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Numerical modeling of seismic wave propagation and ground motion in underground mines

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A B S T R A C T

Dynamic rock support plays a critical role in ensuring mine safety and its design depends on several key design inputs. For rock support design and forensic analysis of rockburst damage, it is important to understand seismic wave propagation and ground motion distribution near excavation boundaries for seismic waves generated from a remote fault slip seismic event. This study aims at achieving a better understanding of wave propagation patterns around mine tunnels and capturing ground motion (Peak Particle Velocity - PPV) accurately for dynamic support design and forensic analysis. An advanced seismic wave propagation modeling tool, SPECFEM2D, is used to study complex wave propagation in underground mines. Attentions are paid to studying the influence of different mine excavations and geological structures on wavefields and ground motions near excavation boundaries. The simulation results show that the wavefields and the ground motion distributions become more complicated as more mine excavations and geological structures are involved. Moreover, the PPV distribution around a tunnel can be altered, leading to high and low PPV zones around the tunnel. In addition, modulation of travel time and long S-coda waves can be observed in the complex seismograms. Using the modeling approach, areas in an underground mine that may experience high potentials of rockburst damage could be identified and mine safety could be improved by implementing dynamic rock ground support in these areas.

1. Introduction

Progress has been made in understanding rockburst in underground hard rock mines since the 1980s (e.g., Kaiser et al., 1992, 1996; Tannant et al., 1993; Yi and Kaiser, 1993; Lightfoot et al., 1996; Kaiser and Maloney, 1997; Stacey and Ortlepp, 2000; Simser et al., 2002; Cai and Champaigne, 2009; Wang et al., 2009; Holub and Rusajova, 2011; Bukowska, 2012; Cai, 2013; Kaiser and Cai, 2013; Konicek et al., 2013). However, many deep mines in Canada, China, Chile, Australia, South Africa, and some other countries are still facing rockburst issues due to high in-situ stress and complex geological and geometrical conditions in the mines. It is expected that the rockburst problem will further increase as mining occurs at greater depths. Although rockburst research has been accelerated over the past decade, ineffective rock support always contributes to the toll of injuries and fatalities as a result of seismic wave loading that triggers violent rock failure (e.g., Kaiser et al., 1996; Yeryomenko et al., 1999; Cai et al., 2000; Cai, 2013; Kaiser and Cai, 2013). In order to reduce the rockburst damage hazard, there is a need to install appropriate rock support system that is capable of absorbing the dynamic energy resulted from rock failure in burst-prone areas in a mine.

In general, rock support design in burst-prone mines needs to consider stress redistribution due to excavation and dynamic loading resulted from seismic waves generated by large fault-slip induced seismic events. The excavation effect on stress redistribution has been investigated extensively by many researchers (e.g., Tajdus et al., 1997; Kwasniewski and Wang, 1999; Jing et al., 2002; Martin et al., 2003; Albrecht and Potvin, 2005; Cai and Kaiser, 2005; Kontogianni and Stiros, 2005; Tang, 2005; Roth and Ranta-Korpi, 2007; Cai, 2008a, 2008b; Cheng and Sun, 2010; Tang and Xia, 2010; Wang et al., 2010; Zhao and Cai, 2010; Dou et al., 2012; Xu et al., 2012). Compared with research on excavation effect on stress redistribution, however, the effect of underground openings and geological structures on seismic wave propagation and ground motion has not been studied extensively for dynamic rock support design.

Analysis of seismic wave propagation is of great interest for solving some engineering problems in a number of industries, such as the mining, oil extraction, nuclear waste disposal, and earthquake engineering (Goldstein, 1995; Dubinski and Mutke, 1996; Hildyard and Milev, 2001; Hildyard and Young, 2002; Sprenke et al., 2002; Wright

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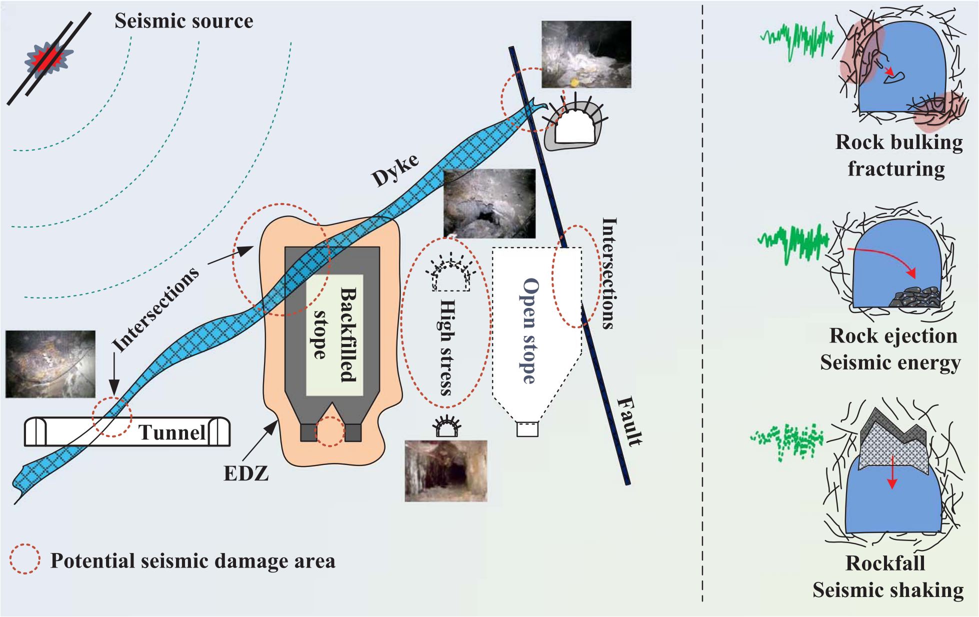

Fig. 1. A schematic drawing showing the complex environment in underground mines (left) and three rockburst damage mechanisms (right). All three rockburst damages can be trigged by seismic wave loading. Modified from Hudyma (2013) and Kaiser et al. (1996).

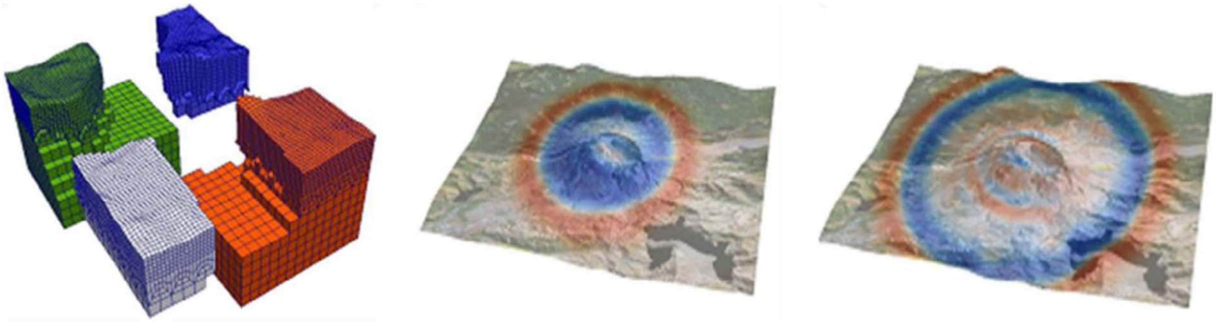

Fig. 2. Wave propagation modeling using SPECFEM3D (from Peter et al. (2011)). Left panel: the model with meshes partitioned and load balanced can be run in parallel (four cores indicated by different colors). Middle and right panels: wavefield snapshots around a mountain at two consecutive times, showing the vertical displacements (up and down colored by red and blue, respectively) at the free surface of the model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
2D models considered in the simulation.

Model type	Model name	Description
Background	$M_{1\text{-R}}$ $M_{1\text{-L}}$	No excavation, homogenous medium
Excavation	$M_{2\text{-R}}$ $M_{2\text{-L}}$	Tunnel T1 is excavated
Backfilled stope	$M_{3\text{-1-R}}$ $M_{3\text{-1-L}}$ $M_{3\text{-2-R}}$ $M_{3\text{-2-L}}$ $M_{3\text{-3-R}}$ $M_{3\text{-3-L}}$	3 levels of backfilled stopes (S1, S2, and S3) are added near tunnel T1, at a distance of 20 m from the tunnel
Dyke	$M_{4\text{-1-R}}$ $M_{4\text{-1-L}}$	A 3 m wide dyke is added at the right side of tunnel T1
Multiple openings	$M_{5\text{-1-R}}$ $M_{5\text{-1-L}}$ $M_{5\text{-2-R}}$ $M_{5\text{-2-L}}$	Multiple openings (tunnels T2, T3, and T4) are considered

Notes: M_i (i = 1, 2, …, 5) indicates the case number of the models. Subscripts -R and -L denote that the seismic source is located at the upper-right and upper-left side of the model, respectively. Subscripts -1, -2, and -3 means different mining stages of the stope in the backfilled model: -1 denotes that the first level (S1) is mined out; -2 means that the second level (S2) is excavated and the first level is backfilled; -3 means that the third level (S3) is mined and the other two levels are backfilled. In the multiple openings models (i = 5), -1 and -2 mean that three openings are considered in the backfilled stope models and the dyke models, respectively.

et al., 2003; Dubinski and Mutke, 2005; Hildyard et al., 2005; Kozyrev et al., 2005; Milev and Spottiswood, 2005; Hildyard, 2007; Potvin, 2009; Orlecka-Sikora, 2010; Wuestefeld et al., 2011; Triviño et al., 2012; Yoshimitsu et al., 2012; Hatherly, 2013). A good understanding of seismic wave propagation in a complex mining context is essential for rock support design in burst-prone mines. For instance, as can be seen from Fig. 1, many factors such as opening, intersection, dyke, fault, and high mining-induced stress make the underground settings very complex. Both analytical and experimental methods are of limited use in solving seismic wave propagation problems. Fortunately, with the rapid advancement of computer technology and numerical techniques, numerical modeling is becoming an important and irreplaceable tool in investigating seismic wave propagation in global, regional, and local scales (Komatitsch and Tromp, 1999; Komatitsch et al., 1999; Fichtner, 2011; Sato et al., 2012; Triviño et al., 2012; Yoshimitsu et al., 2012; Hatherly, 2013).

It is known that wave propagation medium heterogeneity contributes to the variation of wave propagation patterns, which can make wave patterns very complex. In general, heterogeneities in underground mines can be attributed to the presence of faults, ore bodies, different types of rocks, mined-out and backfilled stopes, and tunnel systems (Fig. 1). Among these heterogeneities, the mined-out openings will introduce strong velocity contrasts, which will cause multiple scattering of wave and result in a complex wavefield (Aki and Richards, 2002; Chapman, 2004). Phenomena of wave reflection, refraction, dispersion, diffraction can be observed when the seismic waves encounter a change of material property, and they often induce complicated wave patterns.

As shown in Fig. 1 on the right side, Kaiser et al. (1996) proposed three rockburst damage mechanisms, which include bulking due to rock fracturing, ejection due to seismic energy transfer, and rockfall due to seismic shaking. All the three rockburst damage mechanisms can be

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