



Safety threshold of blasting vibration velocity in foundation excavation of Baihetan super-high arch dam

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Abstract

Blasting damage control is one of the main problems in the dam foundation excavation of Baihetan Hydropower Station, and it is important to study the relationship between the blasting vibration and blasting damage. In this paper, a horizontal presplit blasting experiment was carried out at the dam foundation. By combining vibration monitoring and sonic wave detection before and after blasting, the corresponding relationship between the peak particle velocity (PPV) and the damage degree was established. On this basis, the function of grouting in the blasting excavation was analyzed. The results indicate that grouting is very helpful for the blasting damage control. After grouting, the P-wave velocity of the rock mass is increased by approximately 20%, the blasting damage depth is reduced by approximately 14%, and the safety threshold of the PPV is increased by approximately 25%. Meanwhile, the safety threshold of the PPV is positively correlated with the P-wave velocity of the rock mass. According to the damage control standard and rock mechanical properties, the blasting parameters can be rationally optimized.

Keywords Blasting damage · Peak particle velocity · Safety threshold · Grouting

Introduction

Baihetan Hydropower Station is located at the gorge between Ningnan county of Sichuan province and Qiaojia county of Yunnan province in the lower reaches of the Jinsha River, as shown in Fig. 1. It has an installed capacity of 16,000 MW and is another 10 million kilowatt-class hydropower station after the Three Gorges. As an economic and efficient method for rock breaking, blasting is widely used in dam foundation excavation at Baihetan Hydropower Station (Gao et al. 2019). However, a large amount of columnar jointed basalt is distributed at the dam site, which makes the geological conditions complicated and the construction difficult (Fan et al. 2018). Therefore, the blasting scheme must be optimized to control the blasting damage strictly during excavation.

During the process of rock formation, in addition to the geological discontinuities between the blocks formed in the

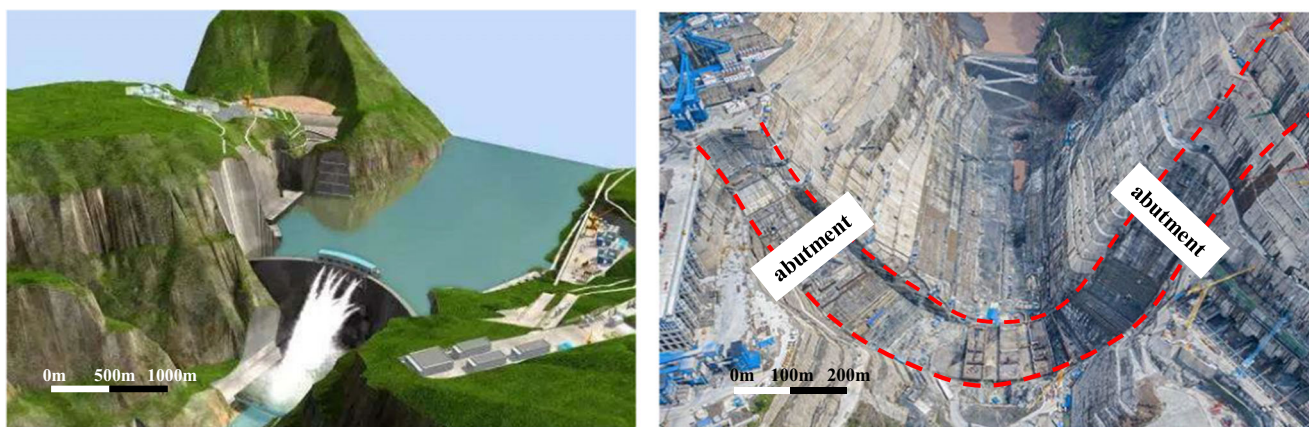
incipient stage (Shang et al. 2018), there are also many defects in the blocks, such as holes and cracks, which are called the initial damage. Under the action of blasting stress waves, these cracks are activated and extended, increasing the degree of rock damage and weakening the mechanical properties of the rock mass (Grady and Kipp 1980; Taylor et al. 1986; Yang et al. 1996). Researchers have defined the damage degree by the statistical distribution characteristics of microcracks and developed detection techniques for blasting damage, such as borehole television observation (Kanaori 1983) and borehole core sampling. Because the deterioration of the mechanical properties can be expressed as a reduction of the sonic wave speed, the sonic wave detection is often used in engineering to study the damage range in blasting excavation (Xia et al. 2007). This method is easy to operate, and the results are simple to read. Therefore, it has become the most important method for damage detection in blasting excavation at Baihetan Hydropower Station.

The propagation of blasting stress waves will induce rock vibration. Persson (1997) revealed the intrinsic relationship between the blasting damage and strain energy, and found that the peak particle velocity (PPV) is proportional to the blasting damage. Yang et al. (1994) and Holmberg and Persson (1978) used the acceleration sensors to measure the blasting vibration in a borehole and determined the safety thresholds of the PPV

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(a) Simulation model of dam

(b) Excavation contour of dam abutment

Fig. 1 General view of Baihetan Hydropower Station under construction

that would lead to rock cracking, but the relationship between the PPV and rock damage is lacking. Due to the difficulty in measuring the vibration in rock mass, in recent years, researchers began to predict the safety threshold of the PPV based on the statistical relationship between surface vibration and rock damage (Xie et al. 2009; Li et al. 2011; Zeng et al. 2018), making this work easier and more efficient. According to the research of the US Bureau of Mines (Duvall and Fogelson 1962), the safety threshold of the PPV can be used to predict the maximum explosive charge per delay and guide the blasting design.

At present, researches on the safety threshold of the PPV mainly focuses on the surface vibration, but this vibration is easily affected by the surface landform, and it lacks mechanical correlation with rock damage. Meanwhile, the relationship between the safety threshold of the PPV and the damage degree determined by sonic wave detection has not been established, so the research cannot be directly applied in engineering. Therefore, this paper measured the attenuation law of vibration and damage distribution in rock mass by field tests and numerical simulation, proposed a method to determine the safety threshold of the PPV under different damage degrees, and applied it to determine the safety threshold of the PPV before and after grouting at dam abutment. This work is helpful for optimizing the blasting design and ensuring blasting safety in dam foundation excavation at Baihetan Hydropower Station and can also provide a reference for similar projects.

Damage characteristics of columnar jointed basalt based on blasting vibration

Blasting excavation damage of columnar jointed basalt

Columnar jointed basalt is widely distributed at the dam site. It is an irregular tensile fracture structure in volcanic lava, which is mainly formed in the cooling process because of thermal stress (Spry 1962; Kantha 1981). Under natural condition, columnar jointed basalt is hard with a high deformation modulus, and the sonic wave speed can reach more than 4500 m/s (Jiang et al. 2018); the main mechanical parameters are showed in Table 1. However, because of blasting disturbances, the mechanical properties of rock mass will decline, thus threatening the engineering safety (Hetényi et al. 2012; Lin et al. 2019).

Therefore, a series of measures have been taken to reduce the blasting damage. Presplit blasting is most commonly used in dam abutment excavation, and it can generate precracks to block the propagation of stress waves induced by the main blasthole (Hu et al. 2014). Some advanced technologies, such as anchoring and grouting before blasting, were also used to reduce blasting damage, as shown in Fig. 2. After grouting, the P wave velocity of rock mass is generally increased by approximately 20%, and the blasting damage depth is controlled within 1.0 m.

Table 1 Main mechanical parameters of columnar jointed basalt

ρ (kg/m ³)	E (GPa)	ν	σ_t (MPa)	σ_c (MPa)	C_p (km/s)	f (MPa)	C (MPa)
2600~2800	30~40	0.22~0.24	5.0~6.0	90~100	4500~4700	1.2~1.4	1.3~1.5

ρ , rock density; E , elastic modulus; ν , Poisson's ratio; σ_t , tensile strength; σ_c , uniaxial compressive strength; C_p , longitudinal wave velocity; f and C , shear strength

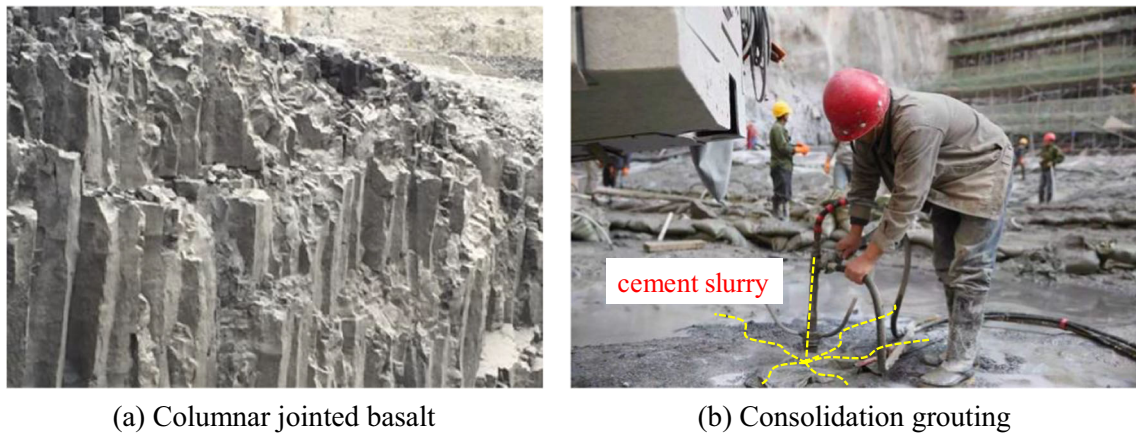


Fig. 2 Columnar jointed basalt in excavation and the reinforcement

The interaction between explosions and rock is a complex dynamic process (Fakhimi and Lanari 2014). First, the shock wave formed in an explosion strongly crushed the rock mass around the blasthole. Then the shock wave transforms into a stress wave and propagates outward, causing compressive strain in the radial direction and tensile strain in the tangential direction. When the tangential tensile stress is greater than the tensile strength, the rock is broken, and radial cracks are formed. Meanwhile, shear cracks may develop because of the radial stress and tangential stress. Subsequently, with the expansion of explosive gas, the cracks continue to extend, forming a cracked zone. Figure 3 shows the different types of damage zone for bench blasting. The zone is funnel shaped, and the maximum damage depth and radius are mainly determined by tensile failure. For columnar charge, the ratio of the damage radius and depth is approximately 3:1.

In engineering, the rock blasting damage is represented by the reduction of the sonic wave speed, and sonic wave tests are widely used for damage detection in foundation excavation.

According to the Construction Technical Specifications on Rock-foundation Excavating Engineering of Hydraulic Structures (NDAR 2007), the reduction rate of the sonic wave speed η is calculated as follows:

$$\eta = 1 - \bar{C}_p / C_p \tag{1}$$

where \bar{C}_p is the sonic wave speed after blasting excavation. Damage variable D is used to describe the deterioration of the mechanical properties in rock damage mechanics ($0 < D < 1$):

$$D = 1 - \bar{E} / E \tag{2}$$

where \bar{E} is the elastic modulus after blasting and E is the elastic modulus before blasting. The P-wave velocity C_p can be calculated as follows (Achenbach 1973):

$$C_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{3}$$

Fig. 3 Excavation damage zone in bench blasting

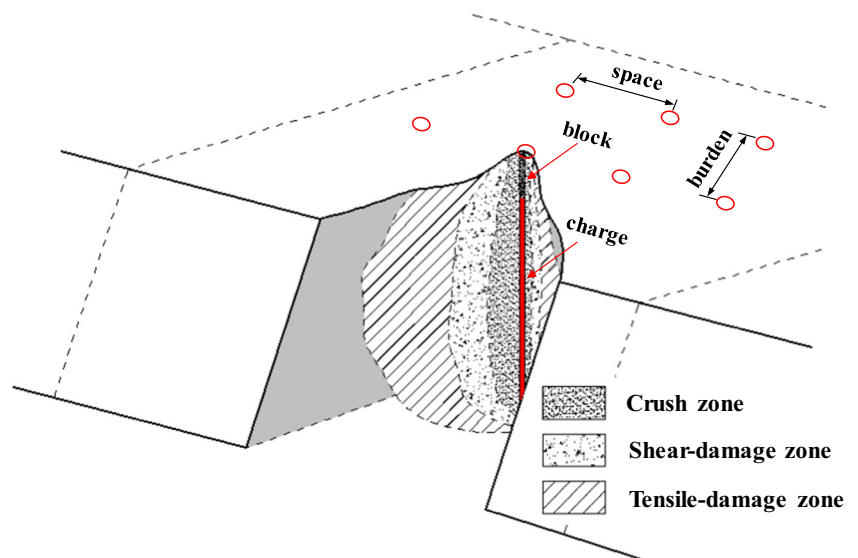
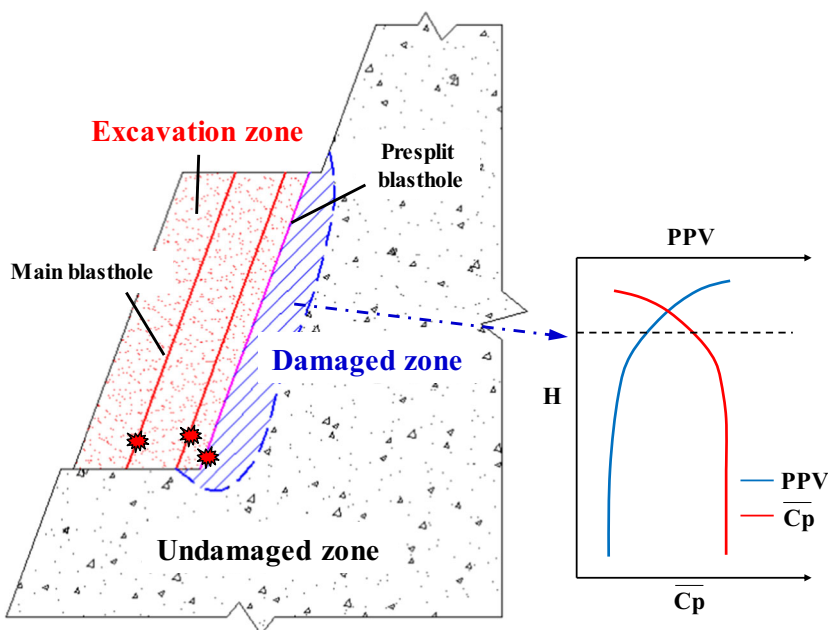


Fig. 4 Relationship between the blasting damage and PPV



Based on Eqs. (1), (2), and (3), we can obtain:

$$D = 1 - (1 - \eta)^2 \tag{4}$$

In engineering, when $\eta \leq 5\%$, it can be thought of as the reading error of the instrument; when $5\% \leq \eta \leq 10\%$, blasting has a slight adverse effect on the rock mass; when $10\% \leq \eta \leq 15\%$, blasting has an obvious adverse effect on the rock mass; and when $\eta \geq 15\%$, the adverse effect of blasting is very obvious. Based on Eq. (4), when the reduction rate of the sonic wave speed η is 5%, 10%, and 15%, the corresponding thresholds of damage variable D are 0.10, 0.19, and 0.28, respectively.

Safety threshold of the PPV in blasting

Under the action of a blasting load, the maximum damage depth of the rock mass is mainly caused by tensile stress. Considering the initial damage, the damage variable and crack density can be expressed as follows (Zhang et al. 2004):

$$D = 1 - \exp(-C) \tag{5}$$

$$C = \Delta C + C_0 \tag{6}$$

Table 2 Critical values of the peak particle velocity for intact rock

Threshold of the PPV	Damage degree
< 25.0	Intact rock will not be broken
25.0~63.5	A slight stretch crack
63.5~254.0	Severe tensile cracks and some radial cracks
> 254.0	Completely broken

$$\Delta C = \alpha (|\varepsilon| - |\varepsilon_{cr}|)^\beta \Delta t \tag{7}$$

where C is the crack density, which represents the number of cracks in a unit volume; C_0 is the initial crack density; ΔC is the increase in the crack density due to rock blasting; Δt is the time increment; α and β are material parameters related to rock properties; ε and ε_{cr} are the tensile strain under dynamic load and ultimate tensile strain under static load, respectively:

$$\varepsilon_{cr} = \sigma_t / E \tag{8}$$

As the distance to the explosive source increases, the cylindrical stress wave caused by blasting gradually changes into a plane stress wave. According to Persson’s research (1997), based on one-dimensional elastic wave theory, the strain can be expressed as follows:

$$\varepsilon = v / C_p \tag{9}$$

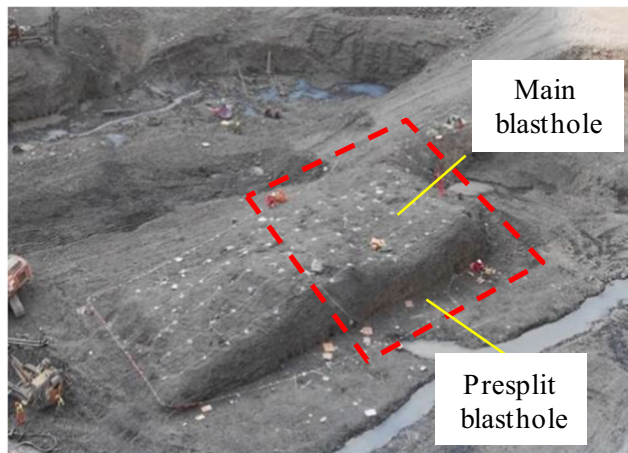


Fig. 5 General view of the horizontal presplit blasting experiment

Table 3 Main parameters of the blasting experiment

Test type	Hole type	$d(\text{mm})$	$\phi(\text{mm})$	$S/B(\text{m})$	$Q(\text{kg})$	$Q_m(\text{kg})$
Horizontal presplit blasting	Presplit hole	76	32	0.6	2.2	8.8
	Main hole	90	32/70	1.8/1.8	2.7~4.3	4.3

where v is the particle vibration velocity. According to Eqs. (5), (6), (7), (8), and (9), the damage degree is positively correlated with the particle vibration velocity of rock mass. By combining the PPVs and damage degrees at different depths, the corresponding relationship can be established, as shown in Fig. 4.

At present, combined with sonic wave tests, crack investigations, and other methods, many scholars have statistically analyzed the cracking criterion for various kinds of rocks under different peak particle velocities: Långfors and Kihlström (1978) believed that the upper safety limit of PPV is 60 cm/s; Holmberg and Persson (1978) supposed that hard bedrock

cracks at a peak vibration of 70~100 cm/s; Bauer and Calder (1978) made recommendations on PPV criteria for intact rock mass, as shown in Table 2.

Blasting field experiment at the dam foundation

Test plans

To study the corresponding relationship between the PPV and the damage degree of rock mass, a horizontal presplit blasting

Fig. 6 Vibration monitoring scheme in rock mass

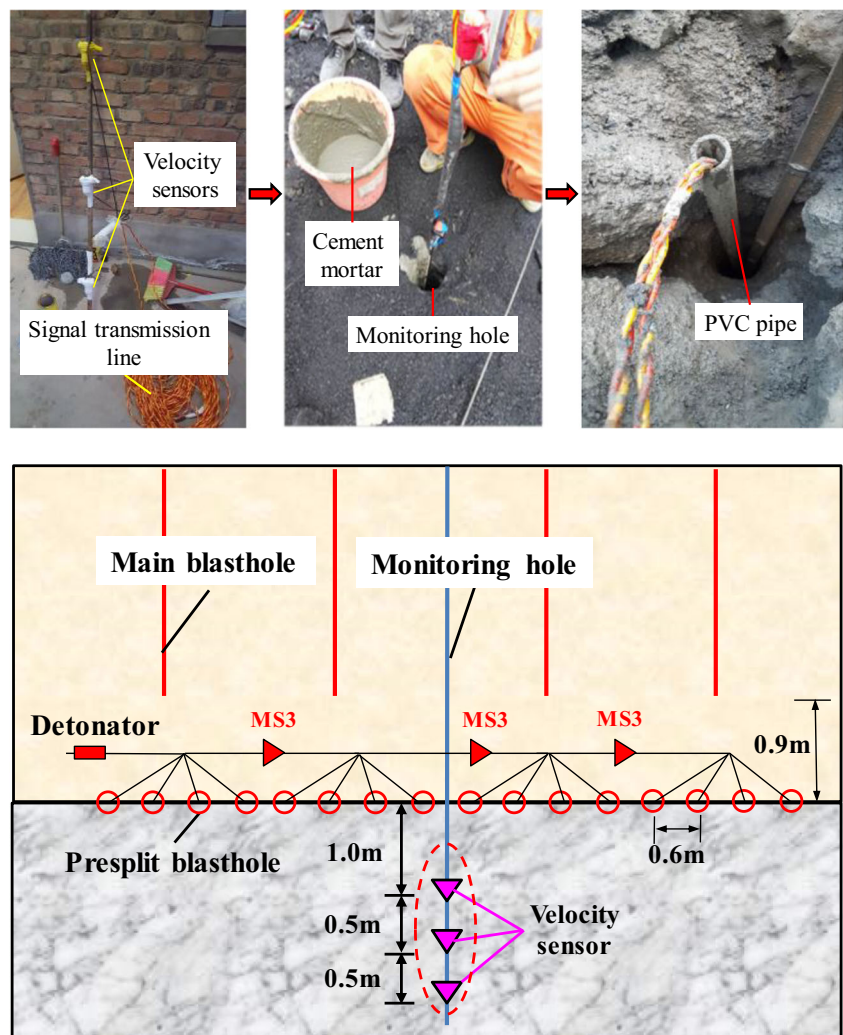
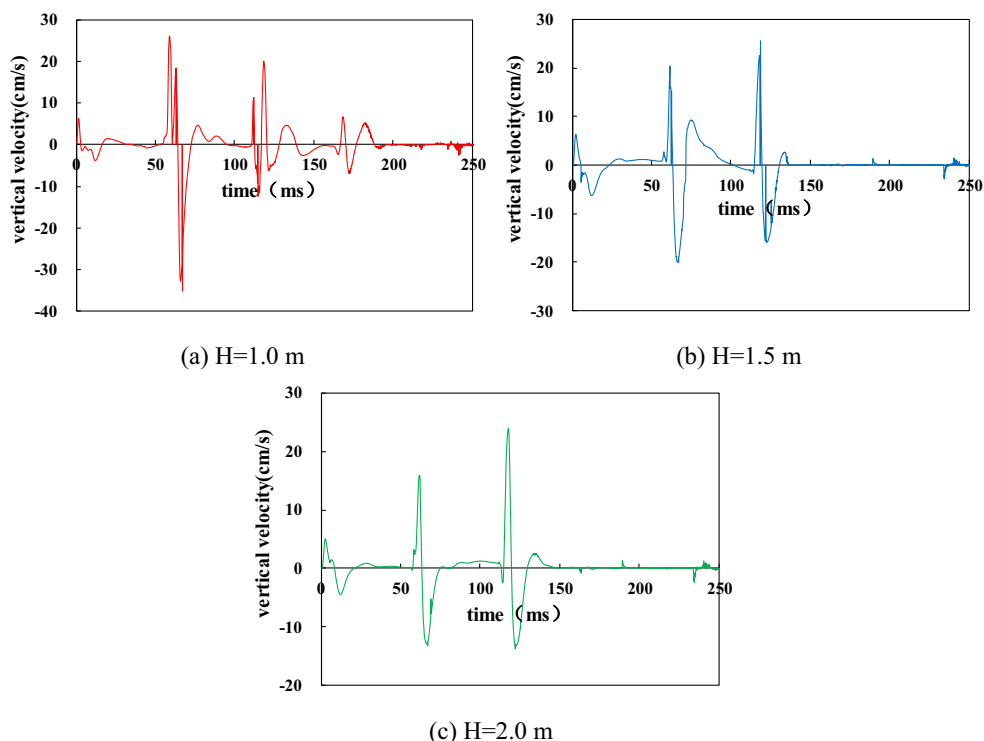


Fig. 7 Vibration waveforms of different measurement points in the blasting experiment



experiment was carried out at the riverbed dam foundation of Baihetan Hydropower Station, as shown in Fig. 5. MS2, MS3, and MS5 non-electrical millisecond detonators were used to construct the differential detonation network; all detonators were double-initiated to ensure the accuracy of the explosion; and MS11 detonators were used in the main blasthole for delay. The blasting parameters are shown in Table 3.

Vibration monitoring

Velocity sensors were buried in the rock mass to record the vibration. Adjacent velocity sensors were spaced 0.5 m apart, and they were fixed on rebar by tape tying and glue bonding. The velocity sensors were arranged at 1.0 m, 1.5 m, and 2.0 m below the foundation surface. When the devices reached the designated position, premixed cement mortar was poured into the monitoring hole so that the

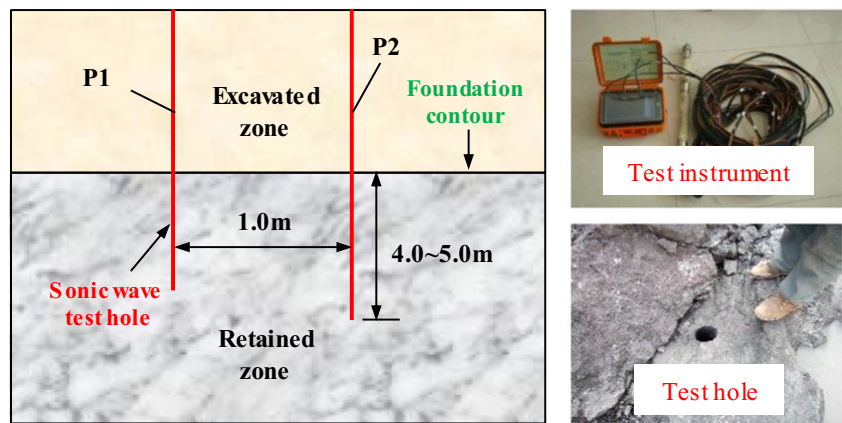
velocity sensors could be cemented with the surrounding rock mass. Meanwhile, a PVC pipe was used to protect the signal transmission line buried in the rock mass. Figure 6 shows the arrangement of vibration measurement devices in the blasting test, which used a TC-4850 blasting vibration intelligent monitor produced by the Chengdu Zhongke Measurement Corporation to record data.

To avoid mutual interference of blasting vibrations, the MS3/MS5 detonators were used for delay between each segment so that the single segment blasting vibration waveform could be obtained. Figure 7 shows the vibration waveforms at different depths. The blasting vibration caused by each segment can be clearly distinguished, which is beneficial for studying the internal propagation and attenuation law of explosive stress waves. Table 4 shows the PPV induced by each segment of the blasting test at the specified depth.

Table 4 PPV monitoring results of each segment in the blasting experiment

Test type	Segments	PPV (cm/s)		
		$H = 1.0$ m	$H = 1.5$ m	$H = 2.0$ m
Horizontal presplit blasting	1	6.5	6.5	4.7
	2	35.1	20.5	16.1
	3	20.0	25.6	24.1
	4	6.7	2.9	2.6

Fig. 8 Sonic wave detection plan



Sonic wave detection

The sonic wave detection technique was used to test the blasting damage depth and blasting damage degrees in this experiment. The equipment was an HX-SY02B intelligent rock non-metal sonic instrument produced by the Yueyang Aocheng Technology Corporation. The test was carried out within 24 h, so the rock relaxation because of time lapse can be neglected. Before each test, the instruments should be calibrated based on the specifications to ensure the accuracy of test results;

water was used as the coupled medium, and the sonic wave speed was recorded every 0.2 m from the bottom to the orifice. Figure 8 shows the sonic wave test plan for the blasting experiment.

The sonic wave test holes were drilled between the blastholes and passed through the blasting zone to 4.0~5.0 m below the foundation surface. Two parallel holes were drilled in this experiment, and the hole spacing was 1.0 m. Two single-hole and one cross-hole sonic wave tests were carried out before and after blasting. Figure 9 shows the curve of the sonic wave speed at

Fig. 9 Sonic wave speed at different depths before and after blasting

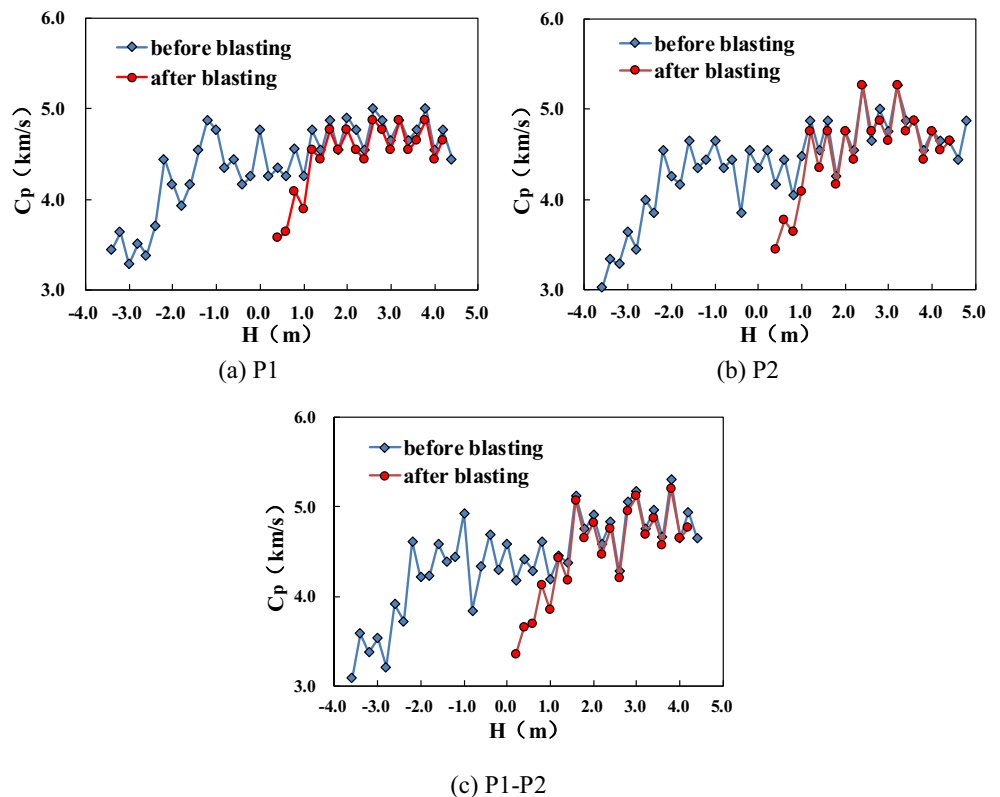


Table 5 Sonic wave speed detection results

Test type	Average sonic wave speed after blasting (m/s)	
	Damaged zone	Undamaged zone
Horizontal presplit blasting	3732	4651

different depth before and after blasting. According to Eq. (1), the reduction rate of the sonic wave speed could be obtained and used to divided the foundation into the blasting damaged zone when the reduction rate of the sonic wave speed was $\eta > 10\%$, as shown in Table 5. After blasting, the sonic wave speed was 3732 m/s in the damaged zone, while it was 4651 m/s in the undamaged zone, and the adverse effect of rock blasting was significant. Table 6 shows the damage depth under different damage degrees. It should be noted that the final damage depth mainly depends on presplit blasting in the horizontal presplit blasting test. As the precracks can effectively block the propagation of stress waves, the influence of main hole blasting can be ignored (Hu et al. 2014).

Safety thresholds of the PPV for different blasting damage degrees

Numerical model and material parameters

The propagation and attenuation law of blasting vibration in rock mass is the key to establishing a corresponding relationship between the PPV and the reduction rate of the sonic wave speed. Because the vibration monitoring points are few in the field experiment, there may be large errors in regression analysis, and numerical simulation with the nonlinear finite element software AUTODYN was adopted. The fluid-solid coupling algorithm was used for calculation. The top surface of the model is set as a free boundary, and the remaining is setting as non-reflective boundary to reduce the reflected stress wave. According to the blasting design, 16 blastholes are detonated in 4 segments, and each interval is 25 ms. The diameter of the blastholes is 76 mm, and the diameter of the explosive cartridges is 32 mm. Figure 10 shows the numerical model of the horizontal presplit blasting.

Table 6 Blasting damage detection results

Test type	Damaged depth of blasting (m)		
	$\eta = 5\%$	$\eta = 10\%$	$\eta = 15\%$
Horizontal presplit blasting	1.16	0.84	0.57

The Jones-Wilkins-Lee (JWL) state equation is used to describe the relationship between the pressure and volume of detonation products (Lee et al. 1968):

$$P_d = A \left(1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E_0}{V} \omega \quad (10)$$

where $A, B, R_1, R_2,$ and ω are independent constants; V is relative volume; and E_0 is initial internal energy in a unit. Table 7 shows the main parameters of explosive.

The mechanical parameters of rock are shown in Table 1, and the Cowper-Symonds model was used to describe the constitutive relationship of rock mass under a blasting load, which considers the effect of strain rate on the plastic strain hardening of rock mass (Xia et al. 2007):

$$\sigma = \left[1 + \left(\frac{\dot{\epsilon}}{C} \right)^{\frac{1}{P}} \right] \left(\sigma_0 + \beta E_p \epsilon_p^{eff} \right) \quad (11)$$

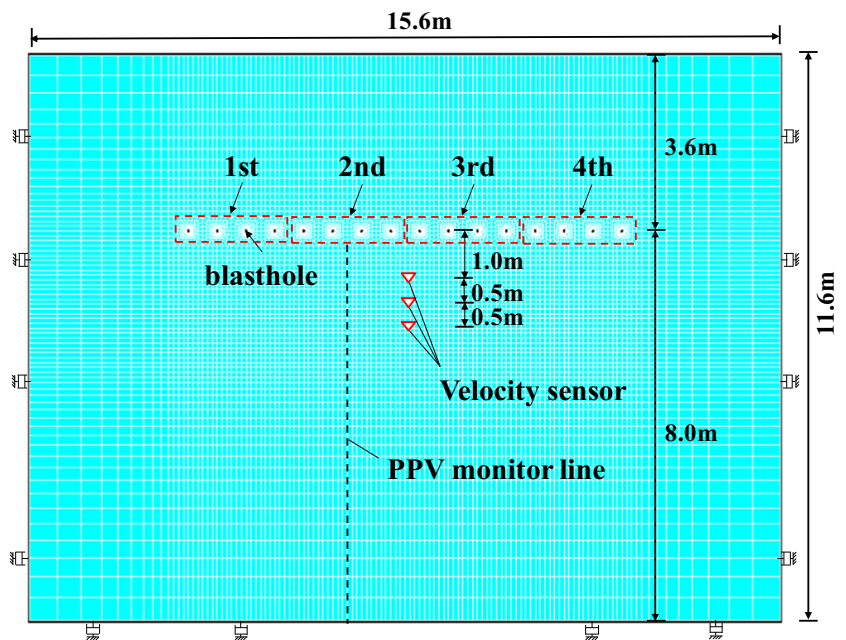
where σ_0 is the initial yield stress; β is the hardening coefficient, with $0 \leq \beta \leq 1$; E_p is the plastic hardening modulus; C and P are the strain rate parameters. Referring to Yang’s research (1996) on the stress time history curve of rock mass at different strain rates, these parameters can be taken as 2.5 s^{-1} and 4.0, respectively.

To verify the accuracy of the simulation, the vibration waveforms and the PPV measured at different depths were compared. The second segment was selected for analysis. Figure 11 shows the comparison between the measured and simulated vibration waveforms. It is obvious that the two methods are in good agreement except for in local areas. Table 8 shows the comparison between the simulated and measured PPVs at different depths; the error is small and basically less than 20%. Considering the randomness of blasting vibration in the near field and the heterogeneity of natural rock mass, the numerical methods used in this paper are reliable and can represent the blasting vibration propagation and attenuation law in rock mass.

Safety threshold of the PPV in the blasting experiment

For the horizontal presplit blasting test, considering that the sonic wave detection boreholes were drilled between

Fig. 10 Numerical model of the horizontal presplit blasting experiment



two blastholes, the vertical bisector of the central line of the second segment blasthole is chosen as vibration monitoring line. As the depth increases, the PPV rapidly decays. Combined with the relationship between the reduction rate of the sonic wave speed and the depth, the safety threshold of the PPV under different damage degrees can be determined, as shown in Fig. 12. Considering that sonic wave detection reflects the average damage of the blasting zone, the safety threshold of PPV determined by the study is also the average value.

Previous studies have shown that the safety threshold of the PPV is an inherent natural characteristic of rock and is mainly related to the mechanical properties (Bauer and Calder 1978; Mojtabai and Beattie 1996). In this experiment, as shown in Fig. 12, when the reduction rate of the sonic wave speed is $\eta = 5\%$, 10% , and 15% , the damage variable is $D = 0.10$, 0.19 , and 0.28 , and the corresponding safety threshold of the PPV is 58.8 cm/s , 79.2 cm/s , and 128.5 cm/s . Considering the safety margin of blasting excavation and inhomogeneity of the rock mass, the safety threshold of the PPV for the columnar jointed basalt at dam foundation can be roughly determined as 50 cm/s , 65 cm/s , and 90 cm/s , respectively.

Table 7 Parameters of the JWL state equation for explosives

$\rho_e(\text{kg}/\text{m}^3)$	VOD(m/s)	A(GPa)	B(GPa)	R_1	R_2	ω	$E_0(\text{MJ}/\text{m}^3)$
1050	3850	209.7	3.50	5.8	1.29	0.39	4.19×10^3

Safety threshold of the PPV before and after grouting

The dam foundation will bear great pressure when the construction of the arch dam is finished, which puts forward higher requirements for the mechanical properties of the rock mass, and the adverse effect of blasting excavation should be strictly controlled. For the dam foundation with the elevation below 600 m, 5-m thick protective layers were reserved for anchoring and grouting before blasting excavation, as shown in Fig. 13. Because the joints and weak interlayers were filled with cement slurry, so the integrity of columnar jointed basalt was improved.

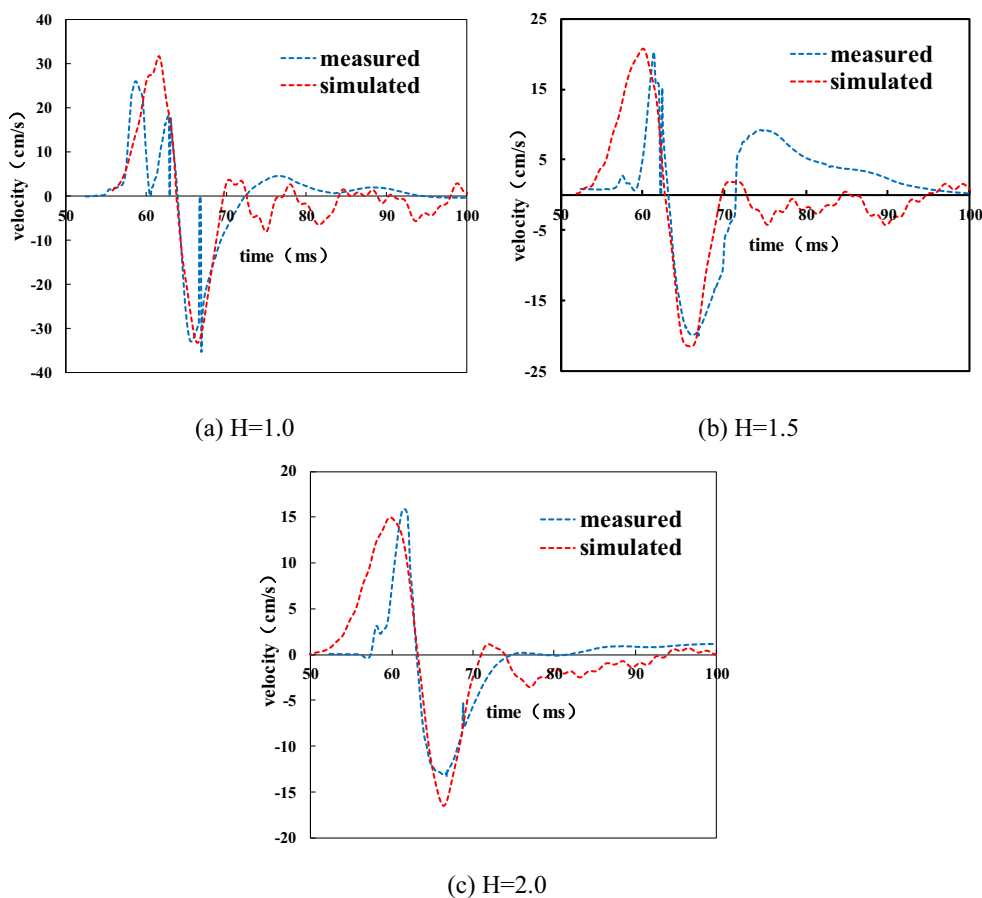
Table 9 shows the P-wave velocity of rock mass before and after grouting as well as damage depths. It is obvious that the P-wave velocity of the rock mass can reach more than 4800 m/s after grouting; as it is $3600\text{--}4000 \text{ m/s}$ without grouting, the mechanical properties of the rock mass were significantly improved. The damage detection results show that the damage depth of the rock mass significantly decreases after grouting by approximately 14%. Grouting can effectively reduce the adverse effects of blasting on rock mass.

As the rock mechanical properties are not the same after grouting, the PPV and the blasting design should be optimized. Many researchers have found that the density is positively correlated with the P-wave velocity of rock mass (Gardner et al. 1974; Gaviglio 1989; Khandelwal 2013). Based on Khandelwal’s research, the relationship between the sonic wave speed and density can be calculated as follows:

$$\rho = 0.202C_p + 1794.7 \tag{12}$$

According to Eq. (3), the elastic modulus of rock mass will change with density and P-wave velocity. By

Fig. 11 Comparison of vibration waveforms between simulation and measurement at different depths



adjusting material parameters in numerical simulation models, the safety threshold of the PPV before and after grouting can be obtained. As shown in Fig. 14, the safety threshold of the PPV obviously increases after grouting for the same damage degree, by approximately 25%. Consolidation grouting has remarkable influence on the control of blasting excavation, and a more aggressive blasting design may be acceptable after grouting.

The blasting stress wave will transmit and reflect when it is incident from the intact rock to the joints, and the incident compression wave will be converted into a reflected stress wave (Achenbach 1973). This will lead to the tensile failure around the joints, which is one of the main reasons for blasting damage of columnar jointed basalt. The cement slurry enhances the mechanical properties of the joints, reduces the

strength of the reflected tensile stress wave, and is conducive to blasting damage control. Macroscopically, the increase in the P-wave velocity can reflect the grouting effect and the improvement of rock mechanical properties (Khandelwal and Singh 2009). Figure 15 shows the relationship between safety threshold of the PPV and P-wave velocity. Obviously, the safety threshold of PPV has a positive correlation with the P-wave velocity, which indicates the rock with better properties is less vulnerable to damage under a blasting load.

Discussion

During the excavation of the dam foundation at Baihetan Hydropower Station, the damage control standards are

Table 8 Comparison of the PPV between simulation and measurement at different depths

Type	Depth (m)	PPV (cm/s)			
		Simulated	Measured	Err (%)	Ave err (%)
Horizontal presplit blasting	1.0	35.3	35.1	0.6	7.2
	1.5	23.8	20.5	16.1	
	2.0	16.9	16.1	5.0	

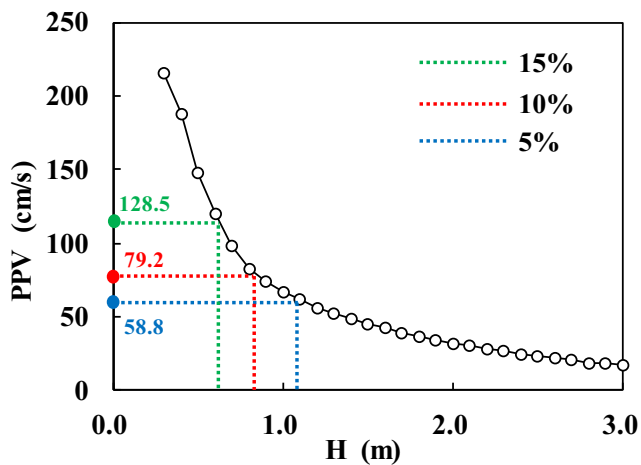


Fig. 12 Safety threshold of the PPV for different reduction rates of the sonic wave speed

different at different parts. In the excavation of the upper rock mass of the protective layer, the damage depth should be controlled within 1.0 m when the reduction rate of the sonic wave speed is 10%, while it should be controlled within 0.8 m in the protective layer excavation. The excavation of the protective layer of the plunge pool should be accelerated as much as possible so that the reduction rate of the sonic wave speed could be controlled to approximately 15% at 1.0 m. By combining the safety threshold of PPV under different damage control standard and blasting vibration prediction method,

the modified blasting parameters can be obtained (Yilmaz and Unlu 2014). They can be used to rationally optimize the blasting design.

In this paper, the effect of aging relaxation of columnar jointed basalt due to stress release during excavation is not considered. This is because although the relaxation depth of columnar jointed basalt can reach 1~3 m, the process takes a long time, usually more than 3 months (Jin et al. 2015). The sonic wave test in this study was carried out within 24 h after blasting, and the rock mass was not relaxed. Therefore, the decrease in the sonic wave speed is mainly due to the blasting damage. On the other hand, the influence of joints of columnar jointed basalt on stress wave propagation has not been considered in this paper. However, as it is impossible to simulate every joint accurately, the propagation law of vibration is simulated macroscopically by fitting the vibration waveforms of different measuring points. Therefore, the accuracy of vibration simulation can be guaranteed in this paper.

Conclusion

In this paper, a horizontal presplit blasting test was carried out at the dam foundation in Baihetan Hydropower Station, and the corresponding relationship between the damage degrees of columnar jointed basalt and the peak particle velocity (PPV) was studied. On this basis, the influence of consolidation grouting on the safety threshold of the PPV in blasting

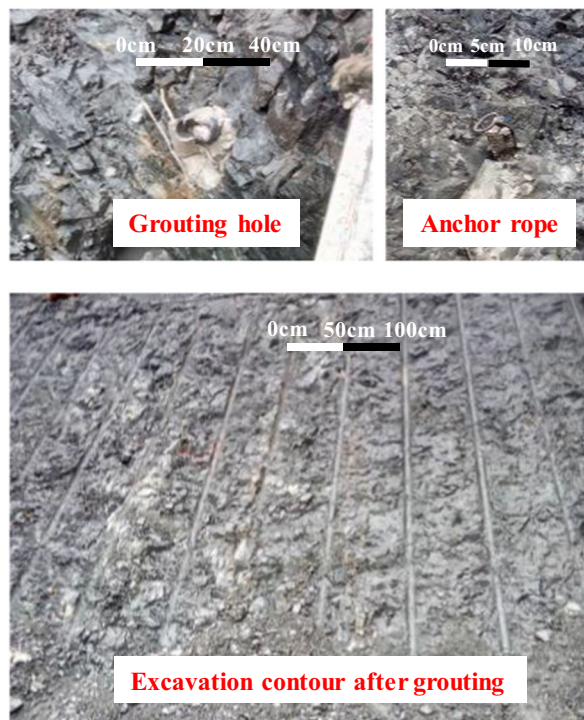
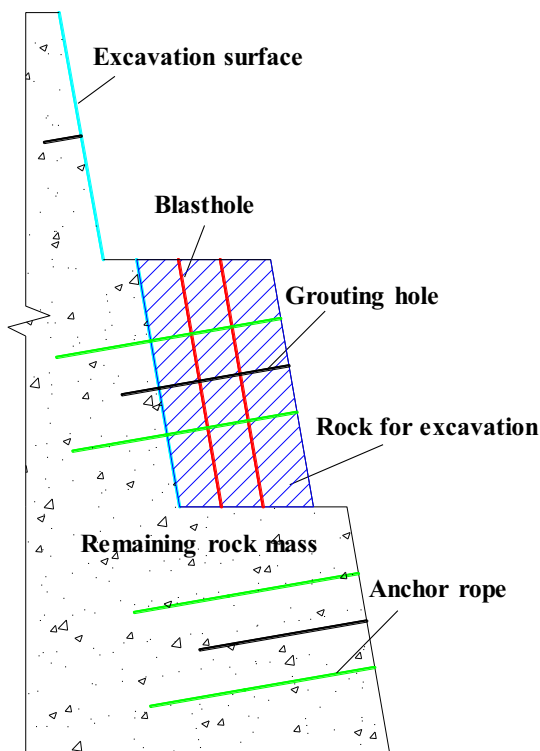


Fig. 13 General view of the blasting excavation contour after grouting at dam abutment

Table 9 Blasting excavation damage depth before and after grouting

Bench no	Position	Time	Cp (m/s)	Damage depth (m)		
				$\eta = 5\%$	$\eta = 10\%$	$\eta = 15\%$
1	Upstream	Before grouting	3971	1.31	0.97	0.59
		After grouting	5043	1.21	0.74	0.53
	Downstream	Before grouting	4027	1.23	1.00	0.61
		After grouting	4923	1.35	0.80	0.55
2	Upstream	Before grouting	3960	1.53	0.89	0.58
		After grouting	4843	1.21	0.79	0.52
	Downstream	Before grouting	3617	1.57	0.95	0.65
		After grouting	4860	1.35	0.79	0.54

excavation of dam abutment was analyzed. The results indicate the following:

- (1) The vibration attenuation law could be obtained by embedded velocity sensors and numerical simulation. By combining the sonic wave detection results before and after blasting, the safety threshold of the

PPV for different damage degrees could be determined. In this experiment, considering the heterogeneity of rock mass and safety margin, when the reduction rate of the sonic wave speed at the dam foundation is 5%, 10%, and 15%, the safety threshold of the PPV can be roughly determined to be 50 cm/s, 65 cm/s, and 90 cm/s, respectively.

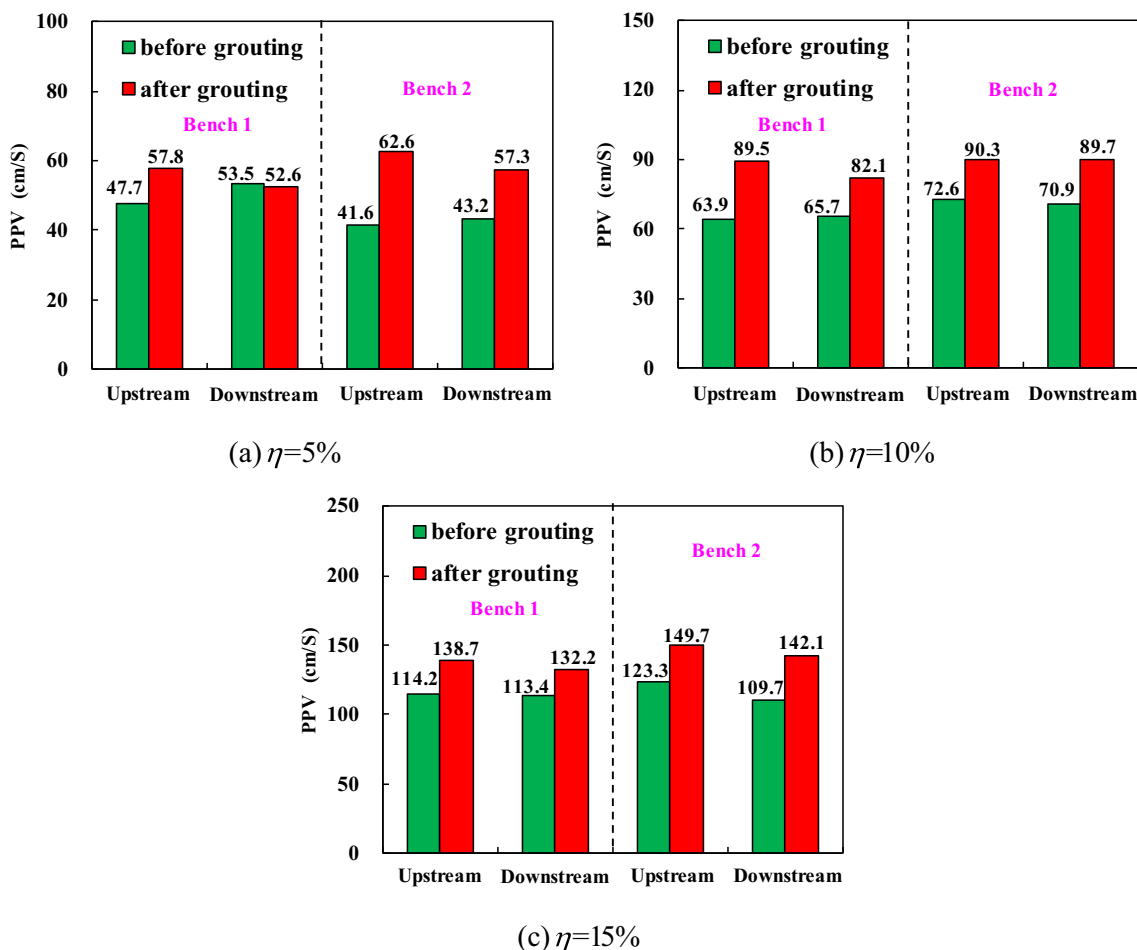


Fig. 14 Safety threshold of the PPV before and after grouting at dam abutment

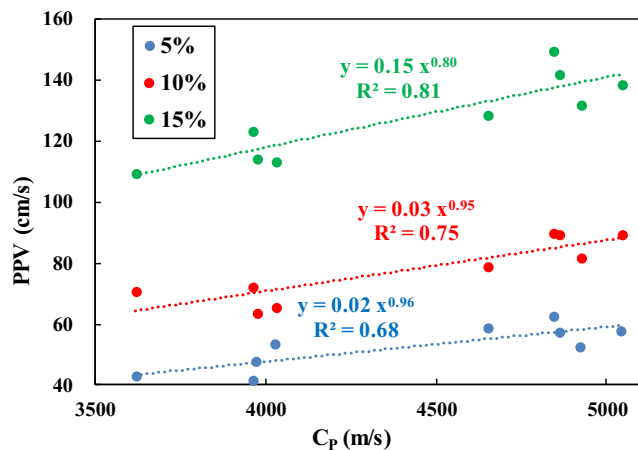


Fig. 15 Safety threshold of the PPV under different P-wave velocities

- (2) Consolidation grouting can effectively improve the mechanical properties of columnar jointed basalt. After grouting, P-wave velocity is increased by 20%, while damage depth is reduced by 14%, and the corresponding safety threshold of the PPV is increased by 25%. The adverse effect of blasting excavation on retained rock mass is significantly controlled with grouting.
- (3) The safety threshold of the PPV shows a good positive correlation with the P-wave velocity. Combined with the different damage control standard and corresponding safety threshold of the PPV, the blasting design can be rationally optimized.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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