Model test study on propagation law of plane stress wave in jointed rock mass under different in-situ stresses

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Abstract. The study of propagation law of plane stress wave in jointed rock mass under in-situ stress has important significance for safety excavation of underground rock mass engineering. A model test of the blasting stress waves propagating in the intact rock and jointed rock mass under different in-situ stresses was carried out, and the influencing factors on the propagation law, such as the scale of static loads and the number of joints were studied respectively. The results show that the transmission coefficient of intact rock is larger than that of jointed rock mass under the same loading condition. With the increase of confining pressure, the transmission coefficients of intact rock and jointed rock mass both show an trend of increasing first and then decreasing, and the variation of transmission coefficients in intact rock is smaller than that of jointed rock mass. Transmission coefficient of jointed rock mass decreases with the increase of the number of joints under the same loading condition, when the confining pressure is relatively small, the reduction of transmission coefficients decreases with the increasing of the number of joints, and the variation law of the reduction of transmission coefficients is contrary when the confining pressure is large.

1. Introduction

Within the Earth crusting, the underground rock mass is usually in a certain initial in-situ stress environment. The natural rock mass usually contains a large number of joints, when the stress wave across the joints, the amplitude and velocity of stress wave will be attenuated. And the criterion of the damage degree of rock mass is related to the propagation parameters of stress wave, such as the peak particle velocity (PPV) and the wave velocity [1]. Hence, it is of great significance in the research of the propagation law of explosive stress waves in in-situ stressed rock mass.

Experimental research is an effective method, which is widely used in the study of stress wave propagation in jointed rock mass. At present, experimental research on the propagation law of stress wave is mainly through the Split Hopkinson Pressure Bar (SHPB) system [2], and most of them involve one-dimensional stress waves propagating in rock mass without in-situ stress [3-7]. The previous experimental studies had focused on the effects of in-situ stress on the dynamic mechanical properties of rock [8-10]. However, few studies have been carried out on the propagation law of stress waves in jointed rock masses under initial stress.

Therefore, this paper conducts a model test research to study the propagation law of the plane stress wave in the intact rock and jointed rock mass under different initial stresses. In the model test, the
effects of the scale of the initial stress and the number of joints on the transmission coefficients of the plane stress wave in the intact rock and jointed rock masses were analyzed, respectively.

2. Model test

2.1. Initial stress loading equipment

The initial stress loading equipment used in the experiment is shown in Fig.1(a), which can provide steady static loading. The size of the test sample of the loading experiment is 1600 mm×1300 mm×400 mm (length × height × thickness), and the loading diagram of the test sample is shown in Fig.1(b) and the maximum static load of the equipment is 5 MPa.

![loading equipment and diagram](image)

Figure 1. Multifunctional testing machine for rock and soil

2.2. Determination of physico-mechanical parameters of model test similar materials

The prototype in the model test is the rock mass under the initial in-situ stress, and physico-mechanical parameters of the prototype are obtained based on the analysis of the physico-mechanical parameters of representative surrounding rock mass of some deep underground engineering in China, as shown in Table 1. Where, \(R_c\), \(\sigma_t\), \(E\), \(\varphi\), \(C\), \(\mu\) and \(\rho\) are the uniaxial compressive strength, tensile strength, elastic modulus, internal friction angle, cohesion, poisson ratio and density of the prototype rock mass, respectively.

| Type          | \(R_c\)/MPa | \(\sigma_t\)/MPa | \(E\)/GPa | \(\varphi\)/(°) | \(C\)/MPa | \(\mu\)  | \(\rho\)/kg/m³ |
|---------------|-------------|-----------------|-----------|-----------------|-----------|---------|---------------|
| prototype     | 120         | 12              | 50        | 30              | 30        | 0.223   | 2600          |
| Similar material | 5.864       | 0.613           | 5.226     | 23.2            | 1.49      | 0.203   | 1980          |

In the model test, the propagation characteristics of the explosive stress wave in the jointed rock mass under in-situ stress are simulated. Because the gravity of the model test sample is borne by the restrained steel girders on both sides of the loading equipment, so the stress similarity coefficient \(C_s\) and the geometric similarity coefficient \(C_L\) can be selected independently without considering the gravity similarity coefficients \(C_p\) [11]. According to the test accuracy requirements, the similarity scale of stress \(C_s\) is selected as 20. Through the orthogonal tests of different mixture ratios, the mixture ratio of test sample material is cement: sand: water: plasticizer = 1: 4: 1.2: 0.0267, and the detailed physico-
mechanical parameters of similar materials can be tested by a series of physical and mechanical tests, as shown in Table 1.

Owing to the prototype in the model test is the jointed rock mass under the in-situ stress, so the joint in the rock mass is in closure state under compression. Therefore, the joints in the model test samples are made as closure. In order to ensure that the joint simulation materials does not deform during the pouring process of the similar materials, the mica plate with certain strength and thickness of 1 mm is used to simulate the joint in rock mass, which is consistent with the mechanical properties of joints under high in-situ stress [12], and the initial stiffness of the mica plate is 12 GPa/m.

2.3. Design and manufacture of the model test sample
In order to study the propagation law of plane stress wave in the intact rock and jointed rock mass under different in-situ stresses, a model test sample was designed, as shown in Figure 2. In the model test, the plane stress wave was generated by detonating fuses arranged at the center of test sample, which along the thickness direction of samples. Because the size of test sample is relatively large, in order to make full use of the test sample, and due to the characteristics of cylindrical charge structure, four measuring lines were arranged in the test sample. Two PVDF stress sensors were arranged in each measuring line in the test sample, which was located at 150 mm and 350 mm from the blasting source, numbered from 1 to 8 as shown in Figure 2. According to the number of joints on each measuring line, the corresponding research objects are intact rock, single-joint rock mass, double-joints rock mass and three-joints rock mass, respectively.

![Figure 2. Schematic design of the model test sample (unit: mm)](image)

2.4. Model test procedure and boundary static loading
To save the funds and time of experiment, it is designed that the test sample is used to repeatedly apply the explosive loads. The plane stress wave applied in the test sample is generated by four detonating fuses, and the charge is kept constant during the model test. The model test procedure is as follows:

1. The detonating fuses are fixed in the seamless steel pipe in the center of the test sample, then the quick-drying material is poured into the seamless steel pipe and maintained for 1 d until the strength reaches the test requirement.

2. A static load is applied on the test sample to the design value in two steps in advance, and then keep the static load steady for 30 min, so the model test sample can be fully deformed.

3. The data acquisition system is changed from static measurement to dynamic measurement, and the explosive load is applied under constant static load. The stress time-history curves of the measured points in the test sample under dynamic load are acquired.
(4) After the stress data acquisition is completed, an electric drill is used to break the broken quick-drying material in the seamless steel tube and clear it out.

After completing the above procedure, the new detonating fuses can be arranged in the test model and ready for the next boundary static loads. In the model test, the boundary static loads applied on the test sample are shown in Table 2, and the corresponding initial in-situ stress is also shown in Table 2 according to the similarity theory.

| NO. | Experiment load/MPa | Initial in-situ stress/MPa |
|-----|---------------------|---------------------------|
|     | Vertical            | horizontal                |
| 1   | 0                   | 0                          |
| 2   | 0.75                | 0.75                       |
| 3   | 1.5                 | 1.5                        |
| 4   | 3                   | 3                          |

3. Analysis of test results

3.1. Transmission coefficients of rock mass under different confining pressures

In order to intuitively analyze the propagation law of plane strain waves in intact rock and jointed rock mass under different confining pressures. The transmission coefficients of plane stress wave in intact rock, single-joint rock mass, double-joints rock mass and three-joints rock mass were sorted out as shown in Figure 3.

![Figure 3. Transmission coefficients of plane stress wave in intact rock and jointed rock mass under different confining pressures](image)

Figure 3 shows that the transmission coefficient of intact rock is obviously larger than that of jointed rock mass under the same confining pressure, indicating that when plane stress wave propagate in jointed rock mass, attenuation not only occurs in rock, but also in the process of stress waves passing through joints. With the increase of confining pressure, the transmission coefficients of intact rock and jointed rock mass show an trend of increasing first and then decreasing, and the variation of transmission coefficients of intact rock is smaller than that of jointed rock mass.

When the confining pressure is increased from 0 MPa to 1.5 MPa, the increase magnitude of the transmission coefficients of intact rock, single-joint, double-joints and three-joints rock mass are 22.9%, 124%, 188% and 200% respectively, the reason is that the stiffness of the joint increases rapidly with the increase of confining pressure, resulting in a decrease in the attenuation of stress wave propagation in joints, so the transmission coefficient rises sharply. When the confining pressure increases from 1.5 MPa to 3 MPa, the decrease magnitude of the transmission coefficients of intact
rock, single-joint, double-joints and three-joints rock mass are 23.7%, 21.4%, 12.2% and 8.9% respectively, and the decrease of transmission coefficient in jointed rock mass is smaller than that of intact rock, indicating the attenuation of the stress wave propagation in joints decreases in this process, therefore, the transmission coefficient decreases more slowly.

3.2. Transmission coefficients of rock mass with different number of joints

It can be seen from the Figure 3 that the transmission coefficient of jointed rock mass decreases with the increase of the number of joints under the same confining pressure. The transmission coefficients of plane stress wave in rock mass with different number of joints were sorted out as shown in Figure 4.

![Figure 4](image_url)

**Figure 4.** Transmission coefficients of plane stress wave in rock mass with different number of joints under different confining pressures

Figure 4 shows that when the confining pressures are 0, 0.75 and 1.5 MPa, and the number of joints increases from 1 to 3, the transmission coefficients decrease by 32% and 12.5%, 20.5% and 20% ,12.5% and 8.2%, respectively, it is shown that the reduction of transmission coefficient decreases with the increasing of the number of joints. When the confining pressures is 3 MPa, and the number of joints increases from 1 to 3, the transmission coefficients decrease by 2.3% and 4.7%, indicating reduction of transmission coefficients increases with the increasing of the number of joints.

The reason for this phenomenon is that when the confining pressure is small, the increase of joint stiffness is not large, although the increase of joint number increases the attenuation of stress wave propagation in jointed rock mass, meanwhile, the effect of the multiple transmission and reflection between joints is stronger, lead to the decrease of the reduction of transmission coefficients. When the confining pressure is large, the stiffness of the joint increases dramatically, and the attenuation of the stress wave at the joint decreases. Therefore, the effect of the multiple transmission and reflection between joints is weaken, the stress wave attenuation due to the increase of joint number is dominant, so the reduction of transmission coefficients of the joint rock increases.

4. Conclusion

In this paper, the propagation law of the plane stress wave in the intact rock and jointed rock mass under different static load was studied by a model test research, the results show that:

1) Transmission coefficient of intact rock is larger than that of jointed rock mass under the same confining pressure, indicating that when plane stress wave propagating in the jointed rock mass, attenuation not only occurs in rock, but also in the process of stress waves passing through joints.

2) With the increase of confining pressure, the transmission coefficients of intact rock and jointed rock mass both show an trend of increasing first and then decreasing, and the variation of transmission coefficients in intact rock is smaller than that of jointed rock mass.

3) Transmission coefficients of jointed rock mass decreases with the increase of the number of joints under the same confining pressure. When the confining pressure is relatively small, the
reduction of transmission coefficients decreases with the increasing of the number of joints, and the variation law of the reduction of transmission coefficients is contrary when the confining pressure is large.

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