Reflections on destress blasting for deep level hardrock mining: Key considerations for successful application of the techniques

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Abstract

Deep hardrock mines worldwide increasingly face rockbursts as mining depths increase. These events result from the accumulation and sudden release of stress, causing rockmass damage and posing major safety and operational challenges. This paper focuses on destress blasting as a critical strategy to mitigate rockburst hazards. Although limited practical experience exists in Swedish deep hardrock mines, international case studies demonstrate that, when well implemented, destress blasting redistributes peak stresses by promoting controlled fracturing around mining excavations. The success of such techniques is highly dependent on site-specific factors such as stress regime, rockmass brittleness, structural geology, and blast layout. Although destress blasting is especially effective in massive, brittle rock under high stress, typical conditions for strainburst prone environments, its design cannot rely solely on numerical models. Simulations can offer preliminary evaluation of stress redistribution trends and guide early design assessments but their current limitations, including sensitivity to input data and simplified fracture mechanics, mean they are best used as supplementary tools rather than final decision-makers. Field trials, supported by microseismic analysis and fracture mapping, remain essential for validation. The study critically synthesises international experiences and presents a structured framework for destress blasting design, offering practical and academic perspectives aligned with Swedish geological conditions to support safer and more efficient application in deep hardrock mines.

Keywords

destress blasting, hardrock mining, rockbursts management, numerical modelling, energy balance, seismicity

Introduction

As mining goes deeper, the overburden rockmass imposes higher stress on the underground excavations. It is natural for the high stresses in the rockmass to seek redistribution as underground excavations are established. This results in the violent rockmass failure (rockburst). Rockbursts have several undesirable effects on the mine. This includes fatalities, injuries, loss of mining equipment, closure of productive sections of the mine, costs related to failed rockmass clean up, force majeure as well as social and political implications, among many others.

Different approaches can be used to contain rockbursts. As noted by Saharan (2004), these include varying mining methods, preconditioning of the ground (destress drilling, destress blasting, and water infusion) and implementation of rock support (backfilling or rock reinforcement). The focus of this study is the use of destress blasting as a rockburst control measure. Destress blasting has been used to reduce the rockburst potential of the rock surrounding mining excavations. Besides the technical benefits of addressing the aforementioned rockburst challenges, Harling (1965) (cited in Blake et al., 1998) noted that destressing has a positive psychological effect on the mining personnel as they feel a sense of safety due to the extra mile walked by management to implement underground mine safety measures such as destressing.

This paper analyses the different destress blasting techniques, which have been practised in the past with a view to indicate shortcomings and suggest possible improvements. This study is crucial in the development of suitable destress blasting designs for deep level hardrock mining conditions in Sweden. This study reflects on several aspects which are critical in developing the most suitable destress blasting design for given geotechnical and geological conditions. These aspects include stress regime, rockmass properties, blast borehole dimensions and spacing, explosives properties and initiation, and mining sequence. Issues such as destress blasting theory, destress blasting layouts, destress blasting design, evaluation of destress blasting design, and destress blasting modelling are covered in this study.

Destress blasting, as postulated by Roux et al. (1957), is premised on the observation that fractured rockmass zone ahead of a mining face offers pathways for stress release, enabling the transfer of peak stress concentration from the immediate vicinity of the mining face into the mining solid. Therefore, the destress blasting holes incorporated in a normal mining blast round are meant to extend the existing rock fractures and establish a well-connected fracture network for stress release. The most used explosive type in the past studies to achieve this fracturing effect is ammonium nitrate fuel oil (ANFO), due to its propensity to produce enormous amounts of gas with low shock to the rockmass. The use of ANFO in destress blasting is not merely for convenience but is technically justified based on its energy characteristics. ANFO has a relatively low detonation velocity (VOD of about 3200 m/s – 4000 m/s), as indicated in Table 5, and produces high gas volumes, which enhances heave energy. This energy form is effective for mobilising existing joints and promoting tensile fracturing in brittle, massive rockmasses, key mechanisms for stress relief in strainburst-prone environments (Toper et al., 1997). ANFO has been used historically in several deep mining operations (Kabongo, 1995; Widodo et al., 2019) due to its ability to induce distributed damage zones while limiting near-field shock and overbreak. Higher VOD explosives, such as emulsions, however, produce more shock energy and are better suited for initiating fractures in intact or confined zones with limited preexisting weaknesses (Drover, Villaescusa, 2019). The choice between high and low VOD explosives should be governed by the rockmass conditions and the intended fracture mechanism. Although ANFO remains widely used due to its effectiveness in generating tensile damage, emerging approaches such as mixed explosive loading and decoupling strategies offer promising alternatives to optimise fracture propagation and improve destress blast performance.

Upon implementation of a destress blasting design, different practical methods can be used to evaluate its effectiveness, the most used in practice being deformation monitoring and seismic activity monitoring before and after destress blasting. Other useful approaches for practical evaluation of destress blasting design include fracture frequency monitoring through ground penetrating radar, borehole periscope, and physical assessment of drillcore from the mining face. Achieving the most suitable destress blasting design is more of an art than a science, as the design needs to be fine-tuned and updated to account for actual prevailing ground conditions. The beauty of stress management strategies devised from practical observations (empirical) is that they can account for aspects which are difficult or impossible to account for in analytical and numerical simulations. Starfield and Cundall (1988) concur with this observation by noting that 'rock mechanics models fall into the class of "data-limited problems"; one seldom knows enough about a rockmass to model it unambiguously'.

Rockburst source mechanisms and rockburst damage mechanisms

Ortlepp and Stacey (1994) argued that while it is of little significance to comprehend a seismic source in order to design effective rockburst control measures, it is critical to distinguish seismicity from rockburst as the two are not necessarily the same. To differentiate the two, Potvin et al. (2000) provide the following definitions:

Seismic event:

> "A transient vibration or stress wave caused by an inelastic deformation in a rockmass. The deformation may be in the form of physical displacement, intact rock cracking or rockmass degradation. Seismic events are a normal response of a rockmass to stress readjustments near an excavation."

Note that there are also many events which occur at a certain distance from the excavation, especially the fault-slip events.

Rockbursts:

> Seismic events that cause significant physical damage to excavations. Damage can vary in intensity from minor rock spalling to catastrophic rockmass fracturing. The dynamic nature of rockburst damage means that there is the potential for extensive damage to or complete destruction of supported and unsupported underground excavations.

Source mechanism versus damage mechanism

Wang et al. (2022b) explained that the source mechanism in rock bursting is the triggering factor inducing rockbursts. They note that the damage mechanism is the rock failure mode (rock ejection, rock bulking, rockfall, rock buckling, shear displacement) caused by the rockburst. Wang et al. (2022b) noted that the rockburst damage mechanism research is crucial to understanding the onset, development, and extension of rock failure types encountered in the rockmasses due to rockbursts. Rockbursts are classified into five types, as follow: strainburst, buckling, face crush/pillar burst, shear rupture, fault-slip burst (Ortlepp, Stacey, 1994; Ortlepp, 1997; Kaiser, Cai, 2012).

Kaiser and Cai (2012) noted that buckling can be considered as strainbursting and shear rupturing can be considered as fault-slip bursting. This reduces the rockburst types to three, as explained by Kaiser and Cai (2012):

- ➤ Strainburst
    - "Violent release of stored energy at the mining face. This is due to tangential stress (σ1) accumulating in the excavation face and a soft loading environment created by the rockmass around the fracturing rock. The released energy does not come from the seismic source but emanates from the failing rock and its surrounding rockmass. Failure of the rockmass typically occurs when the induced stress acting on the rockmass is greater than the rockmass strength."
- ➤ Pillar burst
    - "Core of pillar fails violently, or the entire pillar breaks down. Associated with deep level mining where ratio of extraction is high, imposing significant stress on pillars."
- ➤ Fault-slip burst
    - "Dynamic slip down an already existing fault or a new shear rupture. Slippage is due to shear stress along the fault being more than the fault shear strength. Many factors can reduce the shear strength of the fault, these include water ingress, reduction of clamping stress, reduced coefficient of friction, and reduced fault waviness, among others."

Strainburst is considered to be the most common rockburst damage mechanism in civil engineering excavations (Ortlepp, Stacey,1994; Zhang et al., 2012; Cai, 2013). Strainburst type is most associated with deep underground mine drifting and therefore, key to understand when developing effective and efficient destress blasting designs. It is vitally important to understand rockburst damage mechanisms in order to select the most appropriate rockburst control measure. Different rockburst damage mechanisms, together with their associated severity of damage, and needed support function are illustrated in Figure 1.

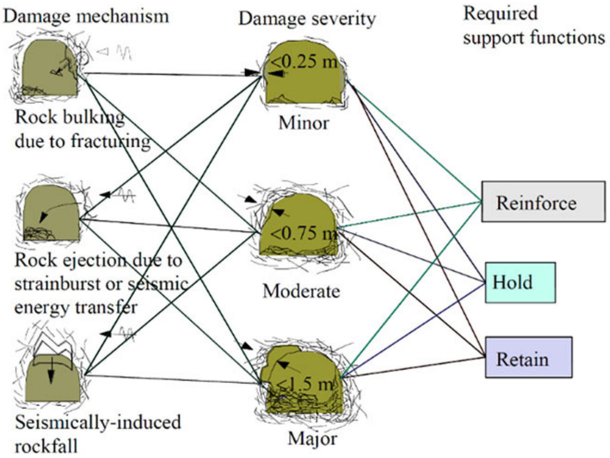


Figure 1—Damage mechanism and severity of damage associated with rock bursting as well as the needed support function (Kaiser et al., (1996) as modified by Kaiser and Cai (2012))

Table 1

Key rockburst damage influential factors (Kaiser, Cai, 2012)

Seismic event	Geology	Geotechnical	Mining
Event magnitude Rate of seismic energy release Distance to seismic source	In situ stress Rock type Bedding Geological structures (dykes, faults, and shears)	Rock strength Joint fabric Rock brittleness	Mining induced static and dynamic stresses Excavation span Extraction ratio Mining stiffness Excavation sequence (stress-path), blasting Installed rock support system Backfill Production rate

Strainburst		Pillar burst		Fault-slip burst
Mining induced	Dynamically induced	Mining induced	Dynamically induced	Dynamically induced. Can initiate strainburst and pillar burst at remote locations from the seismic source

- Dynamically induced rockburst occurs when a stress wave propagates to the rockburst point from a seismic source which is remotely located

Rockburst damage emanates from several different factors, of which the main ones are summarised in Table 1.

Relevance of rockburst mechanisms to destress blasting applications

As can be noted from the preceding discussion, rockburst phenomena include a range of failure mechanisms. The focus of this study is specifically on those burst types where energy is released from the intact rockmass surrounding excavations, primarily under high stress and brittle failure conditions. The mechanisms most relevant to the application of destress blasting in this context are strainbursts, which manifest as sudden, violent spalling or ejection of rock in response to excavation induced stress redistribution. Kaiser et al. (2016), classify both strainbursts and facebursts as manifestations of energy release due to excessive tangential stresses in brittle rock. Although facebursts are typically associated with development headings or advancing stopes, and strainbursts occur in tunnel sidewalls or roof zones, both share a common underlying mechanism; the rapid accumulation and release of strain energy from over-stressed, low-ductility rock volumes. In this study destress blasting is therefore examined primarily as a method for mitigating strainburst type behaviour in brittle, hig stiffness rockmasses. Strainbursting is most prevalent in hard, massive rock units with high compressive strength, low preexisting fracturing, and minimal capacity for inelastic deformation (Diederichs, 2018, Askaripour et al., 2022; Waqar et al., 2023). These conditions promote stress concentration near excavation boundaries, where even small excavation advances can trigger violent failure. Swedish deep hardrock mines, developed in competent granitic and metavolcanic lithologies, exhibit these geomechanical conditions, making strainburst mitigation highly relevant. This paper focuses on destress blasting as a preconditioning method intended to reduce the potential for strainburst initiation by locally altering the stress field and initiating controlled fracturing. The evaluation techniques, modelling approaches, and monitoring methods discussed in the paper are all directed toward understanding and mitigating this specific class of rockburst hazard.

Scope, objectives and contributions of the study

This study presents a comprehensive technical analysis of destress blasting as a critical tool for managing rockbursts in deep level mining. It systematically explores the theoretical underpinnings, practical applications, and challenges associated with destress blasting, while emphasising its significance in Sweden's deep hardrock mines, where practical experience with the technique remains limited. The study aims to consolidate knowledge on destress blasting by integrating global experiences to inform Swedish mining operations. It identifies destress blasting as a proactive stress management technique that facilitates stress redistribution away from excavation zones, thereby mitigating the risk of rockbursts. The paper discusses various key parameters influencing the success of destress blasting, including stress regime, rockmass properties, borehole dimensions, explosive selection, and blast initiation sequence. It highlights the necessity of numerical modelling to optimise blast designs before field trials, given the high costs and impracticality of extensive experimental permutations in real mining conditions.

One of the key contributions of this study lies in addressing the lack of extensive field experience with destress blasting in Swedish deep level mines. While other mining regions, such as South Africa and Canada, have documented applications of the technique, its implementation in Sweden has been sparse. The paper systematically examines case studies from various international mining operations and assesses their relevance to Sweden's geological conditions. The study also identifies gaps in the fundamental understanding of destress blasting mechanisms. As an example, there remains uncertainty regarding whether destress blasting merely extends preexisting fractures or actively generates new ones. This distinction has crucial implications for blast design, particularly in massive, low fracture rockmasses. The study also underscores the need for integrating geostatistical methods and machine learning approaches into numerical modelling frameworks to better predict and optimise destress blasting outcomes. The novelty of this study lies in its multi-dimensional evaluation of destress blasting, bridging theoretical, numerical, and empirical perspectives. The research emphasises a structured approach to destress blasting design, incorporating engineering design principles, cost considerations, and technological advancements such as seismic monitoring and ground penetrating radar (GPR) for real-time effectiveness evaluation. It provides a structured methodology to refine the application of this technique in the deep hardrwock mining industry of Sweden while contributing to broader advancements in underground mining safety and efficiency.

Destress blasting theory and practice

The concept of destressing was coined by Roux et al. (1957) in South Africa, as they grappled with the challenge of rock bursts in the deep mines of South Africa (Roux et al., 1958). They noted that destressing created a good network of fractures around the mining rockmass, thereby aiding stress release and reducing the burst potential of the rockmass. Vannes et al. (2020) described destress blasting as *a rockburst control technique where highly stressed rock is blasted to reduce the local stress and stiffness of the rock, thereby reducing its burst proneness*. Destressing is meant to migrate the peak stress in the rockmass from the immediate excavation face to further into the rockmass, thereby reducing the propensity of the rockmass surrounding the excavation to burst. This phenomenon is illustrated by Sainoki et al. (2017) after Tang (2000) in Figure 2.

Drover et al. (2018) gave an alternative description of destress blasting as *a construction technique in deep tunnels, whereby explosives are used to fracture the rock in such a way that strain energy is dissipated from the rockmass, with minimal deformation*. Topper et al. (2003) proposed that the mechanism underlying successful destress blasting is not solely the generation of fractures in the rockmass, but rather the subsequent mobilisation or removal of the crushed and fractured zone through routine mining activities such as face advance or stope development. They emphasised that if the blasted material remains confined, such as in an unmined pillar or static region, the surrounding stress field is not meaningfully relieved, despite the presence of damage. The rockmass must be physically disturbed or displaced instead, to enable effective stress redistribution and energy dissipation. This conceptual model highlights the critical importance of integrating destress blasting within the ongoing mining cycle, ensuring that preconditioned zones are mobilised in a timely manner. It also reinforces the need to coordinate blasting geometry, timing, and excavation sequencing to fully realise the benefits of destress techniques in deep level hardrock environments. Dissecting the descriptions of destressing from several researchers, it can be noted that there are different aspects which affect the implementation of the techniques. The aspects include in situ stress, explosive properties, rockmass properties, blast holes design and layout, blast timing etc. Many authors have expressed their opinions on the mechanism of destress blasting and how it works. The works of these authors are covered in different sections of this paper.

Destress blasting versus preconditioning

Circumventing the complexity of semantics can be a gargantuan task, which can fling researchers into a vortex of concept misperception, hence the need to bring clarity on the meaning of

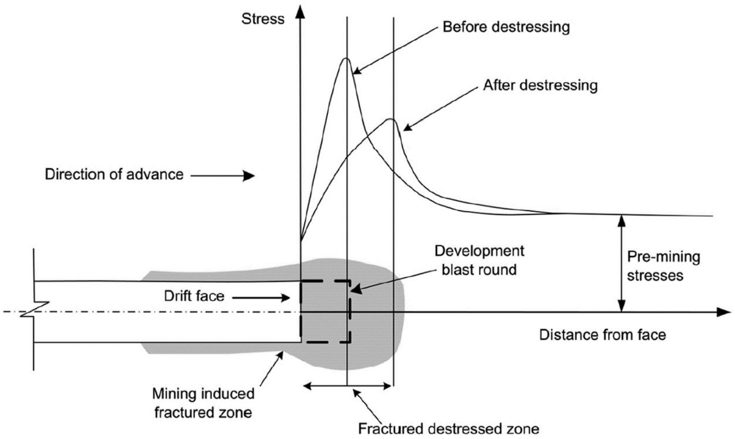


Figure 2—Illustration of peak stress migration from mining face as a result of destressing (Sainoki et al., 2017 after Roux et al., 1957, Tang, 2000)

the two terms – destress blasting and preconditioning. Reflecting on the works of Rojas et al. (2017) and Rahimi et al. (2020), Gonzalez et al. (2022) note that:

> "Preconditioning techniques have been widely applied to decrease the seismic hazard on a large scale (hydraulic fracturing) by altering a significant volume of rock or on a local scale (destress blasting) by modifying the rockmass immediately in the excavation vicinity." Yao et al. (2019) define destress blasting as a "rockburst control technique, which involves the application of explosive energy to highly stressed zones to reduce the local stress and stiffness of the rock, hence diminishing the potential for rockburst."

Effectively, preconditioning in underground stress management is the practice of proactively implementing measures ahead of time to bring ground conditions to the desired stable state before further excavation or mining operations are undertaken. For mining development drifting, this entails putting the mining excavation face in a stable state of stress before a blasting round is set off, that is incorporating destress blasting holes in the normal production holes to transfer the high state of stress from the immediate vicinity of the mining face, further into the rockmass. Destress blasting is, therefore, one of many ways of preconditioning the rockmass, paving way for safe mining operations. Miao et al. (2022) buttressed this observation by pointing out that:

> "…destress blasting has been applied to numerous mining conditions to precondition highly stressed rockmass to mitigate the risk of rockburst occurrence in deep mines as well as in deep underground constructions."

Hashemi and Katsabanis (2021) also explicitly highlighted this observation in their study on "Tunnel face preconditioning using destress blasting in deep underground excavations." Figure 3 illustrates the benefit of destress blasting as a means of preconditioning tunnel face, lowering the peak stress in the immediate vicinity of the tunnelling face.

Figure 4 highlights how a zone of a mining tunnel is preconditioned for future safe blasting through destress blasting, together with a section view of the layout of destress blasting boreholes on the mining face.

This view on preconditioning and destress blasting is seconded by other authoritative researchers (notable experts) including Saharan (2004); Larsson (2004a); Larsson (2004b); Toper et al. (1998); Blake et al. (1998); Toper et al. (1997). Following this train of thought, it can be noted that destress blasting can also be used as a technique to reduce or transfer the stresses in already highly stressed areas using a large number of explosives, in contrast with the traditional approach. This still falls within the realm of preconditioning since the overall goal is to proactively implement measures ahead of time to bring ground conditions to the desired stable state before further excavation or mining operations are undertaken.

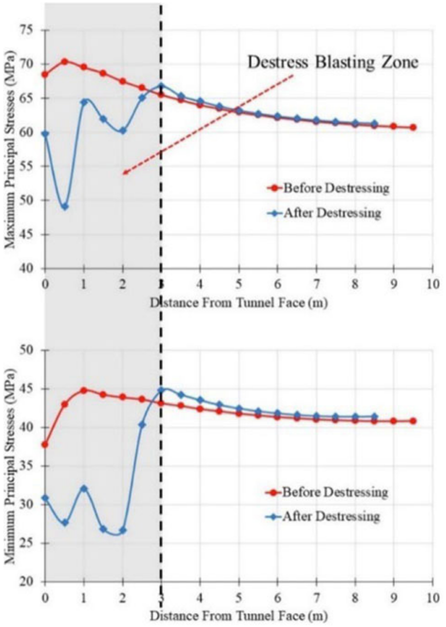


Figure 3—Stress distribution ahead of the tunnel face before and after preconditioning by destress blasting (Hashemi, Katsabanis, 2021)

Destress blasting – influence of fracture mechanics and geology

In the context of confined blasting, various researchers have extensively explored the mechanics and effectiveness of controlled blasting techniques, especially in applications where precision and fracture management are crucial, such as destress blasting in underground mining. Understanding the interaction between single and multiple blast holes, the mechanics of fracture propagation, and the influence of dynamic loading and geological factors is critical in getting to grips with how destress blasting functions effectively in real mine environments.

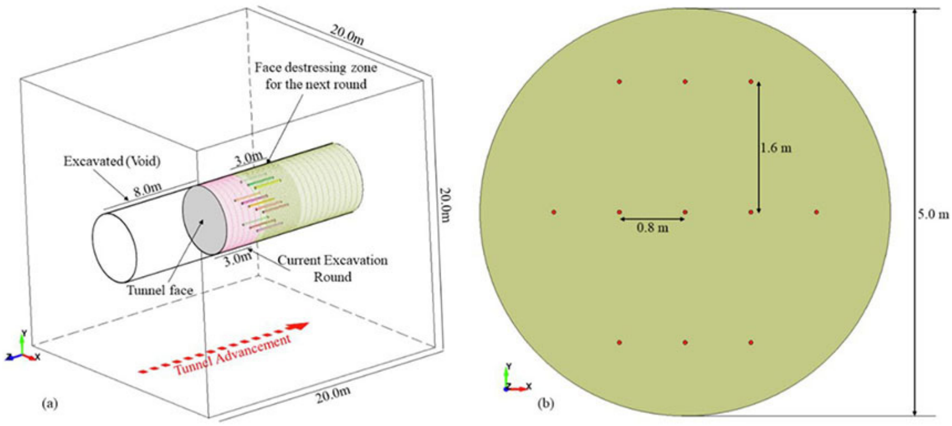


Figure 4—Illustration of destress blasting by preconditioning (a) excavation regions' isometric view (b) destress blasting holes layout section view (tunnel face) (Hashemi, Katsabanis, 2021)

Single hole blasting mechanics and fracture generation

Research on single-hole confined blasting has shed light on how fractures initiate and propagate in rock around a blast hole. The mechanics of single blasting events, as described by several studies, involve the rapid release of energy upon detonation, causing high-pressure gases to expand within the borehole. This results in the generation of tensile and compressive stresses around the hole, leading to the formation of radial and hoop fractures. These fractures emanate from the blast hole, extending outward and creating zones of weakened rock. The confined nature of the blast controls the fracture pattern and size, allowing engineers to manage and predict the extent of rock breakage. Studies such as those by Dotto and Pourrahimian (2024), and Hajibagherpour et al. (2020) have demonstrated that the fracture characteristics are influenced by factors like the blast energy, hole diameter, and rock properties.

Interaction between multiple blast holes

The use of multiple blast holes introduces an additional layer of complexity, as the interaction between blast induced stresses from adjacent holes can significantly alter fracture patterns. Researchers have shown that when blast holes are placed in close proximity, the overlapping stress fields can cause more extensive fracturing compared to single-hole blasts (Kutter, Fairhurst, 1971; Rossmanith et al., 1997; Rossmanith, 2002, Yi et al., 2016; He, Yang, 2019). The interaction between pressure waves generated by each blast hole leads to constructive interference, amplifying the intensity of stress waves and promoting additional fracturing between holes. This concept, sometimes referred to as 'blast synergy', has been crucial for understanding how to optimise hole spacing and blast timing in destress blasting applications. The understanding of how fractures generated by multiple holes interact and propagate in various rock types, provides a basis for designing efficient destress blasting patterns in real mine scenarios.

Fracture propagation and destress blasting in mine drifts

The mechanics of fracture propagation around blast holes are central to the effectiveness of destress blasting in mine drifts. Destress blasting works by inducing controlled fracturing in highly stressed rock zones, thereby relieving accumulated stress and reducing the risk of violent failure. In practical mining environments, the fractures generated by destress blasting create pathways for stress redistribution, weakening the rockmass in a controlled manner. Mining practitioners can achieve a stress-relieved zone, effectively preconditioning the rockmass to withstand ongoing mining activities without sudden failures through strategically positioning blast holes and carefully managing the energy release. The application of destress blasting has shown to be effective in creating a buffer zone around critical excavation areas, such as tunnels and stopes. The effectiveness of destress blasting in reducing the likelihood of rockbursts is significantly influenced by the design parameters, including blast hole spacing, charge weight, and blast sequence (Konicek et al., 2011; Konicek, 2018; Miao et al., 2022). Properly designed destress blasting ensures that fractures do not compromise the overall stability of the drift, instead forming a protective fractured shell around the excavation that dissipates high-stress concentrations.

Role of dynamic loading and geological conditions in destress blasting

The role of dynamic loading in destress blasting has been highlighted by researchers like Brummer et al. (1990), who emphasised that the impact of dynamic forces on rock fracturing is substantial in high-stress environments. Dynamic loading refers to the instantaneous application of stress from the blast, which not only generates fractures but also accelerates stress redistribution around the blast zone. The work by Brummer et al . (2000) has shown that dynamic loading is critical in cases where rapid and extensive fracturing is desired, as it facilitates the formation of microfractures and increases rock permeability around the blast zone. This process allows for the controlled release of stress, minimising the chances of uncontrolled rockbursts or sudden ground failures in deep mining operations. Geological conditions, including the inherent properties of the rockmass, joints, and preexisting fracture networks, also play a crucial role in the effectiveness of destress blasting. However, it is important to note that destress blasting is generally most effective in massive, brittle rockmasses prone to strainbursting. In highly jointed or intensely prefractured ground, the natural discontinuities can already accommodate stress redistribution through deformation, making destress blasting unnecessary or less effective. Widely spaced discontinuities in otherwise competent rock may influence fracture propagation and energy dissipation, requiring careful consideration in blast design. This highlights the need for site-specific geological assessment when determining the appropriateness and expected effectiveness of destress blasting. Hard and brittle rocks with fewer natural fractures may require higher energy blasts to achieve the desired fracture propagation, whereas softer rocks with more jointing may respond to lower energy blasts. The orientation of geological structures, such as faults and bedding planes, influences how fractures propagate (Aliabadian et al., 2014; Agrawal et al., 2022). The alignment of fractures with preexisting structural features can significantly alter the outcome of destress blasting, often necessitating adjustments in blast design to accommodate geological variability.

Practical applications and challenges

The integration of theoretical and experimental observations from confined blasting studies into practical applications has led to optimised destress blasting techniques in mining. Several challenges remain though, especially in adapting these models to complex underground environments where dynamic loading and geological heterogeneity can impact blast effectiveness. Real-time monitoring of rockmass response during and after blasting, including the use of microseismic sensors and displacement meters, has been instrumental in assessing the success of destress blasting in real-world applications. It is important to tailor blasting techniques to specific mine conditions. The spacing of blast holes, charge size, and sequence of blasts etc., need to be adjusted based on site-specific factors such as depth, rock type, and existing stress fields. Without these considerations, destress blasting may not achieve its intended purpose and could potentially destabilise the surrounding rockmass rather than relieve stress.

Destress blasting layouts for hardrock mine drifting

Several researchers have implemented destress blasting around the world, presenting an opportunity to learn how destress blasting performs in different designs and layouts. A Canadian deep hardrock mine case study for destress blasting is presented by Sainoki et al. (2017), as shown in Figure 5. The blast design utilises six destress blasting holes: two on the bottom corners, two on mid height of the drift, and two on the top corners of the drift.

Toper et al. (2003) reported on the observed performance of several destress blast (preconditioning) practical implementations in different South African mines, but predominantly at Mponeng mine

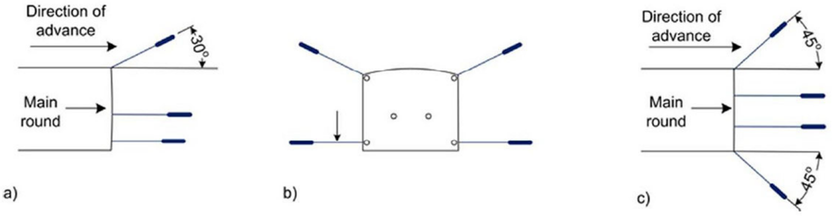


Figure 5—Destress blast pattern used at a hardrock mine in Canada: a) Longitudinal view; b) Side view; c) Plan (Sainoki et al., 2017)

(deepest mine in the world, operating at 3.16 km to 3.84 km below ground surface (NS Energy, 2020). These trials were carried out in narrow tabular stopes, which are mined with jack hammers. While the stope layout is significantly different from tunnels, the objectives and destress blast pattern are essentially the same. The height of the stopes is only 1.0 m, so the face blastholes are only 1.0 m long. The destress/preconditioning holes are longer than the face blastholes. The field investigations by Toper et al. (2003) included both face perpendicular and face parallel preconditioning strategies, with a refined comparison of their operational performance and geotechnical impact. The face perpendicular preconditioning design was noted for its logistical simplicity and reduced drilling complexity. This layout mirrored the geometric orientation typical of tunnel-based destress blasts, which is precedent in deep level tabular mining. The operational benefits include improved drilling accuracy, better control over burden dimensions, and enhanced workplace safety due to minimised exposure to unsupported hangingwall conditions during drilling and charging. The analysis of ground response monitoring data and seismological outputs suggested that face parallel configurations, although more complex to implement, may deliver slightly superior results in terms of energy dissipation and local stress redistribution. It is important to note that the marginally reduced effectiveness of the face perpendicular layout, likely due to reduced fracture propagation along the plane of maximum stress anisotropy, must be weighed against its consistent operational execution. The face perpendicular design efficiently redirected explosive energy orthogonal to the stope face, facilitating controlled fracturing and preconditioning of the face zone. This makes it a practical compromise for large-scale implementation. The face perpendicular layout effectively serves as a variant of tunnel destress blasting but tailored for stope geometries. The orientation aligns explosive induced fractures along structurally favourable planes and enhances preconditioning through stress shadowing and controlled dilation ahead of the mining face. This balance between technical effectiveness and logistical feasibility underpins its selection as the preferred field method in many deep level stoping contexts explored in the study by Toper et al. (2003).

As noted by Toper et al. (2003), when implemented correctly, preconditioning makes the work environment safe by shielding the mining faces from possible facebursts. The layout adopted for the face perpendicular preconditioning in the field studies is shown in Figure 6. The cross section ahead of the mining face showing positions of production and preconditioning holes is shown in Figure 7. It is important to note that, over and above other properties related to the rockmass and explosives, stemming plays a critical role in the success of destress blasting. The goal should be to direct most of the generated explosives gas and energy towards the mining face, with little to none lost into the mining opening due to stemming leakages.

Toper et al. (2003) thoroughly articulate the influence of stemming on the performance of preconditioning blasts. While stemming is conventionally understood to function as a mechanical barrier that prevents premature gas venting, thereby enhancing energy confinement and rock breakage, Topper et al. (2003) offered a deeper mechanistic view on its geomechanical implications, particularly for destress blasting. They postulated that effective destress blasting is not merely a function of high energy release but critically depends on the ability of the explosive event to mobilise and displace the crushed rockmass generated during the blast.

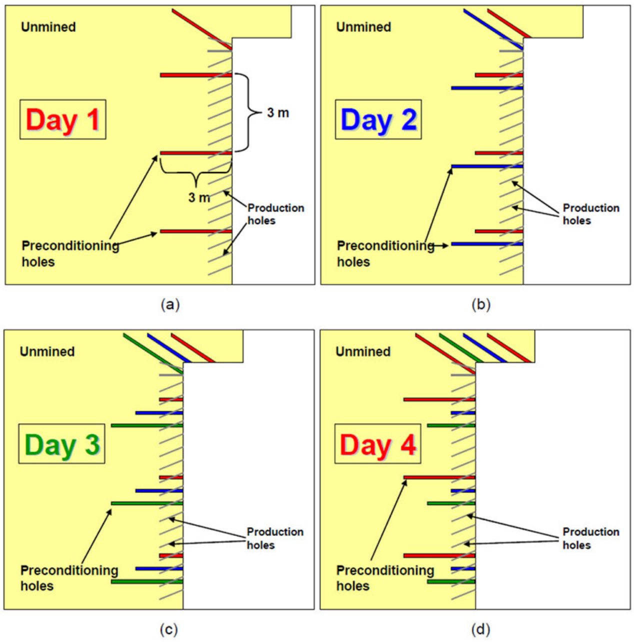


Figure 6—Three-day cycle layout for face-perpendicular preconditioning adopted in the field study (Toper et al., 2003)

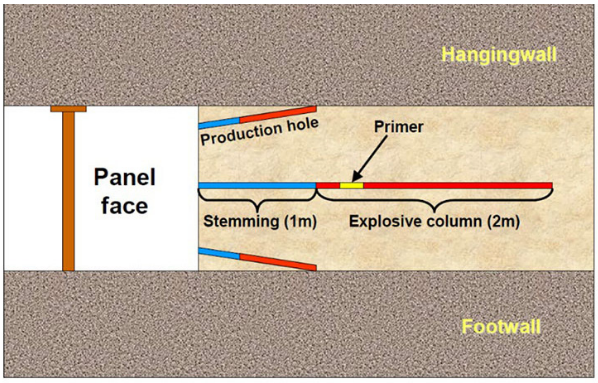


Figure 7—Longitudinal view of the mining face showing production and preconditioning holes positions (Toper et al., 2003)

This hypothesis introduces a key distinction: without sufficient development or advance of the mining face, confined destress blasts may fail to induce meaningful stress relief, as the crushed material remains locked in place and continues to bear load. Energy transfer from the blast to the surrounding rockmass becomes inefficient as a result, and desired seismic and mechanical outcomes (e.g., stress shedding and fracturing) are not achieved. The role of the stemming therefore extends beyond containing gas pressure, it must complement the broader blast design to ensure adequate rockmass mobilisation. This necessitates precise timing, optimal explosive distribution, and careful matching of stemming length to burden dimensions. The effectiveness of preconditioning is greatly enhanced when stemming supports the full mobilisation of fragmented rock, allowing stress transfer and dilation to propagate effectively away from the blast source. This conceptual model implies that destress blasts confined within undeveloped headings (i.e., without sufficient free face or void) are inherently less effective, as the induced crushed zone lacks the necessary kinematic freedom to enable stress redistribution. Stemming must be viewed not only as an energy-retaining feature but also as a catalyst for mobilising the fragmented zone, an aspect that redefines best practices in deep level mining destress strategies. This understanding reinforces the criticality of coordinated blast sequencing and void management in achieving successful preconditioning outcomes.

Toper et al. (2003) noted that, while destress blasting has undisputed technical merit, its benefits may not be sufficiently recognised if those responsible to implement it do not have sufficient appreciation of the value of destress blasting. The human factor needs to be appropriately taken into account since some of those responsible for implementing the destress blasting approach may feel it is unnecessary extra work to drill destressing blast holes over and above the production holes. Due to the culture of giving bonuses for meeting production targets, some of the miners may be tempted to cut corners and not implement destress blasting in the desired manner in pursuit of earning bonuses. An appreciation by the miners that destress blasting actually enhances safety and reduces mining costs in the long run due to elimination or minimisation of the need to address negative rockburst consequences, incentivises the miners to implement the destress design appropriately.

Drover et al. (2018) presented a conceptual study on the most suitable destress design to be adopted, considering factors such as the strength of rock, geological structures, and the stress regime existing in the rockmass. They adopted the Hybrid Stress Blasting Model (HSBM) (Onederra et al., 2013). The HSBM was used to simulate the destress blasting outcome of different destress blast layouts by doing an iterative sensitivity analysis of different parameters affecting destress blasting. The model can give the optimum destress blast design to adopt after considering different scenarios. The HSBM gives the associated damage zones associated with the chosen blast design. Figure 8 shows a conceptual layout of the production and destressing holes adopted by Drover et al. (2018) in their study, where a distance of at least 0.75 m is maintained between the destressing holes and the opening boundary. This is meant to ensure that the excavation is not over broken. An effective destress blast design should result in a good network of fractures established within a row of drill holes and across columns of drill holes. It is noted from the study that destress blasting should aim for the rockmass to fail in shear, since it is the best failure mechanism to release accumulated strain energy in the rockmass (Saharan, Mitri, 2011). “This mechanism requires that a fracture plane or series of fracture planes exist at a sufficient angle of incidence with respect to the azimuth and plunge of the major principal stress”. (Drover et al., 2018).

All destressing charges are offset from the excavation perimeter by at least 0.75 m

The layout adopted by Drover et al. (2018) in the HSBM model is presented in Figure 9.

Sengani et al. (2019) showed the benefit of face perpendicular preconditioning in deep level gold mining in South Africa. They showed the effectiveness of adopting a destress blast design where five preconditioning holes are incorporated in the usual blast design to relieve stress ahead of the mining face and migrate it further into the rockmass. The layout of the design is presented in Figure 10.

Special highlights on the Swedish mining industry experience of destress blasting

Larsson (2004b) reports that destress blasting has been adopted in Swedish mines, notably Näsliden, Laisval, Malmberget, and Kristineberg mines. Näsliden and Laisval mines are no longer operational as they have been closed. Larsson (2004b) noted

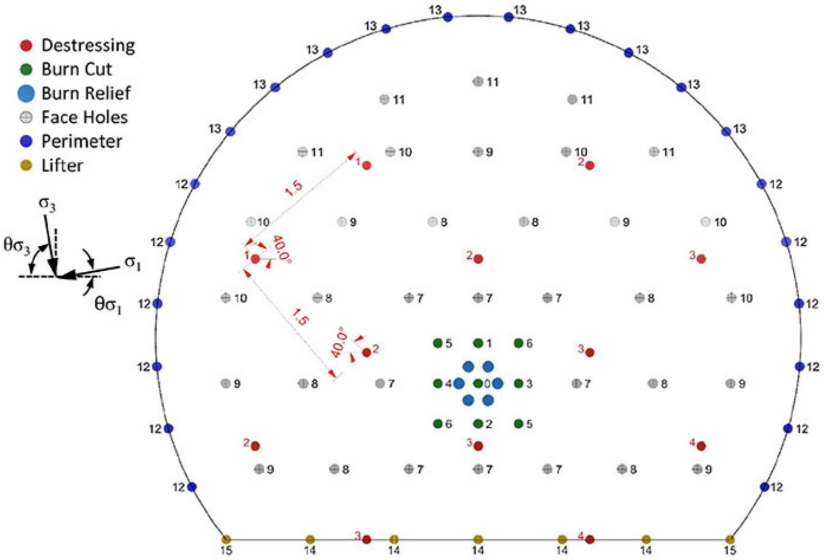


Figure 8—Concept of destress blasting optimisation considering strength of rock, its structure and stress conditions (Drover et al., 2018)

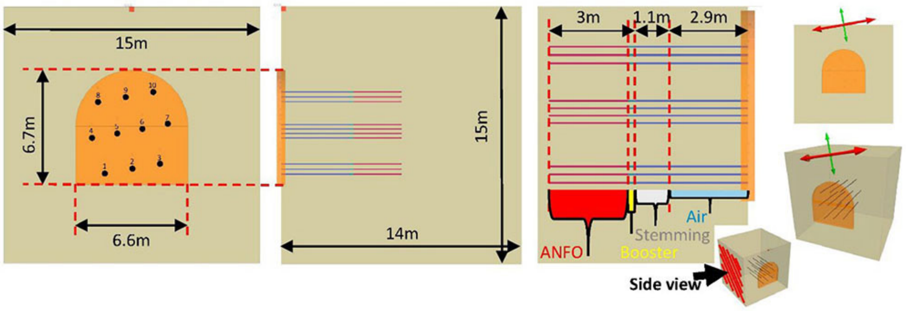


Figure 9—Destress blasting design layout considering stress regime, and explosive charge for the HSBM model (Drover et al., 2018)

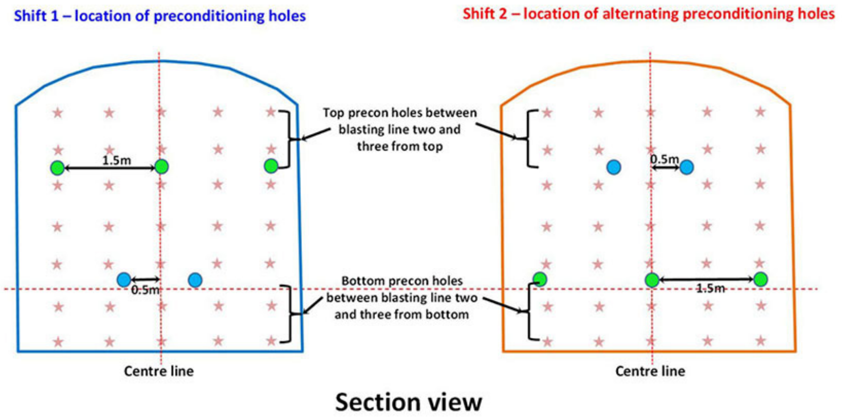


Figure 10—(a) Production blast holes and destressing holes layout in five face-perpendicular preconditioning (destressing) practice – section view (Sengani et al., 2019)

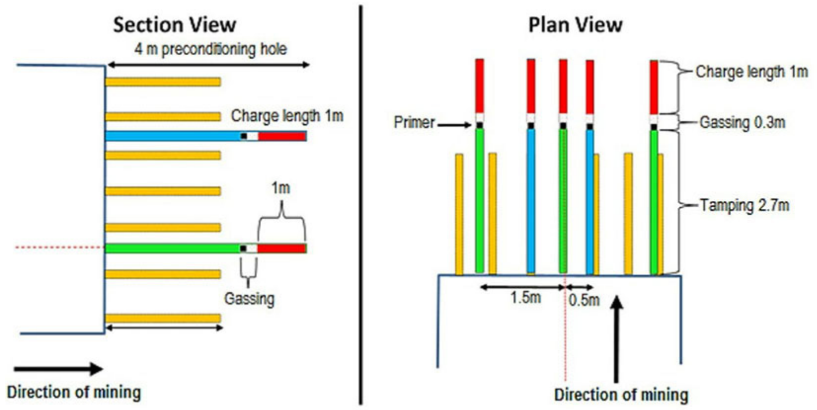


Figure 10—(b) Production blast holes and destressing holes layout in five face-perpendicular preconditioning (destressing) practice – side view and plan view (Sengani et al., 2019)

that Krauland and Söder (1988) summarise the destress blasting practised at Boliden mines until 1998. Following here is a summary of Larsson (2004b) discussion on destress blasting in Swedish mines:

Näsliden mine

Destress blasting was first attempted at the cut and fill mine in 1978 to manage extensive stopes roof spalling due to high horizontal stresses experienced at the mine. The main goals of the destress blasting were to quantify the effectiveness of cut and fill stope destressing through a slot place correctly and determining the most appropriate explosive that can satisfactorily crush the rock surrounding a blasthole. Numerical models with the set-up shown in Figure 11 were run to simulate this problem.

Field tries were contacted in one of the stopes, but the destressing was not successful. This was due to the low VOD of the explosive and the placement of the slot in ductile chlorite. This field study highlights immensely important aspects, which should never be taken for granted in destress blasting design, that is accounting for explosive properties and rockmass properties.

Due to occurrences of rockbursts and intensive stope roof spalling in another stope as a result of the high horizontal stresses, destress blasting was attempted in 1988. This entailed blasting together the production round with destress blasting holes. The effect of destress blasting (stoppage of rockbursts and reduced stope roof spalling) was only noticed after the fourth blasting round. This shows that a certain number of destress blasting rounds may need to be developed before the effect of destress blasting is evident.

Laisvall mine

The approximately 220m (from Engberg, 1989) deep room and pillar mine (with a tabular, sub-horizontal orebody) had high

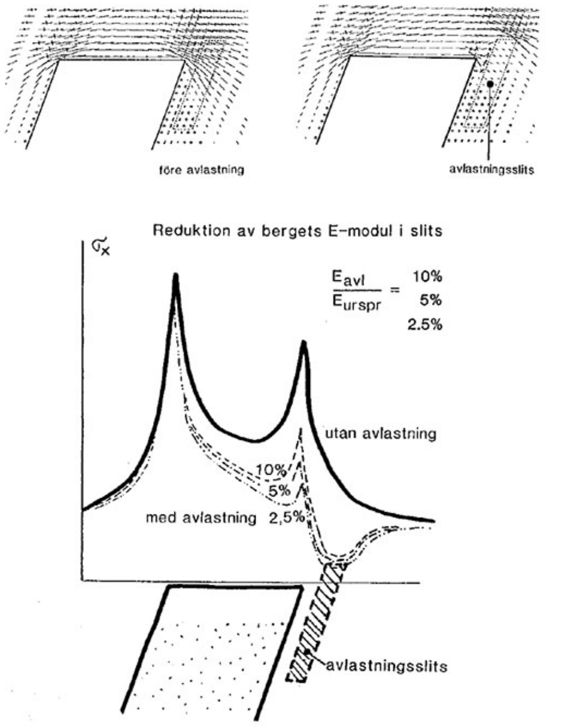


Figure 11—Model set up to determine appropriate slot placement and explosive to destress a cut and fill stope (Larsson (2004b) after Krauland, Söder (1988)

horizontal stresses, regardless of its shallow depth. The gravitational vertical stress was about 6 MPa at the depth of apprriximately 220m, yet the horizontal stresses ranged from 20MPa to 25MPa, giving a k-ratio (virgin horizontal stress to virgin vertical stress) ranging from 3.3 to 4.2. Due to spalling roof failure caused by the high horizontal stresses, destress blasting (with a layout shown in Figure 12) was decided on and implemented to address this challenge.

The production round was blasted together with the destress blasting boreholes of which the bottom part (0.6m to 0.7m) had been charged with 1 kg of explosives per blasthole. The blasted area was drilled to assess the rock fracturing effect of destress blasting and indicated that a 2 m to 2.25 m width and 1.5 m height cracked zone had been created as a result of destress blasting, highlighting the significance of physical drill core assessment as one of the practical means to evaluate destress blasting effectiveness in the practical field.

Two areas, one where destress blasting had been performed and the other where destress blasting was not done, were investigated through roof damage mapping to assess the effect of destress blasting. The damage area and failure depth were less pronounced in the area where destress blasting was performed, compared to the area without destress blasting, showing the effectiveness of destress blasting in controlling roof stresses. It is of significant value to future development and implementation of destress blasting designs to note that, in the Laisvall mine case study, destress blasting was not effective in a few places where it was not implemented according to plan, leading to increased roof damage in these areas.

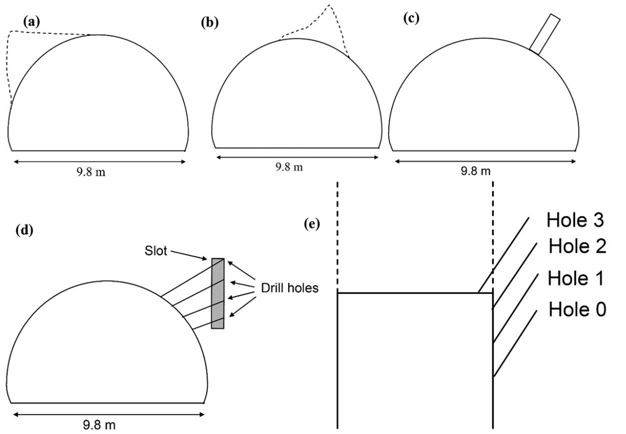


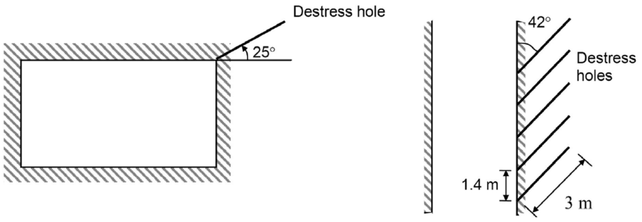
Figure 13—Destress blasting modelling and practical trials at Malmberget mine: (a) sloping roof profile sketch, (b) roof churching sketch (c) sketch of modelled mining drift and 2.7 m high slot, (d) adopted destress blasting layout for mine trials (section view), (e) adopted destress blasting layout for mine trials (plan view). (Larsson (2004b) after Borg (1988))

Malmberget mine

The Malmberget mine is one of the deep hardrock mines of Sweden, with the main level located at a depth of 815 m in 1985. The drifting of the main level was severely impacted and slowed down by seismic events. Spalling was experienced in the transportation drift roof due to severe seismic activities, extending the excavation height by 4 m and producing a sloping roof (see Figure 13). Numerical modelling was done to select the appropriate destress blasting design to attempt at the mine. The model tested a 2.7 m high slot (Figure 13c) with simulation parameters given in Table 2. Isotropic, elastic, and non-dynamic conditions were assumed in the model.

Results from numerical modelling showed that the slot effectively reduced roof centre stresses; with the use of a slot, which is high, long, and soft proving to be the most effective. The goal of destressing was to redistribute the excavation boundary stresses and transfer them further into the solid, eliminating or reducing excavation rock boundary damage. Trials of destress blasting were done with a view to increase the rate of drifting and also create a stable mining excavation using the layout shown in Figures 13 (d) and (e).

Note that only three holes were ultimately used after a few rounds of destress blasting. This decision was taken to avoid



Note that the destress holes are drilled on the sidewall abutment with the configuration illustrated in Figure 12

Figure 12—Destress blasting layout implemented at Laisvall mine (from Larsson (2004b) after Engberg (1989))

Table 2

Parameters used for destress blasting design and numerical modelling at Malmberget mine (after Larsson, 2004b)

Parameter	Value
Mining depth (m)	815
Roof spalling depth (m)	4
Uniaxial compressive strength of rocks (MPa)	194 (aplite); 178 (Leptite)
Slot height (m)	1 or 2.7
Slot length (m)	4
Young's modulus (E) - slot (GPa)	12 to 28
Young's modulus (E) – rock surrounding slot (GPa)	40
Hole spacing (m)	1

excessive damage to the excavation boundary rock, hence the labelling of one of the holes as *Hole 0*, since it was later not used. The same layout of the destress blasting holes was used on both sides of the drift. The destress blasting trial was observed to have been successful since seismicity and spalling overbreak reduced remarkably in all sections where destress blasting was implemented.

It is interesting to note, from this practical case study, that seismicity was observed to correlate with geology, with high seismic event occurrences noted in high UCS rock types at the mine, aplite (194 MPa) and red leptite (178 MPa), leading to high roof overbreak. This goes to show the need to accurately account for a wide range of parameters influencing destress blasting to achieve the most appropriate design, tailor-made for the prevailing geotechnical and geological conditions at the mine to be destressed.

Destress blasting design

No single approach in terms of the actual parameter values is applicable everywhere. It should be noted that, while literature gives the fundamental considerations in designing destress blasting, it would be necessary for each mine to devise its own actual parameter values depending on the rockmass conditions and stress prevailing at the mine as well as the type of explosives to be used. Hence, the need to practically investigate the best destress designs for deep mines of Sweden. Andrieux and Hadjigeorgiou (2008) noted that: “Irrespective of the scale at which it is carried out, destressing with explosives is still largely a trial-and-error procedure based on past—and usually site-specific—experience.” Mitri (2018) observed that the design of effective destress blast is more aligned to art than engineering science due to a wide range of available information and paucity of destressing programmes, which are described in detail. He also notes that the lack of design or analysis method, specifically for destress design, complicates the development of an effective destress blast, calling for the artistic trial and error approach. Table 3 presents the destress blasthole parameters for the study done by Sainoki et al. (2017).

Andrieux and Hadjigeorgiou (2008) presented properties needed for evaluating rockmass destressability, as shown in Table 4. It is important to note that this work was based on creating destress slots with long, large diameter holes to create a destress shadow. The techniques are used to destress larger volumes, and therefore different from tunnel face and stope face, and destress blast configurations, which have a very localised destressing effect (Toper et al., 2003). This example is presented in the following to illustrate some of the properties needed for evaluating rockmass destressability; aspects applicable to tunnel face and stope face destress blasting. Rockmass destressability parameters should be interpreted with respect to the scale and objective of the destress blasting method.

Table 3

Destress blasthole parameters used in a Canadian deep mine drift (Sainoki et al., 2017)

Parameter	Value/Description
Drift advance	1.83 m (6ft)
Number of destress blast holes	6
Blast hole diameter	0.1 m (0.33ft)
Face hole length	2.44 m (8ft)
Corner hole length	3.66 m (12 ft)
Charge length	0.6 m (2ft)
Charge diameter	0.1 m (0.33ft)
Explosive type	ANFO
Charge density	0.9 g/cc
VOD	4700 m/s
Priming method	Emulsion with bottom priming
Stemming	Drill cuttings throughout the length of hole

Explosives considerations

Explosives used for destressing the rockmass play an important role in the development of new fractures and extension of the existing fractures. It has been noted in explosives engineering that explosives, like ammonium nitrate fuel oil (ANFO), which produces much gas on detonation, are more desirable in destress blasts. The released pressurised gas can open further preexisting fractures and develop new ones, creating a conducive environment for the release of built-up stress in the immediate vicinity of the mining face. ANFO consists of ammonium nitrate (94%) and fuel oil (6%) (Louw et al., 1993). It should be noted, however, that ANFO is soluble and performs badly in wet conditions. The alternative to use in wet conditions is emulsion. Explosive selection is critical in achieving desired fracture behaviour and energy distribution during destress blasting. Different explosive formulations vary in their detonation velocity, energy partitioning (shock vs. heave), and compatibility with environmental factors such as moisture. ANFO is widely used due to its simplicity and gas-generating properties, but its poor water resistance limits application in wet or saturated boreholes. Emulsion-based and slurry explosives provide better confinement and water resistance, making them suitable for deeper or more saturated conditions. Cartridge and PETN-based charges, though costlier, offer precision in controlled blasting applications. Table

Table 4

Properties needed for evaluating the destressability of a rockmass (Andrieux, Hadjigeorgiou, 2008)

Properties	Symbol	Unit	Value
Density of the targeted rock (massive sulphides)	ρr	kg/m^3	4300
Young's modulus of the intact rock material	$E_{\mathrm{Laboratory}}$	GPa	130
Unconfined compressive strength (UCS) of the intact rock material	$\sigma_{c\ \mathrm{Laboratory}}$	MPa	235
Rock mass rating of the massive sulphides	RMR	%	85
Hoek–Brown parameter m of the intact rock material	$m_{\mathrm{Laboratory}}$	–	16.000
Hoek–Brown parameter s of the intact rock material	$s_{\mathrm{Laboratory}}$	–	1.000
Effective σ_1 component at the time of the destress blast	$\sigma_{1\ \mathrm{actual}}$	MPa	56[a]
Effective σ_3 component at the time of the destress blast	$\sigma_{3\ \mathrm{actual}}$	MPa	30[a]
Angle of incidence of the blast with respect to the σ_1 component	θ	degrees	90
Length of the pillar to destress	L	m	30.0[b]
Height of the pillar to destress	H	m	27.2
Number of blasting rings in the destress blast	N	#	2
Diameter of the blastholes	D	mm	165.1
Distance between blasthole rings	B	m	2.40
Distance between blastholes on the same ring	S	m	2.40
Unloaded toe length in the blastholes[c]	T	m	0.00
Unloaded collar length in the blastholes	C	M	5[d]
Usage of inert stemming material[e]	–	Yes or No	Yes
Density of the explosive product	ρ_e	g/cm^3	1.25
Absolute weight strength of the explosive agent	AWS	cal/g	645

[a] As estimated with 3DEC numerical stress simulations (Brummer et al., 2000).
[b] Corrected to account for the geometrical shape of the blast (dumped rings on the north side).
[c] Use zero for non-breakthrough holes.
[d] Minimum value – eventually irrelevant since already yielding the maximum confinement rating of 2.
[e] Add 50% confinement if stemming material is used.

5 provides a comparative overview of commonly used explosives, aiding practitioners in selecting appropriate products based on site-specific requirements and performance goals. It summarises key properties relevant to mining and destress blasting, such as VOD, gas energy characteristics, water resistance, application context, limitations, and supporting literature. The table serves as a practical reference for aligning explosive selection with specific geotechnical and operational conditions.

An understanding of explosives' properties suitable for destress blasting is instrumental in the successful implementation of a chosen destress blast design. The explosives should be able to initiate crack growth, resulting in a network of rock fracturing ahead of the mining face, which aids stress release. The blasting formulae presented in Equations 1 to 6 by Ouchterlony et al. (2002) are crucial in incorporating a feasible, effective blast design in the destress blast layout. However, it is important to note that the effect of high in situ stress is not considered for the calculation of crack length and suitable adjustments of the equations are necessary in high in situ stress environments.

$$Coupling\ ratio\ (f) = \frac{Explosive\ diameter}{Hole\ diameter}\ \frac{\phi_e}{\phi_h} \qquad [1]$$

$$Effective\ density\ of\ explosive\ (\rho_{e,eff}\ (kg/m^3)) = 6\rho_e \frac{\gamma^\gamma}{(\gamma+1)^{\gamma+1}} \qquad [2]$$

$$Borehole\ pressure\ (p_h\ (MPa)) = \frac{\gamma^\gamma}{(\gamma+1)^{\gamma+1}} D^2 f^{2.2} \qquad [3]$$

$$Borehore\ presure\ necessary\ to\ initiate\ crack\ growth\ (p_{h,crack}(MPa)) = 3.3\frac{K_{IC}}{\sqrt{\phi_h}} \qquad [4]$$

$$Pressure\ exponent\ (e') = \frac{2}{3\left(\frac{D}{c}\right)^{0.25} - 1} \qquad [5]$$

$$Uncorrected\ crack\ length\ (R_c\ (m)) = 0.5\phi_h \left(\frac{p_h}{p_{h,crack}}\right)^{e'} \qquad [6]$$

Where:
ρ_e is density of explosive (kg/m^3),
γ is the adiabatic expansion exponent,
D is velocity of detonation (m/s),
K_{IC} is fracture toughness (Pa.m$^{0.5}$),
c is P-wave velocity in rock (m/s).

Of course, these equations can be incorporated in blast simulation computer software for ease of analysis and investigation of many different blast designs, a task cumbersome when executed by hand calculation. Be that as it may, it is important to understand

Table 5

Comparative characteristics of explosives commonly used in mining applications

Explosive type	Typical VOD (m/s)	Energy characteristics	Water resistance	Typical application context	Limitations	Example references
ANFO	3200–4000	High gas volume, low shock energy. Produces strong heave useful for joint mobilisation.	Poor – degrades in moisture.	Dry boreholes in competent rock. Common for general blasting and where tensile breakage is preferred.	Ineffective in wet holes. Low shock energy limits use in high-confinement scenarios.	Dick et al., 1982; Toper et al., 2003; ISEE, 2011.
Emulsion	4000–5500	Balanced shock and gas energy. Produces uniform energy release under high confinement.	Excellent – water resistant.	Wet or highly confined conditions, especially where deeper fracture propagation is required.	More expensive. Requires specialised pumping or loading systems.	ISEE, 2011; Agrawal, Mishra, 2018; Kramarczyk et al., 2022.
Water gel / slurry	4000–5200	Moderate energy. Performs well in wet holes with moderate confinement.	Excellent – designed for wet use.	Saturated boreholes or deep stopes where charge integrity must be maintained.	Shorter shelf life. Can be sensitive to storage conditions.	Frost, Zhang, 2009; ISEE, 2011; Nikolczuk et al., 2019.
Cartridge explosives	5000–7000	High shock energy. Delivers focused energy in controlled blasting applications.	Good if casing is intact.	Presplit blasting, contour blasting, and situations needing high precision or small charge volumes.	Cost-prohibitive for bulk use. Limited to small-diameter applications.	ISEE, 2011; Mesec et al., 2015; Meyer et al., 2016
PETN-based charges	7000–8300	Very high detonation velocity and strong shock energy.	Low to moderate.	Specialised applications such as preconditioning in tight geometries or precise charge control.	High sensitivity. Risk of overbreak and safety constraints in handling.	ISEE, 2011; Dreger, Gupta, 2013; Anderson et al., 2022.
Heavy ANFO	3500–4500	Enhanced gas energy compared to ANFO. Some added shock energy.	Moderate – partial water tolerance.	Blasting in mildly damp conditions or where better coupling is needed without switching to emulsions.	Still moisture-sensitive. Requires good mixing and borehole preparation.	ISEE, 2011; Mesec et al., 2015; Žganec et al., 2016.
Emulsion blends	4200–6000	Customisable energy profile. Combines gas and shock effects effectively.	Good to excellent (formulation-dependent)	Sites with mixed conditions – wetness, high confinement, or mixed rock types.	Requires controlled on-site mixing and careful handling.	ISEE, 2011; Mishra et al., 2017; Balakrishnan et al., 2019.

the background chemistry and physics concerning blast design from first principles in order to use the software properly. When it comes to numerical modelling; experts note that models solve equations while people solve problems. This emphasises the need to understand engineering problems from first principles for one to be able to prescribe sound engineering solutions informed by numerical modelling results.

Some blast simulation computer software, which can be used for practical blast design are presented in Table 6.

In general, the more advanced software is able to provide more accurate simulations of blast fragmentation and throw but can also be more computationally expensive. The choice of software will depend on the specific needs of the project. For simple problems, relatively easy-to-use software like BLASTX, FOIL, or AUTODYN may be sufficient. For more complex problems, more advanced software like LS-DYNA, CTH, SHARC, or HSBM may be needed.

Table A1 in the Appendix presents a summary of some of the key parameters to consider in order to have a suitable destress

Table 6

Some of the computer simulation software for practical blast design (modified from Mortar et al. (2016) after Ngo (2007))

Software	Ability	Author/Vendor	Rock discontinuities simulation	Blast prediction capacity
LS-DYNA	Structural response+ CFD (couple analysis)	Livermore Software Technology Corporation (LSTC)	Can simulate rock discontinuities using a variety of methods, including explicit modelling, implicit modelling, and hybrid modelling.	Powerful and versatile tool for blast design but can be computationally expensive for large and complex problems.
BLASTX	Blast prediction, CFD code	SAIC	Can account for the effects of rock discontinuities on fragmentation and throw but does not explicitly model the discontinuities themselves.	May not be as accurate as more advanced software for complex problems.
CTH	Blast prediction, CFD code	Sandia National Laboratories	Can account for the effects of rock discontinuities on the blast wave propagation but does not explicitly model the discontinuities themselves.	Is a powerful tool for simulating large-scale blasts but can be computationally expensive.
FEFLO	Blast prediction, CFD code	SAIC	Can account for the effects of rock discontinuities on the blast wave propagation but does not explicitly model the discontinuities themselves.	Has the potential to be a valuable tool for simulating blasts in fluidised beds.
FOIL	Blast prediction, CFD code	Applied Research Associates, Waterways Experiment Station	Can account for the effects of rock discontinuities on fragmentation and throw by using empirical models.	May not be as accurate as more advanced software for complex problems.
SHARC	Blast prediction, CFD code	Applied Research Associates, Inc	Can account for the effects of rock discontinuities on the blast wave propagation and fragmentation process.	Has the potential to be a powerful tool for blast design in complex geological conditions.
ALE3D	Couple analysis	Lawrence Livermore National Laboratory (LLNL)	Can account for the effects of rock discontinuities by using interface elements.	Is a powerful tool for simulating complex fluid-solid interaction problems but can be computationally expensive.
Air3D	Blast prediction, CFD code	Royal Military of Science College, Cranfield University	Can account for the effects of air blast on the ground surface but does not explicitly model the rock material.	Is a powerful tool for simulating air blast effects on structures and people
CONWEP	Blast prediction (empirical)	US Army Waterways Experiment Station	Can account for the effects of rock discontinuities by using empirical models.	May not be as accurate as more advanced software for complex problems.
AUTODYN	Structural response+ CFD (couple analysis)	Century Dynamics	Can account for the effects of rock discontinuities by using interface elements.	Is a powerful tool for simulating complex problems but can be computationally expensive.
ABAQUS	Structural response+ CFD (couple analysis)	ABAQUS Inc	Can account for the effects of rock discontinuities by using interface elements.	Is a powerful tool for simulating complex problems but can be computationally expensive.
Blo-up	Structural response+ CFD (couple analysis)	Itasca Consulting Group	Can account for the effects of rock discontinuities explicitly, including their influence on wave propagation, fragmentation, and burden movement.	Can handle complex geological conditions and intricate discontinuities.

blasting design. Several case studies, as observed from the following authors are included in the table: Fuławka et al., 2022a; Hashemi, Katsabanis, 2021; Sengani et al., 2019; Baranowski et al., 2019; Drover et al., 2018; Sainoki et al., 2017; Andrieux, Hadjigeorgiou, 2008; Saharan (2004) (Strathcona Mine); Toper et al., 2003; Toper, 2003; Malmberget Mine in the year 1985 (Larsson, 2004b). The table has footnotes highlighting some points to note from it.

Design principles for a robust and reliable destress blast design

A well-structured process is essential for developing an effective destress blasting design that balances safety and cost. Bieniawski (1993) outlined six fundamental design principles and a ten-stage flow process, which, though general, offer a useful foundation for structuring destress blasting design. These principles stress the need for clear problem definition, critical in convincing all stakeholders of the value of destress blasting, especially as it involves additional drilling and cost. The design must be informed by adequate site characterisation and evaluated through a combination of empirical, analytical, and numerical methods to improve reliability. Of note, Bieniawski (1993) and Stacey and Hadjigeorgiou (2022) highlight the value of simple, implementable, and adaptable designs. Stacey and Hadjigeorgiou's quantified value-created process (QVP) builds on these principles to promote mine designs that maximise safety and economic return. Together, they guide the optimisation of destress blasting strategies tailored to specific geotechnical conditions.

Evaluation of destress blasting performance

Evaluating the effectiveness of a destress blasting design is crucial for ensuring its success in mitigating rockbursts and managing stresses in deep level hardrock mining. Several approaches exist for this assessment, each targeting specific aspects of rock behaviour before and after blasting. These methods include numerical modelling, rock fracture monitoring, rockburst prediction criteria, and seismic monitoring. Each of these methods offer unique perspectives into the performance of destress blasting. A combination of numerical modelling, empirical observations, predictive indices, and seismic data provides a comprehensive evaluation, minimising uncertainties and ensuring the successful application of destress blasting in deep mining environments. Zvarivadza et al. (2025) present a detailed coverage of destress blasting performance evaluation.

Numerical modelling

Numerical modelling plays a critical role in assessing destress blasting efficiency by simulating stress redistribution, energy dissipation, and fracture propagation. Two primary modelling approaches are used: static and dynamic simulations. Static models adjust rockmass properties to represent post-blasting conditions, while dynamic models simulate real-time fracturing processes. Note that traditional numerical models may oversimplify the extent of stress relief by assuming uniform damage zones, leading to overly optimistic predictions. A more refined approach evaluates the contribution of each blast hole separately to yield results that better reflect ground conditions (Sainoki et al., 2017). Parameters such as the fragmentation factor (α), Poisson's ratio changes, and stress dissipation factor (β) serve as quantitative indicators of blasting effectiveness. This is especially so since field testing of multiple designs is impractical due to high costs. Numerical modelling helps identify the most promising configurations before implementation.

Numerical modelling offers valuable feedback on stress redistribution, energy dissipation, and fracture development trends, but it remains a complementary tool rather than a substitute for field validation in destress blasting. Current modelling capabilities, though increasingly sophisticated, still face challenges in accurately replicating the complex dynamic responses of brittle rockmasses under high stress, especially where preexisting fractures, geological variability, and blast-induced damage mechanisms are difficult to parameterise. Numerical simulations, as such, are best used to guide preliminary design configurations and to understand the sensitivity of blast performance to different parameters. Field trials remain essential for validating predicted outcomes, calibrating models, and refining design strategies. This iterative approach, where numerical modelling informs field implementation, and field data in turn improves modelling accuracy, offers the most reliable path for optimising destress blasting in deep mining environments. This study acknowledges that, while modelling supports design decision making, empirical evidence and site-specific calibration continue to underpin robust destress blasting evaluation.

While numerical modelling plays a critical role in evaluating destress blasting, its reliability is highly sensitive to uncertainties in input parameters such as rockmass strength, elastic modulus, and stress field anisotropy. These parameters often exhibit spatial variability that deterministic models cannot capture effectively. To address this, probabilistic modelling approaches, such as the Monte Carlo simulation, Latin Hypercube sampling, or stochastic finite element methods, should be considered. These techniques allow for quantification of uncertainty and sensitivity analysis, offering a more robust framework for assessing design performance. Incorporating geostatistical data and performing multiple realisations can improve the confidence and realism of destress blasting simulations, especially in heterogeneous, high-stress environments.

Rock fracture monitoring

Assessing the extent of fracturing induced by destress blasting is vital for understanding its effectiveness. Ground penetrating radar (GPR) provides a non-destructive means to detect and map fractures in the rockmass, offering high-resolution, real-time imaging of subsurface conditions. Its depth penetration, however, can be limited in highly conductive environments, and its accuracy is influenced by surface roughness and geological variability. Borehole periscopes offer a complementary method by providing direct visual observations of fractures inside drill holes. This approach allows for detailed inspections of fracture orientations and densities, but its effectiveness is constrained by limited coverage and the risk of equipment damage in deep underground settings. Drill core analysis, another viable method, involves collecting and examining core samples to identify changes in fracture patterns post-blasting. This technique provides high-quality geological information but is time-consuming and spatially limited.

Rockburst prediction criteria

Energy balance analysis provides a theoretical framework for evaluating destress blasting performance by analysing the redistribution and dissipation of energy within the rockmass. Three key criteria: strain energy storage coefficient (F), brittle shear ratio (BSR), and Burst Potential Index (BPI), quantify rockburst proneness based on stress and energy considerations. The strain energy storage coefficient measures the ratio of stored to dissipated energy in a rock sample. A decrease in F post-blasting suggests successful energy dissipation, reducing rockburst risk. BSR evaluates the stress-to-strength ratio in the rockmass, with lower values indicating reduced potential for brittle failure. BPI, in a similar manner, compares stored energy to the critical energy capacity of the rock. A BPI greater than 100% signifies a high likelihood of strain bursting. These indices help in optimising blasting parameters and ensuring stress relief in hazardous zones.

Adopting Salamon's study (1984), Sedlák (1997) describes the basic energy balance due to mining as presented in Equations 7 and 8.

$$W_t + U_m = U_c + W_r \qquad [7]$$

Where:

W_t is the change in potential energy of the rockmass.
U_m is the stored strain energy in the mined material.
U_c is the increase in strain energy in the surrounding rock.
W_r is the energy released.

In the context of destress blasting, the system includes additional energy terms related to explosive input and induced fracturing. The energy balance is then extended, as presented in Equation 8.

$$W_t + U_{m1} + W_e = U_c + U_{m2} + W_f + W_k \qquad [8]$$

Where:
U_{m1} is the stored strain energy before destressing.
Um_2 is the stored strain energy after destressing.
W_e is the energy of the explosive.
W_f is the energy consumed in rock fracturing.
W_k is the seismic energy released.

This formulation allows rock engineering practitioners to assess how much of the explosive energy is used for productive fracture propagation (W_f) and how much is lost as seismic radiation (W_k). Effective destress blasting should ideally maximise W_f while limiting unwanted seismic release. These Equations support evaluating destress designs by comparing input energies to observable outcomes, such as reductions in modulus, energy release rates, or seismic activity, thereby offering a valuable analytical tool for blast optimisation and model calibration in high-stress mining environments.

Seismic monitoring

Microseismic analysis provides real-time data on stress redistribution following destress blasting. Seismic event monitoring tracks the location, frequency, and magnitude of induced seismicity before and after blasting. A significant reduction in seismic activity post-blasting indicates successful stress dissipation. Seismic moment magnitude and energy release assessments further quantify the extent of stress redistribution. In addition to these parameters, changes in seismic source mechanisms, such as shifts from tensile to shear-dominated failure modes, can provide further insight into how the rockmass responds to destress blasting. Drover and Villaescusa (2019) present a comprehensive evaluation of destress blasting performance using seismic monitoring, including the interpretation of source mechanisms and their implications for destress blasting effectiveness. Given the unpredictable nature of rockbursts, seismic monitoring is an essential tool for validating numerical predictions and fracture assessments, ensuring that destress blasting effectively reduces the risk of violent failure.

Discussion and concluding remarks

This study considered the concept of destress blasting as a stress and rockburst management tool, with particular focus on deep level hardrock mining. It is evident from the previous studies dating back to 1957 up to the current studies (2025) that destress blasting significantly contributes to rockburst management in deep level mining. Its usefulness is confined to the blasting round and some local short distance ahead of the mining face. In the practice of destress blasting, it is therefore mandatory to continuously incorporate the destress blasting holes with each mining round, lest the stabilising influence from the previous blasting round is lost.

Comprehension of rockburst source mechanisms and rockburst damage mechanisms is crucial in the management of rockbursts, including destress blasting approach. The theory and practice of destress blasting was covered to highlight the need for a holistic understanding of the mechanism of destress blasting and how it can be used successfully to manage rockburst challenges in mining. To bring clarity to the discussion, the terms destress blasting and preconditioning were clarified. It was noted that destressing is effectively one of the many ways of preconditioning the rockmass to a desired state in a bid to manage rockbursts, which would potentially happen in future blasting rounds. Several practical case studies on destress blasting, including the Swedish experience were covered, culminating in the development of the summary table in Appendix A presenting some of the key parameters to consider for successful destress blasting design.

To ensure that all steps needed to derive a robust destress blast design for any mining conditions, engineering design principles, and cost considerations as postulated by Bieniawski Bieniawski (1993) and, Stacey and Hadjigeorgiou (2022), respectively, were covered and should be a hallmark of any destress blasting design approach. As several aspects related to stress regime, rockmass properties, blast borehole dimensions and spacing, explosives properties and initiation, as well as mining sequence, influence the effectiveness of a destress blasting design; it is critical that these are adequately accounted for in the destress blasting design. It is clear that several iterations of numerical models would need to be run before the most suitable destress blasting is chosen for practical test in the deep level mine. Numerical modelling has proved to be a vital and invaluable tool aiding destress blasting design. Numerical models need to be carefully calibrated using field destress blasting observations for their results to be reliable. No numerical model can account for all aspects influencing destress blasting design, hence the need to continuously fine-tune a design based on practical field observations (accounting for prevailing geological and geotechnical conditions) and numerical modelling results.

Evaluation of the destress blasting efficiency is fundamental to the successful application of the technique. The two most used destress blasting evaluation methods are microseismic monitoring (assessment of seismic source parameters – seismic energy release, and moment magnitude) and deformation monitoring. These are already implemented in Sweden's deep hardrock mines for other mining purposes and would easily be adopted for destress blasting implementation in the mines.

It is vitally important that the value of destress blasting is correctly and adequately explained to mining personnel, operators in particular, for them to understand that drilling the destress blasting holes over and above the normal production holes is not a waste of time hampering them from missing production targets. Destress blasting enhances safety and can improve the availability of production areas by reducing the frequency of strainburst type events in massive, brittle rockmasses. Although effective in managing strainbursts, destress blasting has limited influence on large-scale shear type rockbursts caused by fault slip or dynamic rupture. These larger seismic events are more effectively controlled through appropriate mining layouts, sequencing, and by taking structural features such as faults and dykes into account. An exception is the work by Andrieux and Hadjigeorgiou (2008), where large-volume slot destress blasts were used to create a stress shadow that contributed to mitigating shear-type seismicity. It can be noted that when correctly applied in suitable conditions, destress blasting contributes to improved operational safety and reduced unplanned downtime by lowering the occurrence of damaging localised dynamic failures. This also psychologically boosts operators' morale and enhances productivity, dealing with the psychological effect of unsecure attachment and negative reinforcement bias in mining production.

Limitations of current studies and suggested further studies to inform destress blasting strategies in Sweden's deep level hardrock mines

- Rockmass variability is a fundamental consideration in rock engineering, but its relevance to destress blasting must be viewed through the lens of specific failure mechanisms. Strainbursts, including face bursts, predominantly occur in massive, brittle rockmasses with high GSI values and elevated in situ stress. These are the typical conditions under which destress blasting is applied. In such settings, stiffness contrasts, often caused by geological intrusions, can amplify local stress concentrations, increasing the likelihood and severity of strainbursts. Rocks with higher stiffness bear more load than their surroundings and are thus more prone to bursting. In jointed or laminated rockmasses, on the other hand, the presence of natural discontinuities allows the ground to deform more readily, and failure is usually non-violent. In cases of severe alteration or intense jointing, squeezing behaviour dominates, and destress blasting is generally not required. It is vitally important to note that, although rockmass variability is a key design input, its significance to destress blasting lies in identifying conditions where brittle failure under high stress is likely, reinforcing the need for site-specific assessment.
- Rockbursting is a challenge which can be explained by the concept of energy balance - looking at the energy supplied to the rockmass, energy used for rock failure and the energy dissipated. Management of this energy can lead to effective rockburst management. The concept of energy balance has not been fully explored in destress blasting design numerical modelling; it is suggested that this approach be pursued. This could be practically achieved by integrating energy tracking capabilities into numerical codes, such as calculating stored strain energy pre- and post-blast, evaluating fracture energy consumption, and comparing these to explosive input. Hybrid FEM-DEM platforms, as an example, could simulate energy redistribution during blasting to assess Wf, Wk, and Um terms in Equation 8. Calibration could be supported by microseismic monitoring and stress remeasurement. Applying such models could help identify designs that maximise fracture energy absorption, while minimising seismic release, improving safety and efficiency.
- Accounting for geological and geotechnical variability remains a significant challenge in numerical modelling for destress blasting design. While the role of large-scale variability has been discussed in relation to burst-prone conditions, localised stiffness contrasts (such as those introduced by intrusions) also play a critical role by concentrating stress and increasing strainburst potential. Although spatial geological variability has been successfully represented in other rock engineering applications using geostatistical methods like kriging, such techniques have not yet been widely applied to destress blasting design. Incorporating these tools could enhance our ability to map stiffness contrasts and high-risk zones, leading to more targeted and effective preconditioning strategies. This presents an important opportunity for future research, also see Zvarivadza (2023).

  Some destress blasting studies argue that no new fractures are created in destress blasting, but only extension of existing fractures. Toper et al., 2003 postulate that:

  > "While it has been found that no new fracture sets are generated as a result of preconditioning, regular detailed fracture mapping should reveal that fractures with favourable orientations are enhanced and re-mobilised when preconditioning is used."

  Furthermore, Scoble et al., (1987), state that:

  > "The only evidence of destress blasting creating new fractures was in close proximity to blast holes; fracturing appeared predominantly to be related to preexisting discontinuities."

  The mechanism of new fracture creation during destress blasting remains a key topic in rock mechanics. Shnorhokian and Ahmed (2024) identify two dominant interpretations: the generation of new fractures and the reactivation of existing ones. In North American and coal mining contexts, the creation of new fractures is widely accepted as it softens the rockmass, lowers stiffness, and redistributes stress (Blake, 1972; Board, Fairhurst, 1983; Hedley, 1992; Andrieux, Hadjigeorgiou, 2008). Supporting this, field studies show a post-blast fracture density increases of 15% – 100% and modulus reductions of up to 95% (Shnorhokian, Ahmed, 2024). While fracture creation is widely observed, local geology and design conditions influence whether fracture generation or reactivation predominates (Shnorhokian, Ahmed, 2024). As can be noted from the works of other researchers, it is not always the case that no new fractures are created in destress blasting. In massive rockmass conditions, where there may not be fractures intersecting the destress blasthole, the explosive high gas (from ANFO) will not be able to penetrate the rockmass to extend the existing fractures if no new fractures are created by the blasting. This has significant implications on the destress blast design and numerical modelling of destress blasting. This area of study still needs to be developed further.
- With the fourth industrial revolution springing into the mix of mining technology, aspects such as machine learning and artificial intelligence can be used to evaluate destress blasting implementation results related to deformation monitoring, seismic monitoring, and fracture frequency monitoring to continuously optimise the destress blasting design. Machine learning is credited with the ability to detect patterns in large data sets to predict future patterns, which can be a way of forecasting destress blasting performance.
- Blasting induced crack length is a key parameter in rock fragmentation studies and also holds potential in evaluating destress blasting efficiency. While the primary objective in destress blasting is indeed to create a crushed and fractured zone that can be mobilised by subsequent development blasting, as noted by researchers like Toper et al. (2003), the extent and connectivity of radial cracks surrounding the crushed core are critical for enabling effective stress redistribution. Studying minimum crack length thresholds could help quantify the development of a continuous fracture network that facilitates energy dissipation and deformation control. Such an approach could complement traditional measures of destress effectiveness by offering a physical parameter linked to fracture propagation. Further investigation into the role of crack length, alongside crushing and mobilisation mechanisms, could enhance an understanding of the overall destressing process and inform both design evaluation and numerical model calibration.

- While destress blasting is indubitably effective in managing rockburst challenges at a local scale, calling for the implementation of the strategy with each blasting round for the destressing efficiency not to be lost, it needs to be complemented with hydraulic fracturing of the rockmass to achieve regional stability of the mine. Studies on the combination of destress blasting and hydraulic fracturing to manage rockburst challenges have not been conducted and need to be explored.

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Appendix

Table A1: Destress blasting design parameters for different case studies

	Value/Description										
Parameter	**Unit**	**¤Fulawka et al., 2022a**	**Hashemi and Katsabanis, 2021**	**Sengani et al., 2019**	**Baranowski et al., 2019**	**Drover et al., 2018**	**Sainoki et al., 2017**	**Andrieux and Hadjigeorgiou, 2008**	**Saharan (2004), Strathcona Mine**	**Toper et al., 2003; Toper, 2003**	**Malmberget Mine in 1985 (Larsson, 2004b)**
Destress blasthole parameters											
Drift advance	m		3		4		1.83 (6ft)				
Number of destress blast holes	-		11	4 and 5	4		6			4	
Destress blasthole diameter	mm		50	51	64.5		100 (0.33ft)	165.1	63	36 - 40	
Destress blast face hole length	m						2.44 (8ft)				
Destress blast corner hole length	m						3.66 (12 ft)				
Destress blasthole length	m		6	4		7			5.5	3	
Destress blasthole dip	°			0 (parallel to drive)		0 (parallel to drive)					
Destress blasthole burden (B)	m		1.6	2.25	0.80	2		2.40	2.1		
Destress blasthole spacing (S)	m		0.8	0.5 and 1.5	1.60	1.5 and 1.65		2.40	2.1		
Destress blasthole stemming	m			2.7		1.1			1.2	1	
Destress blasthole charge length	m			1		3	0.6 (2ft)			2	
Destress blast charge diameter	m						0.1 (0.33ft)				
Air Gap	m					2.9					
Explosives											
Explosive type	-		ANFO	Emulsion		ANFO	ANFO		Emulsion (Magnafrac)	ANFO	
Charge density (Density of the explosive product)	g/cm^3		0.85				0.9	1.25	0.11 to 0.16		
Absolute weight strength of the explosive agent (AWS)	cal/g							645			
Explosive Powder Factor	-										
Velocity of detonation (VOD)	m/s		3930		4805	4000	4700				
Detonation Pressure (Chapman–Jouget pressure) (CJ)	GPa		3.5		7.4					0.5 or 1	
Priming method							Emulsion with bottom priming				
Stemming material							Drill cuttings throughout the length of hole	Inert stemming material		Clay, bentonit, angular sand or a combination of these	
Jones-Wilkins-Lee (JWL)											
A	GPa		7143.31		252.00						
B	GPa		2.309		15.57						
R1	-		2.527		6.08						
R2	-		0.918		2.05						
ω	-		0.39		0.25						
E	kJ/cm^3		3		3.70						
Rock material parameters											
Rock quality index (Q)	-								25		
Rock mass rating (RMR)	%			59				85	73		
Uniaxial compressive strength (UCS)	MPa		210	79	149.6		190 (Norite), 240 (Granite)	235	300		178 (Red leptite); 194 (Aplite)
Elastic modulus (E)	GPa		65	16.5	77.32		78 (Norite), 60 (Granite)	130	40	71.9	40

Appendix

Table A1: Destress blasting design parameters for different case studies (continued)

Poisson's ratio (ν)	-		0.27	0.25	0.24		0.28 (Norite), 0.26 (Granite)		-	0.3	
Friction angle (φ)	°						59.1 (Norite), 63 (Granite)				
Unit weight of rockmass (γ)	KN/m^3						28.0 (Norite), 25.5 (Granite)				
Tensile strength (σ_T)	MPa		16		30.23		12.6 (Norite), 16 (Granite)				
Shear strength	MPa				18.44						
Dilation angle (ψ)	°						8.75 (Norite), 8.75 (Granite)				
Bedding planes (cohesion, friction angle, spacing)	MPa; °; cm									0; 30; 30	
m_i	-			1.19				16	10		
s	-			0.0013				1	0.05		
Rock mass density (ρ)	kg/m^3		2650	2900	2840.00		2850 (Norite), 2600 (Granite)	4300 (Massive Sulphides)	-		
P-wave velocity	m/s		5300								
Hugoniot elastic limit, HEL	MPa				2500						
HEL pressure, P_{HEL}	MPa				1440						
Intact strength coefficient, A	-				0.73						
Fractured strength coefficient, B	-				0.56						
Strain rate coefficient, C	-				0.026						
Intact strength exponent, N	-				0.57						
Fractured strength exponent, M	-				0.57						
Bulk factor, β	-				1						
Damage coefficient, D_1	-				0.001						
Damage coefficient, D_2	-				1.17						
Pressure coefficient 2, K_2	MPa				−78000						
Pressure coefficient 3, K_3	MPa				9400000						
Maximum normalised fracture strength, σ_{max}	MPa				0						
Stress regime											
Mining induced stress	MPa								100		
Insitu stress	MPa										
Major principal stress (σ_1)	MPa		60	27*		50	0.042D + 10.35	56[a]		100	
Intermediate principal stress (σ_2)	MPa			24*			0.033D + 8.69	-			
Minor principal stress (σ_3)	MPa		40	6*		27	0.029D	30[a]		50	
Angle of incidence of the blast with respect to the s1 component (θ)	°							90			
Destress blasting simulation parameters											
Fragmentation factor (α)	-						0.4 (Average), 0.1 (Maximum)				
Stress dissipation factor (β)	-						0.6 (Average), 0.9 (Maximum)				
Development size (Width; Height)	m; m				6; 3.5	6.6; 6.7					9.8; 9.8
Model size (Length; Width; Height)	m; m; m					14; 15; 15					

D is depth below surface.

[a] Estimated using 3DEC (Brummer et al., 2000).

* Values from Andrews (2020).

Note: Bulk modulus and shear modulus can easily be calculated from E and v.

All the parameters listed in Table A1 are fundamentally important in illustrating that no particular destress blasting case accounted for all the parameters, highlighting the importance of practical tests (empirical observations - fine-tuning the destress blasting design from these observations helps in accounting for parameters, which are next to impossible to account for in numerical modelling) for any mine intending to implement destress blasting, the practical observations from the tests work hand-in-hand with numerical modelling to achieve the most suitable destress blasting design.

¤ Fuławka et al. (2022a) is a case study on destress blasting efficiency evaluation using seismic monitoring. It does not provide the destress blasting parameters used in the study. The case is included here for readers who need to pursue this case study by contacting the authors directly.