Journal of Rock Mechanics and Geotechnical Engineering xxx (2017) 1–10

CSRME

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Analysis of rockburst in tunnels subjected to static and dynamic loads

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ARTICLE INFO

Article history:
Received 11 January 2017
Received in revised form
25 June 2017
Accepted 26 July 2017
Available online xxx

Keywords:
Rockburst
Numerical modeling
Geological structure
Static load increase
Dynamic disturbance
Tunnel

ABSTRACT

The presence of geological structures such as faults, joints, and dykes has been observed near excavation boundaries in many rockburst case histories. In this paper, the role of discontinuities around tunnels in rockburst occurrence was studied. For this purpose, the Abaqus explicit code was used to simulate dynamic rock failure in deep tunnels. Material heterogeneity was considered using Python scripting in Abaqus. Rockbursts near fault regions in deep tunnels under static and dynamic loads were studied. Several tunnel models with and without faults were built and static and dynamic loads were used to simulate rock failure. 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. Compared with models without discontinuities, the results showed that the velocity and the released kinetic energy of failed rocks were higher, the failure zone around the tunnel was larger, and the mesh was more deformed in the models with discontinuities, indicating that rock failure in the models with discontinuities was more violent. The modeling results confirm that the presence of geological structures in the vicinity of deep excavations could be one of the major influence factors for the occurrence of rockburst. It can explain localized rockburst occurrence in civil tunnels and mining drifts. The presented methodology in this paper for rockburst analysis can be useful for rockburst anticipation and control during mining and tunneling in highly stressed ground.

1. Introduction

Mankind's life is very dependent on the Earth's materials. Continuous mining over the past years has depleted most surface and shallow reserves and forced us to go deeper inside the Earth for more natural resources. Mining conditions are difficult in deep grounds; it is harder and more risky to mine at depth. One of engineering hazards of mining at depth is rockburst. A rockburst is an unstable failure of rock associated with a sudden release of energy, and it imposes a great danger on the safety of workers and investment.

Case histories in mining have documented violent rock failures that were accompanied by rapid ejection of debris and broken rocks into working areas of mine openings and tunnels (Shepherd et al., 1981; Ghose and Rao, 1990; Hedley, 1992; Young, 1993; Gibowicz and Lasocki, 1997; Blake and Hedley, 2003; Zhang et al., 2012; Andrieux et al., 2013). In some cases, these violent unstable failures have resulted in loss of life and total collapse of mine panels (Chen et al., 1997; Whyatt et al., 2002; Zhu et al., 2009; Zhang et al., 2013). Violent rock failure can occur locally in isolation, which may not affect the general stability of a mine, but poses a great threat to personnel in the area. Modern mining operations take available measures to reduce the likelihood of unstable rock failures, but complete elimination of unstable rock failures is difficult in practice due to the uncertainty in rock stress, strength, stiffness, and other mechanical properties (Cai, 2013). Over the past five decades, researchers have studied unstable rock failure and rockbursting using various means such as analytical, numerical, experimental, and statistical approaches (Sun et al., 2007; He et al., 2010, 2012; Li et al., 2012, 2013, 2014; Tao et al., 2012; Zhu et al., 2014; Zhao and Cai, 2014; Xiao et al., 2016). However, many conditions leading to rockburst occurrence are not fully understood and further studies are needed to understand the mechanisms of rockbursting so as to control and mitigate rockburst risk.

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2017.07.001

Ortlepp (1997) classified rockbursts into five types (strainburst, buckling, face crush/pillar burst, shear rupture, and fault-slip burst). In a broad sense, they can be grouped into three rockburst types, i.e. strainburst, pillar burst, and fault-slip burst. Strainbursts, which are due to stress concentration and strain energy accumulation and release, can be assessed based on stress or energy consideration (Mitri et al., 1999). Pillar bursts can be assessed by comparison of local mine stiffness to pillar's post-peak stiffness (Zipf, 1996). Fault-slip bursts, which are larger seismic events in general, can be assessed based on potential movement (slip) of the fault, slip rate, and seismic moment (Sainoki and Mitri, 2014).

Rockburst case histories reveal that rockburst damage is often localized and not uniform. In other words, the damage extent in a tunnel caused by a rockburst varies at different locations. The localized rockburst damage originates from the complex mechanisms that drive rockbursts and the contribution of influence factors on rockburst occurrence. Many factors influencing rockburst damages have been identified, but no one knows the exact condition for the occurrence of a rockburst in a complex underground setting (Kaiser and Cai, 2012).

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). Some studies have been conducted to explain the influence of structural planes on rockburst. For example, Zhang et al. (2013) conducted a numerical study that considered a fault near the drainage tunnel of the Jinping II hydropower station in China to explain a rockburst that occurred in the drainage tunnel. They showed that the presence of the fault near the tunnel could affect the rock failure. However, they could not estimate failure intensity (in terms of ejection velocity of broken rocks and released kinetic energy). In another study, Zhou et al. (2015) conducted some laboratory experiments to explore the role of weak planes on rockburst damage in tunnels. In their study, the role of weak planes on rockburst damage observed in the intake tunnels of the Jinping II hydropower station was explained by their observations from laboratory shear test results. They stated that weak planes could induce rockburst in tunnels with three possible mechanisms including fault-slip, shear rupture, and buckling. Manouchehrian (2016) used numerical models to study rockbursts near fault regions in deep tunnels. It shows in this study that weak planes around a tunnel may change the loading system stiffness of the failed rocks and induce rockbursts because when there is a weak plane near an underground opening, a large volume of rock is able to move more freely than that without a weak plane.

In this paper, the influence of geological weak planes on rockburst occurrence in tunnels that are subjected to static load increase and dynamic disturbance is investigated using Abaqus[2D] explicit models. In Section 2, model responses between homogeneous and heterogeneous materials are studied. In Section 3, simulation of rockburst in tunnels without and with a nearby weak plane or fault is conducted. Static load increase and dynamic disturbance are considered in the models and the mechanism of rockburst in each loading condition is explained. A comparison of results between the models with and without a weak plane is also presented.

2. Rock failure simulation using Abaqus

Unstable rock failure is a dynamic phenomenon and should be treated as a nonlinear dynamic problem. Studies have shown that the explicit numerical method is more suitable than the implicit numerical method for solving nonlinear dynamic problems because the issue of convergence is eliminated. Abaqus is a FEM (finite element method)-based numerical tool which is equipped with implicit and explicit solvers, making it applicable for solving a large variety of physical and engineering problems (Dassault-Systems, 2010). Manouchehrian and Cai (2016a) simulated uniaxial and poly-axial compression tests using the Abaqus explicit tool and demonstrated the suitability of the tool for simulating unstable or dynamic rock failure. In this study, Abaqus explicit tool is used to simulate rockburst in deep tunnels.

A key characteristic of geomaterials is material heterogeneity, which cannot be readily modeled in Abaqus through GUI. Fortunately, Abaqus provides scripting capability for introducing material heterogeneity into models. In this section, a simulation of rock failure processes in compression using homogeneous material models is presented first, followed by a simulation of rock failure processes in compression using a heterogeneous material model.

2.1. Homogeneous model

To study rock failure using Abaqus, the laboratory tested mechanical parameters of T_{2b} marble (Table 1) are used as the base case. T_{2b} marble is the host rock of the diversion tunnels at the Jinping II hydropower station in China (Zhang et al., 2012).

Unconfined and confined compression tests are simulated to investigate the failure mechanism of homogeneous rocks. An elastoplastic Mohr-Coulomb strain-softening model with homogeneous material properties is used to model the strength of the T_{2b} marble. Table 2 presents the calibrated parameters for defining the strain-softening behavior of the rock in the homogeneous model. A rectangular specimen with a height of 250 mm and a width of 100 mm is used for simulation. A plane strain model is used. In the unconfined compression test simulation, one end of the specimen is fixed in the maximum stress direction and the other direction is free (roller constraint), and a constant velocity of 0.03 m/s is applied directly to the other end to load the specimen. The same end boundary conditions are applied to the specimens in the confined compression test simulations and the confinements applied are 5 MPa, 10 MPa, 20 MPa, and 40 MPa. In the developed homogeneous model, a uniaxial compressive strength (UCS) of 113.6 MPa, a friction angle of 30°, and a cohesion of 32.9 MPa are calculated, which are similar to the reported laboratory test data (Table 1).

Fig. 1 shows the failure pattern in the homogeneous models indicated by the plastic shear strain. The figure shows that confinement does not affect the failure patterns in the homogeneous model because all of them show distinct shear failure. Despite that the mechanical parameters of the T_{2b} marble are captured by the homogeneous model, it fails to capture the splitting failure under low confinement.

2.2. Heterogeneous model

In order to overcome the deficiency of the homogeneous models, Manouchehrian and Cai (2016b) introduced heterogeneity

Table 1
Physico-mechanical properties of the T_{2b} marble (Zhang et al., 2014).

Density, ρ (kg/m^3)	Young's modulus, E (GPa)	Poisson's ratio, ν	UCS (MPa)	Cohesion, c (MPa)	Friction angle, φ (°)	Post-peak modulus, E_{pp} (GPa)
2780	55	0.27	110.7[a]	32.6	29	150[b]

[a] UCS of the T_{2b} marble was reported between 100 MPa and 160 MPa in Zhang et al. (2014). This value was calculated according to $UCS = \frac{2c\cdot\cos\varphi}{1-\sin\varphi}$ for the present study.

[b] Post-peak modulus (E_{pp}) of the T_{2b} marble is extracted by digitizing curves presented in Zhang et al. (2014).