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Influence of wavelength-to-excavation span ratio on ground motion around deep underground excavations

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ABSTRACT

Accurate estimation of ground motion around excavations is important for dynamic rock support design in deep civil tunnels and underground mines. Among the influencing factors, the wavelength-to-excavation span ratio (λ/D) has a large effect on ground motion. Using an advanced wave propagation simulation tool, we performed two series numerical experiments to study the effect of the λ/D ratio on ground motion near excavation boundaries. The modeling results reveal that the wave field becomes more complex as the λ/D ratio decreases. The absolute PPV (Peak Particle Velocity) values around an excavation are closely related to the intensity of the seismic source but the relative PPV value depends on the λ/D ratio. Amplification factors, defined as the PPV in the excavation model to the PPV in the background model without any excavation, are calculated for each case. The amplification factor around the excavation increases significantly as the λ/D ratio decreases. When the λ/D ratio is greater than 30, the wave amplitudes are less affected by the excavation and a seismic wave loading can be considered as "quasi-static." When the λ/D ratio is less than 20, significant wave interaction occurs and the wave loading needs to be considered as "dynamic." The numerical results provide additional insights into the ground motion behavior around excavations under both "quasi-static" and "dynamic" loading conditions.

1. Introduction

Compared with surface structures, underground structures such as subways, railway and highway tunnels, powerhouse caverns and nuclear waste repositories are more earthquake resistant (Chen et al., 2012a,b; Hashash et al., 2001; Ji et al., 2009; St John and Zahrah, 1987; Wang et al., 2001). Despite of this fact, many underground structures have experienced damage in recent large earthquakes and considerable effort has been devoted to addressing tunnel damage due to seismic loading (Abokhalil, 2007; Alejano et al., 2009; Aydan et al., 2010; Geniş, 2010; Kontoe et al., 2008).

The fact that deep civil tunnels (overburden depth $H > 60$ m) seem to be less vulnerable to earthquake shaking than shallow tunnels ($H < 60$ m) (Abokhalil, 2007; Hashash et al., 2001; Wang et al., 2001) can be attributed to several factors such as higher moduli of competent rock masses, smaller excavation dimensions relative to the dominant wavelength in deep grounds (e.g., Barton, 1984; Bhasin et al., 2008). For tunnels located in deep underground mines ($H > 1000$ m), seismic loading caused by fault-slip rockbursts can cause large damage to the openings. Several factors, such as high in-situ stress and highly non-uniform mining-induced stress, can alter ground motion in rock masses around underground excavations (Cai and Kaiser, 2002; Cai and Wang, 2015; He, 2006). Complex geology (e.g., dykes, faults, shear zones) and layout of the tunnel system (e.g., haulages, stopes, crosscuts, orepasses) can affect wave propagation. As shown in Fig. 1, a few high risk areas (denoted by red) such as highly stressed pillars and locations where dykes intersect mine openings can be expected in an active underground mine. More attention should be paid to these areas because additional seismic wave loading that can trigger rock mass failure in these areas.

Rockburst can cause large damage to underground mine infrastructures and pose a threat to the safety of mine personnel (Cai, 2013; Cai and Champaigne, 2009; Kaiser et al., 1996; Ortlepp and Stacey, 1994; Potvin et al., 2000; Zhang and Fu, 2008). Incoming seismic waves may be altered in their intensity near the excavation boundary which in turn can shake down loose rocks directly or trigger ejection of rocks in these high risk areas. Kaiser et al. (1996) proposed three rockburst damage mechanisms: bulking due to rock fracturing, ejection due to seismic energy transfer,

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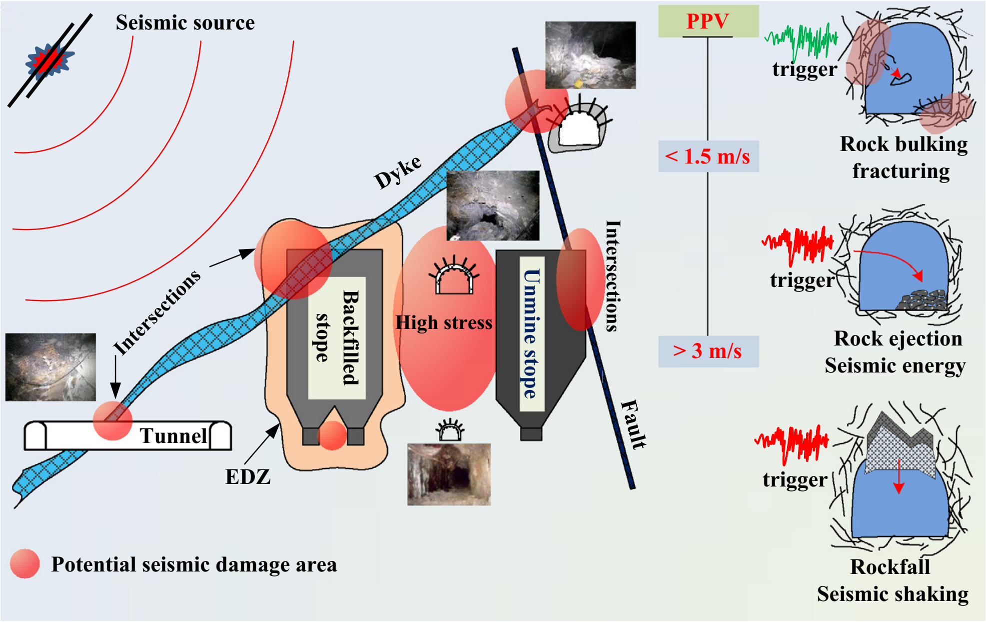

Fig. 1. A schematic drawing showing the complex environment in underground mines (left) and three rockburst damage mechanisms (right). All three rockburst damage mechanisms can be triggered by seismic wave loading. Modified from Hudyma (2013) and Kaiser et al. (1996).

and rockfall due to seismic shaking (right insert in Fig. 1). All the three damage mechanisms can be triggered by seismic wave loading caused by a remote seismic event. If a rock mass has already reached a stress state near failure, a small seismic wave disturbance is sufficient to trigger failure. If a rock mass is in a stress state not near failure, a large seismic wave disturbance can also cause rock mass failure.

Both the absolute values of PPV (Peak Particle Velocity) and the site amplification around excavations are of concerns in engineering design. Rock deformation moduli are reduced in fractured zones around excavations and various frequency contents (waves with multiple wavelengths) can be produced due to reflection and refraction of waves. Hence, seismically induced rockburst in underground excavations is complex and site-dependent.

The factors that affect ground motion in underground mines can be grouped into: (1) structure factors, e.g., shape and dimension of openings, rock mass properties, in-situ stress, geological structures, rock support conditions, and rock discontinuities (Cai, 2013; Cai et al., 2012; Deng et al., 2014; Zhu et al., 2012); (2) seismic event factors, e.g., seismic event magnitude, seismic source-target distance, duration of strong ground motion shaking, wave-passage effects, and angle between incidence wave and tunnel axes (Dowding, 1984; Hashash et al., 2001; St John and Zahrah, 1987). Among these factors, wavelength λ to excavation span D ratio (λ/D) has a large influence on ground motion, as discussed in some studies (Chen and Chen, 2004; Chen et al., 2012a; Chen, 2005; Wang et al., 2014). For instance, Chen et al. (2012a) found that seismically induced stresses were strongly related with the wavelength of the seismic wave. Chen and Chen (2004) and Chen (2005) found that a strong impact on tunnel lining occurred when the λ/D ratio was between 1.0 and 4.5; less impact to the tunnel lining could be expected as the λ/D ratio increased. The above results revealed that ground motion in shallow tunnels are related to tunnel dimension and the corner frequency of an earthquake and the tunnels can become vulnerable if the λ/D ratio is small.

The corner frequency f_0 of seismic waves can be derived from displacement or acceleration amplitude spectrum analysis (e.g., Abercrombie, 1995; Aki, 1967); it can also be estimated from a scaling relationship (e.g., $M_0 \propto f_0^{-3}$) between the corner frequency (f_0) and seismic moment (M_0) (for instance, Brune, 1970; Hashash et al., 2001; Izutani and Kanamori, 2001; Kanamori and Rivera, 2004). One major difference between a rockburst event and a natural earthquake event is that the frequency of the rockburst event is higher (Cai et al., 2007). For a seismic event of certain magnitude, complex frequency components can be generated due to seismic wave propagation involving wave reflection, refraction, and interaction in underground mines. Waves with different frequencies (e.g., ranges from several Hz to several hundred Hz) can cause various degrees of amplification and de-amplification of waves around mine openings. High frequency ground motions may cause local spalling of rocks along weakness planes (Hashash et al., 2001).

Most previous studies on the influence of the λ/D ratio on ground motion focused on different tunnel spans under the same seismic source (fixed) f_0 and the λ/D ratio is more than 10 or 20 for "quasi-static" loading problems; only a few studies considered dynamic problems when the wavelength is close to the tunnel span (e.g., $\lambda/D \approx 1$) (e.g., Dowding, 1984; Tshering, 2011). Because of the need to better understand the complex seismic waves traveling in underground mines, we are interested in seismic waves generated from fault slip rockbursts that have higher frequencies than natural earthquakes; we are also interested in not only the absolute value of ground motions (PPV) but also the relative values of ground motions that can be indicated by amplification factors (α). α is defined as the ratio of PPV from a model with an excavation to that from a model without any excavation. Hence, the research questions are: are the ground motions around tunnels with different λ/D ratios the same if one fixes the tunnel span and changes the wavelength or fixes the wavelength and changes the tunnel span? What are the amplification factors of ground motions around the excavations?

Using an advanced numerical code, SPECFEM2D, this paper attempts to shed light on the above questions by carrying out a series of numerical experiments to study the effect of the λ/D ratio on ground motion, with a focus on finding the distribution of PPV and the amplification factors. Seismic wave propagation from fault-slip events is modeled using moment tensor source models. Two tunnel cross-sections (circular and back arched) are considered. The influence of the λ/D ratio on ground motions is examined using