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Damage-vibration couple control of rock mass blasting for high rock slopes

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ABSTRACT

This paper focuses on the damage-vibration couple control method which is appropriate for the blasting of high rock slopes. Firstly, the correlation characteristic between the blasting damage depth and the Peak Particle Velocity (PPV) was investigated with regression analysis based on the site measurement of several famous high rock slopes in China. Results demonstrate that a power function relationship could be found and the correlation coefficient exceeds 80%. 3D Numerical simulation of blasting excavation was employed to verify the relationship, and results agree well with that of site experiment. Then, a new damage-vibration couple control approach of high rock slopes was proposed by introducing an Equivalent Blasting Vibration Control Standard (EBVCS). The mathematical description of EBVCS was determined with the stress attention law, and the rationale was verified with the experimental and numerical data. Finally, the damage-vibration couple control approach was implemented carefully during the excavation of Wudongde high rock slope, and the optimization suggestion was put forward. Results demonstrate that the PPV in the radial direction is most suitable for the control approach. The appropriate position of EBVCS established is at the inside of the berm. The detonation distance could affect the correctness of damage-vibration couple approach significantly, and the ideal position is the nearest berm.

1. Introduction

In mining and hydraulic operations, drilling blasting is probably the most widely used and cost-effective excavation method.[1–3] Detonation of explosives generates a chemical reaction occurs very rapidly and a relatively small quantity of explosive is converted into gas of very high temperature.[4–7] This procession results in two types of loadings applied on the borehole wall, namely a stress wave and a gas pressure with longer duration. Only a small fraction of the energy (less than 30%) is used for the breakage and movement of the rock mass, while the remainder of the energy is wasted in undesirable effects such as ground vibrations, fly rock, air blast, lights, and back breaks.[8–11]

The capability of predicting and controlling blasting induced damage in the remaining rock mass is important. For the last many years considerable efforts were made to minimize damage resulting from rock blasting.[12–15] Site monitoring was conducted to study the damage and vibration distribution of a rock mass under blasting. For example, S. S. Rathore et al. investigated the controlled fracture growth by blasting while protecting damages to remaining rock.[16] Lu et al. investigated the spatial distribution characteristics of blasting damage zone with methods of sonic logging.[17] However, investigation of rock blasting and its effects by scaled or full size experiment is very expensive and time-consuming. With the development of computer technology, numerical method, derived from sound mechanical principles and validated against experimental data, indicates a promising approach to reveal the blasting induced damage (BID). In consequence, extensive research activities in the field of blast damages have taken place in recent years.[18–23]

It is known that the major part of the explosion energy is used in crushing and breaking the rock in a properly designed blast. However, some energy also causes ground vibration. The ground shock and vibration can have an environmental impact on neighbors, and cause structural damage to those structures such as buildings, bridges, dams, tunnels, etc.[24–27] Hence, more and more attention has been focused on the spatial distribution and prediction of blasting vibration in rock mass. The Peak particle velocity (PPV) has been accepted as an important indicator of structural or rock mass damage during blasting. Li et al.[21] investigate the relationship between PPV at 30 m away from the charge hole and the damage of rock mass depth with numerical simulation. Sheng et al.[28] suggested the damage threshold values of PPV for the granite of the Three Gorges Project. It is known that the better understanding of blasting vibration has a great importance in the minimization of the environmental complaints.

In recent years, the strictly requirement of blasting not only contains separate aspect of damage or vibration, and it has evolved into full control of the blasting response. For example, during the excavation of several large hydropower stations which has been built in China, the blasting induced damage and vibration in the remaining rock mass

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Table 1
Blasting requirement of several famous high rock slope in south west of China.

Order	Name	Slope height (m)	Angle (°)	Excavation height(m)	**Damage depth (m)**	**PPV at last bench (cm/s)**
1	Xiaowan	700–800	47	670	1.2	12
2	JinpingI	> 1000	> 55	530	1.2	12
3	Da gangshang	> 600	> 40	380–410	1.5	15
4	Xiluodu	300–350	> 60	300–350	1–1.2	10
5	Tianshenqiao	400	50	350	1.5	15
6	Xiangjiaba	350	> 50	200	1.2	12
7	Baihetan	440–860	> 42	280	1	10
8	Nuozhadu	800	> 43	400–600	1.2	12

around the slope contour face were all limited strictly to protect the safety of slope. Table 1 plots the blasting control requirement of several famous high rock slopes in south west of China. It should be pointed out that the existed literatures mainly focus on the control of separate damage or vibration, but few attentions have been paid to the couple control of them. The relationship between damage depth and PPV of high rock slope is always ignored.

This paper focuses on the damage-vibration couple control which is appropriate for the blasting of high rock slope. The relationship between the blasting induced damage depth and PPV was investigated with measurement regression analysis and numerical simulation. Then a new damage-vibration couple control approach of high rock slope was proposed by introducing an Equivalent Blasting Vibration Control Standard (EBVCS). At last, the damage-vibration couple control approach was implemented during the excavation of Wudongde high rock slope, and the optimization suggestion was put forward. It is expected that this study could provide a good reference for the damage and vibration control of rock blasting excavation.

2. The investigation of relationship between damage depth and PPV

In the past ten years, several important high rock slopes have been built southwest China. Xiluodu and Baihetan high rock slope are two famous examples. To protect the security of slope during the blasting excavation, the sonic wave test and blasting vibration measurement were implemented to understand the blasting response fully. Fig. 1 shows the schematic diagram of blasting response measurement of these slopes. The sonic wave test holes which are perpendicular to the presplit face exceed the remaining rock mass by 8 m. The measurement points of blasting vibration were fixed at the inside of berm at the upper bench. With above test, the damage depth at the current bench and PPV at the upper bench could be determined severally. It is no doubt that the site testing provides a good condition for studying the connection between the damage depth and PPV.

2.1. Regression relationship between damage depth and PPV of several famous slopes

It is difficult to get precise theoretical solution because of the blasting process is too complex. The regression analysis derived from the experimental data, indicates a promising approach to study this problem. Fig. 2 shows the regression results of relationship between the damage depth and PPV for Baihetan and Xiluodu high rock slope.

By using the linear, logarithmic, exponential and power function to describe the curves, results indicate that the correlation coefficient of power function is the largest, which could exceed 0.85. The regression formulas are shown as follows:

$$PPV = 10.169(d_h)^{1.396} \tag{1}$$

$$PPV = 11.277(d_h)^{1.432} \tag{2}$$

where PPV is the Peak Particle Velocity at the upper bench, d_h is damage depth at the current bench. It can be seen that the damage depth and PPV are not divided, and if one of them is determined, the other may be predicted with a power function relationship. If the damage depth was limited within 1 m, the PPV at the berm of last bench should limited within 10.18 cm/s and 11.28 cm/s for two high rock slopes respectively. To reveal the mechanism of this relationship, the attending process of blasting wave in the rock mass should be taken in consideration. Fig. 3 plots the schematic diagram of the longitudinal wave velocity, PPV and stress wave attenuation during blasting.

Recent studies have revealed that the damage will be subsequently produced if the stress wave exceeds the material strength. But due to further attenuation of the stress wave, only the blasting vibration could be induced in the far field. As the damage scope could be determined with the value of stress wave at the point A, while the blasting vibration at the point B is also quite related to the stress. So, the attenuation law of blasting stress wave between the A and B could be seen as the link of the damage depth and vibration.

2.2. Validation of the relationship between damage depth and PPV by numerical simulation

In our previous study, we proposed a tensile-compressive damage model by incorporating the compressive damage into the exited damage model.[23] The feasibility of the model is verified by comparing with four different existed blasting damage models. The tensile damage scalar D_t is related to the damaged Poisson's ratio and the crack density parameter C_d through

$$D_t = \frac{16}{9}\frac{(1-\overline{\mu}^2)}{(1-2\overline{\mu})}C_d \tag{3}$$

On the other hand, when the rock material is in compression, based on the coupling principle of strain-rate effect in the Furlong-Davis-Alme (RDA) model, the compressive damage D_c is expressed as.[29,30]:

$$\dot{D}_c = \frac{\lambda \dot{\mathrm{W}}_{\mathrm{p}}}{1-\mathrm{D}_{\mathrm{t}}} \tag{4}$$

The constitutive relations recording the damage effect could be definited with Hooke's law of increment as follow:

$$d\sigma_{ij} = \overline{K}d\varepsilon_{kk}\delta_{ij} + 2\overline{G}de_{ij} \tag{5}$$

where ε_{kk} and e_{ij} are the volumetric and deviatoric strains respectively, while δ_{ij} is the Kronecker delta function.

The blasting of EL.750 berm of Baihetan high rock slope was selected as the numerical simulation target. The blasting process was simulated in a 3D FE model using LS-DYNA. Fig. 4 shows the developed numerical model to study the blast response in rock media. The model size was set to be 30 m long, 50 m wide and 60 m high. 300,863 elements and 118,715 nodes were used in the numerical simulation. The source of explosive is represented by a detonating cord containing a core load of emulsion explosive. Non-reflecting boundaries are applied to the other surfaces, except the top surface which has the free boundary condition.

Material Type 9 of LS-DYNA (*MAT_NULL) is used to calculate the pressure P from a specified EOS, which defines the relationship between pressure, density and internal energy. As for the air, the polynomial EOS is usually employed, in which the pressure P is expressed as:

$$\mathrm{P} = \mathrm{C}_0 + \mathrm{C}_1\mu + \mathrm{C}_2\mu^2 + \mathrm{C}_3\mu^3 + (\mathrm{C}_4 + \mathrm{C}_5\mu + \mathrm{C}_6\mu^2)\mathrm{e} \tag{6}$$

where e is the internal energy per volume. The compression of the material is defined by the parameter $\mu = (\rho/\rho_0) - 1$, with ρ and ρ_0 being the current and initial density of the material, respectively. As a matter of fact, the air is often modeled as an ideal gas by setting $C_0 = C_1 = C_2 = C_3 = C_4 = 0$ and $C_4 = C_5 = 0.401$. Air mass density and initial