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Predicting pillar burst by an explicit modelling of kinetic energy

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ABSTRACT

Violent pillar failures known as pillar bursts are suspected to be a possible cause of large collapses in underground mines. A classical stability criterion for mine pillars, based on the relative stiffness of the host rock and the pillars during their post-peak unloading, was proposed by Starfield & Fairhurst (1968)[6] and further demonstrated by Salamon (1970)[7]. An energy balance indicates that an excess kinetic energy is generated when this pillar stability criterion is violated. The present study focuses on demonstrating how an explicit numerical modelling method may be used to calculate and locate the damping of this kinetic energy during pillar failure, considering simple 2D geometries. Arguments in favour of the validation of the numerical results are provided by comparison to analytical calculations and to an empirical classification of rockbursts proposed by Ortlepp (1997)[1]. The good correlation between numerical, analytical and empirical approaches suggest that explicit numerical modelling of kinetic energy damping, following a procedure proposed in this paper, could be a useful tool for predicting zones submitted to a pillar burst hazard in underground mines and for consequently optimizing the mining method.

1. Introduction

Violent pillar failure is a problem commonly encountered in underground mines, such as those exploited with the room-and-pillar method. It refers to the quick collapse of an isolated pillar, or of part of it, sometimes leading to the fragmentation and expulsion of rock pieces from the pillar. The phenomenon is known as “strain burst” or “pillar crush” depending on the severity of damage and of the magnitude of the associated seismicity (see Ortlepp's classification[1]). The more general term “pillar burst” is also used.[2] Because it is difficult to predict, pillar violent failure can be the source of serious disorders for mining operations, particularly when it is at the origin of a “cascading pillar failure”[3,4] finally causing the collapse of a large mine panel and its overburden. Since the studies published by Cook,[5] Starfield & Fairhurst[6] and Salamon[7], which can be considered as reference works on this topic, violent pillar failure has been considered as a mechanical instability affecting the host rock – pillar system during the post-peak phase of the pillar's behaviour, and not only the pillar itself.

Instability somehow is a catchall concept whose interpretation depends on the specific context in which it is used.[8] At the microscopic scale, the theoretical definition of instability commonly used in rock mechanics derives from the original expression of the tensile strength of a pre-cracked material, such as proposed by Griffith.[9] He showed that a pre-existing crack in an elastic plate will spontaneously propagate when its length is such that the rate of decrease of the elastic energy stored in the plate is higher than the rate of increase of the surface energy due to the crack growth. Trefftz[10] formalized another definition of instability applied to elastic structures submitted to conservative forces – the equilibrium of such a structure is unstable if the total potential energy is at a local maximum. Hill's definition[11] for elastoplastic solids states that the equilibrium of such a solid is unstable if the work done by constant (dead) external forces applied at its surface is greater than the energy stored or dissipated within it due to small virtual displacements of its free boundaries (compatible with the system's geometrical constraints).

In the end, regardless of the definition we consider, an unstable system is one that spontaneously moves away from an equilibrium position when a small displacement is applied on it. In other words, it is a system whose kinetic energy spontaneously increases when submitted to a constant external loading[12]. This definition falls within the general mathematical framework of the Lyapunov[13] stability approach.

A literature review has allowed us to identify three major aspects of the pillar instability and burst phenomenon that require further attention. First, in the knowledge of the authors, the analytical 1D criterion for pillar instability developed by Cook,[5] Starfield & Fairhurst[6] and Salamon[7] has never been quantitatively compared to more realistic 2D or 3D calculations. Second, the relationship between rockburst damage and kinetic energy release has been studied numerically[14] for explaining how micro-seismicity could indicate an imminent pillar-burst.

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However, the generation, propagation and dissipation of the excess kinetic energy at the scale of one failing pillar and its close environment, including the host rock and the neighbour pillars, have been the subject of only few studies up to now.[15,16] Third, the kinetic energy is an indicator of the seismicity traditionally measured experimentally but, as it was highlighted by Spottiswoode[17] and cited by Ortlepp,[18] there are limited interactions between numerical modelling and seismicity in mines. More generally, there is a lack of comparison between the analytically, numerically and empirically estimated magnitudes of excess kinetic energy during pillar instability and burst. As a consequence, the use of numerical modelling for assessing sectors submitted to rockburst hazard in mines is not as developed as it could be, even if it is crucial for mining risk management.

Based on these observations, the present paper tackles three main objectives. I) understanding where kinetic energy is released and how it propagates during pillar failure, II) comparing 2D local numerical modelling solutions with a graphical (analytical) solution and an empirical classification, and III) proposing an easily reproducible modelling procedure, based on continuum mechanics only, for a rough prediction of the zones prone to burst in mines. For this purpose we used the explicit time-marching modelling scheme of the FLAC software (Itasca C.G. Inc.), the benefits of which will be highlighted.

The following Section 2 defines the concept of instability by referring to energy calculations, and then exposes its application to the problem of pillar stability. In Section 3, an explicit numerical method for calculating the damped kinetic energy at the local scale, based on the calculation scheme of the FLAC software, is succinctly presented and it is applied to calculate the kinetic energy generated and dissipated during the failure of a strain-softening pillar, as well as its distribution in time and space. The total amount and local density of damped energy as well as its relationship with the global pillar behaviour are then analysed and compared to Ortlepp's classification of rockbursts[1] in Section 4. Finally, conclusions are drawn about the practical significance of the results and their applicability for rockburst prediction.

2. Analytical calculation of the dissipated kinetic energy W_k in a lab test and in a mine pillar

2.1. Mechanical energy balance

According to the first law of thermodynamics, the mechanical energy balance of a closed system can be written as follows:

$$\Delta E_k = W_s - (\Delta E_{gp} + \Delta U_c + W_{diss}) \tag{1}$$

where Δ denotes a variation from one mechanical state to another. E_k is the kinetic energy of the system, E_{gp} is its gravitational potential energy, U_c is the elastic strain energy stored in the system, W_{diss} is the dissipated mechanical energy between the two considered states (always positive) and W_s is the work done by the boundary (surface) forces.

As an example, let us consider a rock mass at static equilibrium. At stage (I), the rock mass is in its natural state. A stage (II), two parallel excavations are realized in order to form a pillar. At stage (III), a long time after the excavation, the pillar fails.

Isolate the system within a virtual contour located far enough from the pillar so that the external forces (stresses) intensity may be considered as unaffected by the excavations (Fig. 1). Then, let us analyse the energy changes from stage I to stage II and from stage II to stage III alternatively.

2.1.1. Stage I

Before excavation, the considered isolated rock mass is at equilibrium under a set of boundary forces, involving an internal state of stress. Consequently the rock mass entails a certain amount of elastic strain energy U_c (see[19] for a complete derivation of the elastic strain energy). Due to the altitude of its centre of gravity, the rock mass also has a gravitational potential energy E_{gp}. The other terms of the energy balance are null at stage I.

2.1.2. Transition from stage I to stage II

In response to the excavation, the external boundary forces do a work W_s. In the remaining volume of rock, there is an increase of elastic strain energy ΔU_c compared to the initial state and the gravitational potential energy of the system varies by an amount ΔE_{gp} according to the displacement of its centre of gravity (Fig. 1). Salamon[20] demonstrated through various analytical examples that $W_s > \Delta U_c - \Delta E_{gp}$. According to Eq. (1), the consequence of this inequality is that a dissipation of energy $W_{diss} > 0$ must be involved for the system to recover equilibrium after the excavation, that is for $\Delta E_k = 0$. In other terms, the work done by the conservative forces (gravitational and elastic) alone cannot fully accommodate the energy brought by the external forces work; there is an excess energy to be dissipated.

At least three situations are conceivable. (A) The stress field after the excavation may be such that, at the macroscopic scale, the surrounding rock, including the pillar, remains elastic. Under this condition, the excess energy takes the form of kinetic energy and propagates through elastic waves. In practice, the rock mass is not perfectly elastic and the oscillations are progressively damped through internal friction at microscopic scale (heat creation). The damped kinetic energy is noted W_k ($W_{diss} = W_k$). It has to be noticed that W_k depends on the number of excavation steps leading to the final excavated volume[20]. It is theoretically a maximum for a one-step excavation while it is theoretically zero for an infinitely-slow excavation rate. (B) The pillar and the abutments may fracture and develop macroscopic non-elastic strains. We can imagine an idealized situation where the rock fractures very slowly so that the whole excess energy is dissipated by quasi-static deformation. In this situation, no kinetic energy is involved ($W_k = 0$). This is a stable rupture. (C) There may be an intermediate situation where the fracturing does not dissipate the whole excess energy and where, as a consequence, a dynamic dissipation of kinetic energy is also involved ($W_{diss} > W_k > 0$). This is an unstable rupture that may eventually lead to a rockburst.

2.1.3. Transition from stage II to stage III

A long time after excavation, the pillar strength may be significantly lower than its initial strength due to progressive rock deterioration, and the average pillar stress will eventually increase due to adjacent mining so that pillar stress becomes equal to the pillar strength. Accordingly, the pillar will fail and recover a new state of equilibrium (stage III, Fig. 2). During pillar failure, rock mass displacement are expected to be small and localized near the pillar. Consequently, W_s is expected to be close to zero assuming that external forces are located far enough from the failing pillar. ΔE_{gp} is also expected to be negligible due to the small displacements involved. The elastic strain energy of the pillar and the host rock however, will significantly vary (ΔU_c) because of the pillar stress reduction due to failure (elastic energy is related to the square of the stress variation). Finally, Eq. (1) shows that the energy to be dissipated due to pillar failure is $W_{diss} \approx -\Delta U_c > 0$.

Two situations are conceivable. A) The pillar fracturing is able to dissipate the whole energy W_{diss} to be dissipated by quasi-static plastic deformation so that no dynamic phenomenon is involved ($W_k = 0$). Pillar rupture is stable. B) The pillar fracturing does not dissipate the whole excess energy so that a dynamic dissipation of kinetic energy is involved ($W_{diss} > W_k > 0$). Pillar rupture is unstable. If W_k has a sufficient magnitude, this latter situation is known as a pillar burst.

The objective of Section 2.2 is to identify the conditions in which pillar burst occurs. For this purpose, it will be necessary considering infinitesimal changes of the system energy around an equilibrium position rather than great changes between two states of equilibrium like it has been proposed in the previous idealized example.