Research Article

Experimental Study of Blast-Induced Vibration Characteristics Based on the Delay-Time Errors of Detonator

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The delay-time of detonators in hole-by-hole blasting is generally calculated accurately considering they have great influence on the blasting effect, such as blasting vibration and blasting slungshot. The high-precision nonel detonator and digital electronic detonator are been commonly used because of their accuracy of delay-time. However, each detonator has an allowable error range of delay-time due to the difference in manufacturing process. In the initiation network, the errors of delay-time often accumulate gradually as the number of detonators increases. Therefore, theoretical delay-time and actual delay-time with error in the detonating network were discussed based on the delay-time errors of detonators. The single-factor variable method was used to carry out the comparative test in deep hole blasting. The results showed that the particle peak vibration velocity (PPV) was 13.1783 cm/s and 3.4856 cm/s with a drop of 73.55% in comparison with a nonel detonator and digital electronic detonator, which proved that hole-by-hole blasting in the high-precision nonel detonator network was not achieved due to the delay error of detonators. Furthermore, the location distribution map of holes where the same section of detonators might occur was obtained. Finally, the probability of blasting in the same section changes with the number of blast holes was discovered by theoretical analysis, which provided a basis for accurate hole-by-hole blasting.

1. Introduction

Blasting is one of the most efficient methods for excavation in mines, hydropower projects, and tunnel. However, it also brings some harmful effects, such as blast-induced vibration. Many methods have been considered to research blast-induced vibration. Different empirical formulae and prediction models were established to explore the relationship between charge weight per delay and peak particle velocity (PPV) based on blast-induced monitoring data [1–4]. The influence of geological conditions on blast vibration was revealed combining blasting tests and numerical simulation [5–8]. Singh et al. [9] illustrated the impact of blast-induced vibration on the roof and sidewalls of underground mine caused by open-pit mining. Lu et al. [10] calculated the

equivalent blast load applied to the blast hole wall in different blasting and estimated the peak blasting load and peak particle velocity through the commercial dynamic FEM software ANSYS/LS-DYNA. Singh and Roy [11] demonstrated the damage of blast-induced vibration to reinforced concrete and cement mortar structure using blast vibration monitoring. Blair [12] proved the influence of charge weight on blast vibration during surface blasting and underground blasting, which showed that the charge weight had a great impact on surface blasting but less on underground blasting. The support vector machine was applied to predict blast-induced vibration after 80 blasting works in a dam [13].

Some attempts have been made to confirm that millisecond blasting technique was the most effective method to control blast-induced vibration by accurately designing the

initiation interval time of each blast hole [14]. The studies on delay-time were gradually increasing. Short-delay blasting has been proposed to reduce the charge weight per delay to reduce the peak particle velocity [15]. The new methodology was put forward to analyze seismic properties during blasting in different geology conditions to ensure the optimal delay-time [16, 17]. Qiu et al. [15] reported the stress wave superposition characteristics in short-delay blasting with numerical simulation.

However, researchers mainly focused on the length of delay-time and believed that hole-by-hole blasting could be realized by accurately designing the delay-time in each hole to reduce blast-induced vibration. The mechanism of delay-time in different kinds of detonators has nothing in common. At present, high-precision detonators and digital electronic detonators are most commonly used in hole-by-hole initiation technology. The former realize the delay-time through chemicals in detonators, and the latter use electronic chips. Both of them have delay-time errors. The delay errors of detonators would affect blast-induced vibration by changing the initiation time of blast hole. So far, few research studies concentrated on delay-time errors of detonators. This paper focuses on the influence of delay-time errors of detonators on blast-induced vibration thorough theoretical analysis and field experiments.

2. Delay-Time Errors Mechanism

2.1. Theoretical Delay-Time. In millisecond blasting, the postblast hole is delayed tens of milliseconds compared with the preblast hole, and the postblasting blast hole is in the state of prestress under the stress and vibration of the adjacent blasting, which strengthen the blasting effect of postblasting on the surrounding rock.

The delay-time per blast hole can be expressed as follows,

$$T_{ij} = t_{ij} + (j-1)t_a + (i-1)t_b, \quad (1)$$

where T_{ij} is the total theoretical delay-time in blast hole No. i , row No. j ; t_{ij} is the delay-time of the detonator in blast hole No. i , row No. j ; t_a is the delay-time of the surface detonator between two holes; and t_b is the delay-time of detonators between two rows.

The delay-time difference any two holes in the initiation network is as follows:

$$\begin{aligned} \Delta t &= T_{AB} - T_{CD} \\ &= (t_{AB} - t_{CD}) + (B-D)t_a + (A-C)t_b, \end{aligned} \quad (2)$$

when $\Delta t \neq 0$, hole-by-hole blasting can be realized.

2.2. Actual Delay-Time. Because high-precision detonators are delayed by chemical agents, they have larger delay-time errors due to the influence of chemical dosage and properties compared with digital electronic detonators. The actual delay-time of the high-precision detonator is as follows:

$$T'_{ij} = (t_{ij} \pm \eta_{ij}) + (j-1)(t_a \pm \eta_a) + (i-1)(t_b \pm \eta_b), \quad (3)$$

where T'_{ij} is the total actual delay-time of blast hole No. i , row No. j ; η_{ij} is the delay-time error in blast hole No. i , row No. j ; η_a is the delay-time error of the surface detonator between two holes; η_b is the delay-time error of detonators between two rows.

The delay-time of surface detonators in open-pit deep hole blast generally adopted 17 ms, 25 ms, 42 ms, and 65 ms. The delay-time in blast hole was 400 ms, and the delay-time errors [18, 19] are shown in Table 1.

The delay-time errors of high-precision detonators were larger than that of the digital electronic detonator, and the delay-time of high-precision detonators has been identified before delivery. When there are many blast holes in a blasting, the delay-time errors accumulated gradually between rows and holes, and the delay-time of two holes may overlap as shown in Figure 1.

When $T'_{AB} \cap T'_{CD} \neq \emptyset$, two blast holes can realize hole-by-hole blasting.

2.3. Initiation Probability of the Same Section. When high-precision detonators are used for surface detonation, the delay-time errors of detonators gradually accumulate with the number of surface detonators; then, the probability of the same section blasting of two blast holes will increase with the increase of the blasting scale, and the probability of the same section blasting is as follows:

$$P = \text{MAX} \left[\frac{T'_{ij} \cap T'_{(i-m)(j-n)}}{T'_{ij} \cup T'_{(i-m)(j-n)}} \right]. \quad (4)$$

3. Experimental Procedure

3.1. Experiment Scheme. In order to analyze the influence of delay-time error of detonators on the blast-induced vibration, the digital electronic detonator and high-precision detonator were used to carry out comparative tests. The areas of comparative test blasting were selected in two adjacent positions of 1135 m steps in Panzhuhua iron mine. The structure of ore completes with few joints and fissures, in which the compressive strength was 140 MPa.

In the process of blasting tests, the single factor variable is used to compare the test results, that is, the hole network parameters of the two blasting areas are the same, as shown in Table 2.

According to the actual situation of the mine, three rows of blast holes were arranged in the two blasting areas, eight blast holes were arranged in the front two rows, and other seven blast holes were arranged in the last row. All were charged with emulsion explosive on site (Figure 2). The total charge of single blasting is 14 tons, only the detonators were different, and the plum-shaped holes were used. The delay-time in the blasting holes was 400 ms, the delay-time between holes was 25 ms, and the delay-time between rows was 65 ms, as shown in Figures 3 and 4.

TABLE 1: Delay-time error of different detonators.

High-precision detonator		Digital electronic detonators	
Delay-time (ms)	Error (ms)	Delay-time (ms)	Error (ms)
17	± 2	0–500	< 1
25	± 2	501–16000	$< 0.2\%$
42	± 2		
65	± 2		
400	± 5

FIGURE 1: The influence of delay error. (a) Theoretical delay-time. (b) Actual delay-time.

TABLE 2: Blasting test parameters.

No.	Parameters	Unit	Value
1	Bench height	m	15
2	Hole diameter	mm	250
3	Inclination of borehole	—	90
4	Depth of blast hole beyond step	m	2.5
5	Hole depth	m	17.5
6	Toe burden	m	6.5
7	Pitch-row	m	8
8	Pitch-array	m	7
9	Specific charge	kg/m ³	0.72
10	Maximum charge of single hole	kg	606
11	Linear meter charge	kg/m	68
12	Stemming length	m	7–8.5

FIGURE 2: Site mixed emulsion explosive blasting.

3.2. Delay Time Analysis. By analyzing the delay-time error of different detonators, it was found that the delay error of the digital electronic detonator had no effect on the initiation network because of its small errors. However, the delay error

of the high-precision nonel detonator was also small, and the cumulative error was large, so it had great influence on the whole initiation network, as shown in Figure 5. The accumulated errors were 19 ms, 21 ms, and 23 ms from the first

FIGURE 3: High-precision detonator blasting network.

FIGURE 4: Digital electronic detonator blasting network.

row to the third row, respectively. Obviously, the delay-time errors grow with the increase of blasting row number in the high-precision nonel detonator network.

3.3. Test Equipment

3.3.1. Device Parameters. Blast-induced vibration was monitored by the L20-S blasting vibration tester of JiaoBo Technology. The main performance parameters were as follows.

- Number of channels: parallel acquisition of three channels;
- Frequency range: 5Hz-500 Hz;
- Amplitude range: 0.001 cm/s-35.5 cm/s;
- Test accuracy: test accuracy $\pm 5\%$ and reading accuracy 0.01%;
- Trigger level: 0.001 cm/s-35.5 cm/s, continuously adjustable.

3.3.2. Measuring Point Arrangement. After blasting networks were connected, L20-S blasting vibration testers were arranged at 55 m, 65 m, and 75 m away from the blasting source to monitor the blast-induced vibration speed, as shown in Figures 6 and 7.

4. Result and Discussion

4.1. Experimental Results. It is found that the blast-induced vibration of the high-precision detonator was reduced by 60% more than the digital electronic detonator. The blast-induced vibration results at 65 m distance were compared and analyzed, as shown in Figure 8.

According to the blast-induced vibration data (Figure 9), the maximum blast-induced vibration velocity of the digital electronic detonator and high-precision detonator in X direction was 2.224 cm/s and 13.1783 cm/s, respectively, and the amplitude was reduced by 83.12%; the maximum blast-induced vibration speed in Y direction was 1.5523 cm/s and 5.9929 cm/s, and the

FIGURE 5: Delay-time error of different rows. (a) First row. (b) Second row. (c) Third row.

FIGURE 6: Layout of the blasting vibration tester.

amplitude was reduced by 74.10%; the maximum blast-induced vibration speed in Z direction was 3.4856 cm/s and 9.3371 cm/s, respectively, and the amplitude was reduced by 62.67%. The PPV in three directions was 13.1783 cm/s and 3.4856 cm/s, with a decrease of 73.55%.

5. Discussion

According to the blasting safety regulations [20], the formula of blast-induced vibration velocity can be expressed as follows:

FIGURE 7: Site layout of the blasting vibration tester. (a) L20-S blasting vibration meter. (b) Site layout of measuring points.

FIGURE 8: Blasting vibration velocity. (a) X-direction, (b) Y-direction, and (c) Z-direction.

FIGURE 9: The particle peak vibration velocity.

FIGURE 10: Probability distribution of blasting in the same section.

$$V = K \cdot \left(\frac{Q^{1/3}}{R} \right)^\alpha \quad (5)$$

The blast-induced vibration velocity was proportional to the blasting charge (equation (5)) due other parameters (K, R, α) that were same in an iron mine. While the blast-induced vibration velocity of high-precision detonators was

higher than that of the digital electronic detonator, which showed that the high-precision detonator had not really realized the hole-by-hole blasting due to the delay-time error, several blast holes are blasted in the same section.

According to the delay-time errors of the high-precision detonator, the delay-time of each hole in the blasting area was analyzed. The delay-time rule of blast holes is as follows,

$$\left\{ \begin{array}{l} T'_{1j} = T_{1j} \pm 2, \left(j + \frac{3}{2} \right), \\ T'_{2j} = T_{2j} \pm 2, \left(j + \frac{5}{2} \right), \\ T'_{3j} = T_{3j} \pm 2, \left(j + \frac{9}{2} \right), \\ \dots\dots\dots \\ T'_{ij} = T_{ij} \pm 2 \left[j + \frac{(2^i + 1)}{2} \right]. \end{array} \right. \quad (6)$$

FIGURE 11: Probability of the same section blasting with the increase of the number of holes.

Taking this blasting comparative test as an example, the theoretical delay-time of the high-precision detonator in the blast hole was 400 ms, and the delay-time between holes and rows was 25 ms and 65 ms. Then, the actual delay-time of each hole in three rows and the holes that may be detonated in the same section is shown in Figure 10. The holes with the same color distribution may be blasted in the same section.

In Figure 10, the actual delay-time area of blast holes marked with the same color overlaps, which was likely to detonate at the same time, i.e., K_{13}, K_{21} ; K_{14}, K_{22} ; K_{15}, K_{23} ; K_{16}, K_{24}, K_{32} ; K_{17}, K_{25}, K_{33} ; K_{18}, K_{26}, K_{34} ; K_{27}, K_{35} ; and K_{28}, K_{36} , which were likely to blast with two or three blast holes at the same time, resulting in blast-induced vibration was greater than the expected result. It can be seen that the number of single row of blast holes and single row of blasts increases with the increase of the blasting scale. The number of blast holes in the same section increased gradually when using high-precision detonators. When using 3×2 (3 holes in a row, 2 rows) hole network structure, two blast holes in the same section may occur. When using 5×3 hole network structure, three blast holes in the same section may occur. When using $(2n-1) \times n$ (when $n \geq 2$) network structure, n holes may blast in the same section.

The probability of blasting in the same section increased as the number of blast holes increases through equation (4), and the probability of initiation in the same section No. 3–8 holes was 2/32, 6/36, 10/40, 14/44, 18/48, 22/52, respectively, as shown in Figure 11.

After regression analysis, it is found that with the increase of the number of holes row, the probability of the same section blasting is as follows,

$$P = \frac{2 + 4(n - 3)}{32 + 4(n - 3)} \quad (n \geq 3). \quad (7)$$

6. Conclusions

- (1) Based on the delay-time errors of high-precision detonators, the calculation formula of theoretical delay-time and actual delay-time of single hole in the initiation network was obtained through theoretical

analysis, and the general formula of blasting probability in the same section was analyzed.

- (2) In view of the characteristics of 25 ms delay-time between surface holes, 65 ms delay-time between rows, and 400 ms delay-time of blast holes in open-pit deep blasting, the comparative test of blast-induced vibration is carried out by using the high-precision detonator and digital electronic detonator, respectively. The blast-induced vibration produced by high-precision detonator blasting was obviously greater than that of the digital electronic detonator, and the PPV was 13.1783 cm/s and 3.4856 cm/s, with a drop of 73.55%. It was proved that different blast holes may have the same section of blasting, and the hole-by-hole initiation is not realized due to the delay-time errors of high-precision detonators.
- (3) Through the analysis of the test results, it was found that the actual delay-time could be expressed as $T_{ij}^i = T_{ij} \pm 2[j + (2^i + 1)/2]$ due to the delay-time errors of high-precision detonators. With the increase of the blasting scale, the probability of the same section blasting increases gradually, and the probability of the same section blasting can be expressed as $P = (2 + 4(n - 3)/(32 + 4(n - 3)) (n \geq 3))$.
- (4) The test results showed that the digital electronic detonator is recommended for the hole-by-hole initiation network to improve the blasting scale, increase the blasting efficiency, and reduce the impact of blasting vibration on the stability of high slope.

Data Availability

The data used to support this study are available within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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