Journal of Applied Geophysics 134 (2016) 159–171

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Back analysis of fault-slip in burst prone environment

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ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form 23 June 2016
Accepted 6 September 2016
Available online 10 September 2016

Keywords:
Fault-slip
Seismic source parameters
Peak particle velocity
Mining-induced seismicity

ABSTRACT

In deep underground mines, stress re-distribution induced by mining activities could cause fault-slip. Seismic waves arising from fault-slip occasionally induce rock ejection when hitting the boundary of mine openings, and as a result, severe damage could be inflicted. In general, it is difficult to estimate fault-slip-induced ground motion in the vicinity of mine openings because of the complexity of the dynamic response of faults and the presence of geological structures. In this paper, a case study is conducted for a Canadian underground mine, herein called “Mine-A”, which is known for its seismic activities. Using a microseismic database collected from the mine, a back analysis of fault-slip is carried out with mine-wide 3-dimensional numerical modeling. A back analysis is conducted to estimate the physical and mechanical properties of the causative fracture or shear zones. One large seismic event has been selected for the back analysis to detect a fault-slip related seismic event. In the back analysis, the shear zone properties are estimated with respect to moment magnitude of the seismic event and peak particle velocity (PPV) recorded by a strong ground motion sensor. The estimated properties are then validated through comparison with peak ground acceleration recorded by accelerometers. Lastly, ground motion in active mining areas is estimated by conducting dynamic analysis with the estimated values. The present study implies that it would be possible to estimate the magnitude of seismic events that might occur in the near future by applying the estimated properties to the numerical model. Although the case study is conducted for a specific mine, the developed methodology can be equally applied to other mines suffering from fault-slip related seismic events.

1. Introduction

Fault-slip that occurs in underground mines occasionally entails intense seismic waves, which could inflict severe damage when hitting the surfaces of nearby mine openings (Ortlepp, 2000). The damage to rockmasses can be predicted on the basis of peak particle velocity (PPV) caused by the seismic waves (Saharan, 2004), seismic moment and seismically radiated energy of the seismic events (Hedley, 1992). PPV is defined as the maximum particle velocity at an arbitrary location in a transmitting medium in the course of the propagation of stress (seismic) waves. It is widely used as a threshold for damage to the rockmass (Brinkmann, 1987) and is associated with the severity of damage caused by mining-induced seismic events (Hedley, 1992). To date, a number of studies have been conducted numerically and analytically to estimate these values. McGarr (2002) proposed a formulation to predict near-field PPV provided that seismic efficiency of mining-induced tremors is less than 6% (McGarr, 1999). In this context, the term “near-field” implies the vicinity of a source location of a seismic event where it is unnecessary to consider seismic wave attenuation or propagation. Note that seismic efficiency is defined as a ratio of seismically radiated energy to the change in potential energy calculated from $(\tau_1 + \tau_2)DA/2$, where τ_1 and τ_2 are the stresses before and after an earthquake; A is a fault area loaded to failure by the applied stress τ_1; D is a final slip when the shear stress decreases to τ_2 (Kanamori, 2001; McGarr, 1994). Back analysis to simulate seismic source parameters has been also carried out by many researchers. Hofmann and Scheepers (2011) simulated the fault-slip area by calibrating the cohesive strength of a causative fault with seismic moment. Potvin et al. (2010) and Sjöberg et al. (2012) conducted back analysis with seismic moment, considering an increase in shear displacements on causative geological structures for each mining stage.

Although the seismic moment of fault-slip related seismic events and near-field particle velocity excited by seismic waves might be approximated with the aforementioned methods, it is not still straightforward to estimate the PPV in the vicinity of mine openings for several reasons. First, the formulation proposed by McGarr (2002) is applicable only in the vicinity of source regions; hence ground motion in active mining areas cannot be estimated in the case that the seismic events are located far from the mining areas due to regional unclamping (Castro et al., 2009). Here, regional unclamping denotes stress change, which results in the reduction of normal stress acting on a fault, taking place in an extensive region caused by the extraction of a large amount of ore. Secondly, previous back analyses were carried out under static conditions by means of the classical Mohr-Coulomb criterion, which implies that the results obtained from the back analyses are not validated

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http://dx.doi.org/10.1016/j.jappgeo.2016.09.009

with respect to the dynamic behaviour of rockmass, such as PPV. Furthermore, as reported by Ryder (1988), the cause of fault-slip in underground mines is a sudden stress drop induced by asperity shear on fault surfaces. The classical Mohr-Coulomb criterion cannot take fault surface asperities into account. As the seismic source parameters of fault-slip are strongly dependent on the fault surface properties (Sainoki and Mitri, 2013), it is postulated that the intensity of seismic waves is also dictated by the fault surface properties. Static analyses adopted in previous studies cannot simulate the propagation of the seismic waves nor the ground motion created by the seismic waves.

For these reasons, there is still a pressing need to develop a robust methodology to simulate fault-slip that occurs in underground mines, so that the magnitude of particle velocity excited by seismic waves within active mining areas can be estimated. Based on the estimated particle velocity, the selection of appropriate support system to control ground motion due to the seismic waves can be achieved. This is of paramount importance for steady mining production and the safety of mine operators.

In the present study, back analysis of a fault-slip related seismic event that took place in “Mine A” is attempted under dynamic conditions, considering asperity shear as the cause of the seismic event. The back analysis is carried out with respect to the physical and mechanical properties of causative fracture/shear zones within which the seismic event took place. Moment magnitude (i.e. seismic moment) estimated from recorded waveforms in the mine and far-field PPV recorded by a strong ground motion sensor are used for the calibration of the fault properties. The estimated values are then validated with ground acceleration recorded by accelerometers.

2. Case study mine

The case study mine, herein called “Mine-A” is a base metal operation extracting ore primarily with sublevel stoping method with delayed backfill. There are two mining ore zones: shallow and deep. The upper zone is situated above the 1400 m level and is completely mined out. Current mining activities take place in the deeper zone below the 1400 m level, which consists of two orebodies #1 and #2 striking nearly in the east-west direction. Fig. 1 shows a schematic of the two orebodies on the 1500 m level. The #1 orebody extends from surface to 1700 m level and dips generally at 75° to the south with an average width of 9 m. The #2 orebody extends from 850 m level to 1800 m level and dips sub-parallel to the #1 orebody at 60° to the south. An important geological structure in the area is the shear/fracture zone identified in the vicinity of the orebodies, which is shown in Fig. 1. The width of the shear zone ranges from 15 m to 150 m, the strike is north-west (dip direction is 45°), and the dip is 85° to the east.

The rocks in Mine-A are generally classified into five types, namely Norite (NR), Greenstone (GS), Olivine Diabase (OLDI), Massive Sulphide (MASU), and Metasediment (MTSD). Norite and Metasediment are generally located in the footwall and hanging wall, respectively. Greenstone appears to be a subdivision of the more massive rock within the metasediments of the hanging wall, and the orebodies consist of MASU. The mechanical properties of the rock masses are shown in a later section.

3. Microseismic analysis

Microseismic activity in Mine-A has been recorded for more than 5 years with a microseismic monitoring system that consists of 29 uniaxial accelerometers, 5 triaxial accelerometers and one strong ground motion sensor (4.5 Hz geophone). The accelerometers installed in the mine have a sensitivity of 30 V/g and a clipping Voltage of 3.9 Vare, whereby acceleration up to 1.3 m/s^2 can be measured as a maximum. The strong ground motion (SGM) sensor is, on the other hand, installed near the ground surface and capable of capturing large seismic events with low frequencies, of which moment magnitude ranges from 0 to 3. By utilizing these types of instruments, both of small and large seismic events can be detected, and seismic source parameters for each seismic event are calculated on the basis of waveforms recorded by the microseismic monitoring system. The calculations are conducted with ESG software (ESG, 2011), which is a specialized seismic data analysis software widely employed for various kinds of field applications related to induced seismicity. The overview of the monitoring system being used at the mine and an actual case study is summarized by Urbancic and Trifu (2000). In addition, a number of case studies have been undertaken with monitoring systems similar to that installed in this mine, not only for understanding seismicity in underground mines but also for investigating induced seismicity related to long-term production, hydraulic fracturing, and CO_2 sequestration all over the world (Li et al., 2014; Maxwell and Urbancic, 2001; Trifu and Shumila, 2010).

There are a number of sources for seismic events in underground mines, such as production blasts, generation and nucleation of extension fractures, and propagation of shear rupture. The seismic data analysis software being used at the mine is capable of distinguishing blast-induced seismic events from the others with recorded waveforms. However, it is still necessary to ascertain the seismic events caused by a shear movement along a discontinuity. This is referred to as fault-slip related seismic event in this paper. The back analysis conducted in the present study aims at simulating a fault-slip related seismic event and estimating the properties of shear/fracture zones where the seismic event took place. To do so, the present study adopts the magnitude time history (MTH) analysis and time between events (TBE)-rate chart proposed by Hudyma and Beneteau (2012). The fundamental idea behind the methods is that seismic events related to rockmass shearing and a slip along a fault take place without having a strong correlation with blasting activities because the direct triggering mechanism of fault-

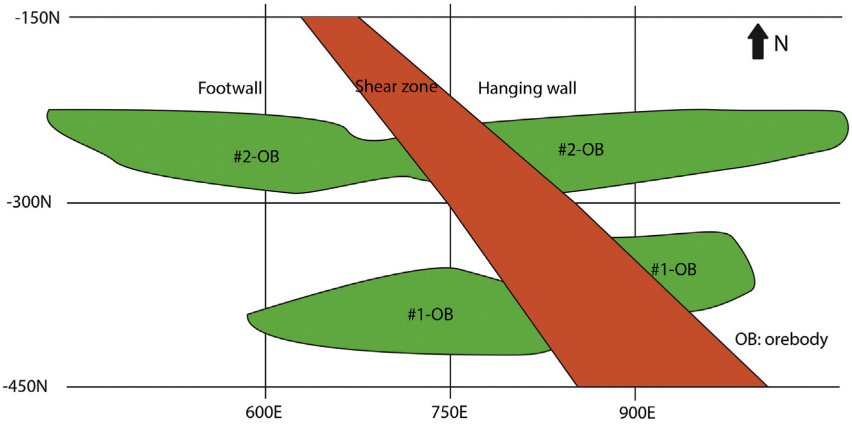

Fig. 1. Schematic illustration of the orebodies and intersecting shear zone at 1500 m below surface.