Method of S Wave Identification: Application to Measured blasting vibration signals

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Abstract: S wave identification is an indispensable step in the process of deriving the dynamic parameters of rock masses, which are highly significant in guiding the design and construction of hydraulic engineering projects. However, it is difficult to identify S waves accurately because of 1) the influence of overlapping within the P wave coda and 2) the incomplete separation between S and P waves owing to the characteristic short distances of blasting seismic wave propagation. This paper presents a modified method for accurately identifying S waves at the engineering scale using blasting vibration signals. The proposed method combines the application of the short-time average zero-over rate with polarization analysis. By using the short time average zero-over rate, it is possible to effectively reduce the computational time while improving the computational efficiency. Polarization analysis is used to improve the accuracy of the method. A comparison of numerical identification and theoretical results revealed that the improved method is clearly capable of S wave identification with errors of less than 2%. To demonstrate the capability and accuracy of the proposed method, measured vibration signals were introduced to the Fengning pumped-storage power station and the S wave velocities obtained from the first arrival times were compared to obtain an estimated S wave velocity.

Keywords: S wave identification, rock masses, engineering scale, short time average zero-over rate, polarization analysis

1. Introduction
With the rapid development of the Chinese economy, an increasing number of hydropower stations are being constructed in the southwest and northwest regions of the country. Bench blasting, which remains the primary excavation method in hydraulic engineering construction, can lead to several safety problems, including deformation and stability issues arising under the action of the dynamic loads induced by blasting vibration [1-2]. A prerequisite to solving these problems is the determination during the construction process of dynamic rock mass parameters such as the dynamic elastic modulus and the dynamic Poisson ratio. As one of the primary components of signal processing, S wave identification plays an indispensable role in the back analysis of rock mass parameters. Accordingly, it is a necessary investigate method for improving S wave identification at the engineering scale.

The basic methods developed to date for S wave identification have arisen directly from research on naturally occurring earthquakes. In the study of earthquakes, much research and discussion has focused on P wave determination. A number of methods for obtaining P wave onset time have been proposed and through several application examples have been shown to be feasible and reliable [3-5]. The identification of S waves, however, is more difficult than P wave identification because of the slower propagation velocities of S waves, which are always influenced by the P wave coda and by converted waves such as PmP and PS waves [6-7]. During the last decade or so, considerable effort...
has been made to improve S wave identification and to determine S wave first arrival times more accurately. In this regard, several methods based on the comparison of differentiating characteristics of P and S waves such as linear polarization and particle motion direction have been proposed [8-10]. Earle and Shearer [11] proposed an automatic picking algorithm based on a short-term-average to long-term-average ratio (STA/LTA) computed using an envelope function generated from seismogram data, which they applied to global earthquake data recorded over a period of more than seven years. A comparison of their results with International Seismological Centre (ISC) data revealed that their method was a useful tool for distinguishing seismograms containing phases that are useful for further study. Gentili and Michelini [12] proposed IUANT2, an efficient and precise method characterized by a high generalization capability, for identifying P and S waves based on the use of neural networks. Their method was easier to implement and more effective than the STA/LTA phase picker method and performed better in lower signal-to-noise ratio environments. Application of IUANT2 to data produced by 342 earthquakes recorded by 23 different stations revealed that the method had standard deviations of 0.064 and 0.11 s for P and S waves, respectively. Diehl et al. [6] proposed a new S wave picker based on a combination of various detection techniques, including STA/LTA, polarization analysis, and application of the auto regressive-Akaike information criterion (AR-AIC). Despite its advantages in terms of higher picking precision and enhanced robustness, however, this method has large computational and time requirements, making it unsuitable for real-time signal analysis.

For the automatic identification of S waves from the three-component seismic data, Cichowicz [13] proposed an algorithm based on polarization analysis that employed a characteristic function built on three parameters, namely, deflection angle, degree of polarization, and the ratio of transverse and total energies. In practical application, this automatic S wave picking method is effective at discriminating 65 to 70% of data produced over a magnitude range from 1 to 3. Amoroso et al. [14] proposed a method for S wave identification that combined polarization filtering and lateral waveform coherence analysis in the seismic wave data analysis process. The feasibility and effectiveness of this method was validated through application to local earthquake data recorded by the Irpinia Seismic Network.

In this study, a modified identification method designed to specifically identify the first arrival times of S waves produced by blasting vibration was developed. The proposed method is a modified form of S wave identification based on a combination of short time average zero-over rate and polarization analysis, enhancing its applicability to the engineering scale. Following a numerical simulation to verify the accuracy and efficiency of the proposed method, field experiments were conducted in which it was applied to vibrational signals produced at the Fengning pump power station to clearly identify S waves. It is hoped that the method described in this paper will engender new applications in the identification and analysis of S waves at the engineering scale.

2. Method of S-wave identification

During blasting excavation in the construction of railways, highways, and hydraulic engineering projects, most of the explosion energy propagates outward in the form of seismic waves, which leads to ground vibration. Following engineering experience, these seismic waves primarily comprise compression waves (P waves), shear waves (S waves), and Rayleigh waves (R waves) [15]. In the propagation process, P and S waves have different vibrational mode and propagation velocities. During blast vibration measurement, the first vibration signals observed by monitoring instruments are triggered by P waves, which are simple to identify because they have relatively few influencing factors. To recognize S waves, by contrast, it is necessary to consider the influence of factors such as P-SV converted waves and the P wave coda, all of which can make it difficult to determine the S wave onset [7]. It is possible, however, to distinguish S waves from the P wave coda based on their unique properties, which include linear polarization and specific vibrational frequencies. The next section presents a brief review of related parameters, including the short-time average zero-crossing rate (which is related to frequency) and polarization parameters such as deflection angle, degree of polarization, and the ratio of transverse to total energy. In conducting S wave identification, we
assume that the P wave has been identified using other methods and follow the approach proposed by Bear and Kradolfer [16].

2.1 Determination of Calculation window width
The calculation window width is a key parameter in the analysis of blasting vibration signals that must be precisely determined. For non-stationary vibration signals, the computational process is complicated as a result of rapid changes in frequency. For convenience, therefore, the window width can be calculated using the formulation proposed by Cichowicz [13]:

\[ l_w = \frac{f_i}{f_p} \]  

where \( f_i \), \( f_p \) are the sampling rate and predominant P wave frequency, respectively. It has been shown [17] that \( f_p \) can be calculated as follows:

\[ f_p = \frac{\sqrt{\int u(f)df}}{\int v(f)df} \]  

where \( \int u(f)df \) and \( \int v(f)df \) are the displacement and velocity power spectra, respectively. It should be noted that in this process the data are recorded in 2-ms intervals, as the P wave first arrival is used for Nyquist theory-based analysis.

2.2 Short time average zero-over rate
The blasting waveform shown in Figure 1 shows an obvious change in the frequency of vibrational signals before and after the S wave onset. To some extent, therefore, the S wave can be identified by quantifying the variation in frequency. Although this can be measured in terms of the period of vibration for stationary signals, this approach is not valid for non-stationary signals such as blasting vibration and seismic signals. To calculate the frequency changes in non-stationary signals, the short time average zero-over rate can be applied as follows:

\[ K = \frac{\sum_{i=m}^{n} [\text{sgn}[x_{i+1}] - \text{sgn}[x_i]]}{(n-m)\Delta t} \]  

where \( \text{sgn}[x] = \begin{cases} 1 & x \geq 0 \\ 0 & x < 0 \end{cases} \) \( n,m \) are the sequence numbers of the blasting vibration signals, and \( \Delta t \) is the sampling time.

![Figure 1. Waveform of blasting vibration signal](image-url)
We define the period between the first arrivals of the P and S waves as “P-S” and the following interval \((n_s - n_p)\Delta t\) as “S-S1”. The short time average zero-over rate before and after arrival of the S wave can then be written as

\[ K_1 = \frac{K_{P-S}}{K_{S-S1}} \]  

where

\[ K_{P-S} = \frac{\sum_{i=0}^{n_p} [\text{sgn}(x_{i+1}) - \text{sgn}(x_i)]}{(n_s - n_p)\Delta t} \quad ; \quad K_{S-S1} = \frac{\sum_{i=0}^{n_s} [\text{sgn}(x_{i+1}) - \text{sgn}(x_i)]}{(n_{S1} - n_s)\Delta t} \quad ; \quad n_{S1} = (n_s - n_p) + n_s, \]

where \(n_p, n_s\) are the first arrival times of the P and S waves, respectively.

According to the study on mine microseisms conducted by CX Zhang et al. [18], the S wave first arrival will have a direct relationship with the short time average zero-over rate. Their results indicated that an S wave could be confirmed at values of \(K_1\) greater than or equal to 1.2. Using this parameter, therefore, the first arrival time of an S wave can be roughly obtained, thereby significantly reducing the computational burden and effectively increasing the computational efficiency.

2.3 Analysis of polarization characteristics

To obtain more accurate results, the S wave first arrival can be further analyzed in terms of the polarization characteristics of blast vibration signals. To do so, the proposed method rotates the measured vibrational data coordinates from that of the ground motion monitoring system defined by the vertical (Z), horizontal (X), and horizontal tangential (Y) directions into a wave particle motion system defined by LQT coordinates, in which the L-axis represents the direction of P wave particle motion and the Q- and T-axes represent the S wave (SV and SH wave, respectively) particle motion directions [19], as shown in Figure 2. A covariance matrix of the set of three-component length data \(l_n\) from the start of P wave arrival can be calculated as follows:

\[ M = \begin{bmatrix} \text{cov}(x, x) & \text{cov}(x, y) & \text{cov}(x, z) \\ \text{cov}(y, x) & \text{cov}(y, y) & \text{cov}(y, z) \\ \text{cov}(z, x) & \text{cov}(z, y) & \text{cov}(z, z) \end{bmatrix} \]  

(5)

in which the covariance between any two components can be expressed as follows:

\[ \text{cov}(n, m) = \frac{1}{l_w} \sum_{i=1}^{l_w} (n_i - \bar{n})(m_i - \bar{m}); n, m = x, y, z \]

(6)

![Figure 2. Polarization characteristics of blasting-induced seismic waves](image-url)
The three eigenvectors corresponding to the covariance matrix in Eq. (5) can be used to rotate the X, Y, Z coordinate system into the L, Q, T system as follows:

\[
\begin{bmatrix}
L \\
Q \\
T
\end{bmatrix} =
\begin{bmatrix}
u_{11} & u_{12} & u_{13} \\
u_{21} & u_{22} & u_{23} \\
u_{31} & u_{32} & u_{33}
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]

(7)

where \(u_{i,j}(i=1,2,3)\) are the cosine values between the eigenvector corresponding to the \(i\)-th eigenvalue and the X, Y, Z axes.

The polarization properties of blast-induced seismic waves can be analyzed using the eigenvalues and corresponding eigenvectors of the covariance matrix. In practice, S wave phase identification can be carried out effectively using three parameters, e.g., the deflection angle, \(D(t)\), the degree of polarization, \(P(t)\), and \(E(t)\), the ratio of the transverse to total energy, which is related to the covariance matrix. The deflection angle \(D(t)\) is defined as the normalized angle between the direction of P wave particle motion (L) and the direction of the eigenvector corresponding to the largest eigenvalue and is given by

\[
D(t) = \frac{\alpha}{\pi/2}
\]

(8)

where \(\alpha\) is the angle between L and the eigenvector associated with the largest eigenvalue at time \(t\) following the arrival of the P wave. Because the P and S wave polarization directions are mutually vertical, the value of \(D(t)\) is changed from zero at the P wave first arrival to one at the onset of the S wave. To determine the polarization degree, \(P(t)\), the equation proposed by Samson [20] is used:

\[
P(t) = \frac{(\lambda_1 - \lambda_2)^2 + (\lambda_1 - \lambda_3)^2 + (\lambda_2 - \lambda_3)^2}{(\lambda_1 + \lambda_2 + \lambda_3)^2}
\]

(9)

where \(\lambda_1, \lambda_2, \lambda_3\) are the eigenvalues of the covariance matrix at time \(t\). The value of \(P(t)\) is one at the first arrivals of the P and S waves and varies over the range of zero to one in the P wave coda region. The ratio of transverse to total energy, \(E(t)\), is related to the covariance matrix in the L, Q, T coordinate system and can be calculated as follows:

\[
E(t) = \frac{\sum_i (Q_i^2 + T_i^2)}{\sum_i (L_i^2 + Q_i^2 + T_i^2)}
\]

(10)

In the L, Q, T coordinate system, the value of \(E(t)\) becomes one and zero upon the first arrivals of the S and P waves, respectively. This parameter enhances the discrepancies between the P and S waves by squaring their respective amplitudes to make the S waves more easily identifiable. Using the following characteristic function of these three parameters, the S wave first arrival can be identified rapidly:

\[
CF = D^2(t) \times P^2(t) \times E^2(t)
\]

(11)

This characteristic function can be used to improve the degree of linear polarization of vibrational signals. To ensure a sharp distinction between P and S waves, each element of CF(t) is squared to enhance its increase upon the arrival of the S wave during seismic wave propagation. In practical application, the point at which there is a sudden jump in the CF(t) curve can be considered to correspond to the time of S wave arrival within the P wave coda region. However, as shown in Figure 3, S wave arrival cannot always be identified using this approach because there is not always a clearly sudden increase in CF(t). To simplify this problem, a weight identification function, \(CF_w\), can be built using an optimizing weight parameter \(w(t)\) given by

\[
w(t) = \sqrt{Q^2(t) + T^2(t)}
\]

(12)
to produce the following weight identification function:

$$CF_w(t) = CF(t) \cdot (Q^2(t) + T^2(t))$$

(13)

The arrival of an S wave can cause a rapid increase in the amplitudes of both the characteristic function $CF$ and the weight parameter $w(t)$. In this case, the vibrational signal corresponding to the maximum value of $CF_w(t)$ will represent the S wave first arrival. To enhance visualization, the value of $CF_w(t)$ can be normalized to serve as an identification marker using the following normalized weight identification function:

$$N = \frac{CF_w}{\text{max}(CF_w)}$$

(14)

Figure 3. Examples of identification results obtained using CF and $CF_w$: (a) example of vibration signal time history; (b) time histories of identification parameters $D(t)$, $P(t)$, and $E(t)$; (c) identification results for two different functions (CF and $CF_w$)

3. Numerical simulation experiment

To validate the proposed S wave identification method, a series of numerical simulations were carried out. Based on a field experiment conducted at the Fengning power station, one of the largest pumped storage power stations in China, a finite element model was built, as shown in Figure 4. The symmetry of the numerical simulation model enabled us to employ a quarter-model to study the recognition of S waves in blasting vibration signals. The length, width, and height of the model were 20, 10, and 9 m, respectively, and the SOLID 164 element, which has an eight-node brick element, could be applied. According to Kuhlemeyer and Lysmer [21], the element size of a numerical model has a significant influence on its computational accuracy, and they suggested that the element size should be less than 1/8–1/10 of the analyzed wavelength. Accordingly, the element size was increased from 0.01 m on the blasthole to 0.8 m on the border. The overall model had 260,012 nodes and 240,304 elements. The borehole had a 3-m depth and stemming was applied at its upper 0.9 m. The diameters of the hole and charge were 90 and 32 mm, respectively. A symmetry boundary was employed along the normal
direction to the plane; for the other model faces (with the exception of the free surface), non-reflecting boundaries were applied to prevent wave reflection at the model surface. Imaginary monitoring points were arranged along the top surface of the model. For the purposes of simulation, the rock mass was assumed to be homogeneous and isotropic; the rock parameters are listed in Table 1.

![Finite element model (FEM) used for calculations](image)

**Figure 4.** Finite element model (FEM) used for calculations

**Table 1.** Physical parameters of rock mass

| Bulk density (kg·m⁻³) | Elastic modulus (GPa) | Poisson ratio | Tensile strength (MPa) | Damage constant | K̂IC (MN·m⁻³/²) | Damage constant λ (kg·J⁻¹) |
|----------------------|-----------------------|---------------|------------------------|----------------|-----------------|---------------------------|
| 2530                 | 40                    | 0.22          | 2                      | 2.33×10²⁴      | 7               | 0.92                      | 0.0001                   |

**Table 2.** Comparison of S wave identification example results

| Distance from the explosion center R/m | S wave arrival time obtained using proposed method /ms | Theoretical value of S wave arrival time /ms | Deviation /% |
|---------------------------------------|------------------------------------------------------|---------------------------------------------|--------------|
| 10                                    | 3.85                                                 | 3.92                                        | 1.3          |
| 15                                    | 5.90                                                 | 5.89                                        | 0.3          |

By substituting the rock values listed in Table 1 into $V_p = \frac{E_d(1-\mu_d)}{\sqrt{\rho_d(1+\mu_d)(1-2\mu_d)}}$, $V_s = \frac{E_d}{2\rho_d(1+\mu_d)}$, the P and S wave velocities were calculated as 4,248 and 2,545 m/s, respectively.

Based on these values, the theoretical S wave first arrival times at various monitoring points could be calculated and compared with the automatic identification results obtained using the methods developed in Section 2 (Table 2). The identification results are also shown in Figure 5. It is seen that the results obtained using the identification method deviate from the theoretical values by approximately 2%. These simulation results indicate that the proposed identification method has a high degree of accuracy and can meet engineering requirements.
4. Field experimental studies on S wave identification

4.1 Field experiment background and data sources

Field blasting tests to assess S wave first arrival through the monitoring of blasting vibration signals were carried out at the Fengning pumped storage power station. The station, which is under construction, will have a capacity of 3,600 MW and is located in the Fengning Manchu Autonomous County in Hebei Province, China. The project construction is to be divided into two phases, and the underground power house blasting excavation to be carried out during the second phase will have inevitable effects on the first-stage engineering. To guarantee the reliability and security of the underground power house constructed following the second stage excavation, it will be important to obtain dynamic mechanical parameters of the rock mass quickly and efficiently. Taking this second-stage excavation blasting as a background, a number of site blasting experiments were conducted. Based on the available topographic maps, the experimental area could be considered to be flat. As the rocks in the test area are dominated by intact granite with high mechanical intensities, the rock mass could be regarded to be a homogeneous and isotropic elastic body.
To carry out the site experiment, six vertical boreholes were drilled and initiated in sequence using a half-second delay detonator. The blasting design layout is shown in Figure 6. A No. 2 emulsion explosive was used to carry out site blasting. The parameters of the boreholes are listed in Table 3.

Table 3. Site experiment blasting design parameters

| borehole No. | Diameter of borehole /mm | Depth of borehole /cm | Diameter of charge/mm | Length of charge/cm | Stemming /cm | Charge per borehole/kg |
|--------------|--------------------------|-----------------------|-----------------------|---------------------|--------------|------------------------|
| I-1          | 76                       | 800                   | 50                    | 600                 | 200          | 12.0                   |
| I-2          | 76                       | 800                   | 50                    | 600                 | 200          | 12.0                   |
| II-1         | 76                       | 600                   | 50                    | 420                 | 180          | 8.4                    |
| II-2         | 76                       | 600                   | 50                    | 420                 | 180          | 8.4                    |
| III-1        | 76                       | 450                   | 50                    | 270                 | 180          | 5.4                    |
| III-2        | 76                       | 450                   | 50                    | 270                 | 180          | 5.4                    |

Monitoring of the vibrations produced by the field blasting was carried in accordance with blasting safety regulations and codes for the safety of blasting monitoring of hydropower and water resource engineering. As shown in Figure 6, six monitoring points were set up along a measuring line on the ground surface. To monitor the blasting vibrations, a TC-4850 device was used (Figure 7). The monitoring instrument system had several components, including a three axis velocity detector, signal gathering recorder equipment, and a data processing system. The amplitude measuring range was 0.001–35.4 cm/s and the measurement precision was 0.001 cm/s. The system had a wide vibration frequency detection band (01–1000 Hz) and a high degree of resistance to interference. Owing to the limited amount of space in the testing area, the distances from the explosion to the monitoring point positions ranged from 10–150 m. Aldas’ results [22] confirm that blasting-induced vibrational signals could be accurately recorded using the TC-4850 within this distance range. Figure 8 shows the original horizontal tangential velocity signal recorded by monitoring point (10#).
4.2 Identification results and analysis

The field blasting vibration signals were analyzed using the proposed P and S wave identification methods. The identification results are listed in Table 4, in which the figures in brackets are S wave arrival times. Figure 9 shows the results of applying the proposed S wave identification method at a typical monitoring point (10#).

Figure 9. S wave identification result charts for 10# monitoring site: (a) vibration-time history for borehole 2; (b) vibration-time history for borehole 3; (c) vibration-time history for borehole 4; (d) vibration-time history for borehole 5
Table 4. Results of P and S wave arrival identification at experimental site

| Borehole | First arrival times of P and S waves (units: ms) |  |
|----------|--------------------------------------------------|---|
|          | 1#                                               | 2#  | 4#       | 6#       | 8#       | 10#      |
| 1        | 429.25(431.63)                                  | −0.38(3.25) | −0.63(5.50) | −0.63(8.75) | −1.25(12.13) | −8.25(11.25) |
| 2        | 897.13(899.50)                                  | 467.50(471.13) | 467.00(473.13) | 467.13(476.50) | 466.50(479.88) | 459.13(478.63) |
| 3        | 1531.50(1533.63)                                | 1101.88(1105.13) | 1101.13(1107.00) | 1101.13(1110.25) | 1100.25(1113.38) | 1093.25(1112.50) |
| 4        | 1628.75(1630.88)                                | 1199.13(1202.50) | 1198.38(1204.25) | 1198.50(1207.50) | 1197.00(1210.13) | 1190.63(1209.88) |
| 5        | 2583.13(2585.00)                                | 2153.50(2156.50) | 2153.00(2158.50) | 2153.13(2161.88) | 2153.13(2164.00) | 2145.00(2164.13) |
| 6        | 3053.00(3054.88)                                | 2623.25(2626.38) | 2622.63(2628.25) | 2622.75(2631.63) | 2621.13(2634.00) | 2614.75(2633.75) |

The values listed in Table 4 were then used to obtain the time differences, Δt, between the P and S wave arrivals in units of ms:

\[ Δt = \frac{l}{V_S} - \frac{l}{V_P} \]

where \( l \) is the distance between the explosion source and the monitoring point in units of m. From this, the P and S wave velocities in the region between the blasting source and each monitoring point could be obtained (Table 5).

Table 5. Average propagation velocities of P and S waves based on field blasting vibration signals

| Area                        | P wave velocity /km/s | S wave velocity /km/s |
|-----------------------------|-----------------------|-----------------------|
| area between explosion source and 1# monitoring point | 4.988 | 2.977 |
| area between explosion source and 2# monitoring point | 5.531 | 3.259 |
| area between explosion source and 4# monitoring point | 5.301 | 3.125 |
| area between explosion source and 6# monitoring point | 5.293 | 3.143 |
| area between explosion source and 8# monitoring point | 4.840 | 2.914 |
| area between explosion source and 10# monitoring point | 5.068 | 3.016 |

Figure 10. S wave travel time at different distances from explosion center

A geological exploration report provided by BGI Engineering Consultant LTD. suggested S wave velocities in the test area of between 2.77 and 3.34 km/s. The plot of the S wave velocity values listed in Table 5 in Figure 10 reveals that the S wave travel times obtained using the proposed method fall within the range of values obtained from these suggested velocities, indicating the reliability and accuracy of the proposed method.
Because of the complexity of the rock mass properties and the underground environment, it is very difficult to extract S waves precisely at the engineering scale. As an extension of the preceding analysis, we suggest an improved method for doing so that focuses on the use of the short time average zero-over rate and polarization properties.

Because of the large amount of vibrational data produced by blasting vibration, the S wave identification process faces a number of difficulties in terms of, for example, computational complexity and long computational times. Using a parameter based on the short time average zero-over rate can reduce the computational time and improve the efficiency. At the same time, the differences in the polarization properties of P and S waves can be used to quickly identify S wave onset.

In engineering construction, the propagation velocities of P and S waves—parameters closely related to engineering security—can be used directly for engineering analysis and design optimization. Although conventional approaches, such as field tests or indoor testing of rock samples, to obtaining these parameters exist, these methods tend to be time-consuming and costly. The proposed modified S wave identification method has been successfully applied in a preliminary investigation of propagation velocity inversion of seismic waves induced by engineering construction-associated blasting. The proposed method can provide timely and effective feedback velocity data to ensure the safety of rock engineering-based construction. Up to now, S wave identification remained at the initial stage in engineering scale; although the methods developed in this study advance the state of knowledge, there remain many problems to be solved that are worthy of further study.

5. Discussion and Conclusions

In this paper, a new method for identifying S wave first arrival from measured blasting vibration signals based on polarization properties and the frequency differences between P and S waves was proposed. Based on our numerical simulation analysis and experimental assessment of the measured vibration signals produced at the Fengning pumped storage power station, the following conclusions can be drawn:

1. It was demonstrated that S wave first arrival can be determined roughly by using the short time average zero-over rate parameter to narrow the calculation space needed for subsequent analysis. The use of this factor plays an important role in improving computational efficiency. Further analysis to measure the differences in polarization, vibration direction, and energy of P and S waves can then be carried out to more precisely extract S waves. The advantages of using the weight identification function, \( CF_w \), to distinguish S and P wave characteristics were also demonstrated, and the indicator \( E(t) \) was shown to be capable of enhancing the energy differences between P and S waves. The results of numerical simulation revealed that the proposed S wave identification method is accurate to within an error of less than 2%.

2. To identify S waves using the method presented in this paper, it is necessary to first identify P wave’s first arrival. Accordingly, the accuracy of S wave identification relies heavily on that of P wave recognition. Although the influence of R waves is not considered in this process, it will be addressed in future research to improve the accuracy of the proposed method.

3. S wave identification is an important tool for the back analysis of the physical parameters of rock mass. Accurate extraction of S waves from measured blasting vibration signals can provide timely and robust guidance in the design and execution of construction engineering. In our study, we assumed that the underground rock masses were homogeneous and isotropic. It is generally understood, however, that P and S wave velocities are primarily linked to the initial defects of the rock mass, which include holes, micro-cracks, and joints. As the S wave identification method based on measured vibration signals proposed in this paper primarily relies on the average properties of the rock mass, it will be necessary to strengthen our analysis to include the influence of these defects on S wave identification in future studies.
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