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Research Article

Mechanism and Application of Blasting Technology Using Phase-Difference Vibration Mitigation on Adjacent Railway Tunnel

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The blasting vibration velocity is a widely used controlling index for the safety assessment of tunnel structures. How to reduce the impact of blasting vibration on the operation of adjacent railway tunnels is worth studying. In this paper, the initial phase-difference of blasting using phase-difference shock absorption is derived from the propagation theory of the blasting stress wave. When the initial phase-difference is $\Delta\varphi_i = \pm(2n+1)\pi$ ($n = 1, 2, 3, \ldots$), the peak particle velocity (PPV) in the tunnel structure is decreased to the minimum. On the basis of blasting theory using phase-difference shock absorption, the blasting parameters were designed for the No. 2 drainage tunnel excavated which adjacent a railway tunnel from Guiyang to Changsha, and it carried out 4 times blasting tests. It was found that the PPV of the railway tunnel structure in X, Y, and Z directions reduced by 64.6%, 66.25%, and 81.26%, respectively, which compared with the conventional blasting with the same total quality. Meanwhile, the amount of overbreak and underbreak can be controlled within 5%. The results show that the effect of blasting technology using phase-difference vibration mitigation is obvious, which is able to match with the design requirements for the tunnel excavation contour. The blasting technology using phase-difference vibration mitigation can be achieved via controlling the blasting time interval accurately. Moreover, it is beneficial for enriching and developing the blasting vibration control technology.

1. Introduction

As the most common method for tunnel excavating, drilling and blasting technology are widely used in tunnel construction all over the world. This technology can make use of the energy which is generated by the explosion of high-energy explosives to break the rock mass and form the tunnel section. During blasting, the explosives instantly release huge amounts of energy and propagate from the explosion center outward in the form of seismic wave [1–4]. On the microscopic level, it shows the transmission and dissipation of explosion energy. From the macroscopic point of view, it represents that the particle vibration is caused by the seismic wave which is produced by blasting [4–6].

The blasting vibration velocity is benefited from the convenient measurement which is widely used for the controlling index on the structure safety assessment [7, 8]. Actually, both the blasting parameters and the characteristics of surrounding rock have important influence on PPVs, such as the maximum quantity of single blasting, the propagation velocity of surrounding rock, and the distance between the structure and the explosion center [9–12]. The damage ranges of tunnel lining and different surrounding rock under the blasting load through field tests were proposed by previous studies, which provide a reference for blasting damage controlling on surrounding rock [13, 14]. In fact, the concrete structure works with the microcracks, when the blasting vibration velocity exceeds a certain limit value that will lead the microcracks extending into a larger crack. As a consequence, it will reduce the safety and durability of the concrete structure. In recently years, the damage of tunnel lining and surrounding rock under explosion load has also been investigated [15–17]. To obtain the propagation law of blasting seismic wave, some scholars conducted research on the energy attenuation law of seismic wave propagation during the process of blasting on the basis of seismic wave theory [18–21]. The results would be a benefit for revealing the propagation characteristics of blasting stress waves. In another study presented by Yang et al. [22], blasting excavation and the frequency characteristics of blasting vibration based on the vibration frequency of high-stress rock mass were obtained. In terms of reducing the degree of damage, the blasting method of phase-difference shock absorption using the electronic detonator to effectively control the structural vibration response has been proposed [23]. These research results above have been applied to blasting vibration controlling in civil engineering. Simultaneously, these research studies also provide a theoretical basis for blasting using phase-difference shock absorption. However, due to the complexity of tunnel geological conditions, the blasting parameters cannot be unified, and the control of structural vibration velocity in the blasting of adjacent railway tunnels needs to be further explored. In this research, based on a practical project, the phase-different shock absorption method suitable for tunnel excavation blasting near an existing railway is proposed.

Previous studies have shown that the superposition and attenuation of stress waves for porous blasting are related to both the time difference of detonation and the physical property of the surrounding rock [12]. With the development and application of digital electronic detonator technology [24, 25], it is possible to reduce the blasting vibration velocity by the time difference of detonation on the basis of the superposition principle of blasting stress waves. Subject to the complexity of the actual working conditions, the amount of experimental and theoretical research conducted in this area is very limited; especially in a new tunnel excavation adjacent railway tunnel, the construction standard is extremely strict and the specification cannot be unified. In this paper, based on the characteristics of the stress wave, the vibration damping mechanism of the blasting stress wave is derived from the wave superposition theory. By means of the phase-difference shock absorption of blasting design and field test, combined with the theory and experimental data, the blasting parameters using phase-difference shock absorption for tunnel excavation are effective in reducing blasting vibration, which is of great significance to enrich the application of blasting vibration reduction theory.

2. Propagation Characteristics of Blasting Stress Wave

2.1. Effect of Blasting Vibration. The effect of blasting vibration is a phenomenon that the energy propagates in the form of an elastic wave in the rock mass or other medium, which causes blasting vibration within a range of spatial areas, as shown in Figure 1 [18, 26, 27]. Meanwhile, the particle of medium to reciprocate in a straight line or a curve along its equilibrium position is caused by the blasting stress wave, and it changes periodically over time, where the phenomenon of mass points can be called "mechanical vibration." Actually, the elastic wave generated by blasting earthquakes drives the particle of medium to generated mechanical vibrations, which can be described by a wave equation.

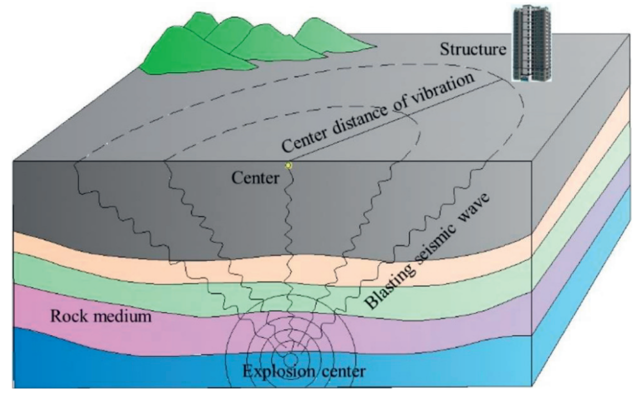


Figure 1: Diagram of blasting vibration effect.

2.2. Blasting Wave Theory. It is well known that a common way of energy transfer is in the form of waves. The energy is produced by blasting that makes the particle of medium move back and forth in the form of mechanical waves as well, and the distance from the equilibrium position changes with time [28–30]. It can be described by a cosine function as follows:

$$y = A\cos(\omega t + \varphi), \tag{1}$$

where y is particle displacement, A is the amplitude, ω is the angular frequency, and φ is the initial phase.

The relationship between the angular frequency ω and the frequency f is as follows:

$$\omega = 2\pi f. \tag{2}$$

During blasting, the expression of peak particle velocity in the medium can be derived from (1), and it can establish the function as follows:

$$v = -A\omega\sin(\omega t + \varphi). \tag{3}$$

3. Theory of Blasting Using Phase-Difference Shock Absorption

Drilling and blasting are ways to form underground space by segmented detonation in different types of blast holes. In order to achieve the purpose of shock absorption, the principle of blasting technology using phase-difference vibration mitigation is controlling the time difference between the detonations of each blast hole in the process of tunnel blasting.

Assuming that the blasting stress waves are generated by the explosion center of two holes, the S1 and the S2 are transmitted to one particle at the same time; this particle would be affected by the two waves, as shown in Figure 2.

If the particle propagates in the x direction and the vibration in y direction, and when the two columns of stress wave propagations start at the same time, the vibration equation is as follows:

$$
\begin{aligned}
y_1 &= A_1 \cos(\omega t + \varphi_1), \\
y_2 &= A_2 \cos(\omega t + \varphi_2).
\end{aligned} \tag{4}
$$

Since the wave propagation has the characteristics of directionality, which follows the principle of vector synthesis, as shown in Figure 3. When the two waves are superimposed, the angle between A_i and y axis is φ_i, and the projection of A in the y-axis direction is as follows:

$$
\begin{aligned}
y_i &= y_1 + y_2 \\
&= A_i \cos(\omega t + \varphi_i).
\end{aligned} \tag{5}
$$

On the basis of the parallelogram law, the calculation formula of the sum amplitude is as follows:

$$A_i = \sqrt{A_1^2 + A_2^2 + 2A_1A_2 \cos(\varphi_2 - \varphi_1)}. \tag{6}$$

On account of the same direction and the same frequency of the longitudinal wave, $\varphi_i = \varphi_2 - \varphi_1$ is independent of time. Thus, the amplitude of the combined vibration A_i is independent of the beginning time. Whether the amplitude A_i is strong or weak depends on the difference of the initial phase by the two waves, as shown in Figure 4.

When the difference of the initial phase for the two waves meets the conditions $\Delta\varphi_i = \varphi_2 - \varphi_1 = \pm(2k+1)\pi$ ($k = 0, 1, 2, 3, \ldots$), $\cos(\varphi_2 - \varphi_1) = -1$. The combined amplitude can be calculated by the following equation:

$$
\begin{aligned}
A_i &= \sqrt{A_1^2 + A_2^2 - 2A_1A_2} \\
&= |A_1 - A_2|.
\end{aligned} \tag{7}
$$

That is to say, when the difference of the initial phase is $\Delta\varphi_i = \varphi_2 - \varphi_1 = \pm(2k+1)\pi$ ($k = 0, 1, 2, 3, \ldots$, n), the combined amplitude is the difference between the two amplitudes that reaches the minimum value at this time.

Provided that the third wave and the following waves are ($n = 3, 4, 5, \ldots$), the vibration equation is as follows:

$$y_3 = A_3 \cos(\omega t + \varphi_3). \tag{8}$$

$$y_n = A_n \cos(\omega t + \varphi_n). \tag{9}$$

The formula for the amplitude of y_3 and y_i after superposition can be derived as follows:

$$A_{i+1} = \sqrt{A_i^2 + A_3^2 + 2A_iA_3 \cos(\Delta\varphi_i - \varphi_3)}. \tag{10}$$

When the phase difference of the two waves of y_3 and y_i satisfied $\Delta\varphi_{i+1} = \Delta\varphi_i - \varphi_3 = \pm(2k+1)\pi$ ($k = 0, 1, 2, 3, \ldots$), $\cos(\Delta\varphi_i - \varphi_3) = -1$. The combined amplitude can be calculated as follows:

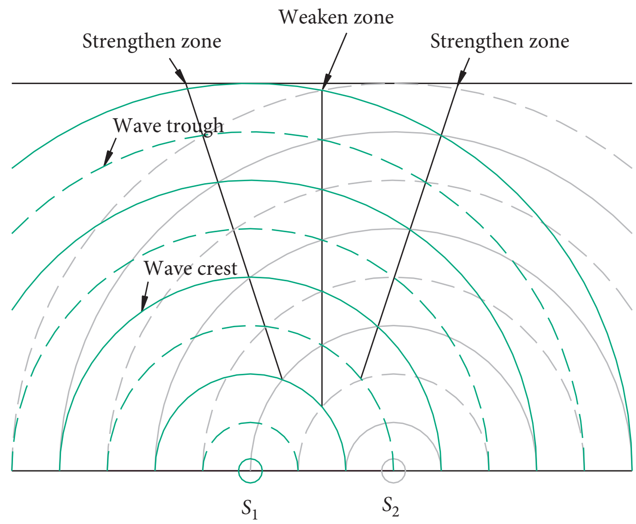


Figure 2: Phase superposition model of blasting stress wave.

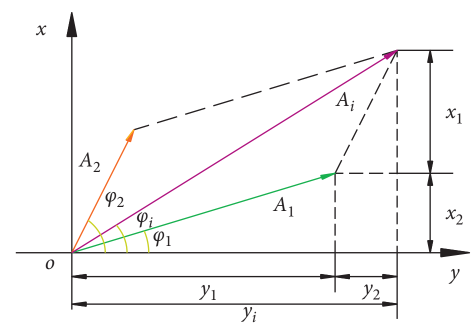


Figure 3: Vector synthesis.

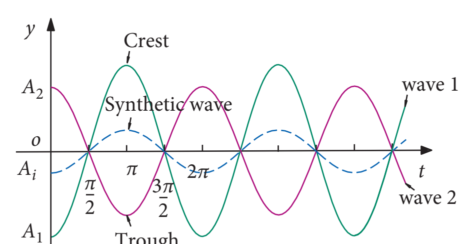


Figure 4: Stress wave superposition model.

$$
\begin{aligned}
A_{i+1} &= \sqrt{A_i^2 + A_3^2 - A_iA_3} \\
&= |A_i - A_3|.
\end{aligned} \tag{11}
$$

Similarly, the formula of the amplitude after the multiwaves is superimposed one after other as follows:

$$A_{i+n-2} = \sqrt{A_{i+n-3}^2 + A_n^2 + 2A_{i+n-3}A_n \cos(\Delta\varphi_{i+n-3} - \varphi_n)}. \tag{12}$$

Likewise, when the phase difference of the two waves of y_{i+n-2} and y_n satisfied $\Delta\varphi_{i+n-2} = \Delta\varphi_{i+n-3} - \varphi_n = \pm(2k+1)\pi$ ($k = 0, 1, 2, 3, \ldots$, and $n = 3, 4, 5, \ldots$.),

$\cos(\Delta\varphi_{i+n-3} - \varphi_n) = -1$.The combined amplitude can be calculated by the following equation:

$$\begin{aligned} A_{i+n-2} &= \sqrt{A_{i+n-3}^2 + A_n^2 - 2A_{i+n-3}A_n} \\ &= \left|A_{i+n-3} - A_n\right|. \end{aligned} \tag{13}$$

In other words, when the phase difference $\Delta\varphi_{i+n-2} = \Delta\varphi_{i+n-3} - \varphi_n = \pm(2k+1)\pi$ ($k = 0, 1, 2, 3, \ldots$, and $n = 3, 4, 5, \ldots$.), the amplitude is the difference between the two amplitudes, it is the minimum value at this time. Actually, this is the main principle of blasting technology using phase-difference shock absorption.

4. Engineering Application

4.1. Engineering Background. The karst conduit in limestone strata is well developed and often connected with the surface. Therefore, tunnel construction in limestone strata is often affected by heavy rainfall. For instance, in one of the railway tunnels from Changsha to Guiyang, a large amount of rainwater flowed into the tunnel through the karst conduit which was affected by torrential rain, as shown in Figure 5. The operation safety of railway tunnels is greatly threatened by this extremely heavy rainfall.

In order to reduce the risk of railway tunnel operation, the drainage tunnel needs to be built to drain the groundwater in the surrounding strata of the railway tunnel. The No.1 and No.2 drainage tunnels are built in between the original drainage tunnel, and the karst cave catchment area is shown in Figure 6. Meanwhile, from the section D1K640 + 205 to D1K640 + 260 of this railway tunnel, a catchment tunnel parallel to the railway tunnel was constructed at a distance of 2.1 m away from the tunnel, as shown in Figure 6. The project has played a role in the drainage and reduction of water pressure in the water-abundant section of this railway tunnel, which could be more effective in the stability of the lining structure and the safety of long-term operation in this tunnel.

The original designs of the No.1 and No.2 drainage tunnels were excavated by a machine. However, the surrounding rock was revealed to be limestone with the compressive strength of 51.3 MPa, and the mechanical properties of surrounding rock are excellent. Obviously, the drainage tunnel excavated by a machine could not be carried out. Finally, the drilling and blasting technology has been adopted for drainage tunnel excavation determined by engineers. So far, it is the first time that the drainage tunnel is constructed by drilling and blasting without stopping the tunnel operation that is within 15.86 m distance from the railway tunnel, which put forward to a great challenge to engineers and technicians. Thus, the blasting technology using phase-difference vibration mitigation is proposed for the drainage tunnel excavation on the basis of the superposition principle of blasting waves.

4.2. Design Principle of Blasting Vibration Reduction. There are many ways to control the vibration of tunnel blasting. One of the most important ideas is "short grubbing and weak blasting." The particle vibration velocity can be effectively suppressed by controlling the explosive quantity for a single detonation. Moreover, the explosive consumption per cubic meter of rock in tunnel excavation is relatively fixed, and the quantity of a single stage is inversely proportional to the number of sections at a certain unit of explosive consumption [3, 11, 25]. Therefore, the blasting technology using phase-difference vibration mitigation can be achieved via effectively controlling the time difference of single-stage detonation [23, 25].

4.2.1. Explosive Quality Calculation. The blasting holes of tunnel excavation are divided into cut holes, auxiliary holes, bottom holes, and periphery holes. The function of cut holes is to increase the free surface of excavation for blasting, which is beneficial to improving the blasting efficiency of auxiliary holes. The principle of short grubbing and weak blasting should be followed where there are important buildings around the tunnel. Theoretically, the blasting energy can be dissipated in the process of transmission by means of blasting technology using phase-difference vibration mitigation; it can better control the blasting vibration of the structure.

4.2.2. Blasting Parameter Design. The total blasting quality can be calculated by the following equation:

$$\begin{aligned} Q &= qV \\ &= qsL\eta, \end{aligned} \tag{14}$$

where q is the explosive consumption per cubic meter; generally, the value of q is taken from 0.8 kg/m^3 to 2.4 kg/m^3. L is the average depth of blast holes. S is the tunnel excavated section. η is the utilization ratio of blast holes; generally, the value of η is taken from 0.8 to 0.95.

The number (N_1) and quality (Q_1) of the cut hole can be calculated by the equation as follows

$$Q_1 = N_1\tau_1L_1\gamma_1, \tag{15}$$

where τ_1 is the charging coefficient, L_1 is the average depth of cut holes, and γ_1 is the explosive roll weight of cut hole per meter.

The number (N_2) and quality (Q_2) of periphery holes can be calculated by the equation as follows:

$$\begin{aligned} N_2 &= \frac{B_l - B}{a} + 1, \\ Q_2 &= N_2\tau_2L_2\gamma_2, \end{aligned} \tag{16}$$

where B_l is the circumference of tunnel excavated section, B is the tunnel excavated width, a is the distance between periphery holes, τ_2 is the charging coefficient of periphery holes, L_2 is the average depth of periphery holes, and γ_2 is the explosive roll weight of periphery holes per meter.

The number (N_3) and quality (Q_3) of bottom holes can be calculated by the equation as follows:

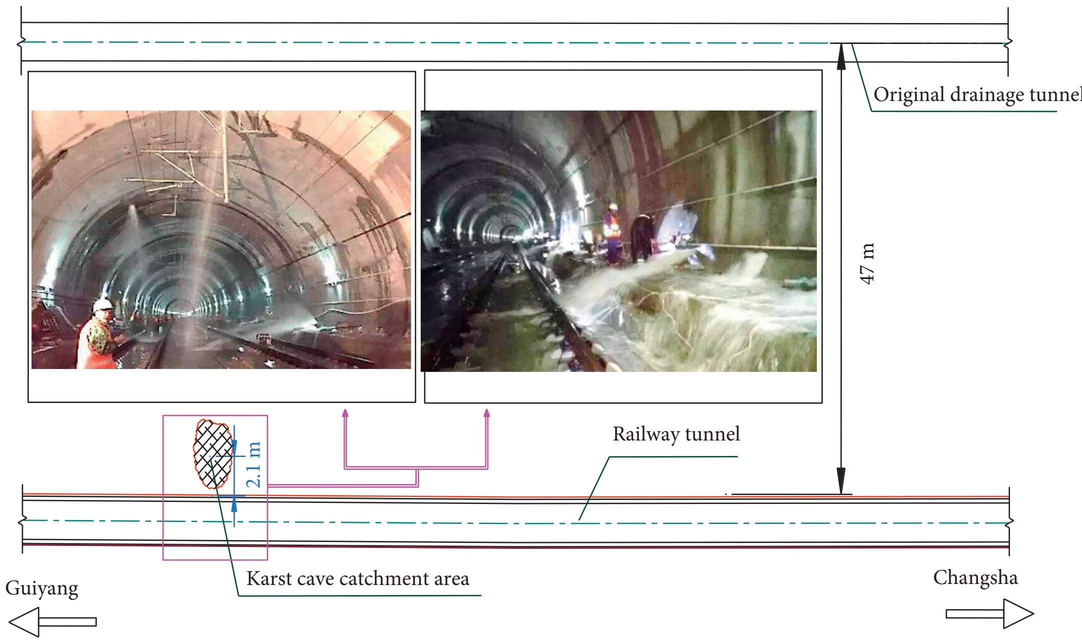


Figure 5: Water gushing from tunnel lining.

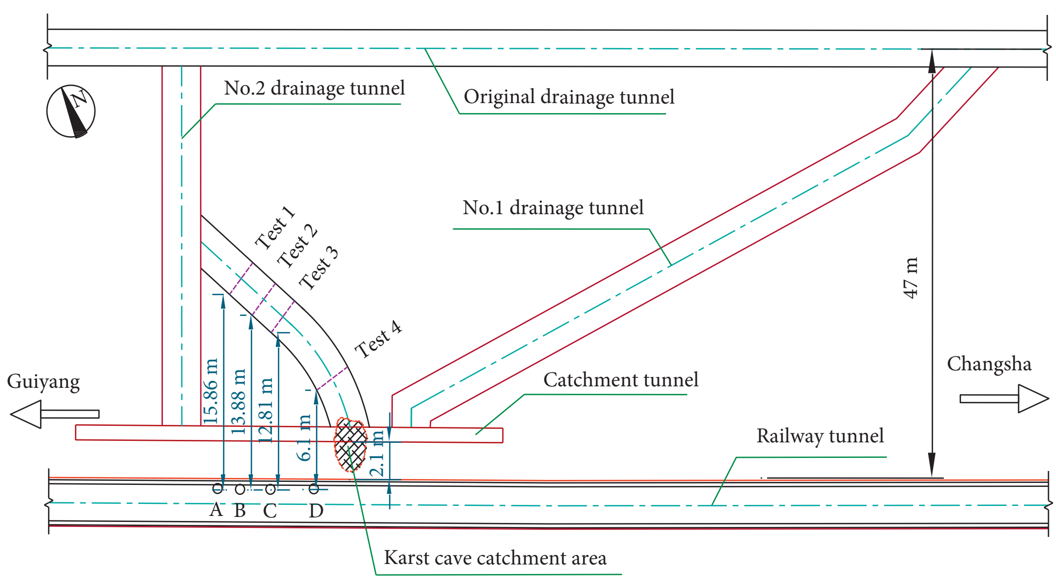


Figure 6: Plane position diagram of tunnel.

$$Q_3 = N_3 \tau_3 L_3 \gamma_3, \quad (17)$$

where L_3 is the average depth of bottom holes, γ_3 is the explosive roll weight of bottom holes per meter, τ_3 is the charging coefficient of bottom holes.

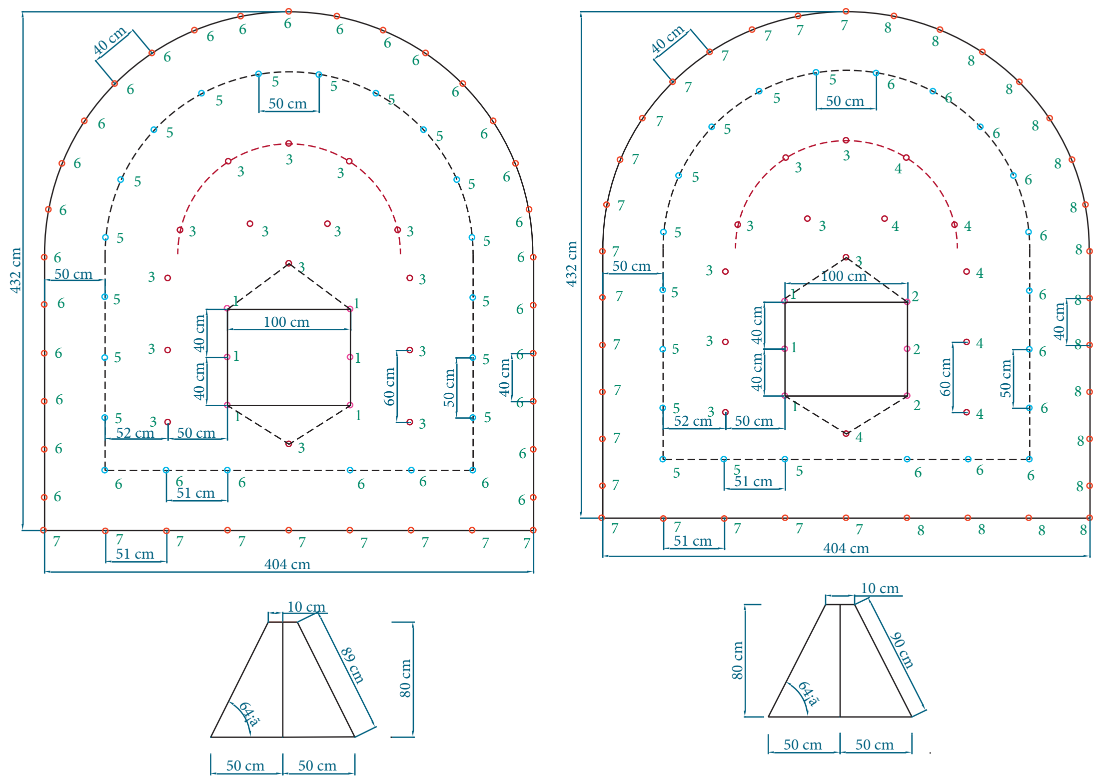
The number (N_4) and quality (Q_4) of auxiliary holes can be calculated by the equation as follows:

$$N_4 = \frac{Q - Q_1 - Q_2 - Q_3}{\tau_4 L_4 \gamma_4}, \quad (18)$$

where L_4 is the average depth of auxiliary holes, γ_4 is the explosive roll weight of auxiliary holes per meter, and τ_4 is the charging coefficient of auxiliary holes.

The No.2 drainage tunnel was selected as the experimental section, and the design section was horseshoe shaped. The drainage tunnel excavation's contour height and width were 4.32 m × 4.04 m. In order to reduce the single explosive quality, the tunnel excavated footage was 0.8 m. The blasting hole layout is shown in Figure 7.

For the sake of analyzing the effect of blasting using phase-difference shock absorption, the No. 2 drainage tunnel carried out4 times blasting tests, as shown in Figure 6. Test 1 was conducted by conventional blasting technology, and Test 2 to Test 4 were adopted by the blasting technology using phase-difference vibration mitigation. The measuring



(a) (b)

Figure 7: The blasting hole layout: (a) conventional blasting holes and (b) phase-difference shock absorption blasting holes.

points are A, B, C, and D, respectively, in the railway tunnel, as shown in Figure 8.

For blasting technology using phase-difference vibration mitigation, the cut holes and auxiliary holes adopt continuous charging, and the periphery holes' charging structure adopts the noncoupling form. The charging structure is shown in Figure 9. In this way, the purpose of shock absorption can be achieved. In addition, it formed smooth contour lines for tunnel excavation after blasting.

The surrounding rock of the No. 2 drainage tunnel is limestone, and the propagation velocity is 3500 m/s by the tests. The time difference can be calculated from the relationship between distance and propagation velocity in rock mass, provided that the distance between the blast hole and the test point is S_i. It is possible to calculate the time difference between two waves arrived at a same particle after blasting.

$$\Delta t = \frac{S_1 - S_2}{V} = \frac{L}{V}, \tag{19}$$

where V is the propagation velocity of limestone, S_1 and S_2 are the distances between the blast hole and the test point.

The time difference between two explosives is an important parameter of the blasting using phase-difference shock absorption. The condition of the blasting using phase-difference shock absorption is the time difference between the two adjacent holes' detonation within 15~20 ms by testing and calculating the limestone geology. In order to achieve the purpose of phase-difference vibration reduction, the time interval of the blasting using phase-difference shock absorption is 17 ms in Table 1.

4.3. Results of Phase-Difference Shock Absorption Blasting. The blasting vibration velocity was measured by the vibration instrument that the type is TC-4850, and the instrument accuracy is 0.01 cm/s, which can monitor and record PPV in the process of blasting, as shown in Figure 10.

In order to compare and analyze the damping effects between conventional blasting and the blasting using phase-difference shock absorption, Test 1 was conducted by conventional blasting parameters with the total quality of 26.9 kg. Test 2 to Test 4 were carried out by the blasting using phase-difference shock absorption parameters with the same total quality. The measuring points from Test 1 to Test 4 are A, B, C, and D, respectively, in the railway tunnel, as shown in Figure 8. The vertical vibration velocity curve of 4 times blasting experiments is shown in Figure 11.

Test 1 is the conventional blasting, the explosive quality is the conventional blasting parameters, as shown in Table 1, and the PPV of the corresponding point A is 4.06 cm/s, as shown in Figure 11(a). It can be shown that the PPV of conventional blasting presents a dense area, and the peak appears 11 times within 0.4~0.5 s, where the average time of the peak is 0.0091 s and the frequency of PPV is 110 Hz. Test

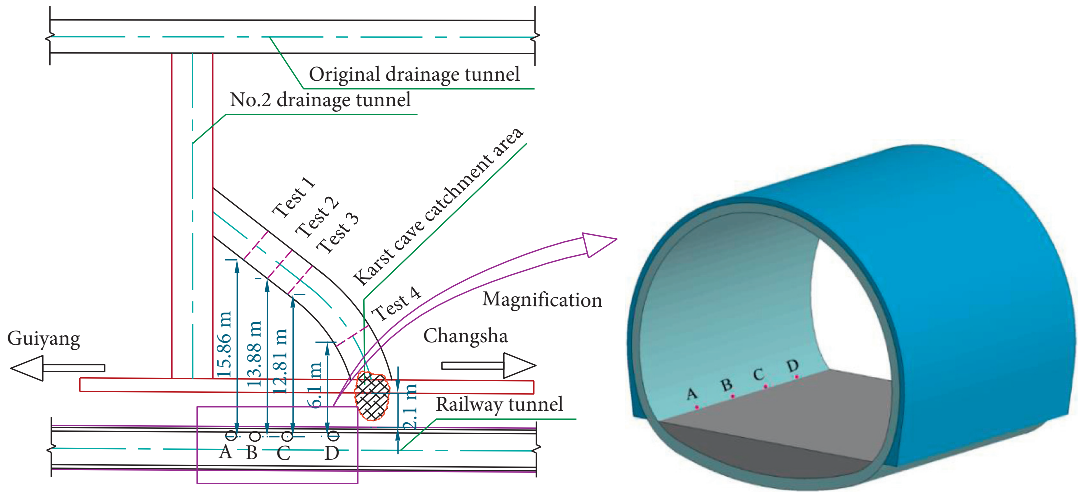


Figure 8: Relationship between explosion site and location of measuring points.

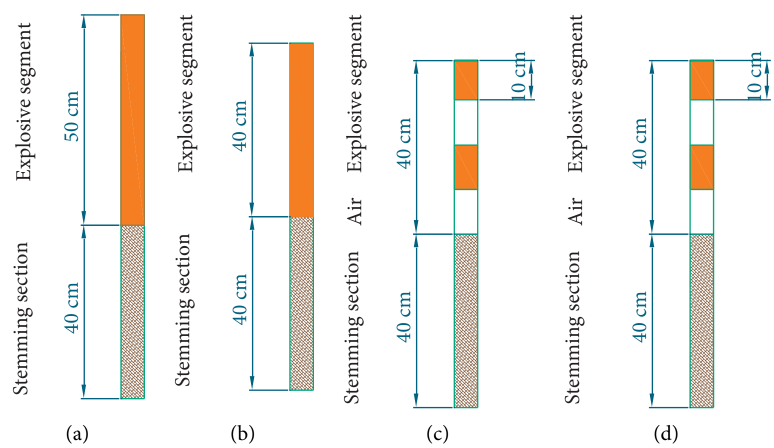
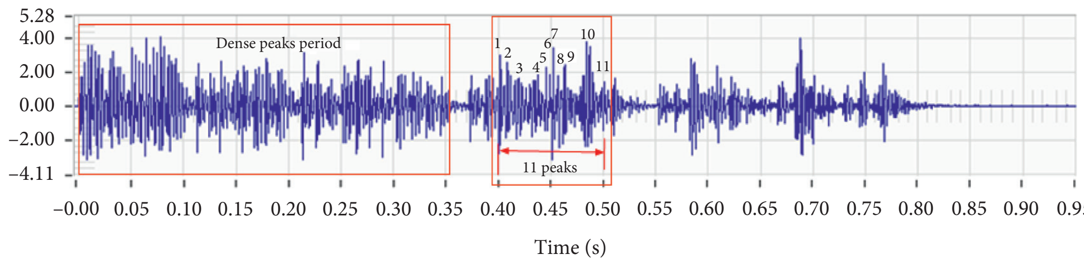


Figure 9: The charging structure: (a) charging for cut holes, (b) charging for auxiliary holes, (c) charging for periphery holes, and (d) charging for bottom holes.

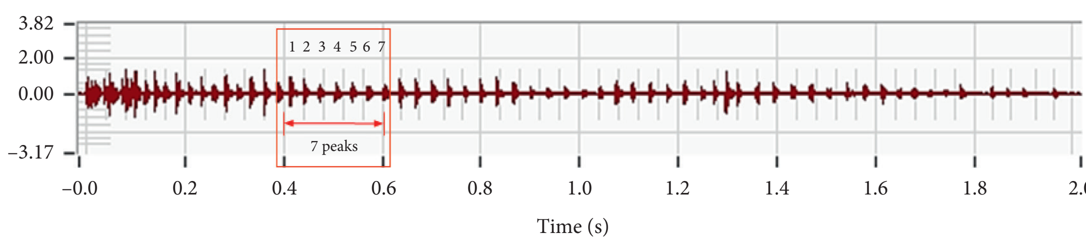
Table 1: Blasting parameters.

No.	Blasthole type	Period	Initiation time (ms)	Number of blastholes	Charging coefficient	Quality per hole (kg)	Total quality (kg)
(1) Conventional blasting parameters							
1	Cut holes	1	0	6	0.55	0.5	3.0
2	Auxiliary holes	3	50	15	0.5	0.5	7.5
3	Auxiliary holes	5	110	16	0.5	0.5	8.0
4	Bottom holes	6	150	6	0.25	0.2	1.2
5	Bottom holes	6	150	9	0.25	0.2	1.8
6	Periphery holes	7	200	27	0.25	0.2	5.4
7	Total			79			26.9
(2) shock absorption blasting parameters							
1	Cut holes	1	0	3	0.55	0.5	1.5
2	Cut holes	2	5	3	0.55	0.5	1.5
3	Auxiliary holes	3	22	8	0.5	0.5	4.0
4	Auxiliary holes	4	39	7	0.5	0.5	3.5
5	Auxiliary holes	5	56	8	0.5	0.5	4.0
6	Auxiliary holes	6	73	8	0.5	0.5	4
7	Bottom holes	5	56	3	0.25	0.2	0.6
8	Bottom holes	6	73	3	0.25	0.2	0.6
9	Bottom holes	7	90	5	0.25	0.2	1.0
10	Bottom holes	8	107	4	0.25	0.2	0.8
11	Periphery holes	7	90	14	0.25	0.2	2.8
12	Periphery holes	8	107	13	0.25	0.2	2.6
13	Total			79			26.9

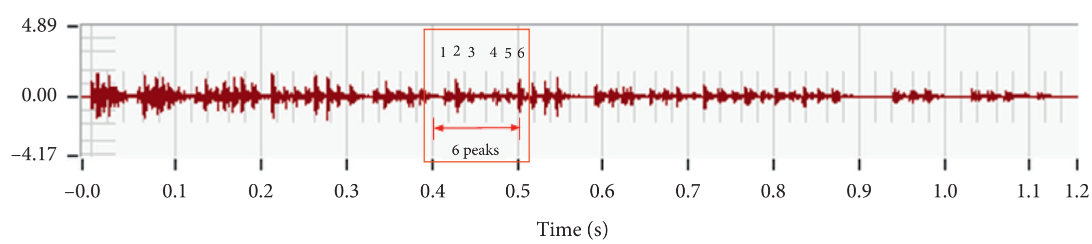
Figure 10: Blasting vibration test instrument.



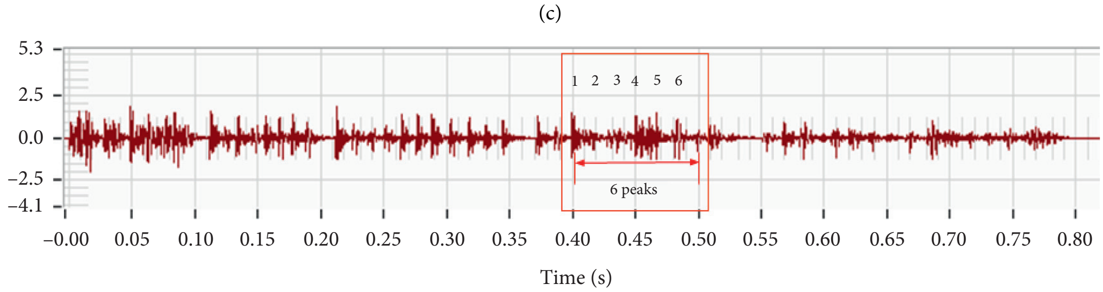
(a)



(b)

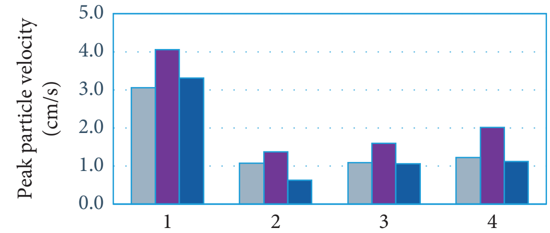


(c)



(d)

Figure 11: Vertical vibration velocity curves of blasting tests: (a) point A, (b) point B, (c) point C, and (d) point D.



	1	2	3	4
X-direction	3.05	1.08	1.09	1.22
Y-direction	4.06	1.37	1.60	2.02
Z-direction	3.31	0.62	1.05	1.12

Figure 12: The peak particle velocity in X, Y, and Z directions.

(a) (b)

Figure 13: The explosive quality and blasting effect of Test 2: (a) explosive charge and (b) after blasting.

2 to Test 4 were carried out by the blasting technology using phase-difference vibration mitigation, the PPV of the point B, C, and D are 1.37 cm/s, 1.60 cm/s, and 2.02 cm/s, respectively, as shown in Figures 11(b) and 11(d), and the PPV of the blasting using phase-difference shock absorption was dispersed. The PPV appears 7 times within 0.4~0.6 s for Test 2, where the average time of the peak is 0.0285 s, and the frequency of PPV is 35 Hz. Both from Test 3 and 4, the PPV appears 6 times within 0.4~0.5 s, and the frequency of PPV is 60 Hz. The experiments have shown that the superposition of blasting stress wave crest and trough extends the time interval of the PPV.

The PPV in X, Y, and Z directions can be obtained by the 4 times tests in the No.2 drainage tunnel, and the PPV is shown in Figure 12.

After analyzing the experimental data of the 4 times tests, as shown in Figure 12, it was found that the PPV in X, Y, and Z directions is reduced by 64.6%, 66.25%, and 81.26%, respectively, which compared with the same stratum and the same total explosive quality.

The results have shown that the blasting technology using phase-difference vibration mitigation can effectively reduce the PPV structure. The blast hole arrangement and the effect of blasting for the Test 2 detonation point are shown in Figure 13.

It can be seen from the above figures that the excavation contour is consistent with the design tunnel contour after blasting, as shown in Figure 13(b). The overbreak and underbreak amounts are less than 5% by measuring the excavation contour line. The test results have shown that the blasting technology using phase-difference vibration mitigation is satisfied with the requirements of design tunnel contour as well.

5. Conclusions

The theoretical formula of the blasting using phase-difference shock absorption was derived by the propagation characteristics of blasting stress wave. The expected effect of blasting vibration reduction is achieved through the application of the blasting using phase-difference shock absorption. The research conclusions are as follows:

(1) According to the superposition and synthesis theory of the propagation for blasting stress wave, when the difference of initial phase is $\varphi_i = \pm(2k+1)\pi\,(k = 0, 1, 2, 3\ldots)$, the particle vibration velocity could reach the minimum in the structure. Actually, the purpose of the blasting using phase-difference shock absorption can be achieved.

(2) After analyzing the experimental data, it was found that the PPV performs in a dispersion region by the blasting technology using phase-

difference vibration mitigation. However, the peak value of vibration velocity is an intensive area by conventional blasting. For the blasting technology using phase-difference vibration mitigation, the time interval of particle vibration velocity is prolonged due to the superposition of the blasting stress wave. It was verified by the theory of the blasting technology using phase-difference vibration mitigation by experiments.

(3) Compared with the conventional blasting, the PPV of the railway tunnel structure in X, Y, and Z directions was reduced by 64.6%, 66.25%, and 81.26%, respectively. Meanwhile, the amount of overbreak and underbreak can be controlled within 5%. The results have shown that the effect of the blasting technology using phase-difference vibration mitigation is obvious, and it is able to match with the requirements of design tunnel contour.

Data Availability

The data used or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

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

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