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Research Article

Experimental Study on Vibration Reduction Technology of Hole-by-Hole Presplitting Blasting

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In order to effectively reduce the disturbance of the precrack blasting vibration on slope rock mass, except paying attention to the damping effect of the precrack, it is also necessary to optimize the blasting parameters and initiation mode of the precrack itself. Based on the blasting theory and empirical formula, the parameters of presplitting blasting such as the hole diameter, hole spacing, charge decoupling coefficient, and line charge density were determined, and field tests of conventional pre-splitting blasting and presplitting blasting with precise delay and hole-by-hole initiation were carried out on the west slope of Buzhaoba. Regression analysis was carried out on the vibration monitoring data, and the blasting vibration attenuation regularity of slope particles was obtained. By comparing the monitored vibration velocity of the two presplitting blasting tests and the forecast results of theoretical calculation, the average reduction rate of the conventional same row blasting vibration is 26.40%, while that of the hole-by-hole blasting vibration can reach 41.45% with a half hole rate of 80.7% and an irregularity of about 130 mm. Results show that the effect of precise delay initiation between preholes based on the digital electronic detonator is better than that of the simultaneous initiation of preholes. Therefore, it is suggested that the hole-by-hole presplitting blasting technology should be applied in the excavation of boundary slope and the treatment of high and steep slope.

1. Introduction

Buzhaoba open-pit coal mine, which belongs to the Xiaolongtan Mining Bureau in Kaiyuan City of Yunnan Province, is the main operating mine crater. With the increase of mining depth, the tension cracks which formed on its western side are increasing in number and length [1]. The problem of the high-steep slope is becoming more and more serious, as the slope deformation is gradually accelerated. These hazards may cause damage of equipment, or even lives if no proper precautions are taken [2].

The upper portion in the west slope of the Buzhaoba is made up of a thin layer of argillaceous limestone with hard mudstone rocks and weak rock mass, with clear bedding and small fold, and there are $4 \sim 6$ jointed cracks per cubic meter. The rocks are weak or moderately weathered rock mass, and the integrity of the rock mass is poor. Besides, many structural planes in rock mass are soft interlayers. Considering the combined effects of blasting, weathering, unloading, and water scouring, a lot of difficulties are brought in the maintenance of the permanent stability of the slope. In order to reduce negative effects induced by blasting operation in the final high wall and prevent landslide due to slope instability in the future, presplitting blasting technology is the first choice when conducting blasting operation on the Buzhaoba area [3–5]. On one hand, presplitting blasting can prevent the spread of explosion stress wave to the reserved rock mass by way of forming cracks with a certain width and depth between the main area and the reserved zone, so as to reduce or even cut off the blasting vibration damage to the reserve rock mass [6]; on the other hand, the integrity of the reserve rock mass can be maintained because the cracks extending from the main area to the reserved zone is also cut off [7].

A lot of studies have been carried out on the precrack blasting. For example, Yang et al. [8] applied vertical and horizontal uniaxial pressures and blasting loads on gypsum by numerical simulation and studied the damage distribution characteristics of blasted specimens by using fractal theory, digital image method, and acoustic detection method. In addition, Raina [9] used historical data to establish the precracking response surface analysis model of explosion damage index and semimold coefficient. The above failure criteria are compared by the angles of blast hole relative to the main joint orientation, joint spacing, blast hole spacing, drill deviation, linear charge concentration, and compressive strength. Besides, Wang et al. [10] verified the synergistic antireflection technology of hydraulic fracturing and deep hole presplitting blasting in low permeability coal seam by field engineering test. Moreover, Yang et al. [11] obtained the deformation characteristics and failure mechanism of DHPB through numerical simulation and model test of specimens under horizontal compressive stress, compressive vertical stress, and noncompressive stress, as well as morphological analysis of presplitting cracks after presplitting blasting. What is more, Cheng et al. [12] put forward the pressure relief technology of advanced deep hole nonthrough directional presplitting blasting. The influence of nonpenetrating crack length on presplitting effect is studied by numerical simulation. Different from the above researches, Yuan et al. [13] studied the bearing characteristics and stress distribution characteristics of residual coal pillar by theoretical analysis and numerical simulation, analyzed the influence mechanism of presplitting blasting on residual coal pillar, revealed the disaster reduction mechanism of presplitting blasting on shallow buried residual coal pillar, and determined reasonable blasting parameters. Furthermore, Chen et al. [14] put forward the deep hole presplitting blasting, weakening THR to alleviate the strong pressure. LS-DYNA was used to establish the deep hole presplitting blasting model, and the crack evolution law and the attenuation characteristics of peak particle velocity of rock under the synergistic effect of blasting stress wave and detonation gas were analyzed to verify the rationality of blasting parameters. Besides, Shin et al. [15] studied the phenomenon that the blasting damage zone developed on the rock slope surface can be affected by the joint characteristics rather than the explosive force when the rock slope is presplitting excavated. However, more and more attention has been paid to the blasting seismic intensity produced by presplitting blasting itself [16–29].

It can be seen that parameter selection of the presplitting blasting and the initiation mode of presplit holes have great influence on the damage of surrounding rock. In view of the stability control requirements of west slope cutting and load reduction in the open-pit mine, it is urgent to optimize the conventional presplitting blasting control scheme to further reduce the harmful effect of vibration.

2. Selection of Presplitting Blasting Parameters

2.1. Blasting Diameter. Normally, the smaller the diameter of the presplit hole, the higher percentage of half hole and the easier controlling the roughness of slope surface, and also the less the damage ranges of surrounding rock mass. But at the same time, the drilling and charging will be more difficult to implement, and the decoupling charging becomes more difficult to control [30]. Combined with the existing construction machinery and equipment of Buzhaoba, hole diameter $d = 100$ mm is selected in this test [31].

2.2. Decoupling Coefficient of Charging. (1) According to the theory of explosive detonation, the initial average pressure p_0 of the exploding gas in hole can be determined by the following equation [32]

$$p_0 = \frac{1}{8}\rho_0 V^2, \tag{1}$$

where ρ_0 is the density of explosive in kg/m^3, and V is the explosive detonation velocity in m/s.

(2) The calculation method of decoupling coefficient is discussed theoretically by Zong et al. [33], and the following formula is used

$$\sigma_{r0} = p_a = K_d^{-8/3} K_l^{-4/3} p_k \left(\frac{p_0}{p_k}\right)^{4/9}. \tag{2}$$

In this formula, σ_{r0} represents the absolute value of the initial peak stress on the hole wall in MPa, p_a is the quasistatic pressure when blasting gas filled the holes, K_d is the radial decoupling coefficient, K_l is the axial decoupling coefficient, and p_k is the critical pressure, which is usually taken as 200 MPa.

In order to avoid the failure due to compression which might happen in the wall rock, it is required to ensure the peak value of the initial radial stress acting on the rock of hole wall lower than the compressive strength of the rock. According to the above formula, the following formula is obtained for calculating the axial decoupling coefficient:

$$K_l < \frac{1}{K_d^2}\left(\frac{p_k}{S_c}\right)^{3/4}\left(\frac{p_0}{p_k}\right)^{1/3}, \tag{3}$$

where S_c stands for the compressive strength of rock in MPa.

The above requirements must be satisfied when the axial charge decoupling coefficient of presplitting blasting determined. At the time of application, the axial decoupling coefficient is determined according to the formula (3). K_l is slightly greater than the required value to ensure that there is enough gas pressure in the blasting holes to form a long burst fracture.

The physical and mechanical rock indices are listed in Table 1. Considering these indices, theoretical research and engineering application results published by Zong et al. [33] and Wang et al. [34], it is found that the value of the decoupling coefficient is between 3.0 and 3.6. In this project,

Table 1: Rock physical and mechanical indexes.

Rock mass	Elasticity modulus (GPa)	Poisson ratio (μ)	Cohesion (MPa)	Internal friction angle (°)	Natural bulk density (kN.m^{-3})	Tensile strength (MPa)	Compressive strength (MPa)
Limestone	12.6	0.20	3.49	40.5	22.4	3.44	30.12

the presplit hole diameter is set 100 mm, and the cartridge diameter is set 32 mm, thus, the decoupling coefficient K_d is determined as 3.1.

2.3. Hole Spacing. (1) Since presplit hole spacing largely determines the blasting quality of the slope surface, the choose of the hole spacing should guarantee the explosive detonation formation of presplit cracks, while reserved rock mass is not damaged [35]. Only when the hole spacing is less than the length of the critical flaw can the cracks form between the blast holes [36], and the way forming such a crack can be approximated as

$$E = R_c + R_a, \tag{4}$$

where E is the hole spacing in mm; R_c and R_a are the length of cracks produced by the explosion stress wave and the blasting gas under the action of static pressure, respectively, which are calculated by:

$$R_c = r_b \left(\frac{\beta p_r}{S_t} \right)^{1/a}, \tag{5}$$

$$R_a = r_b \left(\frac{p_a}{S_t} \right)^{1/2}, \tag{6}$$

where S_t is the tensile strength of rock in MPa, r_b is the hole radius in mm, α is the stress wave attenuation index of rock in the equation $\alpha = 2 \pm \mu/(1-\mu)$, β is the proportionality coefficient of tangential and radial stresses in the equation $\beta = \mu/(1-\mu)$, μ is the rock's Poisson ratio, which takes "+" in shock wave action area and "-" in stress wave action area. As one of the main purpose for decoupling charging of the presplitting blasting is to eliminate shock wave action in rock, "-" is taken. p_r is the initial pressure produced on the hole wall of borehole when blasting gas expansion influence the hole wall, whose value is determined by Wang et al. [37]

$$p_r = \frac{n \rho_0 D^2 K_d^{-6}}{8 K_l} = \frac{n p_0 K_d^{-6}}{K_l}. \tag{7}$$

The following formula can be obtained:

$$E = r_b \left(\frac{n \beta p_0 K_d^{-6}}{S_t K_l} \right)^{1/a} + r_b \left(\frac{p_a}{S_t} \right)^{1/2}, \tag{8}$$

where n is the multiple pressure when blasting gas expansion affects the hole wall and is generally set to 8.

(2) In order to avoid compression damage around the hole wall, the sectional charging structure is adopted to reduce the charge, but the reasonable hole spacing should be selected to ensure the penetration of cracks between holes. The presplit hole spacing can be calculated by the following empirical formula [33]

$$a = d_b \left(21 D_e^{-1.4} + 47 D_e^{-2.4} \right), \tag{9}$$

where a is the presplit hole spacing in mm, d_b is the hole diameter in mm, and its value is 100 mm, D_e is the decoupling coefficient, with the value of 3.1. Therefore, $a = 7.4 d_b$ and the presplit hole spacing is taken as 0.8 m.

2.4. Linear Charge Density. Linear charge density is the ratio of charge quantity in a hole to charge length. It determines whether the cracks can run through between two adjacent holes, and the damage degree of rock on the hole wall. The empirical formula for calculating linear charge density can be referred to the following formula:

(1) Calculation formula by Changjiang Academy of Sciences:

$$q_l = 0.034 \left(\sigma_{cj} \right)^{0.63} a^{0.67}. \tag{10}$$

(2) Calculation formula by Gezhouba Engineering Bureau:

$$q_l = 0.367 \left(\sigma_{cj} \right)^{0.5} d^{0.36}. \tag{11}$$

(3) Calculation formula by Wuhan Institute of Water Resources and Hydropower:

$$q_l = 0.127 \left(\sigma_{cj} \right)^{0.5} a^{0.84} \left(\frac{d}{2} \right)^{0.24}, \tag{12}$$

where q_l is the linear charge density, and the unit is kg/m, σ_{cj} is the uniaxial compressive strength of rock, which takes as 30.12 MPa, a is the presplit hole spacing, which takes as 0.8 m, and d is the hole diameter, which takes as 0.1 m. Thus, the linear charge density is about 250~800 g/m.

2.5. Blast Hole Stemming. In presplitting blasting, the quality of hole stemming has a great influence on the energy utilization of explosive, the hole wall pressure, and the action duration, especially that completely depends on the blasting quasistatic pressure to destroy the rock mass. Therefore, it is necessary to ensure that the unloading time of the full lasting of the packing is greater than that of the gas pressure in the full lasting of the charge, so as to maximize the specific impulse transmitted to the rock.

Long stemming lasting can prolong the action time of the explosive gas, but it will cause no cracks or poor quality of cracks in the packing section. If the stemming is too

(a) Digital electronic detonator with 15 m wire

(b) A380 data collector detonator

Figure 1: Digital electronic detonator and priming equipment.

dense, it is easy to produce blasting funnel due to the lifting effect of the explosive gas. Therefore, the following empirical formula is used to determine the stemming length:

$$l_2 = (8 \sim 20)d, \tag{13}$$

where l_2 is stemming length, and the unit is m; d is the hole diameter, and the unit is mm. Therefore, according to the engineering experience, the stemming length is 1.0 m, and it can be compacted gently.

3. Field Tests of Presplitting Blasting

3.1. Selection of Explosives. The explosive used in the presplitting blasting should meet the basic performance indices of low detonation velocity, low brisance, low density, and good detonation transmission performance. According to the decoupling coefficient and the existing explosive in the mine, the 2# rock emulsion explosive with diameter of 32 mm is selected.

3.2. Selection of Detonator. The industrial electronic detonator uses electronic delay components to achieve delay function, and it can set and modify the delay time in the application site. It contains identity information and initiation password to control initiation. It can test its own integrity and conduct two-way communication. The detonator has high reliability, high stability, and strong anti-interference performance. The delay range is 0 ~ 10000 ms, and the minimum time interval is 1 ms. The detonator and digital electronic detonator are shown in Figure 1 as below. In this test, the digital electronic detonator with 15 m wire is adopted, and the delay accuracy is 1 ms.

3.3. Charge Structure of Blast Hole. When charging of the presplit holes, the following principles should be complied with: strengthen the charge at the bottom, keep normal charge in the middle, and weaken the charge at the top.

Table 2: Charge increase of reinforced charge section at the bottom of hole in presplitting blasting.

Depth of the hole L/m	<3	3 ~ 5	5 ~ 10	10 ~ 15	15 ~ 20
L_1/m	0.2 ~ 0.5	0.5 ~ 1.0	1.0 ~ 1.5	1.5 ~ 2.0	2.0 ~ 2.5
q_{l1} / q_l	1.0 ~ 2.0	2.0 ~ 3.0	3.0 ~ 4.0	4.0 ~ 5.0	5.0 ~ 6.0

Note: L_1 is the length of bottom stiffening charge section in meters; q_{l1} is the linear charge density of the reinforcement section of the presplit hole, and the unit is g/m; q_l is the linear charge density of the normal section of the presplit hole, and the unit is g/m.

The length ratio of the three sites can be taken as the experience distribution of 2 : 5 : 3. The empirical value of the added charge amount at the bottom of the hole can be selected by referring to Table 2.

Combined with the previous production experience of the mine, the lithology of the presplitting blasting produced in the nearest mine is the same as that in this test. The 2# rock emulsion explosive is used, and the average linear charge density of the whole hole is $q_l = 450$ g/m. The designed drilling depth in this project is $L = 9$ m, and the stemming length is 1.0 m. According to the actual conditions of the down-the-hole drill in the mine, vertical holes are made. The length of bottom stiffening charge section $L_1 = 0.2\,L = 1.6$ m, $q_{l1} = 4.0 q_l = 1800$ g/m; the length of middle normal charge section $L_2 = 0.5\,L = 4.0$ m, $q_{l2} = q_l = 450$ g/m; the length of top weaken charge section $L_3 = 0.3\,L = 2.4$ m, $q_{l3} = (1/3)$, $q_l = 150$ g/m. Therefore, the explosive quantity of a single blast hole is 5.0 kg. The charge structure of blast hole is shown in Figure 2, and the drilling and charging are shown in Figures 3 and 4, respectively.

3.4. Delay Time. Optimal delay time can not only induce the seismic waves which produced by the adjacent holes interfered with each other to reduce the blasting vibration effect, at the same time, it can also add new free faces for the post-detonation blast hole and increase the rock collision and

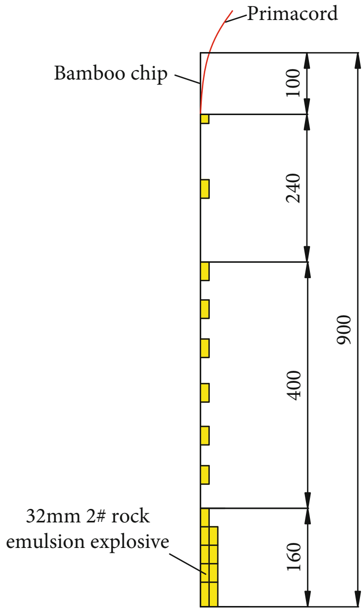

FIGURE 2: The charge structure of blast hole (unit: cm).

FIGURE 3: Down-the-hole drilling.

crushing to improve the rock blasting effect. Considering the stress wave and explosive gas energy [38], and correcting the semiempirical formula from previous study, a theoretical model of millisecond blasting delay time is obtained as follows:

$$\Delta t = t_1 + t_2 + t_3 = \frac{2W}{C_p} + \frac{2A}{V_t} + \frac{b}{V}, \tag{14}$$

$$C_p = \sqrt[2]{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}, \tag{15}$$

$$V_t = \frac{\pi r^2 C_0}{0.76Z}, \tag{16}$$

$$V = \frac{\pi r^2 a C_0}{2b\gamma Z}\left(\frac{Z}{C_0 t - H}\right)^{\gamma - a/\gamma}. \tag{17}$$

FIGURE 4: Air interval charging.

TABLE 3: Presplitting blasting parameters.

Bench height (m)	Hole depth (m)	Linear charge density (g·m^{-1})	Single hole charge (kg)	Delay time (ms)	Tilt angle (°)
9	9	450	5.0	12	90

When $r = \alpha$, the limit speed of crack propagation is as follows:

$$V_m = \frac{\pi r^2 C_0}{0.76Z}, \tag{18}$$

whereΔt is the delay time, t_1 is the time of elastic stress wave propagation to free face and return, t_2 is crack formation time under explosion stress wave, t_3 is crack formation time under explosion gas pressure, W is line of least resistance, C_P is elastic longitudinal wave velocity, A is failure radius of explosion stress wave, V_t is crack propagation velocity affected by explosion stress wave, b is crack propagation width affected by explosive gas pressure, V is crack propagation velocity under explosive gas pressure, it takes $0.25V_m$, E is the elastic modulus, ν is the Poisson ratio, ρ is the density, α is the fracture length under explosive gas pressure, C_0 is the swelling pressure, which is usually taken as 1.5 ~ 2.0 Pa, r is the blast hole radius, set as 50 mm, on the hole-by-hole detonated application, a takes 1.55, γ is the adiabatic exponent and it takes 1.4, L_b is the length of hole set as 9 m, $Z = 0.27L_b = 2.43$ m, $H = 0.83L_b = 7.6$ m. Therefore, in this test, the detonated delay time of presplit hole is taken as 12 ms.

3.5. Initiation Network. Only a row of 30 presplit holes was drilled and the hole spacing was 0.8 m, with the delay time between holes set to 12 ms. The presplitting blasting parameters of this test are shown in Table 3.

4. Blasting Effect and Analysis

4.1. Quality Evaluation of Presplitting Blasting. Half hole rate and plainness degree of slope are the main control items of presplitting blasting quality acceptance index [39]. The acceptance quality standard of half cast factor is shown in Table 4, and the plainness degree of slope should be less than ±150 mm.

In this test, the total drilled borehole length is 277.9 m, and the total length of reminded half hole on slope is 224.3 m, while the half cast factor of the presplitting blasting is 80.7%, with the degree of flatness of 130 mm. Therefore, the comprehensive evaluation of this presplitting blasting quality is good. The local flatness of the slope surface after the blasting is shown in Figure 5.

4.2. Blasting Vibration Test. During the construction process, in order to grasp the vibration situation of the reserved slope, TC-4850 blasting vibration tester is used for vibration monitoring (as seen in Figure 6), which is produced by Chengdu Zhongke Measurement and Control Co. Ltd.

Due to the high-steep slope, the vibration velocity might demonstrate amplification effect along the elevation, which must be taken into account. According to the domestic and foreign research results, the following experience formula (19) based on the blasting vibration propagation and attenuation rule is adopted [40–43].

$$v = K\left(\frac{\sqrt[3]{Q}}{D}\right)^{\alpha}\left(\frac{\sqrt[3]{Q}}{H}\right)^{\beta}, \tag{19}$$

where Q is the maximum detonation dose per delay in kg corresponding to the peak vibration velocity; D is the horizontal distance in m between the explosion center and the measuring point; H is the altitude difference in m between the explosion center and the measuring point; K is a coefficient related to the geological conditions, blasting method, and other external causes; α is seismic wave attenuation coefficient related to the geological conditions; and β is elevation effect coefficient.

With 30 groups of blasting vibration data during 10 times construction in the final highwall of Buzhaoba west slope, binary regression analysis and calculation gives $\gamma = 0.86$, $K = 189.31$, $\alpha = 1.84$, and $\beta = 0.51$. Putting these data into the particle vibration velocity formula of west slope, the following formula can be achieved:

$$v = 189.31\left(\frac{\sqrt[3]{Q}}{D}\right)^{1.84}\left(\frac{\sqrt[3]{Q}}{H}\right)^{0.51}. \tag{20}$$

4.3. Damping Effect. The vibration test is divided into two groups. The first group is the simultaneous detonated of presplit holes [44], and the second group is presplit holes detonated hole-by-hole [45]. Through blasting vibration monitoring, the damping effect of the two groups is evaluated.

4.3.1. Presplit Holes Simultaneous Detonated. Due to space limit, only five different groups of the maximum detonation dose per time are chosen to be used for analysis of presplitting blasting vibration reduction ratio, and the result is listed in Table 5. Here, Q is the maximum single dose of each blasting, P_n is the number of measured points, D is the horizontal distance between the explosion center and the measuring point, H is the altitude difference between the explosion center and the measuring point, v_m is the measured velocity, v_t is the theoretical velocity, N is the vibration reduction rate, and N_{av} is the average damping rate.

In this site, the position is mainly located in the 1200 m level, and the measure points are, respectively, set in 1200 m, 1210 m, and 1220 m level, as shown in Figure 7.

From Table 5, it is shown that with the increase of the maximum single dose, the damping effect of the presplitting blasting is more and more significant when meeting design requirements, and the vibration reduction rate can even reach up to 40.14% with the average damping rate of 26.40%.

4.3.2. Presplit Holes Detonated Hole-by-Hole. From Table 6, it can be seen that the vibration reduction rate can even reach up to 55.38%, and the average damping rate is

Table 4: Acceptance of presplitting blasting standard according to half cast factor.

Lithologic characters	Hard rock (I ~ II)	Medium-hard rock (III)	Weak rock (IV ~ V)
Half cast factor (η)	$\eta \geq 80$	$\eta \geq 60$	$\eta \geq 30$

Note: $\eta = \sum l_0 / \sum L_0$, l_0 is the total length of reminded half hole on slope, and L_0 is the total length of drilled borehole on the slope.

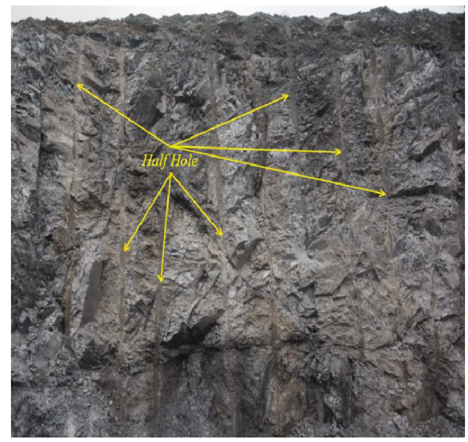

Figure 5: The slope surface smooth effect.

Figure 6: TC-4850 blasting vibration tester.

Table 5: Comparative analysis of blasting vibration by presplit holes simultaneous detonated.

Q (kg)	P_n	D (m)	H (m)	v_m (cm/s)	v_t (cm/s)	N (%)	N_{av} (%)
	1#	70.0	1.5	2.97	4.42	32.79%	
510	2#	85.0	11.5	1.53	2.16	29.33%	31.42%
	3#	110.0	21.5	0.64	0.94	32.16%	
	1#	82.0	1.5	2.64	3.54	25.52%	
455	2#	100.0	11.5	1.30	1.47	11.44%	25.70%
	3#	123.0	21.5	0.44	0.74	40.14%	
	1#	80.0	1.0	2.75	3.47	20.78%	
443	2#	94.0	11.0	1.29	1.75	26.08%	23.30%
	3#	110.0	21.0	0.65	0.84	23.05%	
	1#	83.0	1.2	2.75	3.79	27.39%	
410	2#	110.0	11.2	0.91	1.14	19.84%	27.43%
	3#	135.0	21.2	0.44	0.68	35.05%	
	1#	85.0	0.5	2.96	3.64	18.78%	
345	2#	115.0	10.5	0.87	1.18	26.38%	24.16%
	3#	140.0	20.5	0.43	0.59	27.32%	

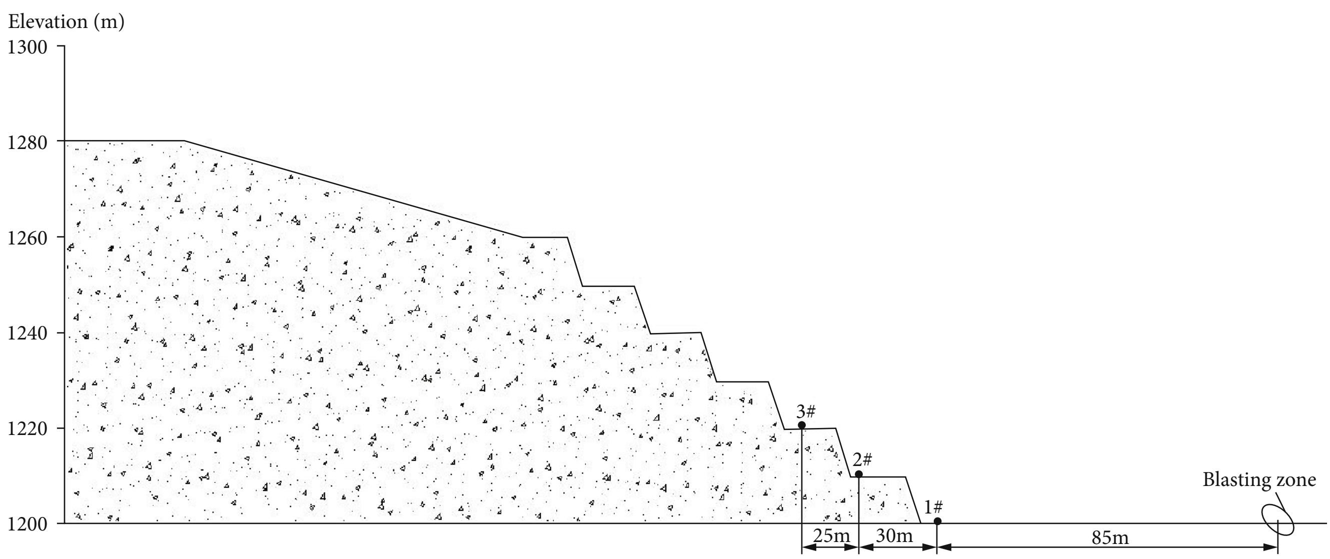

Figure 7: The schematic diagram of monitoring points arrangement.

Table 6: Comparative analysis of blasting vibration by presplit holes detonated hole-by-hole.

Q (kg)	P_n	D (m)	H (m)	v_m (cm/s)	v_t (cm/s)	N (%)	N_{av} (%)
	1#	70.0	1.0	1.78	3.98	55.25%	
446	2#	90.0	11.0	1.04	1.75	40.72%	47.36%
	3#	120.0	21.0	0.39	0.72	46.10%	
	1#	75.0	0.5	1.74	3.57	51.30%	
395	2#	100.0	10.5	0.90	1.31	31.50%	44.21%
	3#	120.0	20.5	0.33	0.66	49.84%	
	1#	90.0	1.0	1.65	2.35	29.77%	
355	2#	110.0	11.0	0.88	1.01	13.22%	32.79%
	3#	120.0	21.0	0.27	0.61	55.38%	

41.45%. When the presplit hole is detonated one by one, the vibration caused by the presplit hole blasting is reduced. Compared with the simultaneous detonated of presplit holes, the blasting vibration is reduced by 15.05%.

5. Conclusions

Based on the field test of high and steep slope mining in open-pit mine, this paper analyzed the difference between the traditional presplitting blasting and precracking hole-by-hole initiation blasting technology, and the following results are obtained:

(1) The calculation method for determining presplitting blasting parameters is summarized, and the parameters of presplitting blasting in the studied experiment site are determined as follows: hole diameter is 100 mm; cartridge diameter is 32 mm (decoupling coefficient $K_d = 3.125$); hole spacing is 0.8 m; charge density is 450 g/m; filling length is 1.0 m; and delay time between hole-by-hole is 12 ms

(2) The precise time-delay hole-by-hole initiation technology based on digital electronic detonator meets the requirements of presplitting blasting. The half-hole ratio of this test is 80.7%, and the irregularity is about 130 mm

(3) The comparison between the field measured vibration velocity value and the theoretical value under the two kinds of pre-splitting blasting schemes in the west slope shows that the average vibration reduction rate of the simultaneous presplitting blasting is 26.40%, and the vibration reduction rate of single-hole presplitting blasting can reach 41.45%. The vibration reduction effect is significant, and the wall smoothness can meet the requirements of relevant specifications

In total, it is shown that the precise delay blasting technology based on digital electronic detonator has a higher vibration reduction rate, which meets the requirements of slope wall smoothness, and has a very important significance for improving the excavation quality of open-pit to boundary slope and maintaining the long-term stability of slope.

Data Availability

The data used to support the findings of this study areincluded in the article.

Disclosure

Xianglong Li is the co-first author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Conceptualisation, methodology, validation, data curation, visualisation, and writing—original draft preparation were done by J.W. and J.M.; experimental guidance and data analysis were performed by X.L.; theoretical analysis was done by Q.L. and T.Z.; field test guidance was done by X.Z. and Z.T.; formal analysis writing—review and editing was done by all authors. All authors have read and agreed to the published version of the manuscript.

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