Mechanisms of vibration differences induced by various blast-holes in rock

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Abstract. Practical rock blasting always involves different kinds of blast-holes, such as production, presplitting, and smooth blast-holes, etc. These blast-holes all have big differences in charging structures and initiation modes, as well as burden conditions, which thereby cause differences in vibration characteristics. In the present study, the peak particle velocity (PPV) and the dominant frequency (DF) induced by various blast-holes were compared based on onsite blasting experiments. Additionally, the inherent mechanisms of the vibration differences were discussed by analyzing rock fracture partitions induced by blasting, with the help of numerical simulation. Results indicate that the PPV and DF induced by presplitting blast-holes are generally higher than those induced by production blast-holes or smooth blast-holes, while the PPV and DF induced by production blast-holes and smooth blast-holes are at the same level. The charging structure, initiation mode, and burden size all play important roles in the blast damage distribution and the development of the plastic zone, which further affects the distribution of explosion energy. The peak vibration level and the spectral characteristics are mainly determined by the proportion of explosion energy converted into blast vibration and the development of the plastic zone.

1. Introduction
It is universally understood that blast vibrations are always considered the first negative effect of blasting excavation in the civil engineering of traffic, municipal, and hydropower projects, etc. When the vibration amplitude exceeds the damage threshold, the reserved rock mass and the surrounding structures or facilities will be seriously damaged [1]. Therefore, it is necessary to make efforts to control the blast vibrations during rock blasting excavation [2]. Taking the blasting excavation of a rock slope as an example, Figure 1 illustrates the commonly used contouring control blasting techniques, including presplitting and smooth blasting. In terms of the initiation sequence and the charging structure (see Figure 1), different kinds of blast-holes can be defined. As shown in Figure 1(a), presplitting blast-holes are fired prior to production blast-holes and buffering blast-holes. The smooth blast-holes are fired as the last sequence (see Figure 1(b)). Therefore, the burden of the presplitting blast-holes is usually bigger than that of the production blast-holes and smooth blast-holes. Moreover, the explosives in the contour blast-holes (i.e., the presplitting blast-holes and smooth blast-holes) are decoupled from the rock mass and are air-gap charged in the axial direction, so the explosives are laterally initiated by the detonating cord. The explosives charging in the production blast-holes and buffering blast-holes are initiated by the...
detonator. In fact, the buffering blast-holes weaken the production blast-holes, and they can be grouped together. As was stated above, different kinds of blast-holes have different blasting boundaries, which will further affect the vibration characteristics.

**Figure 1.** Illustration of the contouring control blasting techniques for rock slope excavation.

Numerous studies about the PPV induced by different blast-holes have emerged in the past several years. Yang et al. [3] analyzed the PPV attenuation laws induced by presplitting blast-holes and production blast-holes, based on the onsite monitoring data. Sanchidrián et al. [4], found that the burdens have obvious influences on the distribution of explosion energy, which will further affect the PPV. Blair et al. [5] investigated the PPV variation behavior under different burdens and initiation modes, with the help of laboratory tests and numerical models. As the blast damage of structures is also associated with the frequency, a frequency-based PPV safety criterion was put forward and indexed in most regulations in recent years [6]. The frequency characteristics of blast vibration are complex. Zhou [7] discovered that the blasting source, rock properties, and initiation modes all have influences on the frequency spectrum, and the DF decreases as the blasting pressure and duration increase. Yang and Lu [8] found that the superimposition of back-propagating tensile stress waves reflected from the free surface and the initial stress waves can lessen the increase and duration of blasting pressure. Rao et al. [9] found that the generation of presplitting cracks also affects the frequency spectrum.

The influence factors of blast vibration are complicated, such as charging structures, initiation modes, burden conditions, etc. However, previous studies rarely considered those different influence factors comprehensively. In this paper, based on onsite blasting experiments and numerical simulations, the PPV and frequency spectrum induced by typical kinds of blast-holes were compared and analyzed. Consequently, the inherent reasons for vibration differences induced by various blast-holes were investigated. This study is helpful for enhancing the understanding of vibration characteristics and can provide a reference for blast vibration safety control.

2. Blasting experiments at Baihetan Hydropower Station

2.1. Experimental design

Baihetan Hydropower Station is located in the lower reaches of the Jinsha River. It is the second step of the four cascade hydropower stations, including Wudongde, Baihetan, Xiluodu, and Xiangjiaba hydropower stations. To compare the vibration characteristics induced by different blast-holes, a horizontal presplitting blasting experiment and a horizontal smoothing blasting experiment were carried out during the dam foundation excavation. The layouts of blast-holes and charging structures in the two experiments are similar: both include vertical production blast-holes and horizontal contour blast-holes. The burden and spacing of the vertical blast-holes were both designed as 1.8 m, while the spacing of the horizontal contour blast-holes was 0.6 m.

Nonelectric millisecond (MS) detonators were used to delay the blasting network. To separate the vibration waveforms of the production blast-holes, the first two or three shot blast-holes were delayed by MS9 (310 ms), as shown in Figure 2. The drilling and blasting parameters are listed in Table 1, and Figure 3 illustrates the charging structure of typical blast-holes. It needs to be pointed that the horizontal smooth blasting experiment was divided into two blasting events. First, the production blast-holes were fired. Then, after the rock fragments were cleared and the vibration sensors were installed, the smooth blasting was conducted.
The first blasting surface
The second blasting surface

Figure 2. Blasting initiation network.

The monitoring holes were drilled before blasting, and the vertical vibration sensors, CDJ28, made by Chongqing Geological Instrument Factory, China, were installed within the monitoring holes. They were placed at 1.0 m, 1.5 m, and 2.0 m below the foundation surface. Figure 4 plots the positions of the monitoring points.

Figure 3. Typical charging structures.

(a) Production blast-hole (b) Contour blast-hole (c) Monitoring points in production blasting

Figure 4. Layout of the monitoring points.

Table 1. Drilling and blasting parameters.

| Blast-hole type        | Diameter /mm | Depth /m | Stemming /m | Charge weight /kg | Charge diameter /mm |
|------------------------|--------------|----------|-------------|-------------------|---------------------|
| Presplitting blast-hole| 76           | 10       | 1           | 2.2               | 32                  |
| Smooth blast-hole      | 76           | 10       | 1           | 2.2               | 32                  |
| Production blast-hole  | 90           | 5.3      | 1           | 4.3               | 70                  |

2.2. Test results

Table 2 lists the measured PPVs induced by different kinds of blast-holes. Figure 5 plots the typical blast vibration waveform measured by the #1 vibration sensor. For comparison, the recorded boreholes were adjacent to and evenly distributed on both sides of the monitoring boreholes. To better record the PPV induced by different blast-holes, left and right designations were used to represent the blast-holes located on the left and right sides of the monitoring hole, respectively. As shown in Figure 5, the PPV induced by presplitting blast-holes is 32.3 cm/s, which is relatively larger than that induced by smooth blast-holes or production blast-holes, which are 14.6 cm/s and 13.8 cm/s, respectively. Moreover, Table 2 indicates that the PPVs all gradually attenuate with distance.
As shown in Figure 6, the frequency spectra of production blast-holes and smooth blast-holes are similar. The dominant frequency (DF) is located from 0 Hz to 50 Hz. The DF of the presplitting blast-holes is 50 Hz to 100 Hz, relatively larger than those of the production blast-holes or smooth blast-holes. As was stated above, the test results indicate that the PPV and DF induced by presplitting blast-holes are both larger than those induced by production blast-holes or smooth blast-holes. The PPV and DF induced by production blast-holes approximates those induced by smooth blast-holes. The reasons for the vibration differences induced by various blast-holes will be further analyzed in the following section.

Table 2. PPVs induced by different kinds of blast-holes.

| Monitor point | Presplitting blast-holes (cm·s⁻¹) | Production blast-holes (cm·s⁻¹) | Smooth blast-holes (cm·s⁻¹) |
|---------------|-----------------------------------|---------------------------------|-----------------------------|
|               | Left | Right | Left | Right | Left | Right | Left | Right |
| #1            | 20   | 32.3  | 13.8 | 10.1  | 14.6 | 8.1   |
| #2            | 20.7 | 20    | 12.4 | 9.2   | 10.7 | 7.6   |
| #3            | 23.7 | 14.6  | 3.6  | 2.9   | 11.4 | 7.2   |

Figure 6. Comparison of the amplitude–frequency spectra of vibration signals induced by different blast-holes.

3. Comparison of blasting responses of different blast-holes based on numerical simulation

3.1. Establishment and verification of the numerical model

3.1.1. Material parameters of the numerical model

The Jones–Wilkins–Lee (JWL)[10] equation of state was used to simulate the detonation process of the explosive. The relationship between detonation pressure, volume, and explosive energy can be described as Eq. (1).

\[
P_d = A \left(1 - \frac{\omega}{R_a V}\right)e^{-\frac{\omega}{R_a V}} + B \left(1 - \frac{\omega}{R_b V}\right)e^{-\frac{\omega}{R_b V}} + \frac{\omega E_i}{V}
\]

Where \(P_d\) is the detonation pressure; \(A_1, B_1, R_1, R_2\), and \(W\) are independent parameters related to the explosive properties; \(V\) is the relative volume of detonation products; and \(E_i\) is the initial value of the detonation energy per unit volume. Table 3 lists the related parameters of the explosive [11].

Table 3. Jones–Wilkins–Lee parameters of the explosive.

| Density(kg/m³) | VoD(m/s) | PCJ(GPa) | A(GPa) | B(GPa) | \(R_1\) | \(R_2\) | \(\omega\) |
|---------------|----------|----------|--------|--------|---------|---------|---------|
| 1630          | 6690     | 21       | 373    | 3.747  | 4.15    | 0.9     | 0.35    |

Table 4. Parameters used in the RHT model for rock
The RHT model was used in the numerical simulation for the rock mass. Strain hardening, softening, and the third invariant of stress deviation are considered in this model. The RHT model has been widely used to simulate the response and damage fracture of concrete, showing a great agreement with laboratory and field experiments. The detailed parameters of the RHT model [11] are provided in Table 4.

### 3.1.2. Numerical simulation cases

To further investigate the influences of charging structures, initiation modes, and burden sizes on damage distribution and plastic zone development, three comparative numerical cases were designed.

1. **Charging structures**
   
   As shown in Figure 7, a plane strain model measuring 5 m × 5 m was developed to simulate the influences of different charging structures, and the explosives in the blast-holes are a coupling charge, decoupling coefficient of 1.5, and decoupling coefficient of 2.0. The diameter of the explosive was 32 mm. The RHT material was simulated using a Lagrangian algorithm, while Eulerian elements were used for the explosive. The model was built using quadrilateral elements with a minimum size of 0.5 mm × 0.5 mm, and a nonreflecting boundary was applied to all surfaces to avoid artificial wave reflections.

2. **Initiation modes**
   
   To study the influence of initiation modes, lateral initiation and bottom initiation conditions were simulated in an axisymmetric model. As shown in Figure 8, the size of this model is 5 m × 5 m and the lengths of the stemming and explosive are 0.5 m and 1.0 m, respectively, with a diameter of 32 mm. The model was built using quadrilateral elements with a minimum size of 0.5 mm × 0.5 mm. The top surface of the model was set as a free surface boundary, while a nonreflecting boundary was applied to the other surfaces. Moreover, a growth reaction model was added to simulate the nonideal detonation, and the related parameters are listed in Table 5.

3. **Burden sizes**
   
   To study the influence of different burden sizes, a plane strain model with burdens of 2.0 m, 1.5 m, and 1.0 m was constructed (see Figure 9). The size of the model is 5 m × 5 m, and the diameter of the explosive is 32 mm. The top surface of the model was set as a free surface, while a nonreflecting boundary was applied to the other surfaces.

### 3.1.3. Verification of numerical simulation parameters

Banadaki [12] captured blasting-induced fracture patterns in laboratory tests. A similar numerical model was built to verify the reliability of the material parameters used in the described numerical cases. The results are provided in Figure 10. It indicates that the rock damage contours and crack propagation calculated by numerical models are similar to the laboratory tests. The numerical crush zone around the blast-hole is 4.5 times the diameter of the blast-hole, while that of laboratory test results is five to six times the diameter of the blast-hole. So, these material parameters are feasible.

### Table 5. Parameters of ignition and growth reaction rate

| I/($\mu$ s$^3$) | a | b | c | d | g | x | y | z | G1/(GPa$^{\gamma_{s+1}}$) | G2/(GPa$^{\gamma_{r+1}}$) |
|----------------|---|---|---|---|---|---|---|---|------------------------|------------------------|
| 50             | 3.7| 0.03| 0| 0| 0.66| 4| 0| 1.2| 0                      | 0.861                  |

**Figure 7.** Numerical models under different charging structures.

**Figure 8.** Numerical models under different initiation modes.
3.2 Numerical simulation results under different charging structures

Figure 11 shows the damage contours under different charging structures. The results indicate that the rock damage and cracks induced by blasting evenly radiate from the blast-hole center. With the increase of decoupling coefficient, the area of the crush zone gradually decreased, as did the rock crack density. The diameter of the crush zone under a decoupling coefficient of 2.0 is 53% of that under a coupling charge, while the crack zone diameter under a decoupling coefficient of 2.0 is 84% of that under a coupling charge. This is because the air barriers in the blast-holes weaken the blast loading pressure, which results in a smaller crush zone area and lower crack density. So, more explosive energy is used for rock breaking and throwing, and less is converted into vibration energy.

3.3. Numerical simulation results under different initiation modes

Figure 12 shows the damage contours under lateral initiation by detonating cord and bottom initiation by detonator. There are time and direction effects of detonation wave propagation in the cylindrical blast-holes. When the explosive is bottom initiated, the explosion energy is transmitted upward, so the damage contour is an erect funnel. However, when the explosive is lateral initiated by the detonating cord, the detonation wave propagates along the radial direction, and the time and direction effects of the detonation wave along the axial direction can be ignored. So, the damage contour under lateral initiation is an approximately uniform distribution.
To minimize the blast-induced damage to unexcavated rock mass, the explosives in the presplitting blast-holes generally use decoupled charging in the rock mass, and are laterally initiated by the detonation cord. Moreover, the presplitting blast-holes are always initiated before the production blast-holes, so the burdens of the presplitting blast-holes are larger than those of the production blast-holes. The numerical results (Figures 11, 12, and 13) indicated that the crush zone and crack zone will be decreased under lateral initiated, decoupled charging, and smaller burdens so less explosive energy will be used for rock fragmentation and more will be transmitted into vibration energy. Therefore, the PPVs
induced by presplitting blast-holes are higher than those induced by production blast-holes and smooth blast-holes (Figure 5). The charge structures and initiated modes of smooth blast-holes are similar to those of the presplitting blast-holes, but the burdens of smooth blast-holes are smaller than those of production blast-holes and presplitting blast-holes. So, the outer blasting effects of smooth blast-holes are stronger, and the blasting-induced rock damage and plastic zone are approximately equal to those of the production blast-holes. The explosive energy used for blast vibrations is also at the same level, as well as the PPV.

Influence factors on blast vibration DF are complex. Zhou [13] put forward a DF attenuation formula based on a spherical charge.

\[ f = \frac{\zeta}{Q_{10}^3} \left( \frac{Q}{R} \right)^\beta \]

\[ Q = \frac{4}{3} \pi q a_o^3 \]

Where, \( \zeta \) and \( \beta \) are the site coefficients; \( C_p \) is the longitudinal wave velocity; \( a_o \) is the plastic zone radius; and \( R \) is the distance from the explosive source.

\( \beta \) is found to be between 0.6 and 0.8 by fitting the onsite experimental data, which indicates that the radius of plastic zone \( a_o \) is inversely proportional to the DF \( f \). As shown in Figures 11, 12, and 13, the charge structure, initiation modes, and burdens are related to the development of the plastic zone. The plastic zone radius under a decoupling charge and lateral initiation was obviously smaller than that under a coupling charge and bottom initiation. Moreover, with the decrease of burden, the external effects of rock blasting promote the development of the plastic zone, which makes the radius of the equivalent plastic zone increase. As was stated previously (Section 1), the explosives in presplitting blast-holes decoupled with the rock mass, and laterally initiated by the detonating cord. Moreover, the burden of presplitting blast-holes is always larger than that of main blast-holes. So, the plastic zone radius of the presplitting blast-holes is smaller than that of production blast-holes and smooth blast-holes, the DF is generally higher than that of production blast-holes and smooth blast-holes (as shown in Figure 6).

5. Conclusion

In this paper, onsite blasting experiments and numerical simulations were conducted to investigate the differences of blast vibration induced by different kinds of blast-holes. Some conclusions can be drawn as follows:

1) The blasting experiments indicate that the PPV and DF induced by presplitting blast-holes are generally larger than those induced by production blast-holes and smooth blast-holes, while the PPV and DF induced by smooth blast-holes are approximately equal to those induced by production blast-holes.

2) The differences between various blast-holes are mainly concentrated on the charging structures, initiation modes, and burden sizes, which affect the blasting damage distribution and plastic zone development. The PPV is mainly determined by the proportion of explosion energy converted into blast vibration, while the DF is associated with the development of the plastic zone.

3) The explosive in presplitting blast-holes always decoupled from the rock mass and was laterally initiated by the detonator cord. The burdens of the presplitting blast-holes are larger than that of production blast-holes and smooth blast-holes. The blasting damage area and plastic zone radius decrease, as more explosive energy is used for rock breaking and throwing. Therefore, more explosion energy is converted into vibration energy.

4) Smooth blast-holes have similar charging structures and initiation modes as the production blast-holes. But the burden of smooth blast-holes is smaller, which strengthens the external effects of blasting. Therefore, the blasting damage and explosive energy distribution of smooth blast-holes are similar to those of the production blast-holes.

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