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Research Article

Prediction of Vibration Waveform and Division of Influenced Partitions under the Action of Blasting

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To study the impact of cutting blasting on the surface, a vibration waveform prediction function was constructed, and a method of dividing the affected area was proposed. Based on the equivalent spherical charge theory, it is possible to establish a connection between the fitting coefficient and the engineering parameters in the equivalent source intensity function. Furthermore, a blasting vibration waveform function suitable for engineering can be constructed. Secondly, the reliability of the method introduced is verified through the data monitored on-site. Finally, the affected partitions of blasting vibration are divided based on the peak particle velocity and vibration displacement as standards. The results show that the vibration waveform prediction system introduced can restore the vibration waveform corresponding to cutting blasting. In addition, the zoning method can reasonably divide the scope of the affected area.

1. Introduction

With the rapid development of highway and railway transportation network, mountain tunnel adjacent to existing structures is becoming more and more common. Due to the advantages of strong operability and good economic benefits, blasting is often used in the excavation of mountain tunnel. However, the environmental problems caused by blasting cannot be ignored, such as structural vibration, flying rocks, and harmful gases caused by blasting construction. Among them, the blasting vibration will adversely affect the stability and structural safety of the surrounding existing buildings and even endanger the safety of the existing buildings in severe cases [1–4].

The effect of blasting vibration is affected by many complicated factors such as topography and geological conditions [5, 6] and blasting parameters [7–9]. It is difficult to accurately predict the intensity of blasting vibration, and there is a certain degree of one-sidedness in evaluating the intensity of blasting vibration using single or combined indicators such as particle peak vibration, frequency, acceleration, and displacement [10–13]. The blasting waveform curve contains rich blasting vibration signal characteristics, which can completely present the vibration history of the vibration signal during the period [14]. Combined with mathematical methods and computer analysis methods, characteristic information such as the vibration velocity, frequency, and acceleration of the particle at any time in the blasting process can be obtained, and the waveform can be changed by technical means. The prediction results based on the waveform can provide a certain scientific basis for the controlled blasting construction of tunnel.

Under the premise of blasting vibration response, the construction site is reasonably divided and corresponds to the risk level in the specification, and different control measures are taken for different risk levels [5, 15]. At present, the research of the proximity influence zoning mainly includes influencing factors, zoning guidelines, and engineering countermeasures. Zhang et al. [16] applied the concept of proportional distance to the partition of tunnel blasting vibration, taking the slope of the velocity attenuation curve as the basis for partition calculation. Park et al. [17] established the relationship between the size of the excavation failure zone and the tensile strength of the rock mass and deduced the distance of the excavation affected area through the induced dynamic strain and the critical tensile strain. Based on the Hoek–Brown nonlinear failure criterion of rock mass, Zhou et al. [18] proposed a method for dividing the influence zone of underwater tunnel. Li et al. [19] obtained the predicted waveform of blasting vibration waveform based on theoretical derivation. Moreover, the application results verify the applicability of this method.

At present, artificial intelligence algorithms [20, 21] and numerical simulation have provided powerful technical means for the prediction of blasting vibration waveforms and the precise study of impact zone. The blasting vibration waveform prediction systems based on fuzzy modeling method [22], neural network algorithm [23], support vector machine algorithm, classification regression tree algorithm [24], and other industrial intelligence algorithms have high prediction accuracy. The Intelligent algorithm has the advantages of strong theory and good prediction effect, but it still has certain limitations in application. A large number of parameters and sample data are required to reconstruct and train the model. Compared with artificial intelligence algorithms, numerical simulation technology [25, 26] can restore the construction site. However, numerical simulation methods are limited by the specific assumptions of numerical calculations and often cannot perfectly reflect the characteristics of actual engineering.

This article mainly relies on the Chong-Li Tunnel blasting project to conduct research. Chong-Li Tunnel is an underpass tunnel. Tunnel blasting will have adverse effects on surrounding buildings. Therefore, it is very important to study the prediction of blasting vibration waveforms and the impact zoning of blasting vibrations. Although many achievements [27–30] have been made in the prediction of tunnel blasting vibration effect and impact partitioning, which have certain guiding significance for practical engineering, there are still some deficiencies. For example, the theoretical results obtained based on the assumption of a uniform and isotropic medium as a research premise are not universal. Artificial intelligence algorithms such as neural network algorithms require large amounts of real-world data as training samples. The complex and time-consuming numerical simulations are not easily mastered by technicians. Therefore, the prediction of blasting vibration waveforms and the division of blasting vibration affected areas in specific projects are still considered a relatively new systematic research method.

To solve the above problems, relying on the Chong-Li Tunnel underpassing project, a blasting vibration waveform function that is simple in form and suitable for actual engineering is first constructed. Then, the PPV and displacement are used as judgment criteria to divide the influence area, respectively. The reliability of the waveform function and the applicability of the influence partitioning criterion based on the waveform theory are verified by the measured data in the field. Finally, the affected areas of Chong-Li Tunnel blasting vibration are divided in detail based on the vibration waveform function.

2. Vibration Waveform Function under the Action of Equivalent Spherical Charge

The propagation of blast vibration waves is affected by many factors such as geological structure, blasting parameters, and propagation distance. Therefore, it is often convenient to model the problem in a simplified form. Tunnel blasting construction generally adopts a multihole multistage blasting scheme, in which the surface vibration effect caused by cutting blasting is the largest [31, 32], so the surface vibration effect generated by cutting blasting is studied. The excavation cycle and tunnel section are both small compared to the blasting vibration wave propagation distance [33, 34]. Without considering the section size factor, the tunnel blasting can be approximated as a dynamic response problem of a semi-infinite rock mass under a spherical transient excitation load.

As shown in Figure 1, a spherical packet can be assumed to exist at a depth (h) below the surface. The spherical package is on the z-axis and the surface is on the $z = 0$ plane. Combined with the theory of equivalent pore model in uniform elastic media proposed by Sharpe [35], this paper equates the porous multistage blasting problem to the action of a spherical cavity pressure source with radius r_e and pressure $p(t) = p_0 e^{-a0t}$. As shown in Figure 1, the distance from the surface mass point A to the origin is D and the distance to the source of the blast area is R.

A large number of studies [5, 33, 36] have been carried out on the vibration waveform functions of spherical packet blasting ground in elastic media. Sharpe [35] idealized the problem of elastic waves generated by blast pressure and simplified it to a perturbation problem in an elastic medium and developed an equivalent pore model for blast tremor sources in elastic media. De Hoop [37] delved into the point source model in elastic half-space to obtain the vibration waveform function of a mass on a free surface under the action of a point source. Achenbach and Thau [38] modified the theory to derive a spherical charge package burst source intensity function. Due to the great difference between the rock properties of the elastic medium and the actual medium and the complex form of the derived vibration velocity function, it is not suitable to be extended to practical engineering applications. Therefore, based on the analytical solution derived from the theory of elastic media, this paper constructs a more concise form that can be applied to practical engineering vibration waveform function.

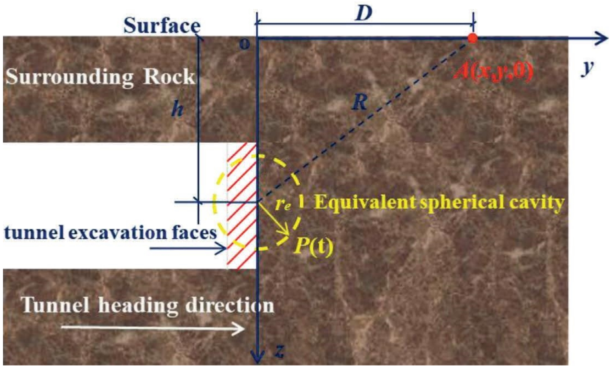

FIGURE 1: Explosion of equivalent spherical charge in elastic half-space.

The application of the study to blast vibrations stems from the understanding of the homogeneity of all vibrating matter through the concept of structural dynamics. The forced vibration equation for seismic wave generation from a spherical cavity pressure source with pressure $p(t)$ is given by Lin and Bai [39] through theoretical derivation as follows:

$$y''(t) + 2\xi\omega_0 y'(t) + \omega_0^2 y(t) = \zeta p(t), \tag{1}$$

where $\omega_0 = 2C_s/r$, $\xi = C_s/C_p$, and $\zeta = -r/\rho$.

The analytical solution of equation (1) is

$$\begin{aligned} y(t) &= \exp(-\xi\omega_0 t)\left[A\cos(\omega_D t) + B\sin(\omega_D t)\right] \\ &\quad - \frac{r p_0 \exp(-\alpha_0 t)}{\left(\omega_0^2 - 2\xi\omega_0 a_0 + a_0^2\right)\rho}, \end{aligned} \tag{2}$$

where $\omega_D = \omega_0\sqrt{1-\xi^2}$. A and B are the parameters to be determined concerning the boundary conditions.

Referring to the form of the analytical solution of the forced vibration equation in structural dynamics, the general fitting expression for the surface vibration velocity waveform function under the action of the equivalent spherical drug package in the actual medium is determined as follows:

$$V(t) = a_1 e^{-b_1 t}\left[\cos(c_1 t) + d_1 \sin(c_1 t)\right]. \tag{3}$$

That is,

$$V(t) = a_1\sqrt{d_1^2 + 1}e^{-b_1 t}\sin(c_1 t + \varphi), \tag{4}$$

where a_1 is the coefficient related to the PPV. b_1 is the decay parameter of the mass vibration velocity. c_1 is the coefficient related to the frequency of vibration of the mass. d_1 is a constant with no practical meaning, and $\tan\varphi = 1/d_1$ [40].

Equation (4) is shifted forward by φ units, and the form of the constructed oscillation velocity waveform function is obtained as

$$V(t) = a_1\sqrt{d_1^2 + 1}e^{-b_1 t}\sin(c_1 t). \tag{5}$$

The Sadovsky formula is now commonly used to predict the peak particle velocity of surface mass. b_1 is related to the decay rate of the vibration velocity, which depends on the characteristics of the surrounding rock. Liu and Chen [40] obtained the approximate range of values for the decay index of the vibration velocity waveform and established a relationship with the RMR grading score of the surrounding rock quality.

Based on the derivation of the PPV under the action of an equivalent spherical explosion source, we can get

$$a_1\sqrt{d_1^2 + 1} = K_1\left(\frac{r_e}{R}\right)^{\alpha_1}. \tag{6}$$

According to structural dynamics, c_1 is related to the main vibration frequency f_m, that is, $c_1 = 2\pi f_m$. Through the derivation of dimensional analysis method, the attenuation formula of the main frequency of blasting vibration under the action of equivalent spherical explosion source can be obtained. Factors affecting blasting vibration frequency mainly include load characteristics and surrounding rock characteristics. Among the many influencing factors, we selected the rock mass elastic modulus E, rock mass density ρ, rock mass longitudinal wave speed C_P, distance from the blast area R, and equivalent elastic radius r_e for research.

E, C_P, and r_e are selected as basic physical quantities, and there are

$$f_m = \varphi(E, C_P, r_e, \rho, R). \tag{7}$$

According to the π theorem, three dimensionless numbers can be obtained:

$$\begin{cases} \pi_1 = \dfrac{f_m}{C_P} r_e, \\[2ex] \pi_2 = \dfrac{E}{C_P^2\rho}, \\[2ex] \pi_3 = \dfrac{r_e}{R}. \end{cases} \tag{8}$$

According to the principle of dimensional harmony, equation (7) can be converted into

$$\frac{f_m}{C_P} r_e = \lambda\left(\frac{E}{C_P^2\rho}\right)^{\partial}\left(\frac{r_e}{R}\right)^{\iota}. \tag{9}$$

For specific tunnel projects, E, C_P, and ρ can be approximately regarded as fixed values. Therefore, equation (9) can be converted into

$$f_m = \zeta\frac{C_p}{r_e}\left(\frac{r_e}{R}\right)^{\varphi}. \tag{10}$$

Based on the above analysis, it can be obtained that

$$V(t) = K_1\left(\frac{r_e}{R}\right)^{\alpha_1} e^{-2\beta t}\sin\left[2\pi\zeta\frac{C_p}{r_e}\left(\frac{r_e}{R}\right)^{\varphi} t\right], \tag{11}$$

where K_1 and α_1, respectively, represent the site coefficient and attenuation coefficient of the particle peak velocity and ζ and φ, respectively, represent the site coefficient and attenuation coefficient corresponding to the main frequency of vibration.

Compared with the traditional blasting vibration waveform prediction method, this paper proposes a waveform prediction method that quantitatively reflects the influence of frequency in symbolic expressions for the first time. The constructed waveform prediction model equation has a simple form and is more convenient for use in prediction research.

The relationship between the value of β and rock classification categories is shown in Table 1 [41].

3. Application of Engineering Case

3.1. Project Background and Monitoring Program. Tai-xi Railway is an important traffic artery connecting Zhangjiakou City, Hebei Province, and Xilingol, Inner Mongolia Autonomous Region. Taking the Chong-Li Tunnel in the railway project as the engineering background, the research on the blasting vibration effect is carried out. The total length of the tunnel is 5490 m.

The specific blasthole layout is shown in Figure 2. The full-section method was used for this construction process. During the construction process, rock emulsion explosive was used during construction. The cut blasting mainly adopts the three-stage wedge cut method, and the charging method mainly adopts the air column interval uncoupled charging method. The charge amount of the cut section is 43.2 kg. In addition, the horizontal angle of the wedge-shaped cutout hole is 60°, and the hole length is 4.2 m. Based on actual engineering conditions, the paper only conducts verification research on the case of tunnel wedge blasting.

The blasting vibration monitoring mainly uses the TC-4850N blasting vibration measurement system developed by Zhong-Ke Speed Control Company. During the on-site installation, the sundries near the monitoring point are removed. The speed sensor can then be rigidly connected to the ground with plaster. The location and layout of the specific measuring points are shown in Figure 3.

Based on preliminary geological survey results, the distance between measurement point #5 and the explosion is 66 m. The distance between measurement point #2 and the explosion is 81 m. The location of the monitoring points is detailed in Figure 3. Based on the seismic wave reflection method [19], we obtained the report of rock overtopping geological prediction of the two measurement points. The specific geological parameters corresponding to the measurement points are shown in Table 2.

The geological parameters and attenuation indices in the prediction equations for PPV and f were initially determined by combining the over-range geological forecast report and blasting tests, and the prediction equations for vibration velocity waveforms were calculated based on the results of the above study. First, the corresponding RMR and β can be obtained based on the results obtained from the field test. Then, based on the on-site monitoring results, the fitting equations about the peak velocity and main frequency of the particle can be obtained through data fitting. In this way, the undetermined parameters in equation (11) can obtain corresponding values based on the fitting results of field data. To sum up, each undetermined parameter in the prediction equation (11) can be obtained through on-site monitoring or the fitting results of on-site monitoring data. Therefore, the prediction model is highly consistent with actual engineering conditions and can meet the prediction of vibration waveforms corresponding to cutting blasting.

TABLE 1: β of surrounding rock at all levels.

Classification of surrounding rock	I	II	III	IV	V
RMR	81~100	61~80	41~60	21~40	0~20
β	0~20	21~40	41~60	61~80	81~100

According to the above calculation process, the specific calculation results are shown in Table 3.

3.2. Example Calculation of Vibration Waveform Function. First, measurement point #5 was taken as an example to conduct verification research. Firstly, the monitoring data were imported into software to draw the measured vibration velocity waveform. Then, the blast vibration waveform of the cutting hole is extracted by using detonator identification technology [5]. The theoretical predicted waveform of surface mass vibration velocity due to cutting hole blasting is plotted according to the calculation results in Table 3. As shown in Figure 4, the waveform obtained from theoretical prediction of cutting blasting and those from monitoring show good agreement. The predicted waveform matches the measured waveform in general, and the peaks and frequencies of both waveforms are approximately the same.

Similarly, the measured vibration velocity waveform at the measurement point #2 and its comparison with the theoretical waveform are plotted in Figure 5. Similar to measuring point #5, the prediction corresponding to measuring point #2 also shows good results.

Theoretical calculation comparison results show that the theoretically predicted waveforms corresponding to the other three measuring points and the actual monitored waveforms also show good consistency. Due to the space limit of the article, the article will not go into details. The above comparison results verify the reliability of the introduced blasting vibration waveform prediction method.

4. Study of Impact Zoning

The blast vibration velocity waveform function contains a wealth of information that enables construction designers to accurately understand in advance the amplitude, dominant frequency, and energy magnitude of each frequency component of the vibration signal generated during the blast. To further guide disaster prevention and mitigation, the above blast vibration waveform theory combined with the corresponding zoning guidelines was used to zone the tunnel proximity construction site. Areas of strong impact generally require adjustments to the blasting program or auxiliary engineering measures for construction. Areas of medium impact require construction personnel to pay attention to the construction site and require vibration damping measures if necessary. Weakly affected areas

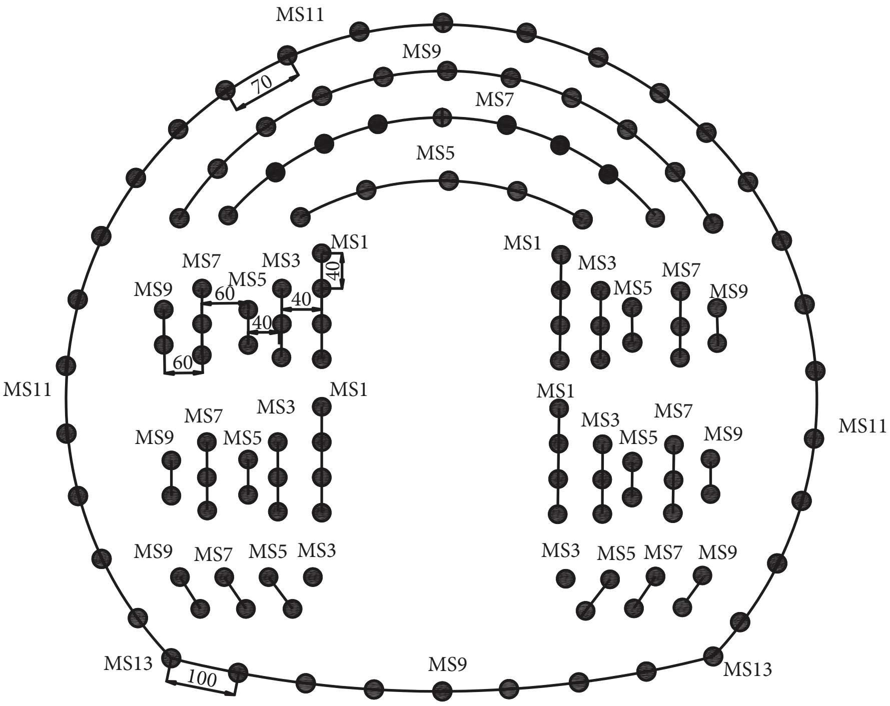

Figure 2: Layout of the blasthole.

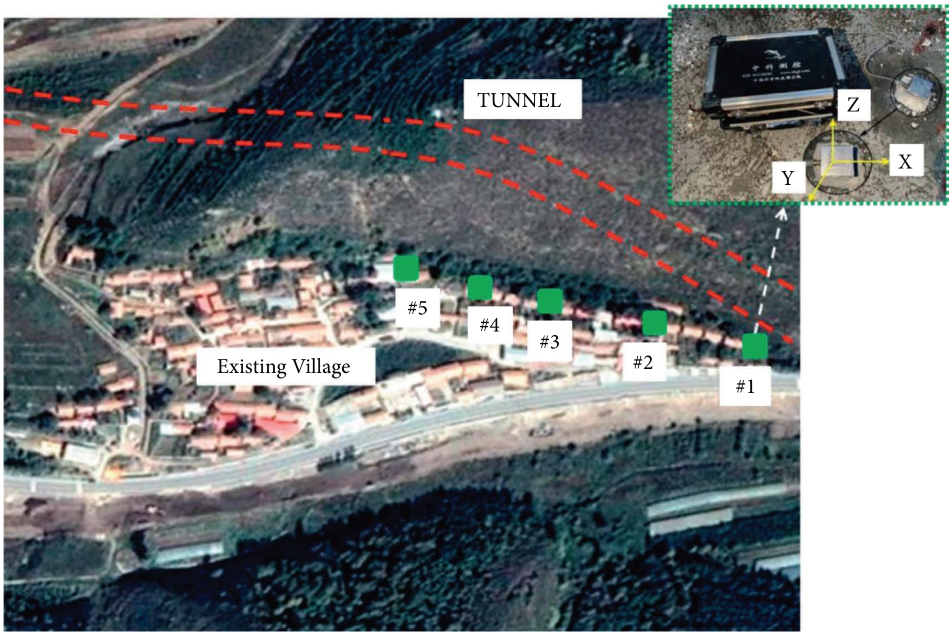

Figure 3: Layout of the vibration monitoring points [1].

Table 2: Geological parameters of surrounding rock of the measuring points.

Measurement point	RMR	β	E (GPa)	μ	C_P (m/s)	ρ (kg/m^3)
#5	65	35	30	0.25	3800	2500
#2	60	40	20	0.30	2900	2300

Table 3: Engineering parameters and attenuation coefficients at 5# and 2#.

Measurement point	K	α	Prediction formula for vibration speed waveform
#5	88	1.13	$V(t)=3.19\times e^{-70t}\times \sin(383t)$
#2	116	1.47	$V(t)=1.15\times e^{-80t}\times \sin(494t)$

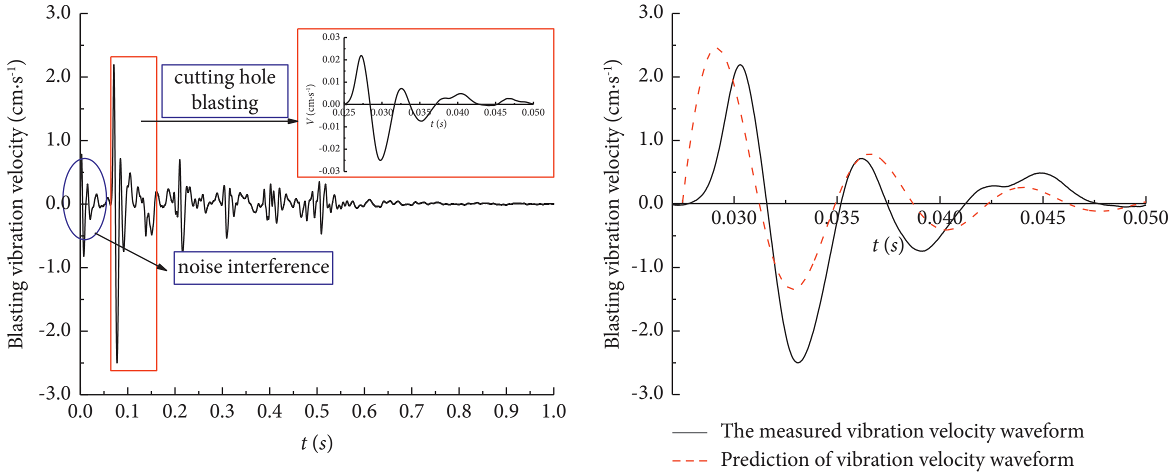

Figure 4: Comparison between measured and theoretical waveforms of cutting blasting at #5.

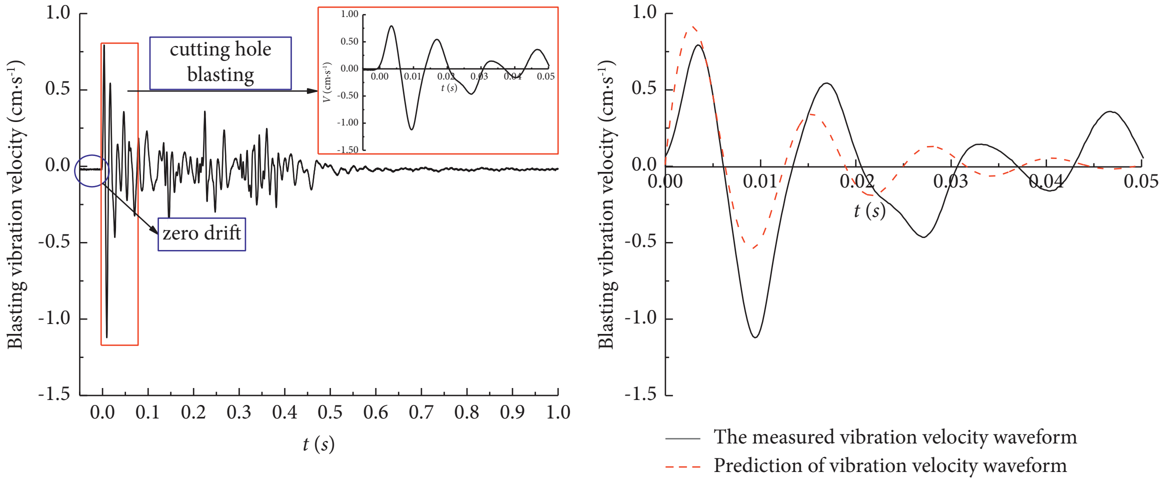

Figure 5: Comparison between measured and theoretical waveforms of cutting blasting at #2.

generally do not require auxiliary engineering measures and can be controlled by strengthening the construction process.

A tunnel blasting project through an existing village is used as an example to study the impact zoning theory. First, the surface mass vibration velocity waveform function is determined according to the above waveform prediction theory. The site factor K and the attenuation index α are obtained by fitting the vibration monitoring data. The monitoring data are shown in Table 4.

The data in Table 4 were fitted with the least-squares method to obtain the site coefficient $K=87$ and the attenuation index $\alpha=1.2$. $\beta=35$. The results of calculating the predicted waveform function are shown in the following equation:

$$V(t)=87\times\left(\frac{\sqrt[3]{43.2}}{R}\right)^{1.20}\times e^{-70t}\times \sin\left[\pi\times 87\times\left(\frac{\sqrt[3]{43.2}}{\lg R}\right)^{0.5}\times t\right]. \quad (12)$$

Table 4: Monitoring data of blasting vibration of the tunnel blasting.

On-site monitoring	Measurement point	R (m)	PPV ($\mathrm{cm\cdot s^{-1}}$)
I	1	138.9	0.924
	2	107.8	1.331
	3	89.9	1.875
	4	79.6	2.055
	5	77.6	2.103
II	1	152.2	0.963
	2	114.4	1.426
	3	91.2	1.873
	4	74.4	2.223
	5	67.1	2.398

4.1. Influence Partitioning with Peak Mass Vibration Velocity as the Discriminating Criterion. Based on on-site results, most of the houses in the village have not been maintained or repaired for years, resulting in more or less damage to the building structure. Especially, some houses have visible cracks on the surface. According to the "Safety Regulations for Blasting" (GB6722-2014) and relevant engineering experience, the severe alarm threshold for blasting vibration in the lower section is determined to be 2.0 cm/s, the alarm threshold is 1.5 cm/s, and the warning threshold is 1.0 cm/s. The engineering monitoring research results [1, 5, 19] indicate that the threshold division range has been effectively applied in the tunnel blasting engineering.

It can be observed that equation (12) is a function of the distance R from the explosion region and the time t. Therefore, a binary function can be used to determine the extreme value of the peak particle velocity theory. When $\mathrm{PPV}_1 = 1.0\,\mathrm{cm/s}$; $\mathrm{PPV}_2 = 1.5\,\mathrm{cm/}$. When $\mathrm{PPV}_3 = 2.0\,\mathrm{cm/s}$, the corresponding blasting distance $R_1 = 110\,\mathrm{m}$, $R_2 = 82\,\mathrm{m}$, $R_3 = 65\,\mathrm{m}$.

As shown in Figure 6, for the underground tunnel blasting project, the spatial position relationship between the explosion source and the measurement point can be characterized by three distance variables, namely, D, H, and R. D represents the distance between the excavation section and the measuring point, which is the absolute value of the difference between the mileage pile numbers corresponding to the excavation section and the measuring point. For example, if the mileage stake corresponding to the excavation section is DK65 + 650 and the mileage stake corresponding to the measurement point is DK65 + 680, then $D = 30\,\mathrm{m}$. In summary, it can be found that D is the easiest to calculate and can be used as a reference variable for controlling the blasting distance. The explosive center distance R can be converted into horizontal distance D, and the corresponding horizontal distances $D_1 = 105\,\mathrm{m}$, $D_2 = 76\,\mathrm{m}$, and $D_3 = 57\,\mathrm{m}$.

4.2. Influence Partitioning with Mass Displacement as the Discriminant Criterion. Tunnel blasting construction inevitably disturbs the surrounding soil, causing it to lose its original stress equilibrium state, resulting in deformation and displacement of the soil and ground surface. If appropriate control measures are not taken, it will cause damage to adjacent buildings and even cause serious economic loss and great social impact. Based on measured data, relevant research [42] suggests that the threshold values for surface vibration displacement zoning are 0.2 mm, 0.5 mm, and 0.9 mm, respectively.

From the theoretical derivation process in the third section, the waveform function of surface blasting vibration induced by cut blasting can be obtained. In theory, this function can be used to integrate time to obtain displacement values. However, it is worth noting that the wave theory and structural response analysis results indicate that the peak velocity and vibration displacement of particles are functions of charge quantity and time, and there is a correlation between the various physical quantities. Considering that the phase transition of particle vibration displacement values lags behind the PPV, the influence of dosage and time should be considered when predicting surface particle displacement values using the waveform function of cutting hole blasting vibration velocity. However, there is a coupling effect between these two physical parameters, which cannot directly establish a relationship between the two. Therefore, this article cites two coefficients to, respectively, characterize the degree of influence mentioned above. That is, $\lambda_1 = Q'/Q$, $\lambda_2 = t/t'$. After statistical regression [36], the results confirm that the maximum value of both is taken as the amplification factor $\lambda = \max(\lambda_1, \lambda_2)$. The obtained calculation result is the best. According to the relevant engineering parameters of blasting engineering, it can be obtained separately ($\lambda_1 = Q/Q' = 4.44$, $\lambda_2 = t/t' = 10$).

To calculate the real surface displacement and to consider the superposition effect of delayed blasting, $\lambda = \max(\lambda_1, \lambda_2) = 10$ was determined. Therefore, the surface vibration velocity waveform function generated by cutting blasting can be used to predict the surface mass displacement. The calculation formula is as follows:

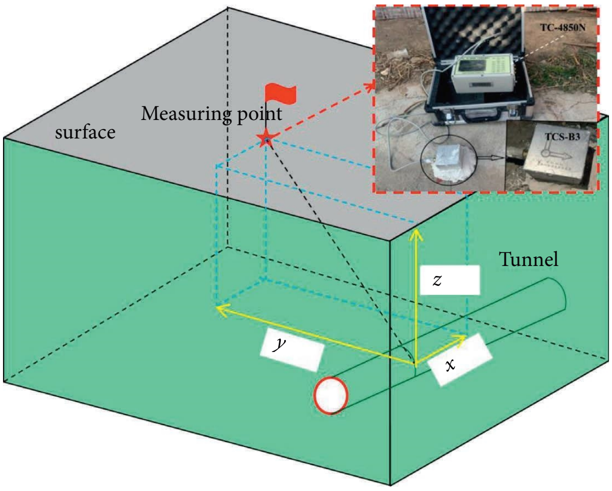

Figure 6: Positional relationship between explosion source and measuring point.

$$u = \lambda \times \int_0^{0.05} V(t)\mathrm{d}t, \tag{13}$$

$$u = \lambda \times \int_0^{0.05} 87 \times \left(\frac{\sqrt[3]{43.2}}{R}\right)^{1.20} \times e^{-70t} \times \sin\left[\pi \times 87 \times \left(\frac{\sqrt[3]{43.2}}{\lg R}\right)^{0.5} \times t\right]\mathrm{d}t. \tag{14}$$

$R_1' = 185\,\mathrm{m}$ when $u_1 = 0.2\,\mathrm{mm}$; $R_2' = 82\,\mathrm{m}$ when $u_2 = 0.5\,\mathrm{mm}$; $R_3' = 53\,\mathrm{m}$ when $u_3 = 0.9\,\mathrm{mm}$. Then, the corresponding horizontal distances, respectively, are $D_1' = 183\,\mathrm{m}$, $D_2' = 76\,\mathrm{m}$, and $D_3' = 44\,\mathrm{m}$. The results of the impact zoning are shown in surface 2 in Figure 7.

As shown in Figure 7, the range of the strongly influenced zone under the PPV of the surface as the discriminant is slightly larger than that under the displacement as the discriminant, while the range of the weakly influenced zone is 42.3% smaller than the other one. The extent of the medium impact zone under the two indicators is approximately the same. In the actual construction process, before the horizontal distance between the palm face excavation construction and the protection object is 90 m, no abnormality is seen in the design construction with ordinary working conditions. When $D > 90\,\mathrm{m}$, the current blasting scheme is still adopted, and the peak vibration speed of a few monitoring points exceeds 1.5 cm/s, and there is even a monitoring point with a peak vibration speed of 1.87 cm/s. The results of surface vibration monitoring were fed back to the construction unit in time, and the technical staff started to substantially adjust the blasting program and take corresponding control blasting measures based on the results of the analysis of the palm face in the vicinity of the protected object at a horizontal distance of $D = 50\,\mathrm{m}$. The monitoring results show that although there are a few monitoring points where the vibration speed exceeds 2.0 cm/s, the overall PPV is effectively controlled, and there are no obvious visible cracks in the house. In summary, the influence partition under the discriminant index of surface PPV is more reasonable than the discriminant index of mass displacement.

5. Discussion

The factors affecting blasting vibration characteristics are complex and variable but limited to practical work; the method proposed in this paper only uses the hollowing hole charge and blast center distance as input parameters to fit typical representative parameters and does not accurately reflect the factors that change the nature of the geotechnical body, which to some extent affects the predictive performance of the waveform function and thus the accuracy of the zoning range. Therefore, the surface mass velocity waveform theory combined with the mass peak velocity zoning criterion to divide the impact area proposed in this paper is suitable for projects with small changes in lithology, rock structure, and geological conditions in the construction area. In practical engineering applications, the waveform function of surface mass vibration velocity should be calculated in a zonal and sectional manner based on the actual geological and topographical conditions, with comprehensive consideration of the factors affecting blasting vibration, to further improve the prediction accuracy of the waveform function and zonal range.

In addition, this paper only predicts the vibration waveform caused by wedge cut blasting. However, factors

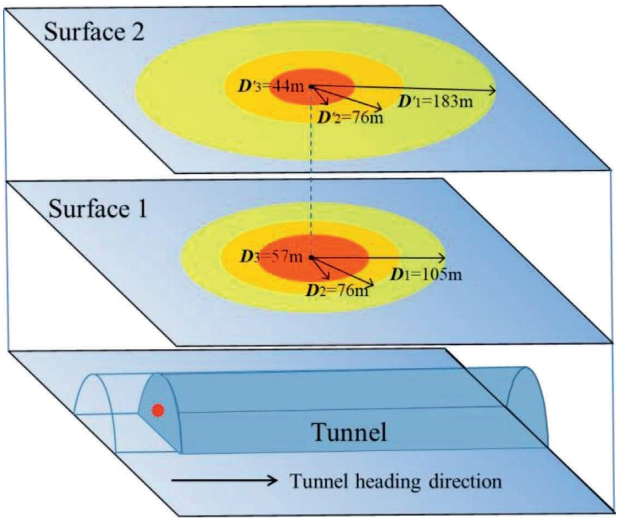

FIGURE 7: Zones affected by tunnel blasting.

such as charge form, millisecond detonation, and cutting methods were not discussed in this article, so subsequent research should focus on the impact of these factors on the waveform prediction accuracy.

6. Conclusion

Based on the equivalent explosion source theory, the article developed a prediction method suitable for cutting blasting waveform. In addition, the peak particle velocity and displacement of the mass point are used as the discriminating criteria to divide the influence area, and the following conclusions are obtained:

1. Combining with engineering example, we study the surface vibration waveform functions caused by cutting blasting under different geological conditions. The predicted waveforms roughly match with the measured waveforms to verify the feasibility of the theoretical prediction method of surface mass vibration waveforms caused by tunnel cutting blasting.
2. The actual construction conditions and real-time monitoring data show that it is reasonable to use the peak particle velocity of the mass as the zoning criterion to divide the influence area, and the zoning results can be used to guide the on-site construction.
3. Through the impact zoning map, the control objectives during the construction of the tunnel through the existing village can be aligned to adopt economical and reasonable construction measures in the corresponding zoning area, which can also be used as a reference for similar projects with similar rock properties.

Abbreviations

PPV:	Peak particle velocity
R:	Distance from the blast area
D:	Horizontal distance
E:	Elastic modulus of medium
v:	Poisson's ratio
$p(t)$:	The pressure corresponding to the spherical explosion source
Q:	Maximum charge per delay
f_m:	Main frequency
r_e:	Equivalent radius of action
ρ:	Density of the rock mass
ρ_e:	Density of explosives
C_{p}:	Longitudinal wave propagation velocity of the rock mass
C_{s}:	Transverse wave propagation velocity of rock mass.

Data Availability

The data used to support the findings of this study are available from the corresponding authors upon request.

Disclosure

It is worth noting that this article conducted a systematic study based on the following preprint. Therefore, the preprint is cited as follows. However, it should be noted that the author of the preprint has already applied for withdrawal in Research Square. The reference to the preprint is as follows: Yan Zhao, Hailong Wang, Yunhe Li et al. Prediction of Vibration Waveform and Division of Influenced Partitions under the Action of Blasting, 13 October 2023, PREPRINT (Version 1) available at Research Square [https://doi.org/10.21203/rs.3.rs3415526/v1].

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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