The Effects of Joint Roughness on Stress Wave Propagation Based on Projection Cover Method

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Abstract. To study the influence of smooth and rough joint on stress wave propagation in rock mass and the mechanical properties of jointed rock, experimental research was carried out using Split Hopkinson Pressure Bar. The influence of fractal dimension of rock joints on stress wave propagation was studied. The results showed that the transmission coefficients and equivalent stiffness of the smooth joints rock specimen reduce very little compared to the intact rock specimen, which indicates that the smooth joints have very little influence on stress wave propagation in the experiment. The transmission coefficient and equivalent stiffness of joint rock specimen were influenced by the difference of joint forms. The bigger of the joint roughness (fractal dimension) are, the smaller of the transmission coefficient and stiffness of the rock joint specimen.

1. Introduction

In the excavation of tunnelling, mining engineering, slope and rock foundation excavation and other projects, the use of blasting excavation method was widely used. At the same time, in deep underground mining engineering, a lot of rock burst and impact of pressure and other disasters increased, and instantly release a lot of energy which produce stress waves. Furthermore, earthquake is also a kind of stress wave. Stress wave propagate across rock masses, and stress wave affects the stability of engineering rock mass in propagation. Rock mass has a lot of structural planes containing discontinuities, including joints, faults, weak inter layers and so on. Due to the existence of the joint surface, the stress wave propagates and reflects at the joint surface, and the stress wave decays and produces energy dissipation. Researchers often carry out rock mass simulation test in the laboratory to obtain the mechanical parameters of jointed rock mass under stress wave and study the propagation law of stress wave in joint.

The influence of the stress wave on the stress wave propagation law and the energy transfer law is mainly studied by different joint types, joint densities, and joint mechanics and wave characteristics. For a single linear deformation joint, based on the linear displacement discontinuity model proposed by Schoenberg [1], Zhao Jian et al. [2] consider the nonlinear normal deformation of joints, and established a joint nonlinear discontinuous model. J.C Li et al. [3] used SHPB equipment to study the propagation law of one-dimensional stress wave in filling joints; many researchers [4-5] have studied the geometric parameters of rock mass joints including the width of joints, the angle of joints.
The rock joints is used to be simplified into a smooth surface. However, the morphology of joint surface is a rough surface. To this end, to simulate the actual joint surface, many scholars conducted laboratory scale experiments. In 1977, Barton [6] proposed the use of joint roughness coefficients (JRC) to characterize the joint surface morphology; Zhao Jian [7] pointed out that JRC can not fully reflect the joint characteristics, and proposed the joint matching coefficient (JMC) to describe the degree of coincidence between joints. X. Chen [8] have studied the JMC by creating man-made rock joints with different JMC. Ju Yang [9] use the fractal theory to quantify the roughness of the joint surface, and studied the law of energy dissipation in stress wave propagation.

To investigate the influence of joint roughness on the stress wave propagation, the SHPB device was used. In the test, two smooth samples were composed of smooth joint specimens, and the rough joints were obtained by splitting test to simulate the rough joints. The roughness of the fracture surface was scanned using a laser scanner to obtain the three-dimensional topography of the fracture surface. To quantify the influence of joint roughness, fractal model was used to describe the rock joints. The effects of joint roughness on the dynamic mechanical properties of joint rock specimens and the effects on stress wave propagation were studied.

2. Experimental procedure

2.1. Sample production and rough joint surface generation
To simulate the natural joints, generate the rough surface by conducting the splitting test of Φ50mm × 50mm cylindrical samples (Figure 1). Scan the rough surface by laser scanner (Figure 2) to get the three-dimensional data (Figure 3). The fractal characteristics of the fractured rough surface were obtained by the projection cover method [12]. After the topography scan, combine the two parts of the specimens in accordance with the rupture position.

![Intact rock specimen, Smooth joint rock specimen, Rough joint rock specimen](image1)

**Figure 1.** Experiments of Different Specimens with Different Joint Forms

A total of eight rough, three smooth single-joint samples were produced and scanned. An intact rock specimen of Φ50 mm × 50 mm was selected as a comparative specimen.

![Laser Scanner](image2) ![Topography of Fractured Surfaces](image3)

**Figure 2.** Laser Scanner  **Figure 3.** Topography of Fractured Surfaces

2.2. Testing program
The experiment was carried out on the Split Hopkinson Pressure Bar device of North China University of Technology. The diameter of the incident and transmit bar is 50 mm, the elastic modulus of steel bar is 250 GPa with density of 7787 kg/m3 and wave speed of 5667 m/s. The 260 mm spindle-shaped...
bullet was used to produce sine wave loading, the method was proposed by Li Xibing et al [10] and recommended by the International Society of Rock Mechanics [11].

The intact specimen, the combination of single joint smooth specimen, the combination of single joint roughness specimen was placed between the incident and the transmit bar. To ensure the specimen is only elastic deformation, the impact rate is 5.0 m/s. The stress wave generates reflection and transmission between the bar and the joint specimen. When the incident waves are same, the incident wave, the transmitted wave and the reflected wave are almost the same which means that the shape of the rough joint is not changed in the test.

3. Experimental procedure

3.1. Fractal surface fractal properties

The high-precision laser scanner device (Figure 2) was used to scan the joint surface. The projection covering method [12] equates the area of the four points in the square area of the fracture surface with the sum of the two triangular areas, and then obtains the true fractal dimension of the rough surface. The fractal dimension of rough surface is calculated as follows

\[ A(\delta) = A_0 \delta^{2-D} \]  \hspace{1cm} (1)

The slope k is determined by a double logarithmic curve

\[ k = \frac{\lg(A(\delta))}{\lg(\frac{1}{\delta})} \quad (k = D - 2) \]  \hspace{1cm} (2)

Then we can get the fractal dimension

\[ D = k + 2 \]  \hspace{1cm} (3)

Figure 4. Measured Fractal Dimensions of Granite Specimen

The fractal features of a section were analyzed. The ratio of area in double logarithmic coordinates has a good linear relationship with the covering code, and the rough joint section has fractal characteristics. The fractal dimension of the rough single joint granite specimens is 2.0206 ~ 2.0366. At the same time, the contact surface of two smooth Φ50 mm × 25 mm samples was analyzed, and the fractal dimension was 2.0000.
Table 1. The Transmission Coefficient and Equivalent Stiffness of Different Specimens

| Number | Single joint forms                  | Fractal dimension of joint surface | Transmission coefficient | Stiffness(GPa/m) |
|--------|------------------------------------|------------------------------------|--------------------------|-----------------|
| W-1    | Intact rock                        | --------                          | 84.1%                    | 1126            |
| GH1-1  | Smooth and perfectly consistent    | 2.0000                             | 81.5%                    | 598             |
| GH1-2  |                                     | 83.6%                              | 572                      |
| GH1-3  |                                     | 81.8%                              | 534                      |
| CC1-1  | Rough and perfectly matched        | 2.0268                             | 73.6%                    | 298             |
| CC1-2  |                                     | 2.0327                             | 65.0%                    | 184             |
| CC1-3  |                                     | 2.0279                             | 69.4%                    | 284             |
| CC1-4  |                                     | 2.0224                             | 78.2%                    | 360             |
| CC1-5  |                                     | 2.0206                             | 79.7%                    | 386             |
| CC1-6  |                                     | 2.0366                             | 61.4%                    | 102             |
| CC1-7  |                                     | 2.0241                             | 76.3%                    | 338             |
| CC1-8  |                                     | 2.0301                             | 68.4%                    | 232             |

3.2. Fluctuating characteristics
The normal incident, transmitted, and reflected pulse signals are shown in the figure when the stress wave is incident on the complete rock joint, the smooth single-jointed rock, the rough single-jointed rock specimen. The transmission coefficient is defined as $T = \frac{\text{Max}(\varepsilon_s)}{\text{Max}(\varepsilon_i)}$. Figure 5 shows the typical pulse curves.

![Figure 5. The Time Pulse Signal of Different Joint Forms](image)

a. Intact  b. Single smooth joint  c. Single rough joint

3.3. Stress and strain analysis
Due to the theory of one-dimensional elastic stress wave, and the stress and strain within the specimen reach the uniformity assumption. The three-wave method can be used to analyse the experimental data

$$
\sigma_s(t) = \frac{S \cdot E_s}{2S_s} \int_0^t [\varepsilon_s(t) + \varepsilon_i(t) + \varepsilon_r(t)]
$$

(4)
The stress-strain relationship corresponding to a certain strain rate can be obtained by applying the three-wave formula of equations (4) to (6)

\[ \varepsilon_r(t) = \frac{c_0}{L_0} \int_0^t [\varepsilon_i(t) + \varepsilon_r(t) - \varepsilon_t(t)] \]  

(5)

\[ \varepsilon_t(t) = \frac{c_0}{L_0} \int_0^t [\varepsilon_i(t) + \varepsilon_r(t) - \varepsilon_t(t)] \, dt \]  

(6)

Where \( \varepsilon_i \), \( \varepsilon_r \) and \( \varepsilon_t \) are the incident wave, reflected wave and the transmitted wave, respectively. The cross-sectional area of the incident and transmission is \( S_B \). The elastic modulus of the bar is \( E \), and the wave velocity of the stress wave in the steel bar is \( c_0 \). The incident strain pulse, the transmission strain pulse and the reflected strain pulse are \( \varepsilon_i(t) \), \( \varepsilon_t(t) \) and \( \varepsilon_r(t) \), respectively.

It is hard to study the stiffness of joint directly. Here we use the equivalent stiffness of joint rock specimens to reflect the influence of joint on stress wave propagation. The equivalent stiffness is defined as the ratio of stress and displacement on both sides of the joint.

\[ k_e = \frac{E}{l_0} \]  

(7)

\( E \) is the elastic modulus, \( l_0 \) is the height of rock samples. The equivalent stiffness of rock samples with different joint forms are given in Table 1 and Figure 7.

It can be seen from Figure 6 that (1) the equivalent stiffness of the rock specimen is less than that of the intact rock, either the rough joint or the smooth joint. (2) The equivalent stiffness of the rough
single-joint specimen is less than that of the smooth single-joint specimen. (3) In the case of different joint combinations, the maximum strain of the samples is different due to the different deformation of the joint. The maximum strain of the rough joint specimen is the largest, followed by the smooth single joint specimen, and the maximum strain of the intact specimen is the smallest.

The relationship between the fractal dimension and the transmission coefficient of the stress wave and the equivalent stiffness of the joint specimen is plotted in Figure 7.

It can be seen from Table 1 and Figure 7 that; (1) the equivalent stiffness of the rough single-joints is consistent with the fractal dimension of the joint surface; (2) The greater the fractal dimension of the joint surface (the roughness of joint surface), the greater the tangential and normal deformation of the specimen, the smaller the equivalent stiffness of the rough joint specimen; (3) The equivalent stiffness and the transmission coefficient of the joint specimen decreases with the increase of the fractal dimension; (4) The equivalent stiffness of the joint specimen decreases linearly with the increase of the fractal dimension, while the transmission coefficient increases slowly with the fractal dimension, and then decreases rapidly.

4. Conclusion

Through the analysis of the experimental results, we can see that the joint roughness (fractal dimension have great influence on the stress wave propagation and the mechanical properties of joint rock.

(1) Under vertical incidence conditions of elastic stress wave, the attenuation of the stress wave through the smooth joint specimen is similar to that of the intact rock, the smooth joint surface in the case of sufficient contact with the same medium has little effect on the stress wave propagation.

(2) Under the same incident stress wave, the presence of joints affects the propagation of stress waves in rock mass. The higher the joint roughness (fractal dimension), the smaller the transmission coefficient of the stress wave crossing the joint specimen and the smaller the equivalent stiffness attenuation of the joint.

Acknowledgments

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