Research Article

Effects of Unidirectional In Situ Stress on Crack Propagation of a Jointed Rock Mass Subjected to Stress Wave

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This paper proposes a large-scale experiment combined with multiple cement mortar blocks to simulate stress wave propagation across a jointed rock mass under unidirectional in situ stress. Two identical mortar block models with smooth, dry, and unfilled joints were poured. The stress waves in Model 1 and Model 2 were generated by an electric spark source and a blast-induced source, respectively. The effects of these two excitation sources on stress wave propagation were compared through crack propagation experiments. The experimental results show that the peak value of the transmitted strain wave decreases as the in situ stress increases. The unidirectional in situ stress has a certain inhibitory effect on the stress wave propagation. It also indicates that for Model 1 with the electric spark source, no cracks on the upper surface, but a Livingstone blasting crater at the bottom is generated. For Model 2 with the blast-induced source, cracks on the upper surface and a blasting crater at the bottom are produced. The results verify the similarity between the electric spark source and the explosive source. The two-dimensional finite element program (ANSYS/LS-DYNA) was applied to further simulate the crack propagation of a jointed rock mass under different in situ stresses. The results of numerical simulation verify that the in situ stress has a clear guiding effect on the crack propagation.

1. Introduction

In recent years, the rapid development of tunneling and hydropower engineering has greatly promoted tunnel excavations to deeper depth [1]. Through this work, high in situ stress has been identified as a characteristic property of deep jointed rock masses [2–4]. Therefore, the stress wave propagation in a jointed rock mass is significantly influenced not only by the joints but also by the in situ stress. In addition, the influence of in situ stress on the stability and failure of the surrounding rock mass at depth has become increasingly clear, improving the prediction of rockburst, large deformation, and complex tunnel geology. The behavior of rock masses is also governed by the in situ geological structure and stress conditions [5]. Consequently, the study of the stress wave propagation across jointed rock

masses under in situ stress conditions has continued to attract considerable attention.

A considerable amount of literature has focused on the following two aspects of stress wave propagation through jointed rock masses: the properties of stress waves and the nature of joints. Research on the properties of stress waves includes the incident angles [6, 7], the amplitude and frequency of incident waves [8], and different types of stress waves [6, 9]. Researchers have also examined the nature of joints, including the joint closure constitutive relationship [10], the joint opening-closing behavior [9, 11], the number of joints [7, 12, 13], the joint stiffness [14], and the joint filling properties [15, 16], etc. Among them, most of these studies adopted small-scale laboratory experiments, i.e., SHPB (split Hopkinson pressure bar) experiments. In general, the diameter and length of the cylindrical sample of

SHPB are 50 mm and 25 mm, respectively. These experiments have significant side effects. Few studies have considered large-scale experiments under the coupling of in situ stress and dynamic stress loading.

The existing literature has indicated that in situ stress has strong effects on the failure strength and dynamic crack propagation of rock masses [17–19]. For instance, according to a biaxial compression test of a jointed rock mass with an opening, the propagation direction of the tensile cracks was found to be roughly normal to the joint surfaces [20]. High in situ stress was observed to resist the radially oriented pressure and damage extension around cut holes during tunneling excavation [21]. The levels and states of the in situ stress in the rock greatly affected the damage evolution, the crack initiation, and development and hence affected the fragmentation [22]. He et al. [23] have experimented with granite under several static and dynamic stresses to examine the crack propagation characteristics of blast-induced shock waves, and the results showed that the direction of the radial crack was related to the lateral pressure coefficient in the biaxial direction. The in situ stress could enhance the compression effect and weaken the tension effect in the radial direction of the borehole, and the jointed plane failure zone in coal masses decreased with increasing in situ stress [24]. Blasting of deeply buried structures is a complex dynamic process that can cause blast loading and in situ stress redistribution [25]. These studies mainly investigated the crack propagation of intact rock masses or rock masses containing microcracks or microvoids. The influence of the joints, large in extent and small in thickness compared with the wavelength of an incident wave, on crack propagation is rarely found in the available literature.

In addition to laboratory test methods, numerical simulation is an important method to investigate the blasting fracture mechanism. Currently, there are many numerical simulation methods, such as the finite element method (FEM), discrete element method (DEM), and boundary element method (BEM). Compared with the other two numerical methods mentioned above, FEM software ANSYS/LS-DYNA is advantageous in that the explicit dynamic analysis method can be used conveniently to simulate the large deformation of the material, and the explosives and other parameters can be input directly with a user subroutine interface. Since the FEM with a contact face can simulate crack growth in both the intact mass and the jointed plane, it may be a good method to study the fracture pattern in a jointed rock mass during the blasting process [26]. For example, the prediction of blast craters in brittle rock due to an underground explosion has been simulated using the LS-DYNA based on the Taylor–Chen–Kusmaul continuum damage model [27]. The Johnson–Holmquist material model was implemented in LS-DYNA through user subroutines to simulate the blasting-induced rock fractures [28]. A constitutive model considering dynamic compressive and tensile failure was applied to analyze crack initiation and propagation in coal masses using LS-DYNA [26]. The propagation characteristics of shock waves subjected to blasting load in a parallel jointed rock mass were investigated using LS-DYNA, and the results showed that the joint

properties had a great effect on the propagation of blast-induced vibration [29]. In the present study, ANSYS/LS-DYNA will be employed for crack propagation of a jointed rock mass under in situ stress.

As mentioned above, both the joints and the in situ stress influence the stress wave propagation across a jointed rock mass and consequently the crack propagation. Researchers have also realized the importance of these two factors in rock masses, but few have considered laboratory studies of wave propagation under unidirectional in situ stress. The theme of this study is to investigate crack propagation of a jointed rock mass caused by stress waves using two experimental models under unidirectional in situ stress. First, to simulate the joint distribution and apply different in situ stresses, a model consisting of multiple cement mortar blocks is presented. Then, we adopt a ZDF-3 (ZhiliuDian Fire-3) electric spark source to excite stress waves. This excitation source is compared with the blast-induced source through the law of crack propagation and the shape and size of the blasting crater in the model. Finally, the dynamic relaxation method of ANSYS/LS-DYNA is applied to study the law of crack propagation in jointed rock masses under unidirectional in situ stress. Our procedure provides a systematic methodology to quantify the crack propagation in a jointed rock mass under high in situ stress.

2. Laboratory Experiment

2.1. Experimental Model. A large-scale experimental model with multiple joints under unidirectional in situ stress was designed, as shown in Figure 1. The model materials mainly selected cement with a compressive strength of 30 MPa and medium sand. The ratio of water, cement, and medium sand was 1 : 4 : 0.5. The experiment did not consider the influence of the self-weight stress on stress wave propagation because the self-weight stress was very small compared to the in situ stress. Accordingly, it was not necessary to consider the weight similarity ratio of the model material.

The model was composed of a parent body and four jointed blocks. Hence, four parallel joints were formed into the model. A single joint was located on the left side of the parent body, and the remaining parallel joints were located on the right side. The experimental model mainly considered smooth, dry, and unfilled joints which mean no thickness joints. It is noted that the joints here are large in extent and small in thickness compared with the wavelength of an incident wave. The total size of the experimental model was 180 cm × 80 cm × 25 cm (length × width × height) and much larger than the size of the sample of SHPB. Among them, the length, width, and height of the parent body were 80 cm, 60 cm, and 25 cm, respectively, and the dimensions of the jointed block were the same as those of the parent body except that the width was 30 cm, as shown in Figure 1(a). Two loads were applied along the length direction to simulate in situ stress. The other two directions had a free boundary. The size of the model is large enough to avoid the influence of reflected stress wave propagation [23, 30, 31]. Eight monitoring points were arranged sequentially from left to right, numbered T1 to T8, as shown in Figure 1(b). As

FIGURE 1: Schematic diagram of the model for stress waves propagating across jointed rock masses under unidirectional in situ stress (unit: cm).

the distance of stress wave propagation increased, it was assumed that the stress wave measured at each pressure measurement point was a plane wave. To avoid the overflow of explosion gas from the bottom of the borehole during the experiment, a nonpenetrative blast hole was pre-cut in the middle of the parent body and was surrounded by a cylindrical steel pipe with a base ($\phi 5 \text{ cm} \times 12.5 \text{ cm}$), as shown in Figure 1(c).

The poured and assembled model consisted of the unidirectional in situ stress loading device, the dynamic stress loading device, and the dynamic strain acquisition system, as shown in Figure 2. The physical and mechanical parameters of the cement mortar block are listed in Table 1, where ρ_c denotes the density of the cement mortar block; E_c and μ_c denote Young's modulus and Poisson's ratio, respectively; σ_c , $E_{\tan}$, and v_p denote the uniaxial compressive strength, the tangent modulus, and the P wave velocity, respectively.

2.2. ZDF-3 Electric Spark Source. Generally, the explosive is used as an excitation source in blasting tests. Once the explosive is detonated, the stress wave and explosion gas will coexist at the same time and are difficult to separate. Although explosive produces a wide frequency spectrum and a large amount of energy, it has poor controllability and is thus dangerous to work with. To study only the attenuation law of the stress wave, a new type of ZDF-3 (ZhiliuDian Fire-3) electric spark was selected as the excitation source, as shown in Figure 2(a).

The ZDF-3 electric spark source produces large energy and rich high-frequency components. The working principle

of the ZDF-3 electric spark is to insert a special launch head into a blast hole filled with water, as shown in Figure 2(b), and then quickly charge the capacitor. Later, it uses ultrahigh voltage to instantly release energy into the water and thus generate stress waves. Compared with explosive detonation, its advantage is that only stress waves are produced without any explosion gas. The frequency range of the electric spark is 40 Hz to 300 Hz. The spark energy can be expressed as follows [32]:

$$Q = \frac{1}{2} C_{\text{cap}} U^2, \quad (1)$$

where Q , C_{cap} ($=420 \mu\text{F}$), and U are the emission energy, the capacitor capacitance, the voltage of the ZDF-3 electric spark, respectively. Due to the repeated application of dynamic loading to the model, a thick seamless steel pipe was embedded in the parent body of the model, as shown in Figure 2(c). The density of the seamless stainless steel pipe ρ_s is 7900 kg/m^3 , Young's modulus E_s is 194.0 GPa , and Poisson's ratio μ_s is 0.25 , respectively. Meanwhile, eight steel bars were welded outside the stainless steel pipe to prevent it from separating from the cement mortar block.

2.3. Loading Equipment. An eight-channel ultradynamic data acquisition machine (DH5930) was used to collect dynamic strain measurements, as shown in Figure 2(d). The loading equipment was composed of two reaction frames, six steel strands, a ZB-500 electric fuel pump, and two center hole jacks, as shown in Figure 2(e)–2(g). The reaction frames were installed on the left and right sides of the model, and three steel strands were placed on the other sides. Uniform

FIGURE 2: The model with cement mortar, including an in situ stress loading system and data acquisition system: (a) ZDF-3 electric spark source; (b) blast hole with water seal; (c) steel pipe; (d) eight-channel ultradynamic data acquisition machine (DH5930); (e) prestressing anchorage; (f) center hole jack; (g) ZB-500 electric fuel pump; (h) strain brick.

TABLE 1: The physical and mechanical parameters of cement mortar block.

ρ_c (kg/m ³)	E_c (GPa)	ν	σ_c (MPa)	E_{tan} (GPa)	v_p (m/s)
2156	2.65	0.47	20	0.85	3227

loads can be applied to the boundary of the model, and the maximum load was 5.0 MPa. To load the in situ stress, a ZB-500 electric fuel pump was used to control two center hole jacks to tension the steel strand. Two strain gauges were pasted on each small strain brick embedded in the model shown in Figure 2(h).

2.4. Experimental Process. Uniform loads of the same magnitude were applied in one direction through the loading equipment including the static and dynamic stages. The static loading onto the cement mortar block was approximately symmetrically distributed, and the stress wave

propagated evenly from the center blast hole of the parent body. Two identical mortar block models were poured. The experimental process of Model 1 was first implemented when using the ZDF-3 electric spark as the excitation source, as shown in Figure 3. The experimental process of Model 2 is the same as that of Model 1 except that blasting in the blast hole is used as the excitation source.

During the static stage, the in situ stress was loaded in one direction with the loading equipment. Six different magnitudes of the unidirectional in situ stress, including 0.5 MPa, 1.0 MPa, 2.0 MPa, 3.0 MPa, 4.0 MPa, and 5.0 MPa, were considered. Each in situ stress loading was held for more than 10 minutes or until the cement mortar block was fully deformed.

During the dynamic stage, the blast hole was filled with water, and an electric spark cable with a copper core was inserted into the blast hole. The blast hole was blocked with plasticine and covered with an iron plate to seal the blast hole. Then, the ZDF-3 electric spark source was turned on

FIGURE 3: Model 1 field test using ZDF-3 electric spark source to generate stress waves.

and charged to the required voltage. Once the voltage was completely stable, it was suddenly released. At this point, the dynamic-static loading was complete. The dynamic strain curve of the measuring point was recorded through the DH5930 apparatus.

In the present study, three charging voltages were considered: 2500 V, 3000 V, and 3500 V. Each voltage was excited three times under each level of in situ stress, and thus 18 sets of dynamic strain data were obtained. Therefore, a total of 54 experiments were completed. When the electric spark was charged to 2500 V, the emission energy was obtained in Table 2. The maximum and minimum average emission energies were 746.3 J and 665.5 J, respectively. Overall, the electric spark excitation energy is adjustable and controllable. It is feasible to use the ZDF-3 electric spark source to replace the blast-induced source with exciting stress waves.

3. Results and Discussion

In this section, the dynamic strains of monitoring points T1 and T8 in Model 1 using the ZDF-3 electric spark source are presented. After that, the crack propagation patterns of the parent bodies of Model 1 using the ZDF-3 electric spark source and Model 2 using the blast-induced source are analyzed.

3.1. Dynamic Strain. Figure 4 shows the waveforms of the transmitted strain wave at T1 under unidirectional in situ stress when the stress wave passes through a single joint, where the symbol “-” indicates compression and “+” indicates tension. The charging voltage is 2500 V. Regardless of the in situ stress, the transmitted strain wave first exhibits a compressive wave and then a reflected tensile wave. When the in situ stress varies from 0.5 MPa to 5.0 MPa, the peak value of the transmitted strain wave decreases from $9.4E4 \mu\epsilon$ to $5.28E4 \mu\epsilon$, and the time interval required to reach the peak of the transmitted strain wave is 217.1 μs , 221.3 μs , 216.4 μs , 213.5 μs , 211.6 μs , 193.1 μs , respectively. The greater the in situ stress is, the smaller the dynamic deformation of the rock mass caused by the stress wave. Therefore, the in situ stress has a certain inhibitory effect on stress wave propagation when the initial in situ stress and the stress waves are superimposed. Although the increasing in situ stress will lead to the closure of the joint to a certain extent, the jointed rock mass may produce new microcracks and plastic deformation under the combined action of dynamic and static stress.

Figure 5 shows the waveforms of the transmitted strain wave at T8 under different in situ stresses when the stress wave passes through multiple parallel joints. The attenuation law of the transmitted strain wave of the three joints is similar to that of the single joint; that is, the compressive wave appears first, and then the tensile wave appears. There are subsequent peaks after the first peak. The peak value of the transmitted strain wave decreases from $2.46E4 \mu\epsilon$ to $1.2E4 \mu\epsilon$ when the in situ stress gradually increases from 0.5 MPa to 5.0 MPa. The results show that the unidirectional in situ stress has a great influence on the stress wave propagation and attenuation. When the in situ stress is the same, the dynamic strain of T8 is significantly less than that of T1 because of the increase in the number of joints.

3.2. Crack Propagation of Model 1. The crack distribution patterns on the upper and bottom surfaces of the parent body of Model 1 are shown in Figure 6. No cracks are observed on the upper surface of Model 1, as shown in Figure 6(a). However, radial cracks and circumferential cracks appear on the lower surface of the matrix along the center of the model, as shown in Figure 6(b). Additionally, a Livingstone blasting crater formed during the experiment, and the funnel body is completely separated from the parent body. The diameter of the crater is approximately 52 cm, and the depth is 10 cm. The results of Model 1 show that a single stress wave loading may not be enough to cause damage to the jointed rock mass, but the repeated stress waves loading can cause the jointed rock mass instability and failure.

3.3. Crack Propagation of Model 2. Model 2 was blasted nine times, and the detonator was buried 12.5 cm deep. Most blast-induced sources used a delay detonator and water as the coupling medium, except for the second blast, which used a detonator and 4.9 g of explosives and blocked the blast hole with mud. The in situ stress loading increased from 0.5 MPa to 5.0 MPa. The specific cases and the parameters of filling delay detonator and explosive in Model 2 are listed in Table 3. The evolution of the crack distribution in the parent body of Model 2 from the first to ninth blast is shown in Figure 7. The following test results were observed:

- (1) No cracks were observed around the blast hole after blasting when the in situ stress loading was 0.5 MPa and 1.0 MPa, respectively. An initially very small crack around the blast hole had appeared since the 3rd blasting when the in situ stress was 2.0 MPa. After the 5th blasting, the crack tended to propagate along the loading direction when the in situ stress reached 3.0 MPa. This phenomenon indicates that the initial in situ stress can affect crack propagation. A superposition effect occurs if the stress wave encounters the in situ stress. Other researchers have reported similar conclusions. For example, Nicholls and Duvall [33] pointed out that the presplitting of test specimens along with the maximum in situ stress under confining pressure much more easily passed field tests than presplitting in other directions. Simha

TABLE 2: Emission energy of ZDF-3 electric spark (2500 V).

In situ stress (MPa)	Number	Charging voltage (V)	Residual voltage (V)	Actual voltage (V)	Emission energy (J)	Average emission energy (J)
0.5	1	2500	640	1860	726.5	734.4
0.5	2	2500	650	1850	718.7	
0.5	3	2500	600	1900	758.1	
1.0	1	2500	600	1900	758.1	745.0
1.0	2	2500	600	1900	758.1	
1.0	3	2500	650	1850	742.2	
2.0	1	2500	620	1880	742.2	742.4
2.0	2	2500	650	1850	718.7	
2.0	3	2500	590	1910	766.1	
3.0	1	2500	640	1860	726.5	746.3
3.0	2	2500	/	/	/	
3.0	3	2500	590	1910	766.1	
4.0	1	2500	710	1790	672.9	665.5
4.0	2	2500	700	1800	680.4	
4.0	3	2500	750	1750	643.1	
5.0	1	2500	700	1800	680.4	719.0
5.0	2	2500	620	1880	742.2	
5.0	3	2500	630	1870	734.3	

Note: “/” indicates that no data has been collected.

FIGURE 4: The dynamic strain curve of T1 in Model 1 versus time.

and Fournery [34] proposed the static stress field to blast fracture mode of testing and concluded that the preferred fracturing direction of polymethyl methacrylate (PMMA) was the direction of maximum principal stress.

- (2) The propagation direction of the cracks around the blast hole was not completely parallel to the loading direction but was at an angle to the loading direction. This phenomenon occurred after the 3rd blast, and the cracks became longer and wider with increasing in situ stress, as shown in Figure 7. For the so-called inclined deflection cracks, the angle between the crack and the in situ stress was between 15° and 45°.

In other words, the crack propagation direction intersected the in situ stress loading direction.

- (3) From the first blast to the end of the experiment, no cracks were observed perpendicular to the loading direction. Due to the steel pipe surrounding the blast hole, the annular crack around the blast hole was very small, and the steel pipe also blocked the explosion gas from wedging into the cement mortar block. The extent of the blasting damage zone around the blast hole decreased as the in situ stress increased.
- (4) After nine blasts, an irregular circular area of deformation appeared at the bottom of Model 2, as shown in Figure 8. The diameter of the profile of the

FIGURE 5: The dynamic strain curve of T8 in Model 1 versus time.

FIGURE 6: The crack distribution patterns of the parent body of Model 1 using the ZDF-3 electric spark. (a) No cracks visible on the top surface of the parent body. (b) A Livingston blast crater with a diameter of approximately 52 cm and a depth of 10 cm at the bottom of the parent body.

TABLE 3: Parameters of filling delay detonator and explosive in Model 2.

In situ stress (MPa)	Explosive charge	Stemming	Number of blasts
0.5	1 delay detonator	Water	1
1.0	1 delay detonator and 4.9 g explosives	Mud	1
2.0	1 delay detonator	Water	1
3.0	1 delay detonator	Water	2
4.0	1 delay detonator	Water	2
5.0	1 delay detonator	Water	2

blasting crater was approximately 30 cm. This crack connected with the upper surface crack on the side of Model 2 (the yellow dotted line). However, the funnel body did not fall off.

The above results show that the in situ stress state of the rock mass greatly affects the damage evolution and crack initiation and development and therefore affects fragmentation [22]. The damage development tends towards the direction at which the unidirectional in situ stress is applied. In addition, the crack propagation patterns of Model 1 and Model 2 verify the similarity between the ZDF-3 electric

spark source and the blast-induced source. Although the energy of the ZDF-3 electric spark is not as large as that of the explosive, it can play an important role in stress wave propagation and can be used as an excitation source in stress wave propagation.

4. Numerical Simulation of Crack Propagation

Since it is difficult to obtain an analytical solution for nonelastic materials under blasting, there has been a considerable amount of researches on the numerical simulation

FIGURE 7: Crack propagation around the blast hole on the top and side of the parent body in Model 2 after nine blasts with a delay detonator and explosive.

FIGURE 8: A blasting crater at the bottom of the parent body in Model 2.

of blasting funnels [21, 27, 35, 36]. To further confirm that the blasting cracks in the jointed rock mass propagate along the loading direction under dynamic and static loading, a numerical simulation to take into account the nonlinear response of jointed rock masses is conducted in this research. A plane strain numerical calculation model is established using the finite element program ANSYS/LS-DYNA. The calculation model is the same size as the parent body of the models described in Section 2. Only unidirectional in situ stress (denoted as P1) is considered in the calculation, as shown in Figure 9.

When the explosive is detonated, the strain of the rock mass near the charge is very large, and the strain rate effect is obvious. Therefore, the Cowper-Symonds model is considered. The elastic-plastic-kinematic model considers the effect of strain rate and strain hardening on the rock mass and can accurately describe the fracture pattern during blasting [37–39]. The expression is written as follows [40]:

$$\begin{cases} \sigma_y = \left[1 + \left(\frac{\dot{\epsilon}}{C} \right)^{1/P} \right] (\sigma_0 + \beta E_p \epsilon_p^{eff}), \\ E_p = \frac{E_c E_{tan}}{E_c - E_{tan}}, \end{cases} \quad (2)$$

where E_c and E_{tan} are the same as before, σ_0 is the initial stress, σ_y is the failure stress, $\dot{\epsilon}$ is the strain rate, E_p is the plastic hardening modulus, β is the hardening parameter ($0 < \beta < 1$), and C and P are Cowper-Symonds strain rate parameter, respectively. The effective plastic strain ϵ_p^{eff} can be calculated as follows:

$$\begin{cases} \epsilon_p^{eff} = \int_0^{t_a} d\epsilon_p^{eff}, \\ d\epsilon_p^{eff} = \sqrt{\frac{2}{3}} d\epsilon_{ij}^p d\epsilon_{ij}^p, \end{cases} \quad (3)$$

FIGURE 9: The numerical model of dynamic and static coupling of the parent body.

where $\varepsilon_p^{\text{eff}}$ is the effective plastic strain, t_a is the cumulative time of plastic strain, and ε_{ij}^p is the partial component of plastic deviation strain of the rock mass. In this simulation, $C = 2.63$; $P = 3.69$; $\beta = 0.15$; $\varepsilon_p^{\text{eff}} = 1.25$.

In LS-DYNA, the Jones-Wilkins-Lee (JWL) equation of state is used to describe the chemical reactions after explosive detonation [40]. The JWL equation of state defines the pressure as follows:

$$p_b = A \left(1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E}{V}, \quad (4)$$

and is usually used for detonation products of high explosives, where p_b is the pressure of the detonation products. V is the relative specific volume of the detonation products. E is the specific internal energy of the detonation products. A , B , R_1 , R_2 , and ω are parameters of JWL equation of state, respectively. In this study, the parameters of the JWL equation of state are listed in Table 4, where ρ_e is the explosive density, P_{CJ} is the Chapman-Jouguet pressure, and VoD is the velocity of detonation.

Four cases are considered: (i) Case I: $P1 = 0$ MPa, and a steel pipe is either included or excluded in the model; (ii) Case II: $P1 = 0.5$ MPa, and a steel pipe is included; (iii) Case III: $P1 = 1.0$ MPa, and a steel pipe is included; (iv) Case IV: $P1 = 2.0$ MPa, and a steel pipe is included. The parameters of the numerical calculation model are listed in Table 1. The SOLID185 with eight nodes of hexahedral element is adopted. Only two elements are set in the thickness direction due to the plane strain assumption. The numerical simulations have a total of 64 250 elements. In the finite element method, the joint is usually treated as a boundary. The boundary conditions were specified as follows: the upper and lower sides are nonreflecting boundaries, while the other two sides are free faces. The numerical simulation adopts the cm-g- μ s unit system.

4.1. Case I. Case I mainly compares the damage zones around the blast hole with and without a steel pipe. In this case, only the dynamic calculation steps of ANSYS/LS-DYNA are required due to the lack of in situ stress. The blast hole without a steel pipe is completely destroyed, and a crushing area is formed, as shown in Figure 10(a). The symmetrical cracks are distributed at the periphery of the crushing zone. The distribution of the damage zone around the blast hole with a steel pipe is shown in Figure 10(b). Compared with that in Figure 10(a), the range of the damage zone in Figure 10(b) is significantly reduced. Only small cracks around the steel pipe are observed, and the steel pipe separates from the parent body. The maximum dynamic strain is $1.87E4 \mu\epsilon$. These findings explain why eight steel bars should be welded outside the stainless steel pipe in the model. The explosion gas does not wedge into the cement mortar block after the explosive is detonated, further confirming that the stress wave can damage the rock mass.

4.2. Case II. In Case II, the unidirectional in situ stress is loaded first, and then a dynamic loading is applied on the blast hole. The dynamic relaxation method of the ANSYS/LS-DYNA is used to obtain the nodal stress and displacement of each element under the initial in situ stress before and after blasting [24, 41, 42]. The distribution of the stress and the damage zone around the blast hole with unidirectional in situ stress ($P1 = 0.5$ MPa) is shown in Figure 11. At the static loading stage, the distribution of the maximum tensile and compressive stress is shown in Figure 11(a). The upper and lower sides of the rock mass are compressed, and the left and right sides are subjected to tension only when unidirectional in situ stress is applied. At the dynamic loading stage, the stress of each element obtained from the static analysis is input into the initial stress of the dynamic analysis, and then the explosion analysis is performed. Very

TABLE 4: Parameters of emulsion explosive and JWL equation of state.

ρ_e (kg/m ³)	VoD (m/s)	p_{CJ} (GPa)	A (GPa)	B (GPa)	R_1	R_2	ω	E (GPa)
1300	4000	0.27	214.4	0.182	4.2	0.9	0.15	4

FIGURE 10: Distribution of damage zone around blast holes with and without a steel pipe (Case I $P_1 = 0$ MPa). (a) Damage zone around the blast hole without steel pipe. (b) Damage zone around the blast hole with a steel pipe. FIGURE 11: The stress distribution and damage zone around a blast hole under unidirectional in situ stress (Case II: $P_1 = 0.5$ MPa). (a) Distribution of tensile and compressive stress. (b) Damage zone around a blast hole.

small cracks form around the blast hole, as shown in Figure 11(b). The maximum dynamic strain is $3.34E4 \mu\epsilon$. The range of crack propagation is small because the applied unidirectional in situ stress is low.

4.3. Case III. At the static stage, the maximum tensile and compressive stress under the action of the static stress field in the rock mass tends to increase when the unidirectional in situ stress increases to 1.0 MPa, as shown in Figure 12(a). After approximately $234.96 \mu s$ of dynamic loading, the

distribution of the damage zone around the blast hole is shown in Figure 12(b). The maximum dynamic strain is $6.68E4 \mu\epsilon$. Two distinctly continuous cracks appear along the loading direction and then extend to the boundary. It is shown that the in situ stress has a clear guiding effect on the stress wave propagation. The crack propagation perpendicular to the direction of the unidirectional in situ stress is not obvious. These results are consistent with the crack propagation of Model 2 in Section 3. The difference between the two is that the crack propagation direction observed in Model 2 is at an angle to the loading direction, but the two

FIGURE 12: The distribution of stress and crack propagation around a blast hole under unidirectional in situ stress (Case III: $P = 1.0$ MPa). (a) Distribution of tensile and compressive stress. (b) Crack propagation along the loading direction.

FIGURE 13: The distribution of stress and crack propagation around a blast hole under unidirectional in situ stress (Case IV: $P_1 = 2.0$ MPa). (a) Distribution of tensile and compressive stress. (b) Two reflective tensile cracks.

cracks in the numerical calculation are parallel to the loading direction. The reason for this discrepancy may be related to the presence of microcracks and the plane strain assumption.

4.4. Case IV. The maximum tensile and compressive stress increase, and the cracks propagate farther when the unidirectional in situ stress is continuously increased to 2.0 MPa, as shown in Figure 13. The maximum dynamic strain is $9.38E4 \mu\epsilon$. In addition to the crack observed in Case III, two reflective tensile cracks form along the direction of the unidirectional in situ stress loading. The reason for this phenomenon may be that the nonreflecting boundaries cannot completely absorb the reflected waves. The crack is still not observed in the vertical direction of in situ stress loading, further verifying that the in situ stress has a guiding effect on crack propagation. Xie et al. [21] indicate that the initial in situ stress has the effect of increasing the tensile

stress and reducing the compressive stress; that is, the initial in situ stress has the effect of inhibiting the development of radial cracks.

5. Conclusions

This paper examines the stress wave propagation through a single joint and multiple parallel joints under unidirectional in situ stress by laboratory experiments and numerical simulations. The crack propagation of the ZDF-3 electric spark source and blast-induced source in the jointed rock mass are compared. Key findings are summarized below:

- (1) We investigate the propagation and attenuation characteristics of stress wave, which are generated by a ZDF-3 electric spark on the larger-scale model with multiple cement mortar blocks. The attenuation laws of the transmitted strain wave are similar for a single joint and multiple parallel joints. The peak value of the dynamic strain decreases as the in situ stress

increases. Due to the increase of joint number, the dynamic strain of rock mass with multiple parallel joints is significantly less than that with a single joint. The in situ stress has a certain inhibitory effect on the stress wave propagation.

- (2) The crack propagation experiments in jointed rock masses under unidirectional in situ stress demonstrate the similarity between the ZDF-3 electric spark source and the blast-induced source. Whether the ZDF-3 electric spark excitation or the explosive excitation is used, a blasting crater appears at the bottom of the model. The blasting funnel body separates from the parent body in Model 1 but does not separate in Model 2. The ZDF-3 electric spark can be used as an excitation source in stress wave propagation. The in situ stress has a guiding effect on crack propagation, and an inclined deflection crack is formed on the upper surface of Model 2.
- (3) The crack propagation in the parent body of Model 2 is analyzed using the dynamic relaxation method of ANSYS/LS-DYNA. The numerical simulation results show that two parallel cracks are generated along the direction of the in situ stress loading, which is consistent with the phenomenon observed in the laboratory experiment. The numerical simulation further verifies that the in situ stress has a guiding effect on the crack propagation.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare no conflicts of interest.

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