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Numerical Study on the Dynamic Propagation Model of Cracks from Different Angles under the Effect of Circular Hole Explosion

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Abstract: A dynamic disturbance will induce cracks around the tunnel in tunnel blasting or shield construction. To investigate the overall stability of cracks with various angles during a fixed borehole (round hole explosion) blasting, models containing an individual crack with different angles were introduced for simulation research. The research set up a thin sheet model with a length of 350 mm and a width of 150 mm, with a 7 mm diameter hole and a pre-existing crack of 75 mm and 5 mm in the middle. The evolution of the stress wave propagation model and the crack propagation model were simulated using the AUTODYN software. And in this study, the theory of stress wave is used to creatively explain the dynamic load under the action of formation and reasons for the danger zone. The results indicate that pre-existing cracks from different angles will have an impact on the blast hole and the new cracks generated around itself. At 45–90°, pre-existing cracks will direct reflected stress waves to promote some cracks around the hole to have faster growth rates than others, and these special cracks with faster growths and longer lengths will more easily connect with the free surface or other cracks, resulting in overall instability. And these conditions are consistent with the prediction made by the stress wave propagation simulation study. The research results have certain guiding significance for the stability analysis and hazardous area prediction of tunnel blasting with existing cracks.

Keywords: P-wave; S-wave; Rayleigh wave; pre-cracks; crack propagation; dangerous area prediction

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1. Introduction

With the increasing demand for mineral resources and the booming development of infrastructure projects for high-speed and convenient transportation, excavation projects such as tunnels [1], mineral mining [2], and pipelines [3] have become increasingly frequent. Such construction projects usually occur in complex rock environments, where large rock masses are the main blasting objects for easy excavation and mining [4]. In a wide range of construction projects, the drilling and blasting method has become the main construction method to effectively control post-blasting disasters and provide effective guarantees for construction safety and quality. However, due to geological activities and induced excavation, the presence of joint planes [5] and cracks in large rock masses is common [6], as shown in Figure 1. In the Figure, the red arrows represent the load generated by the impact of blasting, the black lines represent the naturally occurring joints and cracks in the rock structure, and the white round holes represent the gun holes. These pre-existing cracks have a significant impact on the stability of the overall structure. In addition, under external interference such as blasting, new cracks occur and expand around the blast holes and pre-existing cracks easily, ultimately leading to overall structural instability, seriously delaying work and production progress, threatening the safety of relevant personnel, and

causing incalculable economic losses. Therefore, studying the impact of cracks in rocks on blasting has a profound significance on safe construction.

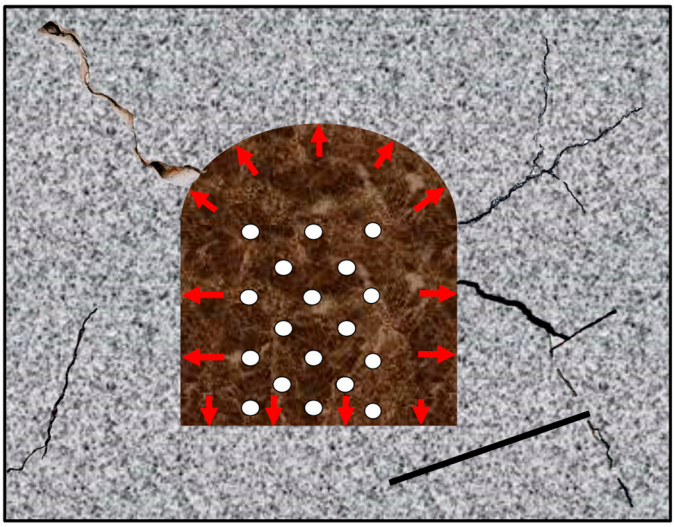


Figure 1. Schematic diagram of rock mass blasting with cracks.

In the past, most studies on excavation or mining have adopted the assumption of rock models without cracks. The advantage of this approach is that fewer factors affect the generation and propagation of cracks, making it easier to simulate. However, in recent years, more and more scholars have conducted research on this type of model with cracks. Suorineni et al. [7] stated that the presence of faults in rocks is an important factor that leads to overall instability. Freund [8–10] systematically studied the crack growth behavior under various dynamic loads and obtained some analytical results and conclusions, which confirmed that when subjected to blasting load, the cracks around the blast hole are more likely to generate new growth at the tip. However, because this process is affected by a complex environment, it is difficult to obtain a sufficiently accurate analytical expression. Moreover, under high-speed dynamic loads such as explosions, the interaction between the crack's tip and the dynamic stress field causes fluctuations in the crack propagation speed at the crack's tip [11]. Therefore, in response to the reasons that affect the initiation of tip cracks, some scholars [12] have studied the process of stress wave propagation and found that when the stress wave propagates to a static crack with two tips, it will scatter near the perturbed tip and reflect on the crack surface, forming a superimposed stress field, which is usually related to the incident angle. Additionally, based on such a model, Wheeler gives some analytical expressions for this field by using integral transform [13]. Regarding rock material models with cracks, some experimental explosion simulation studies [14] or theoretical summaries of rock materials [15] are based on the existence of a large number of natural structural joints or faults in the rock itself. Based on an experimental analysis and numerical simulation, Zhu [16] completed a study on the crack diffraction process using P-wave as an example and determined the influence of joint space and other factors on wave propagation. Uenishi [17] discussed the slope failure under the action of the Rayleigh wave, and the stress wave theory was adopted to analyze the model. Sun and Zhang used finite element models to study the effect of stress wave pairs on crack angles in the cited reference [18]. Zhou et al. [19] specifically studied the crack propagation mechanism of rock as an example material under different loading rates. Zhang et al. [20] specifically focused their research on actual coal mining and revealed the damage development process of this material using acoustic methods based on the spatial aggregation characteristics of cracks. They achieved good prediction and experimental fitting results. Zhou et al. [21] used a software simulation combined with physical experiments and found that compared to other fractured rock masses, the defect roadway with a single root crack and an inclination angle of 45° has the lowest static and dynamic stability. Li [22] also established a fractal damage

joint model based on the fractal damage theory, studied the transmission and reflection of stress waves between joints, and derived the analytical expression of the transmission and reflection coefficient of stress waves across joints from the fractal damage joint model. In Lak's study [23], a general Green's function solution of elastic wave propagation due to rock blasting was analytically derived. Navier's equations of motion were assumed as governing equations, and a general two-dimensional elastodynamic Green's function was obtained in terms of displacement. The strain and stress fields related to the displacement of Green's function were also obtained using the theory of elasticity. In 2021, Zhu et al. [24] conducted a numerical study on the dynamic behavior of stress waves in cracks, indicating that Rayleigh waves have a significant impact on the propagation and variation of cracks in all directions.

The above research is based on practical engineering experiments; due to the short overall time, it is difficult to analyze the propagation of waves after explosions based on the stress wave theory, and the influencing factors cannot be explored by changing a single variable in the same situation. However, based on numerical model calculation research, although models containing existing cracks were set up for research, there is no in-depth and regular research on the different states of crack existence. The field to which this type of problem belongs is almost blank and quite valuable because the brittle characteristics of rock materials can cause the original cracks to rapidly expand and connect under high loading rates such as explosive loads, and even generate huge cracks. The repeated loading of conventional explosive stress waves will cause cracks to continuously expand in a very short period, even leading to hazards such as rock bursts, slope instability, and tunnel collapse. In recent years, some studies have found that interconnected cracks have a significant impact on the dynamic response of deep engineering projects such as tunnels under blasting stress waves. The stress distribution around tunnels changes significantly due to the presence of cracks, leading to the initiation and propagation of new cracks. More importantly, one study found that the dynamic crack propagation behavior is influenced by the direction of blasting stress wave incidence [25].

The main objective of this study is to confirm the feasibility of the stress wave theory for predicting the location of the dangerous area around the gun hole under dynamic load. In this paper, the dynamic propagation behavior of new cracks and existing cracks in a single crack model with different angles around the blasting hole is studied. This study focuses on stress waves as the main research object, but it is evident that the network structure formed by cracks has a significant guiding effect on the propagation of stress waves. Therefore, to eliminate the influence of fragmented regions on the propagation direction, in simulation, the model at the same angle is simulated twice, with the same peak load applied. Regarding the specific methods of this simulation, the experimental setup is divided into two groups, which, respectively, study the propagation of stress waves and crack fragmentation. The model adopts an infinite plane and refers to the most widely used cylindrical explosives. As stress waves play a major role in the propagation process, they can be used to replace the waves generated by explosions [26]. Relevant research has shown that multiple identical cylindrical explosives can be simplified into a single blast hole [27]. The material point method is firstly applied to treat this challenging task by Wan, et al. [28] In this way, some inherent weaknesses can be overcome by coupling the generalized interpolation material point (GIMP) and the convected particle domain interpolation technique (CPDI). The two-dimensional properties of the stress waves generated can be directly calculated using specific functions [13]. Shu et al [29] present a novel constitutive model with three smooth failure strength surfaces and three invariants. The new model can precisely and quantitatively capture the damage mechanisms of hydrostatic pressure based on test data and the interaction of the tensile and shear damages based on the Mohr-Coulomb criterion.

Therefore, in view of the research gaps of many scholars at the present stage, this paper, on the basis of a large number of numerical simulations, takes the angle as the influencing factor of blasting instability and studies the influence of the existing angle on the crack growth around the hole, and creatively uses the stress wave theory to effectively predict

the dangerous area of the model. This study uses a numerical simulation to investigate the influence of the angle on the dynamic crack propagation behavior under stress wave action. The project uses AUTODYN's list of numerical analysis software, uses a triangle stress loading function to simulate blasting, establishes stress wave fields with cracks in different directions, and conducts detailed research on the dynamic propagation behavior of cracks and new cracks around the blast hole. Finally, in this numerical simulation, the stress wave theory is successfully used to analyze and predict the dangerous area after failure, proving that cracks ranging from 45° to 90° will induce characteristic cracks, which will accelerate the instability of the model.

2. Numerical Study

2.1. Determination of Sandstone Parameters

In this study, the numerical simulation is carried out based on the finite difference method, and the research object is divided into different sub-elements after grid division. The acceleration in the X and Y directions can be expressed as follows.

$$a_x = \frac{F_x}{m} \tag{1}$$

$$a_y = \frac{F_y}{m} \tag{2}$$

where F_x and F_y are the nodal forces in the x and y directions, respectively, and m is the mass.

The stress component can be expressed in the following form:

$$\sigma_i = P_i + S_i, \ (i = x, y) \tag{3}$$

$$\tau_{xy} = S_{xy} \tag{4}$$

where P is the external pressure, S_i is the deviatoric stress in the i direction, and there is a calculation relationship as follows

$$S_i^{n+1} = S_i^n + 2G\left(\dot{\varepsilon}_i - \frac{1}{3}\dot{e}\right)^{n+\frac{1}{2}}\Delta t, \ (i = x, y) \tag{5}$$

$$S_{xy}^{n+1} = S_{xy}^n + 2G\dot{\varepsilon}_{xy}^{n+\frac{1}{2}}\Delta t \tag{6}$$

$$\dot{e} = \dot{\varepsilon}_x + \dot{\varepsilon}_y \tag{7}$$

Here, G is the shear modulus of the material and $\dot{e}$ is the volume rate of the material.

For materials, the relationship between the pressure P and density described in the linear equation of state is

$$P = k \cdot (\frac{\rho}{\rho_0} - 1) \tag{8}$$

where P is pressure, k is the bulk modulus, k = 4.04 GPa, and ρ and ρ_0 are the initial and present densities. Here, as sandstone is a brittle rock material, the relationship between stress and strain during deformation can be studied using an elastic strength model.

At the same time, the experimental research is based on to the first strength theory and the third strength theory. If either the principal stress σ_1 reaches its maximum (σ), or the maximum shear stress τ_{max} is greater than the rock dynamic shear strength (τ), the material fails.

Here, a sound wave velocimeter is used to measure the dynamic material parameters of sandstone, as shown in Figure 2. It has two piezoelectric ceramic terminals, the transmitting end can emit waveform signals, and the receiving end can receive signals. According to the geometric configuration of the S-wave and P-wave, the relevant parameters of the material can be calculated by the time when the P-wave and S-wave pass through it.

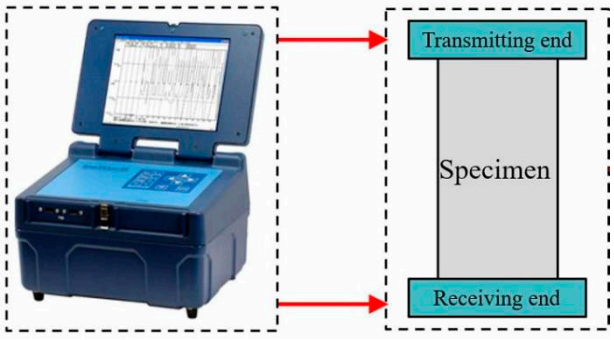


Figure 2. An acoustic velocimeter (Sonic Viewer-SX).

In this paper, the dynamic elastic modulus and dynamic Poisson's ratio of the rock materials are calculated by testing the expansion wave velocity V_p and shear wave velocity V_s of the material, as shown in Table 1. The calculation formula is shown in Equations (9) and (10). This paper adopts a rock sample ultrasonic tester to obtain the measurements of V_p and V_s, and the working principle of the instrument is shown in Figure 2, which consists of a high-voltage pulse transmitter, a receiver, and a converter. The test of the two wave speeds of the material is obtained in accordance with the provisions of the International Society of Rock Mechanics for 100 mm × 50 mm cylindrical specimens, and a total of five tests are prepared to obtain their average values.

Table 1. Parameters of sandstone used in this study.

Material	Density Kg/m^3	Bulk Modulus GPa	Elastic Modulus GPa	Poisson Ratio	V_s m/s	V_p m/s
Sandstone	2380	9.4624	17.60	0.19	2549.4	1459.2

If the velocities V_p and V_s of the P-wave and S-wave are taken into the following equation, the elastic modulus and Poisson's ratio of the material can be acquired.

$$V_p = \sqrt{\frac{E_d(1-\mu_d)}{(1+\mu_d)(1-2\mu_d)\rho}} \tag{9}$$

$$V_s = \sqrt{\frac{E_d}{2(1+\mu_d)\rho}} \tag{10}$$

$$E = \frac{\rho {V_p}^2(3{V_s}^2 - 4{V_p}^2)}{{V_s}^2 - {V_p}^2} \tag{11}$$

$$v = \frac{{V_s}^2 - 2{V_p}^2}{2{V_s}^2 - 2{V_p}^2} \tag{12}$$

where ρ is the density of sandstone, E is the dynamic elastic modulus, and μ is the Poisson ratio.

2.2. Establishment of Numerical Model

The numerical model is shown in Figure 3, which is a rectangular board with a length of 350 mm and a height of 150 mm. We set a hole with a radius of 7 mm to simulate a blast hole and generate cylindrical waves. The distance from the center of the hole to the left boundary is 55 mm and is the same from the center to the top edge. On the right side of the hole, there is a crack with an angle of θ with a length of L.

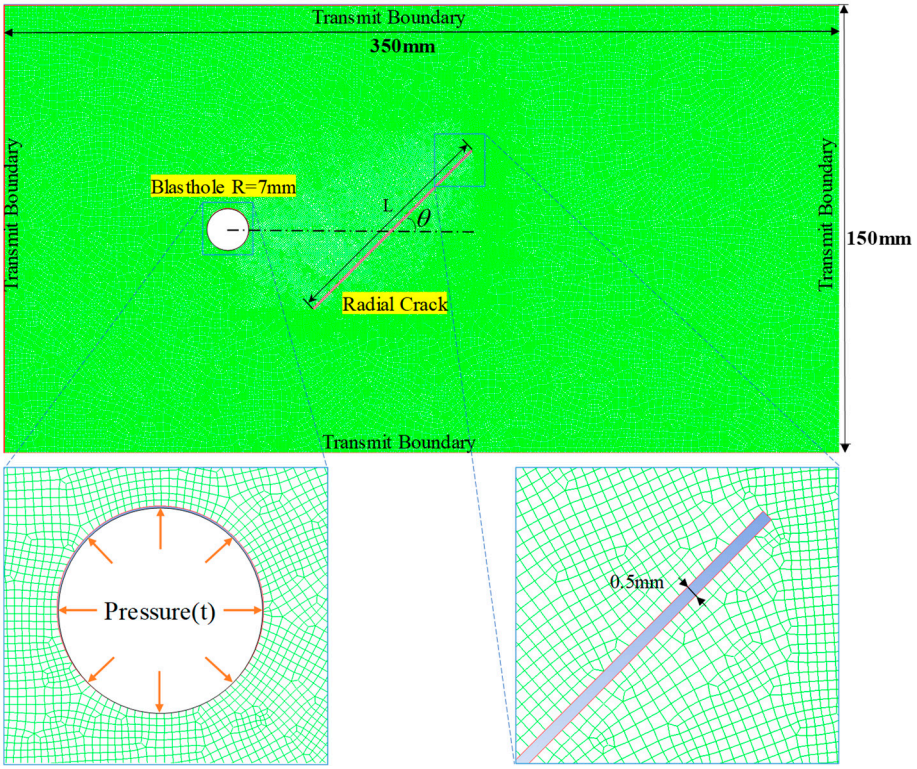
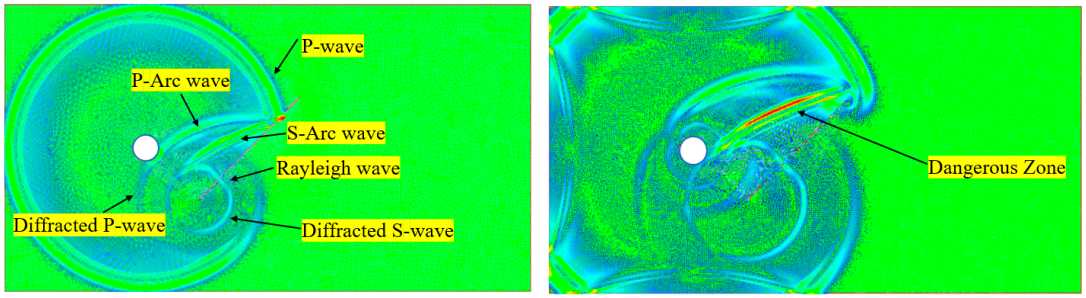


Figure 3. Numerical model.

Considering that the object of this study is deep rock, it can be approximated as an infinite rock plane, but the modeling scope is limited. So, when establishing the model, the boundary is set to transmit boundary, so that the stress waves generated by the blasthole at the boundary will not have any effect on the reflected waves in the subsequent process, greatly reducing the impact of tensile and compressive waves in the reflected P-wave on the model research. This can transform the research object from a finite model to an infinite region.

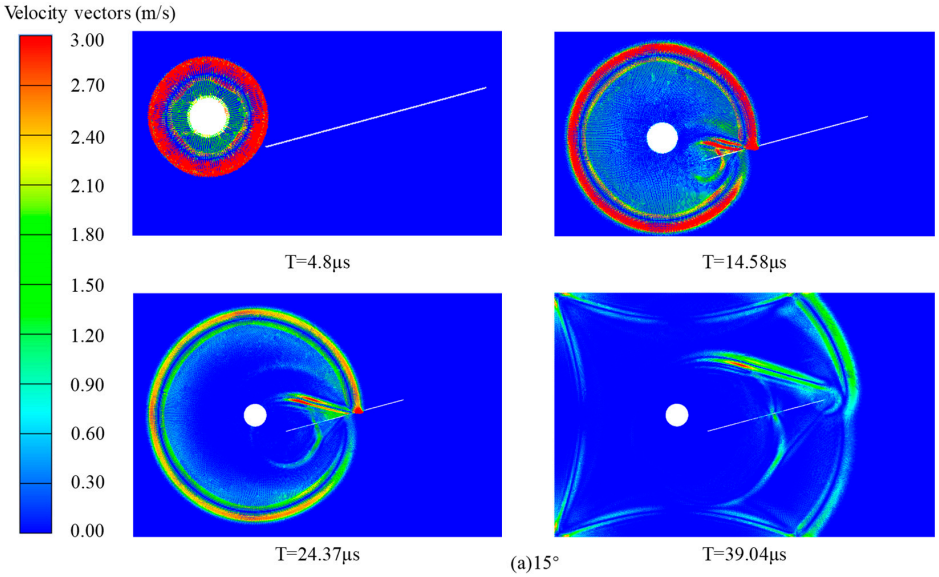
Taking the model with θ = 45° and L = 75 mm as the first exploratory research example, the velocity vector excited by stress waves was collected as shown in Figure 4. We set the loading condition to a peak of 50 Mpa with a loading time of 2 μs. The advantage of designing such a shorter wavelength is that it creates a good separation between different waves, making it easier to study the propagation and characteristics of different waves. By observing the images, it was found that both the P-wave and S-wave of the stress wave diffracted near the crack, especially when observed in the vector plots. And the P-wave and S-wave diffracted by excitation have different effects on the side of the crack near the blast hole and the side away from the blast hole. On the side that is the farther from the explosion hole, due to diffraction, the conventional diffraction P-wave and S-wave are generated, and the conventional lower Rayleigh wave propagates along the direction of the crack. On the side near the blast hole, due to the tensile wave inside the P-wave, its reflected wave propagates together with the diffracted P-wave, forming the first P-arc wave with stress concentration. The diffraction and reflection of the S-waves are mainly composed of shear waves that combine to form a second S-arc wave with stress concentration. It is worth mentioning that the two newly generated arc-shaped waves have the same properties as the diffraction wave at the tip that generates them, namely, the P-arc-shaped wave is also a tensile wave, and the S-arc-shaped wave is also a shear wave. However, the reflection wave still plays the main role in the two types of arc waves, so in future research on crack initiation, only the reflected wave can be considered as the main factor.



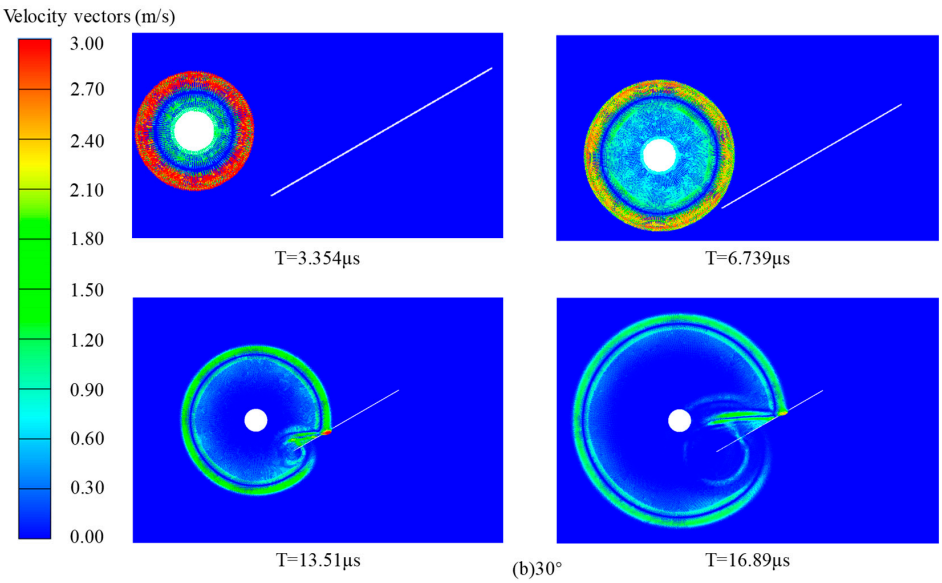
(a)T=28.31μs (b)T=38.95μs

Figure 4. Stress-wave-induced particle velocity vectors.

After the above operations, in this study, the distance from the crack's center to the center of the circular hole is called the center distance, and the fixed center distance is 55 mm. The crack is rotated to change the angle for multiple sets of numerical model research, as shown in Figure 5.



(a)15°



(b)30°

Figure 5. *Cont.*

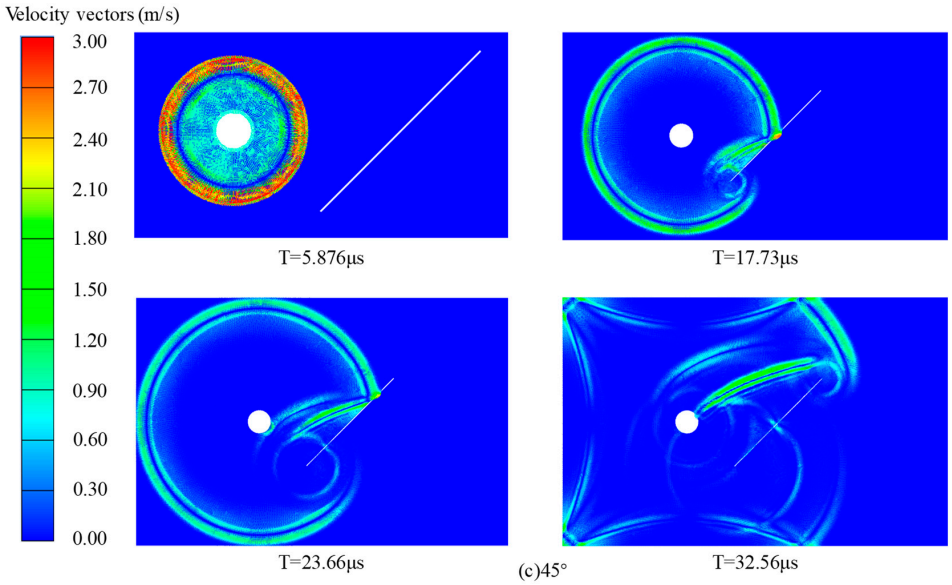


Figure 5. Reflection and propagation of stress waves at different angles.

As the angle increases, it can be observed that the Rayleigh waves on both sides of the crack, which play a dominant role in horizontal cracks, no longer become the main factor affecting the crack. At the same time, the arc wave formed by the combination of reflected and diffracted waves on the side of the crack passing through the blast hole becomes a high-stress concentration area. As the crack angle increases, the effect of the arc wave on the generation of the crack is enhanced.

For this phenomenon, we compare the contours of MIS.STRESS at the exact moment when the P-wave propagates to the far end of four different inclination cracks, as shown in Figure 6. It can be observed that in the first set of simulations at 0–30°, the main stress generated by the arc wave is significantly enhanced, but in the second set of simulations at 45–75°, the intensity of this effect decreases significantly.

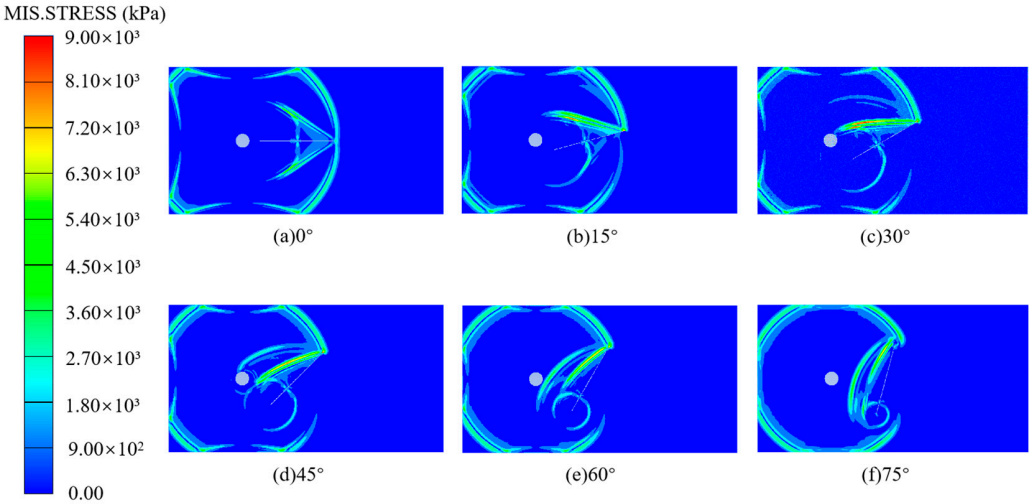


Figure 6. Contours of equivalent principal stress induced by stress waves.

For this phenomenon, the research subjects were divided into two groups for in-depth exploration. For the first group from 0° to 45°, as shown in Figure 6, as the crack inclination angle increases, the reflection wave of the composite-generated arc wave is significantly enhanced, resulting in a high-stress region. For the second set of simulations from 60° to 75°, after studying the velocity vector induced by stress waves at 60°, it was found that due to the large inclination angle, the reflected arc-shaped waves were reflected again at the

borehole, reducing the effect of the arc-shaped waves located at the back, and ultimately directly reflecting the moderate effect of the main stress reduction in Figure 6. The schematic diagram of stress waves is shown in Figure 7.



Figure 7. Schematic diagram of stress wave propagation attenuation under inclination angle in the second simulation.

At the same time, by comparing the distance between the stress concentration area in the two stages and the near end of the crack when the P-wave just reaches the far end, it can be found that the distance simulated in the second group is greater than that in the first group. At the same time, because of the same loading conditions, compared with the first group, there is a longer near end distance, and the initial amplitude of the diffraction wave also decreases, which means that in the second group, the far end and the near end may not be easy to crack.

3. Dynamic Response Behavior of Cracks and Explosive Holes under Dynamic Impact

For the sandstone material used in this experiment, considering the occurrence and propagation of cracks in the material under conventional conditions, the maximum principal stress failure criterion is used to evaluate the material unit state, as shown below:

$$\sigma_1 < \sigma_T \tag{13}$$

σ_1 is the major principal stress in every element, and σ_T is the tensile strength of the sandstone material, with its value being 75 MPa. When σ_1 exceeds σ_T for an element, it will fail and cannot stand any tensile stress but can continue to be compressed.

For the dynamic load loading caused by a single blasting, a triangular curve function is used, with a total loading time of 20 μs. At 10 μs, the peak load reaches 50 MPa, as shown in Figure 8. The advantage of this is that it simplifies the calculation, focuses on the main role of the explosion load, and eliminates the influence of unimportant factors on the set conditions.

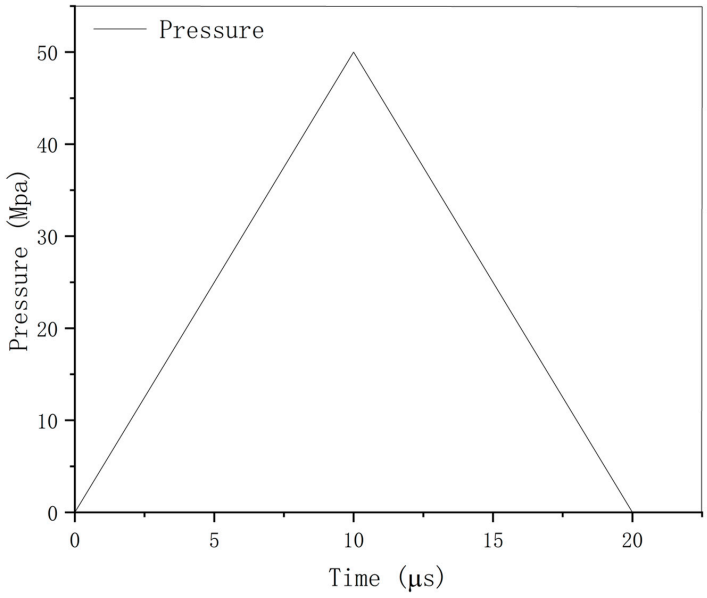


Figure 8. Pressure–time curve.

3.1. Packet Simulation

The loading curve of the simulation experiment is shown in Figure 9. The center distance of the fixed model is 35 mm, and the included angle with the horizontal plane starts from 0°. One study sample is taken every 15° until 90°. There are seven models in total, which are used to explore the impact of multi-angle problems on the crack growth behavior.

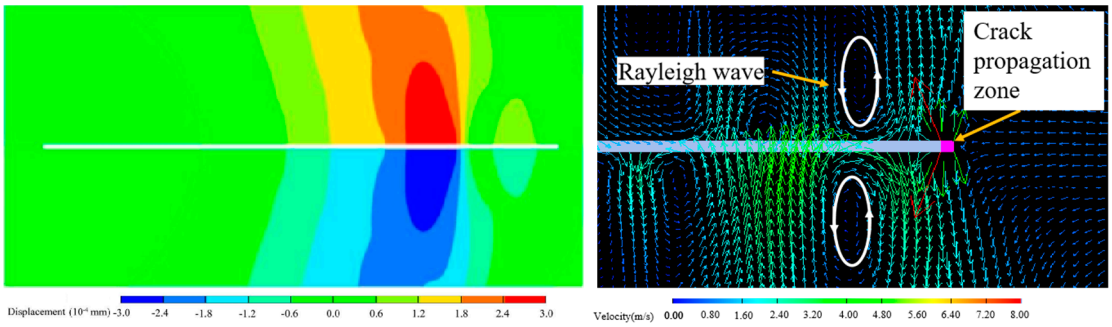


Figure 9. Cracking at the crack's tip under the action of Rayleigh waves.

3.1.1. Crack Inclination Angle = 0°

When observing the propagation characteristics of waves at 0°, due to the small geometric characteristics of cracks, there is almost no tensile or shear effect at the near end. At this point, the dominant factor causing the crack is reflected in the Rayleigh wave after the head wave. Due to the inherent nature of the Rayleigh wave, it will propagate on the surface of the crack, forming two vortex-shaped fields above and below, resulting in a displacement trend of separation between the upper and lower parts, as shown in Figure 9a. Ultimately, it will only propagate at the distal endpoint, as shown in Figure 9b.

3.1.2. Crack Inclination Angle = 15–45°

However, for 15°, 30°, and 45°, as shown in Figure 10, under similar conditions of blasting hole fragmentation, significant cracking occurs at the near end, and even connects with the cracks around the blasting hole, completely destabilizing the model. The cracking behavior at this point can be divided into two parts; the first part is the cracks around the blast hole, and the second part is due to the promoting effect of the existing cracks, resulting in the main crack, which is characterized by narrower and fewer branches compared to the surrounding cracks, and it may become the main cause of the overall instability. This part is further studied in the following text.

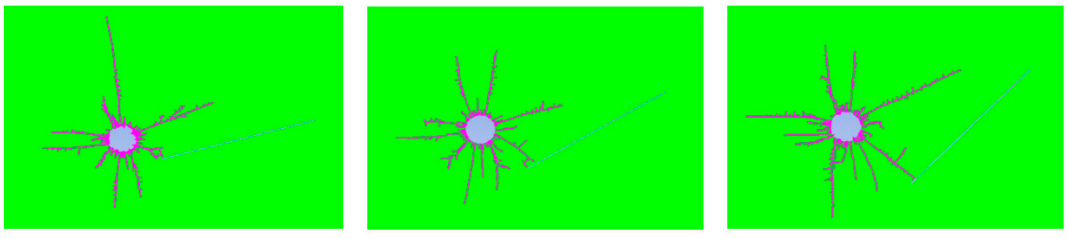
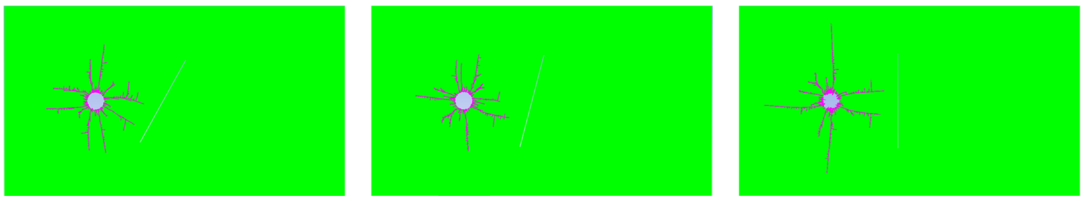


Figure 10. Crack propagation state generated at 15–45°.

The above phenomenon was explained in the first part, and the simulation results above well reflect the influence and results of the stress wave amplitude as the main factor for generating cracks on the cracking behavior of existing cracks, proving the reliability of the previous research and analysis results on waves.

3.1.3. Crack Inclination Angle = 60–90°

At this stage of inclination, the distance between the near end of the crack and the blast hole is relatively far, and the amplitude of the diffraction stress wave generated at the near end of the crack decreases. Moreover, due to the effect of the reflected wave, the effect of the Rayleigh wave is significantly reduced, so there is no cracking behavior at both ends of the crack. And due to the discovery of secondary reflection caused by blast holes in wave research, the reflection wave effect will decrease. At this time, the density of the cracks generated around the blast holes is significantly lower than the density of the cracks around the blast holes with crack angles ranging from 15° to 45°, as shown in Figure 11, which is also in line with the predicted effect.



(**a**) θ = 60°, T = 50.87 μs (**b**) θ = 75°, T = 41.21 μs (**c**) θ = 90°, T = 99.12 μs

Figure 11. Crack propagation state generated at 60–90°.

At this point, it can be observed that the cracks generated by the blast hole on one side near the existing crack have more branches compared to the cracks on the other side, which is consistent with the possible effect of shear waves reflected between the blast hole and the crack as the main cause of cracking, which was analyzed earlier.

3.2. Research on the Influence of Waves Generated by Cracks on the Initiation of Explosive Holes

In the above research, it can be found that compared to existing cracks, the characteristics of the newly generated main cracks around the blast hole are quite obvious and have certain characteristics due to the reflection and diffraction effects of the corresponding stress waves of the pre-existing cracks.

Firstly, by simulating the crack-free model, it can be found that the crack propagation around the blast hole has a high degree of symmetry, and after extending to a certain extent, there will be many bifurcations at the end, as shown in Figure 12.

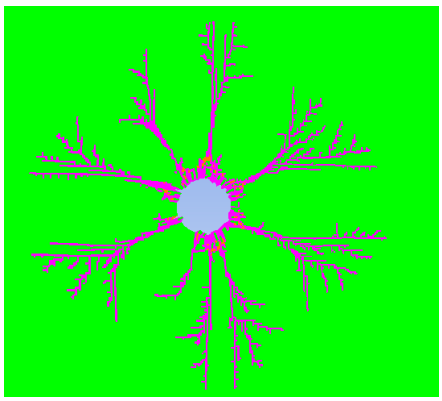


Figure 12. Model without cracks.

By comparing the simulation of the crack-containing model with the crack-free blast hole model, it can be found that in the crack-containing model, there is a narrow and less branched characteristic crack in the upper and lower positions of the blast hole that are approximately parallel to the crack, as shown in Figure 13. However, in the simulation, the generation and propagation behavior of new cracks are only affected by the diffraction of the tip and the reflection of the wave. In this process, the reflection wave plays a major

role. Therefore, it can be considered that the interference of the reflection wave causes the generated cracks to become more narrow. In this study, the characteristic cracks with narrower and fewer branches are also known as the main cracks in the blast hole that are induced by the reflection wave (hereinafter referred to as the main cracks).

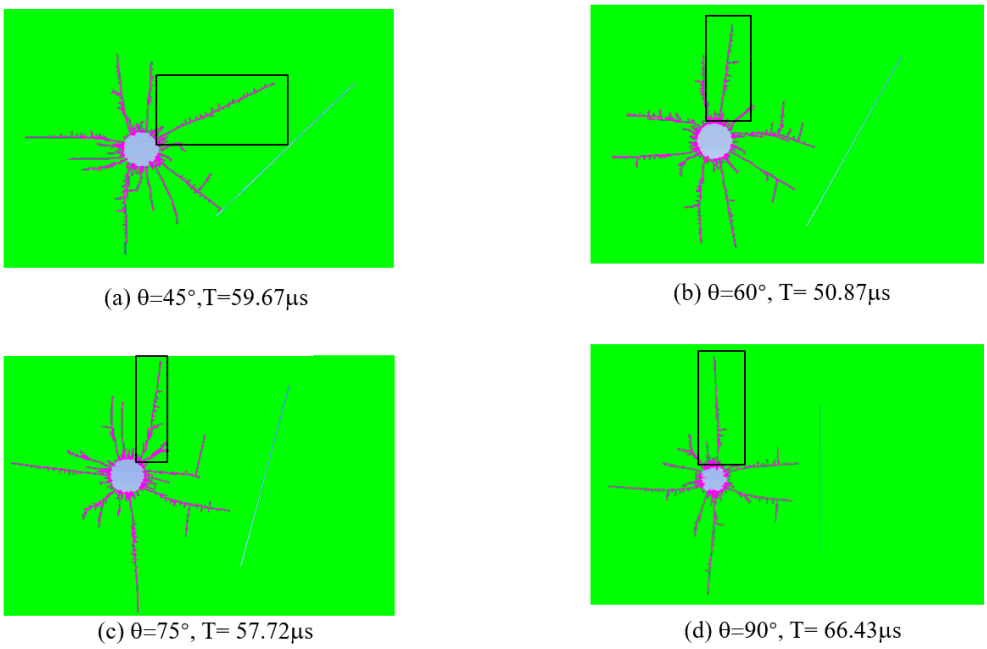


Figure 13. Main crack under different angle crack models.

By comparing the length of the cracks around the blast hole near the end of the crack propagation in the 45° to 90° simulation experiment, it can be observed that the main crack has a longer propagation distance compared to the other cracks, indicating that the main crack may be the main cause of instability. In conventional underground engineering, cracks with a longer or faster growth rate will obviously be more easily connected with the surrounding free surface or other cracks, which will lead to local crushing and instability.

At the same time, the data image of the main crack propagation length changing with time at the same angle is shown in Figure 14.

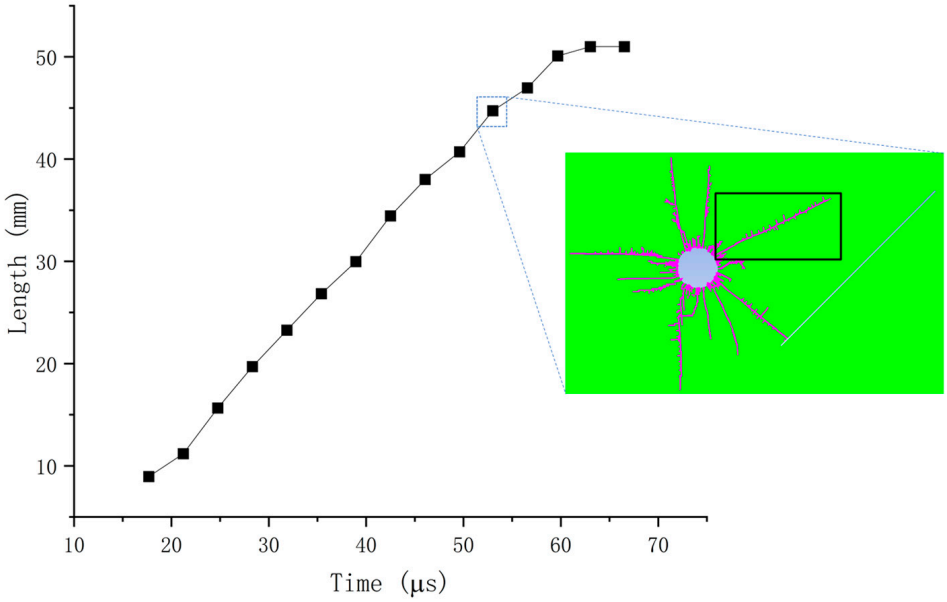
The study of the stress wave propagation in the first part found that at around 30 μs, the length of the main crack is similar to that of the surrounding crack, and even shows an approximate length in various angles of the model. Therefore, it can be considered that the process before 30 μs did not promote the propagation of cracks around the borehole, and the generation of cracks was caused by the stress wave of the initial load.

In the 45° model, the propagation speed of the main crack can be roughly calculated to be about 0.7 mm/μs from 0–30 μs, and the reflection wave begins to affect the main crack after 30 μs. At 30–40 μs, the average propagation speed of the crack is about 1.1 mm/μs, while at 40–50 μs, the propagation speed decreases to about 1 mm/μs, and even to about 0.89 mm/μs at 50–60 μs. This phenomenon indicates that in the 45° state, the reflected wave has a significant promoting effect on the main crack, resulting in a faster propagation rate compared to the initial stress wave load.

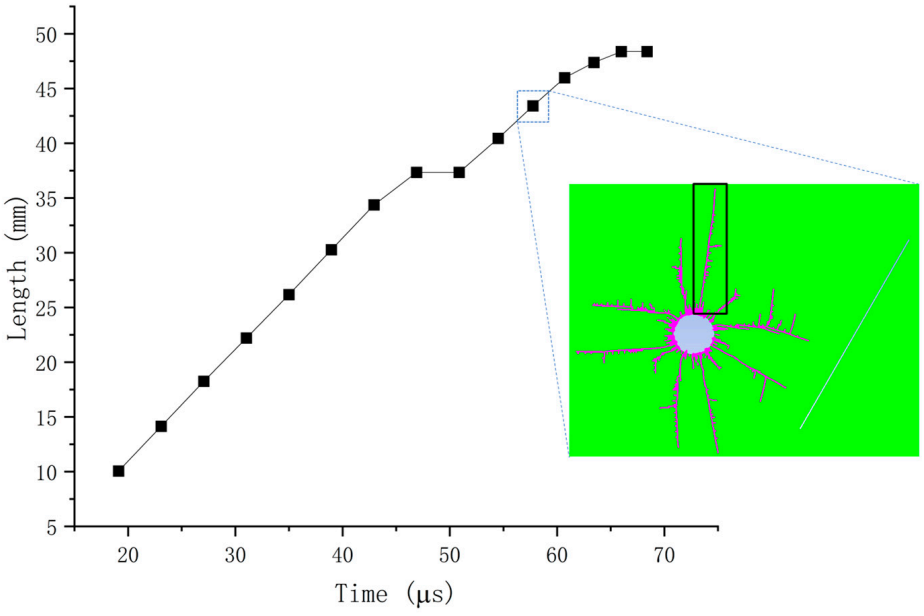
Moreover, by calculating the main crack propagation rates at different stages of 30–60 μs in Figure 14b–d, it can be found that after being affected by the reflected waves, the average propagation rate of the cracks is the highest during the period of 30–40 μs, and then gradually decreases at 40 μs. This phenomenon is common. This indicates that cracks with an inclination angle greater than 45° around them will significantly promote the propagation behavior of cracks that are approximately parallel to the blast hole and cracks.

This study also studied and calculated the 0–30° crack model and found that it also had a promoting effect on newly generated cracks at similar positions in the blast hole.

However, it may be due to the small angle, the formation of fragmented areas, and new free surfaces around the blast hole, which will change the propagation path of the wave. The promoting effect of the reflected waves is not significant, and it is difficult to form parallel or regular positional relationships with pre-existing cracks, which is why this is not included in the above discussion.

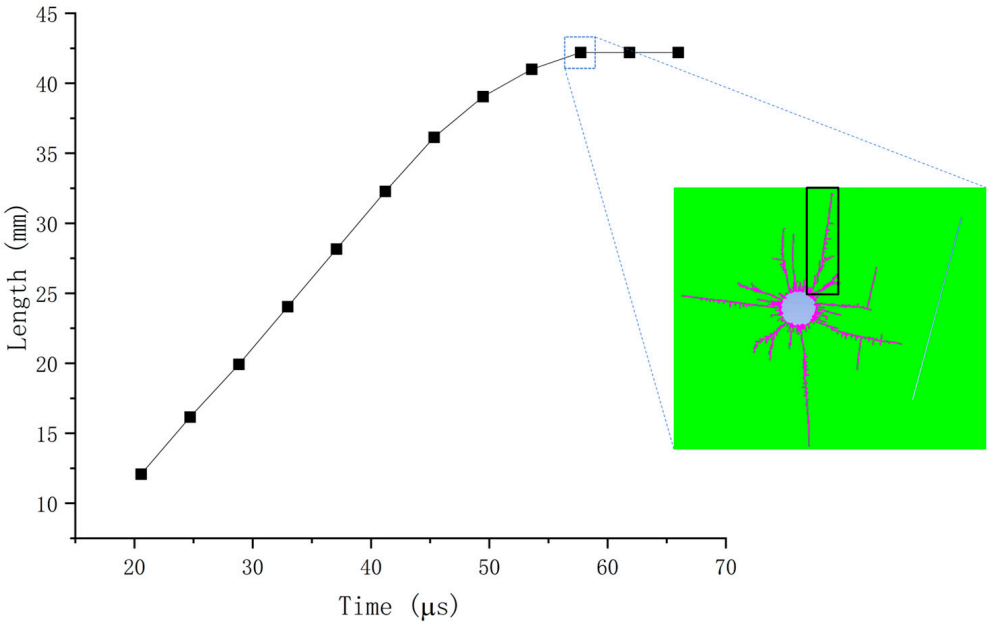


(**a**)

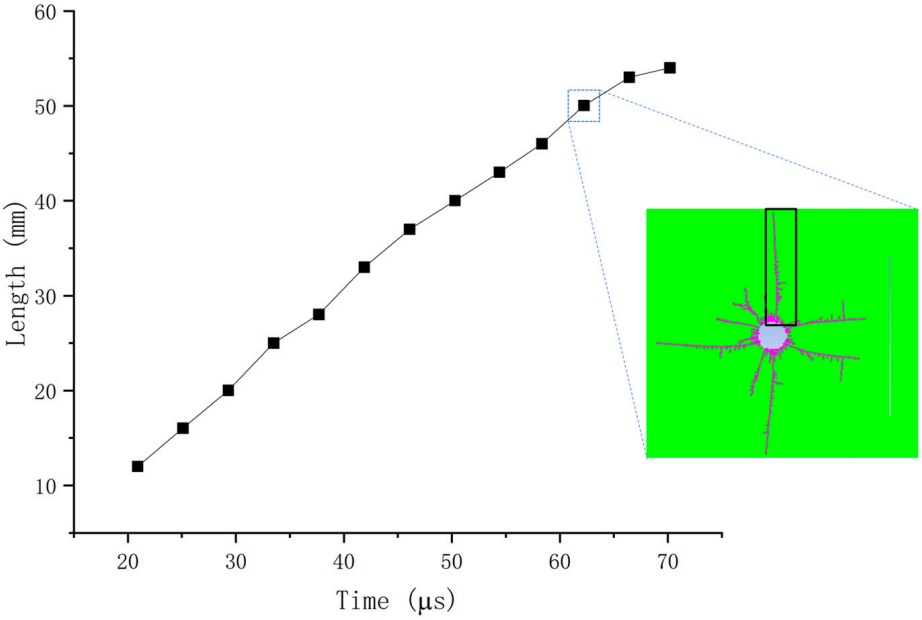


(**b**)

Figure 14. *Cont.*



(**c**)



(**d**)

Figure 14. Models with main crack propagation and length–time curve; (**a**) 45°, (**b**) 60°, (**c**) 75°, (**d**) 90°.

4. Conclusions

The purpose of this paper is to use the stress wave theory to study the dynamic propagation mechanism of the crack and the influence law of the dangerous area from the perspective of the precast crack, and to predict the possible dangerous area in the model with the help of the wave propagation.

In terms of innovation, this study is based on the model of rock models with cracks in a large number of excavation and construction projects. On the one hand, the stress wave theory is considered to study the dynamic load conditions, and on the other hand, the crack propagation of prefabricated crack models with different inclination angles is studied in groups. Finally, the following conclusions are obtained:

(1) The action of the impact load causes the crack and the expansion of the crack behavior and hole around a pre-existing crack angle.
(2) The stress wave theory can predict the crack propagation behavior under the ideal condition of the example in this paper, and has a good fit with the final crack propagation results.
(3) When the inclination angle of the existing crack is 0–45°, the equivalent principal stress effect generated by the reflected wave is enhanced, and it is easier to form a dangerous area of high stress in the area near the crack hole. At 60–90°, the equivalent principal stress is reduced due to the secondary reflection of the reflected wave at the borehole position, and cracking behavior is less likely to occur at the far and near ends of the fracture. At this time, fracture behavior mainly occurs around the hole, and only a few cracks have a high propagation rate.
(4) The reflected wave is the main cause of the crack, followed by a shear wave; compared with the other side of the crack, the reflected wave may lead to more branches near the burst crack, forming a fracture area.
(5) The reflected waves generated by the presence of cracks at different angles will promote the propagation of cracks around the blasting hole. The crack with an angle of 45–90° has a particularly significant effect on the expansion rate of nearly parallel cracks (main cracks) around the blasting hole. Such rapidly expanding cracks will be more easily connected with the free surface or surrounding cracks, which may be one of the main reasons for regional instability.

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List of Notations

a_x acceleration in the x direction
a_y acceleration in the y direction
F_x force in the x direction
F_y force in the y direction
σ_i stress in the i direction
P_i external pressure in the i
S_i directiondeviatoric stress in the i direction
G shear modulus of the material
$\dot{e}$ volume rate of the material
ε_i strain in the i direction
k bulk modulus of the material
ρ initial density
ρ_0 present density
V_p expansion wave velocity of the material
V_s shear wave velocity of the material
E_d dynamic elastic modulus
μ_d dynamic Poisson ratio

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