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A numerical study of spalling and related rockburst under dynamic disturbance using a particle-based numerical manifold method (PNMM)

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ABSTRACT

In this paper, the spalling failure of rock materials and spalling-induced rockbursts in tunnels are numerically investigated using a particle-based numerical manifold method (PNMM). The ability of PNMM for modelling spalling failure of rocks is validated in both one-dimensional (1D) and two-dimensional (2D) cases. The thickness of the first spall in rock bars and the spalling fracture pattern in rock plates are in good agreement with the theoretical analysis and numerical solutions in the literature. The values of spall strength at different loading rates are calculated by the particle velocities on the free surface of rock bar. Afterward, the rockburst in tunnels triggered by dynamic disturbance is simulated by the validated model. The mechanism of rockburst under this condition is proven to be closely related to spalling failure. The effect of the static in-situ stress on rockbursts are considered. Modelling results reveal that rockbursts are most likely to take place when the dynamic disturbance comes from the direction of the higher in-situ stress. Parametric studies also indicate that the larger difference exists between the horizontal and vertical in-situ stresses, the more severe rockburst could be triggered.

1. Introduction

There has been a noticeable trend to mine and construct underground caverns at greater depth in recent years. As in-situ stresses increase with depth, stress-induced rock fracturing, especially the sudden and violent failure of rock, will be a great threat to the construction, equipment, and the safety of mining worker. Rockburst is defined as a sudden rupture and explosion of rock on the surface of rock wall and is associated with a seismic event (Kaiser, 1996). Cai et al. (2012) classified rockbursts into three types, including strain burst, pillar burst, and fault-slip burst. Strain bursting, as the most common rockburst type in many mines, is a phenomenon that a certain volume rock wall is violently destroyed under high stresses (Gong et al., 2012). Strain bursts can be either mining-induced by energy release or dynamically-induced by remote seismic events. The strain energies stored in the failing rock and surrounding masses are released in a strain bursting, such that the failure is in a violent manner. Research shows that strain bursting is closely related to the spalling failure of rock. The term "spalling" here represents the development of visible tensile fractures under compressive loading, induced by either the stress concentration of a stress flow around underground openings or remote seismic event (Kaiser and McCreath, 1994). Ortlepp (2001) described a strain bursting as a superficial spalling with violent ejection of fragments. Diederichs (2007) stated that the spalling failure could happen before the actual strain bursting, and strain bursting is induced by the energy release of parallel and thin spall slabs. He et al. (2012) clearly showed the transfer of dominating failure type from spalling to strain bursting with the increase of in-situ stress in experimental tests.

In this study, the term "spalling" is used to describe the tensile failure process due to the reflection of a compression wave at free surface or material interfaces (Weerheijm and Van Doormaal, 2007). The spalling in this definition is induced by a remote compressive stress wave. This phenomenon has been widely used to determine the dynamic tensile strength of a variety of brittle materials (e.g. rock, concrete and ceramics) under shock wave loading in experiments, as these materials have a much lower tensile strength comparing to their compression strengths. The experimental methods based on the spalling phenomenon fall into the category of indirect tension testing methods (Zhang and Zhao, 2014). The most common type of spalling tests is to utilize long bars under 1D stress wave condition (Díaz-Rubio et al., 2002). Schuler et al. (2006) measured the tensile strength and determined the specific fracture energy at strain rates between 10^1 and $10^2\,s^{-1}$. Forquin and Erzar (2010) measured the tensile strength of both dry and wet concrete under strain rates between 30 and $180\,s^{-1}$. Lu and

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Notation

The following symbols are used in this paper:

C	dimensionless strain rate constant
$\mathbf{d}$, $\mathbf{d}_e$, $\mathbf{d}_i$	vector of DOF for system, manifold element and mathematical cover
$\mathbf{F}$	vector of equivalent loads
h	thickness of the first spall
K_1	bulk modulus
K_2, K_3	JHB constants
$\mathbf{K}$	stiffness matrix
$\mathbf{M}$	mass matrix
$\mathbf{N}_i$, $\mathbf{N}_e$	shape function of physical cover and manifold element
P	pressure variable
P_i	JHB constant
P_H, P_V	horizontal and vertical in-situ stress
ΔP	pressure increment
T	static tensile strength
$\mathbf{u}$, $\mathbf{u}_e$	displacement field of particle and manifold element
$\mathbf{u}_i$	cover function
v_1, v_2	pull-back velocity
v_p	stress wave velocity
$\mathbf{x}^c$	coordinates of the centroid of particle
$\boldsymbol{\varepsilon}$, $\boldsymbol{\varepsilon}_e$	strain of particle and manifold element
ρ	density
λ	wave length
σ_c	JHB strength
σ_p	peak value of the stress wave
σ_i, σ_{max}	JHB constants
σ_t^d	dynamic tensile strength
$\boldsymbol{\sigma}$, $\boldsymbol{\sigma}_e$	stress of particle and manifold element
φ	weight function

Li (2011) determined the tensile strength of dry concrete under strain rates between 10^{-4} and $10^2\,\mathrm{s}^{-1}$. Millon et al. (2016) conducted tests under strain rates varying from 1 to $520\,\mathrm{s}^{-1}$ on two sedimentary rocks, namely sandstone and limestone. Li et al. (2017a) adopted a modified split Hopkinson pressure bar (SHPB) to measure the spall strength of granite with a static confining load up to 30 MPa. Another application of spalling phenomenon is the normal plate-impact experiment under 1D strain wave propagation condition, by which the spall strength as well as the Hugoniot properties of brittle materials are measured (Yuan and Prakash, 2013; Zhang et al., 2017). Efforts have also been made to numerically study the spalling phenomenon of rocks and rock-like materials. Cho et al. (2003) adopted a Finite Element Method (FEM) code to simulate the spalling of rock bars. Erzar and Forquin (2011) numerically studied the spalling of concrete using a mesoscopic method. Zhu and Tang (2006) applied the Rock Failure Process Analysis (RFPA) model to the simulation of spalling in rock bars, and studied the effect of the rock heterogeneity on dynamic tensile strength (Zhu, 2008). Then, Xu et al. (2016) extended the model and studied the spalling of fiber-reinforced concrete in the manner of both long bars and plate impact.

Some researchers have also numerically studied the spalling and spalling-induced rockburst in tunnels. Zhu et al. (2014) adopted the AUTODYN code to study the spalling and zonal disintegration around a tunnel induced by stress wave. Mitelman and Elmo (2016) simulated the blast-induced spalling of tunnels using ELFEN, a hybrid Finite-Discrete Element Method (FDEM) code. However, no in-situ stress is considered in both of their research. Zhu et al. (2010) pointed out that rockbursts may occur when the rock mass is first supposed to be under high static in-situ stresses and then triggered by a far-field dynamic disturbance. Therefore, they adopted RFPA as the numerical method and studied tunnel rockbursts with varying in-situ stresses and dynamic disturbances. Similarly, Weng et al. (2017) utilized ANSYS/LS-DYNA to simulate the tunnel rockburst in three-dimensional cases. The rockburst in their simulation was triggered by a blast loading at the advancing surface of the tunnel. However, as the numerical models they adopted are both based on FEM, they are not able to simulate the post-failure stage of rock (Jing, 2003), including the behavior of fragmented rocks and the effect of spall slabs on rockburst. Besides, their work did not utilize a rate-dependent constitutive model to capture the tensile strength under dynamic loading.

In this paper, we apply a newly developed Particle-based Numerical Manifold Method (PNMM) (Li et al., 2018; 2017b) to simulate rock spalling and spalling-related rockburst. PNMM was modified from the Numerical Manifold Method (NMM) (Ma et al., 2010; Shi, 1991) and Particle Manifold Method (Sun et al., 2013). The abilities of PNMM to simulate the rate-dependent failure of rock (Li et al., 2017b) and stress wave propagation in rock (Li et al., 2016) have been validated. This work will first extend the application of PNMM to the spalling of long rock bars for further validation. Then, the simulation of spalling induced by plate impact will be conducted as a contact issue to confirm the model. At last, inspired by the work in (Zhu et al., 2010), tunnel rockbursts induced by dynamic disturbance will be numerically studied.

2. Numerical model

The numerical model PNMM is adopted in this research. A rate-dependent strength model, namely the Johnson-Holmquist-Beissel (JHB) model, has been incorporated into PNMM to simulate the dynamic behavior of rock materials. This section briefly presents the components, formulations and implementation of PNMM and the determination of JHB constants. More details can be found in Li et al. (2018, 2017b).

2.1. Particle-based numerical manifold method (PNMM)

PNMM is proposed by introducing the particle concept into NMM. The purpose of this development is primarily to simplify the geometrical Boolean operation and contact operation in NMM. Same as NMM, PNMM is inherently a continuum-discontinuum numerical model, providing a unified analysis framework for both pre- and post-failure behaviors. PNMM is flexible in considering the heterogeneity of rock materials and simulating the initiation and propagation of fractures, which separates it from NMM. PNMM inherits the most distinct characteristics of NMM, i.e. the mathematical covers and physical covers, but also utilizes a group of particles to form an extra level of discretization.

The mathematical cover system is a uniform cover system. It is independent of the shape of the modeling domain (including discontinuities, e.g. internal boundaries, cracks), but covers all the space the modeling domain may occupy. The weight function φ_i is defined on each mathematical cover. A physical cover is the intersection of a mathematical cover and the modeling domain. The physical cover is to provide the local approximation function by defining cover functions. The overlap of neighboring physical covers is called a manifold element. A manifold element is the basic computation unit in PNMM. For easy treatment, a regular mathematical mesh is usually adopted, and therefore the finite element shape function could be used as the weight function. Under such circumstance, the displacement field of a manifold element is generated by combing the cover functions of related physical covers using weight functions as