Assessment of energy release and redistribution on excavation instabilities for underground mining

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ABSTRACT: Energy considerations are essential for the evaluation of violent failures which are commonly encountered as mining goes deeper. To address the relationships among different energy components, a series of numerical models were conducted by using *3DEC* and a script was developed for energy visualization. The theoretical and numerical results of the ratio between the released kinetic energy and the excavated strain energy were compared under elastic and plastic models. The distribution of stored elastic strain energy and dissipated plastic strain energy in the vicinities of openings with different shapes were also investigated. Furthermore, the efficiency of a latest destressing method as a proactive measure for seismic management was evaluated based on the energy redistribution patterns. This research can improve the understanding of the energy evolution near excavations and contribute to the evaluation of burst-proneness of excavations as well as effectiveness of rockburst mitigation measures.

Keywords: Rock burst, Released energy, Dissipated energy, Destressing, Seismic management.

1 INTRODUCTION

When underground mining continues to reach deep deposits, significant energy changes take place in rock mass and cause excavation instabilities such as rock bursts (e.g., Cook et al. 1966 and Zhou et al. 2018). The involved brittle failures cannot be represented accurately by the traditional failure indictors such as deformation and stress. The acquisition of the energy variations is essential to describe these violent failure process (Wang et al. 2021).

In view of the importance of energy considerations, more and more studies have been conducted through theoretical analysis, numerical simulation, and laboratory experiments in the past years. Salamon (1984) conducted theoretical analysis on the relationships among energy components during mining by using an elastic model. Different criteria for rockburst proneness of rock mass are proposed based on the strain-stress curves, especially the post-failure behavior obtained from laboratory experiments such as strain energy storage index (Kidybinski 1981 and Gong et al. 2019), potential energy of elastic strain (Wang & Park 2001 and Tajdus et al. 2014), brittleness index (Keneti & Sainsbury 2018) and so on. Meanwhile, several energy indices are introduced in the analysis of numerical simulation results including strain energy density (SED) (Xu et al. 2003 and Weng et al. 2017), energy release rate (ERR) (Cook 1966), local energy release rate (LERR) (Jiang et al. 2010) and excess energy (Khademian & Ozbay 2019).

However, on the one hand, the correctness of the theoretical conclusions obtained under elastic model is doubtful when dissipated plastic energy is involved. On the other hand, it is difficult to have a complete knowledge of the failure potential and intensity with a single energy index. The current work is to verify the theoretical results in more general conditions through numerical simulation, understand the energy redistribution in the vicinities of openings, and evaluate the efficiency of destressing operations as proactive measures for seismic management through energy considerations.

2 RELATIONSHIPS AMONG ENERGY COMPONENTS

Based on energy conservation law, the total released energy induced by excavating a volume of rock material with stored strain energy U_m can be calculated either through Equation (1) (Salamon 1984):

$$W_r = W - (U_c + U_b + W_j + W_p) = U_k + W_k + W_v + U_m \tag{1}$$

where W_r is released energy, W is total boundary loading work supplied to the system, U_c is total stored strain energy in material, U_b is total change in potential energy of the system, W_j is total dissipated energy in joint shear, W_p is total dissipated work in plastic deformation of intact rock, U_m is total strain energy in excavated material, U_k is current kinetic energy, W_k is total mass damping work, W_v is work done by viscous boundaries.

Excluding the strain energy stored in the excavated materials from the total released energy, the remaining part is the released kinetic energy which can be expressed as

$$W_{rk} = W_r - U_m \tag{2}$$

Strain energy density (SED) is commonly used as an evaluation indicator of rockbursts. Its successful application relies on the correctness of the assumption that the released kinetic energy is proportional to the strain energy stored in the excavated materials. Salamon (1984) deduced the energy components associated with an increase from R_0 to R_1 in the radii of a cylindrical tunnel.

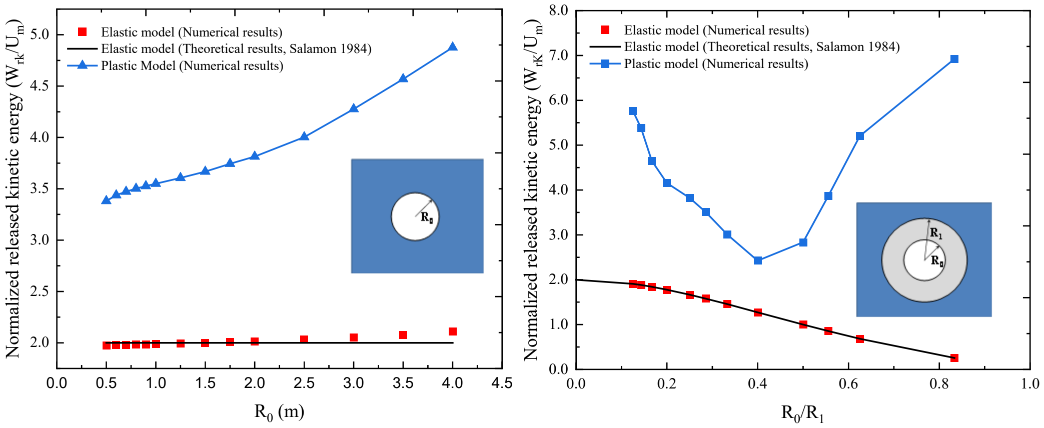
$$\frac{W_{rk}}{U_m} = \beta = \frac{1 - (R_0/R_1)^2}{1 - 2\gamma + (R_0/R_1)^2} \tag{3}$$

where γ is Poisson's ratio.

The above equation is obtained under elastic model. Its applicability for plastic model needs to be verified. A numerical model with the parameters in Table 1 is established. The critical plastic strain is 0.2% when the residual cohesion is reached. The initial stress state is under 10 MPa hydrostatic pressure. The normalized released kinetic energy β is the ratio between the released kinetic energy and the strain energy stored in the excavated material. The results obtained from one step excavation of a tunnel with the radii R_0 and when the tunnel is expanded from its original radii R_0 to R_1 are plotted in Figure 1 (a) and (b), respectively.

Table 1. Parameters in the numerical models.

Models	Young's modulus	Poisson's ratio	Cohesion		Tensile strength	Friction angle	
			Initial	Residual		Initial	Residual
	[GPa]	[-]	[MPa]	[MPa]	[MPa]	[°]	[°]
Elastic model	15	0.25	-	-	-	-	-
Plastic model	15	0.25	2	1	0	20	20



(a) A circular opening of radius R_0 (b) Increase in the radius of a circular opening from R_0 to R_1

Figure 1. Normalized released kinetic energy.

The theoretical ratio β for the excavation of a circular opening with one step is 2 which can be obtained through Equation (4) under the extreme condition $R_0 << R_1$. Numerical results under elastic model are consistent with the theoretical results in Figure 1 (a). It can be inferred that the ratio between released kinetic energy and the excavated strain energy is constant under different excavation radius and only associated with Poisson's ratio when there is no plastic energy dissipated. However, this ratio will become much larger than the theoretical results under elastic model when plastic energy is involved and will keep rising as the increase of the excavation radius.

In Figure 1 (b), the original radii R_0 is fixed to be 0.5 m. The numerical results also agree well with the theoretical results for the elastic model, i.e., the normalized released kinetic energy becomes larger as the increase of R_1 and approaches to the limiting value 2 which is equal to that when the opening is excavated with one step. However, the curve under plastic model does not present a monotonical increasing tendency. As the increase of expanding radius R_1, the ratio will experience a decrease and arrive at the lowest value when R_1 approximately reaches to the edge of the yielding zones induced by the opening with radii R_0.

3 ENERGY DISTRIBTUION

3.1 Energy distribution in the vicinities of openings

To visualize the distribution of the stored elastic energy and dissipated plastic energies, the energy components in each zone are calculated through functions defined by FISH programing. The change of the total strain energy within one timestep can be calculated as

$$\Delta W_T = \frac{V}{2}\left[\begin{array}{c}(\sigma_{11}+\sigma'_{11})e_{11}+(\sigma_{22}+\sigma'_{22})e_{22}+(\sigma_{33}+\sigma'_{33})e_{33} \\ +2(\sigma_{12}+\sigma'_{12})e_{12}+2(\sigma_{13}+\sigma'_{13})e_{13}+2(\sigma_{23}+\sigma'_{23})e_{23}\end{array}\right] \tag{4}$$

where σ_{ij} is current zone stresses, σ'_{ij} is zone stresses from the previous timestep, e_{ij} is incremental strains over the current timestep, and V is volume of zone.

The current elastic strain energy can be determined as

$$W_e = \frac{V}{2E}\left[\sigma_1^2+\sigma_2^2+\sigma_3^2-2\nu(\sigma_1\sigma_2+\sigma_1\sigma_3+\sigma_2\sigma_3)\right] \tag{5}$$

Thus, the change of the elastic strain energy within one timestep can be calculated as

$$\Delta W_e = W_e - W'_e \tag{6}$$

where σ_i is principal stresses in zone centroid, W_e and W_e' are current and previous elastic strain energies, respectively.

Correspondently, the dissipated plastic energy within one timestep can be determined as

$$\Delta W_p = \Delta W_T - \Delta W_e \tag{7}$$

The changes of energies are accumulated over timesteps, and the local energy densities can be determined through dividing the energy in a zone by its volume. The changes of stored elastic energy densities compared to the initial states in the vicinities of circular and rectangular openings with different initial cohesions are shown in Figure 2. Areas with negative changes are rendered in white which can be regarded as energy released regions. Figure 3 presents the corresponding plastic energy density distributions in which the areas without dissipated plastic energy are colored in white.

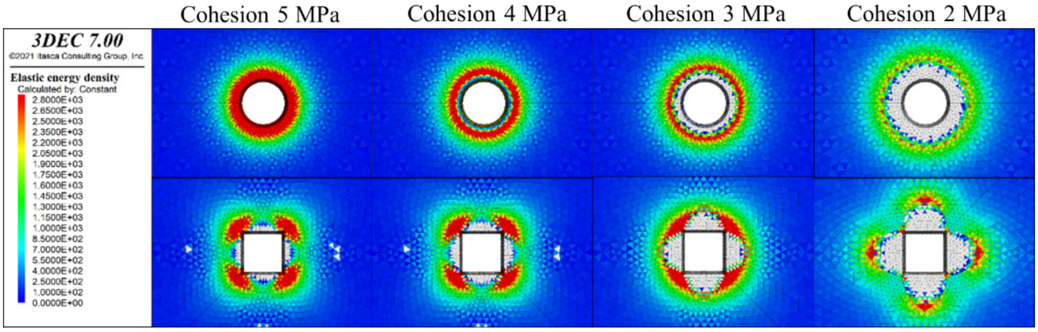


Figure 2. Stored elastic energy density in the vicinities of underground openings.

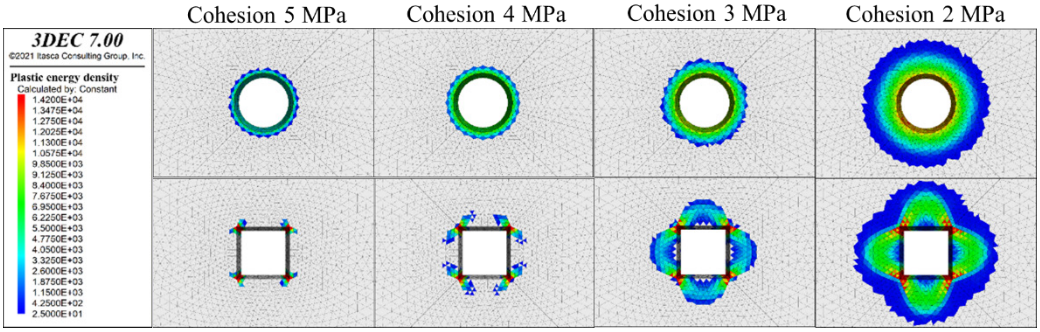
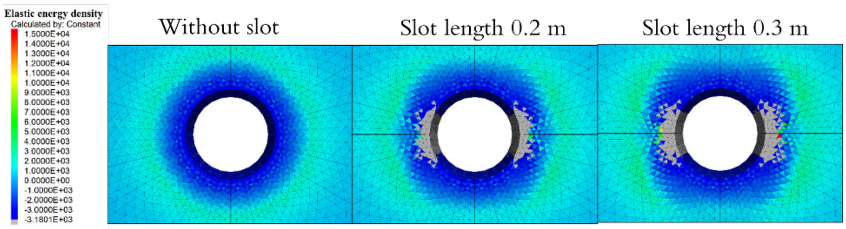


Figure 3. Dissipated plastic energy density in the vicinities of underground openings.

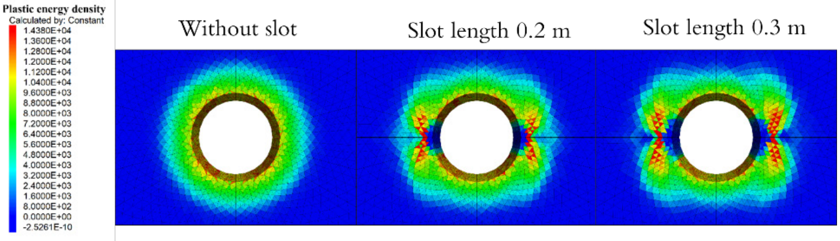
It can be found that adjacent to the excavation boundaries elastic strain energy is released, while the plastic strain energy is dissipated, especially at the corners of rectangular openings. The energy released regions become larger as the decreasing of the cohesion strength. Furthermore, on the edges of the energy released regions elastic strain energy is concentrated.

3.2 Evaluation of destressing methods

When the dissipated plastic energy adjacent to the excavation boundaries is excessively high, severe deformation failure will most probably develop into the deep progressively. Destressing technique is a common measure in deep mines and tunnels to control rockburst. It is necessary to understand its effects on the distribution of the stored and dissipated energy in the vicinities of openings. Slotted excavation method (Manouchehrian et al. 2022) is one of the destressing drilling measurements in which a pilot slot is excavated to create extra spaces for yielding deformation and results in destressing of the rock mass. The distributions of stored elastic and dissipated plastic energy in the vicinities of the openings, and energy variation curves with respect to the distance from the excavation boundaries under different slot lengths (slot width is fixed to be 0.01 m) are shown in Figure 4 and Figure 5, respectively.

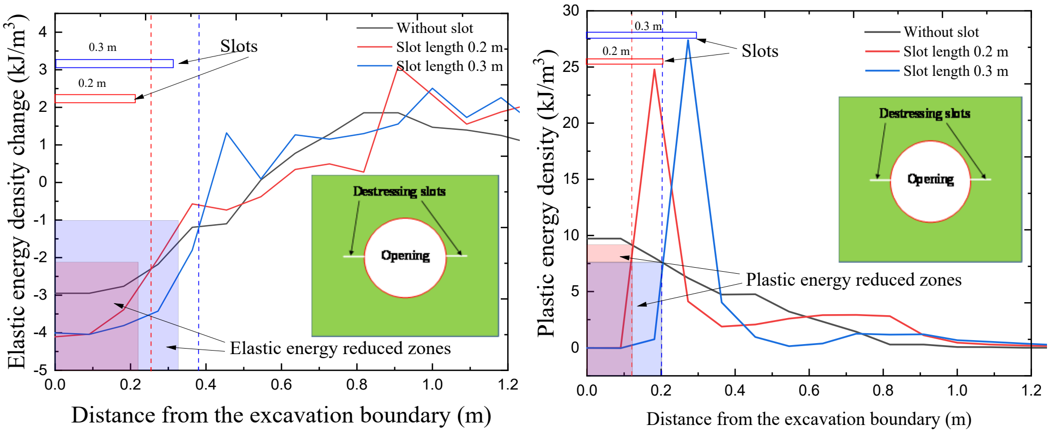


(a) Elastic energy density



(b) Plastic energy density

Figure 4. Energy distribution with slotted excavation method.



(a) Elastic energy density

(b) Plastic energy density

Figure 5. Energy variations with respect to the distance from the excavation boundary.

It can be found that pilot slot can reduce the stored elastic energy along its entire length. Meanwhile, the dissipated plastic energy adjacent to the excavation boundaries will be reduced to be zero. The concentration of plastic energy is shifted from the opening boundaries into a certain depth by the slots. It demonstrates that the destressing drilling as a rockburst control method can also be used as a measurement to preserve the integrity of the opening periphery from progressively failure through its effects on the distribution of the stored elastic and dissipated plastic energy.

4 CONCLUSIONS

Relationship between the released kinetic energy and the excavated strain energy under plastic model is different with the theoretical results obtained under elastic model. The ratio between them is higher when dissipated energy is involved and the variation of this ratio is not monotonically increasing when a tunnel is expanded with different radius.

Dissipated plastic strain energy clusters adjacent to the opening, especially at the corners of rectangular openings, while high elastic energy is concentrated at the boundaries of area where plastic energy emerges.

Slotted excavation as a rockburst control method is also demonstrated to be able to preserve the integrity of the opening periphery from progressively failure through its effects on the distribution of the stored elastic and dissipated plastic energy, i.e., decreasing the stored elastic energy along the slot and pushing the occurrence of dissipated plastic energy from the opening boundaries into a certain depth.

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