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Computational framework for simulating rock burst in shear and compression

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ABSTRACT

This paper presents results from a series of numerical modeling tests conducted with the objective of developing a computational framework for studying rock burst events. A commercially available distinct element code with its explicit time-stepping scheme is adopted for modeling the initial quasi-static and the subsequent dynamic response of rock burst in compression and shear. Ground reaction curves are introduced to discuss criteria for stability of a failure through stress analyses. Energy balance equations are analyzed for assessing the rock burst intensity by estimating radiated seismic energy once conditions of instability emerge. Two methods are discussed for estimating radiated seismic energy: tracking of the energy conversion during failure; recording the kinetic energy that is damped by mechanical damping schemes. Modeling approach and methodologies for studying compressive-type rock burst are developed and calibrated against available analytical solutions with respect to radiated seismic energy and excavation convergence. Factors participating in the intensity of rock burst in compression are examined by modeling a rectangular tabular excavation supported by a single pillar with ductile, semi-brittle, and brittle failure responses under different compressive loading. A shear-type rock burst along a strike-slip fault model is simulated and modeling approach is calibrated by checking the resulting slip distribution, radiated seismic energy, and seismic moment against analytical solutions. Factors contributing to the occurrence and intensity of shear-type rock burst are explored by simulating different slip scenarios under different loading conditions. With presented analyses, this paper provides a computational framework calibrated for studying rock burst events and, as a reference for treatment of more complex cases, shows how Young's modulus of the rock, failure stress drop, rock brittleness, and slip-weakening behaviors of faults govern the rock burst occurrence and intensity.

1. Introduction

Rock burst events are unstable rock failure induced by excavation advances underground. In stable failure, the process of failure is gradual and allows for arresting the failure by, for example, ceasing to enlarge the area of mining, therefore, the workings remain essentially stable. Unstable failure takes place suddenly with or without prior warning.[1] Commonly, unstable events are treated under two categories, one is the crushing of the highly stressed volume of rock in compression, usually with anomalous seismic signatures, and the other is unstable slip failure along mostly through-running large weakness planes such as fault and dyke contacts with typical earthquake-like seismic signatures.[1–5] Although significant progress has been made in understanding the phenomenon and applying mitigating measures, unstable failure continues to be a risk to the miners, especially in pillar workings, and the productivity of the mining operation while their intensity and frequency tend to increase with mining depth.[6–10] Predicting unstable failure requires a clear understanding of their mechanisms under various rock material properties and mining layouts. The effectiveness of mitigating strategies depends on the assessment of rock burst intensity that again is related to the understanding of the rock burst mechanisms and factors contributing to its intensity. Numerical techniques are useful tools for studying large-scale phenomena like rock burst that cannot be exposed by laboratory experiments on geological scales. Once calibrated and verified, numerical analyses can improve our understanding of the rock burst mechanisms and help assess potentials (occurrence and intensity) of this unstable event in mining works. This paper develops a computational framework for studying two major modes of rock burst: compressive and shear, the main research background of each is explained in the next two subsections.

1.1. Compressive-type rock burst

Cook[11] first posed the problem of rock burst theoretically as an issue

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of equilibrium instability. In the laboratory, Wawersik and Fairhurst[12] demonstrated that the failure instability depends on the descending post-peak behaviors of rock and the stiffness of the compressive testing machine (loading system). The behavior of rock after exceeding its peak strength on the stress-displacement curve is called post-peak behavior or rock brittleness. Once a brittle rock is under compressive loading, an increase in the rock deformation is associated with an increase in the resistance of the rock during the unfailed state. In the failing regime, after reaching the maximum stress values in compression, a further increase in the compressive displacement is accompanied by a decrease in the rock resistance. The post-peak behavior in brittle rock is usually accompanied by a localized deformation along shear bands within the failed rock.[13] Laboratory experiments showed when the loading system stiffness is low compared to the rock's post-peak slope, the failure is unstable leading to a sudden release of strain energy from the rock and loading system. This energy is mostly released in the form of kinetic energy, which is commonly known as radiated seismic energy. When the loading system is stiff compared to the post-peak slope of the stress-displacement curve, failure remains stable as the failing rock is able to absorb the energy released from the system.

Salamon[1] and then Petukhovt and Linkov[14] discussed generalizing the simple mechanism of instability in the laboratory compressive test to mining workings. Salamon[1] showed that loading system stiffness in mining settings changes with increasing the pillar panel length. Starfield and Fairhurst[15] suggested that the system stiffness can be tested by hypothetically replacing the pillar with a jack. Using this approach, Salamon[1] provided a process for defining the varying loading system stiffness as a result of advancing mining and numerically modeled brittle pillar failure by substituting pillars with equivalent forces that decay as failure occurs. It was proved that mining works remain stable, regardless of the magnitude of the convergence experienced by pillars, if the post-peak slope of pillar stress-convergence relations is greater than the loading system stiffness. Following the same approach, Zubelewicz and Morz[13] numerically studied instability conditions of compressive failure of several pillars by calculating the difference between available and consumed energy during failure. They investigated the stability of the pillar failure in Finite Element discretization using a dynamic approach. Garvey and Ozbay[16] studied compressive-type instability in a pillar modeled by Finite Difference elements. They estimated the radiated seismic energy by tracking available and consumed energy during the failure and used it to find pillar dimensions that are less prone to large rock burst events. With the progress in our understanding of rock burst hazards, quantitative analyses on rock burst events can shed some light on less-understood parameters that mainly contribute to the occurrence of compressive-type rock burst and magnitude of radiated seismic energy. A calibrated modeling approach with verified methodologies and modeling results presented in this paper can provide a framework for quantitative analyses of rock burst phenomena and for assessing potential bursting hazards during mining operations.

1.2. Shear-type rock burst

Elevation of shear stresses or a drop in confinement on a pre-existing fracture can be a result of the stress re-distribution caused by mining operations, inducing shear slip that can be stable or unstable. While the stable slip is gradual, unstable slip or shear-type rock burst is sudden and generates seismic waves. Pre-existing large fault structures around mine workings behave differently in response to the stress re-distribution and can generate large-scale rock burst and, therefore, tremendously damage underground excavations.[17] Dieterich[18] and Rice[19] used a mass-spring system with one degree of freedom and discussed unstable slip as a problem of equilibrium instability. They confirmed that, if the post-peak slope of the contact shear force-displacement curve stays greater than the spring stiffness (loading system stiffness), unstable slip occurs with a sign of oscillation in the spring. This means the seismological slip-weakening response of a fracture to shear loading is necessary for instability as this response corresponds to the descending part of the shear load displacement curve. In slip-weakening response, contact shear strength decreases as slip progresses until shear displacement reaches a critical distance called characteristic distance (D_c).

Salamon[20] and then Linkov[21] used the concept of slip instability in the mass-spring system and proposed a numerical procedure for assessing rock burst potentials by generating fractures with random length around mine workings. Stiffness of the loading system driving slip on each fracture is calculated based on the fracture length and shear modulus of the surrounding elastic rock. Since fracture length is defined as a special case of Weibull distribution, the loading system stiffness and thus instability of slip on each fracture depends on the prescribed distribution function. This limits the applicability of these methods in simulating slip on a limited part of a large fault partially activated by mining operations. This is because in the case of partial slip on a fault, loading system stiffness depends on the slip length that grows progressively from an initiation point and propagates along a limited part of the fault until equilibrium is regained.[22] Gu and Ozbay[23] discussed the possibility of using UDEC in simulating mining-induced fault slip and modeled a horizontal discontinuity above an advancing tabular excavation. They simulated unstable slip identified by a significant radiation of seismic energy calculated by tracking available and consumed energy during the slip. While each of mentioned studies explains some aspects of rock burst phenomena, they lack a robust numerical calibration, or are incomplete in their energy analyses for both compressive and shear rock burst, or fail to give quantitative descriptions of factors contributing to the expression of these unstable events.

This paper uses UDEC,[24] a code capable of handling non-linear response of rockmass with fault systems, and checks its applicability to develop a framework for assessing both compressive- and shear-type rock burst potentials in mining activities. To this end, numerical methodologies are developed, modeling techniques are calibrated, and results of idealized models are verified against analytical solutions. The solving procedure is divided into two main parts: quasi-static loading for building up stresses before failure and dynamic approach for simulating unstable failure until the system regains equilibrium. The quasi-static and dynamic solving approach is similar to the static-dynamic scheme proposed by Zubelewicz and Morz[13] but is more applicable as it also allows studying complex problems in fractured rock. We discuss two methods for estimating the radiated seismic energy: dynamic calculation of kinetic energy that needs to be damped out of the system for regaining equilibrium[25]; tracking the conversion of energy during a failure.[1,13,26] Analytical solutions are used to calibrate mechanical damping for modeling compressive unstable failure. The basic concept of unstable compressive failure proposed by Cook[11] and developed by Salamon[1] is extended to investigate the occurrence of compressive rock burst in mining settings. A tabular excavation supported by a single mine pillar is modeled and stability of pillar failure is explored with different post-peak responses to stress under different loading systems. Shear-type rock burst along a strike-slip fault is also simulated. The model mesh size, and damping scheme are calibrated by checking the calculated slip distribution, radiated seismic energy, and seismic moment against analytical values. Finally, direct shear test configuration is adopted to explore the slip instability concept proposed by Dieterich[18] and Rice[19] and to study effects of discontinuity frictional behaviors and loading systems on rock burst potentials.

2. Energy balance

Failure of rock surrounding an excavation results in the conversion of energy within the rock. The external work (W) done by the external forces and the initial strain energy (U_i) stored in the rock before failure mainly drive a failure process. Gravitational forces, tectonic loadings, and stresses induced by an underground opening are examples of