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# Quantitative analysis with plastic strain indicators to estimate damage induced by fault-slip

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ABSTRACT

In the present study, methodologies to evaluate damage around an underground opening due to seismic waves arising from mining-induced fault-slip are examined. First, expressions for an associated flow rule with a failure criterion are developed for biaxial stress conditions, which are implemented into FLAC3D code. A three-dimensional (3D) mine model encompassing a fault running parallel to a steeply dipping orebody is constructed, whereby static and dynamic analyses are performed to extract stopes and simulate fault-slip in dynamic condition, respectively. In the analysis, the developed biaxial model is applied to the stope wall. The fault-slip simulation is performed, considering shearing of fault surface asperities and resultant stress drop driving the fault-slip. Two methodologies to evaluate damage caused by seismic waves arising from the simulated fault-slip are examined: (i) the ratio of dynamic plastic strain increment to elastic strain limit and (ii) plastic strain energy density. For the former one, two types of strain increments are tested, namely effective shear strain increment and volumetric strain increment. The results indicate that volumetric strain increment is a suitable index for detecting damage near the stope wall, while effective shear strain increment is appropriate for evaluating damage in backfill. The evaluation method with plastic strain energy density is found to be capable of assessing damage accumulated in an extensive area caused by rock mass oscillation due to seismic wave propagation. Possible damage to mine developments in the proximity of a stope is clearly described with the index. The comparison of the two methods clarifies that the former one assesses "instantaneous" damage, which is found to be different from "accumulated" damage calculated using plastic strain energy density, in terms of damage area and its location. It is thus concluded that the combination of the two methodologies leads to more accurate damage assessment as a proper measure against rockburst.

## 1. Introduction

Stress redistribution caused by mining activities, such as stope extraction, drift development, and production blasting, leads to the reactivation of a pre-existing fault (Alber and Fritschen, 2011; Hofmann and Scheepers, 2011; Sainoki and Mitri, 2014a, 2016). As a result, fault-slip can occur, producing intense seismic waves (Ortlepp, 2000). When the seismic waves hit underground openings, rockbursts, i.e. violent rock ejection and massive collapse, could take place (Ortlepp and Stacey, 1994). In order to ensure safe working environments and stable production, it is paramount to gain a better understanding of the mechanism of mining-induced fault-slip and to elucidate the relation between the seismic waves and the damage to mine openings.

It is common that numerical modeling of mining-induced fault-slip is conducted with the conventional Mohr-Coulomb failure criterion in static conditions (Alber and Fritschen, 2011; Hofmann and Scheepers, 2011; Sjöberg et al., 2012). Unfortunately, the method does not replicate the actual mechanism of mining-induced fault-slip. In reality, the surface of faults in underground mines is undulating and has asperities that interlock with each other (Wallace and Morris, 1986; Sagy et al., 2007). Instantaneous stress drop caused by the shearing of such asperities (Ryder, 1988), which is related to the occurrence of mining-induced fault-slip, cannot be accurately modeled with the conventional method. Furthermore, the numerical analysis in static conditions is incapable of producing seismic waves arising from fault-slip. Therefore,

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it is impossible to evaluate the damage to nearby mine openings inflicted by the seismic waves.

Recently, Sainoki and Mitri (2014b) developed a methodology to simulate mining-induced fault-slip with Barton's shear strength model (Barton, 1973) in dynamic conditions, considering the stress drop induced by asperity shear. The methodology is capable of modeling mining-induced fault-slip in a more robust way than the use of the Mohr-Coulomb failure criterion. Furthermore, as the analysis is performed in dynamic conditions, the propagation of seismic waves can be simulated (Sainoki and Mitri, 2014b). Although a number of studies have been undertaken concerning the effect of seismic waves on the stability of an underground opening, studies especially focused on the effect of seismic waves arising from mining-induced fault-slip have been rarely reported. Recently, Wang and Cai (2015) examined the effect of seismic waves on an excavation while considering a point source of a fault-slip event, but the magnitude of fault-slip is an input parameter, that is, it may fail to estimate the damage induced by fault-slip that could take place under ambient stress state.

Another important aspect to be considered is a failure criterion for an opening where stress state is biaxial. It has been demonstrated that consideration of the intermediate stress is required (Yun et al., 2010) in order to predict the failure of rock under biaxial stress conditions, where spalling resulting from extension fractures is expected (Palmström, 1995; Diederichs, 2007). Numerical analysis is capable of incorporating such failure criterion to analyze specific stress fields generated as a result of mine development and ore extraction in underground mines.

In light of literature review, the present study focuses on estimating the damage around an underground opening induced by seismic waves arising from mining-induced fault-slip whilst considering the failure of rock mass under biaxial stress conditions. The fault-slip is modeled in static and dynamic conditions whilst considering the asperity shear as its source mechanism. The damage induced by seismic waves to a stope in a deep hard rock mine is evaluated whilst considering the failure under biaxial stress conditions.

## 2. Methodology

### 2.1. Constitutive model for fault

As discussed in Introduction, the effect of fault surface asperities needs to be taken into consideration. A number of advanced shear strength models have been proposed by many researchers to estimate the shear behavior of a rock joint with asperities (Ladanyi and Archambault, 1970; Saeb and Amadei, 1992; Kulatilake et al., 1995; Homand et al., 2001; Indraratna et al., 2005, 2008; Lee et al., 2006). Amongst such shear strength models, the present study employs Barton's shear strength model (Barton, 1973) because the model is widely accepted and can be used after estimating a few physico-mechanical parameters that represent the degree of surface asperities and the strength. Barton's model is expressed as follows:

$$\tau_{\max} = \sigma_n \tan\left[JRC \log_{10}\left(\frac{JCS}{\sigma_n}\right) + \varphi_b\right] \tag{1}$$

where $\tau_{\max}$ and $\sigma_n$ are the maximum shear strength and the normal stress acting on a fault, respectively; and $JRC$, $JCS$ and $\varphi_b$ are the joint roughness coefficient, the joint wall compressive strength, and the angle of friction, respectively. Comparison of Barton's shear strength model with the classical Mohr-Coulomb model is shown in Fig. 1. As can be seen in the figure, the shear strength calculated from Barton's model is invariably greater than that of Mohr-Coulomb model.

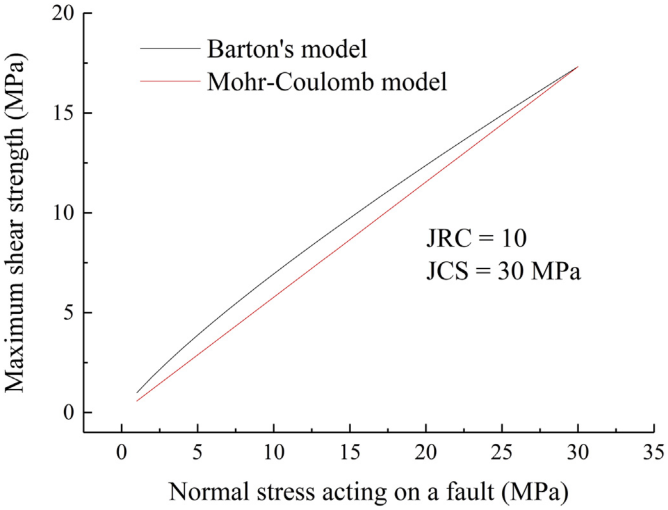

**Fig. 1.** Barton's shear strength model.

The Barton's shear strength model is implemented into the joint model of FLAC3D. The implementation procedure is based on the plastic flow rule, i.e. the increment of plastic strain is determined with the derivative of potential function with respect to its stress components and a scalar variable derived from the consistency condition. The detailed procedure of the implementation is provided in Sainoki and Mitri (2014c). In order to simulate fault-slip triggered by the shearing of fault surface asperities, JRC is instantaneously decreased during a dynamic analysis, which is described in more detail later.

### 2.2. Failure criterion under biaxial stress state and its implementation to FLAC3D

Yun et al. (2010) performed biaxial tests for several types of rocks and established a failure criterion under biaxial stress conditions, which are the stress conditions that take place on the surface of underground openings. The failure criterion is expressed as follows:

$$\frac{\sigma_1}{\sigma_c} = A + B\frac{\sigma_2}{\sigma_c} + C\left(\frac{\sigma_2}{\sigma_c}\right)^2 \tag{2}$$

where $\sigma_1$, $\sigma_2$ and $\sigma_c$ are the maximum compressive stress, intermediate stress and uniaxial compressive strength (UCS), respectively; and $A$, $B$, and $C$ are material constants. In order to implement the equation as a yield criterion into FLAC3D, compression needs to be defined as negative and the equation is multiplied by UCS, consequently giving the following equation:

$$F = \sigma_1 + A\sigma_c - B\sigma_2 + C\frac{\sigma_2^2}{\sigma_c} \tag{3}$$

Note that compression has a negative quantity in Eq. (3). Following the same procedure shown in Sainoki and Mitri (2014a), the scalar variable that determines plastic strain increments is expressed as follows:

$$\lambda = \frac{\{\partial F/\partial \sigma\}^{\mathrm{T}}[D]\{\Delta\varepsilon\}}{\{\partial F/\partial \sigma\}^{\mathrm{T}}[D]\{\partial g/\partial \sigma\}} \tag{4}$$

where $[D]$ is an elastic matrix that relates strain with stress, $\{\Delta\varepsilon\}$ is a strain increment vector, and $g$ is a potential function.

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