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Research and application of a symmetric bilinear initiation system in rock blasting

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1. Introduction

In tunnels excavation, mining, road, and nuclear power station construction, drilling and blasting are generally the most prevalent methods despite the rapid development in the application of mechanical excavators, particularly in hard rock formations.[1,2] Safer and faster rock blasting excavation rates are possible with the rapid developments in explosives and automatic drilling systems. However, in conventional detonator initiating blasting, there often exists overbreak, underbreak, and larger rock fragment size due to the influence of the explosives properties. These issues also increase the cost of secondary crushing, adversely affect excavating machine and slagging, and even potentially affect the project schedule.

Rock properties, explosives performance, blasting parameters, and initiating system directly decide the blasting effect.[3,4] However, it is very difficult to obtain a satisfactory blasting result by simply changing the blasting design parameters. Therefore, seeking a new initiation system or charge structure will be the most effective way to improve the explosive energy utilization rate in order to change the detonation wave distribution in rock blasting, which will create the most effective initial crack and decrease the size of the rock fragmentation. In this study, a novel method of symmetric bilinear initiating system (SBI) was proposed to create converging detonation wave collision. This novel method does not need to use the shaped cover nor concavity, which not only avoids material waste, but the operation is also simple and can be used in the water hole blasting. Also, the amount of explosive loaded into the hole is also increased and is more suitable for blasting engineering with large clamping force.

2. Detonation wave collision theory

In the symmetric bilinear initiating system, the detonation wave will occur successively as first normal collision, then oblique reflection, and finally Mach reflection. According to the conservation equations of mass, momentum, energy, the Chapman-Jouget conservation conditions and the wave reflection law, the ratio of the normal collision pressure p_1 to the Chapman-Jouget detonation pressure p_H can be calculated as following equation[5]:

$$\frac{p_1}{p_H} = \frac{5k + 1 + \sqrt{17k^2 + 2k + 1}}{4k} \tag{1}$$

Where, k is the adiabatic index.

We assumed that the reflection configuration is as shown in Fig. 1. The solid wall surface will form a reflected wave (OR) when the incident wave (OI) is oblique to the incident solid wall at an incident angle φ. According to the detonation wave oblique reflection theory, the relation of incident angle φ, deflect angle θ, and adiabatic exponent k can be calculated as:

$$\tan\theta = \frac{\tan\varphi}{k\tan^2\varphi + k + 1} \tag{2}$$

When the detonation wave reaches the collision point O, the incident wave (OI) tangential components deflects at an angle θ from its original direction. The flow of the detonation product is then obstructed by the solid wall, and a reflect wave (OR) is generated on the solid wall. Its flow direction q_0 is again the deflected angle θ when the detonation product passes through the reflect wave (OR), so that the flow again

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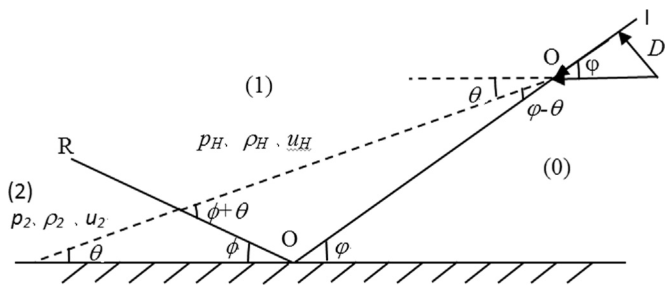

Fig. 1. Schematic diagram of the detonation wave oblique reflection in Coordinate. (0)-Initial state of explosive; (1)-Steady state of detonation; (2)-Reflected shock front.

becomes parallel to the line of the collision.

According to the mass and momentum conservation, and the detonation equation of state, the relation between the incident angle φ and the reflect angle ϕ can be deduced as:

$$\frac{\tan\phi}{\tan\left(\phi+\arctan\left(\frac{\tan\varphi}{k\tan^2\varphi+k+1}\right)\right)} = \frac{k-1}{k+1}+\frac{2k^2}{k+1}\cdot\frac{1}{[k^2+(k+1)^2\cdot\cot^2\varphi]\cdot\sin^2\left(\phi+\arctan\left(\frac{\tan\varphi}{k\tan^2\varphi+k+1}\right)\right)} \tag{3}$$

The ratio of the oblique collision pressure p_2 to the Chapman-Jouget detonation pressure p_H is as follows:

$$\frac{p_2}{p_H}=\frac{(k-1)\tan\phi-(k+1)\tan(\phi+\theta)}{(k-1)\tan(\phi+\theta)-(k+1)\tan\phi} \tag{4}$$

Assuming that the adiabatic index k is 2.42, substituting into Eq. (3) and Eq. (4), which can be obtained the relationship curve of reflection angle ϕ and deflection angleθ, as shown in Fig. 2.

Fig. 2 shows that the deflection angle θ increases and then decreases with an increasing incident angle φ, while the reflection angle ϕ increases with an increasing incident angle φ. However, an imaginary solution occurs when the incident angle φ is greater than 46.4°. In physics, this is meaningless, and the oblique shock wave reflection theory can be described as the reflected wave falling off from a solid wall. The phenomenon was first discovered by Mach, so named Mach reflection.[6]

According to the Mach reflection theory and the three conservation law, the ratio of the Mach reflection detonation pressure p_3 to the Chapman-Jouget detonation pressure p_H can be conducted as follows[7]:

$$\frac{p_3}{p_H}=\frac{1}{\sin^2\varphi}+\frac{1}{\sin\varphi}\left(\frac{1}{\sin^2\varphi}-\zeta\right)^{1/2} \tag{5}$$

Where, ζ is the ratio of the specific chemical energy release of the explosive which passes through the Mach stem to that of which goes through the Chapman-Jouguet detonation front. It is usually value between 1.0 ~ 1.2. For $\zeta = 1$, we can draw the curve of p_3/p_H and incident angle φ as shown in Fig. 3. The Mach reflection detonation pressure p_3

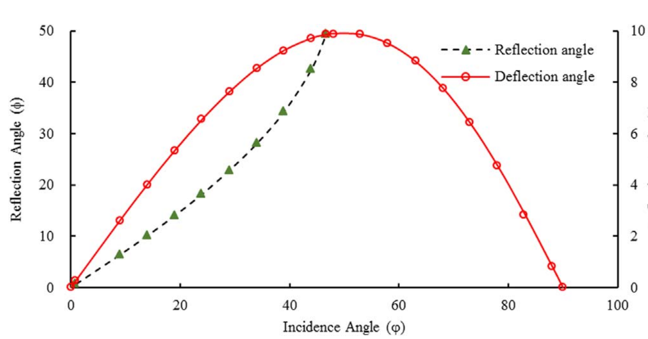

Fig. 2. Detonation wave oblique reflection angle relationship.

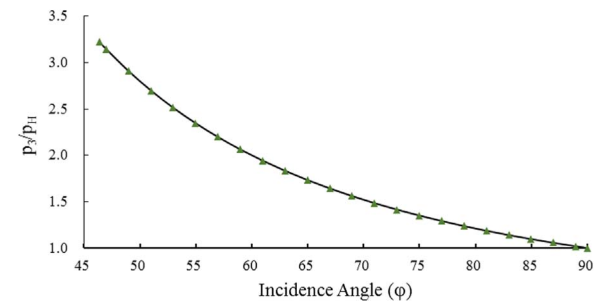

Fig. 3. Detonation pressure increase ratio of Mach reflection.

sharply increases to more than three times that of the Chapman-Jouget detonation pressure p_H, then decreased gradually with the increase of the incident angle φ, eventually decaying to the detonation wave.

3. Numerical simulation research

Many numerical studies on the process governing rock fracture and fragmentation during rock blasting have been conducted.[8–10] In the present study, the fluid-solid coupling model was integrated through user-subroutines into the commercial software LS-DYNA[3d], which is a dynamic, non-linear finite program. To form a contrast test, two types of initiating methods were designed: (1) Central detonator initiating system (CDI), initiating from the center of the charging with a detonator, which simulates the conventional blasting, as shown in Fig. 4a; (2) Symmetric bilinear initiating system (SBI), initiating the main charge with two symmetrical arrangements detonating cord, which forms the detonation wave collision, and to achieve the purpose of the energy converging, as shown in Fig. 4b.

Comparing the simulation of the above two cases. When CDI is used, the detonation wave starts uniformly from the initiation point and extends toward the edges, and it spreads to the borehole wall at t = 7.98 μs (Fig. 4c). At this point, it starts to produce damage to rocks, and damage towards rocks surrounding the hole-wall. Subsequently, the cracks expand in the direction perpendicular to borehole (Fig. 4e). However, when using SBI, the detonation wave starts to spread from the symmetric boreholes initially. Collision occurs at the center line when t = 7.95 μs (Fig. 4d), and the wave starts to spread towards both sides as oblique detonation waves with high detonation pressure, and spreads to the borehole wall. When t = 27.99 μs, cracks appear around the boreholes, but a large diameter crack will initially be generated at the symmetrical center line and then spreads outwards (Fig. 4f), indicating that SBI can change the explosive's energy distribution on rocks.

In order to investigate the explosion energy distribution in detail, Fig. 5 shows the maximum detonation pressure at the borehole with two different initiation methods (CDI and SBI). The detonation pressure at the borehole using SBI can upwards of 13.5 GPa, which is far more than the upper limit of 4.26 GPa using CDI. The results shown that SBI can change detonation pressure distribution of the borehole wall, achieve the purpose of detonation wave collision and detonation pressure increase that is needed for hard rock or high clamping force blasting.

4. Rock fragmentation crack tests

Several relevant studies on the extraction and observation of cracks formed during rock blasting have previously been completed.[11–13] However, the crack propagation tests were mostly performed in the laboratory, which always tends to be limited by the amount of explosive charge allowed. Because SBI uses two symmetrical arrangements detonating cord, the effect of the detonating cord on the energy of the explosive cannot be neglected in the laboratory test. To avoid the effect of the detonating cord and intuitively respond to the effect of SBI