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Scaling rockburst hazard using the DDA and GSI methods

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ABSTRACT

We examine the influence of rock mass quality, as scaled by the Geological Strength Index (GSI), on energy redistribution in tunnels driven through discontinuous rock masses. We assume that in blocky rock masses rockbursts develop as abrupt motion of finite rigid blocks along pre-existing discontinuities rather than by fracture of intact rock elements. We begin by formulating analytically the local energy density around a tunnel in continuous, homogenous, isotropic, linear-elastic medium and demonstrate the significance of the initial principal stress ratio on the result. We then introduce discontinuities into the rock mass and find analytically the peak acceleration of an ejected keyblock when it flies into the tunnel space, to demonstrate the viability of this mechanism as a potential rockbursting source. Using the numerical discontinuous deformation analysis (DDA) method we find the total kinetic energy released during rockbursting and validate our DDA results using monitored seismic energy emissions detected during an intensive rockburst event encountered while excavating one of the headrace tunnels at Jinping II hydroelectric project in China. Utilizing an analytical solution we published earlier for the redistribution of energy components due to tunneling, we explore the effect of rock mass quality as scaled by GSI on the elastic strain energy, dissipated energy, and kinetic energy. We find that the elastic strain energy and the energy dissipated by shear generally decrease with increasing GSI value. The kinetic energy of rockbursts however shows a more complicated behavior. It is low at low quality rock masses, peaks at GSI value of about 60, and decreases again with increasing rock mass quality. This result is supported by documented rockbursts during excavation of the deep tunnels of the Jinping II hydropower project, where the majority of rockbursts were recorded in tunnel segments with characteristic GSI values between 60 and 75.

1. Introduction

Rockbursts are the most serious and least understood hazard associated with deep underground excavations, typically involving violent energy release with sudden ejection of rock fragments that may result in fatalities and damage to facilities (Mazaira and Konicek, 2015). Not unlike artificially induced earthquakes (Zembaty, 2004) triggered by changes in the stress field near the excavation, rock bursts are accompanied by audible acoustic emissions, and trigger ground motions strong enough to eject preexisting rock blocks into the excavation space. Excavation-induced stress concentrations at great depths further increase the risk for spontaneous rockbursts.

With the increase in attempted underground excavation depths, the risk for uncontrolled rockbursts has increased as well. Our ability to predict the temporal and spatial distribution of rockbursts, as well as their magnitudes, however, is constrained by our theoretical understanding of this phenomenon. A fundamental contribution to this field led by the late Professor Neville Cook has been made in South Africa during the 1960's (Cook, 1966). Since then, several research groups from around the world have attempted to explore this issue and to offer efficient prevention measures (Kaiser and Cai, 2012). Based on field observations three rock burst types have been discussed: (1) strain bursts, (2) pillar bursts, and (3) fault slip bursts (Müller, 1991), among which strain bursts are most frequently encountered underground (He et al., 2015). To date, two causative mechanisms have been suggested for triggering rockbursts: (1) remote seismic events, and (2) stress changes close to the excavation boundaries (Ortlepp and Stacey, 1994). It is widely accepted however that stress changes near the excavation boundaries are more significant than remote seismic events (Wang et al., 2015a,b). Rockburst damage intensity is typically discussed in terms of the depth of rockburst notches, volume of rock failed, and seismic energy released. Recently the concept of excavation damage zone (EDZ) around underground openings has been employed in brittle rock masses to predict the depth and extent of rock fracturing as a result of rockbursts (Perras and Diederichs, 2016).

Different rockburst intensity classifications have been developed

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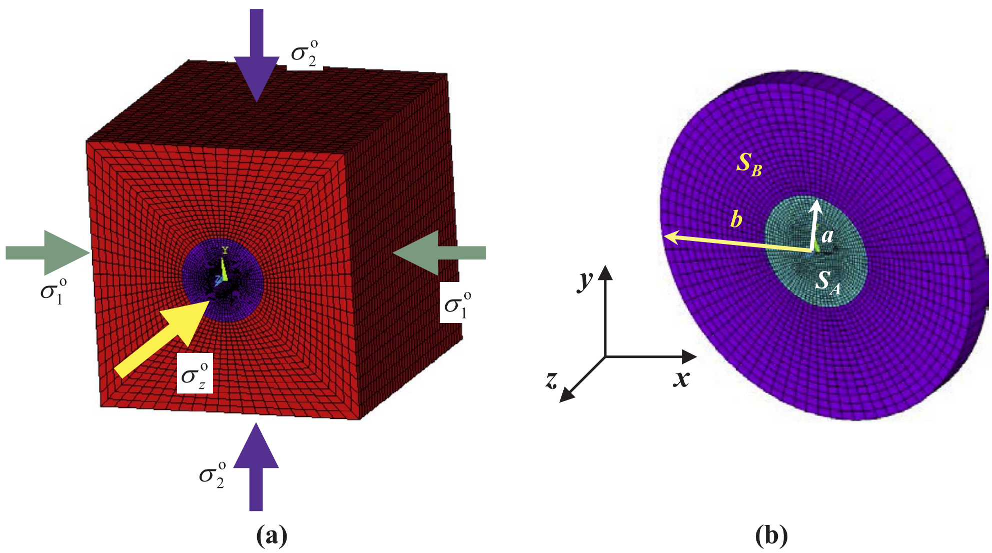

Fig. 1. Sign convention used in this paper: (a) assumed initial stress state; (b) the excavated tunnel of radius a and the analyzed annulus of radius b.

based on experience from different countries (Martin, 1970). The diversity in approaches is evident in the multitude of stress-based criteria. Four well-known such criteria are the ratio between uniaxial compressive strength and the vertical *in-situ* stress (Hoek and Brown, 1980), the sum of the tangential stress and the horizontal stress parallel to the tunnel axis ($\sigma_\theta + \sigma_L$) (Turchaninov et al., 1972), the magnitude of the major principal stress σ_1 (Barton et al., 1974), and the magnitude of the tangential stress σ_θ (Russenes, 1974). Analyzing a single rockburst event with these different criteria yields, however, inconsistencies in the rockburst intensity classification (Zhao et al., 2017). Moreover, none of these criteria includes the influence of the excavation dimension on rockburst potential.

Geophysical methods have been utilized to detect the evolution of mining-induced tremors, both in time and in space, and the results have been used to study fracture initiation and propagation and to assess the corresponding energy accumulation and release (e.g., Brady and Leighton (1977)). Three-dimensional monitoring of micro-seismic (MS) tremors now provides powerful means to detect the location of and compute the seismic energy released from mining-induced motions (Feng et al., 2012). Assessment of rockburst hazard based on recorded seismicity is now standard engineering practice, assisting in making operational decisions in the course of the deep excavation projects, on a daily basis (Mutke et al., 2015). It is recognized however that the phenomenon of rock bursts involves both static as well as dynamic deformation (Adoko et al., 2013).

At the laboratory, true-triaxial unloading experiments have been conducted to clarify the relationship between rockbursts and acoustic emissions in the process of fracturing of prismatic limestone specimens (Gong et al., 2014). Instantaneous rockbursts in granites were studied at the lab to understand the relative distribution of energy components, i.e., the total, elastic, and dissipated energy for a single rock block (Wang et al., 2015a,b). To investigate the mechanisms of rock bursts caused by shear failure along pre-existing interfaces, model experiments and direct shear tests were performed (Zhou et al., 2015).

Numerical methods are useful for assessing the potential for rock bursts and for modeling prevention measures. Based on numerical analysis several indices have been suggested, e.g., failure approach indices which evaluate the stress concentration in the rock mass using a "yield approach index" or a "failure degree index" (Zhang et al., 2011). Three-dimensional finite element modeling was conducted to study stress concentrations after the opening is created in deep, hard rock mines (Wang and Park, 2001). The explicit finite difference FLAC code also was used to compute and analyze the distribution and accumulation of elastic strain energy in the rock mass that was treated as a continuum during an unloading opening (Miao et al., 2016). In combination with experimental results and continuum-based modeling, the strain energy stored in the rock was studied, and rockburst occurrence was assessed using evaluation indices like energy release rate (ERR), energy storage rate (ESR) (Cook, 1966), burst potential index (BPI), and potential energy of elastic strain (PES).

When using continuum based numerical approaches that employ infinitesimal strain theory, separation, rotation, or ejection of finite rock blocks cannot be modeled rigorously. This restriction may be relaxed by using discrete element approaches such as the numerical explicit DEM or the implicit DDA methods.

A useful way to describe the structure of the rock mass is by means of empirical rock mass classification methods that address geometrical attributes like joint set attitude and mean joint set spacing. These geometrical parameters control the block size distribution in the rock mass. Intuitively, it would be expected that the energy associated with rockbursts would be strongly influenced by the blocky structure of the rock mass, however to date this issue has not been studied thoroughly enough. We explore here the relationship between rock mass quality, as scaled by the Geological Strength Index (GSI), and the redistribution of energy components due to tunneling, with particular emphasis on the kinetic energy of keyblock ejections, or rockbursts in the context of this paper.

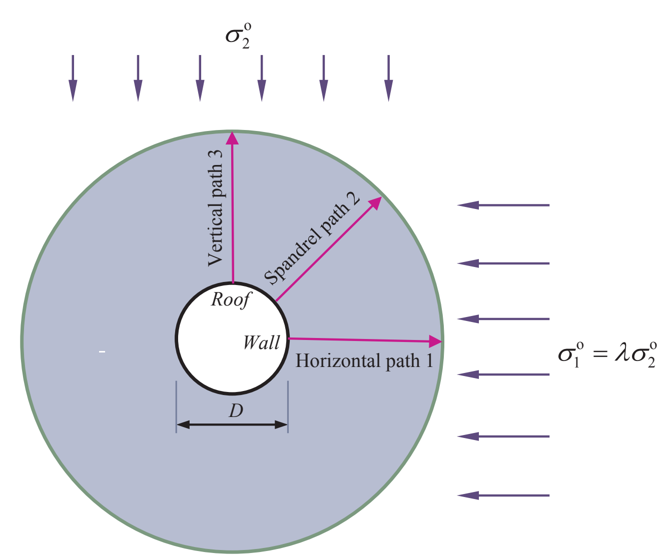

Fig. 2. Three radial paths considered in the analysis.