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Numerical modeling of rockburst near fault zones in deep tunnels

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ABSTRACT

Many factors that influence rockburst damage have been identified but the mechanism that drives rockburst is not fully understood. Weak planes such as faults and shears have been observed near excavation boundaries in many rockbursts and these structures must have played a role in these rockburst events. In this paper, the role of weak planes around tunnels in rockburst occurrence and damage was studied. A heterogeneous Abaqus^{2D} explicit code was used to simulate dynamic rock failure in deep tunnels. Firstly, rock failure near the excavation boundary of a tunnel without any adjacent weak plane was modeled. Then a fault with different lengths, inclinations, and distances to the tunnel was added to the model and its effect on rock failure was simulated. The velocity and the released kinetic energy of failed rocks, the failure zone around the tunnel, and the deformed mesh were studied to identify stable and unstable rock failures. The simulation results showed that the presence of a fault near a tunnel could induce rockburst if the fault is positioned and oriented in such a way that it promotes high stress and low mine system stiffness. Finally, a rockburst occurred in the Jinping II drainage tunnel with an observed nearby fault was simulated. The modeling results captured the field observation of rockburst damage and confirmed that the presence of weak planes in the vicinity of deep tunnels is a necessary condition for the occurrence of rockburst. The presented methodology in this paper can be useful for rockburst anticipation and control during mining and tunneling in highly stressed grounds.

1. Introduction

Rockburst is an unstable rock failure and one of the most hazardous problems in deep mines and civil tunnels. A rockburst is a sudden failure of rock in the form of rapid ejection of failed rocks, accompanied by the release of a large amount of energy. Rockbursts occurred in gold mines in the Witwatersrand area in South Africa and the Kolar Gold Field in India were first recognized to be the consequence of mining, not natural earthquakes, at the turn of the 20th century (Blake and Hedley, 2003; Hedley, 1987). The rockburst problem increases as excavation activities progress to deep grounds. For example, many deep hard rock mines in Canada, South Africa, Australia, and Sweden and some deep civil tunnels in Switzerland, China, and Peru have experienced rockburst problems (Kaiser and Cai, 2012; Cai and Kaiser, 2018). Rockburst imposes a great danger to the safety of workers and investment (Cai, 2013b; Chen et al., 1997; Whyatt et al., 2002; Zhang et al., 2013; Zhu et al., 2009) and many efforts have been made to understand why rockburst occurs. Having the ability to anticipate where a rockburst will occur and how large it will be would be valuable for rock support design.

Unfortunately, there is still a long way to go to anticipate rockburst, partially due to a lack of tools that can be used to investigate rockburst mechanism and damage but most importantly due to the fact that rockburst is a very complex phenomenon. Many factors that influence rockburst damage have been identified (Lee et al., 2004; Mansurov, 2001; Wang and Park, 2001). Kaiser and Cai (2012) categorized the main influencing factors systematically into four groups as seismic event, geology, geotechnical property, and mining activity. Some studies have been conducted to understand the influence of these factors on rockburst damage (Kaiser et al., 1996; Reddy and Spottiswoode, 2001; Salamon, 1983; Zhang et al., 2013; Zhu et al., 2010).

Dynamic disturbance due to seismic activities (e.g. explosion, vibration, stress impact from nearby rockbursts) does influence rockburst damage. Studies have shown that external disturbances during underground mining can induce rockbursts (Blair, 1993; Kaiser et al., 1996; Zhu et al., 2010). In addition, mining provides conditions for rockburst occurrence by changing the stress field and loading system stiffness in the ground around underground openings (Mitri et al., 1999; Ozbay, 1989; Salamon, 1983). Geotechnical factors such as rock strength and rock brittleness affect strain energy storage and release. Rocks that are

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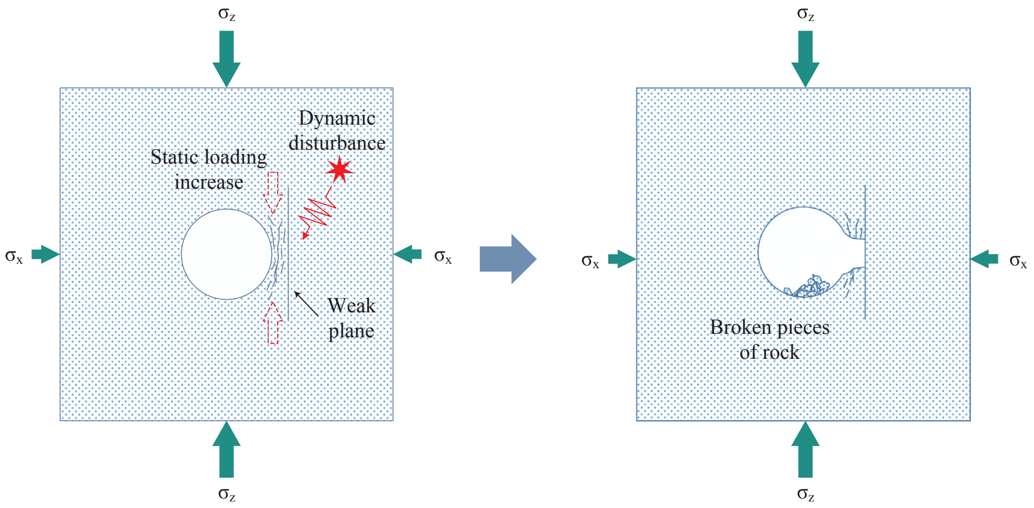

Fig. 1. Schematic sketch of rockburst induced by slab buckling.

more brittle and have higher strengths tend to be more burst-prone. Other geotechnical factors that influence rockburst damage are in situ stress and discontinuities (Reddy and Spottiswoode, 2001; Snelling et al., 2013; Yeryomenko and Sklyar, 1999). In particular, discontinuities such as shears and faults can alter the stress field and the loading system stiffness in such a way that rock failure becomes more violent.

It has been recognized that a deep underground opening is more burst-prone when it approaches a geological discontinuity such as fault, dyke, and contact (Hedley et al., 1992; Snelling et al., 2013). Durrheim et al. (1998) investigated 21 rockbursts in some deep South African gold mines and identified regional structures such as faults and dykes as a major controlling factor that influenced the occurrence of the rockbursts. They concluded that mining near major faults and dykes might result in rockburst. Jiang et al. (2010) studied the rockburst characteristic of the pilot tunnels of the Jinping II hydropower station in China and noticed that rockbursts tended to occur at places where faults and large joints were presence.

Hence, it is logical to study the influence of structural planes on rockburst. For instance, Zhang et al. (2013) conducted a numerical study that considered a fault near the drainage tunnel of the Jinping II hydropower station to explain the damage of a rockburst that occurred in the drainage tunnel. Their results showed that the fault influenced rock failure around the tunnel but they did not provide ejection velocity and kinetic energy release analysis. Zhou et al. (2014) conducted laboratory shear tests to explain the role of weak planes on rockburst damage observed in the intake tunnels of the Jinping II hydropower station. Based on their test results, they hypothesized three possible mechanisms (fault-slip, shear rupture, and buckling) for rockburst occurrence.

Unstable rock failure can be simulated using continuum and discontinuum numerical models. Some numerical simulations were carried out to study unstable rock failure in laboratory tests such as uniaxial and triaxial compression tests (Garvey, 2013; Manouchehrian and Cai, 2015). Moreover, some researchers investigated unstable rock failure around underground openings using numerical methods (Jiang et al., 2010; Jiang et al., 2015; Kias and Ozbay, 2013; Zhang et al., 2014). Results from the above mentioned studies and other similar studies have been used to explain rockbursting phenomenon around deep underground openings. However, it is still not clear how the presence of weak planes near an opening influences rockburst damage.

In this paper, the influence of weak planes on rockburst occurrence and damage around underground openings is investigated using a numerical tool based on the explicit Finite Element Method (FEM). A discussion of rockbursts induced by weak planes is presented in Section 2. In Section 3, simulation of rockburst in a tunnel with a nearby weak plane or fault is conducted using the Abaqus^{2D} explicit code with heterogeneous material properties. A parametric study with different fault lengths (l), inclinations (θ), and positions relative to the tunnel (d) is conducted. A comparison of results between models with and without a weak plane is also presented. In Section 4, the 11.28 rockburst occurred in the Jinping II drainage tunnel is simulated.

2. Rockbursts near weak planes

Case histories from civil and mine tunneling have shown that rockburst occurrence locations are not uniform along the tunnels. Both the rockburst occurrence and the damage extent in a tunnel varies as the result of the influence of many factors such as geology and mining activities (Kaiser and Cai, 2012). The presence of weak planes such as faults, shears, and bedding planes near or at rockburst damage locations has been noticed. Weak planes can change the stress field and the loading system stiffness locally, making a rock mass more burst-prone. In highly stressed grounds, weak planes may induce rockburst through slab buckling and rock rupture, depending on the position of the weak plane relative to the excavation walls and the stress condition.

2.1. Slab buckling

Slab buckling has been identified as a mechanism of rockburst (Bardet, 1991; Nemat-Nasser and Horii, 1982; Ortlepp, 1993). The concept of buckling rockburst is illustrated in Fig. 1. Weak planes parallel to the tunnel boundaries and the maximum principal in situ stress may cause buckling type rockburst. When the rock in the slab are highly stressed, a small increase of stress due to tunnel advance or dynamic disturbance from nearby blasting and rockbursts or remote seismic events may trigger rockburst. The rock slab can fail violently and the stored strain energy in the rock slab is released suddenly and broken pieces of rocks are ejected into the excavation. Some rockbursts occurred in some South African mines and at the Jinping II tunnels in China were resulted from slab buckling (Ortlepp, 1997; Qiu et al., 2014). Rock slabs are normally created by high stress in a 3D stress state with the intermediate principal stress playing an important role (Cai, 2008a).

2.2. Intact rock rupture

Experimental and numerical studies have shown that in a loaded rock specimen with pre-existing weak planes such as cracks and fractures, new fractures nucleate from the tips of the pre-existing fractures