Experimental Study of Open Fracture’s Multifarious Effects on Ultrasonic Wave Propagation in Rock Masses

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A comprehensive understanding of the fracture’s effects on wave propagation is a necessary prerequisite for estimating the dynamic behavior of fractured rock masses. This study presents a series of ultrasonic experiments on the multifarious effects of open fractures on the propagation characteristics of waves, considering various geometric parameters of fractures. The results indicate that fractures disrupt the waveform and attenuates the wave amplitude and velocity. With the increase of fracture number, the amplitude of transmitted wave and the dominant frequency of transmitted wave decrease, while the transmit time of wave in the sample increases. An increasing fracture dip angle generally leads to the increase of wave amplitude and dominant frequency, while reduces the transmit time of wave. As the fracture spacing increases in the testing range, the wave amplitude increases, while the wave frequency exhibits an opposite tendency. Comparing with the experimental results in the cases of single and multiple fractures, it is confirmed that the attenuation effect and the low-pass effect of fractures on wave propagation are enhanced quickly with the increase of fracture number.

Keywords: Fractured rock mass, Ultrasonic wave propagation, Amplitude, Dominant frequency, Waveform, Experimental study

1 Introduction

The propagation characteristic of stress wave in fractured rock masses is the key factor controlling the dynamic behavior of rock masses, and is also one of the most fundamental issues in the fields of rock dynamics and geological prospecting. Rock fractures (e.g., cracks and joints) have significant effects on the propagation of stress wave. Generally, when a wave propagates across fractures, the reflection and transmission of wave occur with the attenuation of wave velocity, the change of propagation direction and the dissipation of energy. Therefore, to acquire a comprehensive understanding of the propagation of stress wave in rock masses, it is indispensable to investigate the effects of fractures on wave propagation.

To date, extensive efforts based on analytical studies have been made to investigate the dynamic response of fracture, and a number of theoretical models were proposed. Those studies provide a basic understanding of the fracture’s effect on wave propagation. However, the common analytical methods can only deal with relatively simple problems based on different hypotheses, thus their applicability is limited. Numerical methods provide another way to solve the complex problems of wave propagation and rock dynamics. Currently, numerous studies have been performed using the boundary element method, the finite element method and the distinct element method, etc. Numerical methods can handle complex problems concerning multiple fractures and various incidence angles, etc. However, the reliability of numerical simulation depends on the validity of numerical model, constitutive relations and boundary conditions, which need to be confirmed by experiments.

Experiments serve as a fundamental and reliable approach to study the wave propagation problems, and different techniques have been utilized. King et al. (1986) carried out cross-hole acoustic measurements to examine the acoustic velocity and attenuation. Li and Ma (2009) used a modified Split Hopkinson Pressure Bar apparatus to study the wave propagation across a filled rock joint. Recently, the ultrasonic testing has an increasing application due to its high sensitivity and accuracy for examining rock fractures and their effects. E.g., Zhao et al. (2006) studied the propagation of ultrasonic waves in intact and fractured samples and verified the fracture’s attenuation effects on wave propagation. Bi et al. (2009) studied the influence of crack distribution on wave propagation, focusing on the attenuation effect on wave amplitude. Huang et al. (2013) investigated the relationship between transmission ratio and normal stress, joint roughness, joint number and wave frequency. Sun et al. (2014) carried out ultrasonic and compression tests on jointed samples and analyzed the attenuation rules of ultrasonic waves.

The previous studies lay a foundation for predicting the dynamic response of fractures. However, the propagation behavior of waves in rock masses is still not well understood. Especially, there is a lack of comprehensive estimation of the fracture’s multifarious effects on wave propagation with the consideration of various geometric characteristics of fractures. In this study, a series of ultrasonic tests based on pre-fractured rock masses...
cement samples were performed to investigate the effects of open fractures on characteristics of ultrasonic waves in the aspects of wave amplitude, frequency, transmit time and velocity, simultaneously considering the influences of fracture width, fracture dip angle, fracture spacing and aperture.

2 Experimental Material and Sample Preparation

2.1 Experimental Material

In this study, the Portland cement (P.O 45.2R) was adopted to prepare samples with a mixing ratio by weight of cement: water = 1.0: 0.4. The pure cement without aggregate has a good homogeneity. Therefore, it can reduce the influence of material heterogeneity, and the effects of rock fractures on wave propagation are confirmed.

Table 1  Physico-mechanical parameters of cement material

| Parameter               | Index | Value  |
|-------------------------|-------|--------|
| Density                 | ρ     | 1.725  |
| Compressive strength    | σc    | 33.10  |
| Young’s modulus         | E     | 18.64  |
| Poisson’s ratio          | ν      | 0.31   |
| Measured P-wave velocity| VPC   | 3732.1 |
| Calculated P-wave velocity| VPC  | 3870.1 |

The physico-mechanical properties of cement are listed in Table 1. This material can model moderate-strength rocks like sandstone. Besides, the P-wave velocity measured by an ultrasonic testing apparatus is close to the theoretical value \( V_{PC} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \) with an error less than 3.6%, further manifesting the homogeneity of material and the accuracy of testing apparatus.

2.2 Sample Preparation

Shapes and dimensions of the cement samples are shown in Fig. 1. All samples have the same dimension of \( W \times L \times H = 100 \times 100 \times 400 \) mm. During tests, ultrasonic waves propagated along the height direction of samples.

Open through-fractures are located at the geometric centers of samples, and penetrate the length direction of samples \( l = L = 100 \) mm. To study the effects of fractures systematically, different geometric parameters of fractures were considered, including the dip angle, width, aperture and spacing of single or multiple fractures. Totally, four groups of samples were designed. Group-1 samples have single fractures with varying widths \( w = 20, 40 \) and 60 mm, respectively, and a uniform dip angle of \( \theta = 0^\circ \) and an aperture of \( a = 1.0 \) mm. Group-2 samples contain single fractures with different dip angles \( \theta = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ \) respectively and a uniform width of \( w = 60 \) mm and an aperture of \( a = 1.0 \) mm. Note that \( \theta \) is defined as the angle between the fracture plane and the cross-section of sample. Group-3 samples contain single fractures with the aperture \( a \) ranging from 0.5 mm to 2.5 mm, with the \( w \) of 60 mm and the \( \theta \) of \( 0^\circ \). Group-4 samples contain three parallel fractures with varying spacing \( s = 40, 60, 80 \) and 100 mm, respectively; \( w = 60 \) mm; \( a = 1.0 \) mm; \( \theta = 0^\circ \).

Samples were prepared following a strict procedure, including material mixing and stirring, mould casting, vibrating and sample curing. Before casting, greased steel sheets with different widths, thicknesses and intensities were preinstalled in the mould. After the initial set of cement, steel sheets were pulled out to form open fractures with varying geometric parameters. After that, the samples were cured for 24 hours for demoulding, and then cured for 28 days for testing. Four groups of prepared samples are shown in Fig. 2.

3 Principle and Method of Ultrasonic Testing

Ultrasonic waves with very high frequencies and short wavelengths have the significant characteristics of high sensitivity, high penetrability, high directionality and accurate positioning, therefore they are widely used to detect flaws and to characterize the dynamic response of fractures. During ultrasonic testing, the ultrasonic wave stimulated by a
sending transducer propagates through the sample containing fractures. A portion of the ultrasonic wave is reflected back at the fractures, and another portion passes across the fractures and reaches the receiving transducer. The presence of fractures changes the characteristics of ultrasonic wave. Through a comparative analysis of the sent and received signals, the effects of fractures on wave propagation are confirmed.

In the test, a non-metallic ultrasonic detector (ZBL-U520) developed by Beijing ZBL Science and Technology Co., LTD. was employed, and the set-up of the testing system is shown in Fig. 3. The ultrasonic detector mainly consists of the host system, ultrasonic transducers and the power and signal lines. The host system is the major part with the functions of test controlling, signal processing and data recording. Two transducers fixed at the geometric centers of both sample ends respectively were used to send and receive ultrasonic signals. Besides, the Vaseline coating that served as a coupling layer was applied to the sample end surfaces to reduce the acoustic impedance difference between the transducers and sample.

![Photo of testing system](image)

(a) Photo of testing system  
(b) Sketch view of testing loops

Fig. 3  Set-up of the ultrasonic testing.

Characteristics of the incident ultrasonic wave stimulated by the sending transduce are vital for the comparative analysis. Besides, an accurate measure of the travelling time of wave in the sample is necessary to estimate the wave velocity and the time-delay effect of fractures. Therefore, two transducers were coupled together directly at the onset of every test to acquire the characteristics of incident wave and to measure the signal delay of testing system for determining the travelling time of wave in the sample (see Fig. 3b).

During the tests, the excitation frequency of ultrasonic detector was set as 100 kHz, and the sampling period was 0.4 μs. Direct coupling tests were performed and the results indicate that the incident wave has a relatively inerratic waveform with a series of crests and troughs. The head wave corresponding to the first trough or crest was utilized to determine the amplitude of the incident wave \(A_0\), due to that it was not influenced by the subsequent wave superposition and interference. The time at the very beginning of head wave corresponds to the signal delay of the testing system \((t_s)\), which needs to be deducted from the total testing time for estimating the wave velocity and the time-delay effect of fractures. According to the results of repeated direct coupling tests, \(t_s\) is around 17.20 μs, and the average value of \(A_0\) is 107.67 dB with a standard deviation of 0.0134 dB, and the average dominant frequency of incident wave is 99.09 kHz with a standard deviation of 0.652 kHz, indicating that the testing system has a good accuracy and stability.

## 4 Testing results and analyses

Four groups of samples were tested to study the effects of open fractures on the propagation characteristics of ultrasonic waves. The wave amplitude and transmit time were measured according to the head waves. The attenuation effect of fractures was characterized by the amplitude and the transmission coefficient \(T\) defined as \(A/A_0\), where \(A\) and \(A_0\) are the amplitudes of the transmitted and incident waves, respectively. The variation of dominant frequency across the fracture was investigated by performing spectrum analyses based on the Fast Fourier Transformation (FFT) method.

### 4.1 Effects of fracture width on wave propagation

Group-1 samples were tested to investigate the effects of fracture width on wave propagation. The waveforms and frequency spectra of transmitted waves across single fractures with varying widths are shown in Fig. 4, and the related characteristic parameters are listed in Table 2.

From Fig. 4(a), (c) and (e), it can be confirmed that the waveforms observed in fractured samples present some degree of irregularity and complexity, comparing with the relatively regular waveform in the intact material without significant change in propagation characteristics. Besides, the amplitudes of subsequent waves in fractured samples are larger than that of the head wave due to the superposition of reflected waves and incident wave in the region between the fracture and the end faces of sample.

The test results indicate that the fracture width affects the propagation of ultrasonic wave greatly. First, the amplitude of head wave \(A\) decreases as \(w\) increases from 20 to 60 mm (see Fig. 4 and Table 2). When the ultrasonic wave reached the pre-existing fracture, the wave scattering behavior including reflection and transmission accompanied by energy consumption resulted in the decrease of wave amplitude. Because the open fractures have close dimensions to the wavelength, it can be speculated that the incident wave diffracted at the fracture and bypassed it through the regions at both ends of the fracture. With the increase of \(w\), the regions at both ends of the fracture became narrow, and the wave diffraction was less easily to occur, resulting in the decrease of \(A\). The transmission coefficient \(T\) in Table 2 reflects the attenuation effect of fracture on the ultrasonic energy and wave amplitude, indicating that an increasing \(w\) leads to the decrease of \(T\).
show the frequency spectra corresponding to different w, and the values of $f_d$ are listed in Table 2. The results manifest that the increase of w leads to a continuous decrease of $f_d$ from 53.17 to 44.56 kHz. The incident wave consists of a series of simple harmonic waves with varying frequencies. According to the dynamic theory of fracture\(^{(3)(5)}\), the fracture behaves as a low-pass filter that removes the high-frequency components of wave, and thus reduces the dominant frequency of transmitted wave. With the increase of w, the low-pass filter effect became more significant, and more high-frequency components of incident wave were absorbed, resulting in the decrease of $f_d$.

Besides, according to the test results, the transmit time of ultrasonic wave in the sample increases slightly as w increases, while the average propagation velocity of wave exhibits a decreasing tendency due to the attenuation effect of fracture.

During the tests, the open fracture hindered the rectilinear propagation of wave. The wave diffraction from both ends of fracture took more time, and the wave signal was delayed. With the increase of w, the diffraction distance of wave became longer, leading to the increase of transmit time.

| Parameter                              | Index | Value       |
|----------------------------------------|-------|-------------|
| Fracture width w (mm)                  | 20    | 40          | 60          |
| Transmit time f (μs)                    | 111.20| 112.0       | 115.60      |
| Wave velocity V (m s\(^{-1}\))         | 3597.1| 3571.4      | 3460.2      |
| Dominant frequency $f_d$ (kHz)         | 53.17 | 49.44       | 44.56       |
| Head wave Amplitude $A$ (dB)           | 95.38 | 93.67       | 88.08       |
| Transmission coefficient T (-)         | 0.8858| 0.8699      | 0.818       |

**4.2 Effects of fracture dip angle on wave propagation**

Group-2 samples were tested to study the effects of fracture dip angle on wave propagation, and the results are shown in Fig. 5 and Table 3. In the cases of inclined fractures, the propagation behavior of ultrasonic waves was more complex than the vertical-fracture situations due to the wave refraction and diffraction at the fractures, and the multiple superposition of refracted, diffracted and reflected waves increased the irregularity of waves (see Fig. 5(a), (c), (e), (g)).

The test results confirm that the fracture dip angle $\theta$ influences obviously the characteristics of transmitted waves. First, the head-wave amplitude of transmitted wave increases continuously with the increase of $\theta$ from 0° to 60° (see Fig. 5 and Table 3). In the test, the projection width of fracture in the cross-section direction of sample decreased as $\theta$ increased. In the large-dip-angle situation, the diffraction of wave across the fracture was more easily to occur, and the attenuation effect of...
fracture became weak, consequently leading to the increase of wave amplitude. Besides, with the increase of θ, more energy was transmitted across the fracture in the wave refraction process, and hence increased the wave amplitude. Fig. 6 shows the variation of the transmission coefficient T which reflects the attenuation effect of fracture. T also increases with θ, and the increase rate is relatively high in the θ range from 15° to 45°. Second, the dominant frequency of transmitted wave exhibits generally an increasing tendency with θ, as shown in Fig. 5(b), (d), (f) and (h). As mentioned before, an increasing θ led to the decrease of projection width of fracture and the weakening of low-pass filter effect of fracture, thereby more high-frequency components of the incident wave passed across the fracture, resulting in the increase of dominant frequency.

Table 3 also lists the transmit times and wave velocities of group-2 samples. Comparing with the vertical-fracture cases, the time-delay effect of inclined fractures was weaker. With the increase of θ, the incident wave was more easily to diffract across the fracture, thereby the transmit time exhibited a decreasing tendency, while the average wave velocity had an increasing tendency, except for the case of θ = 15°.

Fig. 5 Waveforms and frequency spectra of the transmitted waves across fractures with varying dip angles

4.3 Effects of fracture aperture on wave propagation

Group-3 samples were to study the effects of fracture aperture on the wave propagation. The transmitted waves in this group of samples have similar waveforms to the group-1 samples, while the fracture aperture affects to some extent the characteristics of transmitted waves, as listed in Table 4.

As the aperture a increases, the amplitude of head wave and the related transmission coefficient present a decreasing tendency. In the test, the pre-existing fracture reduced the average stiffness of the region surrounding the fracture. An increasing a led to the continuous decrease of the average stiffness of the fracture region, and more energy was absorbed, thus decreasing the amplitude and the transmission coefficient.

According to the test results, the aperture has hardly any impact on the dominant frequency, the transmit time and the wave velocity. This may be due to that the variation range of aperture was much smaller than the wave length, hence the sensitivity of ultrasonic wave was not high enough.
Table 3 Characteristic parameters of transmitted waves corresponding to different fracture dip angles.

| Parameter | Fracture dip angle (°) | Transmit time (μs) | Wave velocity (m·s\(^{-1}\)) | Dominant frequency \(f_d\) (kHz) | Amplitude of head wave \(A\) (dB) | Transmission coefficient \(T\) (-) |
|-----------|------------------------|-------------------|-------------------------------|---------------------------------|---------------------------------|-----------------------------|
| Index     | \(\theta\)             | \(t\)             | \(V\)                         | \(f_d\)                         | \(A\)                           | \(T\)                        |
| 0         | 0                      | 115.60            | 3460.21                       | 44.56                           | 88.08                           | 0.8180                      |
| 15        | 15                     | 112.40            | 3558.72                       | 45.17                           | 88.62                           | 0.8230                      |
| Value     | 30                     | 113.60            | 3521.13                       | 46.39                           | 91.17                           | 0.8467                      |
| 45        | 45                     | 112.80            | 3546.10                       | 51.27                           | 93.85                           | 0.8716                      |
| 60        | 60                     | 111.60            | 3584.23                       | 50.66                           | 94.59                           | 0.8784                      |

Table 4 Characteristic parameters of transmitted waves corresponding to different fracture apertures.

| Parameter | Fracture aperture (a mm) | Transmit time (μs) | Wave velocity (m·s\(^{-1}\)) | Dominant frequency \(f_d\) (kHz) | Amplitude of head wave \(A\) (dB) | Transmission coefficient \(T\) (-) |
|-----------|--------------------------|-------------------|-------------------------------|---------------------------------|---------------------------------|-----------------------------|
| Index     | \(a\)                    | \(t\)             | \(V\)                         | \(f_d\)                         | \(A\)                           | \(T\)                        |
| 0.5       | 0.5                      | 116.00            | 3448.28                       | 45.17                           | 88.45                           | 0.8214                      |
| 1.0       | 1.0                      | 115.60            | 3460.21                       | 44.56                           | 88.08                           | 0.8180                      |
| Value     | 1.5                      | 115.20            | 3472.22                       | 43.95                           | 87.39                           | 0.8116                      |
| 2.0       | 2.0                      | 116.00            | 3448.28                       | 42.11                           | 86.62                           | 0.8044                      |
| 2.5       | 2.5                      | 117.20            | 3412.97                       | 44.56                           | 86.08                           | 0.7994                      |

4.4 Effects of fracture spacing on wave propagation

Group-4 samples with multiple fractures were tested to study the effects of fracture spacing on the wave propagation, and the results are shown in Fig. 7 and Table 5. Transmitted waves in these cases present a high degree of irregularity due to the multiple wave reflection and superposition, and the waveforms drift off the center axes greatly.

The fracture spacing \(s\) influences greatly the amplitude of transmitted wave and then the transmission coefficient. With the increase of \(s\) from 40 to 100 mm, the amplitude increases from 73.12 to 83.94 dB. If \(s\) was small, the diffracted wave across the first (second) fracture was quickly reflected back at the second (third) fracture, and thus the diffraction of wave at the second (third) fractures was less easily to occur, leading to a relatively small amplitude. As \(s\) increases, the wave diffraction across fractures was more likely to occur, and more energy transmitted across the fractures, consequently leading to a large amplitude. The variation of amplitude with \(s\) controls the change of transmission coefficient (see Table 5). The variation of amplitude and transmission coefficient agrees with the theoretical prediction of Zhao (2006).\(^{20}\)

The dominant frequency of transmitted wave decreases gradually as \(s\) increases, as shown in Fig. 7(b), (d), (f) and (h).

The samples contain three parallel fractures that acted as a series of low-pass filters. As \(s\) increased, the region of influence enlarged and the low-pass filtering effect became more significant. Therefore, more high-frequency components of the incident wave were absorbed, resulting in the decrease of dominant frequency of transmitted wave.

Table 5 also lists the related transmit times and wave velocities. These two parameters present no obvious variation tendency with the change of \(s\). However, the transmit times ranging from 122.8 to 129.6 μs were much longer than those measured in the single-fracture cases, due to that the wave diffraction across multiple fractures took much more time.

4.5 Contrast between single & multiple fracture cases

The main characteristic parameters of transmitted waves in four groups of samples are plotted in Fig. 8. It indicates that the attenuation effect of fracture becomes more significant as the fracture number increases. The wave velocity in cement \(V_{cm}\) was measured as 3732.1 m/s, while the average wave velocity in samples with single fractures is 3503.2 m/s, which is reduced by 6.13%, and the average velocity in the multiple-fracture cases is 3186.0 m/s, which is reduced by 14.63%. The amplitude of incident wave \(A_0\) is around 107.67 dB, while the average amplitude of transmitted waves in the samples with single fractures is 90.00 dB, which is reduced by 16.41%, while the average amplitude in samples with multiple fractures is 78.81 dB, which is reduced by 26.80%. In the aspect of wave frequency, the average frequency for samples with single fractures is 46.58 kHz, which is reduced by 52.99% comparing with the frequency of stimulated wave \(f_0\) (99.09 kHz), while the average frequency of multiple-fracture cases is 32.19 dB, which is reduced by 67.51%. It can be inferred from the test results that the low-pass filter effect of

![Fig. 6 Variation of transmission coefficient with fracture dip angle.](image)
fracture enlarges quickly with the fracture number, and the wave frequency is quite sensitive to fractures.

Moreover, the transmit times exhibited a decreasing tendency.

The amplitude of transmitted wave increases, and the dominant frequency decreases owing to the absorption of more energy transmitted across the fractures, consequently leading to the reduction of transmitted wave's amplitude. The frequency of transmitted wave decreases with the increase of fracture dip angle, while the dominant frequency generally increases due to the weakening of attenuation effect and the low-pass filter effect of fracture. Moreover, the transmit time also increases due to the increase of diffraction distance.

(3) With the increase of fracture dip angle, the head-wave amplitude of transmitted wave increases, and the dominant frequency generally increases due to the weakening of attenuation effect and the low-pass filter effect of fracture. Moreover, the transmit time exhibited a decreasing tendency.

(4) The fracture spacing has a positive correlation with the head-wave amplitude in the range of this test due to the diffraction and reflection behavior of wave. The dominant frequency of transmitted wave decreases with the increase of spacing due to enlargement of influence region of fractures.

(5) The complicated wave scattering behavior in the case of multiple fractures raises the irregularity of waveform. The attenuation effect and the low-pass effect of fracture become much more significant with the increase of fracture number, and the wave frequency is quite sensitive to fractures intensity.

### 5 Conclusions

In this study, a series of ultrasonic tests were carried out to investigate the effects of open fractures with various geometric parameters on the propagation of ultrasonic waves. The main conclusions are summarized as follows:

1. Existence of fractures in rock masses disrupts the waveform, and attenuates greatly the wave amplitude, velocity and frequency. The main geometric parameters of fractures including fracture width, dip angle and spacing control comprehensively the propagation behaviors of waves.

2. An increasing fracture width leads to the decrease of amplitude and velocity of the transmitted wave due to the enhanced attenuation effect of fracture, while the dominant frequency decreases owing to the absorption of more high-frequency wave components. Besides, the transmit time also increases due to the increase of diffraction distance.

3. With the increase of fracture dip angle, the head-wave amplitude of transmitted wave increases, and the dominant frequency generally increases due to the weakening of attenuation effect and the low-pass filter effect of fracture. Moreover, the transmit time also increases due to the increase of diffraction distance.

4. The fracture spacing has a positive correlation with the head-wave amplitude in the range of this test due to the diffraction and reflection behavior of wave. The dominant frequency of transmitted wave decreases with the increase of spacing due to enlargement of influence region of fractures.

5. The complicated wave scattering behavior in the case of multiple fractures raises the irregularity of waveform. The attenuation effect and the low-pass effect of fracture become much more significant with the increase of fracture number, and the wave frequency is quite sensitive to fractures intensity.
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Table 5  Characteristic parameters of transmitted waves corresponding to different fracture spacing.

| Parameter                      | Fracture spacing | Transmit time | Wave velocity | Dominant frequency | Amplitude of head wave | Transmission coefficient |
|--------------------------------|------------------|---------------|---------------|-------------------|------------------------|-------------------------|
| Index                          | s (mm)           | t (μs)        | V (m·s⁻¹)     | f_d (kHz)         | A (dB)                 | T (-)                   |
| Value                          |                  |               |               |                   |                        |                         |
| 40                             | 124.40           | 3215.43       | 40.89         | 73.12             | 0.6790                 |                         |
| 60                             | 129.60           | 3086.42       | 35.40         | 79.02             | 0.7338                 |                         |
| 80                             | 122.80           | 3257.33       | 26.86         | 79.14             | 0.7350                 |                         |
| 100                            | 125.60           | 3184.71       | 25.63         | 83.94             | 0.7795                 |                         |

(a) Propagation velocity
(b) Amplitude of head wave
(c) Dominant frequency

Fig. 8 Comparison of characteristic parameters between the single-fracture cases and multiple-fracture cases.