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Methodology for the interpretation of fault-slip seismicity in a weak shear zone

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ABSTRACT

Fault-slip related seismic events that occur in underground mines could inflict severe damage to underground openings; thus a proper estimation of fault-slip potential in active mining areas is of paramount importance in assessing its risk. It is not uncommon in underground mines that large seismic events take place away from stopes being extracted, where fault-slip potential is presumed not to be high enough to result in those seismic events. In the present paper, fault-slip related seismic events taking place within a weak shear zone in Garson Mine, Sudbury, Canada are investigated. First, in order to understand the stress states of rockmass in the mine, numerical analysis is carried out with a 3D mine-wide model whilst assuming isotropic elasticity. The result obtained from the analysis reveals that the shear stress of rockmass in a weak shear zone does not reach the maximum shear strength determined by Mohr–Coulomb failure criterion with basic friction angles of the rockmass. The result contradicts a fact that quite a few seismic events have been actually recorded in the regions with micro seismic monitoring systems installed in the mine. As an interpretation of that, it is postulated that variations in shear stiffness within the shear zone contribute to the generation of high slip potential resulting in the occurrence of those seismic events. In order to justify the postulation, numerical analysis is additionally carried out, in which the shear zone is modelled with transversely isotropic models, of which shear stiffness is decreased in the same direction as a measured joint orientation in the shear zone. For source regions of those seismic events, isotropic models are used without decreasing its shear stiffness, thus resulting in the discrepancy in shear stiffness between the source regions and other areas in the shear zone. The result obtained from the analysis verifies that fault-slip potential drastically increases within the source regions due to the difference in shear stiffness. It is further found out from dynamic analysis in which fault-slip is simulated with Barton's shear strength model that the increasing slip potential is high enough to cause large seismic events in the regions. In the present study, the interpretation of seismic events occurring within a weak shear zone is provided, and a methodology to simulate high fault-slip potential that could be generated within the shear zone is developed. The methodology can be used with back analysis to determine the mechanical properties of the weak shear zone, which lead to the better estimation of fault-slip potential.

1. Introduction

In deep underground mines, extremely high stress regimes can be generated due to large overburden pressure and horizontal stress resulting from plate tectonics. Tectonic movements and resultant high stress conditions form geological structures, such as faults and shear zones, in underground whilst generating complex stress fields within those disturbed zones. Before mining activities begin, those geological structures are more or less in stable conditions, i.e., forces acting on the structures can be considered being in equilibrium since the formation and evolution of those geological structures generally take place over a long period of time. It should be noted, however, that although the state of geological structures is stable in pre-mining stress state, a large amount of strain energy could be stored within the structures as a result of the long-term effects of tectonic stress.

Mining activities, such as the extraction of orebodies and the excavation of mine openings, in an underground mines cause stress re-distributions, resulting in a decrease in normal stress as well as an increase in shear stress acting on geological structures situated in the vicinity of active mining areas. Those stress changes could bring the stress state of the structures to its peak shear strength. When the stress state reaches the peak shear strength, slip occurs within the structures. In a case that the slip takes place violently whilst entailing the breakage of asperities on geological discontinuities, such as faults and joints, seismic waves arise, which could cause severe damage to mine openings (Blake and Hedley, 2003; McGarr et al., 1979; Ortlepp, 2000). When the slip along geological discontinuities, especially faults, results in damage to underground openings in a form of such as rock ejection from the surface of the openings, it is termed fault-slip burst (Blake and Hedley,

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2003), which is known as one of the most dangerous phenomena that take place in underground mines. Therefore, developing a methodology to properly estimate the potential of slip that could occur along geological discontinuities within geological structures is of paramount importance for sustaining stable production of underground mines.

To date, a number of studies have been carried out for the better understanding of mining-induced seismicity in underground mines. McGarr et al. (1975) examine the relationship between the occurrence of mine tremors and in-situ stress. It has been found out from the study that mine tremors do not necessarily take place in the vicinity of underground openings, where it is supposed that stress concentrations are taking place as result of stress re-arrangement due to mining activities. It is then suggested that high residual stress due to the difference in the stiffness of rockmass within geologically disturbed zones can be a cause for mine tremors. Bewick et al. (2009) investigate mining-induced seismicity in Garson Mine, Sudbury, Canada, and then suggest a similar idea in that stress is highly concentrated within rockmass with higher stiffness compared to that of surrounding rockmass. It is further indicated that the interactions of geological structures could trigger seismic events faraway from active mining areas, i.e., stress change due to mining activities are transferred to remote areas through geological structures. The occurrence of mining-induced seismicity at remote distances from active mining areas can be explained with the mechanism described above.

A significant effort has been made as well for investigating seismic activities induced by geological structures, such as a fault, since geological structures sometimes play a key role in the occurrence of mining-induced seismicity. In the studies, numerical analysis has been extensively employed to understand the behaviour of faults in a response to mining activities as well as to estimate the evolution of fault-slip potential according to the progression of mining sequence (Alber and Fritschen, 2011; Alber et al., 2009; Hofmann and Scheepers, 2011; Potvin et al., 2010; Sainoki and Mitri, 2014a,b; Sjoberg et al., 2012; Snelling et al., 2013). For instance, Hofmann and Scheepers (2011) estimate the mechanical properties of a fault that caused a large seismic event, applying back analysis, in order to simulate fault-slip areas. Sjoberg et al. (2012) attempt to calibrate the mechanical properties of causative faults whilst comparing cumulative seismic moment obtained from analysis with that calculated on the basis of data recorded by microseismic monitoring systems. In those studies above, it is presumed that faults are homogeneous and can be modelled with interfaces with a classical Mohr–Coulomb failure criterion determined by a friction angle and cohesion. However, those assumptions could result in inaccurate calibration of the mechanical properties of faults since asperity shear that occurs when a fault slips is influential on the seismic moment of fault-slip (Ryder, 1988; Sjoberg et al., 2012). The cohesion of a fault calibrated by Hofmann and Scheepers (2011) is high when the existence of a pre-existing fault is presumed. When the effect of residual stress arising from asperity shear during fault-slip on seismic moment is considered, the calibrated cohesion would significantly decrease, which is deemed more representative of fault-slip occurring in underground mines. In addition, as mentioned above, assuming homogeneity for a fault could also lead to inaccurate results when model calibration is attempted. For instance, as a result of back analysis that Alber and Fritschen (2011) conducted, a friction angle of 8° was estimated as the mechanical property of a fault with a surface bearing slickensides. Although it might be possible for a completely smooth fault to have such a low friction angle, it is presumed that such a smooth fault is incapable of storing a large amount of energy that causes seismic events. It is natural to assume that there was a significant asperity storing energy on the fault surface, and the seismic event was induced because of the breakage of the asperity.

A number of failure criteria of joints that take into account the effect of joint surface asperities on its peak shear strength have been proposed (Barton, 1973; Indraratna et al., 2005; Newland and Allely, 1957; Saeb, 1990). For instance, the failure criterion proposed by Barton (1973) takes joint surface roughness into consideration, whereby an increase in the maximum shear strength of a joint due to its surface asperities can be modelled. Modified Ladanyi and Archambault's shear strength model (Saeb, 1990) can consider the dilatancy of a joint surface that is dependent upon normal stress acting on the joint as well as asperity failure due to the normal stress. Sainoki and Mitri (2014a) model a slip along a fault parallel to a steeply, dipping orebody, using Barton's shear strength criterion in dynamic conditions. In the study, the effect of a sudden stress drop induced by the breakage of fault surface asperities on seismic source parameters of mining-induced fault-slip is discussed. It is then found out that the magnitude of fault-slip and seismically radiated energy could increase with increasing fault surface roughness. This is because a fault with a rough surface can store more energy, compared to that with a smooth surface. The stored energy is then released when the asperities on the surface are broken off.

In light of those previous studies, the difference in the stiffness of rockmass and the surface properties of geological discontinuities are considered significantly important in dealing with mining-induced seismicity. Accordingly, taking those factors into consideration would give a more rigorous calibration method for mining-induced seismicity, compared to that assuming the homogeneity and planar surfaces of faults. In the present paper, mining-induced seismicity that took place in a weak shear zone is studied whilst examining an increase in slip potential due to the heterogeneity of the mechanical properties of rockmass within the shear zone. Simulating fault-slip within the shear zone is also attempted with Barton's shear strength model, assuming asperity shear as the cause for the fault-slip.

2. Garson Mine

2.1. Overview of geology in Sudbury region

In the present study, investigation of seismic events taking place within a weak shear zone in Garson Mine is conducted. The underground mine is located approximately 15 km northeast of Sudbury, Ontario, Canada. This region has been known as one of the most nickel-rich sulphide deposits in the world. A number of books and literature investigating and describing the characteristics of geology known as the Sudbury Igneous Complex can be found (Bourdais, 1953; Pye et al., 1984). According to Pye et al. (1984), the Sudbury Structure is located at the main contact between the Early Proterozoic Huronian supracrustal rocks of the Southern Province and the Archean plutonic rocks of the Superior Province. A meteorite impact or explosive volcanism contributed to the formation of the deposits, in which nickel, copper, platinum-group metal, and other metals are present. Because of the abundant metals included in ore deposits in the region, a number of underground mines have been developed in Sudbury area since a nickel-rich deposit was discovered in 1856. As is the case with those mines, Garson Mine has been in operation since the end of 19th century, where copper–nickel ore deposits have been extracted with a sublevel stoping method at great depths.

2.2. Geological settings of Garson Mine

As shown in the studies by Bewick et al. (2009) and Shnorhokian et al. (2014), Garson Mine encompasses complex geological structures that are presumed to be the cause for seismic activities in the mine. Fig. 1 depicts a 3D mine-wide model constructed by Shnorhokian et al. (2014), which shows geological structures of Garson Mine. As shown in the figure, the rockmass on the north side of the mine consists of Norite (NR), which then transitions to Green stone (GS). On the south side of the mine is Metasediment (MTSD). Nickel–copper orebodies, which are formed as Massive Sulphide (MASU), appear at contacts between NR and GS or MTSD and GS as shown in Fig. 1. Those orebodies are tabular and steeply dip to south at a range from 60° to 75°. The orebody appearing at the contact between MTSD and GS is called #1-Shear, and another one on the north side is called #4-Shear. Those orebodies are cut by a bifurcated dyke (OLDI) extending