ARCHITECTURE OF A CLASSIFICATION SYSTEM TO EVALUATE FAULT SLIP RISK IN A MINING ENVIRONMENT

by

JESSICA LAUREN VATCHER

A thesis submitted to
The Robert M. Buchan Department of Mining
in conformity with the requirements for
the degree of Master of Applied Science

Queen’s University
Kingston, Ontario, Canada
May 2012

Copyright © Jessica Lauren Vatcher, 2012
Abstract

As the depth of mining increases, so does the risk of fault slip related rockbursts. Currently, there is no way to evaluate this risk, however the need for such a system is clear. Fault behaviour in mining environments is the result of a complex interaction between the mining system and the geological system. Although numerous models exist, the wide spectrum of fault behaviour cannot be fully explained. Additionally, these models are phenomenological, resulting in a disconnect between observable parameters and the models of faults.

Fault behaviour is dependent upon the strength of the fault, the stresses acting along the fault, the boundary conditions and fault-system stiffness. Significant work exists in the field of earth science attempting to relate properties of the geological system to fault behaviour. In mining environments, these relationships become increasingly difficult to determine due to the time variable nature of mining activities. In order of importance, the following factors influence fault behaviour: excavations, tectonic history and in situ stress, fault system, fault zone geometry, pore pressure, fault zone slip surface and core, blasting, fault zone damage zone and wall rock and temperature.

Numerical stress analysis models were created to evaluate the influence of excavations, tectonic history and in situ stress and the fault system on fault behaviour.
Excavations were placed in various locations in a fault system. Results showed that there was no clear relationship between excavation location and fault behaviour; small perturbations in the initial state caused significantly different outcomes.

The architectures of many classification and decision support systems were evaluated for purposes of a fault slip classification system. Due to the chaotic nature of fault behaviour and the time variable nature of the factors that influence fault slip, a typical classification system is not an appropriate architecture. Instead, it is recommended that a fault slip risk identification system be created, allowing for the incorporation of historical and live data to create a real time response. Artificial neural networks, numerical stress analysis, data from the identified important factors, and seismic data is recommended to form the basis of the fault slip risk identification system.

Keywords: fault slip, classification, mining, fault behaviour, numerical stress analysis, structural geology, geomechanics
Acknowledgements

It is my pleasure to thank those who made this thesis possible, for without their relentless support, this would not have been achievable.

I owe my deepest gratitude to my supervisor, Steve McKinnon. I am extremely grateful for his thoughtful guidance, support, discussions and revisions throughout this project. His dedication to my personal career development made this a wonderful experience.

I would like to acknowledge the Centre for Excellence in Mining for partial financial support of this project. I am very grateful for all the opportunities they have provided.

I would like to thank all members of my committee, including Dr. C. Pickles and Dr. J. Marshall. Their thoughtful review greatly improved the manuscript.

I am indebted to the faculty and staff of the Robert M. Buchan Department of Mining as well as my colleagues across the campus for their dedication and support. In particular I would like to thank Wanda Badger, Tina McKenna and Kate Cowperthwaite for making the department a home away from home.

I would like to thank Laura Mason (née Branscombe) for her thoughtful discussions
and advice. Her professional and personal insights provided invaluable guidance. Her sense of humour and generous nature brought much needed warmth to my life during the windy and grey Kingston winters.

I would like to thank all of my friends and family for their support throughout this thesis. In particular, I would like to thank my sister, Celeste Vatcher, for always providing a view of the brighter sides of life.
# Table of Contents

Abstract                                                                 i  
Acknowledgements                                                          iii  
Table of Contents                                                          v  
List of Tables                                                              viii  
List of Figures                                                            ix  

Chapter 1: Introduction

1.1 Motivation

1.2 Objective and Scope

1.3 Organization

Chapter 2: Background

2.1 The Mining System, Mine Seismicity and Rockbursts

2.1.1 Seismicity in Mines

2.1.2 Rockbursts

2.2 Geological System

2.2.1 Fault Network
2.2.2 Fault Zone .............................................. 16
    Geometry ............................................. 18
    Slip Surface and Fault Core ...................... 22
    Wall Rock and Damage Zone ..................... 24
2.2.3 Spectrum of Behaviour ............................ 26
2.3 Models and Evaluation of Potential Behaviour .......... 31
    2.3.1 Fault Stability Models and Techniques .......... 33
    2.3.2 Fault Behaviour Models ..................... 38
2.4 Characterization and Decision Systems .................. 45
    2.4.1 Considerations .............................. 46
    2.4.2 Characterization, Classification Systems, Empirical Design Tools 
        and Decision Support Systems ................... 47
    2.4.3 System Characteristics ..................... 55
2.5 Summary .............................................. 56

Chapter 3: Controls of Fault Behaviour and Preliminary Evaluation

    for Classification System .......................... 59
3.1 Mining System Controls ................................ 64
    3.1.1 Excavations .................................. 64
    3.1.2 Blasting .................................... 67
    3.1.3 Pore Pressure ................................ 68
3.2 Geological System Controls .......................... 73
    3.2.1 Tectonic History and In Situ Stress .......... 73
    3.2.2 Temperature .................................. 76
3.3 Fault Network and Fault Zone Controls ................. 77
3.3.1 Fault Network ........................................ 78
3.3.2 Fault Zone Geometry ................................. 82
3.3.3 Slip Surface and Fault Core ......................... 88
3.3.4 Wall Rock and Damage Zone ......................... 97
3.4 Summary .................................................. 101

Chapter 4: Classification System Architecture ................. 105

4.1 Evaluation of Inputs .................................. 105
4.2 On the Interaction of the Geological and Mining System ........ 113
  4.2.1 Model Construction ................................. 115
  4.2.2 Running the Models ................................. 119
  4.2.3 Modelling Results .................................. 122
    Analysis of Seismicity ................................. 123
    Ground Reaction Curve Analysis ..................... 132
    Recommendations and Summary of Models .............. 135
  4.3 Appropriate Architectures ............................ 137
  4.4 Summary ............................................... 147

Chapter 5: Conclusions, Contributions and Recommendations . . . 150

5.1 Conclusions ........................................... 150
5.2 Key Contributions ..................................... 152
5.3 Recommendations ..................................... 153
List of Tables

3.1 Mining system summary .................................................. 102
3.2 Geological system summary ........................................... 103
3.3 Fault system and fault zone summary ................................. 104

4.1 Time variable versus non-time variable factors over the time span of
interest ............................................................................. 107
4.2 Factors that influence fault behaviour organized by importance . . 109
4.3 Measurement techniques organized by factor ........................ 111
4.4 Desirable information and commonly available information that is a
potential indicator of fault behaviour. Information is grouped by major
factor, which is organized in order of importance. ...................... 112
4.5 Material properties and initial state ................................... 117
4.6 Model cases ..................................................................... 120
4.7 Evaluation of potential classification systems and DSS. Information
from this table was based on Arnott and Pervan (2005); Parten et al.
(1990); Holsapple and Burstein (2007, Hand (1997), ) ................ 142
List of Figures

2.1 A UML diagram of the mining system ........................................ 8

2.2 Diagram illustrating the similarities between intraplate and interplate earthquakes. For both types of earthquakes, as fault length increases, mean slip rate also increases up to an aspect ratio of approximately 10. (Scholz, 2004). ................................................................. 11

2.3 Diagram illustrating the difference between interplate earthquakes a) and intraplate earthquakes b) at various times. The loading in the interplate situation is constant along the fault, however each fault in the intraplate situation experiences different loading due to the initial far field loading being shared by a complex system of interacting faults (Liu et al., 2011). ................................................................. 12

2.4 A UML diagram of the geological system ........................................ 14

2.5 Example sketches of fault zones (a) through c)) and a fault system (d)) 15

2.6 A sketch of common elements across a fault zone in two-dimensions . 17

2.7 A sketch of common elements of fault zone geometry, including multiple types of asperities and self-similar topography ................................. 19

2.8 Comparison of similar structures of faults at different scales. a) is from mapping of the Dasht-e Bayaz fault and b) through d) are from shear box tests (Tchalenko, 1970) .................................................. 21
2.9 Power spectra of rock from in situ fault surface and laboratory experiments. The bottom right is no longer self-similar at the physical grinding limit (Scholz, 2004).......

2.10 Mechanical classification of fault core rock (Riedmiller et al., 2001)...

2.11 Varying degrees of fault gouge ............

2.12 Fault zone evolution from youngest (a) to most mature stage (d). Includes formation type failure and fault slip type failure. For more description, see text. ....................

2.13 Mohr diagram for Coulomb failure criteria for fault formation and fault slip along a pre-existing fault. Pre-existing faults of orientation $\beta$ will be activated before a new fault of optimum orientation is formed. Mohr circle A gives the stresses for faulting, whereas B is the condition for slip on an optimally orientated fault. Mohr circle C shows the conditions for a fault at the lock-up angle of $2\theta_R$, the optimum angle for slip as shown in B. Beyond this angle, the fault cannot be reactivated (Scholz, 2004)........

2.14 Unstable and stable slip conditions from loading system stiffness versus fault stiffness (Esterhuizen, 1994)........

2.15 Relationship between fractional real contact area and applied normal stress during frictional sliding. Data provided for three cases: sandstone on sandstone (SS/SS), limestone on limestone (LS/LS), and sandstone on limestone (SL/LS) (Scholz, 2004)..................

2.16 Slip weakening friction where friction decreases linearly from a static value, $\mu_s$ to a dynamic value $\mu_d$ with sliding distance $s_k$ (Scholz, 2004) 42
2.17 Path of coefficient of friction during fault sliding, where \( a \) and \( b \) are values that describe the path based on rate and state (Scholz, 1998).

2.18 Stable and unstable frictional regimes, where \( \Delta V \) represents the velocity jump necessary to destabilize the system (Scholz, 1998).

2.19 Chronological evolution of the DSS field with identification of underlying structure type. Adapted from Arnott and Pervan (2005) with information from Holsapple and Burstein (2007).

3.1 UML structure diagram of influences on fault stability. See text for further discussion.

3.2 Flooded (“wet”) area and production area (“dry”) of interest in a deep South African mine (Goldbach, 2009).

3.3 Seismicity related to (a) flooded area and (b) dry production area of interest in the deep South African mine. Modified from (Goldbach, 2009).

3.4 Elevation of the water level (solid line) and depth of seismic events (blue diamonds) in the flooding area. The yellow dotted area and arrows illustrate the up dip migration observed (Goldbach, 2009).

3.5 Frictional resistance plotted for crushed layers of common rocks and minerals sheared between granite or sandstone driving blocks (Lockner et al., 2002).

3.6 Dependence of rate- and state-dependent friction parameter on temperature (Scholz, 2004).
3.7 Coulomb stress changes of 1979 Homestead Valley earthquake sequence with superimposed aftershocks. As found in King and Gerald Schubert (2007), redrawn from King et al. (1994).  
3.8 Maximum net slip versus fault length (Schlische et al., 1996)  
3.9 Normalized displacement profiles along normal faults of different lengths showing similar shaped slip profiles (Scholz, 2004)  
3.10 Contacting surfaces of asperities. (a) Section view along fault. (b) Plan view of contact, where Ar is the real contact area between the two sides of the fault (Scholz, 2004).  
3.11 Relationship between fault steps per unit length and net slip for active strike-slip faults (Wesnousky, 1988)  
3.12 Profile of peak shear strength of core samples across shear zone with clay gouge. Strength is lowest in the clay gouge, and recovers to intact rock strength outside of the damage zone (US Geological Survey, 2009b)  
3.13 Core thickness versus fault slip distance, where SAF is the San Andreas Fault (Scholz, 2004)  
3.14 Effect of gouge consolidation on contact area and relation to friction. (a) and (b) are both faults with significant gouge, however (a) has gouge material that is less consolidated than (b). The top half of (a) and (b) provides section views and the bottom half provides plan views of contact area. Note that in (b), the more consolidated case, has greater contact areas (shaded region in plan view) indicating a greater static friction coefficient.
3.15 Relationship between gouge particle size and characteristic displace-
ment (Sammis et al., 1987) .......................................................... 94
3.16 Percentage decrease in frictional strength of gouge minerals after sat-
uration (US Geological Survey, 2009a) ........................................ 95
3.17 Profile of permeability across Nojima Fault, Japan. The clay shear
zone has a low permeability. Note the high porosity associated with
the damage zone that recovers to intact rock porosity with increasing
distance away from the fault (US Geological Survey, 2009b) .......... 99
4.1 Example of the initial model geometry, including grid point random-
ization and constitutive models. Modified from McKinnon (2006) ... 116
4.2 a) Combination of pure and simple shear for boundary displacement.
b) The resulting orientation of principal stresses, where the orientation
of the major principal stress for any combination of pure and simple
shear is $\psi$ (McKinnon and Garrido de la Barra, 1998) .................. 118
4.3 Boundary displacement vectors used (McKinnon, 2006) ............... 118
4.4 Example of maximum unbalanced forces for one model. Major stages
of the model are labelled. The first and second stage shown are the
same for all model cases. The model splits into multiple cases at the
end of the second stage ............................................................. 119
4.5 State of model prior to excavations being created overlaid with exca-
vation locations ................................................................. 121
4.6 State of all models after excavations ........................................ 123
4.7 Magnitude-frequency plot of maximum unbalanced force history ... 125
4.8 Comparison of seismicity between cases over the time of Stage 3, normalized to the base case ........................................... 127
4.9 Plot of differences of maximum unbalanced forces between analogous cases. Differences are plotted as percentages, where the blue series represents the differences between the two fault intersection cases (A & B), the green series represents the differences between the 1 fault intersection cases (C & D), and the magenta series represents the differences between the 0 fault intersection cases (E & F) ........................................... 129
4.10 Histogram of absolute percentage differences of maximum unbalanced forces between analogous case results. Bottom histogram provides full scale, whereas the front histogram has a zoomed scale. .............. 130
4.11 Plots of shear strain rate for all cases at an instantaneous moment of time after excavations (green boxes) have been created. ......... 132
4.12 Ground reaction curves for all excavations ............................ 135
4.13 A simplified example architecture of an ANN. A) Shows the general architecture of the entire network, and B) shows the general architecture of a single node, or processing element. $x_n$ represents input data, $w_{jn}$ represents weights assigned or determined by the network, $f(l_j)$ is a function used for processing the inputs, and $y_j$ is the output value (Shahin et al., 2001). .......................... 144
Chapter 1

Introduction

1.1 Motivation

As the global depletion of resources continues, mining activities are forced to go deeper, resulting in high stress environments with complex structural geology. These environments are particularly prone to rockbursting, which is a violent, damaging ejection of rock caused by a seismic event.

There are three major types of rockbursts: strain bursts, pillar bursts and fault slip bursts. Each of these types of rockbursts poses a threat to personnel, infrastructure and equipment; however, those associated with fault slip events pose a very severe risk to mining operations. Fault slip bursts are typically larger and more violent than other types of rockbursts. Additionally, it is unknown which faults are more prone to slip, the influence of the system configuration on individual fault stability, or how mining excavations influence the overall stability of the local faults. Current
fault stability models are inadequate at forecasting fault slip behaviour, due to several reasons including: phenomenological constitutive models, non-observable input parameters, lack of data, lack of knowledge of what data is critical, and an incomplete understanding of earthquake physics. What is resoundingly clear however, is that as mining depth and consequently stresses increase, the frequency and severity of fault slip rockbursts also increases.

1.2 Objective and Scope

A technique for identifying and predicting the risk of fault slip events is required. The ability to determine which faults in the system are more prone to slip would enable risk-mitigating design, thereby improving safety and reducing the likelihood of unpredictable costs. It is common for mining engineers to use classification systems to support design decisions. The purpose of this research is to support engineering design decisions by creating the architecture of a classification system to identify the risk of fault slip events in an underground mining environment.

The intention of this classification system is not to evaluate rockburst risk, rather fault slip risk. This is because rockbursting is highly related to the specific configuration of the mine excavations. It is likely that fault slip related rockburst risk needs to be evaluated on a case by case basis. The first step in this evaluation, however, is to determine the likelihood of movement along a fault.

The scope of this thesis is limited to the architecture of the classification system and high-level prioritization of inputs due to the the importance of this stage, the
unique nature of the problem being addressed, and poor data availability. Fault slip in a mining environment is not a static problem that is usually encountered in rock mechanics, such as classifying rock mass quality. Fault stability is closely linked to the geological system, the mining system and the dynamic time-dependent interaction between the two. Additionally, mounting evidence from the earth science community suggests that fault networks behave in a self-organized critical manner, indicating that fault systems are dynamical systems. Fault systems are believed to be non-linear; a linear combination of the inputs do not give rise to the outputs. This highly nonlinear aspect of fault system behaviour significantly complicates the use of measurable characteristics to predict future behaviour. Furthermore, there are no well documented case studies capable of providing sufficient data to use as inputs to determine indicators of fault slip risk. This is due to both limited knowledge of what data is worthwhile to collect and use, as well as current limitations of data collection techniques.

The development of the architecture and high-level prioritization of inputs is the first step towards a complete fault slip risk classification system. This work directly identifies major properties that need to be measured to predict fault slip events, as well as provides insights on how faults need to be numerically modelled, the importance of the fault network, and how excavations influence fault stability. The outcomes of this thesis provide a foundation for more research in the area, including motivation for developments in geophysical data collection and manipulation, and the development and accumulation of past and future fault slip related case studies. The culmination of this and future work will ultimately lead to a complete fault slip risk classification system for underground mining environments.
1.3 Organization

In order to fully appreciate the implications of this work, Chapter 1 presents the motivation behind this research. Linked to motivation, the objective and scope of work are also presented in this chapter.

Chapter 2 provides details necessary to understand the work presented in this thesis in the form of a literature review. Initially, a review of the mining system and the geological system are provided, further explaining the problem at hand. Models of fault stability and fault behaviour are reviewed to provide an understanding of current technology and knowledge across many disciplines. The final section in this chapter examines systems and techniques of supporting decision making in conditions of great uncertainty. The architecture of these systems is the focus of this section, with the intention of gaining insights into the potential architecture of a fault slip classification system.

Chapter 3 discusses controls of fault behaviour in the context of a preliminary evaluation for the classification system. Mining system and geological system controls are discussed. Each control is evaluated for use in the classification system by examining: how it controls fault behaviour, how important it is, if it is time dependent, the ease of measurement, and our current ability to effectively use this data.

Chapter 4 discusses the architecture of the fault slip classification system. Based on information from Chapter 2 and Chapter 3, potential inputs to the classification system are evaluated. Numerical models created to explore key concepts identified in Chapter 3 are presented and evaluated. Recommendations for the architecture of the classification system are discussed, based upon information from Chapter 2, Chapter
3, and the numerical simulations.

Chapter 5 concludes this thesis, highlights contributions and presents recommendations for future work.
Chapter 2

Background

This chapter provides a survey and assessment of existing literature that is fundamental to understanding fault slip in mining environments. The first sections discuss the mining and geological systems, including entities and behaviours. For both of these systems, entities that are important when considering fault slip risk are presented in Unified Modelling Language (UML) structure diagrams. UML diagrams are used because UML is a standard modelling technique, with clear language to depict relationships. In this chapter, the influence of each entity on fault stability is not explored; rather the purpose of these diagrams is the introduction of each entity. Chapter 3 uses these introductory UML diagrams presented in Chapter 2 to illustrate the interaction of multiple systems and their impact on fault stability.

This chapter explores other concepts critical to the development of the architecture of the fault slip classification system. Significant discussion is provided on the state of the art of fault stability and slip models and analysis to provide an understanding of
current capabilities, limitations and necessary improvements. Additionally, methods of decision making in data poor and uncertainty rich environments are discussed. Particular attention is paid to the architecture of these systems and the application of these decision support systems to fault slip.

It is of critical importance to understand that there are multiple systems interacting when considering the occurrence of fault slip in a mining environment. The two major systems are the mining system, consisting of the underground mining area and activity, and the geological system, consisting of the natural environment in which mining occurs.

These systems exist over vastly different time scales; the geological system has evolved over billions of years, whereas mining systems typically exist from tens to hundreds of years. When considering the issue at hand, that is fault slip events over the course of mining, the mining system is much more dynamic than the geological system. It undergoes greater variations and changes over that time period. The behaviour produced due to the interaction of these two systems is highly dependent upon the state of both systems at that instantaneous moment of time.

### 2.1 The Mining System, Mine Seismicity and Rock-bursts

The mining system as used throughout this manuscript refers to the underground mining area, excavations and mining activities. Of importance to the scope are the entities of the mining system outlined in the following UML diagram (Figure 2.1):
excavations, blasting and pore pressure. The mining system is represented by a UML package that contains the aforementioned entities. Pore pressure is considered to belong to the mining system rather than the geological system because over the time scale of interest for determining fault slip risk, at most the life of the mine, local pore pressure is controlled by mining activities (such as dewatering and backfilling).

![UML Diagram of the Mining System](image)

Figure 2.1: A UML diagram of the mining system

### 2.1.1 Seismicity in Mines

The time- and scale-dependent interaction of the mining and geological systems causes a behavioural response: seismicity. Seismicity is energy released when rock fractures and/or slips along existing discontinuities; microseismicity is seismicity in a mining environment, named as such typically due to the small magnitude of the majority of events.

As stated by McKinnon (2006), most seismic events around deep hard rock mines occur close to excavation boundaries. This type of seismicity is related to mining-induced stress changes that lead to fracturing of intact rock or slip along pre-existing discontinuities. The mining-induced stress changes are associated with excavation...
geometry and sequencing. Mines that create highly stressed structures, such as pillars and abutments, are more prone to induced seismicity. Near-extraction seismicity is characterized by swarms of events, most often triggered by production blasts. The frequency of events gradually decays over a period of days or hours until it reaches background levels. A certain amount of seismicity occurs further away from mining excavations. This seismicity appears to be uncorrelated in space and time to mining activities, and is often of much greater magnitude than near-extraction seismicity. The greater magnitude of these events increases the risk of rockburst damage, causing great concern for mining activity. Numerical stress analysis codes that are used to assess stability in mining due to the complex geometry and geological environment are unable to explain and reproduce these remote events.

Seismicity exhibits patterns throughout time. It is common that after large events, a series of aftershocks will occur. These aftershocks decay, following Omori’s law (see Omori (1984) and Equation 2.1, where \( n(t) \) is the rate of aftershock occurrence, \( K \) is an activity parameter, \( c \) is an offset time constant, \( t \) is the time from the event and \( p \) is a parameter related to the decay speed), until the background level of seismicity is reached. In mining environments, it is typical that after large events, re-entry of workers is based on the time it takes for seismicity to reach these background levels. For an extensive review of decay of aftershocks in mining environments and the application to re-entry protocols, see McKinnon and Vallejos (2010), Vallejos and McKinnon (2008) and Vallejos and McKinnon (2011). Additionally, a fault system’s seismicity exhibits a linear relationship between the logarithm of magnitude and cumulative frequency of events, known as the Gutenberg-Richter law (see Gutenberg and Richter (1944) and Equation 2.2). The scale invariance seen in this power law is
one of the indicators that the system is exhibiting self-organized critical behaviour, a property of dynamical systems that is a mechanism for chaotic behaviour (Bak, 1999). If this is the case, even a small stress disturbance has the potential to significantly affect the stability of a fault since they are in a critical state (King et al., 2001). Fractals, another property of systems in a self-organized critical state, are common for the spatial distribution of hypocenters as well (Hirata et al., 1999). The fractal dimension of this distribution decreases with the evolution of rock fracturing (Hirata et al., 1999). The fractal dimension is the statistical parameter that indicates how completely fractal a data set is, with a higher value indicating more depth and dimensions of self-similarity.

\[ n(t) = \frac{K}{c + t^p} \tag{2.1} \]

\[ \log n = a - bM \tag{2.2} \]

Seismicity in natural systems has many similarities to seismicity in mining environments. Not only do similar relationships exist between magnitude and frequency, interplate (between tectonic plates) and intraplate (within a plate) earthquakes share similar scaling laws. For both interplate and intraplate earthquakes, the relationship between length, mean slip and aspect ratio are similar (see Figure 2.2). This indicates that parameters that control faults are, most likely, universal regardless of geological setting.
Figure 2.2: Diagram illustrating the similarities between intraplate and interplate earthquakes. For both types of earthquakes, as fault length increases, mean slip rate also increases up to an aspect ratio of approximately 10. (Scholz, 2004).

It is important to note that mining occurs over shallow depths when considering the total depth of interest of the earth science community. Faults that are of interest to mining engineering are located in the upper crust, and are typically brittle rather than ductile. In all cases throughout the manuscript, attention is paid to the valid depths of all information from a earth science and geology perspective. There are, however, subtle differences between seisimicity at interplate boundaries and intraplate seismicity (Liu et al., 2011). Interplate faults typically exhibit quasi-periodic earthquakes concentrated along the plate boundary from constant rate loading; however, intraplate faults have variable loading due to the complex system of interacting faults,
which causes triggering on local faults and migration of seismicity (illustrated in Figure 2.3) (Liu et al., 2011). Intraplate earthquakes are episodic and spatially migrating (Liu et al., 2011). Although interplate and intraplate faults experience different loading conditions, factors controlling fault strength over the depths of interest (depths of mining) are the same, regardless of fault environment. Due to these similarities, faults are examined from an earth science and geology perspective in addition to mining in Section 2.2.3 (on the spectrum of fault behaviour), Section 2.3 (on models of fault behaviour), and Chapter 3 (on the controls of fault behaviour).

Figure 2.3: Diagram illustrating the difference between interplate earthquakes a) and intraplate earthquakes b) at various times. The loading in the interplate situation is constant along the fault, however each fault in the intraplate situation experiences different loading due to the initial far field loading being shared by a complex system of interacting faults (Liu et al., 2011).
2.1.2 Rockbursts

A rockburst is the violent ejection of rock causing damage to personnel, equipment and/or infrastructure. They are commonly associated with the coalescence of fracture and fault slip events (CAMIRO Mining Division, 1995). There are three major types of rockbursts: strain bursts, pillar bursts and fault slip bursts (Blake and Hedley, 2003). Strain and pillar bursts are associated with concentrations of stress, and zones at risk for these bursts can typically be predicted using numerical modelling (Blake and Hedley, 2003). The final type of rockburst, fault slip related bursts, are routinely of greater magnitude than other rockbursts and are not easily predicted by numerical modelling (Blake and Hedley, 2003).

2.2 Geological System

This section describes the geological system, which consists of at most one fault network that has at least one fault zone within it (as illustrated in Figure 2.4). A fault zone, commonly referred to as a fault, is a geological discontinuity that has undergone slip along a portion of its length. Although often considered planar for model simplification purposes, faults are rarely planar, especially in three-dimensions. Pictorial examples of fault zones are provided in Figure 2.5 a) through c). Fault networks are a collection of fault zones. These fault zones often intersect one another and are frequently of different geological ages, an example of which is illustrated in Figure 2.5 d).
2.2.1 Fault Network

Within the geological system, there exists a network of faults, or a fault network (refer to Figure 2.5 d)). This is a semi-continuous series of individual fault zones created due to the tectonic environment. These fault networks exist with a variety of
fault zone sets and geometries, however currently there is no accepted, useful way to quantitatively describe their configurations. Additionally, there is limited information as to how orebody genesis and tectonic environment leads to different configurations of fault networks. It is, however very clear that due to the system nature of fault slip, the physical fault network is an important consideration with respect to evaluating the risk of fault slip.

2.2.2 Fault Zone

This section describes details about individual fault zones that make up a fault network. Fault zones, commonly referred to as faults, are discontinuities that have undergone slip, or movement along that discontinuity. Although faults are often considered to be planar structures, faults are rarely planar, especially in all three dimensions in which faults exist. Commonly, they are a dense network of linked fractures. Although every fault is different due to tectonic setting, faults have common geometric elements that can be used to describe each unique fault: geometry; slip surface and core; and wall rock and a damage zone. These common elements are illustrated in Figure 2.6. Faults are typically a zone of interlaced fractures, connected by asperities or bridges (for a detailed description, see 2.2.2). The slip surface may be found in a zone of cataclastic rocks in the fault core. The fault zone is surrounded by a damage zone consisting of secondary fractures (Scholz, 2004; Twiss and Moores, 1992; Childs et al., 2009).
Faults occur over a large range of scales. Fault slip in a mining environment is mainly concerned with fault zones that span metres, as they are the most likely to contribute to rockburst events. In general, faults at different scales can be described as follows (Twiss and Moores, 1992):

- Microfaults/cracks: scale of millimetres or less and may be visible only under a microscope;
- Shear Fractures: scale of centimetres; and
- Faults or Fault Zones: scale that occurs over distances of metres or longer.
Faults are commonly classified in three main categories based on the relative movements of the fault walls: normal, reverse (thrust), or strike-slip. With normal faults, the hanging wall moves down relative to the footwall block, implying that the major principal stress, $\sigma_1$, is vertical. The hanging wall moves up relative to the footwall block in reverse faults, implying that $\sigma_1$ is horizontal. Strike-slip faults occur when $\sigma_1$ and $\sigma_3$ (minor principal stress) are both horizontal, with $\sigma_1$ orientated sub-parallel to the fault movement.

**Geometry**

This section discusses overall fault geometry, including asperities. Within the field of mining engineering, asperities are considered to not only be physical undulations, but stiffer patches along the fault. They can have the form of physical undulations along a slip surface, relay zones between fault segments or it may be a property of the wall rock (see Figure 2.7). Although relay zones, sometimes known as linkage zones, steps, offsets or bends, are occasionally considered to be part of the damage zone due to their formation during slip (e.g. Kim et al., 2004), for purposes of this document they are considered to be asperities. They are considered as such because their influence on fault rheology and behaviour is akin to the common definition of asperities; the focus of this document is overall fault behaviour, not formation of multiple fault geometries.
Figure 2.7: A sketch of common elements of fault zone geometry, including multiple types of asperities and self-similar topography

Large scale segmentation is self-similar, and faults typically have 2 to 5 major segments independent of length, age and slip rate (Manighetti, 2009). Linkage zones develop between interacting tips of faults and show relative complexity and intense fracturing compared to tip and wall damage zones. Linkage damage zone can be divided into two main categories: extensional steps and contractional steps.

The major focus regarding physical patterns related to faults has been the distribution
of the topology of the wall rock and the population of subfaults and local fracturing. Studies of fractures in rocks have shown that the fracture geometry is self-similar, or fractal, meaning that they have the same geometric pattern and spatial distribution regardless of the observed scale (i.e. microscopic, outcrop or regional), as illustrated in Figure 2.8 (Twiss and Moores, 1992; Tchalenko, 1970). Both the topology of individual faults as well as the distribution of the subfaults has been found to be fractal (e.g. Power et al., 1987; Velde et al., 1991; Hirata, 1989; Scholz, 2004). The self-similarity of fractals can be mathematically described by a power law distribution, and is evident both from field observations and laboratory studies of faults (e.g. Power et al., 1987; Brown and Scholz, 1985). Figure 2.9 provides the power spectra of the topology of rock surfaces (Scholz, 2004). It is important to note that as fault zones and fault systems evolve, the distribution describing their geometry changes. Over multiple scales, faults in the early stage of their development exhibit the self-similar distribution previously mentioned. As slip progresses and the faults evolve, the geometry becomes more Euclidean in nature, and can often be described by an exponential distribution (Ben-Zion and Sammis, 2003).
Figure 2.8: Comparison of similar structures of faults at different scales. a) is from mapping of the Dasht-e Bayaz fault and b) through d) are from shear box tests (Tchalenko, 1970)
Figure 2.9: Power spectra of rock from in situ fault surface and laboratory experiments. The bottom right is no longer self-similar at the physical grinding limit (Scholz, 2004).

**Slip Surface and Fault Core**

The slip surface and fault core is the segment of the fault that has undergone the most deformation. The core most typically includes fault rock that can be of various sizes. This fault rock is most typically categorized by particle size (Twiss and Moores,
1992). Riedmller et al. (2001) have suggested a fault rock characterization based on mechanical behaviour (see Figure 2.10).

![Mechanical classification of fault core rock](image)

**Figure 2.10: Mechanical classification of fault core rock (Riedmller et al., 2001)**

For any given point along the surface of a fault zone, there may be varying extent of gouge materials from no gouge to significant gouge (e.g. Figure 2.11). The width of the gouge zone does not remain constant along the extent of the fault. Fault gouge may be comprised of crushed rock and or fine-grained alteration minerals, such as clay in a variety of distributions (US Geological Survey, 2009b).
Another aspect of fault zones that exhibit a statistically significant distribution is the particle distribution in the breccia and gouge (Ben-Zion and Sammis, 2003). Similar to fault topology and fracture distribution, there is a power law regarding the particle size of the gouge (Sammis et al., 1987). For gouge simulated within the lab the fractal dimension was higher for fine material, likely due to a consequence of a physical grinding limit (Biegel et al., 1989; Marone and Scholz, 1989).

**Wall Rock and Damage Zone**

A damage zone is the volume of distributed wall rock deformation that surround a fault. Damage zones result from nucleation and propagation of slip along a fault, as
well as interaction of slipping faults (Kim et al., 2004). Damage zones are typically classified by location relative to the fault. The major types of damage zones for purposes of this manuscript are wall damage zones and tip damage zones.

Tip damage zones, in the form of fracturing and splaying, can be very complex. Tip damage zones are formed when stresses concentrate at tips of faults and cause the rock ahead of the tip to damage. There is much discussion as to whether these high stresses exist and remain at the fault tips (e.g. Vermilye and Scholz, 1999; Martel, 1997). Tip damage zones are typically of the following forms:

1. Wing cracks: Extensional features that develop where low differential pressures and low confining stress exists. These cracks typically develop when slip decreases rapidly at the fault tip. The direction of the wing crack is locally sub-parallel to the direction of maximum compressive stress at the time of faulting and located in extensional quadrants.

2. Horse tail fractures: Extensional features that develop when slip gradually decreases at the fault tip. The direction of the horse tail fractures are locally sub-parallel to the direction of maximum compressive stress at the time of faulting and located in extensional quadrants.

Wall damage zones result from a build-up of slip on a fault and the extension of shearing type fractures. The damage zone extends from the fault surface for tens to hundreds to metres. The density of fracturing reduces to the background fracture level of the in situ host rock. Three major damage zones have been identified (Kim et al., 2004):

- Wedge shaped wall damage zones: These damage zones are less frequent than
the other kinds because segment linkage is more common.

- Long, narrow wall damage zones: This type of damage zone is typically controlled by the orientation of the extension fractures relative to the fault.

- Intense wall damage zones: These damage zones are caused by the build-up of friction as the fault slips. Typically, these damage zones grow by coalescence of fractures.

### 2.2.3 Spectrum of Behaviour

An introduction to the spectrum of potential fault behaviour and associated models is provided in this section. It is important to understand what types of behaviour can be expected from both individual fault zones as well as fault systems in order to model fault behaviour and mitigate associated risk. The types of behaviour possible from faults is obtained through in situ observations (including exhumed faults, seismicity and behaviour data from faults at depth and boreholes through faults), laboratory models and numerical models. Currently, a complete understanding of fault behaviour and fracture mechanics does not exist; fault zones and fault systems exhibit a wide range of behaviour that cannot yet be fully explained by theory, laboratory experiments or models. The discussion within this section provides a review of what behaviour is understood as well as what is beyond the current limits of our knowledge.

Fault behaviour is a result of the interaction between the mining system and the geological system. When considering the issue at hand, that is fault slip events over the course of mining, the mining system is much more dynamic (changes more over the
time scale) than the geological system. It undergoes greater variations and changes over that time period. The behaviour produced due to the interaction of these two systems is highly dependent upon the state of both systems at any instant over the life of the mine.

As is common with mining engineering, fault behaviour can be viewed as driving forces exceeding resisting forces. This is discussed in more detail in Section 2.3. The changes in driving forces caused by interaction between the two systems at hand results in various forms of fault behaviour, including

- formation,
- growth,
- slip, and/or
- evolution.

Fracture type failure includes the formation and growth of faults. Formation is clearly evident in stages (a) and (b) of the fault zone evolution depicted in Figure 2.12. New fractures are formed in all stages through intact rock. In theoretical fracture mechanics, it is assumed that a characteristic fracture energy per unit area must be exceeded in order for crack propagation to occur (Scholz, 2004). Fracturing in a developed fault occurs both in the damage zone and in asperities between fault segments (evident in stage (d) of Figure 2.12), evolving the fault to a more mature state. All modes of fault behaviour are evident in Figure 2.12:

- Microfracturing and coalescence of tensile microcracks in stages (a) and (b) (formation),
• Propagation of existing faults along their length in stages (b) through (c) (slip, growth, evolution),

• Interaction of multiple fault tips where extension fractures formed at the tips of separate faults interact with one another (interaction and joining of fault segments) in stages (c) through (d) (slip, growth, evolution), and

• Fault wear along the fault surface resulting in gouge material in stage (d) (slip, evolution).

Figure 2.12: Fault zone evolution from youngest (a) to most mature stage (d). Includes formation type failure and fault slip type failure. For more description, see text.

Although present during fault slip type failure at a scale much smaller than the fault, fracture formation has not been identified as a major contributor to the rockburst phenomenon. Since faults exist as planes of weakness in the in situ rockmass, if appropriately oriented faults exist, it is easier for them to accommodate slip in a brittle environment than to create new fault zones. There has been some discussion
of new fracture formation in South African gold mines (e.g. Ortlepp, 2000), however the stress conditions, mining geometry and geological environment are very different from typical metal mines in North America. Hence, slip on existing discontinuities is the major focus of this thesis, not the formation of new fault zones.

Slip contributes significantly to fault zone evolution, changing the physical and mechanical properties of the fault (refer to Figure 2.12 to see some effects of increasing levels of slip). Slip along a fault can be either seismic (unstable) or aseismic (stable) (Segall, 1991). Potential slip behaviour includes continuous creep, episodic creep, earthquake slip, decelerating post-seismic creep and local accelerating slip during earthquake nucleation (Dieterich and Schubert, 2007). Rupture rarely occurs along the entire fault surface. Instead, rupture usually nucleates on one or two fault segments. This rupture may propagate along the original fault or it may jump to a new fault zone. Although propagation along a fault often involves the small scale fracturing of rock in-between fault segments, it is still considered to be fault slip type failure at the scale of the fault zone. Eventually, rupture will terminate, usually at a geological boundary that absorbs the rupture energy.

It is currently not clear whether event nucleation is a surface phenomenon occurring on the prominent slip surface, or a granular phenomenon including the entire fault core (Biegel and Sammis, 2004). In order to build up the required strain for the next instability, it is implied that there is fault locking, re-strengthening or healing (Vannucchi et al., 2009). Recent evidence has suggested that some faults have the ability to completely recover their frictional strength to pre-slip level within one day of an unstable event (Mizoguchi et al., 2009).
Aseismic slip, commonly known as creep, is a slow, ductile shearing process favoured by high effective confining pressures and high temperature at depths typically greater than 15 km (Price and Cosgrove, 1990). Velocity-hardening frictional behaviour is associated with creep events (Vannucchi et al., 2009). Although of less importance to mining than seismic slip, due to the common depth range and slow release of energy associated with this type of event, how creep events redistribute the energy within a system has the potential to significantly affect the behaviour of other faults, other areas of the same fault, as well as the hosting rock mass.

Seismic slip in an earthquake and/or burst initiation context occurs due to abrupt sliding on a fault plane, leading to rupture where the sliding time ranges from milliseconds to tens of seconds (Price and Cosgrove, 1990). In natural fault systems, seismic slip occurs within a critical depth-temperature regime in the brittle upper crust. In the mining context, seismic slip occurs when sufficient transverse strain on a fault or embryonic fracture system overcomes the resistance provided by natural interlock under the given level of confinement. According to Scholz (2004), the two potential mechanisms of rupture in unstable slip are stick-slip friction instability and brittle fracture.

There are a number of intricacies of fault slip behaviour found in nature that are of critical importance to understand. Slip along a single fault surface exhibits heterogeneity often confined to distinct fault segments, both in terms of direction and magnitude of slip. It is also important to consider the dynamic effect that fault behaviour has upon fault zones and the fault system. The mechanical work of fault slip is dissipated in three ways: frictional heating, surface energy of gouge and damage zone formation, and elastic radiation (if seismic slip occurs) (Scholz, 2004). These forms
of energy release have the potential to further alter fault properties and behaviour.

Behaviour modes may occur simultaneously, or at least in the same event, as they are often related. It is important to understand that fault behaviour is a spectrum; there is a great range of behaviour types that blend together (for an excellent review, see Marone and Richardson, 2010). According to Lockner et al. (2002), it is not currently known what fraction of seismic slip occurs on pre-existing faults, what percentage of any rupture represents new faulting, or if rupture nucleation might occur at jogs or locked segments and involve breaking of rock which is at or near the intact rock strength.

### 2.3 Models and Evaluation of Potential Behaviour

The majority of fault stability, strength and behaviour models are phenomenological; that is to say they describe observed behaviour as opposed to predict behaviour from fundamental properties. Additionally, these models are often based on results from laboratory experiments. There are a number of major issues with using fitting parameters as opposed to observable parameters, including:

1. the physical meaning of experimentally derived parameters is unclear,
2. scaling issues exist between the models (numerical and laboratory) and faults in the field, and
3. there is an inability to reproduce all fault behaviour and initial conditions.

Currently, most models are applied to a single, planar, 2-dimensional fault; however the importance of modelling the entire fault system to fully represent the complexity
of a faults topography is becoming clear (e.g. Maerten et al., 2005; McKinnon, 2006; Marshall et al., 2008). Phenomena such as triggering, off-fault damage, stress shadowing and coalescence of fault segments play an important role in fault behaviour. It has been proven that pre-existing discontinuities and their orientation control many properties, such as deformational characteristics, displacement distributions of surface ruptures, the evolution of the main fault orientation throughout time, the geometry of relay fault zones and the geometry of small scale faulting (Lin, 2009; Bellahsen and Daniel, 2005).

This section provides information on models of fault stability and fault behaviour. Within the classification system, it is important to distinguish between initial stability state (potential nucleation of event) and fault behaviour (and potential dynamic triggering of other faults). Although many of the fault stability models and techniques could include fault behaviour models, they are presented separately to keep these entities distinct.

### 2.3.1 Fault Stability Models and Techniques

All modes of fault stability are associated with greater driving forces than resistive forces. The driving force behind all modes of fault behaviour is shear stress acting along the fault. At any given point in the rock mass, the stress is a combination of tectonic loading, mining induced stress and structure/lithologic induced stresses. Fault strength is associated with resistive forces, such as friction, cohesion and normal stress. The orientation and magnitude of stresses constrain fault behaviour. By exceeding the strength of the fault at any given point along its length, changes in
magnitude and orientation of stresses may result in various forms of fault behaviour. Fault stability is controlled by three major factors:

1. stress acting along the fault,

2. the fault’s strength, and

3. boundary conditions.

The most widely used fault stability models, especially in mining environments, are based on the Mohr-Coulomb failure criterion (refer to Equation 2.3), where \( \tau \) refers to shear stress, \( C \) is cohesion, \( \sigma_{eff} \) is effective normal stress, \( \phi \) is the internal angle of friction, \( \sigma_n \) is normal stress, \( \mu_i \) is the coefficient of internal friction, and \( u \) is pore pressure. As illustrated in Figure 2.13, fracture initiates and spreads on the plane when the shear stress exceeds a specific value depending on principal stress magnitudes, cohesion, pore fluid pressure and the coefficient of friction on the failure plane. Sliding occurs when the driving forces exceed the resisting forces of friction and effective normal stress. Byerlee (1978) completed studies on the friction of rocks, and determined the following simplifications of the Mohr-Coulomb sliding relationship for crustal rocks (Equation 2.4). These equations are not valid if the sliding surfaces are separated by a large thickness of gouge with particles that have an inherently low coefficient of friction (such as vermiculite) (Byerlee, 1978).

\[
\tau = C + \sigma_{eff} \tan \phi = C + \sigma_{eff} \mu_i , \text{ where } \sigma_{eff} = \sigma_n - u
\]  

(2.3)
\[ \tau = \begin{cases} 
0.85\sigma_n & \text{if } \sigma_n < 200 \text{ MPa,} \\
50\text{MPa} + 0.6\sigma_n & \text{if } 200 < \sigma_n < 1700 \text{ MPa} 
\end{cases} \] (2.4)

Figure 2.13: Mohr diagram for Coulomb failure criteria for fault formation and fault slip along a pre-existing fault. Pre-existing faults of orientation \( \beta \) will be activated before a new fault of optimum orientation is formed. Mohr circle A gives the stresses for faulting, whereas B is the condition for slip on an optimally orientated fault. Mohr circle C shows the conditions for a fault at the lock-up angle of \( 2\theta_R \), the optimum angle for slip as shown in B. Beyond this angle, the fault cannot be reactivated (Scholz, 2004).

Other models used to evaluate fault stability include:

- **Slip tendency analysis:** Very similar to standard Mohr-Coulomb analysis. Uses the frictional characteristics of the rock type and the ratio of shear to normal stress on a fault surface to evaluate relative slip potential on a cohesionless surface (Morris et al., 1996). The ratio of shear to normal stress on the surface is known as the slip tendency (Morris et al., 1996). Using the stress tensor and
a known fault surface, the relatively likelihood and direction of slip can be de-
termined (Morris et al., 1996). Although useful for evaluating rudimentary slip
potential in geological systems, the assumptions behind this technique make it
less reliable when applied in a mining environment. Not only are there many
assumptions made about the strength of faults and the current stress field, there
is no accounting for the influence of boundary condition changes that mining
undoubtedly introduces (for more discussion on this, refer to Chapter 3).

- **Excess Shear Stress (ESS):** ESS uses the prevailing shear stress prior to slip
  minus the dynamic strength of the plane to indicate rockburst proneness (Ryder,
  1988). Ryder (1988) suggests that ESS be used in combination with Energy
  Release Rate (ERR) studies that are commonly used to evaluate rockburst
  potential.

- **Stiffness:** The stiffness of a material (force units over distance units) describes
  how it responds to deformation. The stiffness of a fault describes how the
  fault responds to deformation. Work exists suggesting that the rockbursts can
  be predicted by comparing the stiffness of the failing rock and the stiffness
  of the rockmass (loading system) (e.g. Wiles, 2002; Gill et al., 1993; Blake and
  Hedley, 2003). If the post peak stiffness of the rock undergoing failure is greater
  than the stiffness of the loading system, the amount of stored strain energy in
  the rock exceeds the work that the rock can do during post peak failure, and
  violent failure occurs. Conversely, if the rock undergoing failure has a post peak
  stiffness that is less than that of the loading system’s stiffness, then gradual,
  gentle failure will occur.
Although not commonly done, this concept has the potential to be applied to fault slip rockbursts as well, as illustrated in Figure 2.14. Figure 2.14 (a) shows stable slip, where the stiffness of the loading system is greater than the post peak stiffness of the fault, while (b) shows unstable slip, where excess stored strain energy will be released because the stiffness of the loading system is less than that of the fault.

![Figure 2.14: Unstable and stable slip conditions from loading system stiffness versus fault stiffness (Esterhuizen, 1994)](image)

2.3.2 Fault Behaviour Models

The stick-slip model became widely accepted in the 1960’s (e.g. Brace and Byerlee, 1966; Dieterich, 1978; Scholz, 2004; Vannucchi et al., 2009). In the stick-slip model, rupture is assumed to occur when the stress on the fault reaches the static friction value and conditions for dynamic instability exist (Scholz, 2004). Dynamic instability refers to a variation of frictional resistance during sliding (Scholz, 2004). For the case of unstable slip, the frictional behaviour exhibited is usually velocity-weakening; the
friction coefficient decreases with increasing slip velocity. The sudden slips along a fault associated with dynamic instability are followed by a stress drop (Scholz, 2004). This stress drop is not immediate however; it requires a certain amount of slip, known as the slip weakening distance or characteristic slip distance, before its onset (Scholz, 2004). This is followed by a period of no motion during stress recharge along the fault, and then another instability, hence the term stick-slip.

The elastic energy which drives instability can lead to a net drop in stress. In its simplest form, that stress drop is static and dynamic friction, however this is an oversimplification as there is no such abrupt change in fault strength. It requires time or displacement weakening for this stress drop to occur, suggesting a need for strain weakening models (Lockner et al., 2002).

The role of fiction in fault stability is critical; friction controls rupture nucleation, propagation (including associated stress drop, seismic wave excitation and stress redistribution), healing of slip and arrest of rupture assuming a sliding model (Bizzarri, 2009). At low stress, friction is associated with surface roughness, however at high stress, rock lithology has no apparent impact on friction (Byerlee, 1978). Determining frictional resistance at any given point along a fault, however, is not currently possible. Not only is the exact influence of physical fault properties on the frictional behaviour unclear, each observable property has its own scale length and duration, and is controlled by certain parameters (Bizzarri, 2009). However, the relationship between physical contact area and sliding remains true; contact area is proportional to the amount of friction that must be overcome. The greater the area between two contacting surfaces, the greater the friction that must be overcome before sliding occurs. Figure 2.15 provides the relationship between contact area and applied normal
stress for faults at the onset of sliding; as contact area increases, more force is required for sliding conditions.

In the earth science field, due to the importance of friction with regard to fault slip, multiple constitutive equations have been developed based on different frictional behaviour. The majority of these models originated in a laboratory, attempting to mimic observed fault behaviour. This method however, has significant shortcomings.
since laboratory behaviour is often unable to be linked to physical and meaningful parameters. The three major frictional models are as follows:

1. Static-dynamic friction models: This type of model represents the most basic form of frictional behaviour. The two components, static friction and dynamic friction, are assumed constant regardless of what type of behaviour is occurring. The static coefficient of friction, associated with an object at rest, for the same material is most often greater than the dynamic coefficient of friction, associated with an object in motion. Sliding occurs when driving forces exceed the static coefficient of friction. Sliding continues until the dynamic coefficient of friction exceeds the applied force. Models of faults that assume this simplistic frictional behaviour miss key aspects of the seismic cycle such as repetitive failure, time-dependent frictional strengthening, fault healing and seismic and aseismic slip (Marone, 1998). Most models of fault behaviour in a mining environment use this form of friction.

2. Velocity-dependent friction models: Similar to the more simplistic static-dynamic friction models, slip initiates when the ratio of shear to normal stress on the surface reaches the static coefficient of friction. However, once initiated, frictional resistance falls to a lower, variable coefficient of friction that depends on the velocity of sliding (refer to Figure 2.16) (Scholz, 2004). Slip-weakening behaviour is most often associated with seismic events, whereas slip-strengthening behaviour is most often associated with aseismic events. This model implies acceleration prior to instability, and requires a critical slip distance in order for friction to change from one value to another ($s_k$ in Figure 2.16) (Segall, 1991;
Models that apply velocity-dependent friction fail to describe nucleation of instability, dynamic slip, re-strengthening and fault healing (Segall, 1991; Scholz, 2004).

Figure 2.16: Slip weakening friction where friction decreases linearly from a static value, $\mu_s$ to a dynamic value $\mu_d$ with sliding distance $s_k$ (Scholz, 2004)

3. Rate- and state-dependent friction models: Principally developed from the work of Dieterich (1979) and Ruina (1983) with significant contributions from Rice (1983), these models include characteristic dependencies of friction on slip, sliding rate, contact time and normal stress history (Scholz, 2004; Dieterich and Schubert, 2007). The dynamic coefficient of friction has a similar dependence upon slip rate; however it also depends upon the history of the sliding surface, or load time (Scholz, 1998). If the sliding velocity is suddenly changed, friction is found to evolve to a new steady-state value over a characteristic slip distance (Scholz, 1998). Figure 2.17 illustrates a potential path of the coefficient of friction during sliding based on rate- and state-dependent friction laws with associated speed of sliding (fast or slow). The initial sliding that occurs over what is known as the characteristic sliding distance happens during the first
onset of slow movement. The dynamic friction related to rate and state parameters begins at the onset of fast movement, and the new coefficient begins to evolve during the period of final slow motion.

Figure 2.17: Path of coefficient of friction during fault sliding, where $a$ and $b$ are values that describe the path based on rate and state (Scholz, 1998)

Stability is based on the velocity dependence of steady-state friction and the characteristic slip distance (Scholz, 2004; Dieterich and Schubert, 2007). Slip events, either seismic or aseismic, can only occur in the regions of a fault that lie within what is considered to be an unstable regime. Events may propagate indefinitely into conditionally stable regions provided their dynamic stresses continue to produce a large enough velocity jump. If however, the event propagates into the stable regime, a negative stress drop occurs resulting in an energy sink that halts further earthquake propagation. The bifurcation between an unstable regime and a conditionally stable regime occurs at a critical value of normal stress related to the characteristic slip distance (refer to Figure 2.18).
Although superior to the other friction models mentioned, rate- and state-dependent friction laws cannot explain the size of stress drops seen in the field, the rupture propagation mode, the increase in the ratio of radiated energy versus seismic moment with earthquake size and the role and occurrence of heat production during seismic slip (Di Toro et al., 2009). It is also important to note that characteristic slip distance and the integral $a$ and $b$ parameters (as seen in Figure 2.17) have no current, clear physical meaning, making it difficult to model a rupture in advance of its occurrence.

Most early constitutive descriptions of friction were created for constant normal stress and pore pressure (Segall, 1991). However, both variations in normal stress and pore pressure have been found to have a dynamic effect on fault stability (e.g. Mase and Smith, 1987; Dieterich and Linker, 1992). Recently, an increasing number of models have attempted to account for this shortcoming. Additionally, due to deficiencies of rate- and state-dependent friction laws, other potential fault weakening mechanisms have been developed. These additions include thermal pressurization, normal interface vibrations, acoustic fluidization, elasto-hydrodynamic lubrication, silica gel
lubrication, thermal decomposition, flash heating at asperity contacts, gouge-related weakening and melt lubrication (Di Toro et al., 2009). None of these models can exhibit the full complexity associated with faults in nature.

Significant work has been completed on understanding strain-weakening and strain-hardening behaviour, fault healing and seismic slip in the earth science community. However, fundamental aspects of earthquake mechanics remain unknown, such as dynamic fault strength, the energy balance of an earthquake and the role of heat production during seismic slip (Vannucchi et al., 2009). For more realistic models of fault behaviour, it would be beneficial to investigate different frictional behaviours of faults in mining environments.

2.4 Characterization and Decision Systems

A review of decision making techniques with particular application to design processes is presented. The intention of this review is to provide guidance as to the architecture of a fault slip classification system. This fault slip classification system will provide direction as to how to assess the likelihood of a fault slip type event for the local mining environment. As such, the focus of the classification system is on hazard identification, and identifying the probability of such hazards occurring based on measurable, observable properties (of faults, of the mining environment and of the system as a whole). This review includes specific considerations related to making a classification system of fault slip risk, an analysis of the architecture of a variety of decision support systems (from mining and other fields) and identification of common characteristics of decision systems.
2.4.1 Considerations

Major considerations for the development and structure of the fault slip classification system include:

1. Natural fault systems exhibit self-organized critical behaviour, making prediction of when and where an event will occur impossible. However, it may be possible to identify the likelihood of one fault slipping as compared to another.

2. Mining is dynamic. This creates a need for reassessment time suggestions (iterative classification system), or continuous feedback classification systems.

3. The system is a negative and positive feedback system. Both physical properties and behavioural properties of faults interact. The addition of mining adds a new level of complexity to the problem. There is great co-dependence of these indicator variables.

4. Due to significant differences caused by geology, the nature of each fault or fault system is very different at each mine site. The classification system will need to be robust enough to provide guidance for a variety of sites and conditions.

5. There are multiple scales of interest, and these scales likely alter the importance of certain property types (such as fault properties versus fault system properties).

6. At this point in time, we are unable to obtain complete three-dimensional properties and characteristics of faults. There is great uncertainty, and vast room for improvement of geophysical exploration techniques. The classification system needs to be able to adapt to new discoveries.
7. A complete view of fault mechanics, controlling properties, fault interaction and fault system behaviour does not currently exist. Uncertainty exists with respect to the mechanics of fault slip. Work in this area is required and may change some parameters of the classification system. The classification system needs to be adaptable to incorporate future work.

8. As with all rock engineering related problems, there is great uncertainty with respect to data; data quantity and quality is very limited. Additionally, as projects progress, it is common that more information is found. The classification system needs to provide an indication of the level of uncertainty as well as have the ability to quickly incorporate new data.

2.4.2 Characterization, Classification Systems, Empirical Design Tools and Decision Support Systems

In geomechanical engineering, classification systems are used with great frequency to characterize the rockmass, to give empirical guidelines for design and support and to estimate rockmass properties. As stated by Stille and Palmström (2003), there is great discrepancy and misuse in the rock engineering world between the terms “classification” and “characterization.” Classification is the result of putting objects into different classes to gain a better overview of a phenomenon or data set, whereas characterization is the act of describing the condition of an entity, and defining or giving value to the various features it displays (Stille and Palmström, 2003). Therefore, for many common techniques currently being applied in rock engineering today, rockmass characterization is a more appropriate description than rockmass classification (Stille
Characterization can employ classification, by putting the properties into distinct classes (Stille and Palmström, 2003). When the outcome of a characterization or classification system leads to a class description, such as "poor rock," it is indeed a classification system (Stille and Palmström, 2003). However, if the outcome is a value, then the system is not a classification system, and may be better termed as an empirical method for engineering design (Stille and Palmström, 2003).

Hand (1997) identified two main types of classification:

1. **Unsupervised classification:** This refers to the act of classification when class structure is unknown and needs to be created.

2. **Supervised classification:** This refers to the act of classification when class structure is known.

The fault slip characterization system is unsupervised classification. This is a significant reason why the scope of this thesis is limited to the architecture of said system.

Examples of classification systems, rockmass characterization techniques, and empirical design tools include:

- **Terzaghi’s rock mass classification:** Suggests tunnel support design based on loads. Loads are estimates based on a descriptive classification

- **Stand-up time classification systems:** Evaluate the stand-up time of an excavated span. Stand-up time is based on the quality of the rockmass.
• **Rock Quality Designation (RQD):** An index to provide a quantitative estimate of rockmass quality from drill core logs. This is done by a simple calculation based on the amount of fractures present in the core. RQD is a percentage value that gives the fraction of core pieces over 10 cm in length.

• **Rock Structure Rating (RSR):** A quasi-quantitative evaluation of geology, geometry of discontinuities, and effect of groundwater inflow. This value is used to estimate appropriate support. It is known as a quasi-qualitative evaluation because each of the major parameters were rated, rather than directly measured. These parameters are simply summed to produce the final value out of one hundred.

• **Rock Mass Rating (RMR):** A quasi-quantitative evaluation that uses uniaxial compressive strength (UCS), RQD and many properties regarding discontinuities. The ratings assigned to all six parameters are summed to produce the final value out of one hundred. Modifications to this system exist (such as Modified Rock Mass Rating (MRMR)) because this system was based on civil engineering cases, not mining. The MRMR adjusts the RMR by taking in situ and induced stresses, stress changes and the effects of blasting and weathering into account.

• **Rock Tunnelling Quality Index (Q):** This index, based on many cases of underground excavations, uses RQD, a variety of joint parameters and a stress reduction factor. These parameters are combined in organized quotients, where the first quotient represents the structure of the rock mass, the second represents the roughness and frictional characteristics of the joint walls/filling material,
The third is stress related. Q is most commonly used to evaluate stability and support requirements. A modification of Q, Modified Rock Tunnelling Quality Index (Q’), exists that eliminates the stress related quotient to ensure stress is not double counted for in later uses of the index.

- **Stability Graph Method:** This method uses an equation which multiplies Q’ by factors that represent the influence of stress, the influence of discontinuities, and the influence of the orientation of the surface being analyzed. This value, along with the hydraulic radius of the excavation is used with graphs to evaluate stability, with and without support. This value can also be used to estimate support requirements for excavations of specified use.

- **Rock Mass Index (RMi):** This is a volumetric parameter that approximates the UCS by including the UCS of intact rock and reducing the overall strength by multiplying the effect of the joints of the rock.

- **Geological Strength Index (GSI):** Estimates the strength of the rock based on matching images.

All of these systems are single use; there is no accounting for dynamic elements or feedback systems. Problems solved by current rockmass classification systems are static in nature; that is to say the inputs and outputs are not dependent upon time. Instead of being static in nature, fault slip is dynamic; the problem is time dependent. Additionally, none of the current classification systems incorporate faults, only joints. No such systems exist for faults in any discipline.

Disciplines other than rock engineering use systems to aid in decision making. Primarily based upon artificial intelligence (AI) and expert systems, Decision Support...
Systems (DSS) is the area of information systems that focuses upon supporting and improving managerial decision-making (Arnott and Pervan, 2005). The early goal was to create an environment in which the human decision maker and the IT-based system worked together, interactively, to solve problems. The former was to deal with the complex, unstructured parts and the latter the structured parts (Arnott and Pervan, 2005). These systems are a popular way to analyze complex problems, and provide the decision maker with a tool to support better decision making.

Each DSS can be classified based on how the system is driven, or its underlying structure. From Holsapple and Burstein (2007), possible classifications include:

- Model-driven (optimization and/or simulation models, of some interest for this application, however model constraints may be too specific for very complex mining environments)
- Data-driven (uses warehoused historical and/or current data for decision support, of great interest for this application)
- Communications-driven (facilitation of decision relevant collaboration, of no interest for this application)
- Document-driven (data mining via documents, of no interest for this application)
- Knowledge-driven (heavily based on AI, often involves data, of great interest for this application)

An evolution of DSS is provided in Figure 2.19.
Figure 2.19: Chronological evolution of the DSS field with identification of underlying structure type. Adapted from Arnott and Pervan (2005) with information from Holsapple and Burstein (2007)
Based on Figure 2.19, the following list summarizes the support systems of interest.

- **Personal Decision Support Systems:** These are small scale systems designed to aid managers with decision making. Development processes are implemented in continuous cycles that brings the system closer to the final answer after each cycle, rather than in a linear or parallel fashion. Significant user participation is required. These systems are infrequently used today, as many advances have been made.

- **Intelligent Decision Support Systems:** Early models of these support systems used rule-based expert systems. Expert systems programs use an interface to reason about the knowledge base, based on “if...then...” conditions. Later models of these support systems use artificial intelligence, including neural networks, genetic algorithms and fuzzy logic. The conventional method of running expert systems is called the conversational method. This method has significant user input to achieve the end goal, in the form of a “conversation” between the user and the system; it is used for problems that are too complex to provide all data and decision making in advance. The intention of artificial intelligence is to replace the human user by teaching the computer using a vast amount of data.

- **Online analytical processing (OLAP):** These techniques allow users to interactively visualize and analyze multi-dimensional data from many perspectives.

- **Dimensional Modelling:** Uses ideas (measures) and dimensions (context) to aid with database design. This database may be relational. It is the user’s
responsibility to identify the ideas, dimensions and grain (focus) of the model.

- **Knowledge Management Based Systems:** These systems focus on the organization of knowledge.

Structurally, a DSS has four components (Holsapple and Burstein, 2007):

1. A language system
2. A presentation system
3. A knowledge system
4. A problem-processing system

Based on the summaries of different techniques above, it is clear that the architecture varies greatly between different systems. The end outcomes differ significantly as well; OLAP and Knowledge Management Based Systems organize and visualize data, whereas the reaming systems summarized above use this data to provide support to decision making.

### 2.4.3 System Characteristics

Stille and Palmström (2003) suggests qualities of successful rock engineering classification systems:

- Classes must be exhaustive and mutually exclusive
- Indicators must be defined
- Rules of division must be established
• Addition must be possible
• Updates must be possible
• Uncertainty must be estimated

Common characteristics of classification systems include:

• Simple input and output
  – Easily measurable and identifiable input
  – Input often in pictorial form
  – Usable output
• Robust
• Easy to calibrate
• Easy to visualize
• Based on significant case history data

These characteristics are typical of classification systems currently used in rock engineering. Additional characteristics may be required to deal with complex, dynamical systems.

2.5 Summary

Seismicity in mining environments is the result of the interaction between the mining and geological systems. Most mining seismicity occurs near excavations. This type of
seismicity is related to mining-induced stress changes that lead to fracturing of intact rock or slip along pre-existing discontinuities. Near excavation seismicity typically occurs in swarms, and is often triggered by blasting activity. Although less frequent, larger seismic events occur further away from excavations. This type of seismicity is attributed to slip along existing faults, and poses a great threat to mining personnel, activities and equipment.

The geological system that interacts with the mining system to create seismicity consists of: tectonic history and in situ stress, the fault network, and fault zones. The fault network refers to a collection of individual fault zones. A fault zone is a single discontinuity, or network of linked fractures, that accommodates slip. Fault zones develop over a geological time frame through formation, growth, slip and evolution. They have the following three major components:

1. **Geometry**: Fault zones are rarely planar in 3-dimensional space, and fractures within a fault zone often have a self-similar geometry. All fault zones have geomechanical asperities, which, from a structural geology perspective, include: classic asperities, undulations, bends, bridges, relay zones, linkage zones, offsets and stiffer patches.

2. **Slip surface and core**: The slip surface is the surface or collection of surfaces on which slip occurs. Fault core between different fault zones varies widely in presence and composition.

3. **Wall rock and damage zone**: Wall rock consists of the type(s) of rock(s) present on either side of the slip surface and core. The result of accommodating slip, damage zones come in two forms: tip damage zones and wall damage zones.
There is a wide spectrum of fault behaviour in nature, ranging from episodic creep to violent slip type failure. Fault behaviour is influenced by fault strength, stresses acting along the fault, boundary conditions and fault-system stiffness. Many models exist to represent fault behaviour, however all are phenomenological in nature. This causes a disconnect between physical measurements and models, scaling issues between laboratory results and nature, and an inability to reproduce all fault behaviour. The major difference in fault models stems from the underlying friction model used, ranging from simple to extremely complex. The role of friction is undoubtedly important; however, the appropriate friction model to use for faults in mining environments is not clear.

There are many systems in existence that aid decision making. In rock engineering, there is no one system that has an architecture that meets the requirements for the fault slip classification system. Decision support systems however may prove to be useful for this application.
Chapter 3

Controls of Fault Behaviour and Preliminary Evaluation for Classification System

This chapter presents and reviews the state of the art regarding controls on fault behaviour, and provides the initial considerations for a fault slip classification system. Therefore, the focus of this chapter is threefold: identify known controls, identify any gaps in knowledge within the relevant literature, and evaluate the utility of each control for the classification system. The evaluation for the classification system is based on the analysis of different decision making tools, as discussed in Section 2.4, with a focus on the architecture of the final system. It is important to note that most of the controls identified work in tandem, and it is the combination of their effects that leads to fault behaviour. To determine the utility of each control, they are individually evaluated on:
• how fault stability is influenced (by changing the fault’s strength, the stresses acting along the fault, the boundary conditions and/or the stiffness of the fault or system),

• the importance,

• time dependency within time scale of interest,

• the ability to measure and predict the controls, and

• the current state of data processing and handling.

These factors are designed to make the development of the classification system architecture possible. Due to the time dependent nature of many of the controls, evaluation of the time dependency within the time scale of interest is particularly important. The time scale of interest for evaluation of fault slip risk in a mining environment will be, at most, the life of the mine. By identifying which controls change over this time scale, it will be clear how to proceed with re-evaluation through new measurements and analyses. Due to the engineering nature of this classification system, it is of critical importance that the identified fault properties are, or potentially can be in the future, measurable, or observable. If a non-measurable property has a correlation to fault behaviour, a related indicator property may be used in proxy for purposes of a classification system. The identification of our current state of knowledge with respect to data processing and handling is essential; it allows for synthesis of information into the classification system and identifies future research opportunities.

As discussed in Section 2.2.3, seismic slip, not aseismic slip, is the major concern for mining environments. In this chapter, controls on seismic slip are identified and distinguished from aseismic slip wherever possible.
From a geological perspective, Sieh (1996) completed a survey of repeated fault rupture showing that slip patches are characterized by a relatively invariant slip function, implying that there are some quasi-invariant physical properties controlling the pattern and magnitude of slip. Scholz (2004) hypothesized that fault zone behaviour depends upon a combination of stored elastic strain energy, fault geometry, other fault zone constitutive properties and stress distribution along the fault. Based on the following literature review, it is posited that measurable parameters may reflect fault stability (frictional behaviour, effective normal stress), fault strength and stiffness, as well as changes in driving forces (refer to Section 2.3). Potential fault zone behavioural characteristics that observable fault properties may indicate include,

- zone of the rock mass or fault at higher risk to rock fracturing or fault slip energy release (slip potential),
- type of slip behaviour (unstable/seismic or stable slip/aseismic/creep),
- magnitude of energy release,
- areas of higher risk of producing a large event (higher risk related to event location and magnitude),
- zone of aftershock activity, and
- potential to trigger other events.

It is important to note that the introduction of mining excavations and activities further alters the state of stability of fault zones; fault zone stability is not entirely dependent upon the geological environment. As discussed in Section 2.1, the influence of mining occurs in a time-continuous fashion, and the interaction of the geological
and mining systems over a continuous timeline creates fault behaviour. Additionally, at any given time, as changes in stability occur due to the influence of mining, slip along a fault zone progresses, stresses redistribute, fault zone interaction continues and the stability state of individual fault zones as well as the fault network evolves. It is beneficial to consider the fault network as a feedback system, with both positive and negative feedback that influences individual fault zone stability. An example of positive feedback in this system is remote triggering of seismicity caused by an original event. An example of negative feedback in this system is fault healing and re-strengthening after slip.

Figure 3.1 illustrates how these systems are related, along with the major components that influence fault slip, via a UML structure diagram. A UML structure diagram was chosen to illustrate the hierarchy and structure of these components because it is a standardized, common modelling technique with a clear language to depict specific relationships. The dashed lines with arrows from “Fault Slip” in the diagram indicate that fault slip is dependent upon the listed entities in the geological system as well as in the mining system (where systems are represented by UML packages). These two systems influence fault stability by creating the inherent fault zone strength, the stresses acting along the fault zone, the boundary conditions that exist and the fault-system stiffness (as discussed in Section 2.3). The systems also have the ability to influence slip behaviour, such as velocity related friction. The geological system contains at most one fault network that has at least one fault zone within it. The configuration of this fault network depends upon the tectonic history. The mining system contains physical excavations as well as blasting activity, both of which depend upon each other. These entities also have the potential to influence fault zone stability,
via altering the parameters listed in the “Fault Slip” box (fault strength, fault’s stress, boundary conditions and stiffness and slip behaviour). Pore pressure also influences fault slip, and is included in the Mining System because it is the combination of in situ pore pressure as well as mining related adjustments.

![UML structure diagram of influences on fault stability. See text for further discussion.](image)

Figure 3.1: UML structure diagram of influences on fault stability. See text for further discussion.

Figure 3.1 also presents the organization of this chapter. The influence of large scale geological and mining systems upon fault zone stability are initially discussed, with narrowing focus on all of the entities of each system. Controls of fault behaviour for each of these major topics are discussed, followed by an evaluation of utility for the classification system. The chapter is concluded with summary tables that will be
directly used in the development of the classification system architecture.

\section{Mining System Controls}

The mining system influences fault stability in a time continuous manner through blasting and excavations. Swanson (1992) evaluated seismicity induced slip potential in a deep hard rock mine in northern Idaho. The mine had significant swarms of seismicity and rockbursting, including events that damaged the shaft. The structural geology of the area was complex, with seismicity falling into two main structural regimes. Small stress changes in the mine, such as blasting and excavations, were shown to trigger local structures. Even relatively small disturbances to the fault network, such as those created by blasting, can have a cumulative effect on fault stability. It is therefore important to include both excavations and blasting as mining system controls.

\subsection{Excavations}

A significant portion of the influence of excavations on fault stability is related to changing the stress acting along a fault. The induced stress from excavations can influence the shear and normal stress acting on nearby faults which can lead to a variety of behaviours in the system, including:

- Slip of an existing discontinuity,
- Increase in stability of an existing discontinuity by clamping,
• Creation of new discontinuities, and/or

• Interaction of fault zones.

Induced stresses from mining excavations have the ability to promote or suppress fault slip through changing the normal and/or shear stresses acting along the fault. The influence can spread across multiple scales, from drift/stope scale to mine wide influence (Castro et al., 2009).

In addition to altering fault stability by induced stress, excavations also have the potential to change the boundary conditions acting along a fault. When a fault daylights into an excavation, new degrees of freedom are available for movement. In a simulated rockburst triggered by a controlled blast, Reddy and Spottiswoode (2001) used pre- and post-rockburst mapping to analyse the influence of geology on rockbursts. This work demonstrated the importance of boundary condition changes caused by excavations; bedding planes exposed by an excavation were significantly more likely to be mobilized during a rockburst, and control the shape and size of burst material. Exposed faults would be under similar conditions to the bedding plane interfaces; they are given the freedom to move since they become unconfined where they are intersected by the excavation.

Excavations also have the potential to influence the stiffness of the system, thereby potentially altering fault stability. Mine stiffness is controlled by extraction ratio, mining geometry and the deformation modulus of the rock. At this time, there are no clear parameters to quantitatively describe mine stiffness and its impact on fault stability.
It is clear that excavations significantly influence the potential for fault slip events and related rockbursts. In general, it is very easy to measure and predict excavation geometry and location since they are planned entities. It is generally understood how to handle induced stress through the use of numerical models. Provided that geological system information is known, the influence of excavations on boundary conditions of faults can be investigated via numerical models, however, only limited studies currently exist.

The influence of the change of system stiffness on fault stability is not well understood. A likely measure of system stiffness is extraction ratio of a given area, however it is not known what scale this extraction ratio should be measured with nor what to do with this information.

This indicates that the influence of excavations on fault stability needs to be re-evaluated over the time scale of interest since excavation geometry is highly time dependent. It is also important to note that when considering mitigation techniques, the mining environment is the only that system one can control and alter. The influence of excavations on fault stability could have a significant impact on mining approach and techniques, however, with our current knowledge it is unclear how to proceed with risk mitigating design.

### 3.1.2 Blasting

Blasting changes the stresses acting along a fault by introducing new energy into the system. Unlike many of the other controls discussed in this section, blasting creates stress waves that may dynamically trigger faults. Stress waves created by blasting
travel away from the sources, temporarily altering the stress state on faults until the waves have decayed. Through laboratory and numerical studies, Uenishi et al. (1999) evaluated dynamic triggering of fault slip. It was found that the direction of shear preloading significantly influenced instability triggered dynamically, for example triggered by a blast (Uenishi et al., 1999). The risk of causing fault slip is greater when there is more energy being released from a blast. The amount and type of explosive, and delays used between charges influence how much energy is released at one given time.

The influence of blasting on fault stability can be significant. Due to the fact that blasting can cause dynamic triggering of faults, it is highly time dependent and occurs over very short time intervals. Fortunately, it is very easy to measure and predict parameters related to blasts, such as location and magnitude, since they are planned events. Currently, however, it is unclear how to determine if the blast related energy will cause slip along any fault. Not only is dynamic triggering a complicated, system related issue, the pre-existing state of stability for any given fault is unknown. Although rarely used in mining, models used in the earth science community that incorporate dynamic triggering may prove successful.

### 3.1.3 Pore Pressure

Pore pressure results from natural ground water as well as the introduction of water from mining (for example, during backfilling of stopes). The presence of water along a fault changes the stress acting along a fault by reducing the overall clamping force; the effective normal stress acting along a fault plane is the total normal stress (in situ
combined with induced stress) minus the pore pressure.

It has been well documented that the presence of fluid can induce slip along faults. Notable examples include seismicity induced during oil well stimulation, reservoir filling and the injection of waste fluids into wellbores (for a review see Goldbach, 2009). In a mining engineering context, it is well accepted that slopes can become unstable due to the influence of water on faults and/or joints. However, limited work has been completed on the influence of fluid on fault stability in deep, underground mines (Goldbach, 2009). A project run over 7 years by the Chamber of Mines Research Organization in South Africa aimed to induce large magnitude fault slip events along existing faults by pumping water through three boreholes to two identified faults. Despite the fact that the injected water pressure was similar to water pressures that induced large magnitude events during borehole injection, only small magnitude events ($M_L < 0$, where $M_L$ is local magnitude) were witnessed over the span of the project. The project concluded that only small magnitude events were induced because the large scale joint systems in the mine were previously unsaturated, reducing the interconnectivity of flow channels between the faults of interest.

Recently, however, it was shown that water can induce seismicity in a deep mine (Goldbach, 2009). In South Africa, a deep level mine was flooded in a previously mined out area adjacent to an active production area (see Figure 3.2). Seismicity was experienced in the active production area (Figure 3.3 (a)) as well as the flooded area (Figure 3.3 (b)).
Seismicity in the active mining area showed a near steady event rate, with a clear, mining activity related distribution of frequency of seismic events (Goldbach, 2009). By contrast, the seismicity in the flooded area showed a rapid increase in the number of events over an 18 month time span and no discernible pattern with respect to time and frequency of events (Goldbach, 2009). As discussed by Goldbach (2009), two
very interesting phenomena are illustrated in Figure 3.4:

1. The onset of seismicity was delayed approximately 14 months behind flooding, and

2. Much of the seismicity related to the flooded area migrated up dip over an 18 month period (shown by the yellow arrows bounded by yellow hatching in the figure).

Figure 3.4: Elevation of the water level (solid line) and depth of seismic events (blue diamonds) in the flooding area. The yellow dotted area and arrows illustrate the up dip migration observed (Goldbach, 2009).

Seismicity lagging behind pore pressure is a common occurrence in the filling of reservoirs (Goldbach, 2009). In this case, it took 14 months for the pore pressure to become sufficiently high enough to induce seismic events. Slip occurred when the pore pressure was a little less than 6 MPa, which is comparable to other wellbore injections (Goldbach, 2009).
Laboratory and numerical models have been used to show the influence of pore pressure on fault behaviour. Elimination of the presence of water within a fault often suppresses temperature, velocity and time effects (Scholz, 2004). Dieterich and Conrad (1984) found that the time-dependent increases in the friction coefficient were eliminated with reduced humidity of samples in a laboratory setting. In models, Harris and Day (1993) found that wet dilational steps are barriers to rupture propagation and that rupture on un-drained pore fluids inhibits the rupture from jumping dilational stepovers. Currently, very little is known about what happens to fault stability when dewatering reduces pore pressures.

It is clear that the channels available for fluid to flow throughout a fault system are of great importance. The availability of these channels will be highly dependent upon fault network configuration as well as individual fault zone properties. These aspects are discussed in following sections.

The impact of pore pressure on fault slip risk in mining environments may be significant, however this effect is likely site dependent. The differences in mining geometry and geology between sites may alter the significance of pore pressure. For example, due to interconnectivity, pore pressure would be more significant in a highly damaged area than in a competent, unfractured area. The influence of pore pressure on fault stability is also highly time dependent, not only because values change over time but also because of delays in behaviour (as seen in the prior example). It is moderately difficult to tell the exact amount of water present, however rough system wide estimates, such as “dewatered” or “flooded” as in the prior example from a South African mine, may be sufficient. The amount of pore pressure can be inferred from piezometers, well head heights, inflow at faces, inflow from intersected faults
and outflow of mine pumps. Once initial values and fluctuation patterns are known, the future presence of ground water is moderately easy to predict.

Although understanding the pore pressure present in a mine is possible, there is very little knowledge about how to use this information with respect to fault slip potential. Some numerical models account for pore pressure by reducing the effective normal pressure acting on a fault, however determining the exact pore pressure along each fault is nearly impossible. It is known, however, that pore pressure has a greater significance along faults that are more permeable and that the significance is highly dependent upon interconnectivity of potential fluid pathways. Due to difficulties in data processing and incorporation into stepped models, significant research opportunities exist as to the role of pore pressure in fault stability in underground mines.

3.2 Geological System Controls

3.2.1 Tectonic History and In Situ Stress

The stress state at any given point in three dimensional space within rock is determined by the superposition of far-field stresses, mining induced stresses, and fault and lithologically induced stresses. It is clear that throughout the rock mass there is great heterogeneity regarding state of stress. The degree of stress field change caused by faults may be related to their strength and their physical geometry, for example, asperity squeezing (McKinnon, 2006; Schmittbuhl et al., 2006). How properties affect stability can be inferred; for example, very weak zones will not support shear stress, and undulations along a fault zone may lock in high shear stress.
As identified in Section 2.3, stress is the driving force for fault behaviour. When compared to fault and rock strength, the orientation and magnitude of principal stresses constrain fault behaviour (either slip and/or fracturing). Stress influences the type of behaviour and has the potential to trigger event nucleation. Increases in stress have the ability to enhance coalescence and fracture formation, while stress-shadowing can arrest fracture formation. Similar to stress-shadowing, regions of low shear stress may arrest the propagation of earthquake rupture (Biegel and Sammis, 2004). It is critical to note that the stress state is not static; it changes within the time scale of interest. Mining induced slip affects fault strength, which in turn influences local stresses.

Due to the sensitivity of earthquake rates to stress changes, there may be a corresponding sensitivity in the probability of earthquakes to stress history (Dieterich and Kilgore, 1996). Also, small changes of shear or normal stress may result in large changes in slip speed (Dieterich and Kilgore, 1996).

Normal stress, which acts as a confining stress, significantly influences the behaviour of faults (Dieterich and Conrad, 1984). A high confining pressure suppresses the growth of dilatant microcracks, as well as increases the frictional contact strength, thereby reducing the amount of slip along grain boundaries (Lockner et al., 2002). It is important to note, however, that confining pressure does not influence the static coefficient of friction for all materials in the same manner; Figure 3.5 illustrates changes in static friction due to variations of normal stress. Also, Byerlee’s law (see Chapter 2) is an overestimate for the majority of these cases. Bergen and Shaw (2010) identified that processes that change effective normal stresses along thrust faults (uplift, erosion and fluid pressure) play critical roles in determining maximum
displacement-length ratios.

Figure 3.5: Frictional resistance plotted for crushed layers of common rocks and minerals sheared between granite or sandstone driving blocks (Lockner et al., 2002)

The tectonic history of a fault is very important. As identified in Chapter 2, there is increasing evidence that rocks exhibit rate- and state-dependent friction. This would indicate that there is a memory of past sliding events that influences future behaviour. Additionally, the tectonic history of a fault determines the maturity of that fault. Fault maturity is an important consideration since parameters that control fault strength and behaviour do evolve on a geological time scale, such as fault gouge granularity or damage zone extent.

Tectonic history and in situ stress are undoubtedly important factors controlling fault
slip. In situ stress caused by tectonic loading was created over a very large time scale, and changes negligibly over the time scale of mining. It is difficult to measure the current state of stress with high resolution. Additionally, as depth increases, stress measurements become less accurate. Provided the location of the faults are known, hypothetically the stress changes caused by tectonic loading and slipping of faults could be measured by overcoring if they were within an appropriate range from an excavation. This is not commonly done. Stress measurement and inferring techniques include: overcoring, borehole breakouts, drift deformations, core discing, seismic inversion and historical data. Once the data has been measured, it is commonly averaged over certain domains to be used effectively in numerical models. It is unclear, however, if high stress changes around faults are indications of their strength.

3.2.2 Temperature

Temperature affects frictional behaviour, as shown in Figure 3.6 (Bizzarri, 2009). Considering the limited temperature gradient associated with mining depths and the scale of temperature change in Figure 3.6, temperature is not likely to significantly alter fault behaviour in a mining environment.
3.3 Fault Network and Fault Zone Controls

As previously mentioned in Chapter 2, behaviours of concern for mining environments are coalescence of fractures and fault slip (CAMIRO Mining Division, 1995). It has been identified that pre-existing structures control deformational characteristics and the displacement distributions of fault surface rupture (Lin, 2009).

Heterogeneities in fault strength and stress conditions have a primary impact on the size/frequency distributions of earthquake ruptures. Dieterich and Richards-Dinger (2010) state that these heterogeneities may develop from:

- remnants of dynamical complexity during rupture,
- interactions during slip of geometrically complex fault systems,
- heterogeneous material properties, and/or
- external processes such as spatially non-uniform pore fluid pressure changes or
In order to determine fault network and fault zone related properties, it is of critical importance that faults can be accurately located. Currently, geological mapping in mines is related to factors that influence ore location and grade. This does not typically involve determination of fault networks or even accurate mapping of faults or their characteristics. Common techniques to locate faults include: examining core, boreholes and excavations; analysing seismic data for planes of seismicity (although rarely done in mines); and using the presence of rotated stresses to infer that geological structures are in the near vicinity. Seismic reflection is used in some industries, however it is not frequently used in mining. As mining progresses, a more detailed picture of the location of faults typically evolves. Depending upon the mining environment, geological environment and fault network and zone properties, the classification system may need to be used again to evaluate fault slip risk based on the new knowledge and data.

3.3.1 Fault Network

Large amounts of recent literature illustrate the importance of fault and earthquake interaction over the entire network of faults. This interaction leads to earthquake sequences, clustering and aftershocks (Stein, 1999). It is widely accepted that slip on one fault zone may trigger slip on others via static or dynamic stress transfer (e.g. Das and Scholz, 1981; Stein, 1999; King et al., 2001; Scholz et al., 2003). Stress changes that influence the nucleation of slip events have a wide magnitude range,
between ~0.01 bar to 1 bar (King et al., 2001). As illustrated in Figure 3.7, after-shock sequences have been found to correlate to modelled stress interactions between slipping faults (King and Gerald Schubert, 2007). The fault network influences fault stability by altering stresses acting along individual fault zones, boundary conditions and system stiffness. For an excellent review of dynamic triggering with an overview of static and quasi-static interaction modes, see Hill et al. (2007).

Figure 3.7: Coulomb stress changes of 1979 Homestead Valley earthquake sequence with superimposed aftershocks. As found in King and Gerald Schubert (2007), redrawn from King et al. (1994).
According to Scholz (2010), theory and observations show that synchronization is occurring between faults; large earthquakes on one fault are triggering other earthquakes on nearby faults within a relatively short time span (examples include up to 7 years). Throughout the fault network, as fault zones evolve, they will tend towards or away from synchronization. When a fault reaches a critical point of stress build up, it slips and its earthquake cycle is reset, redistributing stresses to other faults within the vicinity. This redistribution will enhance or suppress the earthquake cycle on those neighbouring faults. This process continues throughout the fault network, causing seismicity on some faults to be paired due to the redistribution of stresses caused by slip (Scholz, 2010). This synchronization occurs with faults that are subparallel to the fault zone with the original earthquake as well as conjugate fault zones (Scholz, 2010). This aspect of triggering has significant impact on evaluating the risk of fault slip in a mining environment. It is very important to find a reliable way to determine which faults interact with each other.

Dieterich and Richards-Dinger (2010) used a fault system earthquake simulator to evaluate earthquake recurrence in fault systems. The models used rate- and state-dependent friction, quasi-dynamic rupture propagation and high-resolution representations of fault systems. Based on these models, it was found that fault network geometry plays a primary role in establishing the characteristics of stress evolution that control recurrence statistics.

Associated with stress changes is the flow of energy within the fault system. Slip events have been known not only to propagate along the plane of the fault zone on which they started, but also to jump to different fault zones, often through fault segments and steps. Current work on triggering and off-fault damage is attempting
to address this issue. However, limited information exists regarding how energy from fault-slip events propagates and redistributes within the fault system.

Based on observed behaviour and models, it is clear that fault zones are interacting as a system and that the fault network is important when considering the stability of individual fault zones. There are limited changes in the fault network over the time scale of interest, with the notable exception of possible mining created faults. Although the importance of the fault network is clear, it is extremely difficult to measure related properties with accuracy. Current practice is to use known intersections of faults and connect the points with limited statistical considerations applied to gain an overall impression of fault network geometry. This approach is insufficient and inaccurate, and clearly demonstrates a great need for advances, most likely in geophysical techniques.

At this moment, it is unclear what fault network properties and related metrics are required to evaluate the potential risk of fault slip. Incorporating complete, realistic fault networks into models may yield better results in some mining environments, however, sufficient computational power does not exist for this approach. It is unclear which fault zones in a fault network are essential to be included to create realistic system behaviour. Each mining environment will have a different fault network configuration. It is unknown if certain configurations can be grouped, and how to rank the influence of different fault network configurations. Significant research opportunities exist to identify the role of the fault network in fault slip.

The question of how fault zone interactions occur and their impact on fault zone and fault system behaviour is of great importance to understanding how to mitigate
the risk of fault-slip in a mining situation. Perhaps of greatest need that does not yet exist for a fault slip classification system is the ability to identify how to describe different fault networks and relate that description to fault zone, or even fault network behaviour.

### 3.3.2 Fault Zone Geometry

The geometry of the fault and sliding surface offers significant control on behaviour by affecting the fault’s strength, the stiffness of the fault and causing some effect upon stresses acting along the fault. Pre-existing structures control deformational characteristics, displacement distributions, evolution of the main fault zone, geometry of relay zones and geometry of small scale faulting (Lin, 2009; Bellahsen and Daniel, 2005). Geometry can influence fault stability by causing changes in fault strength, stresses acting along the fault and the fault’s stiffness.

Fault length affects slip velocity, rupture velocity and slip velocity profile. In the earth science community, it is commonly accepted that there is a scaling relationship between fault length and the amount of slip on faults and thrust faults (refer to Figure 3.8 and ) (e.g. Walsh and Watterson, 1988; Dawers and Anders, 1995; Bergen and Shaw, 2010). To further the link between fault length and displacement, there is a typical slip gradient shape common to all faults due to geometry, crack mechanics and segment interaction (Cowie, 2001). Figure 3.9 illustrates this concept; normalized distances along faults of different original lengths are plotted against normalized slip. The slip profiles are similar for all faults, regardless of true length. Additionally, when fault lengths are close to nucleation lengths, the length over which slip develops,
rupture velocity and slip velocity increase with increasing fault length (Okubo and Dieterich, 1984). Due to difficulties in measuring in situ faults, this information is difficult to apply in a mining environment.

Figure 3.8: Maximum net slip versus fault length (Schlische et al., 1996)
Asperities are considered to be stiffer patches along a fault. They may take the form of physical undulations along the fault surface, small relay zones between fault segments or they may be variations in properties of the wall rock or infilling. Based on this meaning, asperities will alter fault stability and behaviour by changing the fault’s strength, stress acting along the fault and the fault stiffness over distinct areas of a fault zone. The influence of asperities on static friction is presented in Figure 3.10. The greater the amount of contact between the two walls of the fault due to asperities, the higher the coefficient of static friction becomes. This is because when there are more contact patches, it becomes more difficult to mobilize either side.
Figure 3.10: Contacting surfaces of asperities. (a) Section view along fault. (b) Plan view of contact, where $A_r$ is the real contact area between the two sides of the fault (Scholz, 2004).

The role of asperities in terms of fault failure is of much current discussion (e.g. Vannucchi et al., 2009; Manighetti, 2009). Asperities have been interpreted as areas of high static friction able to accumulate large amounts of locked slip and as areas of lower than average dynamic friction, therefore able to slip more during an earthquake (Vannucchi et al., 2009). Dieterich and Kilgore (1994) found that the characteristic slip distance was directly related to contacting asperities.

Based on satellite images taken before and after the 2010 Maule (Chile) earthquake, pre-seismic locking was observed on asperities that were involved in the large event (Moreno et al., 2010). Prior to the earthquake, back analysis illustrated that these locked asperities were being loaded by a creeping section between them (Moreno et al., 2010). Additionally, rupture arrested in other asperities that had released their
loaded stress in the form of smaller events (Moreno et al., 2010). This signifies that asperities combined with the consideration of tectonic history may be very powerful indicators of fault slip.

For large scale faults, the net slip (offset) is partially controlled by the number of steps per unit length (refer to Figure 3.11). A fault zone with fewer steps per unit length has greater net slip than a fault with greater steps per unit length. This indicates that steps act as asperities that alter the effective fault strength. Manighetti (2009) suggested that large scale fault segmentation controls the largest earthquakes. Additionally, despite the fact that fault topology is self similar, the number of inter-segments broken per fault varies greatly (Manighetti, 2009). Manighetti (2009) posited that this was caused by fault-specific history and system effects; the slip history, structural maturity, tectonic history and connection state at the time of the fault influenced slip.

Figure 3.11: Relationship between fault steps per unit length and net slip for active strike-slip faults (Wesnousky, 1988)

The type of segment linkage alters the slip profile (Bergen and Shaw, 2010). Faults
with hard linkage cause the maximum displacement-length ratio to immediately de-
crease when segments link (Bergen and Shaw, 2010). Soft linked faults may generate
higher displacement-length ratios than isolated faults since the linkage allows slip to
transfer and the faults to effectively behave as one, while maintaining smaller fault
lengths (Bergen and Shaw, 2010). Manighetti (2009) posited that fault segmentation
is likely to influence fault slip by the specific mechanical and rheological behaviour
of the major inter-segments (the rock between fault segments). Manighetti (2009)
furthered this by suggesting that mature inter-segments are likely to be soft, weak
barriers to slip, due to the high strain they accumulate, making them capable of
diffusing high stresses and strain, preventing elastic storage.

Fault geometry is an extremely important control of fault behaviour, as geometry
defines the strength of each fault zone. Aside from potential faults created during
mining, there is little change in fault geometry over the time span of mining. The
largest obstacle that needs to be overcome to create an effective fault slip classification
system is accurately identifying fault geometry. Currently, it is most common to use
intersections of fault zones with boreholes, excavations, etc. to create planar models
of the fault zones with little concern for statistics or knowledge of exact tectonic
history. Due to the arbitrary nature of this measurement technique, there is little
accuracy in fault location and geometry. In some environments, seismic reflection is
used to help constrain fault zone geometry; however there are significant limitations,
especially when it comes to identifying individual asperities. There is a clear need for
advances in geophysical techniques to accurately identify fault geometry.

At this stage, fault geometry can be incorporated into models with some reliability,
if that geometry is known. Considering that is it highly unlikely that the exact
geometry will ever be known, this leads to consideration of using probabilistic or stochastic models to analyse possible scenarios within the constraints of the local tectonic history. Also, since fault geometry is heterogeneous in three-dimensions, modelling all geometry would be beyond the limitations of computational power. It is important that the necessary input information is determined to reduce model size and run-time.

### 3.3.3 Slip Surface and Fault Core

The roughness along a sliding surface influences fault strength and slip behaviour by altering frictional strength, slip velocity and type of slip. Within the lab setting Okubo and Dieterich (1984) identified that slip velocity was influenced by roughness, velocity and roughness are proportional to stress drop, and that roughness significantly influences unstable shear failure behaviour. The rupture velocities on rough faults were much lower than on smooth faults (Okubo and Dieterich, 1984). As previously discussed, Power et al. (1987) demonstrated that surface roughness is self-similar. This implies that there is no single scale-length which might be associated with the characteristic displacement. Dieterich and Smith (2009) demonstrated that slip surfaces with fractal geometry do indeed behave differently than planar slip surfaces in models.

The width of the physical sliding surface controls rupture characteristics. Findings show that a narrow slip surface causes slip localization, large displacements and less high-frequency ground motion (Heermance et al., 2003). There is room for significantly more work in this area; however it is important to note that determining the
slip surface area is not always possible.

In general, the presence of gouge reduces the strength of fault zones and alters frictional behaviour, the mode of slip, and whether displacements are localized (Logan and Rauenzahn, 1987; Chester and Logan, 1986). An example strength profile across the clay gouge Nojima Fault is shown in Figure 3.12. The shear strength steadily reduces from intact rock strength as the fault is approached from either side, reaching a minimum in the fault core. Within a laboratory setting, a rock surface without gouge exhibited steady-state velocity weakening while gouge layers exhibited velocity-strengthening (Marone et al., 1990).

Figure 3.12: Profile of peak shear strength of core samples across shear zone with clay gouge. Strength is lowest in the clay gouge, and recovers to intact rock strength outside of the damage zone (US Geological Survey, 2009b)

A complete picture of how fault gouge controls fault behaviour remains elusive despite numerous studies. As discussed in Chapter 2, there are many degrees of fault gouge, even along one fault zone. These variations significantly affect fault behaviour while simultaneously making it very difficult to create a general approach relating to gouge and behaviour.

As described by Scholz (2004), behaviour dramatically alters based on gouge width.
Gouge width is related to slip distance (refer to Figure 3.13) (Scholz, 2004). As in Figure 2.11 for example, fault strength would decrease from a) through e), however the strength exhibited in d) and e) would likely be significantly weaker than the other examples. Biegel et al. (1989) found that the coefficient of static friction was greater for thin gouge than it was for thick gouge in laboratory experiments. The relationship between gouge width and fault strength is likely nonlinear. In addition, the variable gouge width along a fault also influences local stress conditions.

![Figure 3.13: Core thickness versus fault slip distance, where SAF is the San Andreas Fault (Scholz, 2004)](image)

The composition of gouge materials also controls gouge behaviour, since composition significantly alters slip behaviour and inherent strength. Logan and Rauenzahn (1987) suggested that the composition of gouge material alters the static coefficient of friction as well as the dynamic frictional behaviour based on their laboratory studies. This is
likely due to mechanical properties inherent to specific rock types. Weak gouges are generally velocity strengthening, while strong gouges can be velocity strengthening or velocity weakening (Ikari, 2010). The frictional velocity dependence can evolve systematically with shear strain, indicating that the fault behaviour may evolve from aseismic to seismic through a function of accumulated offset (Ikari, 2010). Ikari (2010) demonstrated that clay-rich gouges are frictionally weak, exhibit velocity strengthening behaviour, have low permeability and are unlikely to show seismic behaviour. However, minerals such as quartz and feldspar tend to be velocity-weakening after a critical amount of shear strain (Ikari, 2010). Gouge composition is speculated to affect mechanical properties such as fault stiffness and dilatancy due to the properties of the rocks.

The physical geometry, including the arrangement of specific gouge materials, gouge compaction and particle size will control fault strength and slip behaviour. In some fault gouges, there are thin, weak layers of clay material that become surfaces for slip nucleation. Since friction is related to the amount of contacting area, it must be affected by gouge consolidation (refer to Figure 3.14). Consolidation of gouge is a function of normal stress acting on the fault and pore volume/packing (a function of particle size and particle shape). It has been experimentally confirmed that velocity effects on the coefficient of friction are related to the pore volume in the gouge, as well a packing geometry, angularity and size of gouge particles (e.g. Morrow and Byerlee, 1989; Dieterich, 1981; Lockner et al., 2002). Nakatani (1998) suggested that compaction is part of the physical reason for fault healing. In laboratory tests, Sammis et al. (1987) found a clear relationship between the largest particle size in the gouge and the characteristic displacement; the characteristic displacement has a
positive linear relationship with maximum gouge particle size, as illustrated in Figure 3.15. Using three-dimensional discrete element simulations, Abe and Mair (2009) demonstrated that gouge fragment shape and the resulting interactions dominate the frictional strength of faults.

Figure 3.14: Effect of gouge consolidation on contact area and relation to friction. (a) and (b) are both faults with significant gouge, however (a) has gouge material that is less consolidated than (b). The top half of (a) and (b) provides section views and the bottom half provides plan views of contact area. Note that in (b), the more consolidated case, has greater contact areas (shaded region in plan view) indicating a greater static friction coefficient.
Additionally, it is widely accepted that the presence of certain types of gouge materials provides a conduit for water. Broken rock provides a better conduit than clay material. Water may lubricate faults by reducing the effective pore pressure (see 3.1.3); however with high velocity slip, water may be driven off by temperature (US Geological Survey, 2009a). Water within fault gouge alters the frictional strength of some gouge materials (refer to Figure 3.16).
In general, properties related to fault gouge can be measured with ease at distinct points in the rock mass. Drill core will give fault core related information such as presence of gouge, width, composition, initial consolidation and porosity, and strength. There is not however, a reliable way to know the heterogeneity of the properties of the fault gouge beyond that point. Based on the literature, fault gouge properties have significant control over behaviour and certain gouge parameters may be indicators of mechanical properties.

The slip surface and core of a fault zone offer important controls of fault behaviour, as these controls define much about fault strength, slip behaviour and fault stiffness. Slip surface and core change very little over the course of mining. Provided that the locations of faults are known, it is of moderate difficulty to identify the slip surface.
and core properties at point locations. Also, it is difficult to identify how pervasive the related properties are along the fault zone. Studies identifying statistical distributions of slip surface and core properties along fault zones for different tectonic settings would be beneficial to the fault slip classification system.

At this time, limited slip surface and core properties are incorporated into models used in mining. Geometry of the slip surface can be accounted for, however it is uncommon that significant gouge parameters are. It is common to complete laboratory tests on gouge for material behaviour information, however it is not usually placed into in situ context with consideration of all of the parameters discussed (i.e. influence of particle size, the geometry of gouge particles, etc.). The majority of models created use a Coulomb constitutive model along the slip surface, with no distinct gouge. This is clearly a simplification of what truly exists (including how gouge influences behaviour as well as constitutive models), however limited discussion exists if these simplifications are appropriate for all models of faults in mining environments.

Currently, research regarding the impact of slip surface and fault core on behaviour is segmented; there have been numerous in-depth studies on the influence of these controls on fault strength and slip behaviour, yet there is limited information on combining the findings into a single framework. Research combining this segmented work to form a general picture of the role of slip surface and fault core on behaviour is necessary.
3.3.4 Wall Rock and Damage Zone

The wall rock lithology is expected to significantly influence fault behaviour, both for fault-slip as well as fracture nucleation and coalescence. It is anticipated that wall rock composition changes many mechanical properties such as frictional behaviour, fault material stiffness, hardness and fault strength. The wall rock lithology affects the presence of gouge on one or both sides of the fault and will affect properties related to the damage zone (for example, damage zone width) (Biegel and Sammis, 2004).

For some faults, the composition of each side of the fault surface is very different (Yamashita, 2009). This situation causes both sides of the fault to have different elastic constants and damage is enhanced (Fukuyama, 2009). It is suggested that this type of bi-material interface causes coupling between slip and normal stress (Yamashita, 2009). Statistical analysis of wall rock surrounding a fault with seismicity exhibited correlations; seismicity was correlated to wall strength, indicating that wall rock composition plays an important part in fault mechanics (Graymer et al., 2005). Creep rates were relatively uniform over the majority of the fault length, however there were indications that seismicity correlates with rock units on one side of the fault or the other, rather than rock interactions across the fault (Graymer et al., 2005).

Variations in the stiffness of wall rock material can cause strong deviations from the idealized symmetrical distributions of slip (Burgmann et al., 1994). For example, a relatively stiff body adjacent to or cut by a fault will tend to reduce slip in its vicinity and tends to flatten the slip profile when cut by the fault (Burgmann et al., 1994). Sharp slip gradients develop near the interface of soft/stiff materials (Burgmann et al.,
Currently, the influence of different types of damage zones (as described in Section 2.2.2) and their specific properties (i.e. width, distribution of fractures, etc.) on behaviour has not been intimately studied. It is however known that the damage zone significantly affects the fault propagation (Yamashita, 2009). This agrees with classic fracture mechanics theories since the stress in that zone is altered.

The damage zones act as a conduit for water, giving the potential to enhance the pore pressure effects if water is in the system. Figure 3.17 presents the influence of damage zone on the permeability around a clay shear zone (Nojima Fault, Japan). As expected, the permeability is greater close to the shear zone, the area with the highest fracture density.

![Figure 3.17: Profile of permeability across Nojima Fault, Japan. The clay shear zone has a low permeability. Note the high porosity associated with the damage zone that recovers to intact rock porosity with increasing distance away from the fault (US Geological Survey, 2009b).](image-url)
Due to the fracturing associated with damage zones, it is anticipated that there is an associated reduction of stiffness and fault strength. Inelastic deformation in the damage zone is associated with off fault damage as fractures form, grow and propagate. These zones can act as both stress shedding areas and stress concentrating areas, increasing or decreasing fault stiffness and strength. The most significant contributors to these parameters are likely damage zone width, density of fracturing and distribution of fracturing across the fault, however very little work has been completed in this area.

Very little information is available relating wall rock and damage zone to fault zone behaviour, however they theoretically control fault strength, the stress acting along a fault and the fault-system stiffness. The damage zone and wall rock are essentially static over the time scale of mining, indicating that once evaluated, re-evaluation is not necessary. Provided the location of the fault is known, measuring the extent and composition of the damage zone and wall rock may be determined by drilling across faults and examining core, boreholes and excavations. Potential measurements of interest include wall rock composition and rock constitutive properties, damage zone width, fracture density and distribution of fractures in the damage zone. Prediction of damage zone and wall rock properties may be difficult; point measurements may not be sufficient since these properties are not always heterogeneous.

Significant research opportunities exist relating properties of the damage zone to future fault behaviour. In most cases, the extent of damage zone may provide an indication as to the amount of past slip on a fault, however it is not clear if this can be related to future behaviour. It is clear that the damage zone has the opportunity to affect both the coalescence of fractures as well as fault slip, making this an important
area from a mining perspective. Potential areas of study include, but are not limited
to: role of different types of damage zones, impacts of asymmetrical damage zones,
and the effect of damage zone parameters on fault stiffness and strength. The tectonic
history and in situ stress would be very important considerations. The wall rock is
typically incorporated into models using the constitutive properties of the type(s) of
rock.

3.4 Summary

The following tables, Table 3.1, Table 3.2 and Table 3.3, are offered as summaries of
this chapter. For each major control discussed in this chapter, the implications on
fault instability and the classification system are provided, including

- how does each control influence fault slip (changes in fault strength, changes in
  stress acting along a fault, changes in boundary conditions, changes in stiffness
  of the system or fault and changes in slip behaviour),

- the importance of each control,

- if each control is time dependent over the time scale of mining,

- how easy it is to measure and predict stability indicators, and

- the ease and current state of knowledge of data processing of these indicators.

The importance of each control was based upon evaluation of the literature provided
in this chapter. No specific reference was available to compare the importance of
each control. Insufficient background information to evaluate the importance of each
control with certainty is indicated by a “?” in the table.

This summary is critical to the development of the classification system architecture, as it outlines the depth and limits of current knowledge, what will need to be re-evaluated, and how each control influences fault stability for grouping purposes within the classification system.
### Table 3.1: Mining system summary

<table>
<thead>
<tr>
<th>Influences on fault slip</th>
<th>Excavations</th>
<th>Blasting</th>
<th>Pore Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆ Fault Strength</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>∆ Fault’s Stress</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>∆ Boundary Cond.*</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>∆ Stiffness (fault or system)</td>
<td>Yes (system)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>∆ Slip Behaviour</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Importance wrt** classification system</th>
<th>Very high</th>
<th>Moderate (?)</th>
<th>Can be high, may be site dependent</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Time Dependent</th>
<th>Highly (defines time scale of interest)</th>
<th>Very highly</th>
<th>Highly (some delays in system as well)</th>
</tr>
</thead>
</table>

| Measuring, Measurability and Predictability | In general, very easy to measure and predict. Use a combination of plans and surveys to determine where exact excavations are in space | Very easy to measure and predict amount of energy and location since blasts are always planned. | Moderate to difficult to tell exact amount of water present. Easier to tell if it is “dewatered” or flooded. Relatively easy to predict once initial values and patterns are known. Can infer from piezometers, well head height, inflow at face, inflow from intersected faults and outflow of mine pumps. Easy measurements. |

| Ease of Data Processing and Handling | How to handle induced stress is well understood if initial conditions are known (i.e. use models). The influence on boundary conditions can be dealt with since the location of excavations can be put into numerical models. The influence on change of system stiffness is not well understood. A likely measure is extraction ratio in 3-dimensional space, however very little is understood about what to measure and what to do with the information | Unsure of what to do with location and magnitude data; it is unclear how to determine if the blast related energy will cause slip. Dynamic models may be a potential solution. | Little knowledge about how to use this information with respect to fault slip potential. It is important to note that pore pressure has a greater significance on fault behaviour when faults are more permeable (controlled by Fault System and Fault Zones). Difficult to incorporate in models. Research opportunities exist as to the role of pore pressure underground. |

* Conditions

** with respect to

96
Table 3.2: Geological system summary

<table>
<thead>
<tr>
<th>Influences on fault slip</th>
<th>Geological System</th>
<th>Tectonic History and In situ Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆ Fault Strength</td>
<td>Yes</td>
<td>No (not actively over time scale of interest)</td>
</tr>
<tr>
<td>∆ Fault’s Stress</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>∆ Boundary Cond.*</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>∆ Stiffness (fault or system)</td>
<td>No</td>
<td>Possibly (system)</td>
</tr>
<tr>
<td>∆ Slip Behaviour</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Importance wrt** classification system</td>
<td>Low</td>
<td>Very high</td>
</tr>
<tr>
<td>Time Dependent</td>
<td>No</td>
<td>Small dependence over time scale of mining</td>
</tr>
<tr>
<td>Measuring, Measurability and Predictability</td>
<td>Ambient temperature easy to measure and predict.</td>
<td>Poor accuracy and resolution; not easy to measure with accuracy. Very difficult to measure or infer along fault. Some heterogeneity can be accounted for by varying the location of measurements. Stress measurement and inferring techniques include: overcoring, borehole breakouts, drift deformations, core discing, seismic inversion and historical data. Accurately determining tectonic history is very difficult.</td>
</tr>
<tr>
<td>Ease of Data Processing and Handling</td>
<td>Limited use over temperatures ranges common to mining environments.</td>
<td>Relatively clear how to use in situ stress as data is commonly used in numerical models. It is unclear what (if anything) high stress changes around faults mean. Limited knowledge of what to do with tectonic history.</td>
</tr>
</tbody>
</table>

* Conditions
** with respect to
<table>
<thead>
<tr>
<th><strong>Fault System</strong></th>
<th><strong>Fault Zones</strong></th>
<th><strong>Time Dependent</strong></th>
<th><strong>Measuring, Measurability and Predictability</strong></th>
<th><strong>Ease of Data Processing and Handling</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>∆ Fault Strengths</strong></td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Provided on has knowledge of the location of the faults, measuring the extent and composition of damage zone seems relatively straightforward. Prediction may prove difficult in some cases. Can measure by drilling across faults and examining core, boreholes and/or excavations.</td>
</tr>
<tr>
<td><strong>∆ Fault’s Stress</strong></td>
<td>Yes</td>
<td>Somewhat</td>
<td>Yes</td>
<td>Can incorporate geometry into models with some reliability.</td>
</tr>
<tr>
<td><strong>∆ Boundary Cond.</strong></td>
<td>No</td>
<td>No</td>
<td>Variable (?), may be site dependent.</td>
<td>Not frequently incorporated at a detailed level. Limited knowledge of how to quantitatively evaluate gouge properties.</td>
</tr>
<tr>
<td><strong>∆ Stiffness (fault or system)</strong></td>
<td>Yes (system)</td>
<td>Yes (fault)</td>
<td>Variable (?), may be site dependent.</td>
<td>Essentially no knowledge of what to do with this information, or if it can be used for slip prediction.</td>
</tr>
<tr>
<td><strong>∆ Slip Behaviour</strong></td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Significant research opportunities exist.</td>
</tr>
<tr>
<td><strong>Importance wrt</strong></td>
<td>Very high (triggering and potential synchronization suggest this), may be site dependent.</td>
<td>Very high</td>
<td>Moderate to high (?)</td>
<td></td>
</tr>
<tr>
<td><strong>Classification system</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Influences on fault slip:**
- **Geometry**
- **Slip Surface and Core**
- **Damage Zone and Wall Rock**

**∆** denotes a change in the specified variable.
Chapter 4

Classification System Architecture

The intent of this chapter is to present recommendations with respect to the architecture of the fault slip classification system for use in mining environments. Potential inputs, as discussed in Chapter 3, are evaluated for their value in the classification system based on their importance, what they influence and information related to measurement. The impact of important inputs were incorporated into numerical stress models to evaluate the influence of excavations on fault system behaviour. The final section of this chapter synthesizes information to provide final recommendations on the architecture of the fault slip classification systems.

4.1 Evaluation of Inputs

This section evaluates the potential inputs of the classification system based on information presented in Chapter 2 and Chapter 3. It is important to note that this
section evaluates the inputs to aid with the development of the architecture of the classification system. Our current level of knowledge regarding how these inputs combine to relate to fault slip is too limited to move beyond this crucial stage.

To develop recommended classification system architectures, the potential inputs have been evaluated based on importance, time-dependency, what the inputs influence, measurement techniques, and current state of data availability and quality compared to the desired state of data. Evaluation is completed from a mining engineering perspective; the classification system needs to be meaningful over the time-span and the depths of mining activities.

The following list ranks the evaluated controls based on perceived importance as presented in the summary at the end of Chapter 3. This list clearly identifies that for mining engineering purposes, temperature is not an important control. Due to this, temperature is no longer included in this evaluation. It is important to note that although this list is based upon the background literature found in Chapter 3, the importance of each control may be site dependent.

1. Excavations: Very high
2. Tectonic history and in situ stress: Very high
3. Fault system: Very high, importance is likely site dependent
4. Fault zone geometry: Very high
5. Pore pressure: Can be high, importance is likely site dependent
6. Fault zone slip surface and core: Moderate to high, more work required
7. Blasting: Moderate, significant work required
8. Fault zone damage zone and wall rock: Variable, significant work required

9. Temperature: Low

As discussed in previous chapters, some controls of fault behaviour experience a significant amount of variation over the time span of mining. Factors that are highly time variable are not typically incorporated into classical classification systems, as discussed in Chapter 2. Time variable controls indicate a need for reassessment or continual assessment. A comparison of time variable and time independent factors are presented in Table 4.1. Each factor is listed in order of importance with respect to impact on fault slip. Due to the impact that time variable controls have upon classification systems, time variable controls are not evaluated in this section past Table 4.1. Instead the influence of some of the more important time variable controls is evaluated in Section 4.2.

Table 4.1: Time variable versus non-time variable factors over the time span of interest

<table>
<thead>
<tr>
<th>Time Variable Factors</th>
<th>Time Independent Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining excavations (geometry)</td>
<td>Tectonic history and in situ stress</td>
</tr>
<tr>
<td>Pore pressure</td>
<td>Fault system</td>
</tr>
<tr>
<td>Blasting</td>
<td>Fault zone geometry</td>
</tr>
<tr>
<td></td>
<td>Fault zone slip surface and core</td>
</tr>
<tr>
<td></td>
<td>Fault zone damage zone and wall rock</td>
</tr>
</tbody>
</table>

A closer evaluation of the time independent factors is provided in Table 4.2. The major factors are listed in order of importance (see above), and their influence on fault behaviour is presented. As discussed in previous chapters, fault behaviour is determined by the fault’s strength, the stresses acting along the fault, the boundary
conditions, the fault and system stiffness and the type of slip behaviour.

It is clear that the stresses acting along the fault and the fault-system stiffness is influenced by all factors. The strength of the fault is generally influenced by fault specific factors, whereas the boundary conditions are more influenced by larger scale geological factors. This type of organization may be useful in the design of the classification system, especially in the early stages of data analysis. Using these categories to organize data will provide an excellent starting point to begin evaluating relationships within the data.
Table 4.2: Factors that influence fault behaviour organized by importance

<table>
<thead>
<tr>
<th></th>
<th>Fault Strength</th>
<th>Fault’s Stress</th>
<th>Boundary Conditions</th>
<th>Stiffness</th>
<th>Slip Behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tectonic History and In Situ Stress</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Fault System</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Fault Zone Geometry</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Fault Zone Slip Surface and Core</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Fault Zone Damage Zone and Wall Rock</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
For any engineering classification system to be successful, it must be based upon measurable and identifiable qualities. Table 4.3 provides a list of measurement techniques organized by the factor being measured, listed in order of importance. Table 4.4 provides a detailed list of what information is desirable, based on Chapter 3, as well as what information is currently typically obtained in mining environments. Data quality and quantity in mining environments greatly improve as projects progress from conceptual through active operations, and these tables capture the general state of data for most operating mines.

Table 4.4 compares a list of desirable properties related to fault slip based on information from Chapter 3 to a list of properties commonly measured and available in mining environments. It is clear that mines are operating in an extremely data limited environment. There is a significant amount of information that has the potential to be useful in the fault slip classification system that we currently do not have common access to. In particular, there is an extreme gap in commonly measured information in the fault zone specific factors when considering the preferred data quantity. A significant reason behind this is the lack of reliable, inexpensive fault location techniques.
### Table 4.3: Measurement techniques organized by factor

<table>
<thead>
<tr>
<th></th>
<th>Measurement Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tectonic History and In Situ Stress</td>
<td>Overcoring measurements</td>
</tr>
<tr>
<td></td>
<td>Drill hole and drift breakouts</td>
</tr>
<tr>
<td></td>
<td>Hydrofracturing measurements</td>
</tr>
<tr>
<td>Fault Systems</td>
<td>Borehole and drift intersections</td>
</tr>
<tr>
<td></td>
<td>Seismic methods (reflection surveys, refraction surveys, tomography)</td>
</tr>
<tr>
<td></td>
<td>Electrical resistivity surveys</td>
</tr>
<tr>
<td></td>
<td>Seismic event clustering</td>
</tr>
<tr>
<td>Fault Zone Geometry</td>
<td>Borehole and drift intersections</td>
</tr>
<tr>
<td></td>
<td>Seismic methods (reflection surveys, refraction surveys, tomography)</td>
</tr>
<tr>
<td></td>
<td>Electrical resistivity surveys</td>
</tr>
<tr>
<td></td>
<td>Seismic event clustering</td>
</tr>
<tr>
<td>Fault Zone Slip Surface and Core</td>
<td>Borehole and drift intersections</td>
</tr>
<tr>
<td></td>
<td>Fault surface laser scanning</td>
</tr>
<tr>
<td>Fault Zone Damage Zone and Wall Rock</td>
<td>Borehole and drift intersections</td>
</tr>
</tbody>
</table>
Table 4.4: Desirable information and commonly available information that is a potential indicator of fault behaviour. Information is grouped by major factor, which is organized in order of importance.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Desirable Information</th>
<th>Commonly Available Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tectonic History and In Situ Stress</td>
<td>In situ stress throughout the area of interest with a high resolution and accuracy</td>
<td>Some information; Point measurements that lack accuracy, many measurements inferred (i.e. stress field is inferred from borehole breakouts)</td>
</tr>
<tr>
<td></td>
<td>In situ stress state near faults with a high resolution and accuracy</td>
<td>Very limited information</td>
</tr>
<tr>
<td></td>
<td>Tectonic history of the area, including faulting, to understand fault maturity</td>
<td>Multiple, potentially incorrect hypotheses</td>
</tr>
<tr>
<td>Fault Systems</td>
<td>Location of faults</td>
<td>Limited information; Location of some faults, often during production stages of operations</td>
</tr>
<tr>
<td></td>
<td>Connectivity of faults and fault sets</td>
<td>Often hypothesized, limited accuracy</td>
</tr>
<tr>
<td></td>
<td>Any faults that commonly trigger other faults</td>
<td>Limited information, highly dependent upon seismic network coverage and ability to accurately locate hypocentres, amount and quality of information increases during production stages of operations</td>
</tr>
<tr>
<td>Fault Zone Geometry</td>
<td>Location of faults</td>
<td>Location of some faults, often during production stages of operations</td>
</tr>
<tr>
<td></td>
<td>Location of asperities, steps and segments</td>
<td>Very limited information</td>
</tr>
<tr>
<td></td>
<td>Fault zone length</td>
<td>Very limited information</td>
</tr>
<tr>
<td></td>
<td>Properties of inter-segment areas (soft, weak or strong, brittle)</td>
<td>No information</td>
</tr>
<tr>
<td>Fault Zone Slip Surface and Core</td>
<td>Location of slip surfaces</td>
<td>Limited information</td>
</tr>
<tr>
<td></td>
<td>Slip surface roughness</td>
<td>Limited information</td>
</tr>
<tr>
<td></td>
<td>Presence and extent of core material</td>
<td>Some information</td>
</tr>
<tr>
<td></td>
<td>Width of slip surface</td>
<td>No information</td>
</tr>
<tr>
<td></td>
<td>Core composition</td>
<td>Some information</td>
</tr>
<tr>
<td></td>
<td>Core thickness</td>
<td>Limited information</td>
</tr>
<tr>
<td></td>
<td>Material properties of core, mechanical behaviour and porosity</td>
<td>Limited information</td>
</tr>
<tr>
<td></td>
<td>Core geometry, i.e. particle size and compaction</td>
<td>Limited information</td>
</tr>
<tr>
<td>Fault Zone Damage Zone and Wall Rock</td>
<td>Extent of damage zone</td>
<td>Some information</td>
</tr>
<tr>
<td></td>
<td>Density and pattern of fractures that compose the damage zone</td>
<td>Limited information</td>
</tr>
<tr>
<td></td>
<td>Wall rock composition</td>
<td>Some information</td>
</tr>
<tr>
<td></td>
<td>Mechanical behaviour of wall rocks</td>
<td>Some information</td>
</tr>
</tbody>
</table>
It is clear that there are a significant number of unknowns with respect to controls of fault slip. However, organizing the factors into meaningful classes is an instrumental step towards the development of a fault slip classification system. Additionally, identifying the desirable measurable information clearly provides advancement goals for measurement techniques, and data interpolation and interpretation systems.

This section neglected to address two items:

1. Time variable factors
2. The interaction of the geological and mining systems

As discussed in Chapter 3, there is very little information known about the interaction of the geological and mining systems. When considering complex systems, the results of their interaction, in this case fault behaviour, is not always a simple summation of the individual parts, rather it is path dependent. The interaction of the two systems of interest, as well as some of the identified time variable factors will be explored in the following section.

4.2 On the Interaction of the Geological and Mining System

Chapter 3 identified that there were two major systems interacting to produce an array of fault behaviour; the geological system and the mining system. For purposes of the classification system, Section 4.1 evaluated individual inputs, with a focus on time-independent variables. However, it is important to also consider the interaction
of the two systems as a whole, as system behaviour is not necessarily represented by
the simplistic addition of its components (refer to Chapter 3).

This section critically evaluates exploratory numerical stress analysis models that ex-
amine the interaction of the geological and mining system. The set-up and method-
ology of the simulations are discussed, followed by an analysis of the results. Specific
attention was given to the influence of the location of excavations relative to faults
in the fault system.

The purpose of these models is to create a simulation of a realistic fault system and
then evaluate the impact of excavations on fault behaviour. These models incorporate
the three most important factors that influence fault slip, as identified in Section 4.1:
excavations, tectonic history and in situ stress, and the fault system. The fault
system created is an extremely large version of models created by McKinnon (2006),
due to the state of the art nature of these models. The model size was increased to
represent a larger view of the fault system and to evaluate the larger scale implications
of excavation placement with respect to faults. Larger models also permit increased
resolution of the stress field and fine structure of the evolving fault system. The other
major difference between the models of McKinnon (2006) and the models created for
this thesis is the inclusion of excavations; models created by McKinnon (2006) did
not examine the influence of excavations on fault behaviour, as the creation of a fault
system with more realistic behaviour than commonly seen in other models was the
primary interest.

The continuum finite difference numerical modelling software FLAC 7.0 2-D (Itasca,
2011) was used for these models. In finite difference models, damped equations of
motion are used on each grid point to evolve the model to a new equilibrium state through a series of small time steps. Faults, represented by strain localizations, have realistic orientations based on rock mass strength and tectonic loading conditions common to a hard rock mine in Ontario. The faults in the system exist in a marginal state of stability, as faults were formed and evolved by simulating tectonic processes through deformation along the model’s external boundary. Tectonic history is retained through permanent deformation of the grid and the post-peak behaviour of the strain-softening constitutive model used. After the creation of a realistic fault system, a variety of excavations were individually introduced to determine the influence of excavation induced stresses and excavation location on system-wide fault behaviour.

4.2.1 Model Construction

Similarly to the author of the original models, attempts were made to reduce the influence of grid characteristics on the formation of shear bands. Similar to the models of McKinnon (2006), steps taken to ensure this include:

- A large number of grid points were used in the model. A total of 1 000 000 zones were used, over 100 times more than found in the models of McKinnon (2006). Advances in computational power made this increase possible.

- A circular boundary was used to reduce the influence of stress concentrations at the corners of the models (refer to Figure 4.1)

- The initial square grid point geometry was randomly distorted by the maximum amount of variation possible (refer to Figure 4.1). The maximum variation
possible was controlled by geometrical limitations of the software. This reduced the tendency of shear bands to follow the grid alignment.

- The Young’s modulus was varied throughout the model. Values were randomly selected from a triangular distribution around a mean value. This mimicry of natural material reduced the impact of the grid on failure by creating a more natural path for shear band formation.

- An annulus of softer, elastic-plastic (Mohr-Coulomb) model material surrounded the strain-softening material (refer to Figure 4.1). Representing the confinement that would be experienced by the faulted (strain-softening) material in situ, this technique permitted rigid displacement control of the external boundary while shear bands were forming in the interior, as well as allowing limited displacements to occur on fault tips at the edges of the area of interest. This reduced the negative influence of boundary effects.
The initial properties were very similar to those used by McKinnon (2006). They were representative of a hard rock environment (such as an Ontario hard rock mine). These properties were valid to use in these models as McKinnon (2006) found that variations of these properties made little difference upon the outcome. Material properties are listed in Table 4.5. It is important to note that a compressive stress (positive in this software) was initialized to avoid tensile failure of the material.
Table 4.5: Material properties and initial state

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniaxial compressive strength ((\sigma_{c(intact)}))</td>
<td>150 MPa</td>
</tr>
<tr>
<td>RMR</td>
<td>69</td>
</tr>
<tr>
<td>Young’s modulus (average) ((E_{r m}))</td>
<td>30 GPa</td>
</tr>
<tr>
<td>Young’s modulus standard deviation</td>
<td>0.6</td>
</tr>
<tr>
<td>Poisson’s ratio ((v))</td>
<td>0.2</td>
</tr>
<tr>
<td>Cohesion ((c))</td>
<td>4.3 MPa</td>
</tr>
<tr>
<td>Friction angle ((\phi))</td>
<td>55°</td>
</tr>
<tr>
<td>Tensile strength ((\sigma_t))</td>
<td>0.5 MPa</td>
</tr>
<tr>
<td>Mean stress</td>
<td>25.0 MPa</td>
</tr>
<tr>
<td>Major principal stress ((\sigma_1))</td>
<td>47.9 MPa</td>
</tr>
<tr>
<td>Minor principal stress ((\sigma_3))</td>
<td>2.1 MPa</td>
</tr>
</tbody>
</table>

Boundary conditions applied for the creation of the fault system were identical to those used by McKinnon (2006). Velocity conditions were applied to the boundary of the outer annulus to create a combination of pure and simple shear conditions (refer to Figure 4.2 for a visual explanation of pure and simple shear, refer to Figure 4.3 for velocity vectors as applied at the boundary of the model). The velocity conditions were applied to reproduce the calculated initial state of stress and deformation. The orientation of the major principal stress was computed as \(\psi = 76.7°\) using the following equation:
Figure 4.2: a) Combination of pure and simple shear for boundary displacement. b) The resulting orientation of principal stresses, where the orientation of the major principal stress for any combination of pure and simple shear is $\psi$ (McKinnon and Garrido de la Barra, 1998).

Figure 4.3: Boundary displacement vectors used (McKinnon, 2006)
4.2.2 Running the Models

The three main stages of each model are described below. All stages are identified in the example plot of maximum unbalanced forces throughout a model (Figure 4.4).

1. Fault system creation

The first stage was the creation of the faults from the velocity conditions applied at the external boundary. Grid point velocities were adjusted as the model stepped so they did not exceed the approximate maximum fraction of the grid point spacing that can occur in one time step ($1 \times 10^{-5}$ m/step was used). These adjustments resulted in a stable range of unbalanced grid point forces. This stage was run until clear sets of shear bands were formed, representing...
faults (approximately 125 000 steps). This stage represents a geological time frame. The resulting fault network and state of stress created in Stage 1 was shared by all models.

2. Model relaxation

The second stage consisted of removing the applied boundary velocity conditions to move from a geological time frame to a shorter, more instantaneous time frame representative of conditions before mining. This stage was run until the unbalanced grid point forces dissipated and reached an equilibrium. This stage was shared by all models.

3. Excavation via ground reaction curve method

At the beginning of the third stage, the model branched into multiple models for excavation purposes. Using the state of the model to identify the location of faults, locations were chosen for excavations. A total of 7 different models were run, including one base case in which no excavations were created and 6 models that had excavations (see Table 4.6 for an explanation of the different cases). Excavation locations are overlaid on the fault system in Figure 4.5.

Table 4.6: Model cases

<table>
<thead>
<tr>
<th>Number of Faults the Excavation Intersects</th>
<th>Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Faults</td>
<td>Case A, Case B</td>
</tr>
<tr>
<td>1 Fault</td>
<td>Case C, Case D</td>
</tr>
<tr>
<td>0 Faults</td>
<td>Case E, Case F</td>
</tr>
</tbody>
</table>
The ground reaction curve method was used to create the excavations. Horizontal and vertical forces at grid points on the excavation boundary were identified. Material inside the excavation was removed and its effect replaced by the equivalent forces on the excavation boundary. These forces were then gradually reduced at specific intervals to allow the ground to relax gradually, mimicking reality. The number of steps it took for the model’s maximum unbalanced force to return to equilibrium decided the interval spacing.

Due to the self-similar nature of fault systems as discussed in Chapter 2, these models can be considered at multiple scales. If the excavations are considered to be drifts (approximately 5 m by 5 m), the diameter of the model is approximately 600 m. If the excavations are considered to be larger cavities (approximately 15 m by 15 m), the diameter of the model is 1800 m.
4.2.3 Modelling Results

The results from the fault creation stage (Stage 1) correspond very well with results from McKinnon (2006). Fault formation showed similar patterns, with an orientation of shear bands that was similar to classical Riedel conjugate shears ($45^\circ \pm \phi/2$). The behaviour in this stage also had similarities to the results of McKinnon (2006). After initial fault formation, deformation mostly occurred on existing planes. Fault activity was intermittent, with a great variation with time throughout the fault network. Similar to natural fault systems and those created by McKinnon (2006), there were many smaller magnitude events and fewer large magnitude events. It is important to note that it was not necessary to explicitly model asperities along faults or to use complicated constitutive models to produce this realistic geological system behaviour.

Figure 4.6 presents the state of each of the models after the excavations have been completed (after Stage 3). The state of these models can be elastic; elastic, yielded in the past; at yield in shear or volume; or at yield in tension. Shear localizations, or faults, are represented by any of the three last options. Elastic material has not yet failed.

In general, the current state of the models is very similar to the state of the models before the excavations were created; slip on existing discontinuities was preferred to the creation of new faults. Case F did see new fault formation at the corners of the excavation in a similar orientation to the other fault sets. When examining the areas of the faults that currently have a critical state of stability (shown by areas that are in yield in shear or tension), it is clear that there are some differences between the models, particularly in the vicinity of the excavations.
Figure 4.6: State of all models after excavations
Analysis of Seismicity

As identified by McKinnon (2006), in this type of model there is no seismicity, however shear strain rate is analogous to fault rupture as it is a measure of acceleration of grid points due to unbalanced forces. The history of maximum unbalanced force provides a measure of seismic activity, as seen in Figure 4.4. McKinnon (2006) found that the seismicity in his created fault system, indicated by the magnitude of the maximum unbalanced force, followed natural fault system laws in that the events were sporadic and reproduced the Gutenberg-Richter magnitude frequency relation (see Section 2.1.1 for a description of this relationship).

Not only did these models confirm the earlier findings that the fault system created reproduces the Gutenberg-Richter relationship, but this relationship is still produced when considering all of the events over the course of the models, including those that occurred during excavation (see Figure 4.7). This figure clearly shows that there are many small magnitude events and that there are few large magnitude events, much like the behaviour of real fault systems. There are few differences between the different cases. The majority of these differences occur at the large end of the magnitude spectrum and may be attributed to the short time span that these models represented, as there were few large events.
Figure 4.7: Magnitude-frequency plot of maximum unbalanced force history

Figure 4.8 presents the seismicity of all of the cases during the excavation stage (Stage 3) normalized by subtracting the seismicity found in the base, no excavation case. This plot shows the patterns of seismicity through time while excavations were being created. Each vertical line represents a reduction in forces in the ground reaction curve method, hence why it is periodic in nature. The large magnitude events along these lines that decay to a background level are typical of this method, and area analogous to aftershock sequences following large seismic events.

It is clear that behaviour between the cases differs over time. In general, there are many small background type events similarly spaced throughout time. These small events are represented by magnitudes near to $y = 0$. Large events most frequently occur right after the change in excavation forces associated with the ground reaction
curve, however there are also instances of larger magnitude events not associated with this method. The spacing, frequency and severity of these larger events is the most significant difference between the cases. It is worthwhile to mention that the case that experienced new fault growth, Case F, has significantly more seismicity from the 40% to 0% steps remaining until 0% force applied at the excavation boundary than the other cases. This is likely during the time in which the new faults were created.

Figure 4.8: Comparison of seismicity between cases over the time of Stage 3, normalized to the base case

Figure 4.9 provides a plot of the percent differences in seismicity over the course of the excavations between analogous cases (two fault intersection cases, one fault intersection cases and no fault intersection cases) to evaluate the influence of excavation
location on seismicity over time. During the time period evaluated, significant differences in seismicity exist between analogous cases. This indicates that the location of the excavation is not a simple predictor of when seismicity will occur. Based on Figure 4.9 and Figure 4.10, most of the events were small background events that were common to all cases. Major differences in seismicity between the cases occur less frequently, and tend to be clustered over a short time span. These major differences are large events that occur in one analogous case, but not the other. This further shows that excavation location with respect to the fault system is not a clear indicator of seismicity throughout time.
Figure 4.9: Plot of differences of maximum unbalanced forces between analogous cases. Differences are plotted as percentages, where the blue series represents the differences between the two fault intersection cases (A & B), the green series represents the differences between the 1 fault intersection cases (C & D), and the magenta series represents the differences between the 0 fault intersection cases (E & F).
An instantaneous snapshot of behaviour for the models is provided in Figure 4.11. Behaviour is captured as shear strain rate, and black represents a smaller shear strain rate than the red. Significant differences exist in instantaneous behaviour between the cases. Clusters of small, low shear strain rate events exist in the north east portion of all models with some variations. The clusters tend to be denser near excavations, although Case D does not have a denser area. It appears that most of the clusters have spread in a northern direction. These areas are likely small deformations occurring within the fabric of the rock.

Examining the larger shear strain contour interval provides more insight into which faults are currently moving. Despite having an identical starting point, the fault
behaviour at this same moment in time is extremely different between the cases. There is no clear controlling rule that identifies the impact of analogous cases on the amount and location of shear strain rate. Interestingly, the cases in which there were 2 faults intersected by an excavation (Case A and Case B) did not cause the intersected faults to move, however the single fault intersection cases (Case C and Case D) did cause the intersected fault to move. As expected, where the new faults were created in the vicinity of the excavation, Case F had significant movement. In all cases, far-field triggering was observed. These plots clearly show that a small perturbation in the system can significantly impact the resulting behaviour, and that the nature of that behaviour is path dependent.
Figure 4.11: Plots of shear strain rate for all cases at an instantaneous moment of time after excavations (green boxes) have been created.
Ground Reaction Curve Analysis

Ground reaction curves were created to evaluate the system response to mining. Although energy changes in the system are most closely related to seismicity, this is extremely difficult to examine as it is very complex and difficult to measure. System stiffness is an accepted alternative to evaluate rockburst potential, especially when considering pillar stability. The influence of system stiffness on fault behaviour is discussed in Section 2.3.1.

“Local system stiffness” is evaluated instead of “system stiffness” due to the nature of the models and our current knowledge with respect to stiffness. As the excavations are created, there is an elastic and inelastic effect experienced in the surrounding rock mass due to the faults in these models. The range of influence is altered by the presence of faults. The range of influence that impacts the response of each excavation and fault is dependent upon the characteristics and the extent of connectivity of the surrounding fault network; the range of influence is not necessarily the entire span of the model.

Figure 4.12 provides the ground reaction curve for all excavations. When evaluating the influence of system stiffness on ground reaction curves, the shallower the curve the lower the stiffness. The linear portion of the ground reaction curves has predictable local system stiffness values; generally, the excavations that intersect two faults exhibit the lowest stiffness while excavations that do not intersect any faults exhibit the highest stiffness. As unloading continues and the ground reaction curves move into the non-linear sections, the stiffness is no longer organized by cases. Deformation between the cases varies widely due to fault movement, as clearly shown by the ground
reaction curve of Case F. Case F starts with one of the stiffest responses, however as deformation progresses, new faults are created, a large amount of slip is experienced, and Case F changes to one of the softest responses. Another notable stiffness response is the extreme change that Case C underwent at 5% of the steps remaining until 0% force applied at the excavation boundary. The significant change in slope indicates that at this point an extremely large amount of convergence occurred, likely due to slip along the fault it intersected.

These ground reaction curves show that excavation response is highly dependent upon the local system stiffness. The amount of elastic and inelastic deformation that contribute to local system stiffness is controlled by the location of the excavation relative to the geometry of the fault network. The unpredictability of the ground reaction curves indicates that ground reaction curves are not a useful indicator to include in a classification system, or that due to the chaotic nature of the system, a fault slip classification system in the traditional sense of classification systems will never be possible.
Recommendations and Summary of Models

There are many opportunities to enhance these models in the future. Of great interest for purposes of classifying the risk of fault slip would be to explore concepts discussed by Cochrane (1991). Cochrane (1991) showed that late stage faults and fractures are more sensitive to changes in the stress field than other faults. It is recommended that these models be adapted to include more realistic geological characteristics of the faults, organized into fault families to numerically analyse the impact of specific fault properties, including age, on fault behaviour.
The model results highlighted that the response of the system and individual fault zones is unpredictable. Similar to our general state of knowledge in most mines, the degree of stability of the fault zones was unknown. If the degree of stability were to be known, the seismicity caused by induced stress changes from mining excavations could be computed. Considering this, it is recommended that methods of determining the in situ stress field be further developed, including the use of stress inversion of mining induced seismicity.

Through the analysis of these models exploring the interaction between the geological and mining system, it is clear that the response of a complex fault system is not simple to predict. Small perturbations can create vastly different responses of the rock mass and faults. Fault behaviour is extremely path dependent and does not seem to be solely related to the measure of simple, time non-variable inputs.

It is recommended that future models be developed to further evaluate the influence of controls on fault behaviour. Simulations to evaluate the sensitivity of fault behaviour is recommended. These simulations will help to further develop our understanding of fault slip risk in mining environments.

4.3 Appropriate Architectures

As discussed in Chapter 2, classification systems are commonly used in rock mechanics. However, the problems addressed by these classification systems are of a very different nature than that of fault slip. Classical systems used in rock engineering address problems that are static in nature; they are not feedback systems. Problems
solved by current rock mass classification systems are deterministic systems; that is to say there is inherently no randomness involved in the development of future states of the system. Due to the nature of the problems being addressed by these classification systems, the inputs used are typically combined in a simple, often linear, manner to create a single, static output.

Conversely, as shown in Chapter 3 and the model results from Section 4.2, the fault slip events in a mining environment are very much a phenomenon of a complex, dynamical system. It is the interaction of the system parts that influences fault behaviour, and the system is continuously evolving within a mining time scale. The parameters that govern fault slip behaviour form a feedback system, consisting of both positive and negative feedback loops. These types of systems are commonly called reactive systems. They are characterized by their highly interactive nature, their state-dependent response, parallel processes and the real-time nature of the problem (Wieringa, 2003). Typical classification systems currently used in rock mechanics cannot handle these aspects of reactive systems.

Due to the chaotic nature of fault systems, it is valid to consider that any form of classification may not be possible. It is extremely unlikely that prediction of location and magnitude of exact events will be possible. However, despite the chaotic nature of fault system behaviour, it should be possible to determine relative risk of fault slip for specific faults or fault families. Since common classification systems are not capable of handling the complex nature of fault slip, it is recommended that instead of classification systems, risk identification systems be explored. Risk identification systems differ from classification systems in their output and application. The term “classification system” denotes that inputs and outputs can be clearly placed into
classes, or containers, with outputs commonly of the form “inadequate,” “marginal,” or “adequate.” A risk identification system, however, implies a broader range of input and output data, including the potential for outputs such as a block model populated with risk values. A risk identification system can include time variable information and produce real-time results.

Table 4.7 evaluates the set of classification systems and DSS that were identified as potential candidates in Chapter 2. They are evaluated upon the requirements as outlined in Chapter 2, as well as those identified by the evaluation of inputs (Section 4.1) and the results of the models exploring the interaction of the geological and mining system (Section 4.2). The evaluation criteria and accompanying descriptions are listed below.

- **Data analysis tool**: The ability of the system to analyse large amounts of various data types. This is important due to the type of input information as well as the fact that the exact influence of most controls is poorly understood.

- **Future prediction**: The ability to create a recommendation or prediction of future conditions based upon the input. This distinguishes database builders and pure data analysis tools from those that provide a final recommendation.

- **Can account for time variable and non-variable inputs**: The ability to easily include the two major classes of controls as identified in Section 4.1.

- **Can incorporate classes**: The ability to easily include and use the organization of controls as identified in Section 4.1.

- **Adaptable and robust**: The capability of the system to be adjusted as more information and knowledge is gained.
• **Easy to calibrate to each site:** The ability of the system to calibrate to each specific geological and mining system. The importance of this is discussed in Section 4.1.

• **Provides indication of uncertainty:** The system’s ability to provide a measure of uncertainty associated with every response. This is extremely important due to poor data quality and quantity. Uncertainty is an important inclusion in engineering systems to provide a more appropriate sense of risk.

• **Ability to predict data when incomplete:** The ability to use statistical techniques to fill in required data. This is important due to the nature of mining data.

• **Ability to incorporate new data:** The ability to add new data to the system. This is important for the changes in data quantity and quality typically experienced over the course of a mining project, as well as for eventual increases in our knowledge of how these systems interact.

• **Ability to identify correlations in data:** This distinguishes between systems that provide a statistical output as opposed to those that use statistical inference. Either approach to this problem is valid, but the level of user interaction and outcomes differ.

• **Ability to handle co-dependence of variables:** This is important for the fault slip classification system due to the complex, co-dependent nature of fault slip controls.

• **Easy to use:** It is important that engineering classification systems are easy to use and implement to ensure that the tool is user-friendly and economical.
• **Simple input possible:** The input to the system must be simple and clear to ensure proper use.

• **Easy to visualize results:** This ensures that results are meaningful in the mining environment.

• **Low amount of user participation after initial assessment or set-up:** This is important because intended users of the system need to effectively spend their time due to limited resources. A system that requires less user involvement is easier to use.

Table 4.7 clearly highlights the major reasons why rock mechanics classification systems do not meet all of the conditions and requirements for the identification of fault slip risk. Due to the difficulty with incorporating time variable inputs, personal decision support systems are also not appropriate for the fault slip risk identification system. OLAP, dimensional modelling and knowledge management based systems do not provide a future prediction. Rather, these systems provide a way to create databases and visualize the data. It is the user’s responsibility to identify the relationships in the data. Due to the complexity of the problem identified by the simulations discussed in Section 4.2, these systems are not recommended for the fault slip risk identification system at this point in time. Intelligent decision support systems, however, do meet all of the desired qualities in a fault slip risk identification system. Due to their ability to analyse large data sets in a time-continuous fashion and provide future predictions, it is recommended that intelligent decision support systems be further evaluated as a potential architecture for a fault slip risk identification system in mining environments.
Table 4.7: Evaluation of potential classification systems and DSS. Information from this table was based on Arnott and Pervan (2005); Parten et al. (1990); Holsapple and Burstein (2007, Hand (1997), )

<table>
<thead>
<tr>
<th></th>
<th>Rock mechanics classification systems</th>
<th>Personal decision support systems</th>
<th>Intelligent decision support systems</th>
<th>OLAP</th>
<th>Dimensional Modelling</th>
<th>Knowledge Management Based Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data analysis tool</td>
<td>X</td>
<td>Some</td>
<td>Some</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Future prediction</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Some</td>
</tr>
<tr>
<td>Can account for time variable and non-variable inputs</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Can incorporate classes</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Adaptable and robust</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Easy to calibrate to each site</td>
<td>Some</td>
<td>X</td>
<td>Some</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Provides indication of uncertainty</td>
<td>X</td>
<td>Some</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ability to predict data when incomplete</td>
<td>X</td>
<td>X</td>
<td>Some</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ability to incorporate new data</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Ability to identify correlations in data</td>
<td>X</td>
<td>Some</td>
<td>Some</td>
<td>X</td>
<td>X</td>
<td>Some</td>
</tr>
<tr>
<td>Ability to handle co-dependence of variables</td>
<td>Some</td>
<td>Few</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Easy to use</td>
<td>✓</td>
<td>X</td>
<td>Some</td>
<td>✓</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Simple input possible</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Easy to visualize results</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Low amount of user participation after initial assessment or set-up</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Expert systems and Artificial Neural Networks (ANN) are common forms of intelligent decision making support systems. Expert systems are an early form of AI that mimic the decision making ability of a human expert, through the application of a variety of user-defined conditions to a database. The conditions are of the form “IF... THEN...” where the ellipses are replaced with expressions. Expert systems are typically used when the relationships between entities are well known, making it inappropriate for the fault slip risk identification system at this time.

ANN are a more mature form of AI. Series of interconnected nodes, or processing units, run in parallel to analyse input data from a database, mimicking neurological activity of the brain (see Figure 4.13). During the learning phase, this system will adapt its internal structure based on information that is explicitly provided or implicitly obtained while evaluating the database. There are many different kinds of ANN algorithms that have been developed, each with their own set of strengths and weaknesses. A comprehensive discussion of ANN is beyond the scope of this thesis, however, there are many references that exist describing the architecture and operation of this system (e.g. Hecht-Nielsen, 1990; Parten et al., 1990; Ripley, 2008; Kohonen, 2000)
Figure 4.13: A simplified example architecture of an ANN. A) Shows the general architecture of the entire network, and B) shows the general architecture of a single node, or processing element. $x_n$ represents input data, $w_{jn}$ represents weights assigned or determined by the network, $f(l_j)$ is a function used for processing the inputs, and $y_j$ is the output value (Shahin et al., 2001).

It is recommended that input data obtained from physical and geophysical explorations be included as input into the ANN that uses a spatial algorithm, finding patterns within three-dimensional space. When data limitations are encountered, it is recommended that geostatistical techniques be explored to appropriately populate the database. Numerical stress analysis should be evaluated to be used as both a source of data, as well as a technique to process data from the ANN.

ANN has been used for mining, geological and earth science applications, including vibration prediction, subsidence prediction, prediction of rock mechanics properties, deposit and grade prediction, earthquake arrival time and waveform estimation and
earthquake prediction (e.g. Khandelwal and Singh, 2006; Ambrozie and Turk, 2003; Koike et al., 2002; Sonmez et al., 2006; Dai and MacBeth, 1995; Adeli and Panakkat, 2009). Shahin et al. (2001) provides a review on the use of ANN for geotechnical applications.

Benefits to using this technology for this application include:

- The ability to use live data, such as seismicity, to help predict fault slip events
- The ease that new data can be added to the database
- Relationships do not have to be explicitly stated; the network can determine relationships within the data
- Output from numerical stress analysis can be included as input data, or output from ANN can be included in numerical stress analysis
- Easy to get an indication of uncertainty
- Can easily incorporate geostatistical methods to aid data quantity and quality issues
- Very easy to adapt to new sites
- ANN technology has been widely developed for many years, new applications are currently being researched

The role of numerical stress analysis in the final development of this risk identification system cannot be underestimated. Due to the dynamic nature of fault behaviour, the wide spectrum of responses, and the high dependency of the result upon stresses, numerical stress analysis will likely be a major component of the system, either as
part of the input data or as a post-processing technique. It is recommended that the technique of numerical stress analysis be adapted to better suit the reactive system. Models are commonly calibrated only once, however it is recommended that models used to explore characteristics of reactive systems adopt a “continuous” model calibration approach. The importance of model calibration with live data, such as seismicity, is extremely important for reactive systems.

Recommended steps to complete the risk identification system are listed below. Many aspects of these steps can be completed simultaneously.

1. Complete more exploratory numerical stress analysis models to help define the role of major factors, focusing on those that were identified as very important. In particular, more analysis of the role of fault system geometry and local system stiffness needs to be completed.

2. Create simulations to explore the viability of ANN to identify and evaluate potential risk

3. Gather case study information with known fault slip events. The application of real-time AI techniques, such as ANN, should be explored. Extensive use of database analysis has the potential to be beneficial (such as OLAP and Knowledge Management Based Systems).

4.4 Summary

From most important to least important, the following list provides the major classifications of potential inputs:
- excavations,
- tectonic history and in situ stress,
- fault system,
- fault zone geometry,
- pore pressure,
- fault zone slip surface and core,
- blasting,
- fault zone damage zone and wall rock, and
- temperature.

These inputs can be divided into two distinct, useful categories: time variable and time non-variable parameters over the course of mining. These categories are important because they have major implications on the architecture of the classification system. Time non-variable parameters only need to be evaluated once, however time variable parameters need to be reassessed or continually assessed.

In addition to being influenced by time variable parameters such as excavations, stresses acting along the faults and fault-system stiffness are influenced by all of the parameters that do not vary over time. Fault strength is controlled by fault specific factors (such as fault zone geometry), and boundary conditions are controlled by larger scale geological factors. This is important as it provides an initial way to organize data to look for correlations.
It has been widely identified that it is important that all inputs to the classification system are measurable. There is significant room for improvement in fault slip related data quantity and quality in mining environments. There are extreme gaps in data related to fault specific factors, which is mainly caused by a lack of fault location techniques used in the mining industry.

Simulations were created using numerical stress analysis software to evaluate the impact of time variable controls on fault behaviour. To produce a variety of reasonable behaviour, including far-field triggering of faults, neither explicit modelling of asperities or complex constitutive models were required. The location of excavations had a significant impact upon the location and time of fault behaviour. Background seismicity was similar regardless of excavation location relative to the fault system, however, large magnitude events were very different between the cases. The response of the excavation and fault system was highly dependent upon the local system stiffness. Unpredictable ground reaction curves between the cases indicated that the chaotic nature of the system caused fault behaviour to be extremely path dependent and that a small perturbation in the system can significantly impact the resulting behaviour. These results highlight the importance of using seismicity information to assist with potential future fault behaviour prediction.

After the evaluation of many different types of classification and risk identification systems, it is clear that classical rock mechanics systems are not well suited to this problem; the chaotic nature of the fault system combined with the time-dependent nature of mining activities are beyond the capabilities of classification systems. Instead, it is recommended that a fault slip risk identification system be created. The recommended technique to be used in the risk identification is ANN, as it is well
suited to aiding decision making in this reactive system. Benefits of using ANN techniques include the ability to incorporate live and historical data, the ease of which the system can be adjusted to specific sites, and the ability of the system to identify complex relationships in the input data.
Chapter 5

Conclusions, Contributions and Recommendations

5.1 Conclusions

Fault slip is an increasing risk to many underground mining environments. A result of the interaction of mining and geological systems, fault slip can lead to large rockbursts, endangering personnel, equipment and operations. The mining system consists of excavations, blasting and pore pressure. The geological system includes tectonic history and in situ stress, the fault system and fault zones. Faults exhibit a wide range of behaviour that cannot yet be fully explained by laboratory experiments or numerical models. Numerous models have been developed to represent fault behaviour, however all are phenomenological. This leads to a disconnect between physical measurements and models, scaling issues between laboratory results
and nature, and an inability to reproduce the complete spectrum of fault behaviour. Regardless of the disconnect between physical measurements and models, it is clear that correlations should exist. Based on reviewed literature, fault behaviour is controlled by fault strength, stress acting along the fault, boundary conditions and fault-system stiffness. The mining system in general is highly time variable over the time span of mining, however the influence of blasting and pore pore pressure on fault behaviour are unknown. The geological system is less time variable over the time period of interest. The following list provides factors from both systems that influence fault behaviour in order of importance, from most important to least.

- Excavations,
- Tectonic history and in situ stress,
- Fault system,
- Fault zone geometry,
- Pore pressure,
- Fault zone slip surface and core,
- Blasting,
- Fault zone damage zone and wall rock, and
- Temperature.

Numerical stress models were created to evaluate the influence of the more important factors: excavations, tectonic history and in situ stress, and the fault system. Excavations were placed in different locations within a created fault system, and
the impact on fault behaviour was evaluated. Despite using a comparatively simple constitutive model, realistic fault system behaviour was achieved. Additionally, the excavations created extremely complex fault behaviour; correlations between excavation location with respect to the fault system and fault behaviour were not found. Small perturbations in the initial state caused significantly different outcomes.

The architectures of many classification systems and decision support systems were evaluated for purposes of a fault slip classification system. Based on the time variable nature of inputs and chaotic behaviour of fault systems, it is clear that a typical classification system is not appropriate for evaluating fault slip risk. Instead, it is proposed that a fault slip risk identification system be created; a system that can incorporate historical and live data and create a real time response. It is recommended that this system be based upon AI techniques (such as ANN) and numerical stress analysis, using the inputs identified earlier as important to fault behaviour and historical and live seismic data.

5.2 Key Contributions

Key contributions made by this work are presented in the following list:

• An extensive review of mining, structural geology, seismology and earth science related literature was created to assess the state of the art understanding on controls on fault behaviour. This review is the first of its kind.

• Preliminary controls of fault slip behaviour were evaluated and ranked.
• Direction and motivation for improvements in physical and geophysical measurements techniques related to faults and the geological environment were suggested.

• Direction and motivation for the creation of case studies in mining environments were suggested.

• Direction and motivation for the creation of exploratory models were suggested.

• The architecture of a risk identification system was recommended, as well as steps to further its development.

5.3 Recommendations

Based upon the work presented in this manuscript, the following recommendations are suggested for future work.

• Further development and application of geophysical techniques in mining environments, specifically related to location of faults and fault geometry.

• Improvements in stress measurement quality and quantity in mining environments are recommended. Stress acting along the fault is an extremely important factor influencing fault behaviour. Development of new stress measurement techniques and their application to mining environments, such as stress inversion, should be explored.

• At existing mines and new projects, it is recommended that more geomechanical data, especially that related to faults, be collected. This will help the creation
of case studies that are necessary to further the fault slip risk identification system. It is recommended that mines strive to collect the data listed in Table 4.4 under “Desirable Information.” Advances in measurement techniques will be required to achieve this.

- It is recommended that numerical stress analysis models be developed to further investigate the interaction between the mining and geological system. Specifically, it is recommended that models be developed to evaluate the influence of: incorporating different sets of faults with distinct properties, complex constitutive models in mining environments, fault geometry on fault behaviour, damage zones, blasting and pore pressure. Significant effort should be placed upon developing new techniques of modelling faults. These models can provide information to simulate realistic conditions to further evaluate the usefulness of ANN.

- Further development of the fault slip risk identification system is recommended. It is suggested that this be done by developing case studies with strong amounts of geomechanical data related to faults and a well developed seismic network. ANN, the case study data and numerical stress modelling are recommended techniques to develop the fault slip risk identification system.
References


Bergen, K. J. and Shaw, J. H. (2010). Displacement profiles and displacement-length


Esterhuizen, G. S. (1994). Preliminary study of the effects of fault properties and mining geometry on the stiffness of the loading system in fault slip seismic events as a basis for identifying situations prone to seismic activity. Technical Report GAP003, University of Pretoria, Department of Mining.


153
Itasca (2011). FLAC 2D version 7 users manuals. Minneapolis, MN.


China: How earthquakes in midcontinents differ from those at plate boundaries.


