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Dynamic behaviour of mining-induced fault slip

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ABSTRACT

Fault slip bursts induced by mining activities could inflict severe damage to nearby mine developments. Considering a variety of factors that might exert an influence on the fault slip, dynamic numerical analyses are conducted for models having a fault parallel to a tabular ore deposit. The results obtained from the analyses show that the maximum dynamic shear displacement increment induced by stope extraction is significantly affected by the friction angle of the fault, as well as mining depth and position of fault with respect to the orebody, while the stiffness and the dilation angle of the fault do not have as much influence. Seismic source parameters are computed based on the numerical results and as is the case with the maximum relative shear displacements, the position and friction angle of the fault appear to have the strongest influence on seismic moment and energy released by fault slip. The limitations of Mohr–Coulomb criterion as applied to the dynamic analysis of fault slip bursts are discussed in light of the results obtained. Lastly, slip rates and rupture velocity are investigated. The results show that the maximum slip rates are associated with the maximum increments of relative dynamic shear displacement. It is shown that extremely high rupture velocity could be induced by stope extraction. This could be the cause for a severe seismic event.

1. Introduction

Since the last century, there has been a growing demand for mineral resources worldwide. As a result, the depth at which mineral deposits are mined has increased substantially reaching up to 3 km in Canada and 5 km in South Africa. Deep mining has been conducted under unfavourable in-situ stress conditions due to extremely large overburden pressure and tectonic movements. The extraction of ore deposits at such great depths could induce significant stress re-distribution and rotation to the area surrounding mine openings. The change in in-situ stress regimes, in turn, leads to the higher risk for the occurrence of dynamic phenomena, such as rockbursts.

Rockburst is one of the phenomena caused by stress re-distribution and rotation arising from mining activities. Many efforts have been made for better understanding of the mechanism of rockburst since the first rockburst had been reported in the gold mines of Witwatersrand in South America and Kolar Gold Field in India at the turn of the century [1]. Owing to the research on rockburst, the means by which the occurrence of rockburst can be controlled or predicted have been developed by many researchers [2–5], considering the work done by extracting ore, the mechanical properties of rockmass and stress field in mining area. However, the aforementioned methods cannot be applicable to all the types of rockburst, only to a certain type of rockburst called strain burst, which is caused by violent fracturing of intact rock and, in many cases, occurs in the vicinity of mining openings or pillars.

There is another type of rockburst, to which the methods cannot be applied, called fault-slip burst, which is caused by the movement of pre-existing fault or the formation of seismically active structural zones. In spite of the many attempts made for understanding of the mechanism of fault slip bursts, as of now, effective means to predict the magnitude of the event and the damage caused by seismic waved resulting from the fault slip burst if it occurs have not yet been developed because of the following two reasons: the complexity of mechanism governing fault behaviour and the difficulty of precisely assessing the change in stress in complicated rockmass fabric. First, determining the physical and mechanical properties of the surface of faults is quite challenging though many studies have been conducted through laboratory experiments and numerical simulations with the data of fault-slip bursts measured in fields. At present, many types of friction models of fault-slip for simulating the dynamic behaviour of shear sliding have been proposed, such as static-dynamic friction model, velocity-dependent model, slip-weakening model, and rate- and state-dependent model. In spite of the efforts to develop the friction models, the dynamic behaviour of fault-slip has not yet been fully understood due to many physical

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phenomena to be taken into account and the uncertainty of scale effect on the physical properties of faults. Second, complicated geological structures in mining area also make it difficult to predict the occurrence of fault-slip burst, that is to say, stress re-distribution, which does not occur evenly around the area surrounding stopes and mining opening, depends on in-situ geological structures. In details, the change in stress induced by mining activities is transferred to surrounding area through not only elastic medium but also creep process, the fracturing of rockmass and geological discontinuities, such as rock joints. Additionally, in mining development, the information of geological structures far from ore deposits tend to be ignored compared to the area in the proximity of mining openings and ore deposits. Therefore, identifying the fault that has the possibility of being mobilized due to stress readjustment induced by mining activities is quite difficult in a real situation.

Many attempts have been made in understanding the relationship between extracting ore deposits and the properties of fault slip by means of numerical analysis while taking into account some of the factors described above. Alber and Fritschen [6] investigated the decrease of fault safety factor by using an elastic 3D boundary element code for a coal mine where fault planes are present, assuming Mohr–Coulomb failure criterion as the friction model of the faults. Hofmann and Scheepers [7] made an attempt in simulating fault slip area with Mohr–Coulomb failure criterion in which cohesive strength changes when sliding occurs. The relationship between the location of excavated area and the increment of shear displacement along faults has been studied with typical cases that would be encountered in underground mines by means of the 2D finite element method by Castro et al. [8]. Bewick and Valley [9] showed that seismic events that occur far from mining area are dominated by the large-scale interaction between geological structures, based on the seismic data, geological information and numerical analysis. The authors concluded that understanding the interaction necessitates the methodology that takes into account a fault system.

The aforementioned studies have been conducted for better understanding of fault-slip and seismic events in a mining context. In the studies, static analyses to investigate the relation between mining development and the occurrence of fault-slip have been mainly carried out assuming uncomplicated failure criterion to express the frictional strength of a fault. As it is clearly seen from fault-slip bursts and the damage inflicted by ground motion arising from seismic waves, shear sliding that could cause fault-slip bursts should be considered as a dynamic event possessing a similar mechanism to shallow earthquakes with seismic energy radiation. While few studies taking into account dynamic behaviour of faults have been made amongst mining engineers, the research on the dynamic behaviour of fault-slip has been addressed in geophysics for the purpose of simulating the rupture process that occurs on a fault during earthquakes. Owing to the studies, quite a number of friction models considering factors, such as slip rates, frictional heating, and restrengthening, have been developed by many researchers [10–16]. The friction models have been applied to numerical analyses in order to simulate the dynamic sliding behaviour of a fault both at laboratory scale and at global scale [17–20]. The analyses showed the characteristic of each dynamic friction model and provided clues as to the relationship between slip rates and rupture velocity as well as that between fault-slip and ground motion, though it has not yet been accomplished to model the process of occurrence of earthquakes completely.

As described above, static analysis using mine-wide models in which dominant geological structures are reconstructed have been attempted in a mining context. In geophysics, on the other hand, the dynamic features of fault-slip have been primarily investigated, paying attention to neither rockmass fabric nor geological structures. It is evident that combining knowledge gained from the two fields would be required in order to figure out the mechanism of fault-slip bursts and predict the magnitude of induced seismic events. If accomplished, the influence of fault slip bursts on mining openings could be evaluated prior to the occurrence of fault-slip, hence stable production and a safe environment for mining workers could be achieve. This study focuses on the numerical analyses of the dynamic behaviour of faults in a mining context, considering quite simple geological structures, mining sequences and a friction model. The simplification was intended to assess factors that could have an influence on the behaviour of faults in mining sequences. For the purpose, in the analyses conducted, various parameters, such as in-situ stress, the mechanical properties of fault, and geometry of the model were changed in order to yield insights into how such parameters affect the dynamic behaviour of faults. Thus, this study could lay a foundation for calibrating and assessing numerical models where complicated geological structures and dynamic friction models are applied.

2. Model description

To investigate fault slip induced by mining activities, numerical models are generated by means of FLAC3D, a three dimensional explicit finite-difference program, considering factors that might have an influence on the behaviour of faults, such as physical properties of rock, in-situ stress regimes, fault properties and mining method. In the following sections, detailed descriptions of the four factors are given.

2.1. Ore deposit and proposed mining method

The geometries of ore deposits vary significantly with the origin of the deposits, metamorphism and subsequent alternation, in which the deposits have been involved since the deposits had formed in ancient times. In the present study, a steeply dipping and tabular ore deposit, which is frequently encountered at mine sites in Canadian Shield [1,9] is modelled. Sublevel stoping method with delayed backfill is widely used in Canadian mines because of the advantages of safety, a high production rate, and the high percentage of ore recovery [21]. This type of ore deposit and mining method are adopted as the model of this study.

2.2. Fault configuration geometry for numerical models

There exist quite a number of types of faults, depending on scale, structures involved, shape, fabrics and mechanical properties [9,22–24]. For each type of faults, the response to the change in in-situ stress fields induced by mining activities differs; some faults exhibit sliding behaviour along pre-existing geological discontinuities, and others respond to the stress re-distribution by creating a new fault surface or by interacting surrounding geological structures. Whether the response leads to seismic events that cause devastating damage to mine openings depends on the characteristics of the fault and in-situ stress regime. The behaviour of faults for seismic events related to fault-slip was classified as [25–28] development of new faults through intact rock, coalescence of en echelon fractures producing a linked fault, or slip along pre-existing faults. The formation of new faults and coalescence of embryo fault systems tend to release comparatively small seismic energy during the process because the part of energy arising from stress re-distribution or stress drop is expended to generate new fault surfaces. Sliding along pre-existing faults, on the other hand, has the potential of releasing large energy during the slip and causing more severe damage far from the hypocenter of the event