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Short-delay blasting with single free surface: Results of experimental tests

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ABSTRACT

Delay blasting with relatively long-delay intervals is widely used in mining engineering since the former detonated blast-holes can produce new free surfaces for the later detonated blast-holes. With the application of electronic detonators, which have a minimum delay and a delay accuracy of 1 ms, a new blasting pattern using short-delay intervals is proposed in the present study in order to improve rock breaking and control blast-induced vibrations in cutting blasting with single free surface in underground mines. Theoretical analyses are firstly conducted to investigate the mechanisms of blasting crater formation and vibration reduction of short-delay blasting. Then a series of blasting crater tests with different delay intervals are performed to compare the characteristics of blasting craters and blast-induced vibrations produced by short-delay and simultaneous blastings. The results of crater sizes show that it is possible to form a common blasting crater only when the delay intervals are shorter than the formation time of a new free surface. It is also found that the short-delay blasting can effectively reduce PPV compared with the simultaneous blasting, particularly in the near-field. Spectral analysis indicates that there is less energy in the low-frequency content in short-delay blasting than simultaneous blasting. The possibility and feasibility of reducing vibration via short-delay blasting in underground mines are also discussed in this study.

1. Introduction

The use of blasting for hard rock fragmentation is widely adopted in mining and quarrying engineering (Nateghi, 2012; Changping et al., 2017). In rock blasting, delay blasting technique is an effective measure to improve rock breaking and reduce blast-induce vibration by controlling the initiation time and sequence of detonators (Wu et al., 2004; Aldas and Ecevitoglu, 2008; Shi and Chen, 2009). Researchers have conducted small-scale experiments, field trials and numerical simulations to investigate the influence of delay intervals on rock fragmentation and blast-induced vibration (Tatsuya et al., 2000; Yi et al., 2015; Katsabanis et al., 2006). Delay blasting with long-delay intervals is widely used in mining engineering since the former detonated blast-holes can produce new free surfaces for the later detonated blast-holes (Shi et al., 2016a). With the application of electronic detonators, which have a minimum delay and a delay accuracy of 1 ms, a new blasting pattern using short-delay times was proposed in order to improve rock breaking and control blast-induced vibration (Rossmanith, 2002).

Rock blasting researchers have long tried to improve fragmentation via stress wave interaction between adjacent blast-holes in short-delay blasting. By constructing a 2D model, Rossmanith (2002) and Rossmanith and Kouzniak (2004) showed how a positive effect of shock wave interaction could be achieved. Field observations by Vanbrabant and Espinosa (2006) showed that the average fragmentation was improved by nearly 50% by choosing the delays such that an overlap of the P-wave particle velocity was created. Blair (2010) indicated that the stress waves in the field were markedly different in shape and that even if stress wave superposition did occur, there was only a localized range where it could improve fragmentation. Johansson and Ouchterlony (2013) carried out small-scale tests on short-delay detonations and concluded that there were no obvious differences in fragmentation when the delays were in the time range of stress wave interactions compared with no interactions. The numerical results of Yi et al. (2016) also indicated that it was impossible to increase fragmentation via stress wave interaction. Li et al. (2017) studied the mechanism of crack propagation in smooth blasting excavation under short-delay intervals. On the other hand, there is much less literature concerned about the vibration effect of short-delay blasting. Blair (2010) provided an extensive discussion and noted that there was no possibility of channelling energy into higher frequencies by using short-delay intervals. Qiu et al. (2017) made some primary attempts to investigate the vibration reduction effect of short-delay blasting. However, until now, there are unfortunately no final conclusions on rock breaking and blast-induced vibration of short-delay blasting.

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It is noted that most of the previous studies focused on short-delay blasting were based on the blasting model in open-pit mines. Unlike open-pit engineering, and limited by the terrain, blasting in underground mines often associates with the situation of only a single free surface. Therefore, in order to increase blasting efficiency, cutting blasting must be carried out to artificially create new free surfaces for subsequent blasts. A typical cutting blasting scheme in underground mines involves simultaneously initiating explosive columns in several blast-holes which are arranged in a bunch with short spacing, and forming a large common blasting crater. A major challenge for this cutting blasting with a single free surface is to reduce the hazardous vibration since the charge weight per delay is very large. Shi et al. (2016a) noted that the short-delay blasting with the use of electronic detonators could be an effective way to solve this problem.

This study focuses on short-delay blasting with a single free surface in underground mines. Theoretical analyses are firstly conducted to investigate the mechanisms of crater formation and vibration reduction in short-delay blasting. Subsequently, a series of blasting crater tests with single and multiple blast-holes are performed to compare the characteristics of blasting craters and blast-induced vibrations produced by short-delay and simultaneous blastings.

2. Theoretical analysis of short-delay blasting

2.1. Mechanism of crater formation of short-delay blasting

According to Henrych and Abrahamson (1979) and Xahykaeb (1980), the crater formation process of single hole blasting with a single free surface can be described as follows. A shock wave firstly arises after the detonation of an explosive column in a borehole, and it causes a blasting cavity (crush area) as the detonation pressure exerted on the borehole wall at the moment of initiation can exceed 10 GPa (Zhu, 2009). It soon decays to a high-amplitude stress wave that propagates at the velocity of a longitudinal wave and causes radial cracks in the rock mass (Mchugh, 1983). The stress wave is immediately followed by a longer-duration gas pressure loading, which causes not only the further extension of the existing radial cracks but also new circular cracks. When the stress wave reaches the free surface, it transforms into a tensile stress wave. As the tensile strength is far less than the compressive strength of rock, the reflected tensile stress wave not only causes rock spalling on the free surface but also promotes the extension of the radial and circular cracks induced by the initial stress wave and the gas pressure. It then causes the coalescence of the rock spalling and the cracks. The on-going inflated gas pressure pushes the fractured rocks in the direction of the free surface and finally forms a blasting crater (Fig. 1a).

There is a depth limit for the blasting crater of single-hole blasting, which means that when the charge depth is longer than the optimum depth, the blasting crater will not increase with the increase of the charge depth. Because of this limit, several blast-holes arranged in a bunch with short spacing are simultaneously initiated to form a big common blasting crater. However, considering the large scatter of the pyrotechnic detonators used in most underground metal mines in China, the simultaneous cutting blasting is actually "short-delay blasting" with completely random delay intervals. Thus, it is possible to form a common blasting crater using short-delay intervals with the use of electronic detonators (Fig. 1b). In order to reduce blast-induced vibration, the short-delay cutting blasting in underground mines is proposed in this paper.

The crater formation process of short-delay blasting is as follows (Shi et al., 2016a). The former blast-hole detonates firstly and causes initial cracks around the hole and the free surface. After several milliseconds (e.g. 8 ms) the later blast-hole detonates and arises outspread stress waves. Apart from the conventional stress wave reflections in the free surface, there are also some interactions between the adjacent blastholes: complex stress wave reflections on the initial cracks induced by the former blasthole, and complex stress fields superimposed by the stress wave induced by the later blasthole and the gas pressure loading induced by the former blasthole. Drived by all these loadings, the crack coalescence between adjacent blastholes is formed. As the duration time of gas pressure loading is much longer than stress waves, the explosive gasses have not spilled out from the former blasthole at this point. Thus the explosive gasses induced by the adjacent blastholes gather together through the cracks, and pushes the fractured rocks in the direction of the free surface, which finally forms a common blasting crater. Different from the simultaneous blasting which promotes the stress wave superposition, there is scarcely stress wave superposition in the short-delay blasting. But the short-delay situation promotes stress wave reflections on the initial cracks induced by the former blast-hole, and causes stress fields superimposed by the stress wave induced by the later blast-hole and the gas pressure loading induced by the former blast-hole.

Determining the delay intervals for short-delay blasting is the key factor in the formation of the common blasting crater. If the delay intervals are longer than the formation time of a new free surface, as shown in Fig. 1c, there will be two free surfaces for the later detonated blast-hole: the initial free surface and the new free surface produced by the former detonated blast-hole. As a consequence, the processes of rock fracture for the former and later detonated blast-holes are completely separate, and thus it is impossible to form a common blasting crater. Therefore, the optimum delay interval for short-delay blasting with a single free surface must be shorter than the time required for the formation of a new free surface.

However, the determination of the formation time for a new free surface is still under discussion. Xahykaeb (1980) stated that the delay time should not be shorter than 20 ms to form a new free surface. According to Henrych and Abrahamson (1979), three different time intervals are included in the formation time of a new free surface: the time needed for the explosive stress wave to propagate to the free surface and return to the explosive, the time required for the crack to expand to the free surface, and the time required for the crack to continue expanding and form a new free surface with a certain crack

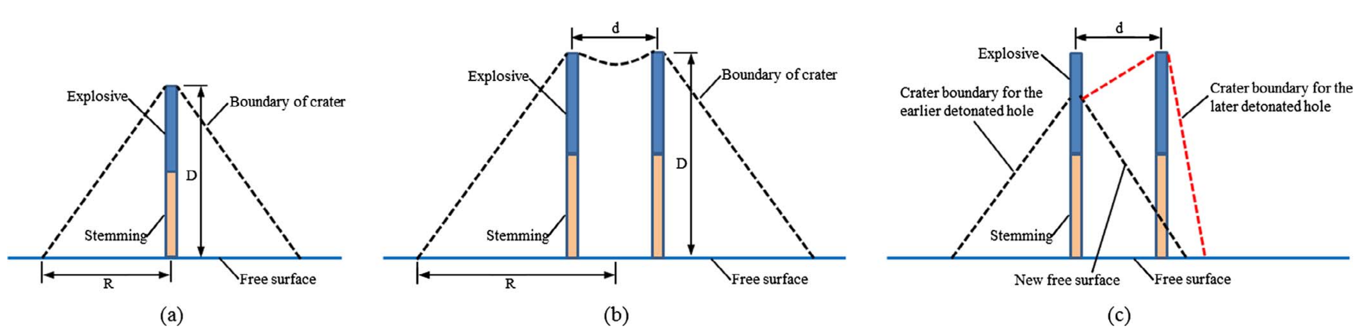

Fig. 1. Blasting crater models: (a) single blast-hole; (b) multiple blast-holes with a short delay interval; (c) multiple blast-holes with a delay interval longer than the formation time of a new free surface.