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The Safety Effect of Advanced Consolidation Grouted Rock under Blasting Shock Wave

Ke Deng[1, *], Man Zhang[2], Kuoyu Yang[1], Li Zhang[3], Yunchi Xia[3]

[1] School of Civil Engineering and Architecture, Henan University, Kaifeng, 475000, Henan, China.

[2] Miami College, Henan University, Kaifeng, 475000, Henan, China.

[3] China Construction Seventh Engineering Division. Corp.Ltd, Zhengzhou, 450004, Henan, China.

*Corresponding author's e-mail address: dk@henu.edu.cn

Abstract: Strong blasting disturbance leading to damage or even destruction of weak and fractured rock masses is a crucial problem to be solved during the construction process of underground engineering. For the blasting construction problem of advanced consolidation grouted rock near the excavation contour, the safety effect of blasting shock waves on grouted rock is investigated using a theoretical analysis method. The interaction process between blasting shock waves and grouted rock was studied based on the propagation characteristics of shock waves and the strain rate effect of rock strength. Considering the critical failure state, a safe vibration velocity model was established to analyze the effects of proportional distance, age, and grouting material. Results show that the first transmission and reflection effect creates the most dangerous state for grouted rock. SVV of super rapid strengthening cement is larger than that of ordinary cement. Choosing a suitable grouting material is essential to the following blasting design.

1. Introduction

The weak and fractured rock mass is increasingly common in underground projects. As an efficient excavation method, blasting is often used for rock excavation. However, the intense blasting disturbance can easily cause weak and fractured rock damage. Advanced grouting can strengthen the weak rock and fill the fractures with high-strength cement stone to create an environment that is helpful for blasting. As shown in Figure 1, the construction operation of pre-consolidation grouting and post-blasting excavation has been applied in underground engineering. The grouted rock is close to the design contour, and it is likely to cause safety accidents under the strong blasting load [1]. Thus, it is of great engineering significance to study the safety effect of blasting on a grouted rock near the blasting source.

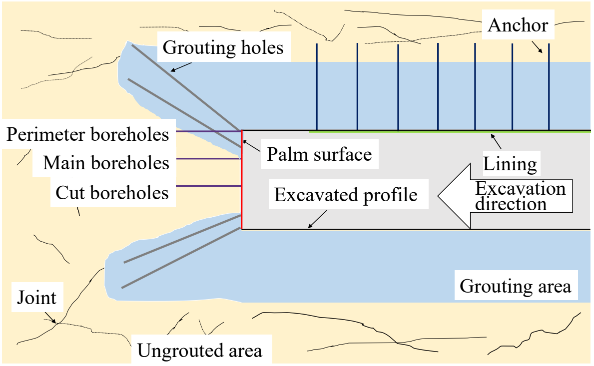

Figure 1. Diagram of "pre-consolidation grouting and post-blasting excavation" construction operation for underground tunnel

During blasting excavation, the shock waves excited by blasting first act on the rock mass. Grouted rock is different from homogeneous rock. The existence of interfaces between cement stone and rock affects the wave propagation characteristics [2]. Zhao and Cai [3] proposed a nonlinear (BB) model to analyze the propagation characteristics of P waves that incident vertically on the joints near the blast source. Zhu et al. [4] simulated wave transmission across a jointed rock with UDEC and found that the joint intersecting angle plays an important role in wave propagation. Besides the mechanical properties of the joint-filling medium, the surrounding environment also affects wave propagation [5,6].

In actuality, advanced consolidation grouted rock is mainly within the range of 3 – 5 m of the excavated contour. Blasting shock wave with high amplitude and velocity threatens rock safety. However, there needs to be more systematic research about the blasting safety control of grouted rock. This paper aims to study the interaction process between blast shock waves and grouted rock based on the multiple wave process and strain rate effects of rock strength. Considering the critical failure condition, a safety velocity calculation model is established to analyze the safety effects of proportional distance, age, and grouting material on the grouted rock. The research results have important theoretical significance and engineering application value for the blasting safety control of weak and fractured rock.

2. Propagation law of blasting shock waves in grouted rock

2.1. Interaction of shock waves with advanced consolidation grouted rock mass

The interaction process between the shock wave and grouted rock can be divided into four stages, as shown in Figure 2.

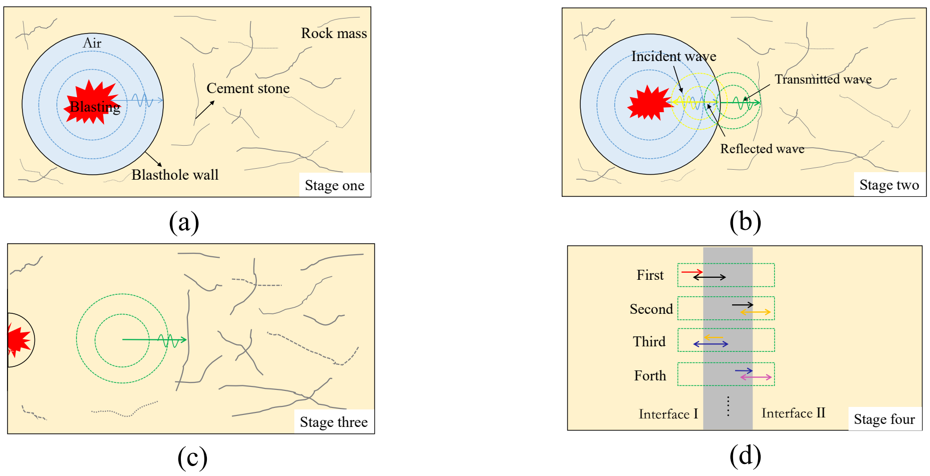

Figure 2. Propagation process of the shock wave on the grouted rock

The first stage is the interaction between the blast products and air inside the blast hole. The second stage is the shock wave and blast-hole wall interaction. The transmission and reflection effect occurs at the hole wall. The third stage is attenuating the shock wave propagating from the blast hole wall to the cement stone. The fourth stage is the multiple propagation process of the shock wave on the two interfaces between rock and cement stone. According to relative research, vertical incident waves have a strong effect on the safety of grouted rock [7,8]. Thus, the condition that blasting shock wave incident vertically on the grouted rock is analyzed based on stages three and four. The Hugoniot line can describe the interaction process between the blast shock wave and the interface of grouted rock [9], as shown in Figure 3.

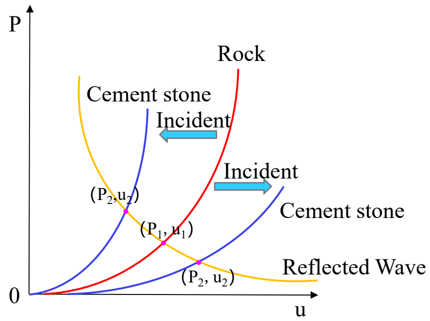

Figure 3. Hugoniot curve of shock wave on the grouted rock

Assuming that the cement stone and rock are located on the right side of the blast hole, and the initial velocity of the shock wave is 0, the Hugoniot equation for the right-transmitted shock wave of the rock is

$$P_r = \rho_r(a_r + b_r u)u \tag{1}$$

where P_r is the pressure induced by the shock wave at a mass point; ρ_r is the rock density; a_r and b_r are the constants related to the rock properties determined by the impact test; u is the vibration velocity.

The Hugoniot equation for the right transmitted shock wave of cement stone is

$$P_c = \rho_c(a_c + b_c u)u \tag{2}$$

where ρ_c is the density of the cement stone; P_c is the pressure induced by the shock wave at a mass point of the cement stone; a_c and b_c are constants related to the properties of the cement stone.

For most solid media, the Hugoniot curves of the incident and reflected waves can be regarded as mirror symmetric in the p-u plane. Based on Equation (1), the Hugoniot curve of the reflected wave in the rock can be expressed as

$$P_{Rer} = \rho_r\big(a_r + b_r(2u_1 - u)\big)(2u_1 - u) \tag{3}$$

where $P_{Re\,r}$ is the pressure caused by the reflected wave at a point in the rock.

The initial state parameter (p_2, u_2) of the transmitted wave at the interface I can be obtained by combining Equations (2) and (3). The grouted rock is treated as an ideal elastomer. And the geometric attenuation, decayed in $1/\sqrt{r}$, due to the increase of the spatial distribution of stress wave energy is considered [10]. The initial state point incident to interface II is denoted as $\left(p_2^{'}, u_2^{'}\right)$. Then the incident wave pressure on the interface II is

$$p_2^{'} = p_2\left(\frac{r_c}{r_c+L}\right)^{0.5} \tag{4}$$

where r_c is the distance between interface I and blast-hole; L is the thickness of the cement stone.

The Hugoniot curve of the reflected wave in the cement stone can be obtained by combining Equations (3) and (4):

$$P_{Re\,c} = \rho_c\big(a_c + b_c(2u_2' - u)\big)(2u_2' - u) \tag{5}$$

After combining Equations (1) and (5), the initial state parameters of the secondary transmitted waves generated in the rock can be obtained. The shock wave propagates reciprocally between interface I and

II until the intensity of the new incident wave tends to be infinitesimal. The total additional stresses can be obtained by superimposing the additional stress generated by each transmission and reflection effect. Compared to additional stress generated at the first transmission and reflection effect, superimposed stress is smaller due to the reflected sparse wave. Thus, the safety analysis considers the first transmission and reflection effect.

2.2. Calculation model of safe vibration velocity

According to experimental results of grouted rock, shear slipping is more likely to occur[8]. Considering the high strain rate in the near field of the blasting source, the dynamic Mohr-Coulomb criterion is used to describe the shear failure:

$$\tau_n \geq [C] + \sigma_n \tan \varphi_s \tag{6}$$

where $[C]$ is the dynamic cohesion, which is related to a high strain rate [11]; φ_s is the angle of internal friction; σ_n and τ_n are the normal and tangential stress on the interface.

Assuming the grouted rock is in a critical failure state, the state incident wave can be deduced backward. And the safe vibration velocity (SVV) caused by the critical incident wave functions as follows:

$$SVV = f([C], \varphi_s\ a, b, \rho). \tag{7}$$

3. Factor sensitivity analysis

MATLAB is applied to calculate the SVV model. Relative parameters are shown in Table 1 and Table 2 [12,13].

Table 1. Mechanical parameters of the rock and cement stones

Category	Density ρ (kg/m^3)	Poisson's ratio υ	Modulus of elasticity E (GPa)	Impact insulation parameters	
				a (m/s)	b
Fractured rock	2000	0.3	1	917	1.46
Cement stone	2400	0.22	30	2260	1.58

Table 2. Mechanical parameters of the interface between cement stone and rock

Cement type	Age	*C* (MPa)	*φs* (°)
Ordinary cement	1 day	0.09	20
	3 days	0.15	20
	7 days	0.21	20
	28 days	0.30	20
Super Early Strength Cement	1 day	0.18	20
	3 days	0.24	20

3.1. Proportional distance

The action range of the blasting shock wave is about 10 times of blast hole radius. The proportional distance, n, is the ratio of the distance from the blast hole wall to interface I and the blast hole radius. As shown in Figure 4, SVV is maintained at a specific value first and gradually decreases to another constant value. The high value of SVV is related to the high dynamic strength affected by a high strain rate. With the shock wave propagating outward, dynamic strength gradually decreases to static strength, and SVV decreases to a constant value. The minimum value of the SVV is about 30.05 cm/s at the outer boundary of the shock wave action range.

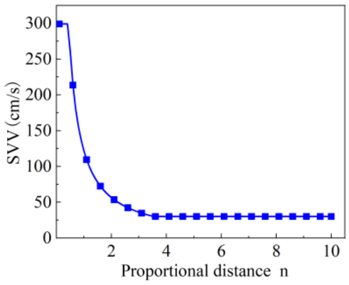

Figure 4. The variation law of safe vibration velocity of grouted rock with proportional distance under the action of shock wave

3.2. Age and grouting material

Table 3 shows the SVV at different ages. With age increasing, the strength of grouted rock increases, which results in SVV increasing. In underground engineering, it is often necessary to blast excavation immediately after grouting to shorten the construction period. Thus, the blast shock resistance of early-age grouted rock is significant. At the same age, the SVV of super rapid strengthening cement is larger than that of ordinary cement. Suitable grouting material affects the design of blasting excavation and project progress.

Table 3. SVV of grouted rock at different ages

Cement type	Age (days)	SVV (cm/s)
Ordinary cement	1	9.01
	3	15.02
	7	21.03
	28	30.05
Super rapid strengthening cement	1	18.03
	3	24.04

4. Conclusions

(1) Multiple transmission and reflection effects occur at the interface I and II advanced consolidation grouted rock. Shear failure is more likely to occur along the interface. Due to the reflected sparse wave, the first transmission and reflection effect creates the most dangerous state for grouted rock.

(2) With the proportional distance increasing, SVV is maintained at a specific value first and gradually decreases to another constant value. The SVV of grouted rock gradually increases with age increasing. At the same age, the SVV of super rapid strengthening cement is larger than that of ordinary cement.

(3) Mechanical property and distance are essential factors that should be considered for the blasting design of grouted rock. For underground engineering, rock is usually under a high in-situ stress environment. The effect of the surrounding environment on the blasting safety control of grouted rock is worthy of further study.

Acknowledgment

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