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Simulating intense shock pulses due to asperities during fault-slip

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ABSTRACT

Seismic waves arising from fault-slip that occurs in underground mines could inflict severe damage to mine openings. Experimental results have revealed that intense shock pulses could generate due to the unloading of fault surface asperities that move apart during the fault-slip. This study focuses on examining the effect of fault surface asperities on the seismic waves arising from fault-slip. By means of a mine-wide model, dynamic analyses are carried out in order to simulate collision and unloading of fault surface asperities. Saeb and Amadei's model and Barton's shear strength model are newly implemented into constitutive models of FLAC3D code for the analyses. Parametrical study is conducted with the dynamic analyses in order to examine the most influential factor on the generation of intense seismic waves. The results reveal that stress release due to the unloading of the asperities has a significant influence on the intensity of seismic waves, while the collision of asperities, stiffness of the fault, and asperity geometry have a much lesser influence. When the stress release is large, the peak particle velocity excited by seismic waves is found to increase threefold, compared to that for fault-slip occurring along a planar surface. It indicates that significant deterioration of rockmasses could be induced due to the high particle velocities. This study has numerically confirmed the hypothesis that intense shock pulses could occur due to the unloading of fault surface asperities.

1. Introduction

In underground hard rock mines, the occurrence of rockbursts is not uncommon at great depths, and severe damage to mine openings is occasionally inflicted due to the violent failures of rockmasses (Blake and Hedley, 2003; Kaiser and Cai, 2012; White and Whyatt, 1999). Rockbursts are generally characterized into 3 types, namely strain burst, pillar burst, and fault-slip burst, according to the volume of rockmasses involved and underlying mechanism by which the rockbursts are induced (Blake and Hedley, 2003). Amongst the types of rockbursts, fault-slip bursts could cause the most significant damage to large areas that extend over several levels in underground mines given that intense seismic waves arise from the fault-slip. In such a case, seismic waves play a critical role in causing damage to mining openings, while stress changes induced by the fault-slip would be limited to areas in the vicinity of the fault.

The propagation of seismic waves excites the particle velocity of rockmass, and there is a strong correlation between the particle velocity and rockmass damage (Brinkmann, 1987; Hedley, 1992) as an increase in stresses induced by the propagation of seismic waves is proportional to the particle velocity (Brady and Brown, 1993). Thus, it is imperative to estimate peak particle velocity excited by the seismic waves in order to optimize secondary support systems for sustaining additional loads and deformations induced by the seismic waves. Although there are a number of studies that examine the influence of seismic waves on underground openings (C.M.D.M.R. Directorate, 1996), these studies are mainly based on numerical models, in which seismic waves are applied to its boundaries in the form of displacement, velocity, or acceleration. In other words, neither the mechanisms by which seismic events take place nor the locations of the seismic events are considered. Through the studies, it is certainly possible to examine the effect of seismic waves on mine openings, such as the extent of yielding zones and stress changes, whereas from a practical engineering view point, it would be difficult to propose optimized secondary support systems to accommodate the energy and deformation induced by the seismic waves since the characteristics of seismic waves expected from seismic events cannot be estimated. Hence, developing a methodology which considers source mechanisms and the locations of seismic events is of paramount importance in order to estimate the intensity of seismic waves accurately.

As described above, an appreciation of the characteristics of seismic waves arising from rockbursts is indispensable, especially when fault-slip is involved that seismically radiates a large amount of energy while inducing shear rupture and slip movements. Gay and Ortlepp (1979) conducted microscopic analysis of infilling materials on fault surfaces arising from significantly violent seismic events that took place in a deep South Africa gold mine. Ortlepp (2000) further investigated the electron micrographs of the micro-cataclastic materials showing remarkable uniformity in size and shapes of rhombic dodecahedron; and the author mentioned that the characteristics are inconceivable as

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ordinary crystallographic structures for the material. The author postulated that the particular morphology results from intense shock unloading that takes place when fault-slip takes place along a non-planar, incipient or pre-existing surface as shown in Fig. 1. In other words, violent tensile failure due to sudden reduction in normal stresses acting on the fault gives rise to the formation of the infilling materials that have the particular structure. It was further discussed that locally intense shock pulses (seismic waves) could generate as a result of the sudden release of the stresses acting on the fault where significant impact asperities occur at intervals. It is then suggested that the generation of the intense shock pulses could be one of plausible explanations for rockburst damage that is locally significant as shown in Fig. 2. It is to be noted that the term "asperity" is used to describe a saw-toothed fault surface that carries highly concentrated stress thus inducing fault-slip when the asperities are broken and sheared off in the present paper.

Although the plausible mechanism of generation of locally intense seismic waves has been proposed, a specific framework for estimating peak particle velocity expected from the intense seismic waves has not yet been established. Thus, a better understanding of the mechanism is required in order to propose practical support systems for the locally intense shock pulses. It is found from Fig. 1 that a number of factors, such as the amount of slip displacements and the size of impact asperities could have an influence on the characteristics of the generated seismic waves. A rise in normal stresses due to the impact that occurs when the asperities collide is also assumed to be an influential factor since a normal stress level prior to the unloading would more or less affect the unloading. This paper focuses on simulating the intense shock pulse, considering these factors that could affect the characteristics of the intense shock pulses, with the purpose of establishing a methodology to estimate the peak particle velocity quantitatively.

2. Methodology

In this study, examining the effect of fault surface asperities on the generation of intense shock pulse is attempted. It is admittedly ideal to develop a numerical model encompassing a fault on which asperities as shown in Fig. 1 are modelled, and to conduct numerical analysis with a numerical simulation technique that can allow for the dynamic motion of the asperities colliding and moving apart. However, shear rupture due to fault-slip in underground mines extends to large areas (Hofmann and Scheepers, 2011; Ortlepp, 2000; Swanson, 1992), and the occurrence of fault-slip is strongly dependent upon mining-induced stress state (Alber et al., 2009; Potvin et al., 2010; Sjoberg et al., 2012) as well as in-situ stress state. Thus, constructing a mine-wide scale model is essential in order to simulate fault-slip induced by mining activities. However, it is difficult to simulate fault surface asperities in the model as a significantly large number of nodal points and zones would be required for the modelling. Considering these facts, for this study, FLAC3D code (Itasca, 2009), which adopts explicit finite difference method, is utilized, and a couple of constitutive laws governing the behaviour of faults are implemented into the code with C++ programming language to simulate the intense shock pulses. Furthermore, new constants are proposed and incorporated into the constitutive models to allow for the simulation of fault-surface asperities that are difficult to actually model. The analysis procedure is first explained in detail. A detailed description of the analysis and the constitutive models is then provided.

Fig. 2. Localized damage to a mine tunnel (Ortlepp, 2000).

2.1. Analysis procedure

In the present study, one static analysis and two dynamic analyses are conducted in sequence. Fig. 3 depicts the overall procedure. As shown in the figure, static analysis is first performed with a numerical model encompassing a steeply dipping, tabular orebody and fault running parallel to the orebody. During the static analysis, stopes in the orebody are extracted following mining sequences as per sublevel stoping method with delayed backfill. The reason why the extraction of stopes and backfilling are carried out prior to simulating fault-slip is to simulate mining-induced stress re-distribution on the fault. As reported in many studies (Hofmann and Scheepers, 2011; McGarr et al., 1975; Sneilling et al., 2013; White and Whyatt, 1999), the occurrence of fault-slip in underground mines is strongly associated with the stress re-arrangement, such as unclamping of fault surfaces (Castro et al., 2009), due to mining activities. Hence, the static analysis is intended to only simulate slip potential induced by the mining activities. Subsequently, dynamic analysis is carried out on the basis of the stress state obtained from the static analysis in order to simulate fault-slip. As shown in the flowchart, fault-slip resulting from asperity shear is simulated. This is due to the fact that faults in underground mines cannot be considered planar (Ortlepp, 2000; Ryder, 1988; Wallace and Morris, 1986), and as shear stress acting on the faults reaches peak shear strength, asperities on the fault are expected to be sheared off (Ryder, 1988). Excess stress determined by a difference between shear strength

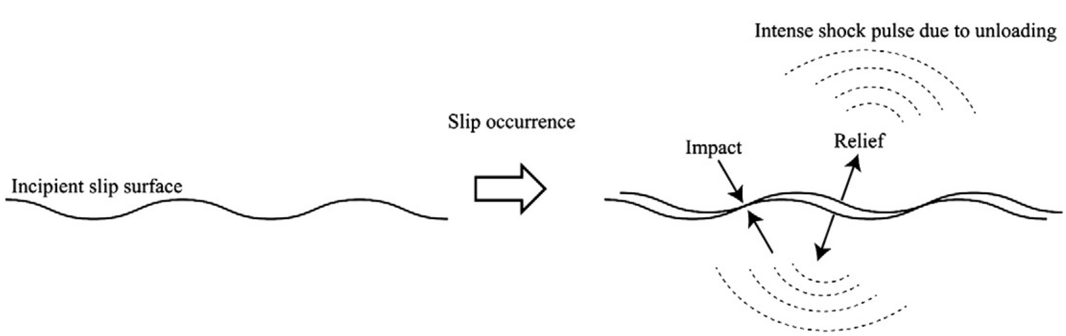

Fig. 1. Slip along a non-planar surface and generation of intense shock pulse.