An implicit numerical modeling approach for destress blasting design optimization for tunneling and mine development in high stress conditions

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ABSTRACT: Tunnelling and underground mine development in high-stress conditions are exposed to potential rockburst hazards. Rockburst risk management may include multiple hazard control and/or exposure management strategies. Rockmass preconditioning, such as destress blasting, is a tactical approach to hazard control by introducing blast-induced fractures to the rockmass. Introducing fractures softens the rockmass and reduces potential stored strain energy. This paper explores a case study where a large-magnitude rockburst occurred in the floor of a mine tunnel located approximately 2km below the surface, in a strong, massive rockmass. Subsequently, destress blasting was implemented in all active development headings for risk mitigation. This paper presents a geotechnical study to optimize the utilization of destress blasting. A detailed numerical modeling investigation with implicit representation of blast damage is done using a calibrated FLAC3D model. The influence of destress blast design on rock burst hazard potential is numerically studied and discussed.

Keywords: Rockburst, Destress Blasting, Risk Management, Numerical Modeling

1 INTRODUCTION

Preconditioning of rock mass using destress blasting is a tactical approach to alleviate strain burst potential in a rock mass by introducing new fractures which in turn leads to lowering the stiffness of the rock mass and thus dissipating the excessive stored strain energy in the immediate excavation periphery (O'Donnell, 1999). The destressing fractured zone, sheds stress concentration away from development heading.

A deep gold mine complex experienced a 1.0Mw seismic event in an advancing tunnel located in fairly strong and massive basalt, resulting in approximately 20 tonnes of material displaced from floor. Several non-damaging macro events (>0.2Mw) were also experienced leading up to the floor burst event during advance of this particular mine tunnel. Following the occurrence of the floor burst event, destress blasting was implemented in all active development headings as a means of hazard management. This introduced significant operational challenges and slowed advance rates.

To optimize the use of floor bursting, extensive multi-scale numerical modelling work has been conducted to characterize the mechanics of the floor burst event (using local tunnel-scale simulations) and identify similar conditions at the mine scale (using global mine-scale simulations) to develop hazard maps of floor burst hazard susceptibility (Dadashzadeh and Kalenchuk 2022, Kalenchuk 2022). Despite gains made in identifying conditions where destressing was most valuable, the practice of destressing the floor remained an operational challenge for burst-prone headings (for example, challenges associated with potential bootlegs in the excavation floor where difficult to overcome). As such a study was conducted to explore blast design optimization opportunities.

The calibrated local tunnel-scale numerical model was used to characterize the rockburst volume (mechanically and geometrically) in the tunnel floor. Blast design optimization was completed by numerically investigating stress redistributions achieved by rock mass preconditioning which targeted the burst-prone volume. This paper presents an implicit numerical modelling approach for blast design optimization using FLAC3D.

2 NUMERICAL MODELING APPROACH

The numerical modeling of blast-induced damage in this study followed an implicit modeling approach meaning that the dynamic loading and blast-induced fractures were not modeled explicitly. Instead, the role of each blast hole, in terms of the extent and intensity of damage, has been characterized based on empirical studies. A static numerical model was used to evaluate the impact of destressing by adjusting the rock mass properties and constitutive model in the destressed zone to implicitly incorporate blast damage in the numerical model.

The modeling steps are summarized as follows, and described further below:

a) Estimation of blast-induced damage extent per hole (damage radius around each blast hole) based on empirical methods with consideration of site-specific variables.
b) Estimation of rock mass behaviour and associated numerical mechanical properties within blast damage zone.
c) Incorporating destress damage zone (geometry and properties) in the local tunnel-scale FLAC3D simulation.

The Holmberg-Persson blast damage criterion (1978) has been used in this study to estimate the blast damage zone per blast hole. This criterion correlates the blast-induced damage to the Peak Particle Velocity (PPV) for a given spherical charge. Figure 1 illustrates the PPV attenuation as a function of distance from the center of an explosive column, for ANFO and Emulsion (two explosive types used at the mine site); Table 1 summarizes the input parameters.

Table 1. Holmberg-Persson PPV attenuation parameters for ANFO and Emulsion.

Explosive material	ANFO	Emulsion
Explosive density (kg/m^3)	950	1150
Charge density (kg/m)	1.9	2.3
α (originally suggested by H-P)	0.7	0.7
β (originally suggested by H-P)	1.5	1.5
K (suggested by Dyno Nobel for heavily confined rock)	5000	5000

Using the graphs shown in Figure 1, the maximum blast-induced damage radii for each blast charge can be determined by considering the critical peak particle velocity (PPV_{max}) of basalt which accounts for the minimum PPV required to induce plastic deformations (or the critical PPV inducing maximum elastic deformations) in the rock. PPV_{max} can be obtained from mechanical properties of the intact rock as following (Forsyth 1993):

$$PPV_{max} = UTS \times \frac{V_p}{E} \tag{1}$$

where PPV_{max} is the critical peak particle velocity, UTS is the uniaxial tensile strength (dynamic tensile strength here to account for the loading conditions), V_p is the P-wave velocity, and E is the intact rock elasticity modulus. As indicated on Figure 1, 1.0 m and 0.36 m damage radius per blast charge was estimated for Emulsion and ANFO respectively.

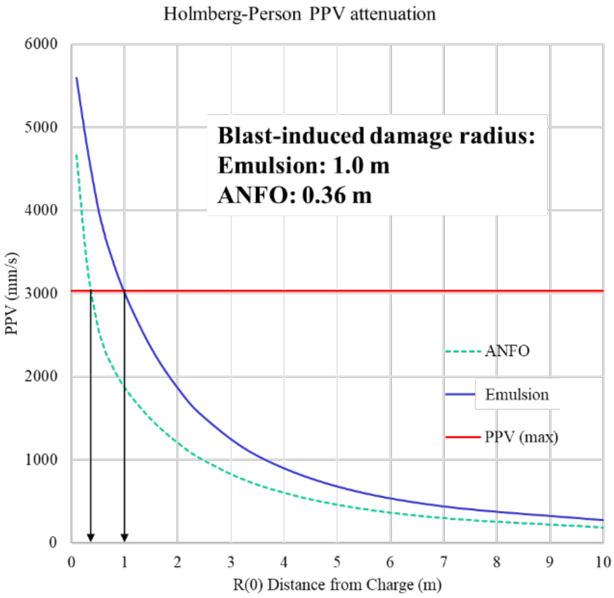

Figure 1. Blast-induced damage radius of ANFO and Emulsion charged in the destressing holes.

The properties of the rock mass for the blast damage zone were adjusted based on the recommendations of Torbica & Lapcevic (2015). According to this study, the additional blast-induced fractures in the rock mass were implicitly accounted for by reducing original GSI and adjusting the stiffness properties accordingly. A brittle constitutive model (Cohesion Weakening Friction Strengthening-CWFS) was used for the host rock mass (non-destressed areas in the numerical model) while the generalized Hoek-Brown failure criterion was used for the estimated blast damaged zones.

Table 2. Rockmass properties in the blast-induced damage zones.

Parameter	Destressed Rock Mass	Host Rock Mass (Basalt)
GSI	60	70
E_{rm} (GPa)	47	66
m_b	2.8	4.0
s	0.012	0.036

3 DESTRESS BLASTING PATTERN

As mentioned in the previous section, two different explosive types were examined and the blast-induced damage radii around each explosive type was estimated. The original destressing practice at the mine site was conducted using ANFO in the pattern that is schematically shown in Figure 2-a (this pattern was implemented at the time of floor rock burst incident). The potential blast induced damage zones shown in Figure 2-a clearly indicate the inadequate damage interaction between blast holes. As concluded by Hashemi & Katsabanis (2021), using ANFO as the explosive material for destress blasting would create localized destressed zones which might not successfully redistribute the stresses ahead of the tunnel face. Therefore, Emulsion was used instead of ANFO and further blast pattern optimization was explored accordingly.

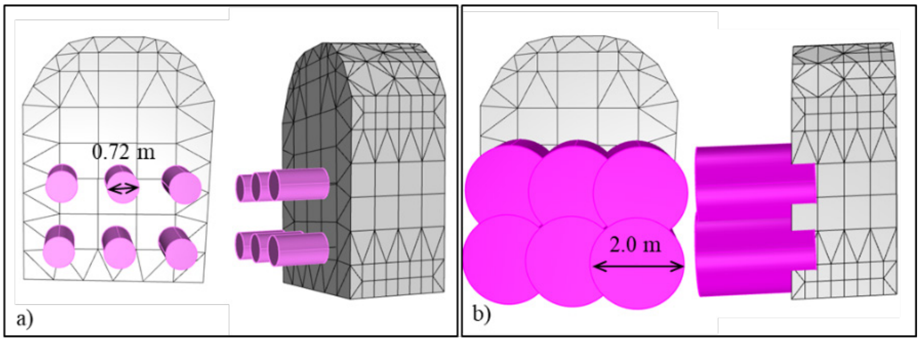

Figure 2. Estimated blast-induced damaged zone (shown by pink circles) using a) ANFO and, b) Emulsion.

Three different destress blasting patterns are examined with numerical models: I) tunnel face destressing, II) tunnel floor destressing, III) both face and floor destressing. The patterns consist of nine face holes in which the top two rows are drilled on grade with the tunnel development while the bottom row has a 6° downward angle. Four holes are designed with a 29° downward angle to target the floor burst volume. The toe of each hole is charged with emulsion for a maximum of 0.7 m (1.6 kg) which produces a 1 m damage radius as shown in Figure 2-b. The design pattern and potential blast damage zones around each hole is schematically shown in Figure 3. Each development round is 2.4 m as per the development standard for seismically active development headings at the mine site. 3.6 m drill holes were used in the face and 4.2 m holes were used in the floor (lengths are defined based on observations of stress concentrations and burst volume locations in calibrated tunnel-scale numerical model from Dadashzadeh and Kalenchuk, 2022).

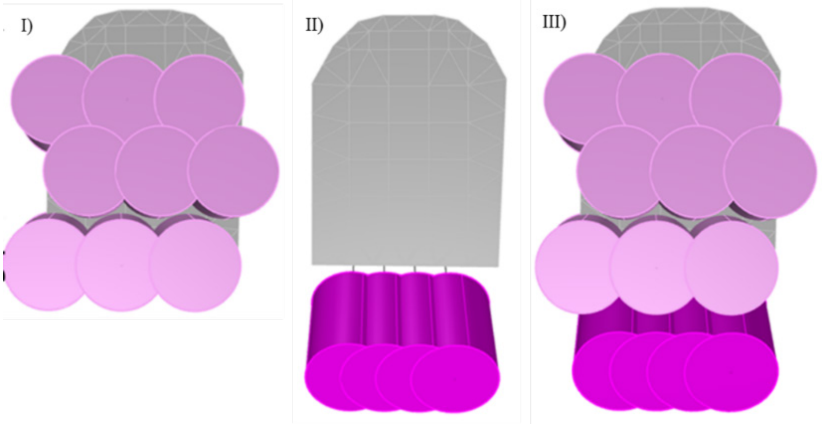

Figure 3. Potential damage zones of destress blasting I) face only, II) floor only, III) both face and floor.

4 MODELING SEQUENCE

The sequential destressing, excavation, and support installation are numerically incorporated as: 1) change material properties and constitutive model within the specified destress damage zone in round *i*+1 where *i* is the current round to be excavated, 2) excavate current round *i*, and 3) install ground support in current round *i*. Figure 4 shows the destressing sequence modelled in FLAC3D with representation of blast-induced destressed zones ahead of the tunnel development and installation of different ground support elements.

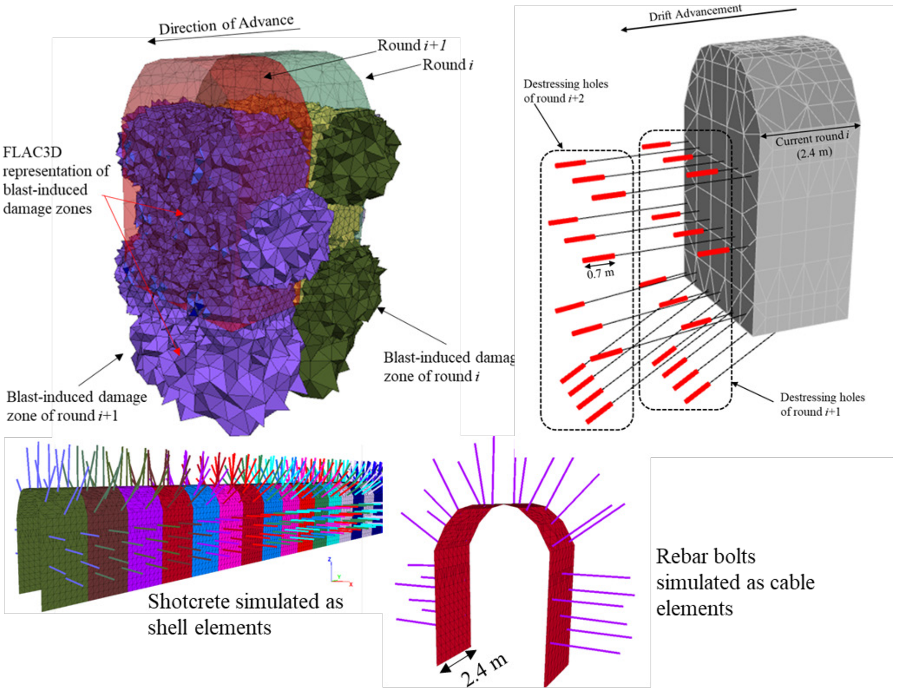

Figure 4. Numerical modeling sequence of destress blasting and installation of ground support in tunnel face.

5 NUMERICAL MODEL RESULTS

The distribution of Major Principal Stress along the longitudinal profile at the center axis of the tunnel is shown in Figure 5. Figure 5-a shows the stress states with no destressing incorporated in the modeling sequence; here the maximum stress concentration occurs approximately 2.0 m below the floor. Figure 5-b illustrates the case where only the face destressing is modeled; in this case destressing has a clear impact on stress conditions near bottom corner of the face, however high stress concentrations remain in the floor. As shown in Figure 5-c, destressing only the floor successfully reduces stress concentration in the floor, however the stresses ahead of the face and near the bottom corner remains high, indicating rock burst potential in the lower face. Figure 5-d illustrates that effective destressing of the floor is achieved when both the face and the floor are destressed.

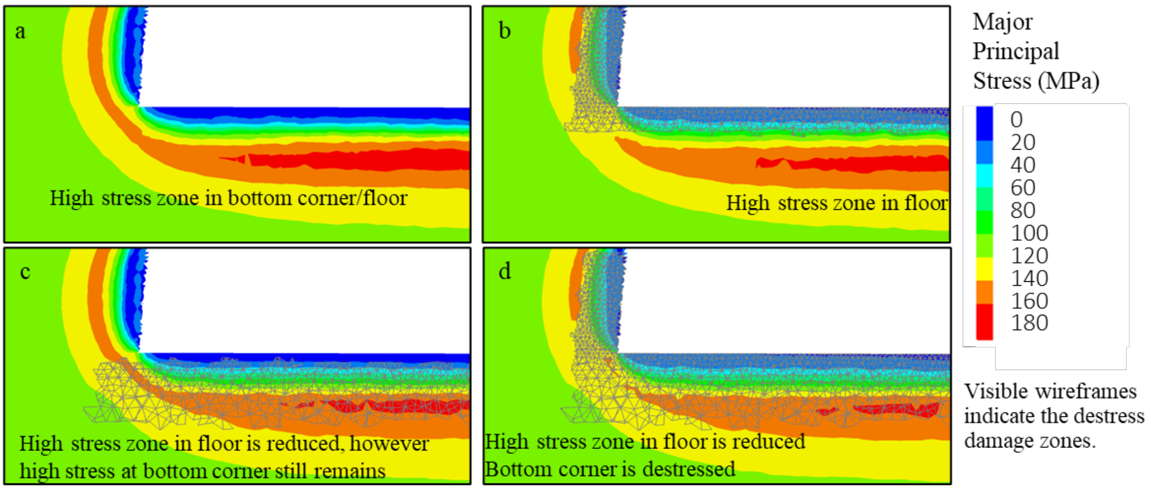

Figure 5. Major Principal Stress Contours at the longitudinal section along tunnel axis. a) No destressing, b) Face destressing only, c) Floor destressing only, d) Combined destressing of face and floor.

The failure intensity is conceptually characterized by the study of stress paths as an example shown in Figure 6 for the immediate corner of the excavation at the floor. The failure mechanism in the yielded volume can be violent or non-violent, depending on the evolution of stress paths. Stress hardening after the onset of damage (which potentially stores strain energy and can be released in a violent manner if the spalling threshold is reached) was observed in the model cases of no destressing, destressing with ANFO, and destressing the floor only. Stress hardening was successfully alleviated in the cases of face destressing and face and floor destressing using emulsion as explosive material.

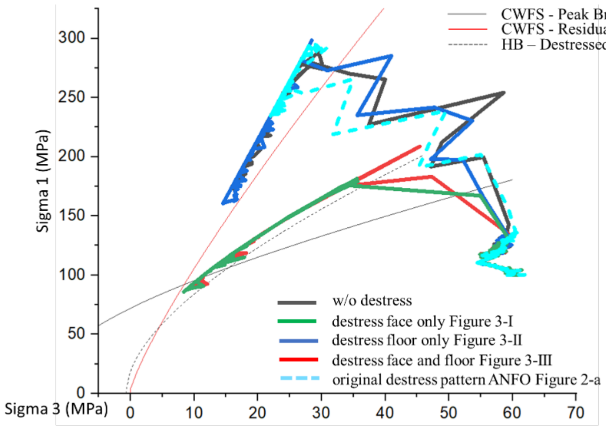

Figure 6. Stress path evolutions at the floor corner with various destress design options.

6 DISCUSSION AND CONCLUSION

Destress blasting of a development heading in a deep seismically active mine was evaluated using numerical modeling. The blast-induced damage zone extent and mechanical properties were modeled using an implicit approach to consider the blast-induced damage zone. These two critical components (extent and properties) are nearly-impossible to explicitly define for site-specific conditions in the absence of rigorous material testing and field program instrumentation and have therefore been determined based on literature (i.e., empirical and theoretical tools). While some degrees of uncertainty are inherently introduced by implicit analyses, these are deemed not worse than uncertainties that would otherwise be introduced by poorly informed explicit simulations.

Model results showed that isolated destressing of tunnel floor and tunnel face would not redistribute the stresses sufficiently (considering both lower face and floor burst hazards) and therefore simultaneous destressing of both face and floor is necessary in order to reduce the rock burst potential. The simplified approach of implicit blast damage modeling was successfully capable of providing preliminary understanding of effect of destress blasting, which can be verified by more complex explicit modeling, provided that the site-specific conditions were obtained based on experimental approaches and field instrumentation.

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