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Frequency comparison of blast-induced vibration per delay for the full-face millisecond delay blasting in underground opening excavation

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ABSTRACT

Responses and damage to the structures subjected to blast-induced vibration are highly dependent on vibration frequency. Understanding the vibration frequency characteristics and its formation mechanism is essential for the safe and economic design of mining and construction blasts. When millisecond delay blasting is used in excavation, a global frequency value of all of the delays of vibrations fails to present a true picture of the vibration frequency characteristics. In the present study, comparisons of frequency characteristics for the blast-induced vibration per delay were first conducted via an underground opening case excavated by the full-face millisecond delay blasting sequence. The results show that if the blasthole geometry and charge structure are kept the same in each blast delay, the frequencies of single-delay vibration signals will decrease as the dimensions of the equivalent blasting vibration sources increase. However, the cutting blast used for the headmost holes inside is an exception, and its vibration frequency is lower than that of the breaking blast outside. It is the authors' belief that this counter-intuitive phenomenon is caused by the free faces created by the cutting blast for the breaking blast. A small-scale blasting test and the related numerical simulation were subsequently performed to demonstrate this belief. It is found that the vibration frequency from the holes in the free-face blast is higher than that in the confined blast. In terms vibration frequency, therefore, the vibration from the breaking blast is less harmful to structures compared to the cutting blast for a certain velocity, and decreasing the burden of breaking blastholes is beneficial to reduce the vibrational damage of structures.

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1. Introduction

Rock fragmentation by drilling and blasting is widely used in mining, quarrying and civil engineering constructions. However, only 20–30% of the energy released during explosion is utilized directly for rock breakage, while the rest of the energy is dissipated in the form of ground vibrations, air blasts, flying rocks and noises (Hagan, 1977; Trivedi et al., 2014). Among all of the ill effects, blast-induced ground vibration adversely affects the integrity of surrounding structures such as buildings, dams, roads, pit slopes, and underground workings, and has become a major concern in mining and construction blasts (Khandelwal, 2010; Verma and Singh, 2013). When explosive charges are detonated in blastholes, intense dynamic stresses are initiated around the blastholes due to the instantaneous acceleration of rock masses caused by the detonation gas pressure on hole walls (Singh et al., 2008). The dynamic stresses spread away from the source into the surrounding rock masses in the form of wave motion, and the waves in the elastic zone are known as ground vibration. It is well known that three parameters of blast-induced vibration, i.e. peak particle velocity (PPV), frequency and duration play an active role in the relationship of blasting vibration and structural hazard. Some researchers emphasized the importance of the frequency content in the blasting vibration-induced structural damage because a resonance occurs and the resultant vibration amplitude on the structures gets amplified if the vibration has a frequency in the range of the natural frequency of the structures. Responses and damage to the structures subjected to blasting vibration of various frequencies have been extensively studied by means of wave theory, field tests and numerical simulation (Siskind, 1997; Ma et al., 2000; Ozer, 2008; Aldas, 2010; Singh and Roy, 2010; Sazid and Singh, 2013). It is generally accepted that a low-frequency vibration has a greater possibility of structural damage than a high-frequency vibration for a certain velocity because the natural frequency of the structures is generally below 10 Hz (Siskind, 1997; Ozer, 2008; Aldas, 2010; Singh and Roy, 2010). Ma et al. (2000) noted that although high-rise buildings have a natural frequency far

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away from the dominant frequency of the blast-induced vibration, it is still vulnerable because of the concentrated damage at low stories, which greatly affects the overall structural stability.

Frequency characteristics of blast-induced vibration are influenced by a variety of parameters, such as physico-mechanical properties of rock masses, explosive characteristics, propagation distances of waves, blasting geometry and sequence. It is well known that each type of rock mass and each terrain has a dominant transmission frequency that favors wave propagation for that frequency (Singh and Roy, 2010; Alvarez-Vigil et al., 2012). The dominant frequency of ground vibration on a soil surface is lower than that on a rock surface, and the deeper the soil layer is, the lower the dominant frequency of vibration is (Ma et al., 2000). In general, the frequency content of blasting vibration decreases with the increase in propagation distance. The Earth's crust is considered as a low pass filter, hence the high-frequency vibration component attenuates more rapidly than the low-frequency vibration (Singh et al., 2008). The presence of discontinuities in rock masses also contributes to the propagation of low-frequency vibration by filtering the higher frequencies (Park et al., 2009; Li et al., 2011b). Therefore, extra care must be taken for large blasts where low-frequency energy may exceed vibration limits at far distances. Explosive charge detonated per delay is one of the most important parameters related to blast-induced vibration. Ling et al. (2005) found that the ratio of the high-frequency energy to the total energy decreases with the increase of the maximum charge per delay. Ground vibration induced by different types of explosives conducted experimentally by Leidig et al. (2010) shows that black powder with relatively long blast duration and opening of long fractures, accentuates the low-frequency energy of the ground vibration, while Composition B causes more high-frequency energy of vibration as the detonation gases are unable to drive the long fractures. Yilmaz and Unlu (2013) stated that the most efficient explosive in rock fragmentation is the one with a low frequency content but a sufficiently high borehole wall pressure. There is a popular conception in the spectral control of ground vibration that a smaller delay interval generates a higher-frequency vibration, and it will be more readily attenuated in the ground, thus reducing the blasting vibration. However, Blair (2009) found that the delay time and accuracy can be used to control the frequency content of vibration just over a restricted distance range. Although some progress has been made in the propagation and attenuation laws of blasting vibration frequency, it is still much less compared to the large amounts of research achievements in the PPV. Therefore, it is significant to study the frequency characteristics and its mechanism of blast-induced vibration.

Because structural responses and damage characteristics are highly dependent on the vibration level and dominant frequency, to determine in which level of vibration the surrounding structures are damaged, many blasting vibration standards and damage criteria have been developed in terms of the PPV limits in combination with the dominant frequency of vibration (Rai et al., 2005; Singh and Roy, 2010; Aldas, 2010; Karadogan et al., 2014). According to these standards and criteria, structural hazard assessments were made by many authors using measured particle velocities and frequency values in the field (Ozer, 2008; Nateghi, 2011; Caylak et al., 2014; Yu et al., 2014).

In underground opening excavation, the full-face millisecond delay blasting technique is generally used to reduce the charge weight in a single fire for meeting the safety control criterion. It should be noted that in the current evaluation of ground vibration-structural hazard, a global frequency value which covers the vibration waves in all of the delays is always adopted to be compared with the frequency limits of the structural hazard standards and criteria. Actually, the global vibration frequency of all of the delays is unable to represent the actual frequency characteristics of blast-induced vibration very well because blasting geometry, charge characteristics and boundary conditions per delay of blast are not strictly consistent. Most obviously, cutting blastholes detonated in the first delay are blasted under a confined boundary condition, while breaking blastholes and contour blastholes detonated in the subsequent delays are blasted under free-face conditions. This study focuses on the frequency comparison of blast-induced vibration per delay for the full-face millisecond delay blasting in underground opening excavation. In the present study, analytical analyses and a case study are first conducted to find the frequency variation of the blast-induced vibration per delay. Subsequently, a small-scale blasting test and related numerical modeling are performed to explain the mechanism lying behind the frequency variation.

2. Analytical frequency spectrum of blast-induced vibration

The study of a blasting vibration frequency begins with the analytical frequency spectrum of blast-induced seismic waves to determine the factors influencing the vibration frequency. Blasting technology using cylindrical charges has found widespread application in underground opening excavation in mining, hydropower and transportation industries. A cylindrical charge can be divided into a series of spherical charges when analytically determining the blast-induced stress field, for example by using the Starfield superposition method. Thus, the frequency spectrum of blast-induced vibration just for the spherical charge is introduced in this section. It is generally accepted that during rock fragmentation by blasting, a crushed zone and a cracked zone are generated around a blasthole by explosion shock waves and subsequent explosion gas pressure where rock masses are broken or damaged to a different extent. The outer boundary of the cracked zone is located outside the region of individual far-reaching fissures, and it is also the beginning of the seismic zone where the propagation of stress waves is nearly elastic. Blast-induced vibration in the far field results from the propagation of elastic seismic waves. To analytically determine seismic wave propagation by the elastic wave theory, the concept of equivalent radius of the blasting vibration source is introduced here. In this concept, the crushed zone and the cracked zone are treated as parts of the blasting vibration source, and the blasting load is applied to the boundary of the equivalent blasting vibration source. Let an equivalent source of blasting vibration with radius r_e, be located in a homogeneous, isotropic and elastic medium, characterized by the elastic constants of Lame λ and μ and longitudinal wave velocity c_p. At the boundary of the equivalent source, the applied action $p_e(t)$ is (Kuzmenko et al., 1993)

$$p_e(t) = \sigma(t) \tag{1}$$

Dynamic disturbances arising from this action satisfy the wave equation

$$\frac{\partial^2 u}{\partial r^2} + \frac{2}{r}\frac{\partial u}{\partial r} - \frac{2u}{r^2} = \frac{1}{c_p^2}\frac{\partial^2 u}{\partial t^2} \tag{2}$$

where u is the particle displacement, r is the distance from the sphere center, and t is time.

The solution to Eq. (2) can be found in

$$u(t) = \frac{\partial f(\tau/r)}{\partial r} = -\frac{f(\tau/r)}{r^2} - \frac{1}{rc_p}\frac{\partial f(\tau/r)}{\partial \tau} \tag{3}$$

with $\tau = t - (r - r_e)/c_p$.

$f(\tau/r)$ is an unknown function which can be established from boundary conditions

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