Consideration of Rock Mass Violent Failure
Mechanisms around Underground Excavations

Ali Keneti
MSc, Civil Engineering – Geotechnical, University of Calgary, Canada
MSc, Rock Mechanics Engineering, University of Tehran, Iran
BSc, Mining Engineering, Isfahan University of Technology, Iran

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ABSTRACT

This research investigates strain-burst failure (as one of the main types of rock mass violent failure mechanism) and the associated risk for underground excavations.

Throughout reviewing selected case study data from around the world, in-situ conditions leading to rockburst events in a macro (drive)-scale were identified. The main contributing factors include unfavourable states of stresses, geometry of the excavation (its size and orientation in relation to principal stresses) and the rate and direction of advance. Factors also included unfavourable rock mass characteristics including mineralogy, contrast in geomechanical properties, and presence of geological intensifiers.

In the second phase, failure mechanisms on a micro-scale were studied. To do this, igneous rock fragments from a strain-burst event site were studied under a Scanning Electron Microscope (SEM) in order to characterise their surface features and allow interpretation of the failure/fracture propagation mechanisms. SEM image analysis indicated that anisotropy, a contrast in geomechanical properties, and adverse effects of the geometry and contact patterns present at the micro-scale as they do at the large scale. It is proposed that these micro-scale features can lead to anisotropic material behaviour and stress concentrations that manifest as strain-burst events.

In order to assess the severity of strain-burst failures around underground excavations an index has been developed. This index ($I_{VFse}$) incorporates measures of the induced stress path and the accumulated plastic strain, and is calculated after brittle failure conditions are identified by the established Damage Initiation and Spalling Thresholds (DIST).

Application of the ‘$I_{VFse}$’ index to a conceptual model showed that strain-burst hazard can be related to geological boundaries and their exposure in excavation faces. The potential violence of these strain-burst failures can be quantified by changes in principal stress and plastic strain within the model.

Through numerical simulations factors affecting the severity of strain-burst failures are identified and quantified for use in a risk assessment. A methodology has been developed to evaluate strain-burst risk in active faces of underground excavations. The assessment is based on the feasibility of the seismic mechanism manifesting and its potential consequences, evaluated by four indices: 1) Pre-failure Damage Index $I_D$, correlated to the hardening behaviour assessing the rate of damage within the rock mass prior to peak strength; 2) Energy Release Index $I_E$, correlated to the brittleness index $I_{VFse}$ developed in the previous stage of this research characterising in-situ conditions leading to failure; 3) Frequency Index $I_F$, correlated to the size of damaged area indicating the potential re-occurrence of the event; and 4) Vulnerability Index $I_V$, correlated to the damage size and location identifying vulnerability of the personnel exposed to the hazard. From the calculated risk as $R_{SB} = I_D \times I_E \times I_F \times I_V$, precautionary measures can be implemented and the effectiveness of alternative designs can be examined. The technique is also robust to consider newly available data by site observations to re-evaluate the risk or to assist in micro-seismic data interpretation.
Publications during enrolment


I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

This thesis includes 3 original papers published in and one submitted to peer-reviewed journals. The core theme of the thesis is to develop a methodology to assess strain-burst failure mechanism and the associated risk for underground excavations. The ideas, development and writing up of all the papers in the thesis were the principal responsibility of myself, working within the Department of Civil Engineering under the supervision of Dr. Bre-Anne Sainsbury and Dr. Roger Dargaville.

In the case of Chapter 2 to 5, my contribution to the work involved the following:

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I have renumbered sections of published papers in order to generate a consistent presentation within the thesis.

Student signature: Ali Keneti  
Date: 31/08/2020

The undersigned hereby certify that the above declaration correctly reflects the nature and extent of the student’s and co-authors’ contributions to this work. In instances where I am not the responsible author I have consulted with the responsible author to agree on the respective contributions of the authors.

Main Supervisor signature: Roger Dargaville  
Date: 31/08/2020
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<th>Symbol</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>$\sigma_{\text{yield}}$</td>
<td>yield stress</td>
</tr>
<tr>
<td>$\varepsilon_{\text{yield}}$</td>
<td>yield strain</td>
</tr>
<tr>
<td>$\sigma_{\text{peak}}$</td>
<td>peak compressive stress</td>
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<td>$-\varepsilon_{\text{peak}}$</td>
<td>strain to reach peak tensile stress</td>
</tr>
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<td>$-\varepsilon_{\text{residual}}$</td>
<td>strain to reach residual tensile stress</td>
</tr>
<tr>
<td>DIST</td>
<td>damage initiation and spalling thresholds</td>
</tr>
<tr>
<td>$I_{Bs}$</td>
<td>stress-based brittleness index</td>
</tr>
<tr>
<td>$I_{Be}$</td>
<td>strain-based brittleness index</td>
</tr>
<tr>
<td>$I_{VFS}$</td>
<td>stress-based relative severity index of a violent failure</td>
</tr>
<tr>
<td>$I_{VFe}$</td>
<td>strain-based relative severity index of a violent failure</td>
</tr>
<tr>
<td>$I_{VFse}$</td>
<td>Combined stress-strain related severity index of a violent failure</td>
</tr>
<tr>
<td>$I_D$</td>
<td>Pre-failure damage index</td>
</tr>
<tr>
<td>$I_E$</td>
<td>Energy release index</td>
</tr>
<tr>
<td>$I_F$</td>
<td>Frequency index</td>
</tr>
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<td>$I_V$</td>
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<tr>
<td>$R_{SB}$</td>
<td>Strain-burst risk value</td>
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Chapter 1

Introduction

1.1 Problem statement

Design of underground excavations in rock may involve a complex interaction between parameters such as irregular geometries, complex geological setting (e.g. dyke, faults, sheet facies, etc.), varying stress regime, and non-linear constitutive behaviour of rock mass systems (i.e. intact rock substances discretised by discontinuities/joints). Depending on physical properties of a rock mass as well as its stress history, its failure around underground structures may occur violently or gradually. A violent failure can be characterised as a brittle failure (i.e. a sudden loss of strength following small or no plastic deformation) or a rockburst, when coupled with a rapid ejection that causes damage to the underground infrastructure as a result. A gradual or non-violent failure can be characterised as ductile behaviour (i.e. ability of the rock material to endure large deformation without a significant loss of strength).

The general term ‘rockburst’ is used to describe seismic events that generate sufficient energy to cause the violent failure of a rock mass (Ortlepp & Stacey, 1994). Several authors have proposed mechanisms for rockburst events (e.g. Ryder 1988; Gibowicz, 1990; Gibowicz & Kijko, 1994; Ortlepp & Stacey, 1994), which can be categorised into three mechanisms as: fault-slip, strain-burst, and pillar-burst events. The instantaneous nature of rockbursts (including fault-slip, strain-burst, and pillar-burst mechanisms) makes them a serious hazard affecting the safety, economics and productivity of underground mining operations (Blake & Hedley, 2009; Kaiser & Cai, 2012). As such, the identification of burst prone conditions and development of proactive measures to limit the impact of violent failure events is critical (Hedley, 1992; Singh, 1989; Whyatt et al., 2002).

The scope of this research is limited to strain-bursts since they represent a sub-set of seismic events that are often misunderstood (Lee et al., 2018). Strain-bursts relate to seismic source mechanisms associated with spalling and violent ejection. They have previously been related to the short-term elevated stresses around a new opening (Kaiser et al., 1996). Historically they have been undetected until encountered and have Richter Magnitudes 0.2-0.0 (Ortlepp, 2005). The lack of detection of such seismic mechanisms,
and their high frequency (Whyatt et al., 2002) poses a risk for personnel working in active areas. To allow engineers to recognise and better manage such situations, a better understanding of the underlying reasons for their occurrence and the establishment of a framework for managing their risk is required.

Due to the costs associated with installing dynamic support, rockburst control plans are optimised and only implemented where and when necessary (Kidybinski, 1981). However, in many cases, even when dynamic support is installed, the elimination of rockburst hazards is impossible. This is mainly due to the constraint that design of dynamic support is a case of an ‘indeterminate problem’ (i.e. there are no means of reliably estimating the demand or the capacity of ground support subjected to the dynamic loading of an incumbent seismic wave (Stacey, 2012). In particular, the effect of rock mass anisotropy on the seismic wave radiation pattern can be significant (Hildyard, 2007).

The heterogeneous nature and scale dependency of jointed rock masses have typically resulted in the use of a stochastic model of mining induced seismicity (Board, 1994). Coupled with the discrete nature of large-scale geological structures, understanding the violent failure of in situ rock masses around underground excavations is predominantly based upon large scale numerical simulations (e.g. Alber, 2013; Alber et al., 2009; Castro et al., 2009; Hofmann & Scheepers, 2011; Sainoki & Mitri, 2014ab, 2016, 2018; Sjöberg et al., 2012).

Together with numerical back-analysis of rockburst cases (i.e. after incident), seismic data analysis via event clustering (e.g. Hudyma, 2009) is the most common strategic risk management tool practised by the mining industry to manage seismic risk, by minimising both the frequency and consequences of seismic events (Feng et al., 2013; Wang & Kaunda, 2019; Whyatt et al., 2002). However, the success of such a technique is subject to the availability and quality of seismic data and an in-depth understanding of the in-situ and induced geomechanical conditions as well as the stress regime. Such information is not always available - particularly in the preliminarily stages of excavation development and/or design.

It is believed that if burst-prone areas can be identified in advance, precautionary measures may be implemented, and the effectiveness of alternative designs can be considered. Numerical simulations are employed for this purpose, in the initial stages of the excavation planning and geotechnical designs as a screening tool to identify such
potentially high-risk scenarios that warrant a more detailed quantitative analysis and perhaps would require dynamic support.

1.2 Objectives

Considering the critical importance of controlling the risk associated with violent failure of a rock mass around active faces of underground developments, the main questions are:

1. What are the major contributing factors to violent failure of rock masses around underground excavations (i.e. causes for rock-mass violent failure)?
2. How do the identified key parameters affect the loading condition and/or the response of the rock mass system (i.e. mechanisms of rock-mass violent failure)?
3. Where are the burst prone zones within the rock mass in-situ (rockburst potential)?

This research aims to examine above questions by:

1. Analysing factors controlling strain-burst phenomenon from which mechanisms leading to strain-burst events will be identified
2. Developing a technique to quantify susceptibility to strain-bursting, based on identified factors
3. Developing a technique to characterise risk of strain-bursts in underground excavations

Throughout investigation of the identified shortcomings in the current state of strain-burst hazard assessment and control, outcomes of this research will significantly assist in developing strategies to reduce the consequences of strain-bursts in mines and making them more economically feasible in the future.

1.2.1 Comprehensive review of rockbursts source mechanism in-situ

Documented case studies of rockbursts are numerous (Blake & Hedley 2009; Brown, 2012; Ortlepp, 2005). However, a comprehensive catalogue that can be used to describe and predict the conditions leading to the violent failure of rock masses is not available in the public domain. As a result of this, for significant published rockburst cases, the primary contributing factors that led to the violent failure need to be identified. This can be achieved through a compilation of critical information regarding the rock mass characteristics, mining method, stress conditions and reported potential causes, triggers or intensifiers for each of the violent failure case studies.
1.2.2 Illustrative study of micro-scale features of rockburst fractures

Fractures around excavations in hard, fine-grained, brittle rock sometimes display unique patterns from which an interpretation of the manner of failure/fracture propagation can be made. Hence, visual observation of the fracturing process and the damage caused by an event is required to facilitate the study and analysis of the complex processes involved in bursting ground. Although illustrative study of large-scale fractures has been conducted by researchers, the examination of surfaces of fragments resulting from rockburst have not been conducted at the micro-scale. Studying strain-burst fragments from an event may assist in revealing the true source mechanism; especially when there is no large-scale discontinuity present.

1.2.3 A clear and practical identification of brittleness

The use of rockburst risk indices based on brittleness is prevalent in mining geotechnical design (e.g. Andreev, 1995; Bishop, 1967; Hucka & Das, 1974). Through these empirical relationships, brittleness is a function of parameters such as formation of fines, compressive to tensile strength ratio, formation of cracks at indentation, etc.

Brittleness definitions may also include a commentary based on mineralogy, stress-strain behaviour (pre-and post-failure), elastic parameters and indentation behaviour (Kivi et al., 2018). The identification of input indices for each of these brittleness relationships requires sophisticated testing equipment (Rybacki et al., 2016). Furthermore, the laboratory tests may never be a true representation of the rock mass failure in situ due to complex unloading conditions around an excavation that are difficult to replicate in the laboratory (Martin, 1997). Therefore, a robust definition of brittleness based on the stress and strain path taken by the rock mass is needed to assist in completing a through strain-burst hazard assessment based on spatial variances in geometry, geology, and mechanical properties.

1.2.4 A robust hazard assessment methodology

The current empirical approaches of risk assessment are impractical during the early/conceptual design phase when micro-seismic data is not available. Therefore, a methodology is required to guide the estimation of strain-burst risk through the consideration of parameters that are known to contribute to the occurrence, or increase the consequences, of strain-burst events.
Chapter 1: Introduction

The ‘probability’ component of the risk matrix must be correlated to the likelihood of occurrence and/or reoccurrence of strain-burst events based on the evolving state of the rock mass. The ‘consequence’ part of the risk matrix needs to consider vulnerability. If these input parameters to the risk matrix can be quantitatively derived the comparative risk assessment between alternate design scenarios and mitigation strategies can be conducted. Such framework provides opportunity for incrementally more detailed information to be included as the design phase progresses.

1.3 Outputs of the study

Objectives of this research have been progressively achieved through completing three main stages: Background studies, experimental works and numerical analysis. The scientific contribution of this research is a thesis that includes following four peer reviewed articles:


The research documented by this Thesis has been divided into six chapters, including the four published articles, as follow:

Chapter 1 – Provides some background information of the problem being studied, summarises the motivations, objectives and methodologies for the research conducted, and outlines the structure of the Thesis documenting the research outputs.

Chapter 2 – Critically reviews published large-scale (drive scale) case study data to provide a comprehensive understanding of key contributing factors of a violent failure.
Chapter 3 – An illustrative study of surficial micro-scale features of strain-burst surface fragments to consider the complex processes involved in strain-bursting at another (smaller) scale to what is usually observed.

Chapter 4 – Outlines the development of an in-situ brittle failure index in order to assess relative severity of violent failures in the vicinity of underground structures. The index is implemented in a numerical model to demonstrate its use.

Chapter 5 – Outlines the development of a semi-quantitative risk assessment methodology that has been applied to the result of a numerical simulation results to demonstrate its application to the consideration of evolving strain-burst risk in active faces of underground excavations.

Chapter 6 – Provides a summary of the research contribution and recommendations for future studies associated with this topic.
Chapter 2

Literature Review

This chapter reviews published literature associated with rockburst case-studies. The review identifies in-situ conditions leading to rockburst events. Outcomes of this critical review provide the required background for the development and validation of the quantitative techniques discussed herein.

Main contributing factors to rockburst events highlighted in this chapter are:

- Loading conditions (including high and/or adversely re-oriented stresses by structures; geometry of the excavation; and rate and direction of the excavation advance)
- Rock mass properties (mineralogical properties; contrasting geomechanical properties; and geological intensifiers affecting fracturing behaviour)

Contents of this chapter has been copied from a published article in ‘Engineering Geology’ journal, which can be accessed at: https://doi.org/10.1016/j.enggeo.2018.10.005

2.1 Introduction

The term ‘rockburst’ is applied to the damage that occurs as a result of, or which is directly associated with, a seismic event that generates sufficient energy to cause violent failure of the rock mass. Rockbursts are either mining-induced (e.g. source of energy release and damage are co-incident) or dynamically-induced (damage caused by remote seismic activity). Rockbursts are most common in deep, hard rock mines (Blake & Hedley 2009) and represent one of the most serious mining hazards affecting the safety, economics and productivity of these operations. The violent, unpredictable nature of rockbursts makes them remarkably challenging to mitigate and/or control. Understanding their source mechanism/s is critical in developing prevention tactics and effective support systems (Kaiser & Cai 2012).

In general, the problem of mine seismicity is stochastic, due to the variability in distribution of geological structures and heterogeneous nature of rock masses (Board, 1994). As a result of this variability, relative (rather than exact) assessments of rock mass behaviour is considered more practical for seismic hazard assessment. As a result of this, parametric studies via numerical simulations can provide valuable insights into rock mass
and discontinuity response in deep and high stress conditions. The review of case study data provides constraints for the numerical simulation of seismic events.

2.2 Definition of a ‘rockburst’

For most practical rock engineering purposes, stress versus strength relationships around underground openings and the various modes of failure are reasonably well-understood and predictable (Martin et al., 1999). Depending on the physical properties of the rock mass as well as the loading conditions, failure may occur violently or gradually. Violent failure can be characterised as a brittle failure (i.e. a sudden loss of strength following little or no plastic deformation post-failure) or a rockburst when coupled with a rapid ejection. A gradual or non-violent failure can be characterised by spalling (i.e. non-violent brittle failure) or ductile behaviour (i.e. ability of the rock material to endure large inelastic deformation post-failure without a significant loss of strength, e.g. squeezing ground).

A number of authors have proposed mechanisms for mining-induced seismic events (e.g. Gibowicz, 1990; Ortlepp & Stacey 1994; Ryder, 1988). Gibowicz (1990) offers a simple distinction:

- Those associated with the formation of fractures at excavation faces or pillars. This seismicity is associated with the crushing of highly stressed volumes of rock which is often referred to as a strain-burst. For these instances, the seismic source and damage locations are most likely co-incident and limited to the vicinity of the excavation faces. Occurrences are strongly influenced by the local shape of, and stress concentration around the excavation.

- Those associated with movement on major geological discontinuities. This seismicity is related to the unstable slip or rupture along pre-existing weakness planes in the rock mass. They are referred to as fault-slip burst (Ryder, 1987). These mechanisms represent shear failure along an existing surface, when the shear stress exceeds the normal stress or clamping force acting on the structure.

- A transition case, referred to as face or pillar burst, is also possible. In this case, localized slip surfaces form larger shear bands (perhaps along alignments of induced extension fracturing) which intersect in a conjugate manner ahead of an underground excavation or traverse, in hourglass fashion, through support pillars (Ortlepp, 1997).
Ortlepp (1997) offered the following simple definition of a rockburst that has been used to identify case study data used herein ‘… a seismic event which causes violent and significant damage to the tunnel or the excavations of a mine,’ and added that, ‘Such a definition poses no constraints on the magnitude or nature of the seismic event and is broad enough to encompass the notion of a dichotomy that recognizes the possibility of distinctly separate and different, but necessarily related, mechanisms for the seismic source and for the damage phenomenon’.

2.3 Case study database

Documented case studies of rockbursts are numerous in South Africa, East Europe, North and South America, China and Australia (Blake & Hedley, 2009; Brown, 2012; Ortlepp, 2005). However, even with such extensive documented case studies, a robust methodology to predict the location, timing and severity of events is yet to be achieved and/or agreed upon by the engineering community. Recent studies have been focusing on hypothetical models that add more complications to the definition of brittleness of intact rock samples with a minimal practical field application in deep and high stress mining (Brown, 2012).

For significant cases, an attempt has been made to identify the primary contributing factors that led to the violent failure. Table 2-1 provides a summary of selected case studies that includes critical information regarding the rock mass characteristics, mining method, stress conditions and the potential causes, triggers or intensifiers for the violent failure. For each of the cases summarised, the contributing factors were considered to be correctly identified (e.g. an independent review of the geomechanical conditions were not undertaken).

2.4 Causes of violent rock mass failure

Based on the case study data summarised in Table 2-1, six contributing factors to the seismic events described have been identified. The contributing factors include stress (direction and magnitude), excavation geometry, excavation rate and advance direction, mineralogical properties, contrasting geomechanical properties and geological intensifiers (e.g. dykes).

A detailed discussion on each key driver is provided below.
Table 2-1: Summary of violent rock mass failure case studies in underground excavations (Barrett & Player, 2002; Blake & Hedley, 2009; Charlewood, 1964; Delgado & Mercer, 2006; Hedley, 1992; Heal, 2010; Li et al., 2002; Mikula & Lee, 2002; Morissette et al., 2014; Morrison, 1989; Scott et al., 1997; Simser et al., 2002; Swanson, 1992; Sweby, 2007; Turner & Player, 2000; Whyatt et al., 2002; Whyatt et al., 1995; Williams et al., 1992)

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<tr>
<th>Site</th>
<th>Summary of Rock-bursting Cases</th>
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| 1. Long Shaft – Australia (after Sweby, 2007) | **Geological/Geotechnical Conditions:** Tabular and steep orebody. High horizontal stress field 2. \( \sigma_1 : \sigma_3 \). The rock mass is a complex of units with contrasting strength. Foot-wall (meta-basalt): \( \sigma_c = 275 \) MPa; orebody (massive sulphide): \( \sigma_c = 140 \) MPa; hanging-wall (basalt, antigorite, talc-magnesite/chlorite ultramafic): \( \sigma_c = 75 \) MPa - 250 MPa; dykes (felsic porphyry): \( \sigma_c = 240 \) MPa.  
**Mining Method/Geometry:** Mining commenced with conventional hand-held cut and fill methods. Lower levels have been extracted using mechanised stoping and up-hole benching of crown pillar remnants. This method has concentrated stress in diminishing porphyry pillars, and their subsequent foundation failure with significant rock-bursting events.  
**Contributing Factors:** Seismicity observed along the basalt/porphyry contacts due to the strength difference (75 MPa vs 240 MPa). Strain-bursting observed during development through porphyry since it is stronger (240 MPa) than the orebody (140 MPa). The porphyry is generally left in pillars since it holds no grade.  
**Rockburst Event Type:** Fault-slip; strain-burst; pillar burst  
**Hazard Control:** Effective dynamic support including mesh reinforced shotcrete, yielding tendon bolts, fibre (steel) reinforced shotcrete, friction bolts, mesh and mesh straps. |
| 2. Junction Mine – Australia (after Li et al., 2002; Heal, 2010) | **Geological/Geotechnical Conditions:** The geological environment is complex and includes development through faults, shear zones, dolerite dykes and porphyry intrusions. Mineralisation occurs in shear zones that are hosted in a gabbro that has been intruded into volcanoclastic and epiclastic sediments. High deviatoric stresses exist at a ratio of 2.5 - 3.5 \( \sigma_1 : \sigma_3 \). Modulus ranges from 57 GPa for the Porphyry up to 93 GPa for the Dolerites.  
**Mining Method/Geometry:** The initial mining method included long-hole retreat to a central pillar that resulted in a high stress concentration in the pillars. As a result of this, the pillar size was increased, the strike length of stopes was reduced and the retreat sequence was changed to eliminate the shrinking pillar, progressing from one end of the orebody to the other.  
**Contributing Factors:** Seismicity observed related to elevated stresses, and induced shearing along major structures and geological contacts due to the contrasting properties.  
**Rockburst Event Type:** Fault-slip; strain-burst; pillar burst  
**Hazard Control:** Effective dynamic support system included friction bolts, sliding cables, mesh, straps, fibrecrete and yielding arches. |
Table 2-1: Continued…

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<th>Site</th>
<th>Summary of Rock-bursting Cases</th>
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| 3. Mount Charlotte – Australia (after Mikula & Lee, 2002; Heal, 2010) | **Geological/Geotechnical Conditions:** Several steeply dipping orebodies hosted in a blocky, stiff and strong dolerite (Modulus = 65 GPa). A high and deviatoric (3:1) stress field exists with the major principal stress striking sub-parallel to the orebody. Typical magnitudes at a depth of 1 km are \( \sigma_1 = 75 \text{ MPa}, \sigma_2 = 40 \text{ MPa} \) and \( \sigma_3 = 25 \text{ MPa} \). Two major reverse faults bound the orebody.  
**Mining Method/Geometry:** The dominant mining method has been open stopping, with mass blasting of crown and rib pillars.  
**Contributing Factors:** The two major reverse faults are loaded close to their shear strength. Small reductions in normal or increases in shear stress along these structures (e.g. blasting activities) initiate shearing and fault-slip activity.  
**Rockburst Event Type:** Fault-slip; pillar burst  
**Hazard Control:** Seismic risk is minimised through backfilling, avoiding rib blasts, distressing the rock by tight slot blasting, pre-conditioning, ensuring low rib stiffness, promoting early shearing and avoiding diminishing pillars. |
| 4. Big Bell – Australia (after Heal, 2010; Barrett & Player, 2002; Turner & Player, 2000) | **Geological/Geotechnical Conditions:** Contrasting geomechanical properties exist between the ductile orebody and the massive, brittle foot-wall amphibolite. High and deviatoric stress magnitudes are influenced by foliations in the rock mass.  
**Mining Method/Geometry:** A longitudinal sub-level caving method with a top-down approach. A wider, central 350 m section is mined from a central slot in the orebody outwards. The extremities are developed on ore and retreated back onto a pillar (e.g. a limit retreat).  
**Contributing Factors:** Seismicity is generated by slip on dyke contacts and/or faults. Seismic events also involve shearing along foliations, pillar failure and face bursting.  
**Rockburst Event Type:** Fault-slip; strain-burst; pillar burst  
**Hazard Control:** Yielding tendon bolts (cone bolts) and heavy welded mesh. Sacrificial meshing of the face with split sets to safeguard personnel during scaling, drilling, and charging operations. De-stress blasting ahead of the development face undertaken in the footwall and the decline. Two 4.2m holes are drilled up and out at 45° from the top corners of the drives. Each hole is charged with 700mm packaged emulsion, initiated with the first hole in the cut. |
Footwall (meta-basalt) \( \sigma_c = 160 \text{ MPa} \); orebody (massive sulphide) \( \sigma_c = 55 \text{ MPa} \); hanging-wall (talc-magnesite ultramafic) \( \sigma_c = 30 \text{ MPa} \).  
**Mining Method/Geometry:** A mechanised retreat mining method.  
**Contributing Factors:** Significant fault-slip occurs when mining approaches crown pillars. Mined areas result in stress concentrations in the adjacent rock which produces instability and seismic activity.  
**Rockburst Event Type:** Fault-slip; pillar burst  
**Hazard Control:** Fibre-crete and friction bolts with cable-bolts and mesh over the top of the fibre-crete. Cemented paste backfills used to reduce instability.  
**Figure:** Typical rockburst failure mechanism  
**Figure:** Rockburst caused by a major structure |
Table 2-1: Continued...

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<th>Site</th>
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| 6. Strzelecki – Australia (after Heal, 2010) | **Geological/Geotechnical Conditions:** Narrow vein mineralisation within a steeply dipping shear zone. Shear zones occur along geologic contacts and are less than 1 m wide and greater than 500 m length. They are truncated by faults. Host rock types include greenstones, dolerites, intermediate volcanic, felsic sediments and intrusives.  
**Mining Method/Geometry:** Underhand long-hole, benching starting at the extremities retreating towards a central pillar.  
**Contributing Factors:** The central retreat sequence resulted in a highly stressed diminishing pillar near the point of stope access.  
**Rockburst Event Type:** Fault- Slip; strain-burst  
**Hazard Control:** mining sequence altered to a top-down continuous retreat with a 45-degree lead-lag geometry. Effective dynamic support included yielding tendon bolts (cone bolts) with spacing less than 1m, friction bolts and mesh. | ![Image](image1.png) **Figure:** A seismically active major structure |
| 7. Black Swan – Australia (after Heal, 2010) | **Geological/Geotechnical Conditions:** Nickel sulphide mineralisation is bound by a broad sequence of felsic lavas and volcanic sediments. Mineralisation occurs on, or adjacent to, a steeply dipping ultramafic footwall contact.  
**Mining Method/Geometry:** Mechanised cut-and-fill that later changed to down-hole benching and filling.  
**Contributing Factors:** Seismic events cluster in remnant areas that are characterised by stiff felsic dykes and porphyry intrusions, shear zones, lithological contacts and the large-scale Feral Fault. The presence of structure has contributed to most seismic events.  
**Rockburst Event Type:** Fault-Slip; pillar burst  
**Hazard Control:** An ineffective support system that included friction bolts at a 1.2-1.5m spacing and mesh was installed. The mesh was observed to be opened up at bursting sites at the overlap between pieces. | ![Image](image2.png) **Figure:** Rockburst at the contact of hanging-wall and dyke |
| 8. Kanowna Belle – Australia (after Heal, 2010) | **Geological/Geotechnical Conditions:** Mineralisation is hosted by sedimentary volcanoclastic and conglomerates that are separated by the Fitzroy Fault. Several Felsic dykes intersect the orebody.  
**Mining Method/Geometry:** Mining is completed using mechanised, bulk mining methods. For ore widths greater than 10m, long-hole open stoping with a high strength paste fill is used.  
**Contributing Factors:** The presence of seismically active major structures and geological contacts feature in all seismic events at the site.  
**Rockburst Event Type:** Fault-slip; strain-burst  
**Hazard Control:** Effective ground support systems included a tight pattern of friction bolts, CT bolts, cables, mesh and fibre-crete. | ![Image](image3.png) **Figure:** Violent failure of a stiff intrusive due to movement on a fault |
| 9. Broken Hill – Australia (after Heal, 2010) | **Geological/Geotechnical Conditions:** Lead-zinc mineralization is shear bound and hosted in a deformed and altered meta-sedimentary sequence.  
**Mining Method/Geometry:** Long-hole open stoping of remnant areas  
**Contributing Factors:** Seismicity is controlled by the geometry of excavations with stress concentrated in abutments and pillars. Seismic activity is strongly controlled by active geological structures mobilised by mining induced stresses.  
**Rockburst Event Type:** Fault-Slip; strain-burst  
**Rockburst Control:** Ineffective corroded support system (friction bolts and mesh) was unable to contain largest 3.1 Magnitude event. | ![Image](image4.png) **Figure:** Strain-burst at an intersection |
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<td>10. Perseverance – Australia (after Heal, 2010)</td>
<td><strong>Geological/Geotechnical Conditions:</strong> Ultramafic hosted disseminated nickel orebody that is prone to squeezing. <strong>Minning Method/Geometry:</strong> Sublevel caving methods however, a narrow vein ore zone (in the upper levels) has been mined using long-hole open stoping. <strong>Contributing Factors:</strong> The hanging-wall comprises stiff felsic volcanic and metasediments, which are prone to mining induced seismicity – as opposed to the squeezing ultramafics. Intact rock fracturing and shearing on geological structures is driven by a highly stressed abutment zone. Localized strain-bursting within the felsic domain are the main sources of violent rock failure. <strong>Rockburst Event Type:</strong> Fault-slip; strain-burst <strong>Hazard Control:</strong> Effective ground support included resin bolts with a tighter spacing replacing friction bolts in burst prone geology.</td>
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<td>11. Darlot – Australia (after Heal, 2010)</td>
<td><strong>Geological/Geotechnical Conditions:</strong> Shallow dipping vein mineralisation, bounded between faults, hosted within a stiff, magnetic dolerite domain. Several intersecting major structures cross the orebody. High stress gradients at shallow depths are observed ($\sigma_1 \approx 0.08-0.14\sigma_3$). <strong>Minning Method/Geometry:</strong> Conventional backfilled long-hole open stoping with primary stopes filled with cemented aggregate fill and secondary stopes with waste rock. <strong>Contributing Factors:</strong> Rockburst events concentrated on mine-scale faults, large span intersections (four-way), and abutments of large open stopes and zones of converging mining fronts. <strong>Rockburst Event Type:</strong> Fault-slip; strain-burst <strong>Hazard Control:</strong> Inadequate ground support system at the time of the events that included mesh, 6m cables, friction bolts and rebar.</td>
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<td>12. Macassa – Canada (after Blake &amp; Heal, 2009)</td>
<td><strong>Geological/Geotechnical Conditions:</strong> Mineralisation occurs in fault gouge, quartz veins and intensely fractured zones. It is hosted within volcanic, sedimentary and intrusive lithology units. A parallel series of thrust structures dipping at 70° to 75° that vary in width (0.6 m to 18 m) intersect the orebody. <strong>Minning Method/Geometry:</strong> Mining commenced via shrinkage methods prior to converting to overhand cut-and-fill and long-hole mining with foot-wall access where possible. <strong>Contributing Factors:</strong> Seismicity is observed to be affected by increasing stress on sill pillars as the mining front advances under a mined-out level, causing slippage along faults located within the sill pillars. <strong>Rockburst Event Type:</strong> Fault-slip; pillar burst <strong>Hazard Control:</strong> Modified mining method/geometry to decrease stress concentration in pillars; De-stress blasting practised; re-entry times observed.</td>
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<td>13. Teck-Hughes – Canada (after Blake &amp; Heal, 2009; Chantwood, 1964)</td>
<td><strong>Geological/Geotechnical Conditions:</strong> Syenite porphyry rock mass with tuff inclusions. No major geological structures observed. <strong>Minning Method/Geometry:</strong> Shrinkage stoping with sill pillars recovered by vertical slices or in a rill configuration. <strong>Contributing Factors:</strong> Under-sized shaft pillars, overloaded sill pillars and areas within the brittle tuff experienced seismic events. <strong>Rockburst Event Type:</strong> Pillow-burst; strain-burst <strong>Hazard Control:</strong> Changing geometry by relocating the shaft to the footwall; backfilled voids.</td>
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<th>Site</th>
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| 14. Brunswick – Canada (after Blake & Hedley, 2009; Simser et al., 2001) | **Geological/Geotechnical Conditions:** Sub-parallel lenses of massive sulphide hosted within metamorphosed volcanic sediments and tuffs. The footwall and hanging wall are more competent (but less stiff and weaker) than the orebody that has $\sigma_c = 210$ MPa, $\sigma_1 = 1.9 \sigma_c$ and is oriented sub-horizontal to the strike of the orebody. Orientation of the Main Fault is parallel to the principal stress direction.  
**Mining Method/Geometry:** A combination of primary-secondary open staking, mechanized cut-and-fill and overhand cut-and-fill mining prior to adopting a pyramidal pillar-less mining front.  
**Contributing Factors:** High-stress concentrations in remnant pillars, high extraction ratio, large stiffness and brittleness contrast between units and slip along structures.  
**Rockburst Event Type:** Fault-Slip; strain-burst; pillar burst  
**Hazard Control:** Changed mining method to remove pillars; stopes backfilled with paste; effective dynamic support included shotcrete followed by mesh, straps, and cone bolts at 1 m spacing. |
| 15. Lake Shore – Canada (after Blake & Hedley, 2009; Charlewood, 1964) | **Geological/Geotechnical Conditions:** Narrow mineralised veins associated with a fault system that are intersected by several diagonal structures.  
**Mining Method/Geometry:** Horizontal cut-and-fill mining overlies a v-shaped long-wall configuration.  
**Contributing Factors:** Stress concentrations at crosscut/shaft interaction locations, highly stressed remnant pillars, slippage along geological structures, rapid draw-down of ore in shrinkage stopes, and inadequate sill pillars at depth.  
**Rockburst Event Type:** Fault-Slip; strain-burst; pillar burst  
**Hazard Control:** Minimised pillars; concrete was poured in the first and last lift of a level; effective dynamic support system included steel rings and cables with lagging, in a laced configuration. |
| 16. Wright – Hargreaves – Canada (after Blake & Hedley, 2009) | **Geological/Geotechnical Conditions:** Mineralisation hosted in syenite porphyry with inclusions of conglomerate, tuff, and a granite porphyry. Tuff that is stronger and more brittle than the other domains forms the footwall contact. The ore zone is intersected by sub-horizontal strike faults and steeply dipping cross faults.  
**Mining Method/Geometry:** Shrinkage stoping. Only the stopes near the shafts backfilled. In most cases, stopes were allowed to fail and choke themselves off. Observations suggest this failure increased the original stope size of the stope by a factor of eight.  
**Contributing Factors:** Violent fracturing occurred in undersized shaft pillars due to increasing stress concentrations.  
**Rockburst Event Type:** Pillar burst  
**Hazard Control:** The shaft was relocated to the footwall; back-filling all of stopes was required to minimise failure and reduce mining induced stresses |
| 17. Falconbridge No.5 Shaft – Canada (after Blake & Hedley, 2009; Heal, 2010) | **Geological/Geotechnical Conditions:** Steeply dipping nickel-copper tabular orebody, intersected by faults. The Main Fault (characterized by gouge material up to 1 m thick) is located at the contact between geological domains. The footwall is a Felsic sequence of gneiss and granite. The hanging-wall is Norite. The hanging-wall and footwall are strong and brittle rock compared to the massive sulphide orebody.  
**Mining Method/Geometry:** Upper levels are extracted with shrinkage methods but changed to square set mining due to poor ground conditions. Longitudinal cut-and-fill techniques have been used at depth.  
**Contributing Factors:** Slippage along faults, mining of sill and remnant pillars, and stopes adjacent to faults have contributed to seismic events.  
**Rockburst Event Type:** Fault-slip; pillar burst  
**Hazard Control:** de-stress blasting; Ineffective ground support included rebar and mesh. |
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<td>18.</td>
<td>Geological/Geotechnical Conditions: A narrow (2m-5m) sub-horizontal uranium orebody with massive quartzite forms the footwall and hanging-wall. Mining Method/Geometry: Pillar mining methods. Contributing Factors: Pillars are oriented at 45° to the mining front. This results in a reduced cross-sectional area for the stress to pass through, resulting in a chain reaction of violent pillar failure. Rockburst Event Type: Pillar burst Hazard Control: Seismic activity decreased substantially when the hanging wall failed through to surface. Stresses were driven below the mining horizon.</td>
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<td>19.</td>
<td>Geological/Geotechnical Conditions: Sulphide-nickel orebody that is extensively intersected by dykes and shear zones. Granite/gabbro footwall, norite hanging wall. Mining Method/Geometry: Top-down and centre-out mining method was designed to transfer stress to the abutments. Contributing Factors: Localised mining induced stress concentrations along shear zones has contributed to seismic activity. Rockburst Event Type: Fault-slip Hazard Control: Modified mine design to a pillar-less top-down, centre-out mining geometry to push seismicity beyond the working face; Paste backfill was introduced to replace loose rockfill and ensure tight filling.</td>
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<td>20.</td>
<td>Geological/Geotechnical Conditions: Quartz carbonate ore hosted within a sequence of folded andesite. Steep dipping gold veins offset by minor faults. Shear zones observed parallel to the ore. Mining Method/Geometry: Sub-level, long-hole. Contributing Factors: Recent rockburst events have been associated with contrasting stiffness between the massive rhyolite and a weaker basaltic unit combined with a distorted stress field at a faulted zone. Sill pillar recovery resulted in a series of chain-reaction rockburst events Rockburst Event Type: Strain-burst; pillar burst Hazard Control: Leaving larger sill pillars in cut-and-fill stopes and recovering them by long-hole methods.</td>
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<td>21.</td>
<td>Geological/Geotechnical Conditions: Nickel-copper mineralization Mining Method/Geometry: Initially mined by shrink stoping and then vertical retreat mining. Primary stopes filled with cemented rock fill and the secondary stopes with loose rockfill. Contributing Factors: Pillars intersected by stiffer dykes are the source of most seismic events. Rockburst Event Type: Strain-burst; Pillar Burst Hazard Control: Pillars were eliminated in the mine design.</td>
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<tr>
<td>22.</td>
<td>Geological/Geotechnical Conditions: Massive sulphide-nickel orebody hosted in a stiff gneiss. The footwall is intruded by a moderately dipping olivine diabase dyke. Mining Method/Geometry: Overhand post-pillar, cut-and-fill. Contributing Factors: A combination of high in-situ stresses (locked in at the time of dyke intrusion) and the additional mining-induced stress has been the cause for rock violent failure triggered by blasting. Rockburst Event Type: Fault-slip; Strain-burst Hazard Control: Effective ground support includes grouted rebars, mechanical bolts, wire mesh, and 12-foot-long Super swellex bolts. Standard reinforcement of slot entries was increased utilizing strand-loc and fibre-reinforced shotcrete. In wide sections along stopes shotcrete pillars are used for temporary support. De-stress blasting.</td>
</tr>
</tbody>
</table>

Figure: A rockburst in the vicinity of a dyke

Figure: Differential convergence resulting faults slip burst
<table>
<thead>
<tr>
<th>Site</th>
<th>Geological/Geotechnical Conditions</th>
<th>Mining Method/Geometry</th>
<th>Contributing Factors</th>
<th>Hazard Control</th>
<th>Rockburst Event Type</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>23. Lucky Friday – USA (after Blake &amp; Hedley, 2009; Williams et al., 2002)</td>
<td>Steeply dipping silver-lead vein mineralisation intersected by three major faults, ( \sigma_1: \sigma_3 = 2:1 ).</td>
<td>An initial flat-backed, overhand, cut-and-fill mining method was altered to an underhand cut-and-fill, longwall geometry to improve safety.</td>
<td>Remnant pillar mining that approached a fault contributed to seismic events. These events intensified when mining intersected the hard quartzites and argillitic. The largest bursts occurred in the hanging-wall when faults displayed strike-slip movement towards the vein and in the footwall where shear movement along bedding planes and slippage along the mineralised vein occurred.</td>
<td>Changed mining method; pillar de-stressing; paste backfilling; effective dynamic support included friction bolts and chain link mesh, resin bolts, horizontal rows of cable lacing and 50 mm of steel-fibre-reinforced shotcrete.</td>
<td>Fault-slip; strain-burst</td>
<td>Site 26. Star – USA (after Blake &amp; Hedley, 2009; Whyatt et al., 1995)</td>
</tr>
<tr>
<td>24. Galena – USA (after Blake &amp; Hedley, 2009; Swanson, 1992)</td>
<td>Steeply dipping silver-lead vein mineralisation occurs along a shear zone between two major faults hosted in a stiff quartzite. Strike of the sub-vertical bedding is parallel to the shear zone.</td>
<td>The mining method was initially overhand cut-and-fill, then a reverse stair-stepped geometry was implemented in order to isolate pillars.</td>
<td>A combination of mining geometry (e.g. stopes oriented perpendicular to the direction of maximum principal stress) and geological factors including the hard, brittle quartzite and high-stress conditions have contributed to seismic events.</td>
<td>Changed mining direction and sequencing; decreasing the extraction rate; stress shadowing by advancing stopes in a lower stress environment.</td>
<td>Strain-burst</td>
<td>Site 25. Sunshine – USA (after Blake &amp; Hedley, 1992; Scott et al., 1997)</td>
</tr>
</tbody>
</table>
| 26. Star – USA (after Blake & Hedley, 2009; Whyatt et al., 1995) | The mineralised zone is less competent than the brittle quartzites, argillites, and argillaceous quartzite host rock. Mineralisation intersects the sub-vertical bedding at angles varying from 30° to 60°. Mineralisation is also intersected by dykes. | The mining method includes a centre-lead stope geometry that leaves small pillars. | A waste pillar left in a mined-out area confined by high fill pressure results in a delayed bursting response. | de-stressing the entire stope block prior to mining. | Pillar burst; strain-burst | **Figure:** Raise bore breakouts | **Figure:** Relationship of induced stress to structures slip movement.
2.4.1 Unfavourable stress conditions

Many of the bursting case studies presented in Table 2-1 can be characterised by unfavourable stress states imposed on the rock mass fabric and/or along pre-existing discontinuities. Regional in-situ stresses (i.e. virgin stresses affected by the local geology and major structures) together with the geometry (including shape and size), rate, and direction of the excavation advance control the redistribution and magnitude of the stresses around underground openings as it progresses (Hudson & Harrison, 1997).

(1) Principal stress magnitude and orientation in relation to pre-existing structure

High in situ stresses are a feature of most mining areas, with the major and intermediate principal stresses oriented sub-horizontal and the minor principal stress vertical (Lee et al., 2001). As presented in Table 2-1, the ratio between the major and minor principal stresses can vary from 2:1 in the Canadian Shield up to 3.5:1 at the Junction Mine in Australia.

A relationship between bursting and the presence of geological features (e.g. dykes, geological contacts) is evident throughout the case studies presented in Table 2-1 (Case Study 22 – Strathcona, Case Study 2 - Junction Mine, and Case Study 24 - Galena Mine). The geological features (usually that have contrasting properties) result in elevated stress concentrations and burst-prone behaviour when intersected by excavations (Blake & Hedley, 2009).

Figure 2-1 shows an example of the effect of stiffness on the re-orientation of the in-situ stress state. An open discontinuity (Case A) re-orientates the major principal stress parallel to its surface and drops the minor principal stress to zero in the perpendicular direction. In Case B with contrasting stiffnesses, e.g. an infinitely stiff infill, the major principal stress is drawn in perpendicular to the discontinuity and the minor principal stress becomes parallel to its surface. An intermediate state for the stresses is expected where a soft rock is filled with a stiffer material (Case C).

If structures are not parallel (Figure 2-2) to the excavation, re-orientation of the mining induced stress field parallel to the fabric increases the shear stress along them leading to a seismic event (Durrheim et al., 1998). Seismicity at the Lucky Friday Mine (Case Study 23, Table 2-1) is observed to be co-incident with the bedding structure and known major faults. The various structures contributing to wall rock movements, (shown in Figure 2-3)
provide similarities in rockburst sources and mechanisms with documented case studies from South African gold mines.

Figure 2-1: Effect of discontinuities on the proximate state of stress (after Hudson & Harrison, 1997)

A: Open discontinuity
B: Effectively rigid infills
C: Soft rock with stiffer infills

Figure 2-2: Shear slip derived by an adverse stress trajectory (after Durrheim et al., 1998)
Figure 2-3: Comparison of structures at Lucky Friday Mine, left, and Witwatersrand Gold Reef, right (after Whi
te and Whyatt, 1999)

In each case, seismicity is located in the abutment of the advancing mining front as it passes through areas of fracture localisation resulting in fault-slip movement. The high and deviatoric stress magnitudes, and their orientation relative to rock mass fabric have been shown to have a significant effect on rock-bursting behaviour (e.g. Mount Charlotte Mine, Case Study 3, Table 2-1) through inducing fault-slip events.

(2) **Excavation geometry**

When the size of an opening is large or when multiple openings are created close to each other, the likelihood of a rockburst occurring is greatly increased. This is a result of the reduction in loading system stiffness (Kaiser & Cai, 2012). Inducing the redistribution of the maximum principal stress over a shorter footprint axis will promote higher stress concentrations than when the maximum principal stress is distributed over a larger excavation footprint. As observed at the Big Bell Mine (Case Study 4, Table 2-1) stopes oriented perpendicular to the direction of maximum principal stress are more prone to rockbursts than stopes oriented parallel to this direction.

The most effective approach to minimize stress concentrations around excavations is to implement design geometries and excavation sequences that limit the creation of pillars (Galena Mine, Case 24, Table 2-1) and that progressively transfer stress to hanging-wall
and foot-wall abutments (e.g. top-down, centre-out mining geometry, Creighton Mine, Case 19, Table 2-1).

In many North American mines (Brunswick Mine, Case 14, and Falconbridge Mine, Case 17, Table 2-1), cut-and-fill techniques are employed to minimize the geometry change (Blake & Hedley, 2009). High stress concentrations around the excavation can also be prevented by designing an opening that approximates the stable natural profile (e.g. Figure 2-4).

Figure 2-4: Design and actual profile of Durban Roodepoort Deep Mine (after Ortlepp, 1997)

(3) Excavation rate and direction

As an excavation is advanced in highly stressed ground, a fracture (yield) zone is developed in advance of the face. While most of this damage occurs within hours of the blast, the fracture zone may continue to migrate. The depth of the fracture zone depends on the face dimensions and the magnitude of the induced stress. A rapid face advance does not allow time for the fracture zone to stabilise and, as a result, increases the rockburst potential as observed at the Campbell Mine (Case 20, Table 2-1). The occurrence of rockbursts in these instances (e.g. Sunshine Mine, Case 25, Table 2-1) can be mitigated by limiting the volume of rock affected in any one blast and/or increasing the time between blasts.

In addition to excavation rate, direction of excavation face and stopes sequencing could be critical in inducing stresses around openings. In this regard, mining of the remnant between approaching long-wall faces, parallel or multiple veins (Galena Mine, Case Study 24, Table 2-1), as well as mining through or along certain structural features such as dykes, faults, or dominant joint sets (Lucky Friday Mine, Case 23, Table 2-1) are
inherently hazardous. Where veins branch, stoping should begin at the intersection and mine away from it. Intersecting veins when sequenced to be mined separately can significantly reduce the rock-bursting hazard (Lake Shore Mine, Case 15, Table 2-1). Numerical modelling studies of the Falconbridge No. 5 Shaft Mine (Case Study 17, Table 2-1) indicated that retreating away from a fault results in a succession of small slippages on the fault and relatively low releases of seismic energy; whereas, advancing towards a fault is characterized by a major seismic event (Blake & Hedley, 2009).

2.4.2 Unfavourable rock mass characteristics

The geomechanical properties of a rock mass determine specific behaviour regarding storing and releasing excess strain energy. Energy release can occur violently, in the form of rockbursts, and non-violently, dissipating through the fracturing and squeezing of the near-field rock (Eberhardt et al., 1997). The geomechanical properties of a rock mass are primarily influenced by the mineralogical composition of the intact rock blocks and the fracture network.

(1) Mineralogical properties

Knowledge of the mineralogical properties of a rock is an essential requirement for the determination of rockburst proneness. The main properties which are known to associate with the occurrence of rockbursts are strength, stiffness, and brittleness. Strong, brittle and stiff rocks that are highly stressed possess significant potential for bursting (Blake & Hedley, 2009).

The definition of brittleness has not yet been standardized. However, in general, brittle rock masses share similar characteristics; fracture failure, formation of fines, higher ratio of compressive to tensile strength, higher angle of internal friction, formation of cracks in indentation (Hucka & Das, 1974).

The use of rockburst liability indices to identify the burst proneness of rocks is prevalent in mining geotechnical design. There is no single burst-proneness indicator that can be applied to each and every rockburst cases (Singh, 1989).

Table 2-2 summarizes the current published rockburst indices based on intact rock properties. It is clear from Table 2-2 that unification of these approaches is required to ensure practicality and robustness.
Table 2-2: Indicators of violent failure potential from Intact Rock Properties (Aubertin & Gill, 1988; Kidybinski, 1981; Mitri, 1996; Mitri et al., 1999; Singh, 1989; Stewarski, 1987)

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Classification</th>
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</thead>
<tbody>
<tr>
<td><strong>Strain Energy Storage Index ((W_{ET}))</strong></td>
<td></td>
</tr>
<tr>
<td>(W_{ET} \geq 5.0)</td>
<td>high potential for violent failure</td>
</tr>
<tr>
<td>(2 \leq W_{ET} &lt; 5.0)</td>
<td>low potential for violent failure</td>
</tr>
<tr>
<td>(W_{ET} &lt; 2)</td>
<td>no potential for violent failure</td>
</tr>
<tr>
<td><strong>Brittleness Index Modified (BIM)</strong></td>
<td></td>
</tr>
<tr>
<td>(1.0 \leq BIM &lt; 1.2)</td>
<td>high potential for violent failure</td>
</tr>
<tr>
<td>(1.2 \leq BIM &lt; 1.5)</td>
<td>moderate potential for violent failure</td>
</tr>
<tr>
<td>(BIM \geq 1.5)</td>
<td>low potential for violent failure</td>
</tr>
<tr>
<td><strong>Burst Efficiency Ratio ((\eta))</strong></td>
<td></td>
</tr>
<tr>
<td>(\eta &lt; 3.2%)</td>
<td>no potential for violent failure</td>
</tr>
<tr>
<td>(3.2% \leq \eta &lt; 2.8%)</td>
<td>low potential for violent failure</td>
</tr>
<tr>
<td>(3.8% \leq \eta &lt; 4.4%)</td>
<td>moderate potential for violent failure</td>
</tr>
<tr>
<td>(\eta \geq 4.4%)</td>
<td>high potential for violent failure</td>
</tr>
<tr>
<td><strong>Energy Release Rate (ERR)</strong></td>
<td></td>
</tr>
<tr>
<td>(V_f \geq V_{fc} \text{ and } V_r \leq V_{rc})</td>
<td>high potential for violent failure</td>
</tr>
<tr>
<td>(V_f \geq V_{fc} \text{ and } V_r &gt; V_{rc})</td>
<td>moderate potential for violent failure</td>
</tr>
<tr>
<td>(V_f &lt; V_{fc} \text{ and } V_r \leq V_{rc})</td>
<td>low potential for violent failure</td>
</tr>
<tr>
<td>(V_f &lt; V_{fc} \text{ and } V_r &gt; V_{rc})</td>
<td>no potential for violent failure</td>
</tr>
</tbody>
</table>

\[V_{fc} = \frac{\Delta \sigma}{\Delta t}\text{ where } \Delta \sigma \text{ is stress increment and } \Delta t \text{ is time interval, } V_f \text{ = fragmentation rate, } V_{fc} = \text{critical fragmentation rate, } V_r = \text{stress relaxation, } V_{rc}= \text{critical relaxation rate}\]

| **Burst-Potential Index (BPI)** | |
| \(BPI = \frac{ESR}{e_c} \times 100\%\) | |

where ESR is the energy storage rate and \(e_c\) is the area under the stress-strain curve up to the peak stress

| **Relative Violence at Failure** | |
| This index measures the rebound of the loading system at failure during a uniaxial compression test with a non-stiff loading system. Rebound is proportional to the violence (seismic energy released, volume of rock fragments, etc.) at failure |

| **Energy-Band Failure Index** | |
| The calculation of pillar skin strain-burst using an index based on strain energy which is given by the mining-induced strain energy calculated at the boundary of the opening (pillar skin) divided by the critical strain energy |
(2) **Contrasting geomechanical properties**

Under same stress conditions, two adjacent lithological units with considerable difference in their geomechanical properties (e.g. deformability, grain size, in-situ fracture density, degree of anisotropy, etc.) may present different behaviour in storing strain energy, failure mode, fracture initiation and propagation. Salamon (1974) outlines the occurrence of fault-slip bursts though a difference of stiffness between the loading system and the post-peak stiffness of the fault - the greater the surface roughness, the lesser the tendency for stick-slip (Scholz & Engelder, 1976), the thicker layers of gouge the less tendency for stick-slip (Byerlee & Sunimers, 1976).

Contrasting properties of adjacent geological units have been shown to be a contributing factor to the occurrence of rockburst events in some of the case studies presented in Table 2-1:

- In some of the Canadian mines (Case Studies 14 and 22, Table 2-1), the massive sulphide orebodies are relatively weak and deform in ductile manner. Rockbursts are confined to the stronger disseminated ore zones, waste inclusions, or wall rocks.
- A softer basic syenite unit at Macassa Mine (Case Study 12, Table 2-1) is compressed between stiffer syenite porphyry rock units that are loaded by the high horizontal and mining-induced stresses.
- The Sunshine Mine (Case Study 25, Table 2-1) first experienced rockbursts as they traversed the stiffer Revett quartzite unit.
- Both Teck-Hughes and Wright-Hargreaves (Case Studies 13 and 16, Table 2-1) placed their main production shafts in the hanging-wall. Significant rockburst activity was observed where the shafts intersected, or were in close proximity to, mineralized veins.
- A high in-situ horizontal stress field and a mining method which concentrated stress in diminishing pillars combined with brittle cross-cutting porphyry intrusions at Kambalda Nickel Orebodies (Case Study 1, Table 2-1) have resulted in significant seismicity due to slip along porphyry contacts.

(3) **Geological intensifiers**

When geological weaknesses, such as faults or shear zones, or stress concentrators, such as dykes, are nearby, the released energy may often be larger because these geological features create unfavourable stress and loading system conditions, by involving large rock volumes in the deformation and failure process (Kaiser & Cai, 2012). It is not always
known whether in-situ stress is a factor in promoting a particularly large release of seismic energy or whether the large planar weakness afforded by the discontinuity simply allows failure, by slippage, along a very extensive area. This would tap the stored elastic strain energy from a large volume of rock.

Large intact wedges bounded by two intersecting faults at the Mt Charlotte Mine (Case Study 3, Table 2-1) created a soft local mine stiffness that drove large shear movements with the release of significant seismic energy. A correlation between large-scale fault structures, the location of mining fronts and the resultant seismic activity exist at the Strzelecki Mine (Case Study 6, Table 2-1). Once movement occurred by violent shearing through an asperity created by a bulge in the No. 1 Flat Fault at Falconbridge Mine (Case Study 17, Table 2-1), it allowed other faults to become active. Almost all of the seismic activity and all of the damage were confined to a wedge of rock, bounded by the No. 1 Flat Fault and Main faults, and extending about 200 m into the footwall norite.

The presence of geological discontinuities may halt or divert the fracturing front and therefore intensify stresses leading to a rockburst. This has previously been observed at the Ventersdorp Contact Reef (Ortlepp, 1997). In this case, the prominent joint-set was aligned parallel to the excavation face which prevented the normal development of the mining-induced extension fractures. The resulting concentration of stress on these parallel pre-existing features near the advancing face allowed a state of quasi-stable stress to develop resulting in buckling and violent slab failure. A similar scenario has also been documented at the Strathcona Mine in Canada (Case Study 22, Table 2-1). Figure 2-5 shows a schematic section view showing the basic elements of the proposed buckling mechanism by Ortlepp (1997).

2.5 Prediction of violent failure through numerical models

Given the relative simplicity in identifying each of the violent failure key-drivers as individual geomechanical conditions (Figure 2-6), why is violent failure rarely identified prior to a specific event occurring?

It is proposed that in many cases the complex interaction of stress and geomechanical conditions and the dynamic nature of underground mine workings cannot be accurately represented (or pre-empted) with empirical techniques. While empirical techniques that employ rock mass characterisation and experimental/observational data into account
(Kaiser et al., 2000) are sufficient to identify the general conditions of strain-bursting at a pre-feasibility level, they are unable provide specific dynamic geomechanical predictions (since they are limited to the data-sets that they were developed from). In general, these datasets include low stress environments (e.g. civil tunnelling), failure modes typical of these environments (gravitational) and typical ground conditions encountered (gradually yielding/squeezing).

![Diagram](image)

**Figure 2-5:** Buckling rockburst mechanism intensified by discontinuity at the Strathcona Mine (after Ortlepp, 1997)

![Diagram](image)

**Figure 2-6:** Contributing factors for violent rock mass failure
It is proposed that numerical models be used as a standard design tool in underground excavation to ensure seismic risk can be identified and mitigated prior to its occurrence. In order to establish an appropriate numerical modelling tool for the prediction of violent failure, the following items are considered critical:

- The model mesh must be three-dimensional to be able to account for dynamic geometry and induced stresses in x-y-z space.
- The mesh must have fine enough zone resolution to account for heterogeneity in geology, presence of intensifiers and daily advance rates. Here a global-local or sub-modelling methodology (as outlined by Sjöberg & Malmgren, 2008) may be required.
- An initial state of stress must be initialized through displacement boundary conditions to ensure the most accurate loading history of the rock mass. A spatial heterogeneity in the initial stress state can develop due to the presence of geologic structures. This heterogeneity results from the historical orogenic stress path and the fracture, slip and separation that may have occurred.
- An explicit, dynamic solution scheme as outlined by (e.g. Hart, 2003; Hazzard & Pettitt, 2013; Sainoki & Mitri, 2015, 2016) is required to ensure that the numerical scheme is stable when the physical system being modelled is unstable.
- Boundary conditions must limit the reflection of elastic waves arising from rock-bursting events and mining activities (Sainoki & Mitri, 2014ab).
- A constitutive model such as Sainsbury (2012) that can capture rock mass yielding (including variations in post-peak response) that also includes independent cohesion and tension softening, modulus softening and a dynamic dilation angle to ensure an accurate stress path within the model and hence failure mode is emergent. This constitutive model is based on the Subiquitous constitutive model that is implemented in commercially available discrete element (3DEC) and continuum codes (FLAC3D).
- To simulate fault-slip events at many scales, structures must be incorporated in the mesh. The most efficient method at the present time is documented by Sainsbury et al. (2016). This method includes the consideration of discrete fault structure locations within the model above a critical length (that is related to the excavation size). Below this critical length the presence of discontinuities are considered a rock mass property and are characterized within the constitutive model parameters (e.g. effect on GSI, UCS, m_i). FLAC3D and 3DEC both use the same explicit time-marching calculation scheme. So long as the individual fault structure is modelled as a discrete feature (i.e.
two individual surfaces that can separate or come to contact and slip), the macroscopic response of the fault in both calculations is the same. A global-local modelling methodology may be required here depending on the resolution of the structures (and their complexity) being considered.

The implementation of such modelling criteria has been completed in Chapters 4 and 5 to show how stiffness contrasts in adjacent lithologies can contribute to rock-bursting conditions.

2.6 Summary and concluding remarks

In this paper published case studies of rockburst events have been analysed to establish the contributing factors for violent rock mass failures. It has been shown that the violent uncontrolled failure of rock in the majority of cases occurs by:

- Loading Associated Factors – i.e. overly stressed rock mass or reduced clamping force on large discontinuities, which relates to the effects of the a) high and/or adversely re-oriented stresses by structures, b) excavation geometry, and c) excavation rate and direction.

- Property Associated Factors – i.e. sudden deformation in the forms leading to damage, concerning the effects of the: a) mineralogical properties, b) contrasting geomechanical properties, and c) geological intensifiers affecting fracturing behaviour (e.g. dykes, faults, bedding planes, etc.).

Each of these contributing factors is able be accurately represented in detailed three-dimensional numerical models. However, in many cases, discrete geotechnical domains are difficult to identify, and/or their properties are not always heterogeneous. In this case, sensitivity analysis can be performed through numerical simulations to observe critical parameters to inform Trigger Action Response Plans (TARPs). It is therefore concluded the location and magnitudes of complex violent failure events can be accurately assessed within numerical models. A methodology is proposed that outlines the key requirements of a numerical model in order to predict the violent failure of rock mass. The methodology has been applied to a simple demonstration model (Chapters 4 and 5) that provides an assessment of bursting potential in two different lithological domains.
3. Experimental Investigations

As a fundamental study completing the large-scale observational findings from the Chapter 2, this Chapter presents micro-scale originators and/or intensifiers of a strain-burst event. The geology aspects of the rock-bursting studies have been considered through a parallel research process by Sainsbury and Kurucuk (2019, 2020) and Lee et al. (2018).

Results from an image analysis of strain-burst fragments presented in this chapter reveal that:

- Key drivers for rock-bursting identified at the macro scale also present at the micro (grain-based) scale

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3.1 Introduction

The term ‘strain-burst’ is used to describe cases in which brittle failure in rock occurs violently and usually involves the creation of new fractures. Progressive development of cracks resulting in brittle failure is mainly controlled by the microstructural and mineralogical properties such as composition, grain size and shape. Hence, an intrinsic interpretation of rock failure mechanism requires study of the grain-scale structures governing the macro-scale response such as strength, deformability and failure pattern (Nicksiar & Martin, 2014; Zhang & Wong, 2018).

Strain-bursting has previously been characterised by events with a Richter Magnitude between -0.2 and 0.0 ML (Ortlepp, 2005) and is known to occur at low confinement levels ($\sigma_1 = 0$ to 5MPa), and when the maximum principal stress magnitude ($\sigma_1$) exceeds the peak rock mass strength envelope (Martin, 1999). A strain-burst event (along with any other type of seismic source underground) is only possible when there is stored energy in the rock mass that can be dissipated when a change to the in-situ conditions (geometrical and/or stress related) occurs. Mineral composition, grain size, grade of metamorphism

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1 Complete data sets for rock types considered by Lee et al. (2018) are presented as an appended table at the end of this chapter.
and tectonic history all play a role in determining the characteristics of the rock mass and the stored energy (Mitri et al., 1999).

In general, the problem of mine seismicity is stochastic, due to the variability in distribution of geological structures and heterogeneous nature of rock masses (Board, 1994). Strain-bursting is more likely to occur in massive rocks than in significantly jointed and fractured rock masses (Aubertin et al., 1994). As illustrated in Figure 3-1, under the same in situ stress conditions, two adjacent lithological units present different behaviours in terms of storing strain energy that is observed through the resulting fracture network that has been generated. The sketch of the fractures depicted from the highlighted area of this figure shows that the dark dolerite has a higher fracture density and majority of the fractures terminate at the contact between the dolerite and massive host rock. These behavioural differences are considered to be a direct result of a significant contrast in geomechanical properties such as stiffness (Bewick et al., 2017). As a result of this contrast in behaviour, knowledge of the mineralogical properties is an important requirement for the determination of strain-burst proneness.

To facilitate the study and analysis of the complex processes involved in bursting ground, in the book ‘Rock fracture and rockbursts: an illustrative study’, Ortlepp (1997) outlined details of the observed damage caused by an event. However, the study was confined to visual observations at a large scale, since photographs and thin section samples prepared were lost before an analysis could be undertaken. From the foreword to this book, Stacey proposed the “Readers of this remarkable book compare the case studies with their own observations; ... and to promote or actually undertake similar studies or research”.

![Figure 3-1: Branches of dark-coloured dolerite dykes in the Koster Islands, Sweden (retrieved from http://www.geologyin.com on 20/04/2018): a) A rock mass demonstrating domains with contrasting stiffness, b) sketch of fracture density of the highlighted area where fracture initiation and propagation have been affected by the contrasting material and their contact](image)
Since this initial publication, complementary research associated with investigating the micro-scale features of rockburst surfaces has not been conducted. The research contained herein, assists with complementing the micro-mechanical investigation along with providing detailed information to assist with the validation of numerical simulations of strain-burst events.

### 3.2 Strain-burst fracture mechanics

The fracture process in rock commences at the tip of an existing crack, further growing in the direction of the maximum principal stress. When stress increases slowly, these fractures develop in a stable manner - detected by extreme slenderness of the slabs. Strain-bursting occurs when tangential stress builds up in the immediate skin of the excavation and the rock mass surrounding the fracture creates a relatively ‘soft’ loading environment such that the rock fails locally in an unstable manner (Kaiser & Cai, 2012). This unstable fracture propagation results in violent exfoliation or spalling of the surface which is termed strain-bursting (Ortlepp & Stacey, 1994).

Engelder (1987) has previously characterized a strain-burst failure surface by a ‘mirror zone’ and a ‘hackle zone’: the mirror zone is defined as a flat surface adjacent to the rupture origin. In this zone, the slow but accelerating crack tip reaches a critical velocity beyond which bifurcation occurs forming the hackle zone. The transition from a single crack propagating at the critical velocity to the numerous smaller fractures of a hackle zone ideally occurs along a circular arc as shown in Figure 3-2.

![Figure 3-2: Mirror zones (yellow arcs) and hackle zones (blue branches perpendicular to the mirror zones) on a large block ejected during a strain-burst event. The red arrows suggest the potential direction of fracture propagation (after Ortlepp, 1997)](image-url)
Chapter 3: Background and Methodology

3.3 Investigation of strain-burst fragments

Scanning Electron Microscope (SEM) is a technique used to observe features from the micron-scale to the nano-scale range. A SEM machine uses a focused beam of electrons, scanned over the surface of a sample to reconstruct a magnified image of the sample exposure. Additionally, Electron Backscattered Diffraction (EBSD) can be available within a SEM, allowing phase and orientation related information to be revealed.

In EBSD imaging mode, the backscattering coefficient (i.e. contrast formation) depends on the atomic number (Z) of the sample as well as the orientation of crystallographic (lattice) planes within the material - as presented in Figure 3-3. Through this technique, electrons are ‘channelled’ into a material if the beam is close to a major zone axis (dark contrast). Away from this zone, the backscattering coefficient will be higher (bright contrast). Heavy (high atomic number) elements backscatter more strongly than lighter elements, i.e. high atomic number regions are brighter and low atomic number regions are darker.

![Diagram of backscattered electrons contrast formation](image)

Figure 3-3: Dependency of backscattered electrons contrast formation to the material crystallography (top) and composition (bottom)

Figure 3-4 presents an igneous rock sample (with 6mm×8mm surface area and 3mm thickness) and the JEOL 7001F test machine set-up. In this experiment, a standard (10nA
current, 15kV voltage, and 10mm WD) has been used, with an aperture corresponding to the level No.3 of the apparatus.

Figure 3-4: A strain-burst sample (image a) loaded in to the JEOL 7001F apparatus (image b)

3.4 SEM Image analysis

3.4.1 Contrasting geomechanical properties

The SEM images presented in Figure 3-5 show the inclusion of a dense region (brighter grains highlighted) surrounded by a less dense region (darker region of the SEM images). From this density contrast, a differential in the stiffness of the material/s can be inferred along with a variation in the stored energy of each.

Both the principal stress orientations and magnitudes can be disturbed by the presence of intrusive materials. In terms of stress redistribution, a less stiff inclusion diverts the major principal stress parallel to its boundaries and decreases the minor principal stress in the perpendicular direction (e.g. a void can be considered as an extreme of this case). In the contrasting extreme case (e.g. an infinitely stiff infilling) the major principal stress is directed perpendicular to the discontinuity and the minor principal stress is re-oriented parallel to its surface. In terms of response to loading, a less stiff inclusion deforms in ductile manner to dissipate elevated energy. A stiffer material may concentrate stresses/energy up to a brittle fracturing point when a sudden release of energy occurs. Such contrasts in a seemingly homogenous rock sample (visually) may have contributed to the strain-burst event observed at this location.

At the large (mine/drive) scale, contrasting adjacent geological properties is a major contributing factor to the occurrence of seismic events e.g. Strathcona and Brunswick
Mines in Canada (Blake & Hedley, 2009; Morrison, 1989; Simser et al., 2001). At these locations the massive sulphide orebodies are relatively weak (compared to the host rock) and deform in ductile manner when stressed. Seismic events occur within the stronger disseminated ore zones, and host rock.

Figure 3-5: SEM images illustrating stiff inclusions on fracture surface. The identified stiffer grains (the highlighted brighter elements) influence the fracturing pattern via concentrating stresses and releasing the stored energy at failure violently (brittle failure).

3.4.2 Anisotropy

Figure 3-6 presents closely spaced channels (semi-parallel darker lines highlighted in the figure) indicating four potential planes of anisotropy on the surface of the strain-burst fragment.
Figure 3-6: SEM images illustrating planes of anisotropy (semi-parallel and closely spaced concentration of darker lines highlighted in the SEM images, i.e. planes of weakness). The coloured arrows within the four highlighted sub-regions propose the potential direction of anisotropy of each sub-region. Compared to the matrix material, i.e. lighter elements, the planes of weakness are more prone to sliding in response to shearing load, to splitting in tensile loading, and to buckling in compression. The last two mechanisms can be a violent failure process in low/zero confinement.

The proposed direction of the lines/planes have been presented in Figure 3-6 with coloured arrows within the four sub-regions identified in the SEM images. Such planes can result in micro-scale slip events. The planes of anisotropy highlighted in this figure can also prevent the normal development of extension fractures, resulting in the concentration of stress on these parallel features resulting in buckling and violent slab
failure. There is a significant degree of disturbance of the samples through the anisotropic mineral on the surface of the SEM images analysed.

**Figure 3-7** presents a schematic bursting-buckling mechanism that developed due to closely spaced joints at the Strathcona Mine located in Canada (Ortlepp, 1997). Based on the results of the SEM scan on the strain-burst sample at the micro-level it is not difficult to imagine this failure mechanism occurring at the macro-scale and contributing to stain-burst occurrence at this location.

![Buckling mechanism intensified by discontinuity near excavation face (after Ortlepp, 1997)](image)

**Figure 3-7**: Buckling mechanism intensified by discontinuity near excavation face (after Ortlepp, 1997)

### 3.4.3 Geological contacts

In micromechanical theories of linear elastic fracture mechanics, the development of macroscopic fractures is analysed by considering the growth and coalescence of micro-cracks. The damage evolution and brittle failure processes hinge on local stress concentrations related to initial heterogeneity intrinsic to the rock at the micro scale (Brady & Brown, 2006).

Geological contacts at both the micro and macro scales (e.g. grain boundary and lithological contacts) are an important consideration in the analysis of fracture initiation and propagation. They are the weakest link between the bonded grains that comprise the rock matrix and are therefore most likely to initiate compression induced tensile fractures. Contact surfaces can also act as planes of anisotropy and slip when their shear strength is
exceeded. In terms of fracture propagation, three scenarios are plausible when a propagating fracture reaches geological contacts. Depending on the mechanical properties the fracturing front may be unaffected, halted, or diverted. The last two (halting and diverting) may intensify stresses leading to a strain-burst event. Pronounced directional contacts (e.g. foliations at a small scale or bedding planes at a large scale) can also lead to preferred directional behaviour, i.e. anisotropy.

One of the most important factors affecting the fracturing process, development of the fracture paths and the resulting collapse of rock during brittle failure is the heterogeneity. Throughout progressive failure in brittle behaviour, rock heterogeneity has a marked influence on cracks nucleation, propagation, interaction and coalescence (Tang & Kaiser, 1998). The SEM image presented in Figure 3-8 demonstrates that heterogeneity in this sample presents at the micro-scale through variable grain size, type and distribution on the fracture surface. Hence, the heterogeneity of the microstructure presumably impacted the fracturing process and the resulting patterns during the strain-burst event at the site.

![SEM image illustrating presence of different element geometries (shape and size) and grain types (appear as elements with different brightness in SEM) resulting in heterogeneity on strain-burst surface](image)

**Figure 3-8:** SEM image illustrating presence of different element geometries (shape and size) and grain types (appear as elements with different brightness in SEM) resulting in heterogeneity on strain-burst surface

SEM images in Figure 3-9 present highly interlocked mineral grain structure (associated with low porosity) of the strain-burst rock fragments. Initial micro-defects in the forms
of sharp or open contacts are also present which serve as stress concentrators that promote micro-cracking. A well-defined boundary (or sharp) contact such as the C3 contact in the image ‘a’ and the magnified image ‘b’ of Figure 3-9 can also prevent fracture propagation into the adjacent grain or divert it to continue along the boundary (i.e. the weakest link between the grains).

Figure 3-9: SEM images at different magnification levels illustrating highly interlocked structure (image ‘b’ is four times magnified of the yellow box highlighted in image ‘a’). Sharp contacts (e.g. C1 and C3) and healed contacts (e.g. C2) serve as micro-defects or stress concentrators that promote micro-cracking. They can also affect fracture propagation, as is the case in contact C3 the micro-cracks (indicated by white arrows) have been diverted and terminated at C3.

The SEM images from Figure 3-8 and Figure 3-9 indicate that even at the micro-scale, the effect of geometry (size and shape) and contact type (healed or sharp) on stress re-
orientation and concentration (and as a result, fracturing behaviour) cannot be ignored when considering a rock’s potential for strain-bursting. At the mine scale, adverse stress conditions dictated by contact patterns is a major contributing factor to bursting at the Kanowna Belle Mine that are localised around geological contacts (Heal, 2010).

3.4.4 Identification of plumose patterns

The plumose patterns on the surface analysed are presented in Figure 3-10.

![Figure 3-10](image)

**Figure 3-10:** The strain-burst features ‘mirror’ and ‘hackle’ zones observed at different magnifications of SEM images ‘a’ and ‘b’. The available excess energy is absorbed by growth of a single fracture forming the semi circles mirror zones (M1 in a, M2 and M3 in b) with the fracturing directions as indicated by the white arrows. After this zone (red dotted lines), multiple radial fractures of the hackle zones indicated by blue solid lines develop (H1 in a, H2 and H3 in b) to dissipate the excess energy
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The semi-circular arc on the fracture plane, along which the radial traces annotated on Figure 3-10 may delineate the transition from ‘mirror’ zone to ‘hackle’ zone. The characteristics of this region (even at the micro-scale, as identified on the SEM images of the Figure 3-10) are similar to those observed at large scale events (e.g., the available excess energy can be absorbed by growth of a single fracture of the mirror - red dotted lines). However, the energy absorbed is limited by the terminal velocity of crack growth which is about 60% of seismic shear wave velocity (Ortlepp, 1997). Beyond this limit, multiple radial fractures (blue solid lines) develop to dissipate the excess energy (with the proposed directions as indicated by white arrows on the SEM images).

The nature of the studied surface indicates extensional fracturing; with the mechanism most likely buckling of the thin rock diaphragm at the excavation surface. According to Ortlepp (1997), mirror zones strongly indicate rapid propagation of fractures, therefore violent failure. Such failure occurs as strain-bursting or explosive spalling of a free surface close to the origin of a seismic event.

3.5 Summary and concluding remarks

A rock mass is usually made up of an interlocking matrix of discrete blocks. These blocks may have been weathered or altered to varying degrees and the contact surfaces between the blocks may vary from clean and fresh to clay gouge and/or slickensided. Although a rock block may appear intact in the field (or even at the laboratory scale) it may contain structural features at a micro scale such as micro-cracks (sharp contacts), veins (intrusions), and healed joints, all of which may influence its strength and failure mode. Figure 3-11 schematically presents such micro-macro correlations.

SEM image analysis of igneous strain-burst fragments from a site in Western Australia has showed that anisotropy, contrast in geomechanical properties, geometry and contact patterns all present at the micro-scale are similar to the larger mine/drive scale. As a result of this SEM investigation, it is clear that a complex mechanism that includes the interaction of the intact rock (as explored here), discontinuities, stress regime and stress path may result in seismic events. It is therefore critical that in identifying strain-burst proneness of rocks, a mineralogical index/approach should be considered.
SEM image analysis can also assist in the interpretation and validation of numerical simulations conducted for strain-burst potential evaluation. Studying strain-burst fragments from different locations around the event (if their original source is known) may assist in revealing the true source mechanism of the event; especially when there is no large-scale discontinuity present. In order to highlight this application of SEM, **Figure 3-12** represents a numerical model of a development tunnel advancing into a stiff dyke, where the potential strain-burst has been simulated. The details of identification of brittle failure zones and the potential risk associated with the strain-burst hazard can be found in Chapters 4 and 5.

As presented in **Figure 3-12**, both the principal stress magnitude and failure modes within the drive are affected due to contacting lithologies and contrasting properties. The dyke presents higher stresses and a tensile failure mechanism when compared to the host rock. This suggests that the modelling results can be used in collaboration with SEM imaging to confirm the evidence of plumose patterns and hence interpret failure mechanism.
Figure 3-12: Numerical modelling of strain-burst: a) Lithology and contact setting, b) stress redistribution, and c) plastic deformations (details are provided in the Chapter 4)

From a parallel geological study relevant to this research, suites of the rock properties were collected by Lee et al. (2018) for various rock types at numerous Australian mines to study their violent failure behaviour. Table 3-1 summarises the data from Lee et al. (2018) and the reference should be read for details.
### Table 3-1 Geological Database of the rock properties studied for violent failure analysis by Lee et al. (2018)

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<td>92</td>
<td>5.6</td>
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<tr>
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<td>6351</td>
<td>3483</td>
<td>134</td>
<td>14.5</td>
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<td>0.25</td>
<td>1.98</td>
<td>85.5</td>
<td>1.17</td>
<td>123</td>
<td>50</td>
<td>2.4</td>
</tr>
<tr>
<td>Granite breccia</td>
<td>&lt; 10% hematite, sericitic</td>
<td>3.05</td>
<td>5628</td>
<td>3269</td>
<td>140</td>
<td>13.3</td>
<td>59.1</td>
<td>0.28</td>
<td>5.03</td>
<td>81.1</td>
<td>1.37</td>
<td>165</td>
<td>394</td>
<td>0.4</td>
</tr>
<tr>
<td>Granite breccia</td>
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<td>62.0</td>
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<td>1.74</td>
<td>337</td>
<td>206</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td><strong>Ductile Squeezing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultramafics</td>
<td>serpentinised; carbonated</td>
<td>2.83</td>
<td>3534</td>
<td>2241</td>
<td>80</td>
<td>6.8</td>
<td>26.8</td>
<td>0.40</td>
<td>1.17</td>
<td>33.1</td>
<td>1.23</td>
<td>119</td>
<td>43</td>
<td>2.7</td>
</tr>
<tr>
<td>Ultramafics</td>
<td>serpentinised; talc-carbonate</td>
<td>2.86</td>
<td>4555</td>
<td>1623</td>
<td>53</td>
<td>6.7</td>
<td>34.9</td>
<td>0.26</td>
<td>1.44</td>
<td>21.5</td>
<td>0.62</td>
<td>40</td>
<td>56</td>
<td>0.7</td>
</tr>
<tr>
<td>Ultramafics</td>
<td>serpentinised; talc-carbonate</td>
<td>2.85</td>
<td>5785</td>
<td>3581</td>
<td>41</td>
<td>4.7</td>
<td>44.5</td>
<td>0.44</td>
<td>0.56</td>
<td>87.0</td>
<td>1.96</td>
<td>19</td>
<td>6</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Chapter 4

Numerical Simulations: Severity of Violent Failures

As highlighted in Chapter 2, the use of rockburst liability indices based on brittleness is prevalent in mining geotechnical design. Through these relationships, brittleness is a function of stress or strain that is limited to either the pre- or post-failure. The identification of input indices for each of these relationships requires sophisticated testing equipment. Furthermore, the laboratory tests may never be a true representation of the rock mass failure in-situ due to the complex unloading conditions around an excavation that are difficult to replicate in the laboratory. Dependency of brittleness to the material properties, geometry and loading conditions also contribute to the current confusion in its definition and applicability.

This chapter presents the development of a new brittleness index that can be used to consider the full spectrum of loading-unloading states experienced by a rock-mass in-situ. The motivation to improve this issue was to benefit from the approaches that can be used and tracked in a numerical model for strain-burst assessment. The technique is validated through the implementation in a numerical model of an underground mine with a history of violent failure events. Furthermore, the brittleness index from this chapter has been implemented in a newly developed framework to account for the probability and consequences of violent failure in order to rank the associated risk. The has been described in Chapter 5.

Key points from this chapter include:

- Strain-burst hazard is quantified in relation to induced stresses and plastic strains
- Contrast in stiffness and geological contacts are critical in strain-burst proneness

Contents of Chapter 4 is a copy of an article published in the journal of ‘Engineering Geology’, which can be at: https://doi.org/10.1016/j.enggeo.2020.105596

4.1 Introduction

Fracture is the failure process by which new surfaces are formed or existing crack surfaces are extended through a material. The formation of fractures within a material does not necessarily imply complete failure (Stacey, 1981), but provides an indication of the onset
of damage (Akinbinu, 2017; Sainsbury, 2018). Prediction of the severity of a failure, or the extent of the damaged (or strength softened) region around an excavation is of critical importance during the design phase, since the deformational response will be dominated by the post-peak behaviour (Hudson & Harrison, 1997).

A ductile post-peak response indicates a material that is able to endure large deformation without a significant loss of strength. A brittle post-peak response is characterised by a sudden loss of strength (usually localised along a discrete plane) following little or no plastic deformation (Zhao et al., 2019). Based on these definitions, brittleness not only represents the severity of strength loss after failure, but also indicates the ability of the material to withstand inelastic deformations before failure (Hajiabdolmajid & Kaiser, 2002; Martin, 1997).

The brittleness of rocks has previously been evaluated via empirical techniques (Hucka & Das, 1974) considering parameters such as elongation, fracture failure, formation of fines, compressive to tensile strength ratio, angle of internal friction, formation of cracks at indentation, etc. Britteness definitions also include a commentary based on; mineralogy, stress-strain behaviour (pre-and post-failure), elastic parameters and indentation behaviour. A summary of the commonly used brittleness indices and their corresponding evaluation processes can be found in Raybacki et al. (2016) and Kivi et al. (2018).

### 4.2 Characterization of brittle failure in jointed rock masses

During brittle failure of a jointed rock mass, the formation of new fractures or the extension of existing fractures results in a reduction in cohesive and tensile strength and mobilisation of frictional strength (Hajiabdolmajid & Kaiser, 2002). It also results in the reduction of the deformation modulus (Sainsbury, 2018).

Brittleness has previously been evaluated as an intrinsic property from rock strength parameters (e.g. Andreev, 1995; Bishop, 1967; Hucka & Das, 1974). It is also known to be dependent on loading conditions (Tarasov & Potvin, 2012).

Through each of these relationships, brittleness has been described as a function of stress or strain (considered separately), that is limited to either the pre- or post-failure region of the stress-strain response curve. More recently, Xia et al. (2017) and Rybacki et al. (2016)
have considered the effects of stress and strain together and Hajiabdolmajid et al. (2003) have considered the full stress-strain path of the material through to residual strength.

The identification of input parameters for each of these brittleness relationships requires sophisticated (e.g. non-standard) testing equipment (Rybacki et al., 2016). Furthermore, the laboratory tests may never be a true representation of the in-situ rock mass failure due to the complex loading conditions around an excavation (Martin, 1997). Dependency of the apparent brittleness to material properties, geometry and loading conditions also contribute to the numerous definitions of brittleness and their applicability (Hajiabdolmajid & Kaiser, 2002). Figure 4-1 illustrates typical stress-strain curves for rock mass failure in tension and in compression.

Main characteristics of the stress-strain paths presented in Figure 4-1 are:

- **Shear Failure (OYP-A/B/C stress path/s):**
  - **Pre-Peak (O-Y-P):** Fracture initiation and propagation within the linear elastic deformation region (O-Y section of the curve) is normally considered as stable, since additional loading is required to cause damage. A critical energy release and unstable crack growth generally occurs beyond the yield stress limit (Y) and the axial strain departs from linearity (Hudson & Harrison, 1997). The maximum sustainable stress (P) is a function of induced damage that may be a function of the loading conditions (i.e. different peak strengths (σ_{peak}) and associated strains (ε_{peak}) are reached if either P_1 or P_2 is followed).
  - **Post-Peak (P-A/B/or C):** The post-peak portion of a stress-strain curve is considered to reflect the amount of energy that can be released during failure. It does not reflect a true material property but is considered to be related to loading conditions (Wawersik & Fairhurst, 1970).
    While the residual strength of the P-B and P-C curves are the same, a difference in the gradient is observed. This variation results from a difference in the accumulated plastic strain required to progress from the peak strength to the residual strength state. The post-peak gradient has been shown to be related to the blockiness of a rock mass (Sainsbury & Kurucuk, 2019).
    Variations in the energy release may also result from differences in peak and residual strengths (e.g. P-B versus P-A paths).
• **Tensile Failure (O-T-D stress path):**
  
  o **Pre-Peak (O-T):** The pre-peak portion of the tensile curve (O-T) exhibits linear elastic behaviour, since the processes of stable and unstable fracture propagation will be of very small duration since, in tension, a crack will propagate in its own plane (Bieniawski, 1967).
  
  o **Post-Peak (T-D):** In most cases, tension is considered perfectly brittle. e.g. after the peak tensile stress is reached ($-\sigma_{\text{peak}}$), the stress drops to zero following minimal plastic deformation - 0.2% to 0.25% for fine grained rocks (Fujii et al., 1998; Keneti & Wong, 2011).

![Figure 4-1: Strain-stress curves representing failure in tension and compression](image)

**Figure 4-1:** Strain-stress curves representing failure in tension and compression ($\sigma_{\text{peak}}$: peak compressive stress; $\varepsilon_{\text{peak}}$: strain at peak compressive stress; $\sigma_{\text{residual}}$: residual stress; $\varepsilon_{\text{residual}}$: strain to reach residual stress; $\sigma_{\text{yield}}$: yield stress; $\varepsilon_{\text{yield}}$: yield strain; $-\varepsilon_{\text{peak}}$: strain to reach peak tensile stress; $-\sigma_{\text{peak}}$: peak tensile stress; $-\varepsilon_{\text{residual}}$: strain to reach residual tensile stress)

### 4.3 Identification of brittle failure potential

Brittle-failure has previously been described by mechanisms of rock failure near excavation boundaries that include (in general) high compressive ($\sigma_1$) and low confinement ($\sigma_3$) stress environment (Diederichs, 2007). They may also include tensile failure/s. Failure modes include:

- the non-violent creation of extension fractures in the form of thin parallel slabs (spalling); and/or
- violent rupture of a volume of rock (strain-bursting)
Each of these failure modes have previously been explored in more details by Lee et al. (2018) and Sainsbury and Kurucuk (2019) through an examination of stress and material properties.

The susceptibility of a rock to spalling and/or strain-bursting has previously been defined on the lower limits by a coupled Damage Initiation and Spalling Thresholds (DISL) (Diederichs, 2003, 2007; Diederichs et al., 2004; Eberhardt et al., 1998).

A visual representation of the DISL region is presented in Figure 4-2. The brittle failure zone is bounded by the peak strength envelope and the direct tensile strength cut-off.

![Figure 4-2: Identification of brittle failure zone based on σ1 - σ3 chart (modified after Diederichs, 2003). Brittle failure has the potential to occur in the shaded red stress region. Note: all of the values are scale dependant](image)

**4.4 Estimation of relative violence of brittle failure**

It is generally understood that failure (including damage accumulation) of a rock mass will result in an energy release. The amount of energy released can be calculated by an assessment of the non-linearity of the stress-strain curve – both in the pre- and post-peak regions (Tang & Kaiser, 1998). Since strain-bursts are violent, energy changes in the in-situ rock mass can be used to correlate with strain-burst potential (Xu et al., 2017; Hauquin et al., 2018; Hedley, 1992; Salamon, 1984; Walsh, 1977).

The following section provides a methodology to estimate the relative severity of rock mass failure once it has been identified. The calculation can be completed after induced stress conditions are identified within the brittle failure zone (Diederichs, 2003).
4.4.1 Stress-based Severity Index “$I_{VFS}$”

Bishop (1967) developed a Stress-Based Brittleness Index ($I_{Bs}$) that represents a ratio between the relative stress drop from the peak stress ($\sigma_{peak}$) to residual stress state ($\sigma_{residual}$). The ratio is presented in Equation 4.1.

$$I_{Bs} = \frac{\sigma_{peak} - \sigma_{residual}}{\sigma_{peak}} \quad (4.1)$$

The severity of the stress drop during failure can be comparatively calculated by the ratio between the current strength loss and the maximum expected stress drop at the residual strength level ($\sigma_{residual}$). When the current observed stress ($\sigma_{current}$) after failure in tension or in compression ($\sigma_{peak}$) are substituted into the strength loss calculation of Equation 4.1, and normalised by the maximum stress drop at the residual level given by Equation 4.1, the severity of the stress drop in compression ($I_{VFS,C}$) and tension ($I_{VFS,T}$) can be quantified through Equations 4.2a and 4.2b:

$$I_{VFS,C} = \frac{\Delta \sigma_{current}}{\Delta \sigma_{max}} = \left| \frac{\sigma_{peak} - \sigma_{current}}{\sigma_{peak} - \sigma_{residual}} \right| = \left| \frac{\sigma_{peak} - \sigma_{current}}{\sigma_{peak} - \sigma_{residual}} \right| \quad (4.2a)$$

$$I_{VFS,T} = \frac{-\Delta \sigma_{current}}{-\Delta \sigma_{max}} = \left| \frac{-\sigma_{peak} - \sigma_{current}}{-\sigma_{peak} - \sigma_{residual}} \right| = \left| \frac{-\sigma_{peak} - \sigma_{current}}{-\sigma_{peak}} \right| \quad (4.2b)$$

where $\sigma_{current}$ is the observed stress during failure, $\sigma_{peak}$ is the peak stress in compression, $-\sigma_{peak}$ is the peak tensile stress, and $\sigma_{residual}$ is the residual strength. We note here that, in Equation 4.2b, it is assumed that tensile stress drops to a residual value of zero.

It is important to note that the severity index $I_{VFS}$ should only be calculated for a failure event (i.e. after the peak stress has been achieved). Prior to the peak strength being exceeded the potential for strain-bursting may still exist – however it cannot be quantified through this technique. An $I_{VFS}$ value of 1.0 denotes the residual strength has been reached and there is no more potential for strain-bursting in this rock mass.

4.4.2 Strain-based Severity Index “$I_{VFe}$”

In order to account for cohesion-friction strength transition during complex loading conditions, a strain-based brittleness index ($I_{Be}$) was established by Hajiabdolmajid and Kaiser (2002) – Equation 4.3. The index is based on plastic strain which can be considered
a measure of accumulated damage. The Critical plastic strain represents the deformation required in going from peak strength to the residual strength.

\[ I_{Be} = \frac{\varepsilon_f^p - \varepsilon_c^p}{\varepsilon_c^p} \]  \hspace{1cm} (4.3)

The critical plastic strain parameters \( \varepsilon_c^p \) and \( \varepsilon_f^p \) are related to the mobilised cohesion and frictional component of strength, respectively.

It is known that brittle failure is a progressive mechanism that commences prior to the peak strength - starting after the yield stress level. Equation 4.3 considers only the post-peak components of strain accumulation. An updated index based on Equation 4.3 that also considers the plastic strain accumulation prior to the peak strength being reached has been defined by new equations: Equation 4.4a and Equation 4.4b for compressive and tensile loadings, respectively.

\[ I_{VF\varepsilon,C} = \left| \frac{\varepsilon_{current} - \varepsilon_{yield}}{\varepsilon_{residual}} \right| \]  \hspace{1cm} (4.4a)

\[ I_{VF\varepsilon,T} = \left| \frac{-\varepsilon_{current} - -\varepsilon_{yield}}{-\varepsilon_{residual}} \right| \]  \hspace{1cm} (4.4b)

where \( \varepsilon_{current} \) is the observed total strain, \( \varepsilon_{yield} \) and \( -\varepsilon_{yield} \) are the maximum elastic (yield) strains in compression and tension respectively, and \( \varepsilon_{residual} \) and \( -\varepsilon_{residual} \) are the minimum total strains required to mobilise the residual strength properties in compression and in tension, respectively.

It is understood that jointed rock mass materials may experience strains beyond this minimum total residual strain – however, the strain-bursting potential is considered to have dissipated after the residual strength is achieved and therefore additional strain beyond this (for the current purpose) is irrelevant. The strain-based indices (\( I_{VF\varepsilon,C}, I_{VF\varepsilon,T} \)) may vary between values of 0.0, indicating an elastic state to 1.0 indicating plasticity - up to the residual strength state. A value greater than 1.0 indicates a state in which deformation continues at the residual stress level.

**4.4.3 Combined Stress-Strain Related Index “\( I_{VFse} \)”**

Equations (4.5a) and (4.5b) present the combination of the stress- and strain-related indices presented in Equations (4.2) and (4.4) for compression and tension respectively:

\[ I_{VFse,Compression} = I_{VFse,C} \times I_{VF\varepsilon,C} = \left| \frac{(\sigma_{peak} - \sigma_{current})(\varepsilon_{current} - \varepsilon_{yield})}{\varepsilon_{residual} \times (\sigma_{peak} - \sigma_{residual})} \right| \]  \hspace{1cm} (4.5a)
\[ I_{VFse,Tension} = I_{VFS,T} \times I_{VFse,T} = \left| \frac{(-\sigma_{\text{peak}} - \sigma_{\text{current}})(-\varepsilon_{\text{current}} - \varepsilon_{\text{peak}})}{-\varepsilon_{\text{residual}} \times -\sigma_{\text{peak}}} \right| \] (4.5b)

The relationship for \( I_{VFse,Compression} \) and \( I_{VFse,Tension} \) in Equation 4.5 are presented graphically in Figure 4-3.

Through combining the stress and strain indices defined in Equations 4.2 and 4.4 and the DISL criteria (Section 3.1), a methodology can be established to consider both the material response and the in-situ stress path in order to comparatively quantify the severity of violent failures within rock masses.

![Figure 4-3: Schematic representation of the stress and strain components of the Violent Failure Index \( I_{VFse} \)](image)

It should be noted that a tensile failure is generally perfectly brittle in nature, and therefore \( I_{VFse,Tension} \) can be applied to all tensile failures. For rock masses failing in compression, the stress path should be checked first to satisfy DITSL conditions before applying the \( I_{VFse,Compression} \) criteria.

**Figure 4-4** schematically represents the implementation of the criteria for assessing the severity of violent brittle failure in-situ. This figure represents a stress path of a rock mass from its in-situ state (I) to five hypothetical final state points after excavation. As presented in **Figure 4-4**, these state points are

- elastic (E)
Chapter 4: Numerical Simulations: Severity of Violent Failures

- plastic in DISL area (PB) which has not failed but has the potential for violent brittle failure
- at peak-strength and yielding (non-violently) in shear (F)
- failed violently in tension (VF₁)
- failed violently in compression (VF₂)

Out of the five induced stress states presented in Figure 4-4, only when the stress path migrates into (or through) the DISL zone followed by intersection with the failure envelope can Equation 4.5 be used to assess the potential for a violent brittle mode failure.

In general, \( I_{VFSE} = 0 \) when the material state is either elastic (e.g. point E), plastic but pre-failure (e.g. point PB), or failed but in a non-brittle manner (e.g. point F). For brittle failure cases (e.g. points VF₁ or VF₂), the index values between 0 to 1 indicates that the residual strength has not yet been reached (i.e. further brittle failure potential is possible), a \( I_{VFSE} = 1 \) implies that the material has reached its residual state after a brittle failure,
and $I_{VFSE} > 1$ indicates that the material has reached a residual state after a brittle failure and deformation is being accumulated beyond the minimum residual strain.

It should also be noted that, the index parameters determined Equations 4.5 do not represent a calculation of energy release during a violent brittle failure. Instead, the values are only expected to be used as an indicator of relative severity of violent failure within a numerical model (i.e. the higher the index, the higher the chance that the failed material released its energy in violent manner). The implementation of such a comparative index is presented in the follow section.

4.5 Implementation of the violent failure index in numerical simulations

4.5.1 Simulation Description

Implementation of the proposed methods to identify and quantify the apparent severity of violent brittle failure has been completed on a conceptual numerical model of the Palabora Mine in Itasca 3DEC. This location was chosen since significant seismic activity related to the stiff dolerite domain was identified during Lift 1 development and production (Glazer & Hepworth, 2006). Increased seismic activity has also been linked to the presence of shear zones within the cave column (Reyes-Montes et al., 2010).

Five geomechanical domains have been simulated based on the properties provided in Sainsbury et al. (2016). They are summarized in Table 4-1.

**Table 4-1: Geomechanical Properties**

<table>
<thead>
<tr>
<th>Geotechnical domain</th>
<th>Rock mass parameters</th>
<th>Bi-linear Mohr-Coulomb Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\rho$ (kg/m$^3$)</td>
<td>$\sigma_c$ (MPa)</td>
</tr>
<tr>
<td>Waste (W) ~ MPY</td>
<td>3000</td>
<td>75</td>
</tr>
<tr>
<td>FW/HW ~ FOS</td>
<td>3500</td>
<td>70</td>
</tr>
<tr>
<td>Ore (O) ~ BCB</td>
<td>2850</td>
<td>115</td>
</tr>
<tr>
<td>Dyke (D) ~ DOL</td>
<td>3000</td>
<td>280</td>
</tr>
<tr>
<td>Shear (S) ~ FAULT</td>
<td>2750</td>
<td>100</td>
</tr>
</tbody>
</table>

The Subiquitous constitutive model has been used. A $\sigma_3$ fit of 32 MPa has been used to determine the bi-linear strength segments. The residual responses are consistent with those documented in Sainsbury et al. (2016).
Each of the simulated geomechanical domains dips 80° towards the east and has a north-south strike – approximate to the major structures and stiff dolerite domain at Palabora. An in situ stress regime of $\sigma_H/\sigma_V = 2.0$ (East – West) and $\sigma_H/\sigma_V = 1.5$ (North – South) is simulated. The model includes an 800m open pit immediately above the underground workings. A simplified drift geometry (5m × 5m square cross-section) is modelled for 5m advancements at a depth of 1200m - perpendicular to the strike of the units. Development advances towards the stiff dyke (D) before entering the Shear Zone (S). **Figure 4-5** presents the three-dimensional model geometry.

**Figure 4-5**: Simplified 3D model geometry and geomechanical domains

Two geological exposure scenarios have been considered that are presented in **Figure 4-6** that include an excavation that is developed:

a) with all faces exposed in the same geomechanical domain.

b) on the perimeter of a stiff dyke ‘D’ and shear zone ‘S’. Geological contacts are exposed within excavation faces.

Variances in the violent failure potential based on the above geological exposure profiles have been determined for four development stages within the model that include:

I) First exposure of the dyke in the excavation face
II) Development in the dyke
III) Development in the shear zone
IV) Development only in the orebody
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### 4.5.2 Calculation of $I_{VFSE}$

Figure 4-7 through Figure 4-10 present a compilation of results for each of the stages of development in each of the geological exposure scenarios. Numerical outputs include; geometry/geology, $\sigma_1$, plasticity state, and the calculated $I_{VFSE}$ for each of the expose face zones in the model. The $I_{VFSE}$ values have been calculated based on the descriptions in Section 4.4.3.

It should be noted that the results of these simulations are specific to geometry and the advance rate simulated. Therefore, the model time-step is not related to ‘real-time’ and so the rate of energy release cannot be commented on. Rather, the simulations can be used to determine comparative behaviour.

The model results as the development intersects the dyke for the first time (Stage I) are presented in Figure 4-7. Tensile failure is indicated in the dyke at this development increment. An increase in $\sigma_1$ by 150% is observed in the dyke compared to the ore and/or HW/FW. The calculated $I_{VFSE}$ suggests an increased potential in the dyke, with the greatest value calculated at the stiff dyke/ore contact in the drive face. The stiffness difference between these domains is approximately 150%.

The model results as the development advances through the dyke (Stage II) are presented in Figure 4-8.
Chapter 4: Numerical Simulations: Severity of Violent Failures

Figure 4-7: Models for development scenarios ‘a’ (top) and ‘b’ (bottom) in the stage ‘I’ of the advancement – immediately before intersecting the dyke

Figure 4-8: Models for development scenarios ‘a’ (top) and ‘b’ (bottom) in the stage ‘II’ of the advancement – approximately half way through the dyke
Tensile and shear failure is indicated in the stiff dyke at this development increment. Shear failure is observed in the ore. An increase in $\sigma_1$ by 150% is also observed in the stiff dyke compared to the ore and/or HW/FW. The calculated $I_{VFSE}$ suggests an increased potential (1.0) at the dyke/ore contact in the drive face and walls.

It can also be inferred from the Figure 4-7 that a greater exposure of the contacts (i.e. in the case ‘b’ where the drift is developed on the perimeter of the intrusive materials) resulted in higher potential for violent energy release during these failures.

The model results as the development advances through the shear zone (Stage III) are presented in Figure 4-9.

Figure 4-9: Models for development scenarios ‘a’ (top) and ‘b’ (bottom) in the stage ‘III’ of the advancement

Primarily shear failure is indicated in the ore at this development increment. Tension is observed at the ore/shear zone interface. A decrease in $\sigma_1$ by 50% is observed in the shear zone compared to the ore. The calculated $I_{VFSE}$ suggests no potential for violent brittle failure when a geological contract is not created (i.e. case “a”, where the drive is fully excavated into the shear zone). However, $I_{VFSE}$ increases significantly (2.5) when the excavation exposes higher contrasting geological units (at length) in the back/shoulder of...
the excavation some distance (2-3 times drive diameter) from the face. This area is usually associated with high $\sigma_1$ stresses, as observed in Figure 4-9.

The model results as the development advances only into the orebody (Stage IV) are presented in Figure 4-10.

Figure 4-10: Models for development scenarios ‘a’ (top) and ‘b’ (bottom) in the stage ‘IV’ of the advancement

Primarily shear failure is indicated in the ore at this development increment. An increase in $\sigma_1$ of 150% is observed in the excavation shoulders and floor. With the exception of the zones at the contact of the shear/ore, the calculated $I_{VFSE}$ suggests no potential for brittle failure at this development stage. This can be attributed to the absence of geological contacts and/or due to the dominant shear-only mode of failure.

4.5.3 Consideration of the Induced Stress-Path

It is commonly recognized that strain-bursts occur in over-stressed rock masses (Li et al., 2017). In order to investigate specific stress paths within the models a number of unique locations have been considered in the following section. The location of the stress histories considered are presented in Figure 4-11. Table 4-2 presents a summary of the location of each of the selected 12 history locations.
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Table 4-2: Stress-Path Location and Maximum $I_{VFSE}$ calculated in the numerical models

<table>
<thead>
<tr>
<th>Contact location</th>
<th>Location ID (host unit)</th>
<th>Maximum $I_{VFSE}$ calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dyke – Ore</td>
<td>$D_1$ (Dyke)</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>$O_1$ (Ore)</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>$D_2$ (Dyke)</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>$O_2$ (Ore)</td>
<td>0.0</td>
</tr>
<tr>
<td>Dyke - Shear</td>
<td>$D_3$ (Dyke)</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>$S_1$ (Shear Zone)</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>$D_4$ (Dyke)</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>$S_2$ (Shear Zone)</td>
<td>0.0</td>
</tr>
<tr>
<td>Shear Zone – Ore</td>
<td>$S_3$ (Shear Zone)</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>$O_3$ (Ore)</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>$S_4$ (Shear Zone)</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>$O_4$ (Ore)</td>
<td>3.15</td>
</tr>
</tbody>
</table>

Figure 4-11: A fully excavated model in scenario ‘b’, with the selected contacting elements Dyke/Ore units ($D_1$-$O_1$ and $D_2$-$O_2$) and Dyke/Shear ($D_3$-$S_1$ and $D_4$-$S_2$) and Shear/Ore units ($O_3$-$S_3$ and $O_4$-$S_4$) for stress path analysis. Dashed lines specify units’ boundaries as the drift excavated through the dyke (top) to the shear and ore-only units (bottom)
Figure 4-12 presents the principal stress paths, as derived from the numerical model, for each of the history locations summarised above.

**Figure 4-12:** Stress paths during excavation for each of the history locations presented in Table 4-2

History locations O₃ and O₄ (located in the ore) present the highest $I_{VFSe}$ values (above 3). These values correspond to stress paths that enter the DISL compressive region and are located on the ore-shear contact (domains provide the highest stiffness contrasts). The
other two ore history locations show only a decrease in confinement and do not enter the DISL zone and therefore no violent failure is expected associated with these stress changes. No violent failure is expected in the shear zone domain since the DISL region plots well above the shear zone strength (e.g. $\sigma_1$ stress values to drive violent failure are well above the strength of the shear zone. The DISL zone is plotted on the stress-path figure for reference in this region to demonstrate this point).

Elevated $I_{VFse}$ values (0.19-0.85) are observed for the stress paths located in the Dyke. However, in each of these cases the stress-path does not enter the DISL zone (in fact the stresses do not reach damage threshold values and only tensile failure is observed).

### 4.6 Summary and concluding remarks

This study considers the severity of a violent brittle failure (strain-bursting) around the vicinity of complex underground excavations. The index incorporates measures of the induced stress path and accumulated plastic strain and is calculated after brittle failure conditions are identified by the established Damage Initiation and Spalling Threshold $s$ (DISL). Implemented within a numerical modelling code, the index can be used to complete relative hazard assessments (sensitivity analyses) based on spatial variances in geometry and geology. The impact of contrast in geological domains (e.g. Fern et al., 2017; Yang et al., 2017, 2018) is clearly demonstrated through a numerical implementation of the index.
Chapter 5

Development of a Strain-burst Risk Assessment Methodology

This chapter documents a new method to evaluate the potential risks associated with violent failures around underground excavations.

Highlights of the newly developed risk assessment technique include:

- Likelihood of strain-bursting is considered through parameters that include potential for violent failure (and its relative severity from Chapter 4), frequency of potential events, and potential size of damage
- A vulnerability index based on potential personnel exposure and failure location assesses the consequence of a strain-burst occurring

The risk assessment methodology communicated throughout this chapter is a copy of a revised manuscript submitted to the journal of ‘Engineering Geology’.

5.1 Introduction

The term ‘rockburst’ is used to describe a seismic event that generates enough energy to cause violent failure of the rock mass. Three identified dynamic failure modes of a rock mass are presented in Figure 5-1. The unpredictable nature of these events has historically made them challenging to predict and mitigate. As a result, rockbursts still represent one of the most serious hazards affecting the safety, economics and productivity of underground operations (Cai & Kaiser, 2018).

From an extensive micro-seismic data analysis, Ma et al. (2015) and Liu et al. (2018) proposed that a correlation exists between the occurrence of rockbursts and influencing factors, such as geological structure, construction method, and excavation disturbance. Presented in the Chapter 2, the author has compiled a comprehensive catalogue of previously published case study data associated with rockburst occurrences to identify precursor behaviour. Indicators included stress conditions (including both in-situ, induced, orientation and magnitude) and rock mass characteristics (including mineralogy, contrasting properties and geological intensifiers). From a review of case study data, it was clear that the elimination of rockburst hazards in many cases is impossible. However,
strategic (global) and tactical (local) measures can be effective in minimising both the frequency and consequences of the events (Feng et al., 2013; Wang & Kaunda, 2019; Whyatt et al., 2002).

Seismic data analysis via event clustering (Brown et al., 2015; Hudyma, 2009; Hudyma & Potvin, 2010; Feng et al. 2019a; Potvin et al., 2019ab; Potvin & Wesselloo 2013ab; Wesselloo, 2018,2019) is the most common strategic risk management tool practised by the mining industry to manage seismic risk. However, the success of such techniques is subject to the availability and quality of seismic data and an in-depth understanding of the in-situ and induced geomechanical conditions. Such information may not always be available - particularly in the preliminarily stages of excavation development and/or design. Thus, if burst-prone areas (or designs) can be identified before they are implemented, precautionary measures may be implemented (Singh, 1989) and/or the effectiveness of alternative designs can be considered (Whyatt et al., 2002).

The design of dynamic support is a case of an ‘indeterminate problem’, as there are few means of reliably estimating the demand or the capacity of ground support subjected to the dynamic loading of an incumbent seismic wave (Stacey, 2012). In particular, the effect of rock mass anisotropy on the seismic wave radiation pattern can be significant (Hildyard 2007). Hence, it is difficult to specify effective rockburst control plans prior to events being observed (Kidybinski 1981). Due to this difficulty, numerical simulations can be employed in the initial stages of mine planning and geotechnical designs (i.e. well in advance of seismic data becoming available) as a tool to indicate potentially high-risk scenarios that warrant a more detailed quantitative analysis and perhaps would require an investment in dynamic support.
Since existing rockburst evaluation techniques are empirical in nature (Hudyma, 2009; Feng et al. 2019ab), their use is limited to locations where seismic monitoring data is available. In instances of limited data and observations, a semi-quantitative index-based, geo-hazard assessment approach is proposed - similar to Rizkalla (2008). The proposed technique outlined in this chapter is intended to be most useful to when seismic data is not available e.g. during pre-feasibility or feasibility stage studies. As development progresses and seismic data is gathered, the proposed method provides an additional level of detail to confirm/inform the empirical risk assessment techniques. The methodology proposed has the flexibility and robustness to be improved by the availability of site investigation data and relative effectiveness of mitigation techniques as the engineering / development phase progresses (Figure 5-2).

![Flowchart of the procedure of indexed-based geo-hazard assessment](after Rizkalla, 2008)

**5.2 Development of a strain-burst risk criteria**

The scope of this risk-related research is limited to strain-bursts since they represent a sub-set of seismic events that are often misunderstood (Lee et al., 2018). Strain-bursts relate to seismic source mechanisms associated with spalling and violent ejection. They have previously been related to the short-term elevated stresses around a new opening (Kaiser et al., 1996). Historically they have been undetected until encountered and have
Richter Magnitudes 0.2-0.0 (Ortlepp, 2005). The lack of detection of such seismic mechanisms, and their high frequency (Whyatt et al., 2002) poses a risk for personnel working in active areas. To allow engineers to recognise and better manage such situations, a better understanding of the underlying reasons for their occurrence and the establishment of a framework for managing their risk is required. The typical geometry and characteristics of a strain-burst event are presented in Figure 5-3 and have been described in detail in previous chapters.

The methodology presented herein guides the estimation of strain-burst risk through the consideration of parameters that are known to contribute to, or increase the consequences of, strain-burst events. Using the proposed numerical approach, the risk of strain-bursting can be considered for different excavation scenarios in order to choose an optimum solution prior to significant capital expenditure.

The risk assessment procedure is based on the conventional risk assessment matrix, e.g. Risk = Probability × Consequence. The “Probability” component of the risk is correlated to the likelihood of occurrence/reoccurrence of strain-burst events based on the state of a rock mass before and after failure as well as the amount of energy dissipated/available after each event. The “Consequence” part of the risk value is considered by the vulnerability of an element at risk subject to the potential severity of each event.

The indices are quantitatively derived based on the results of numerical simulations and can be used to rank relative risk between alternate designs and/or mitigation strategies. A similar approach for the consideration of geohazard related damage to underground pipes has been implemented by Rizkalla (2008).

Figure 5-3: Typical geometry of a strain-burst event (left: schematic of the mechanism, right: an image of the event)
5.2.1 Quantification of the likelihood component of the risk matrix

The likelihood of strain-bursting has been categorised by means of a series of index parameters that have been quantified by values ranging from most likely (1.0) to unlikely (0.0). Likelihoods in between these upper and lower bounds (of 1.0 and 0.0, respectively) are scaled by an order of 10 (e.g., 0.1, 0.01, etc.) to reflect the diminishing/increasing contribution to the occurrence of an event. It is important to note that this likelihood scale is arbitrary and reflects only a relative contribution to the likelihood of an event occurring – it does not reflect a probability and, therefore, must be considered a qualitative assessment only.

(I) Pre-failure Damage Index ($I_D$)

Stresses around underground openings are influenced by in-situ stresses, excavation geometry and rate and direction of the excavation advance (Hudson & Harrison, 1997). Induced stresses can also be affected by lithology and structure (Chapter 2). As a result of this, the estimation of a rock mass response to complex and dynamic stress paths requires the prediction of both the pre-peak and post-peak strength and deformation behaviour.

The damage induced in a rock mass during loading/unloading can be indicated through a measure of the dynamic deformation modulus: e.g. As a rock mass is stressed beyond the elastic threshold (~ 35% to 50% of the peak strength), plastic (irreversible) damage is accumulated. As the volume of new cracks gradually increases after a sample exceeds the yield stress, plastic deformation develops until a maximum bearable stress is reached. Within these two stress limits (i.e. yield to peak stresses) the rock mass bulks/dilates and the deformation modulus decreases (Sainsbury, 2018).

The stress-strain characteristic behaviour is best observed in a laboratory experiment of a Uniaxial Compressive Strength (UCS) test (e.g. Figure 4-1). The value of hardening modulus $H$ as illustrated in Figure 5-4 can be used to assess the rate of damage (softening) within the rock mass prior to it exceeding its peak strength (failure). From this figure, the instantaneous modulus is normalised to the in-situ deformation modulus (hereby described as $H_n$ after Rybacki et al., 2016) and is described by Equation 5.1.

$$H_n = \frac{1}{E_{rm}} \left( \frac{\sigma_f - \sigma_i}{\varepsilon_f - \varepsilon_i} \right)$$ (5.1)
where $\sigma_i$ and $\sigma_f$ are the initial and final maximum principal stress levels for an excavation increment, $\varepsilon_i$ and $\varepsilon_f$ are the initial and final total strains level before and after the excavation increment, and $E_{rm}$ is the in-situ (pre-excavation) deformation modulus of the rock mass. All these values are easily obtainable from standard three-dimensional, non-linear constitutive models.

An increasing value of $H_n$ suggests that damage is not occurring, and that energy is being stored. This is considered the highest risk for violent strain-bursting. A lower $H_n$ value reflects that damage (and energy release) is occurring gradually in the rock mass. These values represent some risk, but strain-burst events are likely to be smaller and more frequent (e.g. spitting). As $H_n$ approaches 0 the rock is approaching a fully bulked/damaged state and strain-bursting is unlikely since stored energy has already been dissipated.

Figure 5-4: Stress-strain characteristics of a brittle rock approximated by linear behaviour. ($\sigma_e$: elastic stress; $\sigma_{ci}$: crack initiation stress (onset of dilatancy); $\sigma_{peak}$: peak stress; $\sigma_r$: residual stress; $\varepsilon_e$: elastic strain; $\varepsilon_p$: plastic strain; $\varepsilon_{ci}$: strain at onset of dilatancy (crack initiation); $\varepsilon_{peak}$: strain at peak stress; $\varepsilon_r$: residual strain; E: Young’s modulus; H: hardening modulus; $H_n$: normalised hardening; and M: softening modulus) – after Rybacki et al. (2016)

Table 5-1 provides assigned risk values for a derived Damage Index ($I_D$) for varying values of $H_n$. A lower hardening rate indicates a damage that progresses gradually and is
potentially amenable to monitoring and intervention. This translates into reduced risk compared to a sudden violent failure. From experimental works by Rybacki et al. (2016), values of $H_n$ less than 0.3 indicates a ductile behaviour and values greater than 0.6 or 0.8 are related to a brittle behaviour (0.7 was adopted from this range for the upper band of the criteria in Table 5-1).

<table>
<thead>
<tr>
<th>$H_n$ State</th>
<th>Io Risk value</th>
<th>Io Risk description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_n \leq 0.3$</td>
<td>0.01</td>
<td>Most Unlikely</td>
</tr>
<tr>
<td>$0.7 &gt; H_n \geq 0.3$</td>
<td>0.1</td>
<td>Some likelihood</td>
</tr>
<tr>
<td>$1 &gt; H_n \geq 0.7$</td>
<td>1.00</td>
<td>Most likely</td>
</tr>
</tbody>
</table>

(2) **Post-Failure Energy Release Index ($I_{EF}$)**

Violent failure can be characterised by brittle failure that is coupled with rapid ejection (Akinbinu, 2017). The brittleness of a rock not only represents the severity of strength loss after failure (Lu et al., 2018), but also indicates its ability to withstand inelastic deformations before failure (Hajiabdolmajid & Kaiser, 2002; Li et al., 2017; Martin, 1997; Xu et al., 2017; Zhao et al., 2019).

Strain energy analysis with the aid of numerical modelling is useful in prediction of rockburst (Wang & Park, 2001). The severity index for in-situ violent failure ($I_{VFse}$) described in Chapter 4 can be implemented in non-linear numerical modelling codes (e.g. 3DEC or FLAC3D) to identify the potential severity of rock mass violent failure through a stress-strain path/state dependant index. Here the author is using 3DEC. The methodology can also provide indicative estimates of the accompanying energy release to recognize critical states such as elastic pre-peak state, ductile post-peak state, brittle yielding (post-peak) and, at or beyond residual state after a brittle failure.

The “$I_{VFse}$” index combines the effect of the stress drop after failure and accumulated strains pre- to post-peak for a current failed state (of a numerical model zone), given by the Equation (5.2):

$$I_{VFse} = \left| \frac{(\sigma_{peak} - \sigma_{current})(\varepsilon_{current} - \varepsilon_{yield})}{\varepsilon_{residual} \times (\sigma_{peak} - \sigma_{residual})} \right|$$  \hspace{1cm} (5.2)
where $\sigma_{\text{current}}$ is the observed stress and $\varepsilon_{\text{current}}$ is the observed total strain during failure, $\sigma_{\text{peak}}$ is the peak stress, $\sigma_{\text{residual}}$ is the residual strength, $\varepsilon_{\text{yield}}$ is the maximum elastic (yield) strains, and $\varepsilon_{\text{residual}}$ is the minimum total strains required to mobilise the residual strength properties.

The susceptibility of a rock to spalling and/or strain-bursting has previously been defined on the lower limits by a coupled Damage Initiation and Spalling Thresholds (DISL) (Diederichs, 2003, 2007; Diederichs et al., 2004; Eberhardt et al., 1998). When these two limits are satisfied by the stress path taken by the rock mass, the brittleness criteria (i.e. Equation 5.2) is checked to see if the material experience a violent failure. The severity of such failure is proportional to the calculated $I_{VFSe}$ value.

A proposed Energy Release Index ‘$I_E$’ for varying failure states as identified through numerical simulation is provided in Table 5-2. The 0.5 limiting value of $I_{VFSe}$ in this table is based on the back-analysis example conducted in this study. More case study should be conducted to further classify the severity levels associated with $I_{VFSe}$ between 0.0 to 1. It should be noted that any index of brittleness that gives a relative estimation of the severity of a violent failure may be used for the $I_E$ assignment. A summary of the most common brittleness indices and their corresponding evaluation processes can be found in Raybacki et al. (2016) and Kivi et al. (2018).

Table 5-2: Energy release index ($I_E$) defined by IVFse values

<table>
<thead>
<tr>
<th>$I_{VFSe}$ State</th>
<th>$I_E$ Risk value</th>
<th>$I_E$ Risk description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failed in a ductile manner ($I_{VFSe} = 0.0$)</td>
<td>0.001</td>
<td>Failure has already occurred. Insignificant likelihood of further energy events</td>
</tr>
<tr>
<td>Induced stresses within DISL zone ($I_{VFSe} = 0.0$)</td>
<td>0.01</td>
<td>Some likelihood of a violent brittle, energy release event however brittle failure stress conditions are not satisfied for the assessed rock mass sample scale</td>
</tr>
<tr>
<td>Brittle failure condition is satisfied ($0 &lt; I_{VFSe} &lt; 0.5$)</td>
<td>0.10</td>
<td>$I_{VFSe}$ is satisfied, however less energy has been released at current state</td>
</tr>
<tr>
<td>Brittle failure condition is satisfied ($I_{VFSe} &gt; 0.5$)</td>
<td>1.00</td>
<td>$I_{VFSe}$ is satisfied, and significant energy has been released after failure (e.g. residual state has been reached or strain passed beyond the minimum residual strain)</td>
</tr>
</tbody>
</table>

(3) Frequency Index ($I_F$)

For average mining development sizes, Kaiser et al. (1996) classify seismic event magnitudes based on the depth of damage and volume of material moved. The classification is presented schematically in Figure 5-5.
Chapter 5: Development of a Strain-burst Risk Assessment Methodology

Based on these descriptions, a Frequency Index ‘\( I_F \)’ has been defined to characterize the potential reoccurrence of strain-bursts in active excavations. In general, it is likely that smaller failure events (in terms of volume/area as well as magnitude of released energy) are more frequent than larger events. The reoccurrence is based on a conservative presumption that failures involving a volume less than “minor damage” have not released all their accumulated energy during their most recent activity. Since energy in these instances is being accumulated, it is expected that a strain-burst may occur during future excavation events. The likelihood of a strain-burst event is further increased when remote seismic triggers (e.g. fault slip activity and/or nearby blasting) exist.

Table 5-3 represents the relative risk values assigned for \( I_F \) based on the simulated volume of the damaged zones in a numerical simulation along with the consideration of the presence of remote triggers (e.g. faults) for the same timeframe. Although the presence of a fault may not always contribute to seismicity, faults do influence the flow of stress around excavations (Snelling et al., 2013) and/or induce rockbursts in the competent rock mass adjacent to the fault (Manouchehrian & Cai, 2018; Rehbock-Sander & Jesel, 2018; Simser, 2019).

In the software utilised in this study (3DEC), the volume of each zone is queried when brittle failure is observed. The total volume of the yielded rock mass is calculated, and the instance of remote triggers is considered to determine an \( I_F \) value. The 5% damage area limit in Table 5-3 has been related to an average mining development size (e.g. similar to Kaiser et al., 1996) and is equivalent to 25% of the faces of a 4m x 4m x 4m development advance – see Figure 5-6. It represents a quantity of rock that is approximately equivalent to the ‘minor’ damage defined by Kaiser et al. (1996).
Table 5-3: Frequency index ‘$I_F$’

<table>
<thead>
<tr>
<th>Description</th>
<th>$I_F$ Risk value</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damaged face area &gt;10% total active face</td>
<td>0.01</td>
<td>Rock mass damage (more than moderate) is observed. Majority of the accumulating energy has been dissipated</td>
</tr>
<tr>
<td>Remote triggers do not exist</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Damaged face area &gt; 5 – 10% of total active face</td>
<td>0.10</td>
<td>Increased rock mass damage (at least minor) is observed. Some of the accumulating energy has been dissipated</td>
</tr>
<tr>
<td>Damaged face area &lt;5% total active face</td>
<td>1.00</td>
<td>Rock mass damage (less than minor) is observed. Majority of the accumulating energy has not been dissipated</td>
</tr>
<tr>
<td>Remote triggers exist</td>
<td></td>
<td>Dynamic triggers exist</td>
</tr>
</tbody>
</table>

Figure 5-6: Schematic representation of 5% damaged area in an active advance
5.2.2 Characterization of the consequence component of the risk matrix

(I) Vulnerability Index \( (I_V) \)

Based on data by Whyatt et al. (2002), 90% of seismic events localise around active areas of an excavation. Heal et al. (2006) further show that in the case of an event, 65% of the damage occurs in the roof and 35% in the sidewalls. Based on these observations (which are dependent on the in-situ stress regime and other geological and geomechanical factors of the site), a Vulnerability Index \( 'I_V' \) has been developed for personnel working in strain-burst prone excavations. Inferred from the statistical data high (increased) hazard areas are considered to be (a) at active faces and (b) closer to the back/roof or face. This relates to personnel performing activities such as drilling, charging, or installing ground support having the highest vulnerability to strain-bursting.

A vulnerability risk index, \( I_V \), is defined in Table 5-4.

Table 5-4: Vulnerability index \( 'I_V' \) based on location of the failure

<table>
<thead>
<tr>
<th>Personnel exposure and damage location</th>
<th>( I_V ) Risk value</th>
<th>( I_V ) Risk description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited exposure – Remote location</td>
<td>0.01</td>
<td>Most unlikely</td>
</tr>
<tr>
<td>Active excavation – Failure identified in walls and/or floor</td>
<td>0.10</td>
<td>Some likelihood</td>
</tr>
<tr>
<td>Active excavation – Failure identified in back/roof/shoulders/face</td>
<td>1.00</td>
<td>Most likely</td>
</tr>
</tbody>
</table>

5.3 Risk assessment procedure

Following the assessment of the strain-bursts hazard criteria described in Sections 5.2.1 and 5.2.2, a risk assessment can be completed. In the absence of mitigation measures, the risk of strain-bursting \( 'R_{SB}' \) can be defined by the product of the likelihood indices \( I_D, I_E, \) and \( I_F \) and the vulnerability (consequence) index \( I_V \) through Equation (5.3). Here, we assume that the consequence is rated by the exposure of the personnel to the hazard occurring (which is certain in this case). For an example, if a strain-burst occurs, but is remote, then the consequence is less than if a stain-burst occurs at the working face and personnel are charging a blast-hole.

\[
R_{SB} = I_D \times I_E \times I_F \times I_V \tag{5.3}
\]

The resulting \( R_{SB} \) values can be used to complete a sensitivity analysis and rank excavation designs against each other to assist with design decision making. To aid in the communication of the risk results, a simplified risk scale is presented in Table 5-5.
Table 5-5: Descriptive strain-burst risk criteria

<table>
<thead>
<tr>
<th>Calculated $R_{SB}$</th>
<th>Risk Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{SB} \leq 10^{-6}$</td>
<td>S1 - Insignificant</td>
</tr>
<tr>
<td>$10^{-6} \leq R_{SB} &lt; 10^{-4}$</td>
<td>S2 - Low potential</td>
</tr>
<tr>
<td>$10^{-4} \leq R_{SB} &lt; 10^{-2}$</td>
<td>S3 - Some potential</td>
</tr>
<tr>
<td>$10^{-2} \leq R_{SB} &lt; 10^{-1}$</td>
<td>S4 - High potential</td>
</tr>
<tr>
<td>$R_{SB} \geq 10^{-1}$</td>
<td>S5 – Significant potential</td>
</tr>
</tbody>
</table>

The risk value is a product of the three likelihood and one consequence components detailed in Section 5.2. The risk outcome can be assessed based on each of the contributing components. For example, a $R_{SB} \geq 0.1$ means all four indices have been determined to be at the highest risk value of 1.0, or that three of the indices are determined to be at their highest level (index value = 1.0) and one is deemed to be at the second most critical level (index value = 0.1). In terms of severity of the risk level (e.g. if a design should change at a risk level of 0.1 or 0.01), this will depend on the reliability of the assessment (e.g. site confirmations, previous incidents, etc.) as well as the level of risk acceptance by the owner (e.g. a socio-economical judgment).

5.4 Implementation of the risk framework to numerical modelling results

5.4.1 Simulation description

Implementation of the proposed risk assessment methodology has been conducted based on a conceptual numerical model of the Palabora Mine in South Africa – first presented in Chapter 4. The model includes a range of contrasting geomechanical domains that are described as MPY “Waste”, FOS “Hangingwall/Footwall”, BCB “Ore”, DOL “Dyke”, and FAULTS “Shear Zone”. Material properties used are consistent with those used in Chapter 4 (Table 4-1) and validated through back-analysis (Sainsbury et al, 2016).

A bilinear Mohr-Coulomb fit to the Hoek-Brown curve was used to represent the peak strength properties within the numerical analysis. The Mohr-Coulomb constitutive model is used since softening of the shear strength parameters (cohesion and friction angle) in this model is straight-forward. A bi-linear ‘fit’ allows the cohesion and friction angle to be determined for two intervals of confining stress which provides a more accurate result.
As rock mass begins to yield and exhibit large-scale deformation it undergoes stress reduction (stress shedding). In most cases, the stress shedding and deformation continues until a residual strength value is reached. This behaviour is described as strain-softening. Within a strain-softening material model, the post-peak strength behaviour is a function of plastic shear strain.

The plastic shear strain required in going from peak strength to a residual value defines the critical plastic strain or brittleness of the rock mass. Sainsbury (2012) has previously reported a relationship for critical plastic strain of a jointed rock mass based on Geological Strength Index (GSI) (Hoek & Brown, 1997). The relationship has been validated based on numerical back-analyses of a multiple case studies. One of these was the Palabora Mine (Sainsbury et al., 2016).

Each of the simulated geomechanical domains dips 80° towards the east and has a north-south strike – approximate to the major structures and stiff dolerite domain at Palabora. An in-situ stress regime of $\sigma_h/\sigma_v = 2.0$ (East – West) and $\sigma_h/\sigma_v = 1.5$ (North – South) is simulated. The model includes an 800m open pit immediately above the underground workings.

Within the mining sequence, a simplified drift geometry (5m×5m square cross-section) at a depth of 1200m is advanced in 5m lengths. The advance is perpendicular to the strike of the geomechanical domains. The first 100m of the drift is excavated in the FOS Hangingwall Domain, followed by the second half excavated in the BCB (Ore zone). As the drift enters the Ore, it partially exposes the stiffer dyke/ore followed by the less-stiff shear zone/ore contacts. Each of the exposures is 20m in length, or four advances. Figure 5-7 presents a cross section of the three-dimensional model geometry.

Within the numerical model, for each time-step, the four risk indices proposed in Section 5.2 are calculated for each zone exposed in, or near the surface of the excavation. By calculating the risk indices for each of the zones, rock mass strain-bursting potential can be considered. The calculation process for each zone is described as follows:

1. The simulated post-yield to pre-failure state strain and principal stress values are used to calculate ‘$I_D$’.

2. When a failure state is observed within the zone (i.e. the peak strength has been reached), the stress path of the zone is considered according to the guidelines
outlined in Chapter 4. If the stress path has been determined to enter the DISL region, $I_{VF_{sg}}$ values are determined and ‘$I_E$’ is calculated.

3. The total failed / yielded volume as well as its location is considered in order to evaluate ‘$I_F$’ and ‘$I_V$’.

![Diagram](image.png)

**Figure 5-7**: a) Cross-sectional view of the simplified 3D model geometry and geotechnical domains; (b) drift geometry and the geotechnical units excavated

The product of the four indices is calculated (i.e. $R_{SB}$ is determined) and the value is stored as an extra zone variable so it can be recalled and contour-plotted at each development stage. This stored value of $R_{SB}$ represents the strain-burst risk ranking outcome for that zone (rock mass) for those specific in-situ conditions. Forward predictions can be compared with actual performance and geomechanical parameters can be calibrated to provide better reliability of the model when seismic data is available.
5.4.2 Results and discussions

Detailed simulation results of conceptual model of the Palabora Mine are provided in Chapter 4. Figure 5-8 presents a cross-section through the model in the potential problematic area (i.e. zones that report a higher $I_{VFE}$ index). Through Figure 5-8 it is clearly observed that the FOS and BCB domains located near the dyke and shear zones have a higher potential for a violent release of energy. This is demonstrated through the variations in the $I_{VFE}$ index that are increased at these locations.

![Figure 5-8: Select model results in area of focus: a) geomechanical domains, b) plasticity states, c) re-distributed in-situ stress, d) relative severity of violent failure](image)

Figure 5-9 presents the associated strain-burst risk calculated for this area as the drift intersects the Dyke (Figure 5-9a) and then transitions from the Dyke to the Shear (Figure 5-9b). These values are calculated from the $I_{VFE}$ index (considered within the risk framework as $I_E$) that are presented in Figure 5-8, and a consideration of the other three risk index values established herein ($I_D$, $I_F$, $I_E$).

From Figure 5-9a it is observed that the greatest strain-burst risk ($R_{SB}$) is calculated in the wall of the drive at the Dyke/Ore contact. At this location tensile yield is recorded and increased $R_{SB}$ values of $\sim 1e-3$ are calculated. From Figure 5-9b it is observed that that the greatest strain-burst risk ($R_{SB}$) is calculated in the back and walls of the drive at the Shear/Ore contact. At this location both tensile and shear yield is recorded and increased $R_{SB}$ values of $\sim 1e-4$ are calculated.

Figure 5-10 presents the overall geometry of the model at the end of the drift development. Calculated $R_{SB}$ values are presented, and three locations/zones ‘D’, ‘S’, and ‘O’ are
identified for further consideration. For each location (‘D’, ‘S’, and ‘O’) the four indices and the associated risk at the time of exposure ($t_0$) and three subsequent time increments ($t_0 + \Delta t$, $t_0 + 2\Delta t$, and $t_0 + 3\Delta t$) are presented in Table 5-6. These time increments related to successive 5m drift advances.

Figure 5-9: Calculated strain-burst potential and the associated failure modes a) Stiff dyke and ore contact; b) Shear zone and ore contact
Chapter 5: Development of a Strain-burst Risk Assessment Methodology

Figure 5-10: Location of three history points D (located in the dyke), S (located in the Shear zone), and O (located in the Ore). The boundary of each geomechanical domains is highlight by the yellow dashed line/s

Table 5-6 shows that:

1. The Damage Index ($I_D$) at location ‘D’ is higher than that of the Ore at location ‘S’ and ‘O’. This is a direct result of the comparative strength and stiffness of the units. E.g. The Dyke is the strongest and stiffest unit.
2. The Post-Failure Energy Release Index ($I_E$) is greatest at locations ‘D’ and ‘S’ indicating calculated $I_{VFse}$ values greater than 0.5.
3. The Frequency Index ($I_F$) is greatest at locations ‘D’ and ‘S’ indicating that the damaged / yielded area is calculated to be between 5 and 10% of the total active face in each case. The yielding at location ‘O’ is less than this.

4. Vulnerability Index values ($I_V$) are similar in all cases and greatest at $t_0$ when the face is being developed.

Table 5-6: Calculated risk indices ($I_D$, $I_E$, $I_F$, & $I_V$) and the associated risk values ($R_{SB}$) at selected locations

<table>
<thead>
<tr>
<th>ID</th>
<th>Location</th>
<th>Exposure Time</th>
<th>Risk Indices and the Calculated Potential ($R_{SB}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$t_0$</td>
<td>$I_D$</td>
</tr>
<tr>
<td>D</td>
<td>Dyke/Ore contact, within the Dyke</td>
<td>$t_0$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t_0 + \Delta t$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t_0 + 2\Delta t$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t_0 + 3\Delta t$</td>
<td>1</td>
</tr>
<tr>
<td>S</td>
<td>Shear/Ore contact, within the Ore</td>
<td>$t_0$</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t_0 + \Delta t$</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t_0 + 2\Delta t$</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$v + 3\Delta t$</td>
<td>0.1</td>
</tr>
<tr>
<td>O</td>
<td>Ore Domain</td>
<td>$t_0$</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t_0 + \Delta t$</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t_0 + 2\Delta t$</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t_0 + 3\Delta t$</td>
<td>0.01</td>
</tr>
</tbody>
</table>

It is observed here through Table 5-6, and important to note that, each of the four contributing indices will change over time (as induced stresses and damage change) and therefore the strain-burst potential must also vary. It is therefore important to conduct a progressive risk assessment during the simulated excavation advance. For example, location ‘D’ has a calculated risk index of $1.e^{+3}$ (i.e. some potential) at the completion of the excavation. However, the highest calculated risk for this location is $1.e^{-2}$ (i.e. high potential). This occurs at the first exposure of this location ($t_0$) when $I_V$ is greatest. However, at location ‘O’ the greatest calculated potential occurs once development has been through this area and mining induced stresses are observed to be higher.

The model results and the risk outcomes can be verified and/or calibrated as development progresses and seismic monitoring and operational data becomes available. It is likely the material geomechanical parameters can be updated to provide better estimates of the Damage Index ‘$I_D$’ and Energy Release Index ‘$I_E$’. These values can be better quantified through a calibration of in-situ conditions. Additionally, observations of seismic events within the operation can be used to develop more site-specific descriptions of the damage.
and source mechanisms. This information can be used to update the Frequency Index ‘$I_F$’ and the Vulnerability Index ‘$I_V$’.

5.5 Summary and concluding remarks

The strain-burst risk assessment methodology outlined herein evaluates four semi-quantitative indices based on the results of numerical simulations. The results can be utilised to identify high risk designs during the early/conceptual design phase when micro-seismic data are not available. The framework provides opportunity for incrementally more detailed information to be included in the numerical analyses as the design phase progresses. Input parameters can also be calibrated to match the geomechanical responses indicated by in-situ seismic data, this provides additional reliability in the technique to provide accurate predictions.

The assessment approach is based on the “likelihood” of the seismic mechanism manifesting as well as potential “consequences” determined herein via numerical simulations. The likelihood of an event is evaluated via three indices including: Pre-failure Damage Index ‘$I_D$’, Energy Release Index ‘$I_E$’, and a Frequency Index ‘$I_F$’. A fourth index, Vulnerability Index ‘$I_V$’, evaluates the potential consequences of the identified hazard.

The resulting strain-bursting risk ‘$R_{SB}$’ is calculated by the product of these indices ($I_D \times I_E \times I_F \times I_V$). The calculated risk can be refined as simulation results are validated or updated by field observations and/or in-situ or laboratory testing.

As demonstrated in the numerical models presented herein, the major principal stress magnitude and predicted failure modes are affected by the presence of geological intensifiers. In terms of response to loading, a less stiff inclusion deforms in ductile manner - dissipating elevated energy, while a stiffer material may accumulate stresses/energy up to a point of brittle fracture when a sudden release of energy occurs (see also Fern et al., 2017; Yang et al., 2017). This is observed in the models through the simulation of different geomechanical domains and their resulting calculated strain-burst risk.
Chapter 6

Conclusions and Future Studies

This chapter presents concluding remarks for the thesis by summarising the results and novel contributions and also includes suggestions for future studies.

6.1 Summary of research findings

The research presented in this thesis develops a methodology to assess a violent failure mechanism and the associated risks for underground excavations through the following steps:

• Literature review and experimental investigations of precursor rock behaviour leading to the strain-burst damage mechanisms,
• Experimental investigation of the stain-burst mechanism in micro-scale,
• Identification of factors affecting the severity of a violent failure, and
• Quantification of the potential risk of violent failures through implementation (and validation) in numerical simulations.

6.1.1 Analytical review of previous studies

From the analysis of published case studies of rockburst events, it was determined that the violent uncontrolled failure of rock masses, is mainly controlled by six factors that include:

• High and/or adversely re-oriented stresses by structures,
• Excavation geometry,
• Excavation rate and direction
• Mineralogical properties
• Contrasting geomechanical properties, and
• Geological intensifiers affecting fracturing behaviour

The first three are categorised as loading associated factors, since they are related to adverse redistribution of the in-situ stress regime in the rock mass. The last three factors can be related to the response of the rock mass due to this unfavourable loading system, which is mainly controlled by its geomechanical properties.
Chapter 6: Conclusions and Future Studies

6.1.2 Experimental investigations of key factors in strain-burst failures

The macro (mine-scale) factors that contribute to rockburst mechanisms were confirmed to be present at the micro-scale, via a SEM observational analysis of rock-burst fragments. It was highlighted that anisotropy, a contrast in geomechanical properties, geometry and contact patterns that are present at the micro-scale can lead to anisotropic material behaviour and stress concentrations that manifest as strain-burst events.

It was established that SEM image analysis assists in the interpretation and validation of failure mechanisms associated with strain-bursting. The findings also signify the importance of micro-structural features. Although a rock block may appear intact at the large-scale, it is seen to contain micro-cracks (sharp contacts), veins (intrusions), and healed joints, all of which may influence its strength and failure mode.

6.1.3 Numerical analysis of strain-burst failures and their relative severity

Based on the findings of the macro and micro-scale investigations, and the consideration of induced stress paths and accumulated damage (plastic strain), an index \( I_{VFS} \) was proposed to assess (a) the likelihood of a violent failure occurring and (b) the severity of the violent failure. The index combines the effect of the stress drop after failure and accumulated strains pre- to post-peak for a current observed state.

The methodology has been applied to a demonstration model that highlights that strain-burst hazard can be related to geological boundaries and their exposure in excavation faces. The impact of contrast in geological domains was clearly demonstrated: a less stiff inclusion deforms in ductile manner - dissipating elevated energy, while a stiffer material may accumulate stresses/energy up to a point of brittle fracture when a sudden release of energy occurs.

6.1.4 Evaluation of the risk associated with simulated strain-burst failures

The risk assessment methodology developed through this research is based on the feasibility of the strain-burst mechanism manifesting and its potential consequences. Risk is evaluated by four indices:

- The post-yield up to pre-failure state variables are used to calculate ‘\( I_{D} \)’, a pre-failure damage index, correlated to the hardening behaviour assessing the rate of damage within the rock mass,
• When the material indicates failure/yielding and if the stress path enters the brittle zone, $I_{VF_{Se}}$ values are determined so that the Energy Release Index $I_E$ is calculated.

• The total failed/yielded volume as well as its location is checked in order to evaluate the frequency index $I_F$, as well as the vulnerability index $I_V$.

• The product of the four indices as described in Chapter 5 (i.e. $R_{SB}$, the quantitative risk value) is stored in an extra zone memory slot so it can be recalled and contour-plotted at each development stage.

From the calculated risk as $R_{SB} = I_D \times I_E \times I_F \times I_V$, high risk designs during the early/conceptual design phase can be identified. This is critically important when micro-seismic data are not available and, empirical approaches for risk assessment are impractical. The framework provides opportunity for incrementally more detailed information to be included in the numerical analyses as the design phase progresses.

### 6.2 Future studies

The core theme of this research was based only on assessment of the mechanism of strain-burst type of violent failures. Although strain-bursts and fault-slip event mechanisms are distinctly separate, they are necessarily related (Ortlepp, 2005). In fact, fault-slip and strain-burst events co-exist in many documented case studies of rockbursts around the world as highlighted in the Chapter 2 of this thesis.

The SEM results from this study clarified that a complex mechanism that includes the interaction of the intact rock, discontinuities, and stress regime/path may result in violent failure events. Hence, the author suggests it is critical to study the link between the strain-burst and fault-slip mechanisms of violent failure mechanisms.

Further consideration of more case study data in relation to rockburst mechanisms and performing additional micro-scale studies of rockburst samples from other sites would make the results of this research more comprehensive.

Through the simulation of different geomechanical domains and the completion of a strain-burst risk assessment for a conceptual model, it was verified that induced principal stress magnitudes and rock mass failure modes are affected by the presence of geological intensifiers and contrasting geomechanical properties. It should be restated that these results are case specific, and more case studies should be completed to validate/verify the
violent failure index as a useful tool to assess the mechanism and relative severity of potential violent failures. While the focus of the risk assessment in this study was to develop a numerical framework, calibration of the proposed values for the four risk indices throughout laboratory and field investigations is critically required. Field observations and in-situ or laboratory testing are suggested to make the approach more robust.
References


References


