Rockburst prevention using a novel de-stressing method

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Abstract. De-stressing is a common rockburst control measure used in deep mines and tunnels. The benefits of using the de-stressing method to control rockburst have been demonstrated by its successful implementation. However, rockburst remains a threatening phenomenon in many deep underground excavations. Herein, a new de-stressing method for rockburst control is proposed. In this method, the rock is de-stressed by cutting notches at the excavation boundary. First, a circular tunnel is modeled and the stress distribution around the tunnel is then calculated. Thereafter, a notch was placed at the tunnel wall in a different model. The results revealed that when the notch was introduced to the model, the rock at the tunnel wall de-stressed, and the stress concentration zone moved far away from the wall. Additionally, an analysis of the failure zone around the tunnel and the velocity of the failed elements revealed that the failure of the notched tunnel was less violent than that of the tunnel without notches. Finally, a parametric study was conducted to investigate the influence of the notch length on the de-stressing process around the tunnel. The modeling results indicated that the proposed de-stressing method could be used to control rockburst in deep underground excavations.

1. Introduction
Excavation-induced stresses are an inevitable aspect of mining and tunneling operations, and they can cause failures and instability. Excavation is more difficult in deeper undergrounds, where in situ stresses are naturally high. Rockburst is one of the engineering hazards associated with deep mining and tunneling. Three conditions are required for unstable rock failure to occur: (i) high stress, (ii) relatively soft loading system, and (iii) deformation potential [1]. If these three conditions are met at the same time, an unstable failure occurs; otherwise, no unstable failure occurs. This is the most important aspect of rockburst control. Rockburst can be controlled if at least one of these conditions is not met. Therefore, certain techniques that can be used to manipulate these three conditions have been developed for controlling rockburst [2-8]. Rock de-stressing is a method used for controlling rockburst by eliminating the “high stress” condition. De-stressing refers to several procedures that are used to reduce the stress inside a rock mass.

In de-stress blasting, controlled blasts are employed to induce fractures inside the target rock mass to dissipate the high stress and the energy accumulation. De-stress blasting has been successfully used in many mines and tunnels to reduce the danger of rockburst [9-11]. De-stress blasting occasionally acts as a rockburst triggering factor rather than a rockburst control measure because it causes dynamic disturbance in deep underground openings, which is a rockburst triggering factor. For instance, from 2005 to 2013, the Muchengjian Mine in China experienced intense rockbursts triggered by de-stress
blasts, which affected its production efficiency [12]. De-stress blasting has also been criticized for failing to induce meaningful fractures inside target rock masses [13]. De-stress drilling is another common rockburst control measure. It is mainly used in civil tunnels, particularly those excavated using tunnel boring machines (TBMs) [14]. De-stress hydrofracturing is the third de-stressing method used for controlling rockburst. Hydrofracturing is widely used for increasing production in the oil and gas industry. During hydrofracturing, a pressurized liquid is pumped into boreholes to produce new fractures and/or open pre-existing fractures in rock masses. This method was first used to control rockburst in the Soviet Union in the 1960s and then in China in the 1970s [8].

Despite significant progress in preventing rockburst, rockbursts continue to occur occasionally in many mines and tunnels around the world. This problem originates from the lack of a systematic analysis and design method. In fact, rockburst control measures are more of an art (based on the designer experience) than an engineering science. To control rockburst successfully, a clear and straightforward de-stressing methodology is required. Herein, we propose a new de-stressing method for controlling rockburst.

2. Description of the method
When a body is compressed, it becomes compacted. When a part of the body is removed, the resulting free space allows the remaining parts to expand and fill it according to the elastic properties of the material. This causes the body to release stress. Figure 1 illustrates the concept of de-stressing in a tunnel wall. In this figure, a tunnel section is subjected to in situ stresses. The maximum tangential stress at the tunnel wall is \( \sigma_0 \) under this condition (Fig. 1a). If a narrow notch is cut at the 3 o’clock position on the tunnel wall, the rock around the notch is allowed to expand and fill the free space according to the elastic properties of the rock (Fig. 1b). The tangential stress in the new condition is \( \sigma_0^* \), which is less than \( \sigma_0 \). This technique can be used to de-stress excavation boundaries. Numerical models that were built to investigate this technique’s suitability for de-stressing circular tunnels are discussed in the next section.

3. Numerical models
De-stressing is a proactive measure for reducing the risk of rockburst in deep underground excavations. However, de-stressing fails to control rockburst in many cases. A systematic study of stress, deformations, and failure zones around underground openings before and after de-stressing can be very useful in understanding the role of each parameter and providing insight into the different aspects of the de-stressing process. This task is essential for the successful implementation of de-stressing measures and the prevention of further ground control problems. The simulation of de-stressing in circular tunnels using the described de-stressing method is discussed in this section.

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**Fig. 1.** The concept of the de-stressing method in a tunnel wall
3.1. Model setup
A circular tunnel with a radius (R) of 1 m is modeled using Abaqus2D. Since the tunnel is symmetric, only the right side of the tunnel is modeled to save computation time. To eliminate the effects of the outer boundary on stress redistribution around the tunnel in numerical models, the external boundary width and height should be at least ten times the tunnel diameter. Since one of the objectives of this research is to study the influence of notch dimensions on changes in stress and strain energy as well as the failure zone around the excavation boundary, the models in this study also include notches of various lengths. Thus, the external boundary width and height were set to 15 times the tunnel diameter to ensure that the stress redistribution around the notch is unaffected by the modeling results. It should be noted that because only the right side of the tunnel is modeled, the model size in the horizontal direction is half of the model size in the vertical direction, i.e., 7.5 times the tunnel diameter. Figure 2 illustrates the geometry of the model. Before excavation, in situ stresses are applied to the external boundaries and the boundaries are subsequently fixed with roller constraints. Thereafter, the tunnel excavation is simulated. The horizontal ($\sigma_h$) and vertical ($\sigma_v$) in situ stresses are assumed to be 30 MPa and 60 MPa, respectively. To simulate the gradual excavation of the tunnel in two-dimensional (2D) models, the stress at the tunnel boundary is reduced in seven steps. This simulates a gradual increase in the tangential stress due to tunnel advancement. In this study, a Coulomb model with a friction coefficient ($\mu$) of 0.5 and zero cohesion is used to describe the contact behavior of the notch when it is closed.

3.2. Modeling results
Models were built with and without notches to study the feasibility of using the notched excavation method to control rockburst. First, an elastic analysis was conducted to study the stress distribution around the tunnel and the tunnel convergence. An elastic model with the properties presented in Table 1 was used (column “Elastic”). The tangential stress around the tunnel is shown in Fig. 3a. The modeling results revealed that the stress is concentrated at the tunnel wall in the direction of the minimum principal stress (3 o’clock). The maximum tangential stress at this location is 146.7 MPa, which is in good agreement with the stress value calculated using the closed-form solution, which is $\sigma_0 = 150$ MPa. According to the ground reaction curve presented in Fig. 4, the maximum convergence in the direction of the maximum principal stress is 0.45%.

![Image](image.png)

**Fig. 2.** The geometry of the model
Table 1. Values of the physical and mechanical properties of the rock mass in the elastic and elastoplastic models

| Parameter                          | Model type     |
|------------------------------------|----------------|
|                                    | Elastic | Elasto-plastic |
| Density, $\rho$ (kg/m$^3$)         | 2500    | 2500           |
| Young’s modulus, $E$ (GPa)         | 20      | 20             |
| Poisson’s ratio, $\nu$             | 0.2     | 0.2            |
| Cohesion, $c$ (MPa)                | -       | 20             |
| Friction angle, $\phi$ (°)         | -       | 30             |
| Uniaxial compressive strength, $\sigma_c$ (MPa) | - | 70 |
| Uniaxial tensile strength, $\sigma_t$ (MPa) | - | 5 |

Table 2. Strain-softening parameter values of the elastoplastic model provided in Table 1

| Cohesion yield stress (MPa) | Shear plastic strain | Tension cut-off stress (MPa) | Tensile plastic strain |
|-----------------------------|----------------------|-----------------------------|------------------------|
| 20                          | 0                    | 5                           | 0                      |
| 0.01                        | 0.1                  | 0.1                         | 0.04                   |

Next, an elastoplastic analysis was conducted to study the failure zones around the tunnel. A strain-softening Mohr–Coulomb model was used to simulate the mechanical behavior of the rock mass. The physical and mechanical property values used in the strain-softening elastoplastic model are listed in Table 1 (column “Elasto-plastic”) and Table 2. The failure zone around the tunnel at the position of the stress concentration zone (3 o’clock) is depicted in Fig. 5a. In the numerical models used in this study, the velocity of failed element nodes was used to diagnose the failure type. The velocity of the element nodes around the tunnel at the time of failure is depicted in Fig. 6a. The average maximum velocity of the failed elements in the model is in the range of 0.9–1.3 m/s. In the field, a rock failure with a peak particle velocity, which ranges between 0.8 m/s and 2.1 m/s, is considered low-intensity damage [15]. Thus, it can be interpreted that if the failure occurred in the field, it would be in the form of a light rockburst (spalling, spitting, or shallow slabbing). As discussed in Section 1, some factors, such as geological structures, can intensify rockburst [1]. For the stated tunneling problem, strong rockbursts can be anticipated if the tunnel is excavated near geological structures such as faults.
In a separate model, a notch with a length (L) of 200 mm and a width (W) of 10 mm was added to the model at the position of the stress concentration zone (3 o’clock). Figure 2 illustrates the location and the geometry of the notch. As shown in Fig. 3b, when the notch is added to the model, the tangential stress at the tunnel wall surface (3 o’clock) drops to zero, and the stress concentration zone is transferred into the rock mass at the end of the notch. The formation of a small stress concentration zone with a maximum tangential stress of $\sigma_0 = 233$ MPa can be observed at the end of the notch. However, this concentration zone does not influence the stability of the tunnel. The ground reaction curve in Fig. 4 indicates that a maximum convergence of 0.49% in the direction of the maximum principal stress occurred in the notched tunnel. This is 8% more than that in the regular tunnel. Figure 5b shows the failure zone around the notched tunnel. Here, there are some minor failures at the tunnel surface and a major failure at the end of the notch inside the rock mass. In the notched tunnel, the average maximum velocity of the element nodes at the time of failure is close to zero, as shown in Fig. 6b. The small failure zone at the tunnel surface and a negligible velocity of the failed elements indicate that the failure in the notched tunnel occurred in a small area and was in a stable form.

The elastic analysis results presented in this section revealed that when the notch was added to the tunnel wall, the stress at the tunnel wall reduced drastically and transferred into the rock mass at the end of the notch. Furthermore, the elastoplastic analysis results revealed that the failure zone at the tunnel wall is relatively small in the notched tunnel, and the velocity of the failed element nodes is negligible. Therefore, cutting the notch at the tunnel wall can be beneficial in mitigating the rockburst risk in the stated tunneling problem.

3.3. Influence of the notch length on the rock failure at the tunnel wall

If any failure occurs at the excavation boundaries, an effective rockburst control measure should either prevent it or change its mode from unstable to stable. Therefore, an elastoplastic analysis is required to determine the effectiveness of the method in preventing rock failure or changing the failure mode. Here, elastoplastic models were built to investigate the influence of the notch length on the failure zone and mode of failure around the tunnel. Several models were built, including a notch with a 10 mm width and various lengths at the tunnel wall. The notch lengths were L = 50, 100, and 200 mm, resulting in L/R ratios of 0.05, 0.1, and 0.2, respectively.
The failure zones around the notched tunnel with different notch lengths are illustrated in Fig. 7. As shown in this figure, when the length of the notch is $L = 50$ mm, a large failure zone is formed at the tunnel wall (3 o’clock). As the notch length increases, the failure at the surface decreases, but a large failure appears at the end of the notch inside the rock mass. The bending moment at the sides of a longer notch causes the notch to partially close. This relative movement of the notch sides induces shear stresses at the end of the notch, resulting in failure zones. For the longer notches, the bending moment is larger, resulting in a larger failure zone at the end of the notch. Figure 8 depicts the velocity of the element nodes. When the notch length increases, the maximum velocity of the nodes in the failed elements at the tunnel surface decreases, implying that the failure at the tunnel surface is less violent when the notch is longer. According to the simulation results, a very short notch may not be effective in de-stressing the tunnel wall. However, a very long notch may cause ground control problems by increasing the convergence in the tunnel. For an effective rockburst control operation, the notch length must be chosen carefully.

4. Conclusion

Herein, a conceptualized de-stressing method for rockburst control is proposed. First, the concept of the proposed de-stressing method was analytically described. Thereafter, the method was used to solve a tunneling problem. The effects of the de-stressing process and failure mechanism around the tunnel were studied using elastic and elastoplastic numerical models. The results revealed that when the notch was added to the model, the tunnel wall de-stressed, and the stress concentration moved far away from the tunnel wall. The elastoplastic analysis revealed that the failure zone around the tunnel and the velocity of the failed elements around the notched tunnel were smaller than those around the regular tunnel. This implies that the failure in the notched tunnel was less violent than that in the regular tunnel. A parametric study was conducted to investigate the effect of the notch length on the failure zone and the velocity of the failed elements around the notched tunnel. According to the
results, to effectively control rockburst, the notch length should neither be too short nor too long. This is because extremely short notches do not effectively de-stress rocks, whereas extremely long notches can cause ground control problems by increasing the convergence in the tunnel. The optimal notch sizes for any excavation are highly dependent on site-specific conditions, and different factors, such as in situ stresses, host rock properties, and the excavation geometry should all be considered.

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