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A study of smooth wall blasting fracture mechanisms using the Timing Sequence Control Method

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ABSTRACT

High quality of cracking and low depth of damage in sidewall is usually required in a blasting excavation. On the contrary, large spacing of blast holes can efficiently reduce cost. Therefore Timing Sequence Control (TSC) Method can be applied, so as to meet the challenge. In the TSC method, there is a very short delay between two adjacent blast holes, i.e., the Primary borehole (PBH) and the Target borehole (TBH), in sequence. Study of the cracking process around adjacent borehole indicates, larger stress concentration on the hole wall, if the TBH initiates after the stress wave from PBH has past it. The initial crack generated on the TBH is most likely to occur along the direction of borehole attachment.

Our study also shows that, keeping the borehole spacing and borehole diameter as constant, a through crack can be formed between the adjacent boreholes when the delay time, spacing of PBH and TBH, and transverse wave velocity obey a certain relationship. Keeping the hole spacing between PBH and TBH, borehole diameter and the delay time for PBH and TBH as constant, borehole through cracks between the adjacent boreholes can be formed only when the spacing of TBH equal or below 25 times of borehole diameter.

1. Introduction

At present, the method of blasting is usually implemented for rock excavation in projects related to water resources, hydropower engineering, traffic engineering, mining and nuclear power infrastructure. Although blasting is economical and efficient, it will inevitably cause disturbance and damage to nearby rock mass while breaking of rock mass and throwing broken stones. Especially for some important structures with high importance of surrounding rock, such as the rock anchor beam of an underground powerhouse in hydraulic tunnel, although the technology of smooth blasting is adopted on its contour line, explosive pressure will still cause different damage to the reserved rock mass out of excavation contour. Therefore, the method of protective controlled blasting must be adopted for excavation [1,2]. This paper has proposed to conduct fine smooth blasting in rock excavation with the methods of TSC blasting and non-coupling charging in order to reduce the damage to the surrounding rock.

In recent years, many researchers have studied the methods of borehole delay time blasting, Vanbrabant and Espinosa [3] claimed that the delays should be chosen to create an overlap of the negative tails of the P-wave particle velocity. Their full-scale test results indicated that the average fragmentation improved by nearly 50%. Paley [4] reduced the electronic detonator delay from 25 ms to 17 ms with accurate time delay controlled blasting technology, and reduced block rate by about 30%. McKinstry [5], Lewis [6], Khandelwal and Singh [7] demonstrated the advantage of the accurate time delay controlled blasting technology in reducing vibration and improving rock fracture effect by experiments successfully. Johansson and Ouchterlony [8] studied the delay times to improve blasting effect based on the interaction of explosion waves between holes through small scale model tests, and they found that the decrease of ×50 (mean size) was around 20% at a delay time 0–1.1 ms/m burden when compared to longer delays like 2 ms/m. The purpose of this research is to reduce the blasting vibration and improve the effect of rock fracture by borehole delay time blasting. In addition, this paper also wants to enhance the explosive stress wave superposition effect between PBH and TBH by using the TSC Method, make the hole wall cracks initiate and propagate mainly towards the adjacent hole, thus achieve the effect of cracks occurring towards the adjacent hole.

Practical blasting indicates that delayed initiation yields better results including finer fragmentation and less vibration than simultaneous initiation. The influence of delay times on fragmentation has been investigated by small-scale experiments, field trials and numerical simulations [9,10]. Chiappetta [11] argues that the optimal delay times

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should be in the range where the shock waves interact with each other between the holes, i.e., delays should be short enough so that the shockwave from a previous hole in the row does not reach the next hole before it initiates. Blair [12] argues that stress waves in the field are never similar in shape even if there are shock waves interactions, they are quite localized, i.e., a small fraction of the total volume would be influenced. Rossmanith and Kouzniak [13] have described a 2D model which reveals how a positive effect of shock wave interaction could be achieved. Some complicating issues regarding the relationship between stress and particle velocity have also been pointed out previously [14,15]. Yi and Johansson [16], through analytical results, showed that the tensile stress on the extended line increases due to the stress wave superposition under the assumption that the influence of neighboring blast hole on the stress wave propagation can be neglected. However, the numerical results indicated that this assumption is unreasonable and yields contrary results.

Previous studies have already used a few methods such as V-notched blasting [17,18], cumulative blasting[19,20] and air interval blasting[21,22] for blasting excavation of rock mass, and have achieved some results. However, in actual blasting excavation, the production process of V-notched holes and cumulative material is complex and hard for construction. While TSC blasting[23] only needs to control the initiation sequence of blast holes according to a certain order in order to achieve the effect of cracks extending along the adjacent hole. Based on the dynamic finite element method[24], this paper studied the numerical simulation method of rock smooth blasting excavation under TSC method and air interval blasting, and analyzed the mechanism of initiation and propagation of cracks between blast holes under the combined effect.

2. The stress concentrate of hole wall of TBH

Explosion stress wave includes transverse wave and longitudinal wave, they can produce stress concentration effect in the wall of empty hole. When the borehole using decoupling charge, if the TBH have not had initiation of stress wave but the stress wave of PBH had reached the TBH then the TBH is like an empty hole, the hole wall will produce larger stress concentrations. If the stress wave in the TBH is initiated after appearance of the stress concentration in the wall of the TBH, the initial crack generated on the TBH is most likely to occur along the area of largest concentrated stress. So we need to know how long it takes for the stress wave of the PBH to arrive at the TBH. The longitudinal wave velocity C_P and the transverse wave velocity C_S in the rock mass can be calculated by the formula [25].

$$C_P = \sqrt{E(1-\nu)/(1+\nu)(1-2\nu)\rho} \tag{1}$$

$$C_S = \sqrt{E/2(1+\mu)\rho} \tag{2}$$

where, E represents the modulus of elasticity of rock mass; ρ represents rock density; μ represents the Poisson's ratio of rock mass.

At the same time, controlling the blast hole charge to make PBH walls not generate cracks after initiation under the explosion shock wave of itself, but generate initial cracks along hole attachment under the effect of both the transverse wave of TBH and the explosion stress of PBH.

In practical engineering, the hole size is very small compared to the size of rock mass, the stress wave can be approximated as a plane wave. The longitudinal wave is faster than the transverse wave, so the longitudinal wave of PBH will reach the TBH first, and the hole wall of TBH will generate radial tensile stress for q1; Then the transverse wave reaches the TBH, and the hole wall of TBH generate tangential tensile stress for q2. Stress diagram for the hole wall of TBH when only the longitudinal waves of the PBH has reached the TBH are shown in Fig. 1.

The stress components of the rock mass around the TBH can be obtained by[25,26]

$$\left.\begin{aligned}\sigma_r &= \frac{1}{2}q\left[1-\frac{a^2}{r^2}+\left(1-\frac{4a^2}{r^2}+\frac{3a^4}{r^4}\right)\cos 2\theta\right]\\ \sigma_\theta &= \frac{1}{2}q\left[1+\frac{a^2}{r^2}-\left(1+\frac{3a^4}{r^4}\right)\cos 2\theta\right]\\ \tau_{r\theta} &= -\frac{1}{2}q\left(1+\frac{2a^2}{r^2}-\frac{3a^4}{r^4}\right)\sin 2\theta\end{aligned}\right\} \tag{3}$$

When $r = a$; $\sigma_r = 0$, $\tau_{r\theta} = 0$, $\sigma_\theta = q(1-2\cos 2\theta)$. As shown in Fig. 1, When $r = a$, $\theta = \pm\pi/2$; $\sigma_\theta = 3q$, and so the concentrated tensile stress in the hole wall is three times the average tensile stress; And when $\theta = 0$ or $\theta = \pi$; $\sigma_\theta = -q$. the hole wall is in compressed. When $\theta = \pm\pi/2$, the relation between the σ_θ and r as follows:

$$\sigma_\theta = q\left(1+\frac{a^2}{2r^2}+\frac{3a^4}{2r^4}\right) \tag{4}$$

From the formula we can see that, when $r = 2a$, $\sigma_\theta = 1.22q$, and when $r = 3a$, $\sigma_\theta = 1.07q$. When r is large enough, $\sigma_\theta \to q$. So, the stress concentration effect occurs only at the boundary of the empty hole. Similarly, when the TBH is only affected by transverse waves of the PBH, the stress diagram of the hole wall of TBH are shown in Fig. 2. When $\theta = 0$ or $\theta = \pi$, the hole wall have maximum tensile stress that is $3q$, and when $\theta = \pm\pi/2$, the hole wall have the maximum compressive stress that equals q.

When the concentrated stress of the hole wall is greater than the tensile strength of the rock it can generate the initial cracks along the borehole attachment, namely:

$$3q \geq \sigma_{td} \tag{5}$$

For example, there are six holes. Mark the PBH as A, and the TBH as B, and conduct micro-delay initiation with high precision electronic detonator between A and B. The PBH and TBH network layout is shown in Fig. 3.

For verification of the consistency of the numerical model compared to theoretical analysis, eight points are chosen as a1, a2, a3, a4, c1, c2, c3, c4, in the hole wall of TBH B, as shown in Fig. 4. If the borehole radius is R, then a1=c1=R, a2=c2=2R, a3=c3=3R, a4=c4=4R. Then the tangential stress value at points of different distance, measured from the center of borehole B, before the TBH initiation are compared.

As shown in Fig. 4, three points a1, b1 and c1 are chosen in the hole wall of TBH B, where, a1 is perpendicular to the line joining holes A and B, b1 have 45° angle to the line joining holes A and B, and c1 is in the line joining holes A and B. Under the action of PBH explosion stress wave, the tangential stress value of different direction measured at points a1, b1, c1 in the hole wall of TBH are compared.

The symmetry plane calculation model is analyzed in two different conditions: first condition is when the space between boreholes is constant, L_{BB}=2L_{AB} and the delay time of PBH and TBH varies, as shown in Fig. 5; another condition is when delay time of PBH and TBH is constant and the borehole space of the TBH L_{BB} varies, L_{BB}=(2.25–3)L_{AB}, as shown in Fig. 6.

3. Numerical model size and parameters

The influence of level of borehole during blasting is much greater than the influence of depth of borehole, so it can be approximated as 2D model. This paper used the dynamic finite element method[24] to simulate the crack formation mechanism by TSC and the symmetry semi-infinite body model to conduct calculation and analysis. As shown in Figs. 5 and 6, every model consists of explosive, rock mass and air. Here, bar-type packaged emulsion explosive relies on the hole wall which is wound by flexible polymer to ensure that cartridge is at the center of borehole, in order to effectively use the layer of air to protect reserved rock mass. The air layer model and the model of rock outside borehole are completely overlapped, so that the explosive stress wave