of rock fragmentation. Each certain blasting condition will have an optimal air-deck length value, corresponding to the best rock fragmentation. The research model receives an optimal relative air-deck length is approximately equal to 1,57 for model M1 and 1,73 for model M2.

Recommendation: To improve the efficiency of rock fragmentation when blasting, the solution of intermittent explosive charges can be applied to replace fractional explosive charges. During the construction process, it is necessary to always adjust the blasting passports, adjust the air-deck length, evaluate and compare the results of each blast according to the average particle size to select the blasting plan with reasonable fractional explosive charges.

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NGHIÊN CỨU ẢNH HƯỞNG CHIỀU DÀI ĐOẠN KHÔNG KHÍ TRUNG GIAN GIỮA CÁC LƯỢNG NỔ TRONG LỖ KHOAN ĐẾN HIỆU QUẢ ĐẬP VỠ ĐÁ ĐÁ

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ABSTRACT: Công nghệ nổ mìn phân đoạn lượng nổ trong lỗ mìn mặc dù được ứng dụng khá phổ biến trong thi công phá đá hay khoáng sản rắn trong lĩnh vực xây dựng công trình cũng như trong khai thác mỏ, tuy nhiên cho đến nay chưa có một lý thuyết nào đưa ra được một phương pháp tính toán chính xác các thông số hệ chiều nổ mìn phân đoạn và phương pháp đánh giá hiệu quả của vụ nổ ngoài thực tế. Chính vì vậy trên cơ sở phân tích lý thuyết về nổ mìn phân đoạn, bài báo này đã thiết lập và tiến hành thí nghiệm trên mô hình lượng nổ liên tục và lượng nổ phân đoạn với khoảng cách giữa các lượng nổ thay đổi. Dữ liệu thu được sau thí nghiệm là tỉ lệ kích cỡ các cục đá phá ra sau nổ. Sử dụng phần mềm Exell với phương pháp bình phương tối thiểu để thiết lập sự phụ thuộc thực nghiệm của kích thước trung bình của cục đá phá hủy sau nổ vào thông số chiều dài tương đối

của đoạn không khí trung gian giữa các lượng nổ trong lỗ khoan. Phân tích kết quả thực nghiệm trên mô hình chỉ ra rằng, khi nổ mìn phân đoạn không khí luôn tồn tại một trị số chiều dài tương đối tối ưu của đoạn không khí trung gian giữa hai lượng nổ trong lỗ khoan, để đảm bảo chất lượng đập vỡ tốt nhất, tương ứng với kích thước cục đá trung bình là nhỏ nhất.

Keywords: Nổ phá đất đá, nổ phân đoạn, đập vỡ đất đá, điều khiển nổ.