R wave identification of blasting seismic waves in propagation process and its engineering application

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Abstract. The identification of R wave is helpful to analyze damage characteristics and damage analysis of nearby building caused by blasting seismic waves. According to the characteristics of low frequency, low speed and strong amplitude of R wave, a time-frequency filter for R-wave recognition is constructed and a R-wave recognition method based on S-transform is proposed. Firstly, the measured blasting vibration signal is transformed from time-space to time-frequency domain by S-transform. Secondly, according to the characteristics of R-wave, the R-wave filter is constructed and processed in time-frequency domain. Finally, the obtained R-wave signal in time-frequency domain is transformed into time-space signal by inverse transform. The results of numerical simulation and field measurement show that the R-wave identification method based on S-transform can effectively suppress and extract R-wave without destroying low-frequency body wave signal.

Key words: blast seismic waves; R-wave recognition; time-frequency domain; S-transform; time-space domain

1. Introduction

Blasting excavation is one of the irreplaceable important means in human engineering production, especially in geotechnical engineering excavation, which has been widely used in many major engineering construction fields, such as water conservancy engineering construction, urban railway construction, underground tunnel engineering and so on. However, with the complexity of blasting operation environment and rock conditions and the enhancement of people's awareness of legal system and rights protection, slope and house damage caused by blasting vibration and complaints from residents in the operation area occur frequently, resulting in heavy losses, which makes the vibration safety control in the blasting process a prominent problem [1]. The propagation process of blasting seismic wave in rock mass can be divided into two types: body wave and surface wave. The body wave can be further divided into P wave and S wave. A large number of research and practice show that in the process of seismic wave propagation, the proportion of energy distribution in the far region is about 7% for P wave, 26% for S wave, and most of the energy is carried by R wave, accounting for 67% [2]. In addition, R-wave also has the characteristics of low frequency and wide range of influence [3], which has an important impact on the harm of seismic wave. Therefore, scholars at home and abroad have carried out a lot of research on the suppression and pick-up of R-wave, and achieved rich results [4-6], such as frequency-domain filtering method, frequency wavenumber domain and other surface wave suppression extraction methods. In practical application, the above methods have certain
effect on the suppression and extraction of surface wave, but they are easy to cause the loss of low frequency signal of body wave or incomplete suppression of surface wave signal.

In view of the defects of the above methods, scholars also put forward the corresponding improvement methods [7]. According to the characteristics of frequency and wavelength of surface wave, Li Weizhong et al. [8] proposed an effective method of surface wave suppression and separation. Deighan et al. [9] used the wavelet transform method to analyze the seismic signal, and proposed to suppress the low-frequency signal to eliminate the influence of surface wave. According to the characteristics of measured vibration data, Liu Cai et al. [10] proposed a method of suppressing surface wave based on two-dimensional wavelet transform, and achieved good results in practical application. Flinn [11-12] pointed out that there are great differences in polarization characteristics between surface wave signal and body wave signal through the study of seismic signal, and scholars have done a lot of research on the suppression of surface wave according to this characteristic. However, due to the overlap of surface wave signal and body wave signal in time domain, it is difficult to obtain the polarization parameters accurately, and the suppression effect is often not obvious in actual processing. Ma Jianqing et al. [13] used TT transform to suppress surface wave according to the characteristics of low frequency and low speed of surface wave. This method has good suppression effect, but it is easy to retain part of the interference of surface wave high frequency signal in the suppression process. Wang et al. [14] proposed a surface wave suppression method combining shearlet transform and TT transform for seismic exploration. Wang Deying et al. [15] proposed a surface wave suppression method combining shearlet transform and TT transform when they studied the subject of surface wave suppression. Firstly, shearlet transform is used to separate reflected signal from low frequency and low wavenumber surface wave. Secondly, TT transform is used to filter TT domain signal. Finally, surface wave can be suppressed by inverse transform. The results of the model and practical application show that the method can suppress the surface wave and protect the amplitude and phase information of the reflected wave signal. Ishiyama et al. [16] also conducted extensive research on the extraction and suppression of surface waves from the perspective of dispersion.

Although scholars have made a lot of achievements in the research of seismic phase identification, the existing methods do not consider the protection of the body wave signal in the process of suppressing the surface wave. Directly filtering the measured vibration signal may lead to the loss of the body wave signal, which deviates from the requirements of "high precision and high fidelity" in the process of signal processing; At the same time, most of the existing methods are concentrated in the seismic field. Compared with the natural seismic signal, the blasting seismic wave has the characteristics of short duration, short distribution distance and more propagation on the surface. The above technical methods are often difficult to be applied to the seismic phase recognition of vibration signal in the engineering field, and the recognition effect is poor. Therefore, the phase identification of blasting seismic wave in engineering field is worthy of further study.

2. Review on R wave properties and identification method development

2.1. R wave properties

As we all know, in the case of the existence of the medium interface, in addition to the well-known body wave, there are also waves with appropriate intensity along the medium interface (this paper mainly studies Rayleigh waves). At the same time, the British scholar Rayleigh predicted the existence of a kind of surface wave with exponential attenuation along the vertical displacement depth in the process of solving the plane elastic wave of free surface half space. Later, seismologists also confirmed the existence of this kind of wave in the study of natural earthquakes, and called it Rayleigh wave (Rayleigh wave, R wave).

Taking the wave propagating in a uniform elastic medium as an example, the Rayleigh wave equation can be expressed as:
Where $V_R$ is the R wave velocity, and the longitudinal and transverse wave speeds in equation (1) are

\[
\begin{align*}
V_p &= \sqrt{\frac{E(1-\mu)}{\rho (1+\mu)(1-2\mu)}} \quad \text{MERGEFORMAT (2)} \\
V_S &= \sqrt{\frac{E}{2\rho(1+\mu)}}
\end{align*}
\]

Where $E$, $\mu$, $\rho$ are the dynamic elastic modulus, dynamic Poisson's ratio and rock mass density of the rock mass propagation medium, respectively.

Combining equations (1) and (2), the relationship between longitudinal wave (P wave), transverse wave (S wave), Rayleigh wave (R wave) and Poisson's ratio can be obtained as shown in Figure 1.

Fig.1 Schematic diagram of the relationship between the propagation velocities of P-wave, S-wave, R-wave and Poisson's ratio

According to previous studies, when Rayleigh waves propagate in the medium, the horizontal displacement and vertical displacement equations of the medium pointer caused by it are as follows:

\[
\begin{align*}
u_z &= A \left( \frac{\omega}{V_R} \right) e^{\frac{2\pi \lambda_R}{V_R}} - 2c \omega \lambda_R \sin(\omega (t - \frac{x}{V_R}) \right) \quad \text{MERGEFORMAT (3)} \\
u_z &= A \left( \frac{2\lambda_R}{V_R} \right) e^{\frac{2\pi \lambda_R}{V_R}} - r e^{\frac{2\pi \lambda_R}{V_R}} \cos(\omega (t - \frac{x}{V_R}) \right) \quad \text{MERGEFORMAT (4)}
\end{align*}
\]

Where $c = \sqrt{\frac{1-\mu}{2-\mu}}$, $\lambda_R = \frac{2\pi V_R}{\omega}$, $p = \left( \frac{V_p}{V_R} \right)^2$, $n = \left( \frac{V_S}{V_p} \right)^2$, $r = \frac{\omega}{V_R} \sqrt{1 - \left( \frac{V_s}{V_p} \right)^2}$, $s = \frac{\omega}{V_R} \sqrt{1 - \left( \frac{V_s}{V_p} \right)^2}$.

When the Poisson ratio of rock mass medium is 0.15, it can be calculated by formula (3) and formula (4) that the measurement points on the surface are

\[
\begin{align*}
u_{z=0} &= 0.4246 A \lambda_R \sin(\omega t) \\
u_{z=0} &= 0.6213 A \lambda_R \cos(\omega t) \quad \text{MERGEFORMAT (5)}
\end{align*}
\]

Where $\lambda_R$ is the wave number of R wave.
It can be seen from equation (6) that near the free surface of the rock mass, the particle motion trajectory of the R wave is elliptical, and the ratio of the horizontal axis to the vertical axis of the particle motion is about 2:3, and the vertical displacement phase is ahead of the horizontal displacement phase.

When the P-waves are reflected and the wave motion is suppressed, the horizontal displacement and vertical displacement with the amplitude depth can be calculated by formula (5), as shown in Figure 2.

![Fig.2 Curves of horizontal displacement, vertical displacement with changes of depth](image)

From the above analysis, we can draw several characteristics of Rayleigh surface waves as the theoretical basis for surface wave identification and suppression:

1. In the propagation process of the same rock mass medium, longitudinal waves (P waves) have the fastest propagation speed, followed by transverse waves (S wave), and surface waves (R waves) have the slowest propagation speed.

2. The surface wave propagation velocity (R wave) and the shear wave velocity (S wave) have an approximately linear relationship in value, and as the Poisson's ratio increases, the two are approximately close in value. Therefore, when determining the R-wave region later, you can approximately judged by transverse wave velocity.

3. From equations (4) to (6), it can be seen that the surface wave propagation causes the particle motion trajectory to be elliptical, and this feature can be used as a further judgment after the final surface wave is identified.

2.2. R wave properties

Because surface waves have the characteristics of low frequency, long duration, and large carrying energy, they are the most destructive waveform in blasting vibration data. At the same time, in the actual vibration monitoring data, because the surface waves are intertwined in the reflected wave area, the signal-to-noise ratio of the vibration signal is low, which may further destroy the basic characteristics of the P and S wave signals in the vibration signal. Therefore, when accurately analyzing the measured vibration signal, first extract and suppress the surface wave signal, which is beneficial to improve the signal-to-noise ratio of the measured vibration, and provides effective help for the subsequent further analysis of the propagation and attenuation of the blasting seismic wave in the rock mass.

Surface wave removal from seismic signals is not an emerging issue in the direction of geophysics research. At present, there are some mature surface wave extraction and suppression methods, such as $f - x$ filtering, $f - k$ filtering, Radon transformation, wavelet transformation and other methods. However, the research ideas of these methods are basically the same: by transforming the seismic signal from the time-space domain to the frequency-wavenumber domain, frequency-space domain and other processing domains, the difference between surface wave and body wave (P wave and S wave) is analyzed, then extract and suppress surface waves. The following is an introduction to the above surface wave suppression methods:

1. $f - k$ filtering
$f-k$ filtering realizes surface wave suppression based on the difference in propagation velocity between surface wave and body wave. The specific operation is to project the seismic signal in the time-space domain to the frequency-wavenumber domain through a two-dimensional FFT transformation. The surface wave with the characteristics of low frequency and high wavenumber is concentrated on the upper left end of the FK spectrum, and then the surface wave can be realized through the designed fan filter. Of suppression. However, in actual seismic signals, surface waves and body waves are often mixed together in the frequency wavenumber domain, and the filter window of the sector filter is difficult to select. As a result, when the surface waves are removed, the effective signals of the body waves will also be a certain degree of damage is received, which does not meet the high accuracy and fidelity required in the vibration signal processing process.

(2) $r-p$ transformation

$r-p$ transformation is also called linear Radon transformation. Among them, $\tau$ and $p$ respectively represent the intercept and slope of the transformation function in the time-space domain. After the seismic signal is transformed into the domain, the seismic signal data has the following characteristics: the linear transformation in the time-space domain to the domain corresponds to a point. Using this correspondence, the surface wave is extracted and suppressed. However, because the body wave vibration signal and the surface wave vibration signal cannot be easily identified in the domain, the applicability of this method is limited.

(3) Wavelet transform

Wavelet transform is developed on the basis of Fourier transform. This method has good time-frequency localized management and multi-resolution analysis capabilities, and it is the most commonly used method in the current seismic signal analysis process. Can be better realized for signal denoising, singularity monitoring and so on. Compared with the one-dimensional wavelet transform, the two-dimensional wavelet transform also considers the correlation between the horizontal and vertical directions of the objective function, and can decompose the objective function in three mutually perpendicular directions. After the seismic signal undergoes two-dimensional wavelet transformation, the main energy of the surface wave is distributed in the low-frequency and high-wavenumber area. Further data processing in this area can realize the extraction and suppression of the surface wave signal. However, the existing processing method is to directly set the wavelet coefficients in the corresponding area to zero, so that while suppressing the surface wave, it also causes a certain degree of damage to the body wave signal.

Through the comparison and analysis of the above methods, it is found that they all have an obvious disadvantage, that is, they do not consider the protection of body wave signal in the process of suppressing face wave, so it may lead to further damage to body wave signal, which does not meet the requirements of "high precision and high fidelity" in the process of seismic signal processing.

2.3. R wave identification method based on S-transform

In the process of blasting seismic wave attenuation and vibration prediction, because the energy carried by surface wave is the main part, it is a very important task to suppress and identify surface wave in blasting vibration signal processing, which plays a very important role in improving the accuracy of blasting impact assessment. According to the characteristics of surface wave, such as low frequency, large amplitude, low propagation speed and long duration of vibration, scholars at home and abroad have proposed a variety of methods to identify and suppress surface wave, such as low-frequency filtering and high-frequency filtering, frequency wavenumber domain (F-k domain) filtering, wavelet transform and so on. Each method has a certain effect on the recognition and suppression of surface wave, but there are some limitations. For example, when suppressing surface wave in the whole time domain, the low frequency part of body wave will be removed. In this section, S-transform is proposed to suppress the surface wave information in order to suppress the surface wave interference of the measured blasting vibration signal effectively and not to interfere with the body wave information. This method inherits and develops the advantages of short-time Fourier transform.
and wavelet transform. Its window width shrinks with the increase of signal frequency, and it has high resolution for high-frequency signals. It can flexibly use different filters according to the frequency characteristics of vibration signals at different times, so as to effectively protect the frequency components of body wave signals, it has high practical significance.

S-transform is a time-frequency analysis method for multi-resolution analysis proposed by Stockwell et al. Based on the comprehensive study of multiple time-frequency processing methods, it is the inheritance and development of continuous wavelet transform and Fourier transform.

For the signal \( x(t) \in L^2(R) \), the time-frequency analysis of any non-stationary blasting vibration signal can be expressed as

\[
F(f) = \int x(t)g(t-t,f)e^{-i2\pi ft}dt \quad \text{MERGEFORMAT (6)}
\]

Where, \( t \) is the signal duration; \( f \) is the continuous frequency of the signal; \( i \) is a unit of imaginary number; \( g(t) \) is a window function, and when the window function is expressed as different type function, formula (6) represents different types of time-frequency analysis transformation. The window function can be expressed as

\[
g(t) = \frac{|f|}{\sqrt{2\pi}} e^{-\frac{r^2}{2}} \quad \text{MERGEFORMAT (7)}
\]

Substituting equation (7) into equation (6), the \( s \) transformation can be expressed as follows

\[
ST(\tau, f) = \int x(t)g(t-t, f)e^{-i2\pi ft}e^{-\frac{i2\pi ft}{2}} dt \quad \text{MERGEFORMAT (8)}
\]

Equation (8) is called S-transform of signal.

It should be noted that the necessary condition of S-transform is that the window function should satisfy the following conditions

\[
\int_{-\infty}^{\infty} g(\tau - t, f)d\tau = 1 \quad \text{MERGEFORMAT (9)}
\]

Therefore, equation (9) also guarantees that the inverse transformation of \( s \) transformation is reversible, which is expressed as follows

\[
\int_{-\infty}^{\infty} \left[ \int_{-\infty}^{\infty} ST(\tau, f)d\tau \right] e^{i2\pi ft} df = x(t) \quad \text{MERGEFORMAT (10)}
\]

The effective time-frequency information can be obtained by S-transform of the measured blasting vibration signal, and the signal can be expressed from the time-frequency domain back to the time-domain by the inverse transform of S-transform in equation (10). From the above derivation, it can be seen that the signal will not lose any effective information in the process of transformation, so this method provides theoretical and technical support for the surface wave identification of the measured seismic signal.

2.3.1. Filter design of \( R \) wave identification. The time-frequency filtering process of blasting vibration can be expressed by the following formula

\[
R(t) = ST^{-1}[ST[x(t)] \cdot N(t, f)] \quad \text{MERGEFORMAT (11)}
\]

Where, \( R(t) \) is the recognition surface wave signal, \( S \), \( S^{-1} \) are S-transform and S-inverse transform respectively; \( N(t, f) \) is time frequency filtering function. According to the characteristics of surface wave, if the distribution area \( D_s \) is surface wave signal in time-frequency domain (Fig.3), then the frequency filtering function can be expressed as
2.3.2. $R$ wave identification. The specific implementation steps of $R$-wave suppression and extraction are as follows:

(1) According to the existing research results $^{[18]}$, the first arrival time of S wave is determined. According to the relationship between the propagation velocity of S wave and $R$ wave in rock mass medium, it can be concluded that for general solids, the propagation velocity of surface wave is slightly less than that of S wave and then the time range of $R$-wave in time-frequency domain can be preliminarily determined.

(2) Fourier transform is used to analyze the frequency spectrum of blasting seismic wave, and the frequency of $R$ wave is preliminarily estimated to determine the frequency range of $R$ wave in time and frequency domain;

(3) Combining with steps 1 and 2, the approximate distribution range of $R$ wave in time-frequency domain can be obtained, and then the filtering function can be determined according to equation (13).

(4) The time-frequency distribution of vibration is obtained by $S$ transformation of blasting vibration signal by formula (9), and then filtering in time-frequency domain according to formula (12), and the representation of the surface wave in time-frequency domain is obtained. The signal can be obtained by inverse transformation of $S$-transform, that is, the surface wave signal extracted.

3. Numerical simulation of $R$-wave identification of blasting seismic wave

In order to further verify the effectiveness of the above method, this paper carries out numerical simulation of blasting seismic wave propagation in rock mass based on ANSYS-LSDYNA, and establishes a three-dimensional model as shown in Figure 4 to simulate single hole blasting in semi infinite rock mass. The model size is (length * width * height), the hole diameter is 90mm, the cartridge diameter is 70mm, the hole depth is 6m, and the plugging length is 1.8m; Because the size of the blast hole is much smaller than that of the model, in order to better describe the stress change of the explosive explosion process, the gradual mesh is used; At the same time, Kuhlemeyer R. L. and Lysmer J.’s research$^{[19]}$ show that, the mesh size has a great influence on the calculation accuracy of blasting seismic wave propagation. In order to better simulate the blasting vibration propagation process, the maximum mesh size should not exceed the wavelength. Based on this, the maximum cell size of this model is 2m, and the blasting seismic wave length is about 25m, It meets the requirements of calculation accuracy. In this paper, the numerical simulation of single hole blasting in semi infinite rock mass is carried out. By using symmetry condition and in order to facilitate calculation, the 1/4 model is established, which contains 466920 elements and 481284 nodes. In order to reduce the influence of reflected wave on blasting vibration waveform, the model boundary $x = 0, y = 0$ is set as

$$N(t,f) = \begin{cases} 1 & (t,f) \in D_R \\ 0 & (t,f) \notin D_R \end{cases} \text{ MERGEFORMAT (12)}$$

Where, $f$ is the frequency of surface wave signal.

![Fig.3 Illustration of characteristics of blast seismic waves in T-F domain](image)

In the implementation of the above-mentioned simulation steps, the maximum depth of the blast hole is $25m$, the maximum depth of the mesh is $10m$, the mesh size is $9000$, and the number of time steps is $481284$. The characteristics of the blast seismic waves in the time-frequency domain are shown in Figure 3. The method described above is used to analyze the $R$ wave signal in the time-frequency domain. It can be seen that the $R$ wave signal is extracted, and the signal characteristic parameters are used to determine the wave identification requirements.
symmetrical boundary, \( z = 0 \) is set as free boundary and the other boundary is set as transmission boundary. In the process of numerical calculation, the fluid structure coupling algorithm is used to simulate the explosive explosion process. The explosive material is the \texttt{MAT_HIGH_EXPLOSIVE_BURN} model of LS-DYNA software, and the equation of state \texttt{EOS_JWL} describes the relationship between detonation pressure and volume in the process of explosion.

\[
P = A\left(1 - \frac{\omega}{R_1 V}\right) e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right) e^{-R_2 V} + \frac{\omega E_0}{V}\]

Where, \( P \) is the detonation pressure; \( V \) is the relative volume; \( E_0 \) is the initial energy density and the other parameters are independent constants used to describe the equation of state. The relevant parameters of explosives are shown in Table 1. The values of physical and mechanical parameters of rock mass are shown in Table 2.

| Tab.1 Parameters of explosive |
|--------------------------------|
| density/(kg/m\(^3\)) | VOD/(m/s) | PCJ/GPa | A/GPa | B/GPa | R\(_1\) | R\(_2\) | \(\omega\) | E\(_0\)/GPa |
| 1000 | 3800 | 3.24 | 209.69 | 3.51 | 5.76 | 1.29 | 0.39 | 2.39 |

![Fig.4 Finite element calculation model](image)

![Tab.2 Physical parameters of rock mass](image)

In order to analyze the effectiveness of the method mentioned in this paper, blasting vibration monitoring points are arranged at different blasting center distances on the model surface, as shown in Figure 4. Fig.5 shows the time history curve and time spectrum of blasting vibration velocity in horizontal radial direction and vertical direction of No. 1 measuring point. Through spectrum analysis of the measured vibration signal, the R-wave frequency is mainly concentrated in 100 ~ 150Hz. According to the above surface wave suppression and extraction method, the blasting vibration waveform is analyzed and processed, and the volume wave and surface wave curves are obtained, as shown in Figure 6. In order to verify the extracted R-wave, this paper uses the method proposed by Gao Qidong et al. Based on the particle motion trajectory and the combination of horizontal and vertical vibration phases to draw the particle motion trajectory of the body wave and surface wave vibration curves after separation in Fig. 6(a). It can be seen from Figure 6 that the particle trajectory of the extracted R-wave signal is an anticlockwise ellipse, while the body wave signal after suppressing R-wave can be seen as moving in quadrants 1, 3, 2 and 4; At the same time, in the process of filtering the R-wave, this method does not involve the processing of the body wave signal before the first break of S-wave, which can show that the R-wave suppression and extraction method proposed in this paper can separate the R-wave without causing loss to the body wave signal.
4. Numerical simulation of R-wave identification of blasting seismic wave

4.1. Site description

Fengning pumped storage power station is located in Fengning Manchu Autonomous County, Hebei Province, China. The power station project is developed and constructed in two phases with a total installed capacity of 3600mw. It undertakes the tasks of peak load regulation, frequency regulation, phase modulation and emergency standby in the power grid system. Based on the excavation opportunity and conditions of the geological exploration tunnel of the underground powerhouse of phase II project, the vertical drilling blasting test was carried out. The arrangement of blasting holes and vibration monitoring points in the test process is shown in Fig.7. Half second millisecond delay blasting was adopted and blasting was carried out hole by hole. The parameters of blasting test hole network are shown in Table 3.
4.2. Site description
Six blasting vibration signals were detected in the field blasting test. In this section, the vibration signals caused by blasting of No. 1 (6-1) and No. 2 (6-2) holes measured at 6#-measuring points are taken as examples to verify the effect of the above R-wave identification method. The time history curves of blasting vibration measured at 6#-1 and 6#-2 are shown in Fig.8.

According to the surface wave extraction method described above, the measured blasting vibration signals are analyzed. The vibration waveforms of body wave and surface wave after separation and the corresponding particle trajectory are shown in Fig.9–Fig.10 respectively. It can be seen from the figure that the surface wave separation effect is good, and there is no obvious damage to the body wave signal.
According to the analysis of vibration data from Fengning field test, the attenuation rate of P wave and R wave is different in the process of propagation. With the increase of propagation distance, the body wave decays rapidly, and the proportion of R wave increases gradually. Moreover, it can be seen from Fig.9 and Fig.10 that when the propagation distance is greater than a certain range, the R-wave develops into the main waveform and dominates the vibration, while the lower frequency R-wave is more likely to cause damage to the surrounding buildings. Therefore, it is of great significance to study the attenuation law of different waveform induced vibration for accurate vibration prediction and building safety evaluation.
5. Numerical simulation of R-wave identification of blasting seismic wave

(1) Based on the propagation characteristics of surface wave such as low frequency, low speed and high energy, a method of R-wave recognition and extraction based on measured blasting vibration signal is proposed.

(2) The results of numerical simulation and field test show that the surface wave recognition and extraction method based on S-transform can better reflect the time-frequency characteristics of the vibration signal, and the low frequency characteristics of the body wave signal can be better protected by filtering the signal in the time-frequency domain. The combination of polarization characteristics and particle trajectory can further verify the effectiveness of the separated R-wave vibration curve;

(3) The accuracy of R-wave recognition and pick-up based on S-transform is greatly affected by the length of time window and filtering threshold. These parameters are obtained based on the measured vibration data of vertical borehole blasting test in geological exploration hole of underground powerhouse of Fengning Pumped Storage Power Station Phase II project, whether these parameters can be well applied to other projects still needs further verification.

The ultimate goal of the study of blasting vibration effect is to clarify the dynamic response mechanism of the structure under the action of blasting seismic wave. The wave component separation method based on R-wave suppression proposed in this paper only makes a preliminary discussion on the separation of face wave and body wave. The reasonable and effective separation method should be sought in the future to realize the separation of P wave, S wave and R wave in blasting seismic wave. At the same time, how to apply the research results of this paper to the structural response and the response and failure characteristics of structures under different types of waves need to be further studied.

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