Experimental study of blasting wave propagation in jointed rock mass and vibration reduction effect of barrier holes

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Abstract. Blasting in underground rock opening could generate shock waves, propagating in surrounding rock mass and possibly leading to damage and instability of surrounding underground structures. Barrier holes are widely used in blasting vibration reduction. However, characteristics of blasting wave propagation in jointed rock masses have not been well determined, and the understanding of effect of barrier holes on vibration reduction is still at its infancy. To investigate the blast-induced wave propagation in jointed rock masses and vibration reduction effect of barrier holes, laboratory explosion tests were performed with the super dynamic strain test system and vibration monitor system. Results showed that the joint orientation has significant effects on the first-peak compressive strains in surrounding rock mass and adjacent opening. First-peak compressive strain of surrounding rock mass increases with decreasing scaled distance. The first-peak compressive strain on the wall of the adjacent underground opening is dependent on the characteristics of the adjacent underground opening. In addition, the dynamic responses of the surrounding rock mass are determined by the combined influence of the joint dip angle and location. The experimental results also indicated that barrier hole diameter has great effects on first-peak compressive strains of adjacent underground opening and the vibration-isolation rate of measuring points before and after barrier hole screen. With increasing barrier hole diameter, first-peak compressive strains and peak particle velocities (PPVs) significantly decrease and vibration-isolation rate of measuring points before and after barrier hole screen increases, indicating the vibration reduction effect of barrier hole increases. The findings in this paper could facilitate better understanding blasting wave propagation in jointed rock mass, and be helpful in vibration control of engineering explosions.

Keywords: Explosion; Wave propagation; Rock joint; Barrier hole

1. Introduction

The underground blast constructions are widely used in underground mining and civil engineering for drilling and blast excavation. Blasting induced wave propagation in the rock mass would bring damage to structures near work areas [1-4]. In natural rock masses, complex discontinuities such as joints, faults, fractures, bedding planes or apertures, determine the mechanical behavior of rock masses which would cause wave energy dissipation [5-9]. Explosion stress wave would be reflected and diffracted when it propagates to discontinuity, resulting in reduction of wave propagation energy [10-13]. It is common to lower blasting vibration by setting artificial discontinuity between explosion source and protected
structures, e.g. drilling barrier holes [14-15]. Therefore, it is of great significance to study the blasting wave propagation in jointed rock masses and vibration reduction effect of barrier holes.

The influence of the joint properties on the wave attenuation have been investigated with theoretical analysis [12, 16-18] and numerical methods [1, 10, 19-21]. Some empirical formulas were proposed according to the field test results to describe the dynamic responses of surrounding rock mass and structures [22-24]. In addition, various of numerical methods, e.g., discrete element method [25], finite element method [26, 27] have been used to study effect of barrier holes on blasting ground vibration. In comparison with numerical methods, experiments could show blasting events more realistically. Erarslan et al. [28] and Uysal et al. [29] adopted field experiments to investigate effect of empty holes and water-filled holes on ground motions. Shortcomings such as heavy calculations in numerical modelling with complex engineering environment and high cost of big scale explosion field tests contribute to the alternative and application of the model test. However, few laboratory experiments have been conducted so far for blast wave propagation in rock masses with barrier holes between explosion cavern and adjacent opening.

In this paper, laboratory explosion tests with mortar test blocks were carried out to systematically study effects of joint dip angle and different barrier hole diameter on explosion stress wave attenuation and dynamic responses of adjacent opening. These researches could provide a reference for the stability assessment of underground structures, disaster prevention and reduction projects.

2. Experimental setup

2.1. Mortar test block and explosive preparation

A series of explosion tests were carried out in Huainan, China, to investigate the explosion, the dynamic response of jointed rock mass and vibration reduction effect of barrier holes. The physical and mechanical properties of the cement mortar were similar to those of the rock, which is an economical material and appropriate in moulding. The weight ratio of cement, sand and water is 1:2:0.6. The ordinary portland cement 32.5 and the yellow sand in Huainan were used.

Figure 1 shows cement mortar block with joints. The size of the sample is 750 mm × 750 mm × 400 mm. Two openings with semicircular arches (100 mm in diameter and 100 mm high) were included in the model with a separate distance of 220 mm. One joint set was included in the sample with a uniform joint spacing of 100 mm, and the joint normal and shear stiffness were measured as 72.9 GPa/m and 5.3 GPa/m with a series of laboratory tests. In this test, 18 test blocks with horizontal joint set and inclined joint set (15°, 30°, 45°, 60° and 75°) were made. When preparing the test blocks, the cement mortar was poured, and virgin wood pulp papers were laid flatly before pouring the next layer cement mortar. Since the virgin wood pulp paper was sufficiently thin with respect to the wavelength of blast-induced waves, the simulated joint was considered as a discontinuous interface. Parallel discontinuous planes were embedded in the test block to constitute one joint set. When the joint dip angle is inclined, the mold was fixed obliquely to satisfy the design of the joint dip angle. The mold was removed after 48 hours at which time the cement mortar reached a certain strength, and then the new formed cement mortar block was cured for 28 days to meet the test requirement. Figure 1(a) shows the cement mortar blocks with joints in this test.

Figure 2 shows cement mortar block with barrier holes. The size is 800 mm×600 mm×400 mm. Diameters of two chambers are both 200 mm, the net spacing between two openings is 200 mm. The left is the explosion opening, and the right is adjacent opening. A certain number of barrier holes are set between the two openings. Barrier hole diameter varies from 5 mm to 15 mm, and other parameters are presented in table 1. The cement mortar block mold is composed of 5 special steel plates and two steel cylinders as shown in figure 2(b). The two cylinders are used to simulate two cavities, and barrier holes are formed by inserting smooth steel bars into mortar blocks and pulling out these steel bars after maintenance.
**Figure 1.** Cement mortar block with joints: (a) Cement mortar block; (b) cement mortar block pouring mold; (c) schematic diagram and measuring point layout.

**Figure 2.** Cement mortar block with barrier holes: (a) Cement mortar block; (b) cement mortar block pouring mold; (c) schematic diagram and measuring point layout.

**Table 1.** Barrier hole parameters.

| Test content                     | Test block number | Barrier hole diameter (mm) | Barrier hole spacing (mm) | Distance from explosion source to barrier hole (mm) | Barrier hole row |
|----------------------------------|-------------------|---------------------------|--------------------------|-----------------------------------------------------|-----------------|
| Variation of barrier hole diameter | 1#, 2#            | 5                         | 50                       | 150                                                 | 1               |
|                                  | 3#, 4#            | 10                        | 50                       | 150                                                 | 1               |
|                                  | 5#, 6#            | 15                        | 50                       | 150                                                 | 1               |

The RDX, nonel detonator, sand and glue were encapsulated in a glass tube with diameter of 15 mm. Cylindrical charges in the test consist of 2 g RDX, which was detonated by the nonel detonator made of 1 g RDX. The cylindrical charge was placed in the center of the explosion chamber and fixed by two cardboards. Both ends of the explosive chamber were plugged with viscous mud stemming to guarantee the sealed explosion.

2.2. Testing system

To investigate the blasting wave propagation in jointed rock mass, the strain-time histories of the measuring points a-h or measuring points 1-4 in the block were recorded by the transient dynamic strain gauge testing system. The locations of these measuring points are shown in figures 1(c) and 2(c). For the test blocks with joints, three measuring points a-c are located in the vertical direction above the
explosion opening and three measuring points d-f are located in the horizontal direction on the right side of the opening horizontally. Two measuring points g and h are located close to the adjacent opening walls. The distances from measuring points a, b, c, d, e, f, g and h to the explosion center are 100 mm, 200 mm, 300 mm, 100 mm, 200 mm, 300 mm, 160 mm and 270 mm. For the test blocks with barrier holes, measuring points 1 and 2 are located on the left lateral wall and the vault, and two measuring points 3 and 4 are arranged in front of and after barrier hole screen respectively.

The transient dynamic strain gauge testing system consists of strain measuring elements, a LK2107A super dynamic strain gauge, a TST3406 dynamic test analyser and a 1/4 bridge box connection as shown in figure 3. The strain measuring elements, i.e., strain gauges pasting on the cement mortar strain brick, are linked to the testing system through the bridge box connection. In the blasting process, the deformation of the strain gauge led to the change of its resistance, resulting into the change of output voltage. The relationship between the strain $\varepsilon(t)$ of the strain gauge and output voltage $\Delta U(t)$ is listed as follows:

$$\varepsilon(t) = \frac{4\Delta U(t)}{K_1K_2U_0}$$  \hspace{1cm} (1)$$

where $K_1$ (=2.11) is the gage factor of the strain gauge; $K_2$ is the gain factor, which is 200 herein; and $U_0$ (=2 V) is the bridge voltage.

Vibration-isolation rate is adopted to describe vibration reduction effect of barrier holes. It is calculated according to

$$f = \frac{V - V'}{V}$$  \hspace{1cm} (2)$$

where $f$ is vibration-isolation rate; $V$ is peak strain or PPV of measuring point in front of barrier hole screen; $V'$ is peak strain or PPV of measuring point after barrier hole screen.

![Figure 3. Transient dynamic strain gauge testing system: (a) LK2107A super dynamic strain gauge; (b) TST3406 dynamic test analyzer; (c) 1/4 bridge box connection.](image)

3. Results and Discussion

3.1. Effect of joint orientation

Every three test blocks for six dip angles, i.e., 0°, 15°, 30°, 45°, 60° and 75°, are designed and tested to study the effect of joint orientation on the blasting wave propagation. The explosive charge weight is all 3 g RDX whose charge loading density is 1.68 kg/m$^3$. The strain-time histories of measuring points a-h in the block were obtained.

Figure 4 shows the first-peak compressive strains at measuring points a-h with different joint dip angle. The strain values of every measuring points a-f for different joint dip angle in the figures 4(a) and 4(b) are calculated from three parallel tests. The error bars are added according to their standard deviations. It can be found that first-peak compressive strain of surrounding rock mass increases with decreasing scaled distance. As the joint dip angle increase, the first-peak compressive strain of
measuring points a, b and c in the vertical direction showed an increasing trend and reached the maximum when the dip angle is 75° as shown in figure 4(a). The main reason is more wave energy could be transmitted through the jointed rock mass when wave propagates in the direction parallel to the rock joint. Transmission coefficient increases with increasing incident angle with respect to the joint plane [10, 21]. In previous field measurement analyses, it also showed wave attenuates fastest if it propagates in the direction perpendicular to rock joint set, while it attenuates slowest if it propagates in the direction parallel to the rock joint set [5, 30]. Nevertheless, the first-peak compressive strain of measuring points d, e and f in the horizontal direction first increased and then decreased with increasing joint dip angle, and the first-peak compressive strain reached the maximum for measuring points d and e when the dip angle is 15° and for measuring point f when the dip angle is 45°. This phenomenon was related to the relative spatial position of the explosion source, measuring point and joint. In these condition, the incidence angle of the remaining waves is close to 0° which contributed to the wave transmission through joint and most stress waves would propagate to the measuring points without going through any joint. To observe the dynamic effect of the blasting wave on the adjacent opening, figure 4(c) shows the first-peak compressive strains at measuring points g and h with different joint dip angle. We can notice that owing to the barrier action of cavity on wave propagation, the values at measuring point g are larger than that at h. When the joint dip angles were 15° and 30°, the first-peak compressive strains were relatively large. It is because there is no joint between the measuring point g and explosion source, and the wave propagation direction is almost parallel to the rock joint in these two cases.

**Figure 4.** The first-peak compressive strains at measuring points a-h with different joint dip angles.

3.2. Effect of barrier hole diameter

Barrier holes could disturb blasting induced wave propagation by reflection and refraction, weaken energy of stress wave, and achieve vibration reduction effect, which is affected by change of barrier hole parameters. In this section, based on analyzing explosion test results, effects of barrier hole diameter on stress wave propagation are discussed.

Figure 5(a) shows effect of barrier hole diameter on horizontal first-peak compressive strains of adjacent opening. It can be seen that horizontal first-peak compressive strains at measuring point 1 on left side of adjacent opening and measuring point 2 on roof of adjacent opening both decrease significantly with barrier hole diameter increasing, which indicates that larger barrier hole diameter has better attenuation effect on blast-induced wave propagation. Effect of barrier hole diameter on horizontal vibration-isolation rate is illustrated in figure 5(b). It can be seen that with increase of barrier hole diameter, horizontal vibration-isolation rate rises rapidly. That is, when explosion stress wave passes through barrier hole screen, its energy would be lost. The larger barrier hole diameter, the greater energy loss of stress wave. Thus, vibration isolation effect is enhanced.

Barrier hole screen is a kind of discontinuous screen. When barrier hole diameter increases, discontinuous property of barrier holes enhances, the net spacing between barrier holes reduces, stress wave reflection improves, diffraction path increases, which causes that energy consumption of explosion stress wave grows and vibration reduction effect enhances. Therefore, considering site engineering conditions, cost budget and

[Diagram of first-peak compressive strain vs. joint dip angle for measuring points a, b, c, d, e, f, g, h]
vibration reduction requirements of structures, selecting a larger barrier hole diameter could effectively enhance vibration reduction effect in actual blasting projects.

![Graphs showing first-peak compressive strain and vibration-isolation rate](image)

**Figure 5.** Effect of barrier hole diameter: (a) Horizontal first-peak compressive strains at measuring points 1 and 2; (b) horizontal vibration-isolation rate at measuring point 3-4.

### 4. Conclusion

Cement mortar explosion tests with joints or barrier holes were conducted. The effect of joint dip angle, and barrier hole diameter on blasting wave attenuation, dynamic response of adjacent opening was analysed. The vibration reduction effect of different barrier hole parameters was investigated. Main conclusions are listed as follows:

1. Both the joint orientation and barrier holes have significant effects on the first-peak compressive strains in surrounding rock masses and the adjacent opening.
2. As the joint dip angle increases, the first-peak compressive strain increases for measuring points a, b and c in the vertical direction and increases before decreases for measuring points d, e and f in the horizontal direction. First-peak compressive strain of surrounding rock mass decreases with increasing scaled distance. These phenomena were related to the relative spatial position of the explosion source, measuring point and joint, which corresponds to the incident angle of the blasting wave.
3. The first-peak compressive strain on the wall of the adjacent opening is dependent on the combined influence of the joint dip angle and measuring point location.
4. With increase of barrier hole diameter, horizontal first-peak compressive strains of adjacent opening decrease significantly, and vibration-isolation rate increases rapidly, which shows that increasing barrier hole diameter could improve explosion stress wave energy dissipation, and vibration reduction effect would be enhanced. In real engineering, properly increasing barrier hole diameter is an effective choice to improve vibration reduction effect.

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