An Extended Conceptual Model of Caving Mechanics

By

Daniel Cumming-Potvin
Bachelor of Engineering (Hons)

This thesis is presented for the degree of:

DOCTOR OF PHILOSOPHY

School of Civil, Environmental and Mining Engineering

The University of Western Australia

2018
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The numerical modelling described in Chapter 5 was conducted by staff from Itasca Consulting Group.
The physical modelling described in Section 3 was completed in conjunction with staff from The University of Pretoria. The materials strength testing described in Section 3.4.1 was conducted solely by staff from The University of Pretoria.

This thesis contains published work and work prepared for publication, some of which has been co-authored.

Signature: 

Date: 28/11/2017
Abstract

The Duplancic conceptual model is the industry accepted model of caving and is the framework within which most results from numerical modelling and cave monitoring are interpreted. The Duplancic conceptual model implies that the damage ahead of the cave back decreases continuously with increasing distance from the cave surface. Evidence from a variety of sources indicates that this may not always be the case and that a discontinuous damage profile may be present.

This thesis re-examines the Duplancic model and creates an extended conceptual model of caving. This extended model captures the mechanism of caving through discontinuous damage through parallel fracturing.

A review of literature reveals a number of studies which indicate that the damage ahead of the cave may be discontinuous. These studies come from a variety of sources including site observations, numerical modelling, physical modelling and analysis of microseismicity.

A physical modelling programme was undertaken to investigate the fracturing and propagation of the cave. The testing was performed in the University of Pretoria’s Geotechnical Centrifuge facility to correctly account for the body forces of the problem. The experiments were two-dimensional to allow for visual observations of the failure process. The results showed the cave propagating through a series of fractures oriented parallel to the cave surface. The cave back progressed vertically via ‘jumps’ to the next successive parallel fracture. This caving mechanism is termed ‘fracture banding’.

Field monitoring data from three mines was used to confirm the existence of the damage discontinuity ahead of the cave. The microseismicity from three mines was examined and multiple examples of discontinuity were found. Bands of events alternated with areas with few events were observed, indicating failure in a similar manner to the parallel fracturing of the physical model. Videos of open hole dipping from two mines were reviewed and the location of significant shears, dislocations and the cave back were recorded. Video monitoring data analysis results indicated a change from a mechanism with significant, continuously decreasing damage ahead of the cave and a mechanism showing potential ‘jumps’ in the cave back and with a lack of continuous shear damage ahead of the cave. This was interpreted as a shift between Duplancic and banding style caving behaviour.
Numerical models of one of the physical modelling tests were conducted by staff from Itasca Consulting Group. Two different approaches were used: an Itasca Caving Algorithm approach implemented in FLAC3D and a Bonded Block Model (BBM) approach implemented in 3DEC. The results show that both approaches were able to capture the discontinuity in the damage profile to a degree, each in a different manner. The BBM approach was found to better describe the geometry of the cave shape. Calibration was outside the scope of the project; however, a better match between the physical and numerical models may have been possible through a process of calibration.

An extended conceptual model of caving was created. This new model is able to account for the mechanism of fracture banding, along with the continuous failure of the Duplancic conceptual model. There are still many unknowns about the fracture banding mechanism and propagation of caves. These include the specific conditions under which the caving mechanism changes and whether the mechanisms lie on a continuum, or if there is a sharp, sudden change. Two conceptual models are presented: one which includes only that which is known about the mechanisms of cave propagation and one which speculates upon the factors involved and the underlying origins of the fractures.
Acknowledgements

I would like to thank Dr Johan Wesseloo for imparting his wisdom and guiding me throughout this project. Without him, this thesis could not have existed. Thanks also to my co-supervisors Dick Stacey and Richard Durham for lending their experience and advice to steer me in the right direction.

I would also like to thank my family for all of their love and support throughout, in particular my father Yves, whose advice is always valuable. Thank you to my wonderful partner Jemma for putting up with me and loving me through the years that it took me to get to this point.

Thanks to all of the staff from the Australian Centre for Geomechanics for help with editing, formatting, administration and technical advice. Special thanks go to Paul Harris for teaching me a fraction of his considerable programming skills, along with Fred Coles, Garth Doig and Candice McLennan for aid in creating figures for this thesis. Thanks also to Gillian Carter for proofreading and Garth Doig for help with referencing.

I would like to acknowledge and thank all of the staff involved with the University of Pretoria Geotechnical Centrifuge Laboratory, in particular Prof. SW Jacobsz and Prof. Elsabe Kearsley. Without your hard work and expertise, the physical modelling could not have taken place.

Thanks to Matthew Pierce, Tryana Garza-Cruz and Lauriane Bouzeran of Itasca Consulting Group for their work in creating the numerical models included in this thesis.

Thanks to Fredrik Ersholm, Mirjana Boskovic, Chris Chester, Geoff Capes and James Lett for their support of this project.

This research was supported by an Australian Government Research Training Program (RTP) Scholarship.
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Glossary of seismic terms

Apparent Stress

Apparent stress is a source parameter which indicates the (source model independent) level of stress in the rock mass where the seismic event originated. It is defined by Wyss and Brune (1968) as:

Equation G1

\[ \sigma_A = \frac{\mu E}{M_o} \]

where \( \mu \) is the shear modulus of rigidity of the rock, \( E \) is the seismic energy and \( M_o \) is the seismic moment.

Energy Index

Energy Index (EI) is a scale independent measure of the stress levels at the location of an event’s origin (van Aswegen & Butler 1993). It gives the relative seismic energy of an event for a given seismic moment (where an EI above one indicates above average stress for the seismic moment of the event and an EI less than one indicates below average stress). It is often calculated using the logarithm of both seismic energy and seismic moment. The concept of EI is illustrated in Figure G1.
**Focal Plane Analysis**

A *focal plane analysis* consists of inspection of the first motion of the waveform trace for each sensor recorded for a seismic event (i.e. whether it causes a positive or negative movement). From this, the position of each sensor relative to the source can be found. This is then plotted on a stereographic projection and used in calculating a fault plane solution based on visual inspection of the position of each data point (Lay & Wallace 1995).

**Magnitude**

*Magnitude* is a measure of the size of a seismic event. The most common magnitude scales used in mine seismology are logarithmic to base ten, meaning that a magnitude 2 event is 10 times larger than a magnitude 1. Commonly used measures of event magnitude include Moment magnitude (Hanks & Kanamori 1979), and the widely known Richter scale of magnitude (Richter 1935). Local magnitude scales (mine specific scales which are a function of energy, moment and/or wave amplitude) are also routinely used in mine seismology.

**Principal Components Analysis**

*Principal Components Analysis* (PCA), when applied to seismicity, is a statistical technique for the determination of spatial trends in a cluster of seismic events. It involves finding the mean location of the cluster and finding the spread matrix. The spread matrix is the variance in Cartesian coordinates to the mean location. This matrix can be decomposed into eigenvalues and eigenvectors (or principal components). These principal components give vectors for the direction of seismicity and the orientation of these vectors can be found.

**Seismic Moment**

*Seismic moment* is a measure of co-seismic inelastic deformation at the source of a seismic event (Mendecki 1996). It was defined by Brune (1968) with respect to slip on a fault plane as:

**Equation G2**

\[
\langle u \rangle = \frac{M_0}{\mu A}
\]

Where \( M_0 = \text{seismic moment} \), \( \mu = \text{rigidity of the rock mass} \), \( A = \text{area of fault slip} \) and \( \langle u \rangle = \text{average dislocation over fault area} \).
It is defined by Mendecki (2013) as:

Equation G3

\[ M_0 = \mu P = \Delta \sigma V \]

Where \( P \) = seismic potency, \( \Delta \sigma \) = average stress drop and \( V \) = source volume.

**S:P Wave Energy Ratio**

\( S:P \) wave energy ratio is defined as:

Equation G4

\[ S:P \text{ wave energy ratio} = \frac{E_s}{E_p} \]

where \( E_s \) is the shear wave (s-wave) energy and \( E_p \) is the compression wave (p-wave) energy.

The \( S:P \) wave energy ratio is usually analysed by creating cumulative plots and examining the proportion of events with certain \( S:P \) wave energy ratios. The \( S:P \) wave energy ratio can indicate the source mechanism of the event, with non-shear events having lower \( S:P \) wave energy ratios than events with a shear source mechanism (Urbancic et al. 1992).

**Total Radiated Seismic Energy**

Often referred to as ‘Seismic energy’, total radiated seismic energy is the elastic energy released by a seismic event. This energy is only a small proportion of the energy released from a seismic source. Seismic energy describes the potential for earthquake damage to artificial structures (i.e. buildings) better than the seismic moment (Gibowicz & Kijko 1994).
Introduction

1.1 Block caving

The mass mining method block caving has become the favoured method for large underground mines in recent decades due to its high production rates and low cost of production (de Wolfe & Ross 2016). The block caving method involves undercutting a large sub-vertical orebody to induce failure of the rock mass. If the Hydraulic Radius of the zone of undercut rock is large enough, the rock mass will naturally cave (Laubscher 1994). The failed rock mass is extracted in a controlled manner to induce further propagation of the failure zone.

A schematic of block caving based on the El Teniente mine is shown in Figure 0.1. The undercut is achieved by creating tunnels underneath the orebody followed by drilling and blasting a slice of rock (highlighted in red). As the broken rock is removed from the production level (highlighted in blue), it creates a void. Gravity and the tectonic stresses in the rock cause the roof of the opening to collapse or ‘cave’. After a critical area of the orebody is undercut, the ore will begin to cave as more ore is removed, without any need for drilling and blasting. The cave should propagate upwards towards the surface until it reaches the surface or overlying previously caved levels. After the undercut is complete, no further drilling and blasting is necessary as the rock is simply fragmented by the caving process. The ore is removed via a level of tunnels below the undercut called the extraction level. It is drawn through drawbells, funnel shaped excavations which connect up to the undercut. The broken ore is then hauled to surface, often through shafts or conveyors.
The rate at which material is taken from the drawbells has a significant influence on the rate and direction in which the cave propagates. The block caving method allows continuous mining and, coupled with the large footprint area, results in a very high production rate and low unit cost of production. The method was originally used on shallow and weak orebodies, where the primary driving force for the caving was gravity. In the last few decades the method has been increasingly used to mine stronger orebodies at depth, where the horizontal stress can aid in fracturing the orebody and propagating the cave (Brown 2003).

The large extent of development necessary before production, along with the haulage system, result in a large capital cost. The high capital expenditure characteristic of the method creates an environment where it is critical to mitigate risks in order to ensure the operation’s profitability.

One limitation inherent to the block caving method is a lack of access to the orebody. Access is limited to the undercut and extraction levels and no direct visual observations can be made of the cave. As a result, the state of the rock mass inside the cave column and the cave back location are poorly known. This lack of knowledge limits the opportunity to identify imminent risks and implement adequate risk mitigation measures. Some key geotechnical risks in block
caving include uncontrolled and dynamic large scale caving events, cave back hang-ups, poor fragmentation and undesirable cave propagation outside of the orebody causing dilution (Hebblewhite 2007; Westman et al. 2012).

Due to the lack of access to the cave, the design of instrumentation and modelling programs and the interpretation of their results relies heavily on the conceptual framework used. The Duplancic (2001) conceptual model of caving is widely used and accepted by the caving industry.

1.2 Introduction to the Duplancic conceptual model of caving

The Duplancic conceptual model of caving (Duplancic & Brady 1999; Duplancic 2001) gives a conceptual picture of the caving profile, comprising five different zones of rock mass behaviour. These five zones are the caved zone, air gap, zone of loosening, seismogenic zone and pseudo-continuous domain. The model was developed from a case study of the Northparkes E26 Lift 1 block caving mine, using primarily microseismic analysis, linear elastic numerical modelling and open hole monitoring. The model is applicable to cave propagation from initiation to breakthrough and is illustrated in Figure 0.2.

![Conceptual model of caving](image)

**Figure 0.2** Conceptual model of caving (Duplancic 2001)
1.3 Thesis objective

The Duplancic conceptual model of caving suggests rock mass ahead of the cave progressively goes through each of the different caving zones in order, from pseudo-continuous domain, seismogenic zone, zone of loosening, air gap to caved zone. This in turn implies that the damage profile is continuous through space. Duplancic (2001) also emphasises the role of slip along pre-existing discontinuities in the caving process and downplays the role of intact rock failure. The model is widely accepted by the mining industry as the standard for cave propagation and is the basis upon which most monitoring results (microseismic, open hole, extensometer, etc.) are interpreted (e.g. Brown 2007; Pfitzner et al. 2010). Despite the industry reliance on the model, there are no indications in the literature of any attempts to rigorously and independently verify it.

A review of literature revealed multiple instances of observations of parallel fracturing (often through an extensional mechanism) and discontinuous damage in caving situations, contrary to what would be expected from the Duplancic model (refer to Chapter 2). This suggests that the Duplancic model may not sufficiently describe the failure process in all caving situations.

This thesis re-examines the Duplancic model and creates an extended conceptual model of caving. This model captures the mechanism of caving through discontinuous damage through parallel fracturing.

1.4 Research methods

The model was constructed from multiple sources. These were physical modelling of a generic block caving situation, field monitoring results from block caving mines, analysis of numerical modelling and a review of supporting literature.

The literature reviewed included studies from site observations and point source monitoring, microseismicity, numerical modelling and physical modelling. It focused on the previous research done in the area of caving mechanics, including findings of caving mechanisms which cannot be fully captured by the Duplancic conceptual model.

The physical modelling aimed to create an experiment in which the fracturing ahead of the cave back can be seen and the mechanism of caving can be determined. Visual observations were crucial in determining the mechanism by which the cave propagates.
The field monitoring results are analyses of microseismic monitoring and open hole video camera surveys at a number of caving operations. The microseismic analysis focused on observations of discontinuity in seismicity above the cave back and source parameter analysis of the bands identified. The open hole video camera analysis focused on the frequency and spacing of shear fracturing ahead of the cave back and the resulting damage profile. The location of the microseismic events with respect to the cave back was also examined. These analyses are used to verify and better understand the failure mechanisms seen in the physical modelling.

Numerical models of the physical tests were conducted by staff from Itasca Consulting Group. Two approaches were used, a Bonded Block Model (discontinuum) approach and a Caving Algorithm (continuum) approach (more detail in Section 5.2). These numerical models allowed verification of the results from the physical models and a more thorough understanding of the mechanisms involved.

1.5 Scope of thesis

The case considered in this thesis is a block cave in a greenfields setting which has not yet propagated to breakthrough. The thesis concentrates on the mechanism, location, orientation and spacing of fractures ahead of the cave front and in the cave peripheries, along with the variation through space of said fracturing. The thesis assumes that the specifics of gravity flow of caved material does not have a significant impact on the way the cave propagates and, as such, it is not examined.

This thesis does not address the problem of cave initiation, or the specific mechanism by which block release in the cave crown occurs. It does not consider the breakthrough of a cave. Propagation enhancement techniques (such as hydraulic fracturing, boundary slotting etc.) are also not considered.

1.6 Implications

An updated conceptual caving model has a significant impact on the industry understanding of caving and, in particular, the way monitoring results are interpreted to mitigate geotechnical risks. The design of monitoring systems may also be altered in order to better capture the previously unrecognised failure mechanism of fracture banding in caving. The mechanism of
failure in caving mines can impact the fragmentation of the ore produced. Fragmentation is an important variable to control in block caving, as it impacts not only the processing of the ore, but also the rate of production (in part due to oversize reporting to drawpoints). Thus, if block caving operations can correctly assess the mechanism present, they may be able to improve their fragmentation and ultimately the production rate of the mine. Determining the direction and rate of cave propagation is critical for cave management. Better understanding of the mechanism of caving can help operators to make better assessments of whether the cave is propagating, which direction it is propagating in and whether it will continue to propagate. Incorporating a new mechanism into the conceptual model of caving can also impact the methods used in numerical modelling, which should aim to correctly capture the failure mechanism. This could improve the performance of numerical models in forecasting direction of propagation, potential fragmentation and cavability.

1.7 Organisation of thesis

The organisation of the thesis is outlined in Table 0.1.

<table>
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<th>Chapter</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Introduction</td>
<td>Introduces the Duplancic conceptual model and describes the thesis objective, scope and research methods.</td>
</tr>
<tr>
<td>2. Literature Review</td>
<td>Describes the Duplancic conceptual model and its origin in detail. Examines literature on caving mechanics from site observations and point source monitoring, microseismicity, numerical modelling and physical modelling.</td>
</tr>
<tr>
<td>3. Physical Modelling</td>
<td>Details the centrifuge physical modelling design, material and methodology. Presents results from the testing.</td>
</tr>
<tr>
<td>4. Field Monitoring Results</td>
<td>Presents the methodology and results of analysis of microseismicity and open hole video camera surveys from caving mines.</td>
</tr>
<tr>
<td>5. Discussion of Numerical Modelling</td>
<td>Discusses the methodology and results of numerical models of the physical model conducted by staff from Itasca Consulting Group.</td>
</tr>
<tr>
<td>6. Development of Extended Conceptual Caving Model</td>
<td>Combines the learnings from Chapters 2, 3, 4 and 5 to create an extended model of caving which can account for the previously unrecognised caving mechanism of fracture banding.</td>
</tr>
<tr>
<td>7. Conclusions</td>
<td>Gives the conclusions of the thesis.</td>
</tr>
</tbody>
</table>
2 Literature Review

The Duplancic model has been widely adopted as the industry standard conceptual model of caving. Despite the strides made by Duplancic and others since, in terms of understanding caving mechanics, there is still significant progress to be made. The statement by Brown (2007) on the state of understanding of conceptual caving mechanics still holds true:

… although some advances in understanding have been made in recent years, particularly through the use of microseismic monitoring, the detailed mechanics of caving and of stress caving in particular are not at all well understood. Most importantly, they are not well enough understood to permit reliable predictions to be made of cavability and of the likelihood of the continued propagation of caving.

A number of studies published both before and after the Duplancic model indicate a mechanism of caving involving discontinuous damage through parallel fracturing that cannot be completely captured by the Duplancic model (e.g. Panek 1981; Sharrock et al. 2002; Vyazmensky et al. 2007; Tibbett et al. 2016). This literature review gives a detailed overview of the Duplancic conceptual model of caving, followed by literature from four different areas which give evidence for this previously unrecognised caving mechanism. The areas of literature examined are site observations and point source monitoring, microseismicity, numerical modelling and physical modelling.

In this chapter there are references to both tensile and extensional fracturing. These terms are often used interchangeably. However, the term extensile fracturing implies that the fracture was created in extension with the minor principal (extensional) strain normal to the fracture surface. It is important to note that these fractures can form in environments where all three principal stresses are compressive (Stacey 1981). Tensile fracturing implies that the fractures formed under a tensile stress.

For the purposes of accuracy, the terms tensile and extensile used in each source will be retained. Since the two terms are sometimes used interchangeably in literature, and because this thesis focuses on the mechanism of caving rather than the specific conditions which cause this mechanism, mentions of tensile fracturing in the literature will be treated as extensile fractures.
2.1 Duplancic conceptual model of caving

In his 2001 thesis, Duplancic examines the mechanics of caving in order to determine the mechanism of caving and create a conceptual model of caving. He limits his analysis to stress caving; that is, caving under high horizontal stress conditions in which failure is driven more by stress than by gravity. He proposed two possible rock mass failure mechanisms above the cave: slip along pre-existing discontinuities and compressive failure of the rock mass. He also discussed the potential for kinematic failure through loss of confinement in the cave crown. In order to examine the potential for these rock mass failure mechanisms, Duplancic used a combination of linear elastic numerical modelling and microseismic monitoring.

Duplancic created a series of linear elastic three-dimensional boundary element models representative of block caving mines at the time to examine the stress state and evaluate possible failure mechanisms in the cave. Two stress states were modelled, one with a high horizontal stress and a k-ratio of 2 ($\sigma_h = 80$ MPa, $\sigma_v = 40$ MPa) and one with a high vertical stress and a k-ratio of 0.5 ($\sigma_h = 40$ MPa, $\sigma_v = 80$ MPa). Potential for slip was evaluated using stereonets which showed the mobilised friction angle at different points in the cave. The mobilised friction angle was defined as the friction angle at which slip would occur using the Mohr-Coulomb criterion and the stress state at a given point. The results show that there was potential for slip along steeply dipping discontinuities in the cave periphery under both stress regimes (Figure 2.1 III, IV and Figure 2.2 III, IV). In the cave crown, potential for slip along joints with a dip of 35-50° in the high horizontal stress regime was identified, but there was no potential for slip in the high vertical stress regime (Figure 2.1 I, II and Figure 2.2 I, II).
Figure 2.1  Stereonet showing mobilised friction angles for high vertical stress regime  
(Duplancic 2001)

Figure 2.2  Stereonet showing mobilised friction angles for high horizontal stress regime  
(Duplancic 2001)
Plots of extensional strain showed that there was a large region with significant extensional strain above the cave back for the high horizontal stress model (Figure 2.3A). The plots also show significant extensional strains in the high vertical stress model (Figure 2.3B), however, they concentrate more towards the cave periphery. No specific comment was given on whether intact rock failure through extension strain was likely to occur. However, the significant regions shown in the modelling indicate that there is potential for this failure mechanism.

![Figure 2.3 Plot of extensional strain for high horizontal stress model (A) and high vertical stress model (B) (after Duplancic 2001)](image)

Duplancic also created a linear elastic three-dimensional boundary element model of Northparkes E26 Lift 1. The results indicated that the failure via slip was most favoured on the joint set with a dip of 35°. It was also found that, overall, a very small number of failure plane orientations were favourable for slip and that these favourable joint orientations didn’t always match the known joint sets at Northparkes.

In order to assess the potential for compressive failure of the rock mass via extensional strain at Northparkes, Duplancic created plots of extension strain ($\varepsilon_3$), which can be seen in Figure 2.4. In all sections examined, there was a significant zone affected around the edge of the excavation. Despite the numerical modelling suggesting a large region of influence, it was
assumed that the extension strain failure mechanism would not have a significant role in caving at Northparkes. The reason for this assumption was that slip along pre-existing joint sets was expected to occur preferentially due to the lower strength of joint surfaces when compared with the intact rock strength. This assumption in turn requires the assumption that the joint surfaces are long enough to create blocks in the rock mass, otherwise breaking of intact rock bridges would be necessary for kinematic failure to occur.

![Figure 2.4](image)

**Figure 2.4**  Extensional strain plots for Northparkes E26 for November 1996 (a/b), February 1997 (c/d) and September 1997 (e/f) (Duplancic 2001)

The Hoek-Brown failure criterion (Hoek & Brown 1980) was also used to evaluate the potential for compressive failure of the rock mass at Northparkes. There was a small region of the rock mass in which the Hoek-Brown criterion predicts failure in all sections (Figure 2.5). Duplancic
did not regard this as conclusive evidence for compressive type failure at Northparkes because he stated that it was within the zone of uncertainty in the boundary element analysis.

Figure 2.5  Hoek-Brown strength factor plots for Northparkes E26 or November 1996 (a/b), February 1997 (c/d) and September 1997 (e/f) (Duplancic 2001)

Duplancic examined the seismicity at Northparkes E26 and developed different caving zones based on the location of seismicity. There were three periods examined: the development of the undercut, a period of low caving activity and a period of hydraulic fracturing. He identified a zone of seismic activity (termed the seismogenic zone) and an aseismic zone of loosening between the cave back and seismogenic zone. The seismogenic zone was observed in all three periods. The aseismic zone was most obvious in period 1 (Figure 2.6), difficult to observe in period 2 (Figure 2.7) and did not exist in period 3 (Figure 2.8).
Figure 2.6  Seismicity during period 1 (undercut development) at Northparkes E26, aseismic zone present. (Duplancic 2001)

Figure 2.7  Seismicity during period 2 (low caving activity) at Northparkes E26, aseismic zone difficult to observe (Duplancic 2001)
A focal plane study of 108 seismic events found six different concentrations of plane orientations at Northparkes E26. Four of these concentrations were found to match closely with the orientations of existing joint sets, with the highest concentration of planes matching with joint set 4 (the shallow dipping joint set, with a 30° dip). These results were interpreted as evidence of shear along pre-existing discontinuities. However, this conclusion ignores the fact that intact rock failure can occur as extension and/or coalescence of pre-existing discontinuities (thus giving the same failure orientation). A situation could also arise where fractures form in extension, which subsequently shear, resulting in shearing events in this orientation. Duplancic acknowledged that the preferential selection of the events resulted in a subset of events that all had a significant shear component.

The S-wave to P-wave energy ratio (S:P ratio) of seismic events at Northparkes E26 was used by Duplancic as evidence that the dominant mechanism in the crown of caves was slip along pre-existing discontinuities. A scatter plot of S-wave and P-wave energy can be seen in Figure 2.9. It was observed that only 3% of events had an S:P ratio of < 1 and that almost 75% of events had an S:P ratio of < 10. This was interpreted as indicating that the dominant mechanism of failure ahead of the cave was slip along pre-existing discontinuities. The results of subsequent studies call this interpretation into question.
The S:P ratio from the events at Northparkes are remarkably similar (approximately 76% of events with an S:P ratio < 10 and 0% < 1) to the events recorded from extension fracturing at the Mine-by tunnel at the URL (Wesseloo & Sweby 2008). Gibowicz and Kijko (1994) suggested that events with an S:P ratio of < 10 have a tensile component to the failure and so up to 75% of the events at Northparkes E26 Lift 1 may have a significant tensile component.

Figure 2.9 Scatter plot of P-wave vs S-wave energy for Northparkes E26 (Duplancic 2001)

2.1.1 Summary of Duplancic conceptual model of caving

Based on all of the analyses conducted, Duplancic created a conceptual model of stress caving. The model has five regions:

1. Caved zone. The region where the caved material which has fallen from the cave back sits and provides support to the walls.

2. Air gap. A gap between the caved zone and the cave back.

3. Zone of loosening. A zone of fractured rock which provides no support to the overlying rock mass and where disintegration of the rock mass occurs. Loss of confinement controls failure in this region. The failure in this region is aseismic.
4. Seismogenic zone. An active stress front where seismic failure of the rock mass occurs. It was determined that the most likely mode of failure in this region was slip along pre-existing discontinuities.

5. Pseudo-continuous domain. The volume of rock ahead of the seismogenic zone. Only elastic deformation occurs in this region.

![Figure 2.10 Conceptual model of caving Duplancic (2001)](image)

Although it is widely recognised that the propagation is not occurring at a constant rate, there is an implication within this model that the rock mass ahead of the cave back progresses continuously through each of these zones in turn as the cave propagates vertically. This is how the industry has interpreted the model, evidenced by Brown (2007) who stated that:

… the boundaries between these regions are diffuse rather than sharp [and] the rock mass undergoes a gradual reduction in strength from its in situ state to its caved state.
When assuming that slip along pre-existing discontinuities will happen preferentially to failure through intact rock, Duplancic emphasises the role of pre-existing discontinuities in caving mechanics and downplays the role of intact rock failure.

The Duplancic conceptual model was based only on the case study of Northparkes E26 Lift 1 block cave. When developing the model, he did not have any access to the cave back for visual observation or instrumentation in the cave back to measure fracturing. The model was built on interpretation of linear elastic numerical modelling and simple analysis of seismicity (focal plane analysis, event locations on sections and S to P wave energy ratio). While the analyses conducted were simple when compared with the capabilities of present day technology, it should be noted that Northparkes was one of the first mines to use a microseismic monitoring system to improve knowledge of caving mechanics. Despite the limitations of the data he had to work with, the progress that Duplancic made in the area of conceptual caving mechanics has been incredibly valuable in setting a foundation for the industry’s understanding.

Despite the lack of observations and limited point source monitoring included in the development of the Duplancic conceptual model, there are a number of examples in the literature of studies which detail these sorts of observations.

### 2.2 Site observations and point source monitoring

Due to the inherent limitations in access to the caving front, there are few examples of observations of the failure process in caving mines. Observations are usually limited to the undercut levels, cave periphery or to point measurements from instrumentation.

In cases where observations have been possible, or where monitoring can give indications of fracturing, multiple authors have observed series of extensional fracturing parallel to cave peripheries. These extensional fractures result in an alternating series of fractured and unfractured ground, creating a discontinuous damage profile. The series of extensional fracturing is a mechanism not recognised in the Duplancic model of caving.

Heslop (1976) conducted an extensive monitoring programme using observations and instrumentation at the Shabanie Mine in order to understand various geomechanics aspects of caving. In a rare situation in block caving, there were previously mined cut and fill stopes above the undercut level of some of the blocks. This allowed direct visual observations of the rock mass ahead of the cave back. Horizontal tensile fractures developing above the cave back were
observed in the old cut and fill workings and also inferred through extensometer measurements. Dilation and shear displacements were found on discontinuities in the cave periphery.

From these observations, it was proposed that the probable caving action was due to separation and buckling in the cave back and shear along steeply dipping joints in the cave periphery. Heslop made important strides in defining stress and subsidence caving, although he did not create a conceptual model for the damage ahead of the cave back. However, the direct observations of tensile fractures are significant in that they reveal the importance of this failure mechanism in the caving process at the Shabanie mine.

Panek (1981) conducted an extensive monitoring programme including observations and instrumentation at San Manuel mine in order to monitor fracturing in the undercut level and in the cave peripheries. The results of the monitoring programme suggested a series of parallel extension fractures with strike angles tangential to the cave boundary forming a ‘roughly circular fractured zone of expansion about each active cave’. This concept is illustrated in Figure 2.11.

![Parallel fractures in a circular zone around an active cave – plan view (after Panek 1981)](image)

Panek suggested a model in which there is a yield zone adjoining the caved block, where the rock mass is allowed to expand toward the centre of the cave by removal of caved material.
The deformation leads to extension cracking within the yield zone, which is bounded by a band of higher than normal stress. While no measurements were made directly above the cave, he stated that in theory, the same extensional fractures tangential to the cave boundary should occur above and below the caved block. This led to the conclusion that in-situ stress, under appropriate conditions, is capable of generating flat-lying extensional discontinuities in the rock mass above the undercut, providing an important mechanism in cave initiation and propagation over an isolated block. Panek stated that the conditions under which this mechanism is activated are significant, as they impact the potential of the rock mass to cave upward towards the surface.

This study gives indications that there may be a series of parallel tension cracks ahead of the cave void, both above the cave back and in the cave periphery. No observations or measurements were made above the cave back to confirm the presence of these fractures and no studies since have investigated the importance of this failure mechanism in cave propagation.

Using Time Domain Reflectometry (TDR) monitoring, Carlson and Golden (2008) identified multiple instances of potential tension cracks parallel to the cave advance at Henderson’s 7210 cave. Breaks in the angled TDR cables (highlighted in red in Figure 2.12) were observed in linear formations, which were interpreted as being tension cracks. These cracks lined up closely with the boundaries of overlying caves (Figure 2.13) and so it was postulated that the cracks formed as a response to the contrast in stress conditions along the line of these cave boundaries.

Figure 2.12 TDR monitoring program at Henderson 7210 mine, angled cables highlighted in red (after Carlson & Golden 2008)
Szwedzicki et al. (2004) used extensive TDR monitoring to track cave progression at Freeport. They reported that caving occurred in cycles which could vary in duration from days to weeks. The caving events were alternated with periods of stability. The results of the TDR monitoring showed that the caving occurred in large falls of ground, indicating a discontinuous damage profile. In a number of cases, they found that a few TDR cables broke at the same time over a large area with a significant length of breakage.

There are a small number of examples in the literature of investigations conducted on open stopes whose crown failure began to propagate in a cave like manner. Using in hole camera surveys, Sharrock et al. (2002) observed two types of rock mass failure above an open stope which had caved at the Mt. Isa Mines Lead Mine. The first was large, widely spaced extensional fractures at a distance from the stope crown and parallel to the excavation surface. The second was composite failure between discontinuities and intact rock observed 0-10 m from the crown. This was found to be more prevalent in rocks where there was a higher frequency of discontinuities. A picture of the composite failure in the cave crown can be seen in Figure 2.14. It is interesting to note that the failure appears to form a series of parallel fractures ahead of the

Figure 2.13  Tension cracks in cave periphery at Henderson 7210 mine (Carlson & Golden 2008)
cave back. Sharrock et al. (2002) did not further investigate the importance of the parallel or extensional fracturing on the propagation of the cave.

![Composite failure forming arches in stope crown at Mt Isa (Sharrock et al. 2002)](image)

**Figure 2.14** Composite failure forming arches in stope crown at Mt Isa (Sharrock et al. 2002)

Lorig et al. (1989) investigated caving of an open stope at Falconbridge East Mine. They reported that it was unclear whether failure of the stope back was controlled by gravity failure of existing blocks or by shear and tensile failure due to stress redistribution. They noted that core discing in boreholes above the stope back supported the idea that high stress caused shear and tensile failure, as illustrated in Figure 2.15.
2.2.1 Summary of site observations and point source monitoring

A number of studies have identified both tensile fractures and fractures parallel to the cave surface in a variety of conditions. With the exception of Panek (1981), none of these studies investigated the importance of this failure mechanism in caving mechanics. The observations from these studies do not appear to have been considered in the formation of the Duplancic model. Duplancic did, however, use microseismicity in formulating his model and a number of studies have since been published examining microseismicity in block caving.

2.3 Microseismicity

There are a number of studies examining microseismicity in caving mines using a methodology similar to that used by Duplancic in the creation of his conceptual model. The majority of these have interpreted the results within the Duplancic model of caving and so make conclusions within this framework, instead of making broader conclusions about caving mechanics. In spite of this, the results shown in these studies call into question some of the methods used and assumptions made in the development of the Duplancic model.

Duplancic (2001) used the S:P wave energy ratio of microseismicity to imply that the dominant failure mechanism in the cave back at Northparkes E26 was slip along pre-existing discontinuities. A number of authors have conducted microseismic studies using a similar
methodology (Glazer & Hepworth 2005; Hudyma et al. 2007a, 2007b; Hudyma & Potvin 2008; Glazer & Townsend 2008; Woodward 2011; Reyes-Montes et al. 2010a, 2010b; Abolfazlzadeh 2013; Tibbett et al. 2015, 2016). By examining the proportion of events with an S:P wave energy ratio of greater than or less than 10, some of these studies found a predominant shear mechanism of caving events and others found a predominant extensile mechanism. However, of these studies, only Hudyma et al. (2007a), Hudyma (2008), Reyes-Montes et al. (2010a) and Tibbett et al. (2015, 2016) include any robust verification of the mechanism.

Hudyma et al. (2007a) observed a frequency-magnitude relationship at Northparkes Lift 2 with two different slopes, suggesting that the small events may result from a different rock deformation mechanism than the larger events. Hudyma and Potvin (2008) examined the frequency-magnitude relationships for different areas at Ridgeway Sublevel Cave (SLC). They determined b-values of 0.7, 0.9 and 1.3 in the Rimmer’s Fault, Orebody and Footwall zones respectively. They interpreted the failure mechanisms as being predominantly fault-slip, mixed and volumetric respectively. However, these interpretations are not supported by the results of the S:P wave energy ratio analysis.

When the mechanism derived from the S:P wave energy ratio of the microseismic events is compared with frequency-magnitude analysis, the uncertainty in these studies shows the limitations in the understanding that can be drawn from S:P wave energy ratio when determining mechanism in caving mines.

Using a methodology similar to Duplancic’s, Tibbett et al. (2015, 2016) investigated characteristics of two Seismic Space-Time Sequences (SSTs) in two different mining steps at Ridgeway mine. The SSTs were defined by a minimum of 10 events occurring in a one hour time period within a 10 m search radius.

The analysis consisted of the following steps:

- Determining the orientation of the SSTs by calculating the principal orientations of the event clouds using Principal Components Analysis (PCA). This is similar to Duplancic using Focal Plane Analysis to determine the orientation of potential slip planes for events.

- Comparing these orientations to known joint sets in the mine. Duplancic also compared orientations from seismicity to known joint sets at Northparkes E26 Lift 1.
• Using S:P ratio analysis, the most likely mechanism was determined. Duplancic also used S:P ratio analysis to determine mechanism.

• Creating a 3D linear elastic boundary element numerical model and examining the potential for slip along different orientations (using Excess Shear Stress). Duplancic conducted a similar analysis on Northparkes E26 Lift 1.

Using this methodology, Tibbett et al. (2015, 2016) found that one of the STSSs had a predominant mechanism of shear along pre-existing discontinuities and the other had a predominant mechanism of tensile failure from induced stress. The fact that they concluded that one of the sequences had a tensile failure mechanism using a similar methodology, calls into question Duplancic’s assumption that slip along pre-existing discontinuities will happen preferentially to intact rock failure. Their finding of two different mechanisms from sequences within the same mine also suggests that Duplancic’s approach of assessing the microseismicity from the entire Northparkes E26 Lift 1 mine may have been too large a sample to correctly identify all mechanisms present.

Tibbett et al. (2016) inferred that damage created via a tensile mechanism was occurring subparallel to the cave boundary, specifically referencing the study by Panek (1981). This is illustrated in a schematic showing the fractures sub-parallel to the cave back in Figure 2.16.

![Figure 2.16 Damage inferred subparallel to the cave boundary (Tibbett et al. 2016)](image)

Reyes-Montes et al. (2010a) came to a similar conclusion when analysing seismicity at Northparkes E26 Lift 1. They found that the dominant orientations of failure planes above the
cave were sub-horizontal by using the three point method. This involves calculating plane orientations for every group of three events and plotting the results on a pole density plot. When investigating the S:P wave energy ratio of events, they found that the caving process was initially dominated by a tensile component. These findings implying sub-horizontal tensile fracturing above the cave back were found to be similar to that of a numerical model they constructed of the mine. Further detail on this numerical modelling is given in Section 2.4.

Several authors have attempted to track the seismogenic zone ahead of the cave back (Hudyma et al. 2007a, 2007b; Potvin & Hudyma 2008; Abolfazlzadeh 2013). While these attempts generally appear successful, there was little analysis of the fracturing and damage created. These studies focus more on the progression (speed and directionality) and size of the seismogenic zone.

There are two studies which cast some doubt on the idea within the Duplancic model of caving that the zone of loosening is always present when the cave is propagating. It should be noted, however, that these studies were conducted on the Ridgeway Sublevel Caving mine and not block caving mines.

Hudyma and Potvin (2008) found that the seismogenic zone was typically 20 m in height. When comparing the cave back determined from open hole plumbing results to the middle of the seismogenic zone, it can be seen that the two are often within 10 m of each other and, in February 2002, the hole plumbing was actually below the middle of the seismogenic zone (Figure 2.17). This would imply that the bottom of the seismogenic zone is often right at the boundary of the cave back and that, at times, there may not be an aseismic zone of loosening. This contrasts with the common interpretation of the Duplancic model of caving which requires the zone of loosening to be present when the cave is propagating.
Trifu et al. (2002) postulated that at Ridgeway SLC, the upper limit of the distribution of events above the cave back corresponds to the cave front loosening zone and that the lower limit is the cave back position. They found that a surface above which 90% of events were located correlated well with the cave back location, as determined by open hole monitoring (Figure 2.18). This interpretation, particularly the lower limit corresponding to the cave back, implies that there may not always be an aseismic zone ahead of the cave. It is unclear whether the 'cave front loosening zone' described is analogous to the zone of loosening in the Duplancic model. However, if this is the case, the interpretation in the location of the zone of loosening is significantly different because in the Duplancic model, it is aseismic.
2.3.1 Summary of Microseismicity

While a number of authors have used microseismicity to assess failure mechanisms in caving mines, the majority have used S:P wave energy ratio as the main discriminating factor, with few conducting any verification of this mechanism. The verifications conducted indicate that S:P wave energy ratio is not a robust indicator of mechanism in caving mines. Using a similar methodology to Duplancic, Tibbett et al. (2015, 2016) conclude that a tensile source mechanism was occurring in a block caving mine. This calls into question the assumption that slip along pre-existing discontinuities will always occur preferentially to intact rock failure. Their results also indicate that tensile failure may be occurring sub-parallel to the cave surface in a similar manner to that described by Panek (1981). There are also two studies which indicate that the zone of loosening may not always be present in caving mines.

In addition to analysis of microseismicity, Duplancic used numerical modelling to determine failure mechanisms in caving mines. While there is extensive literature on numerical modelling of caving, there are few examples of literature specifically investigating caving mechanics.
2.4 Numerical modelling

Numerical models cannot be used to determine the mechanism and progression of failure present in reality. The failure mechanisms of numerical models are determined by the constitutive model used, the boundary conditions imposed and the type of code used. Hence, the mechanisms present must be validated through other means. However, numerical models can be a useful tool in attempting to evaluate the stress regime leading to potential failure mechanisms.

There are few examples in the literature of numerical modelling studies specifically investigating caving mechanics. Some studies have interpreted results within the framework of the Duplancic model (Sainsbury 2010; Sainsbury et al. 2011) and, as such, do not aim to investigate the mechanism of caving, but only the impact of different factors on the Duplancic zones. A number of authors have conducted studies using numerical models to investigate aspects of caving other than the failure process, often focusing on final subsidence profiles, fragmentation and stress states. While not analysed in this way, the results from some of these studies can give insight into the potential for certain failure behaviour ahead of the cave. In several of the aforementioned studies, a series of parallel fractures can be seen ahead of the cave back in the figures presented, implying a discontinuous damage profile.

Vyazmensky et al. (2007) created two-dimensional numerical models of a generic block caving situation using the combined continuum/discrete element software ELFEN (Rockfield Software Ltd. 2006). Two models were created, with different approaches. In the first approach (which he named an equivalent continuum approach), discrete fractures were created within the continuum elements once the tensile strength in a principal stress direction reached zero and was oriented parallel to this direction. The second approach (termed a combined discrete network/equivalent continuum approach), was identical to the first approach, but with the addition of discrete fractures incorporated into the model before the simulation began.

The equivalent continuum approach showed a clear discontinuity in the damage ahead of the cave, with a series of parallel fractures forming ahead of the cave surface (Figure 2.19). This phenomenon was less evident in the combined continuum/discrete network model. However, there were indications of discontinuous damage in the locations of breakages of intact rock bridges. This suggests that the phenomenon, although present, may be masked or less prevalent when the rock mass is more fractured. The discontinuous damage was most clear in the
combined model when the undercut length had reached 40 m (Figure 2.20). The focus of this study was subsidence and thus no discussion was given to the discontinuity in the damage profile.

Figure 2.19  Cave growth for different undercut widths using an equivalent continuum approach (Vyazmensky et al. 2007)

Figure 2.20  Cave growth for different undercut widths using combined equivalent continuum/discrete network approach (Vyazmensky et al. 2007)
Lisjak et al. (2012) used the FEM/DEM code Y-Geo to create a generic model of block caving. One of the models presented shows discontinuous damage in space, with a series of fractures parallel to the caved zone (Figure 2.21). Again, the focus of this study was subsidence and, as such, no discussion was given to the discontinuity in the damage profile.

Li et al. (2014) conducted a numerical simulation of block caving using the two-dimensional finite element code RDPA2D in order to observe surface subsidence. A physical model was constructed and an equivalent numerical model created in order to demonstrate the code’s capability. Little detail was given on the physical model. However, it appears to simulate a mining environment typically seen in coal mines; that is, a highly stratified rock mass at low depth (84 m) with zero horizontal stress. The model is not representative of a modern block caving situation and so the failure mechanisms observed will not necessarily be consistent with that of block cave mines. Li et al. (2014) found that the failure pattern in the numerical model was consistent with that of the physical model. A comparison of the two is shown in Figure 2.22.

Figure 2.21  Y-Geo model of caving showing discontinuous failure in space in the form of fractures parallel to the cave front (Lisjak et al. 2012)
The authors then created models more representative of a block cave, with undercut depths between 500 and 2500 m. A set of large discontinuities was randomly generated with an average length of 400 m and spacing of 100 m. The results indicated a series of alternating pressure balancing arches and stress-release zones, as seen in Figure 2.23. The alternating pressure and stress-release zones would result in differing levels of damage and, in turn, a discontinuous damage profile. The authors stated that pressure balancing arches are broken either through extending the undercut or by drawing more caved material, creating a cycle whereby a new pressure balancing arch can form. Li et al. (2014) stated that the failure was primarily due to extension of existing joints and new fractures generated in rock bridges between joints. While this numerical model shows some evidence for it, the authors do not specifically address the discontinuity of the damage in the context of the Duplancic caving model or try to relate the phenomena to field data.
Several authors have also reported tension cracks forming in numerical models, a mode of failure which Duplancic (2001) does not highlight as important to cave propagation.

Reyes-Montes et al. (2010a) created synthetic rock mass (SRM) using Particle Flow Code 3D (PFC3D) for samples with conditions equivalent to two geomechanical domains at Northparkes E26 mine. The models suggested that, at the onset of damage, the breakage of inter-particle bonds was primarily in tension. The bond breaks were clustered into synthetic microseismic events and the orientations of the failure planes were calculated using the three point method.
(previously described in Section 2.3). The failure planes were found to be primarily sub-horizontal.

As previously mentioned in Section 2.3, the observations from the model of growth of new horizontal tensile fractures from the tips of pre-existing subhorizontal joints at the beginning of the caving process matched well with the higher tensile components (interpreted from the lower S:P energy ratio) and sub-horizontal orientations found in the microseismicity. A comparison of the orientations from the model and seismicity are given in Figure 2.24. The significance of these horizontal tensile fractures in the caving process was not further investigated.

<table>
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<tr>
<th>Mine seismicity</th>
<th>SRM synthetic seismicity</th>
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<tr>
<td><img src="image1.png" alt="Mine Seismicity" /></td>
<td><img src="image2.png" alt="SRM Synthetic Seismicity" /></td>
</tr>
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</table>

**Figure 2.24** Comparison of orientations from mine seismicity and synthetic seismicity from the numerical model (after Reyes-Montes et al. 2010a)

Garza Cruz and Pierce (2014) describe the testing of a small 3DEC SRM model to simulate caving conditions. The model was of a cube simulating a massive, veined rock mass with side lengths of 8 m. A significant $\sigma_1$ and $\sigma_2$ was applied, while $\sigma_3$ (vertical) was unloaded in increments (illustrated in Figure 2.25). They found that as the vertical stresses at the cave back decrease, tensile fractures develop sub-parallel to the face and the high differential stresses simultaneously induce shear failure. It was noted that the cave back showed progressive spalling as the back failed and stress was shed upwards. No further details were given on the importance of the tensile fractures on the cave progression.
2.4.1 Summary of Numerical Modelling

While a number of numerical studies of caving have been conducted, there have been very few which have specifically investigated the mechanisms and process of cave propagation. A re-examination of the results from a number of studies indicates that a discontinuous damage profile could be present ahead of the cave and that tensile fracturing could be an important mechanism in cave propagation. However, these studies have not discussed these phenomena in detail, in particular with respect to a conceptual understanding of caving.

2.5 Physical modelling

Physical modelling can be used as a tool to determine the failure mechanism in caving, particularly as two-dimensional models can allow visual observation, something which cannot be commonly achieved in the field. While extensively used in oil and gas geomechanics (Randolph & Gourvenec 2011; Gaudin et al. 2006) There are very few examples of physical models of block caving situations which aim to simulate the caving process. The studies which have been conducted in the past have had serious limitations which impact their usefulness in understanding cave mechanics.

McNearny and Abel (1993) created a two-dimensional model of caving using layers of bricks on top of gravel. The material was drawn from the bottom of the 4.6 m high column. The model
did not include any applied horizontal stress, nor any vertical stress other than the self-weight of the bricks. The brick Unconfined Compressive Strength (UCS) of 52.4 MPa was significantly higher than any induced stresses and so the model could not achieve similarity with mine-scale block caves. This also limited the model's ability to replicate any intact rock failure as part of the caving process. Duplancic (2001) correctly points out the limitations of the model, stating that ‘the regular jointing formed in the model is not very representative of the random nature of a real jointing pattern’ and ‘the lack of horizontal confining stresses limits its contribution to the understanding of caving mechanics’.

While the focus of the study was on the influence of draw and flow of caved material, some observations were made on the caving process. They found that as bricks would peel off the cave back and fall into the caved material, deformation would take place deeper into the rock mass, typically at a two to four brick depth from the cave back. These ‘fractures’ (defined as separation of the bricks) were created parallel to the caving void surface and were described as following the same pattern seen by Panek (1981) at San Manuel Mine. This fracture pattern suggests a discontinuous damage profile, but this was not further investigated.

Baumgartner (1979) created a base friction model to examine caving mechanisms in a jointed rock mass. The material used was a mixture of flour and methanol, which the author found had the correct characteristics to mimic rock behaviour. Joint sets were cut into the material after the material had set. The joints were continuous and through going with regular spacing. This resulted in the model having a regular jointing pattern which could bias the model towards a particular failure mechanism. The model did not include any horizontal stress, only vertical stress supplied via the friction frame. The failure mechanisms investigated using the model included sliding, block rotation, beam-column buckling and intact rock crushing. An example of one of the tests can be seen in Figure 2.26. Baumgartner found that the different failure modes were simultaneously present and that no general conclusions as to caving behaviour could be made.
Nishida et al. (1986) created a base friction model including horizontal stress applied using hydraulic jacks to study subsidence from cave-ins in Japan. The formation of these sinkholes is not a situation equivalent to that of a block caving mine. The test is representative of a very shallow cave, in which the caved material is not removed. The modelling material used is representative of material with strengths from approximately 4 to 49 MPa, with a single jointing pattern with varying dip angles. The horizontal stress is also constant, which would not be the case in a block caving mine. Despite these differences, there are still some similarities in the caving processes between the two cases. Figure 2.27 shows a typical test of the cave-in using the base friction model. The fracture pattern reveals a discontinuous damage profile, with a series of parallel fractures ahead of the cave surface. These fractures do not coincide with the boundaries between the layers in the sample. The authors were primarily focused on the final
subsidence profile and as such gave little discussion on the failure mechanism and damage profile of the cave.

Figure 2.27    Typical cave-in test (Nishida et al. 1986)

2.5.1 Summary of Physical Modelling

Despite the potential for determining failure mechanism in caving, the few examples of physical models created to investigate cave propagation which exist in the literature are not representative of modern caving situations. The studies show indications that there may be discontinuous damage in the caving profile ahead of the cave back, however this phenomena was not further investigated. A physical model which is more representative of a caving situation could be used to provide visual observation of the caving mechanisms and investigate the potential discontinuity in damage ahead of the cave back.

2.6 Conclusion

The Duplancic model of caving was created based on linear elastic numerical modelling and analysis of seismicity, without any access to visual observations or other instrumentation to measure fracturing. It consists of five zones: the caved zone, air gap, zone of loosening, seismogenic zone and pseudo-continuous domain. The model implies that the zones will move continuously and sequentially through the rock mass. As such, it implies the damage ahead of the cave must be continuously decreasing with increasing distance from the cave back and has been interpreted by the industry in this way.
Duplancic also came to the conclusion that the most likely mode of failure in the cave back at Northparkes E26 Lift 1 was slip along pre-existing discontinuities. This conclusion comes primarily from the large proportion of high S:P ratio events in the microseismic record and from examining the potential for slip using linear elastic modelling. The conclusion also relies on the assumption that slip along pre-existing discontinuities should happen preferentially to intact rock failure.

Multiple authors have found a series of fractures oriented parallel to the cave back using either visual observations or point location instrumentation, suggesting a discontinuous damage profile, in contrast with the continuous profile implied by the Duplancic model. The significance of this fracturing profile in cave propagation appears to have been overlooked. There are also multiple observations of extensile fracturing, a mechanism which is not presented as important to cave propagation in the Duplancic model.

There has been a reasonable amount of research on the mechanism of microseismic events in caving mines, including Duplancic (2001), most of which has used S:P wave energy ratio as the critical parameter. The papers which include some verification show that S:P wave energy ratio cannot be used as a reliable indicator of mechanism in caving mines. Tibbett et al. (2016) found a tensile mechanism at Ridgeway Deeps using a similar methodology to Duplancic’s examination of Northparkes E26 Lift 1. This calls into question Duplancic’s assumption that slip along pre-existing discontinuities will occur preferentially to intact rock failure. Additionally, there are two studies of sublevel caving which indicate that the aseismic zone of loosening may not be present at all times in the caving process.

There are few examples in the literature of numerical models created specifically to better understand the mechanics of caving. Re-examination of a number of studies investigating aspects of caving other than failure mechanisms have indicated the potential for a discontinuous damage profile ahead of the cave back. None of these studies further investigated the phenomena. In addition to site observations, there are also numerical modelling studies which give indications that extensile failure may be important in cave propagation.

Literature on physical modelling to reproduce cave propagation is sparse. The few reported studies have significant flaws which limit their potential to improve understanding of caving mechanics. However they give indications of a discontinuous damage profile, without any significant discussion on the implications of how the fracturing pattern evolved.
There are multiple papers from a variety of sources (site observations and point source monitoring, microseismicity, numerical modelling and physical modelling) that indicate that the damage profile ahead of the cave back is discontinuous and that extensile fracturing may be present as part of the caving process. While these indications are numerous, the importance of this damage profile and the extensile failure mechanism in cave propagation has been largely overlooked. The Duplancic model cannot adequately capture this fracturing process and as a result, the conceptual model of caving needs to be extended.

2.7 Issues addressed in this thesis

The conclusions of the literature review show that not only has there been limited research in the area of cave mechanics. The literature also shows that the Duplancic conceptual model of caving is not able to completely describe the damage ahead of the cave in all cases and an updated model needs to be developed. In particular, the phenomenon of a discontinuous damage profile created through (often extensional) fracturing parallel to the cave back has been largely overlooked as an important cave propagation mechanism, despite many observations of the failure mechanism in caving.

This thesis confirms the existence of a discontinuous damage profile and subsequently extends the Duplancic conceptual model of caving to capture this mechanism of failure. This was achieved using a combination of approaches. A physical model was created with aim of creating an experiment which could reveal the process by which a cave propagates, along with the fracture pattern evolved and the mechanism by which those fractures are created. These observations are particularly important as they cannot be easily made in caving mines. Field monitoring data, including microseismicity and open hole video surveys, were also used to confirm the presence of discontinuous damage profiles in operating caving mines. Source parameters of the microseismicity within the discontinuous damage profiles were examined to ascertain whether the parameters can be used as indicators of discontinuous damage and in an attempt to determine the mechanism by which they formed. The results of the analyses conducted, along with supporting literature, are used as a theoretical framework for the creation of an extended conceptual model of caving.
3 Physical Modelling

3.1 Background

A series of laboratory tests using a physical model were performed in order to determine the fracturing profile and failure mechanism present in caving. This allowed the fracturing process to be observed in a controlled environment. In order for visual observations to be made, a two-dimensional model was needed, as the cave progression and fracturing cannot be seen in a three-dimensional model.

When creating a physical model, if the modelled excavation is small with respect to its depth below surface, it can be sufficient to replace body forces by use of externally applied forces. When the excavation spans a significant depth, then this simplification is no longer acceptable and centrifugal loading must be used (Hoek 1965). When modelling the propagation of a block cave, the variation of the vertical stress is a significant factor as the final cave will span a large depth. As a result, the physical model tested as part of this thesis needed to be loaded using a geotechnical centrifuge.

The test work presented in this thesis was performed at the Geotechnical Centrifuge Laboratory at the Department of Civil Engineering of the University of Pretoria and was performed with the support of the personnel at the Geotechnical Centrifuge Laboratory. The geotechnical centrifuge (shown in Figure 3.1) is a fourth generation C67 geotechnical centrifuge manufactured by Actidyn in France, capable of accelerating models weighing up to one ton to 150 times Earth’s gravity (150 g). More detail on the testing facility can be found in Appendix A.
In order for the fracturing process in the scale model to be representative, it was important that the similitude requirements for the model were satisfied. The similitude of systems is governed by dimensional equations (Buckingham 1914). Buckingham’s π theorem uses the independent parameters controlling a system to determine the equations to be satisfied for a scale model to achieve similitude with the prototype.

Hoek (1965) used the Buckingham π theorem to define the following equation governing similitude for scale models in underground mining:

\[
\frac{g_m}{g_p} = \frac{1}{\alpha} \times \frac{L_p}{L_m} \times \frac{\rho_p}{\rho_m} \times \frac{E_m}{E_p}
\]
Where:

- \( L \) – a characteristic length of the prototype/model
- \( \rho \) – The density of the material
- \( E \) – The Young’s modulus of the material
- \( g \) – the acceleration to which the entire body is subjected
- \( \alpha \) – the ratio between the resulting stresses at an equivalent point in the prototype and the model

The physical model did not aim to recreate a specific mine. As a result, the prototype parameters (outside of \( g_p \)) for the scaling equation do not have set values. An example of potential parameters is as follows:

- Gravity: \( g_m = 80 \times 9.81 \, \text{m/s}^2 \), \( g_p = 9.81 \, \text{m/s}^2 \)
- Density: \( \rho_p = 2.80 \, \text{t/m}^3 \), \( \rho_m = 1.55 \, \text{t/m}^3 \)
- Rock mass modulus: \( E_m = 0.46 \, \text{GPa} \), \( E_p = 10 \, \text{GPa} \)
- Vertical stress: \( \alpha = \frac{30 \, \text{MPa}}{0.629 \, \text{MPa}} = 47.7 \)
- Length scale (size of undercut): \( L_m = 0.250 \, \text{m} \), \( L_p = 11580 \, \text{m} \)

While this length scale may be outside of the bounds of current operating block cave mines, it is important to note that the purpose of the physical modelling is to observe failure mechanisms, which can subsequently be verified by other means.

The physical model was well restrained in front of and behind the sample. As a result, the experiment situation was close to plane strain. While the experiment was inherently limited in its ability to reproduce the stresses and cave progression in the third dimension, it allowed direct visual observation of the caving mechanism and cave growth which would not have been possible otherwise.

The basic schematic of the test setup is shown in Figure 3.2. The relatively thin (i.e. two-dimensional) sample was placed in a frame and the sample ‘undercut’ performed by retracting a series of five pistons. These pistons actively supported the sample at the start of the test.
The vertical stress was applied by the self-weight of the sample multiplied by the acceleration of the centrifuge. With the exception of one sample tested at 70 times the acceleration of gravity (70 g), all samples were tested at 80 g. This was found to be the optimum acceleration to promote caving within the samples used.

The horizontal stress was applied to the sample via bladders on both sides of the sample. These bladders were filled with water and were connected to a standpipe, resulting in a hydraulic head of 1 m above the base of the sample, which was multiplied by 80 times due to the centripetal acceleration. The theoretical stress distribution within the sample is shown in Figure 3.3 and a force diagram of the test is given in Figure 3.4.
Figure 3.3  Theoretical stress distribution within sample

Figure 3.4  Force diagram of test (not to scale)
Two different undercutting procedures were used during testing. These two undercutting procedures, named undercutting procedure 1 and 2, can be seen in Figure 3.5 and Figure 3.6 respectively. The lead distance between pistons is approximately 5 mm in both procedures.
Figure 3.6  Undercutting procedure 2
In early tests, the difference in stress between the top and the bottom of the sample was creating deformation and ultimately vertical cracks at the top of the sample. This is illustrated in Figure 3.7. These vertical fractures could impact the caving behaviour of the samples and hence small flexible weights were placed on top of the sample to equalise the deformation at the top of the sample and eliminate the vertical cracks.

Acoustic emission sensors were installed inside the sample in an attempt to track the development of fractures. They were installed in the periphery of the sample and as such, were unlikely to have affected the cave propagation. The results did not, however, allow for any detailed analysis and, as such, the acoustic emission monitoring will not be discussed any further in this thesis. Further detail on the acoustic emission monitoring is given in Cumming-Potvin et al. (2016).

### 3.3 Testing equipment and instrumentation

In order to allow for a larger sample than the strongbox ordinarily used at the University of Pretoria Geotechnical Centrifuge Facility, a custom frame was built for the testing. The frame was primarily constructed from aluminium. This allowed the frame to be light enough to put
on the centrifuge, but also strong enough so that it would not deform from the stresses supplied to the sample.

Two sheets of 10 mm thick glass were placed in front of the sample in order to provide confinement while allowing photographs to be taken and videos to be recorded. Steel rods and bolts were used to hold the glass in place, as the stress applied to the sample would push the glass outward. These are highlighted in Figure 3.8. The frame was bolted to a steel platform which allowed for easy movement of the frame via forklift. The steel platform rested on the swing of the centrifuge. This is illustrated in Figure 3.9.
The sample was ‘undercut’ by a series of five hydraulic pistons which were bolted in place. The pistons used were the DZF 50 mm diameter model manufactured by Festo, the specifications of which can be found in Appendix B. The pistons were filled with water and were retracted by opening solenoid valves to drain the water from the pistons. In preliminary tests, the pistons showed significant settlement as the centrifuge was accelerating to 80 g. In order to minimise settlement of the pistons, any air trapped in the system was bled out before testing.

The piping diagram for the pistons can be seen in Figure 3.10. A standpipe (shown in red) supplied positive pressure on the pistons (shown in orange) before they were retracted to help reduce settlement as the centrifuge acceleration was increased. A pressure transducer measured the water pressure between the standpipe and the first piston. When the pistons need to be retracted, valve 6 needed to be closed and valve 7 opened in order for the pressure from the standpipe to be released and the water from the pistons to drain. The flow restrictor allows the pistons to be retracted in a slow, controlled manner. Valves 1 to 5 allowed the pistons to be
retracted individually. The manufacturer and model of the instrumentation used can be found in Appendix B.

![Piping diagram for pistons](image)

**Figure 3.10** Piping diagram for pistons

The shafts of the pistons had latex coverings to prevent dust from the sample affecting the retraction of the pistons. Holes were drilled into the back plate of the frame so that the wires from the acoustic emission sensors could feed into the back of the sample. A picture of the frame and pistons can be seen in Figure 3.12. The scale used for many of the pictures of the centrifuge testing is shown in Figure 3.11.

![Scale for pictures of centrifuge testing](image)

**Figure 3.11** Scale for pictures of centrifuge testing
The horizontal stress was supplied to the sample using two rubber bladders which were filled with water via a second standpipe. The standpipe had a constant supply of water during the test to ensure that the pressure head would be constant despite any potential leaks. The bladders were hydraulically connected to equalise the pressure in the two bladders. There was space in the frame on both sides of the sample in which the bladders were placed. The bladders, along with a scale, can be seen in Figure 3.13.
A simplified plan view schematic of the test is shown in Figure 3.14. A wooden spacer was used to ensure a tight fit between the sample and the back of the aluminium frame. A low friction plastic sheet was placed between the spacer and the back of the sample to minimise the friction between the sample and failed material, and the wooden spacer. This minimised any induced shear stress on the back of the sample and ensured that the failed material could be drawn down without excessive friction. Wooden spacers were also used in order to keep the bladders aligned with the sample.
Figure 3.14  Simplified plan view schematic of test

The relatively weak samples (strength in the order of 0.5 MPa) were difficult to handle without breaking. To prevent damage to the samples, a special technique of placing it in the frame was adopted. Thin plastic sheets were placed on the frame (marked with a 1 in Figure 3.15) and the sample placed on top of it. The sample was slid forward (shown by the purple arrow in Figure 3.15) until it was aligned with the bladders. The second stage of plastic sheets (marked with a 2) can then be slid under the sample to ensure even contact between the sample and the pistons/frame.

Figure 3.15  Schematic plan view illustrating how sample is placed on frame
Linear Variable Displacement Transducers (LVDTs) were fixed to the back of the frame and measured the movement of the pistons (i.e. the amount that the broken material had been drawn down). Figure 3.16 shows the LVDTs affixed to the frame and in position to measure the movement of the pistons. The make and model of the LVDTs are given in Appendix B. The LVDTs, along with the pressure transducer, were logged at a rate of 5 Hz.

![LVDTs and Pistons](image)

**Figure 3.16** Picture showing the LVDTs fixed to the frame, in position to measure piston movement, including scale

In order to capture visual data, a Canon DSLR camera and web camera were housed in the centrifuge swing and were connected to a computer in the control room via USB link to record real-time pictures and video of the test. The camera was placed approximately 700 mm from the test frame. The minimum interval between photos that the camera could achieve was four seconds. The make and model of the DSLR camera and web camera can be found in
Appendix B. A photograph of the camera and web camera taken from the position of the test frame is shown in Figure 3.17.

![Camera and web camera on centrifuge swing. Photograph taken from the position of the test frame](image)

**Figure 3.17** Camera and web camera on centrifuge swing. Photograph taken from the position of the test frame

Using the pictures taken by the cameras, displacements in the sample could be tracked using specialised software. The displacement monitoring tool Particle Image Velocimetry (PIV), detailed in White et al. (2003), was used to track the cave progression and fracturing in the tests. The software package tracks a grid of square ‘patches’ of pixels through a series of photos. This is achieved by comparing the intensity (brightness) of pixels of the patch with the pixels of consecutive photos within a certain radius. For colour photos, the pixels have three intensity values, one for each channel. The new position of the patch is determined by the peak of the correlation function between the intensity of the two patches. From the new position of the patches, the displacement can be calculated.

The PIV settings used were as follows:

- Patch size: 70 pixels
- Patch spacing: 25 pixels
- Search Zone: 40 pixels
• Leapfrog setting: 2 (i.e. the software compares the current photo to the photo before the previous one)

In order for the PIV method to accurately track displacement, the tested sample must have significant texture on the surface to allow matching of pixel intensity. The material used for testing had a monotone colour and minimal texture on the surface. To give the samples enough texture to perform the PIV analysis, they were splattered with paint. A comparison of the texture of the material before and after painting is shown in Figure 3.18.

![Figure 3.18](image)

**Figure 3.18** Material texture before (A) and after painting (B)

Using fixed control points with known co-ordinates, the PIV software can correct image distortion and can convert relative displacement to absolute displacements. These control points were used for Tests 6-8 and took the shape of a small black dot, on a white background painted onto the inside glass sheet (illustrated in Figure 3.19). However, due to concerns about the visibility of the caving front behind the control points, they were not used for Tests 1-5. Image correction for these tests was done in the image manipulation software GIMP (GNU Image Manipulation Program). More detail can be found in Appendix C.

![Figure 3.19](image)

**Figure 3.19** Example of PIV control points
3.4 Testing material

The basis for the mix design was a weak concrete, chosen as a material that would give consistent results, and with a strength appropriate for the stresses generated by the centrifuge. It was important that the material used was as brittle as possible to imitate rock failure, so that the caving mechanisms could be accurately captured by the test. In order to create a more brittle concrete sample, a number of modifications to the material needed to be made. This included adding fly ash to the mix design, listed in Table 3.1.

### Table 3.1 Sample mix design

<table>
<thead>
<tr>
<th>Material</th>
<th>Proportion</th>
<th>Percentage by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>347.6 kg/m³</td>
<td>18.5%</td>
</tr>
<tr>
<td>Sand</td>
<td>500.9 kg/m³</td>
<td>26.7%</td>
</tr>
<tr>
<td>Cement</td>
<td>25.0 kg/m³</td>
<td>1.3%</td>
</tr>
<tr>
<td>Fly ash</td>
<td>1001.8 kg/m³</td>
<td>53.4%</td>
</tr>
<tr>
<td>Total</td>
<td>1875.4 kg/m³ (rounded up)</td>
<td>100.0% (rounded up)</td>
</tr>
</tbody>
</table>

To further increase the brittleness of the material, samples were dried in an oven. Increasing the strength of the material made it more brittle; however, the samples needed to be weak enough to cave under the centrifuge stresses. Flaws were introduced into the sample matrix to create a weaker sample with the same brittle failure behaviour. The flaws also replicated joints in a rock mass. More details on the creation of flaws in the samples are given in Section 3.5.

3.4.1 Material strength testing

A materials testing programme was undertaken to characterise the properties of the material. The testing programme was conducted by University of Pretoria staff at the University of Pretoria Geotechnical Testing laboratory. The test design was a collaboration between University of Pretoria staff and the author of this thesis.

The samples tested as part of the materials testing programme were cylinders with a height of 100 mm and a diameter of 50 mm. Like the samples used in the experiments, the samples for the materials testing were cured at room temperature for 24 hours and then cured in an oven at 60°C for different intervals of 24 hours. All samples were tested in a triaxial hoek cell. The UCS tests were tested without any applied confinement. The samples were capped with
Rockset mortar (manufactured by Dupre Minerals) in order to prevent edge effects from skewing the test results. The displacement of the samples was measured by LVDTs.

Triaxial tests with different confinement were conducted to characterise the impact of confinement on the material strength. The results of the triaxial testing, show that both the strength and ductility of material increased with increasing confinement (Figure 3.20).

![Figure 3.20 Deviatoric Stress vs Strain for increasing confinement](image)

To define the impact of curing time on the strength of the material, a number of unconfined compressive strength (UCS) tests were conducted. The stress-strain relationships for different curing times can be seen in Figure 3.21. The material became stronger and more brittle with increasing curing time. Figure 3.22 gives the peak strength for each curing time. The peak strength for the sample cured for 240 hours was unexpectedly lower than that of the sample cured for 216 hours. It was postulated that this lower than expected result was simply due to ‘natural’ variation in strength associated with random sampling. This result does not impact the testing programme, as the samples used were not cured for this long.
Figure 3.21  Stress-Strain relationship for increasing curing time

Figure 3.22  Peak Strength vs Curing Time
The average material properties for the material tested after 48 hours of curing are given in Table 3.2.

<table>
<thead>
<tr>
<th>Unconfined Compressive Strength</th>
<th>Young’s Modulus</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>310 kPa</td>
<td>456 MPa</td>
<td>0.2</td>
</tr>
</tbody>
</table>

### 3.5 Test samples

To create the samples, the materials were combined in a mechanical mixer and placed into a metal mould, which was lined with plastic sheets to prevent the sample from bonding to the mould. The mould was lightly vibrated using a vibrating table to remove air pockets from the material.

The samples measured 500 mm x 450 mm x 50 mm and had a mass of approximately 21.1 kg. This was the maximum practical sample size, given that the samples needed to be handled by a single person.

The samples were cured at room temperature for 24 hours, then de-moulded and put into a curing oven at 60°C to further dry and increase the brittleness of the samples. Most of the samples were tested after approximately 24 hours of drying in the oven. However, due to practical considerations outlined in Section 3.7, some of the samples were dried for longer before being tested. An example of one of the samples drying in the oven can be seen in Figure 3.23.
The test samples included pre-made ‘joints’, which served as ‘Griffith flaws’ to reduce the sample strength and promote caving in a similar manner to a joint set in the caving rock mass. The same ‘joint’ network was used for all samples and was quasi-randomly generated. The quasi-random design was chosen so as to not introduce a fabric into the sample. The joint network was limited to the inner portion of the sample, an area measuring 250 mm across by 300 mm vertically. This area was selected to reduce the risk of damaging the sensors by caving into the abutments. The constant application of the horizontal stress could also be compromised.

For the generation of the pseudo-random joint network, the inner portion of the sample was divided into 50 mm by 50 mm squares and the centre-point of 15 joints was placed in a random location within each square (450 joints in total). A random (in-plane) orientation was assigned to each joint. Each joint had a length of 20 mm and penetrated straight down (perpendicular to the plane of the sample) through the entire thickness of the sample.
In addition to the quasi-random ‘joints’, a pattern of ‘undercut joints’ was cut into the bottom of the sample. This was done to break up the sample in order to facilitate cave initiation, a process similar to the breaking of rock by blasting in an undercut. The ‘random’ and ‘undercut joints’ were created by cutting slots on a plastic sheet. This template was overlain on the sample and the ‘joints’ were cut into the sample with a cement knife. The knife was pushed through the slots in the template and the ‘joints’ cut in a consistent manner for all the samples.

The ‘joints’ were cut 2 hours and 45 minutes after the samples were cast. This timing allowed the ‘joints’ in the sample to heal, giving the ‘joints’ significant cohesion. The template for the ‘joints’ can be seen in Figure 3.24. The quasi-random ‘joints’ are shown in thin red lines, the ‘undercut joints’ in thick blue lines and the outline of the sample is the thick green box around them.

![Figure 3.24](image.png) Joint template for sample (both axes in mm). Quasi-random ‘joints’ in red, ‘undercut joints’ in blue and sample outline in green.
3.6 Test procedure

The test procedure is as follows:

- Sample mixture is prepared and poured into mould
- Sample is vibrated on vibrating table then cured at room temperature for 2 hours and 45 minutes
- Joint template is lain over sample and ‘joints’ cut into sample with cement knife
- Sample is cured for a further 21 hours and 15 minutes before being removed from mould and placed into the oven for curing
- Sample is splattered with paint (for PIV analysis)
- Pistons are bled of air and extended back to maximum vertical position, then fixed to the frame
- The wooden spacers, low-friction plastic sheet and bladders are placed into position
- Plastic sheets were placed down and used to slide the sample into place
- First glass pane is pushed against the sample and the second glass pane is placed in front of it, and then bolted in place
- Flexible weights are placed on top of the sample
- LVDTs are fixed to the frame of the sample and adjusted so that they are able to measure piston displacement
- Platform is placed on centrifuge swing
- Camera, lights, pressure transducer and valves are connected to centrifuge
- Centrifuge water is connected to standpipes to ensure they are full
- Centrifuge chamber doors are closed
- Video recording begins, as does logging of the LVDTs and pressure transducer
• Valves 6, then valves 1 through 5 are opened in to allow the pressure from the standpipe to help reduce piston settlement

• The centrifuge is accelerated to 50 g, where the focus on the camera is adjusted (as the focus cannot be adjusted beyond 50 g)

• Camera begins to take photos at four second intervals

• Centrifuge is accelerated to 80 g

• Valves 1 through 6 are closed. Valve 7 is opened.

• Pistons are retracted from left to right by opening and closing valves 1 through 5 and the sample caves

• Valves 1 through 7 are all closed. Recording of LVDTs, pressure transducers and photos from camera is ceased

• Centrifuge is slowed back to 1 g

• Centrifuge chamber doors are opened and lights, LVDTs, pressure transducers and camera are all disconnected

• Platform is removed from centrifuge swing

• Glass panes and sample are removed from frame

• Pistons are removed from frame and frame is cleaned

Once a sample had been prepared and was ready for testing, the testing process took approximately 8 hours including setup, test and clean-up to be ready for the next test.

3.7 Differences between tests

Despite considerable efforts to achieve testing consistency, there were a number of differences between the tests. Due to the fragile nature of the material, Sample 2 was damaged before testing and was split completely into two halves diagonally. A decision was made to test it at 70 g instead of 80 g because of the expected lower global strength of the sample. As previously mentioned in Section 3.3, PIV control markers were included in tests 6 through 8.

As mentioned previously in Section 3.2, the undercutting procedure used for test 1 was the undercutting procedure 2, while the procedure used for all other tests was undercutting.
procedure 1. In test 8, the solenoid valve for piston 3 ceased function partway through the test. The piston retracted very quickly out of sequence, as illustrated in Figure 3.25.

![Figure 3.25](image-url) Piston 3 before (A) and after (B) the solenoid valve ceased function
The differences in curing time between samples were due to practical considerations. Staff working hours did not allow for casting of samples on weekends and so Samples 2, 7 and 8 were tested after a longer curing time, as they were cast on a Friday. Sample 3 was a sample left over from early trials and as such had been cured for significantly longer.

<table>
<thead>
<tr>
<th>Test</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>16/11/14</td>
<td>18/11/14</td>
<td>18/11/14</td>
<td>19/11/14</td>
<td>20/11/14</td>
<td>21/11/14</td>
<td>24/11/14</td>
<td>25/11/14</td>
</tr>
<tr>
<td>Acceleration</td>
<td>80g</td>
<td>70g</td>
<td>80g</td>
<td>80g</td>
<td>80g</td>
<td>80g</td>
<td>80g</td>
<td>80g</td>
</tr>
<tr>
<td>PIV Control markers</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Total Curing Time</td>
<td>48 hrs</td>
<td>93 hrs</td>
<td>192 hrs</td>
<td>48 hrs</td>
<td>45 hrs</td>
<td>46 hrs</td>
<td>70 hrs</td>
<td>92 hrs</td>
</tr>
<tr>
<td>Undercutting Procedure</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

### 3.8 Test results

Three of the eight samples tested (3, 7 and 8) either did not fail at all, or only exhibited localised failure around the undercut instead of continued caving behaviour. As such, they will not be discussed in this section, however pictures of these tests can be found in Appendix D. The lack of caving behaviour was attributed to the additional strength in the samples gained from a longer curing time. The extra 24 or 48 hours of curing time results in a strength increase of 20% and 49% respectively (see Figure 3.22).

In spite of the precautions discussed in Section 3.3, as the acceleration of the centrifuge was increased to 80 g, the pistons showed a small amount of settlement (typically 1-3 mm). A chart showing an example of the settlement of the pistons (measured by the LVDTs) for Test 5 is given in Figure 3.26. The pistons would stabilise after this period of settlement. The settlement caused some of the samples to crack before the pistons were retracted. This effect is illustrated in Figure 3.27.
Figure 3.26  Chart showing settlement of LVDTs (Test 5)

Figure 3.27  Illustration of settlement of pistons (red) and resulting pre-existing fractures (purple)
The pre-existing fractures originating from piston settlement created material discontinuities which influenced the test behaviour. Although these discontinuities are not part of the controlled test procedure they can be considered as analogous to faults, which would exist in mines before the cave is established. In this thesis, they will be referred to as ‘pre-existing fractures’ for convenience.

PIV results were calculated for each test, an example of which is given in Figure 3.28. The square points in the figures are the locations of the centroids of the patches and behind them is a surface on which the displacement is interpolated. Details on the displacement calculation, vector plots and interpolation method are given in Appendix E. A region at the top of the sample was partially obscured by the metal rod in front of the sample and a region on the right hand side of the sample was obscured by the shadow of the frame. The obscuring prevented the PIV process from accurately tracking the patches in these areas and so the results were filtered to exclude these points. This is illustrated in Figure 3.29.

![Figure 3.28 Example of PIV results showing total displacement](image_url)
In test 6 (Figure 3.41) the displacement of the sample cannot be tracked behind the control points, leaving squares with 0 displacement on the image.

While the fracturing could be seen in the PIV results, the smaller, more complex fracturing patterns could not always be perfectly revealed, as shown in Figure 3.30. Large scale displacements and small displacement over larger areas (such as fractures being formed) could be tracked well as indicated by the pink fractures in Figure 3.31.
Figure 3.30  Difference in clarity of fractures between photo and PIV results

Figure 3.31  PIV results with annotations showing parallel fracturing
A brief overview of the progression of the tests which successfully caved is shown in Figure 3.32 through Figure 3.40. For more detailed results, see Appendix D and Appendix F.

Test 1 had a pre-existing fracture from the top left hand side of the sample to roughly the centre of the sample. Undercutting procedure 2 was used for test 1, which appeared to affect the caving progression. The cave expanded significantly in the lateral direction as the pistons were retracted from left to right (stages 1-6 in Figure 3.6). As the pistons were all retracted as one, the cave expanded vertically more quickly. The cave had a rounded shape until it reached the pre-existing fractures when it changed to a more irregular shape (Figure 3.32 H). The cave appeared to progress via a series of ‘jumps’ to successive fractures parallel to the cave back.

Sample 2 was broken in two pieces before testing began, which affected the caving progression. At the beginning of the test, the cave was clearly bounded by the ‘undercut joints’, evidenced by the sharp, triangular shape of the cave (Figure 3.34 B-E). As the cave progressed past the undercut, the mechanism changed; the cave began to progress as a series of fractures parallel to the cave back (Figure 3.34 F-H). These parallel fractures were bounded by the split in the sample. The lead distance between pistons 4 and 5 was unusually large. Once piston 5 began to move, the cave began to progress more rapidly.

Sample 4 had a pre-existing fracture running vertically down the left hand side. Again the cave progressed by a series of fractures parallel to the cave front. The cave front was easy to identify and had a round shape. At the end of the test (Figure 3.36 H), the air gap began to close and the cave shape was more difficult to determine. The pre-existing fracture did not appear to have a significant impact on the caving behaviour. This may be because of the relatively large distance between the fracture and the cave.

Sample 5 had multiple pre-existing fractures, two running vertically down the left hand side of the sample and two running diagonally from the top right hand side towards the centre of the sample. Unlike test 4, these pre-existing fractures had a significant impact on the caving behaviour of test 5. The cave began to progress via parallel fracturing, with a round cave shape and a clear air gap (Figure 3.38 B-E). The cave then begins to deviate to the right as it interacts with two of the pre-existing fractures (Figure 3.38 F-H). These fractures bound the edges of the cave and direct it as it continues to cave as a series of parallel fractures. This is the same behaviour one would expect from a cave mine with faults running through the middle of it.
Sample 6 had a pre-existing fracture running vertically, left of centre. The cave began expanding into a round shape (Figure 3.40 B-C), however this changed to a sharper, more tapered shape when pistons 4 and 5 were retracted (Figure 3.40 D-F). The progression of the cave was again through a series of fractures occurring parallel to the caving front, with particularly clear examples of this in Figure 3.40 D. The cave stalls at Figure 3.40 G, evidenced by the large air gap formed in Figure 3.40 H. A large wedge appeared to have formed in the top left hand side of the cave, the left hand side of which formed along the pre-existing fracture. The cave stalled before this wedge could come loose and fall into the cave void.
Figure 3.32 Caving progression of Test 1
Figure 3.33  PIV results from Test 1
Figure 3.34  Caving progression of Test 2
Figure 3.35  PIV results from Test 2
Figure 3.36  Caving progression of Test 4
Figure 3.37  PIV results from Test 4
Figure 3.38  Caving progression of Test 5
Figure 3.39  PIV results from Test 5
Figure 3.40  Caving progression of Test 6
Figure 3.41  PIV results from Test 6
4 Field Monitoring Results

The results of the physical modelling showed that the cave in the model progressed through a series of fractures alternated with zones that were mostly intact. This failure mechanism is not adequately captured by the Duplancic conceptual model of caving and, despite some observations in the literature, it has gone unrecognised as a caving mechanism in the past. In order to verify the results of the physical modelling and to confirm that the mechanism is present and significant in cave propagation, examples needed to be found in operating caving mines. To achieve this, the caving mechanism in the field was studied through the use of microseismic data and open hole video camera surveys.

Three sites were examined as part of the field monitoring analysis.

4.1 Study sites

4.1.1 Mine A

Mine A is a large copper-gold porphyry block cave operation located in Australia, consisting of two blocks with extraction levels at 1200 and 1400 m depth. The cave footprints are roughly square in shape and cover areas in the order of 70 000 m² each. The rock mass is generally fair with Rock Mass Ratings (RMR) in the order of 55-60 based on the Laubscher (1990) classification. Both blocks of Mine A were preconditioned using hydraulic fracturing. The in situ major and intermediate principal stresses are oriented horizontally with magnitudes of approximately 65 and 40 MPa respectively, and the minor principal stress is oriented vertically with a magnitude of approximately 35 MPa at 1200 m depth.

4.1.2 Mine B

Mine B is a copper-gold porphyry block cave operation located in Australia, with an undercut at 1100 m depth. The block cave sits underneath a sub level caving operation, resulting in a lift height of approximately 200 m. The footprint is roughly rectangular in shape with an area of about 85 000 m². The rock mass is generally fair (RMR 50-60: Laubscher 1990). The in situ major and intermediate principal stresses are oriented horizontally with magnitudes of approximately 65 and 45 MPa respectively, and the minor principal stress is oriented vertically with a magnitude of approximately 30 MPa at 1100 m depth.
4.1.3 Mine C

Mine C is a large iron ore sublevel caving operation in Sweden. Currently 10 orebodies are being mined across an area of approximately 2.5 x 5 km. Despite being a sublevel cave, there were no mine workings above the cave in some orebodies, allowing the cave to propagate in a manner similar to that of a block cave. The study site for this thesis is one of these aforementioned orebodies. The orebody in question is over 1.4 km long and approximately 80-100 m in width. The uppermost level of the SLC in this orebody is situated at a depth of 800 m. The in situ major principal stress at 1170 m is 50 MPa and the intermediate and minor principal stresses are approximately 30 MPa. The major and intermediate principal stresses are oriented sub-horizontally and the minor principal stress sub-vertically.

4.2 Microseismicity

4.2.1 Methodology

The expected pattern of microseismicity evolved from a Duplancic mode of failure would be a ‘cloud’ of events ahead of the cave which moves continuously outwards over time. Failure through bands of fractures alternated with bands of relatively undamaged rock mass would most likely result in a pattern of bands of events alternated with bands containing few events (i.e. discontinuous microseismicity). To identify whether this mechanism of caving was occurring in the field, patterns in date and location of microseismic events at several caving mines was examined using the mXrap software package (Harris & Wesseloo 2015).

The seismic records of each mine were examined in 3D using time slices to see if bands of events could be identified. In order to make the progression through time more clear, the events were coloured by date. The events were only filtered by a basic quality filter, detailed in Appendix G.

A study of the microseismic source parameters of the events was conducted to determine if source parameters could be used to distinguish differences in mechanism between the bands and surrounding events or to help reveal the location of otherwise ‘hidden’ bands. The distribution of source parameters of each band was compared with that of events in the same vicinity, but outside of the bands.

The source parameter distributions examined were:
• Seismic energy
• Seismic moment
• Apparent stress
• Energy index
• Corner frequency
• S:P wave energy ratio
• Static stress drop
• Frequency-moment
• Time of day (diurnal analysis)

Microseismic monitoring systems with poor spatial distributions can lead to system artefacts, whereby event locations can be biased to create artificial linear features. To investigate the potential for system artefacts, the sensors used in the location of each event were analysed, for Mine A. The number of times a trigger from each sensor was used in the location of an event was calculated for each of the bands. This was then normalised by the total number of accepted triggers for each band. These relative proportions allow us to see which sensors are used more and less often in event location and if there was a difference between the sensors used in location of events inside and outside of the bands. The data used in this analysis for Mine A was not available for Mines B and C so an alternate method was adopted.

The Configuration Quality Index (CQI) (Mendecki 1993) was used to quantify the quality of the array configurations. Mendecki et al. (1999) suggested that arrays should aim for a minimum CQI of 0.3 for good quality location of events. For Mine A, the CQI for each event was calculated and the CQI distributions for events inside of the bands was compared with those outside of the bands. For Mines B and C, a distance-magnitude relationship was developed for event location for each mine using the method described in Wesseloo (2011). Grids were created in 3D and the CQI of an event of local magnitude -1.0 at each grid point was calculated. This was displayed as a series of isosurfaces, giving an indication of the configuration quality within each mine.
All event locations used in this thesis are the ‘raw’ locations supplied by the mines’ microseismic systems supplier, using their homogeneous velocity model and standard location algorithm.

4.2.2 Microseismic systems at the study sites

The microseismic monitoring system at Mine A included 88 total sensors over time. An example of the system is given from two angles in Figure 4.1.

Figure 4.1 Microseismic system and events at Mine A from January 2013 to June 2013
The microseismic monitoring system at Mine B included 48 total sensors over time. A number of sensors were added and removed as the mine transitioned from SLC to block caving method and as the cave propagated. An example of the system is given in Figure 4.2.

![Figure 4.2](image)

**Figure 4.2** Mine B microseismic monitoring system at 2010-01-01. Events for 2009-07-01 to 2010-01-01 shown in grey.

The microseismic monitoring system at Mine C included 211 total sensors over time, of which 36 were in the general vicinity of the orebody examined. An example of the system around the orebody is given in Figure 4.3.
Only examples which exhibited very obvious, distinct bands of events are presented in this thesis. These consisted of zones of high event density alternated with zones of low event density in which the cave appeared to propagate via ‘jumps’ to successive zones of high event density. There were also a number of examples found which suggested that bands may have been forming. However clear, distinct delineation of the bands could not be made.
4.2.3 Instances of event banding

There were five obvious instances in which the microseismic events appeared in patterns of banding. These are relatively tight groups of events forming repeated features in space. The thickness and spacing of these features can be difficult to define, as the events present as a ‘zone’ instead of single distinct lines. This may be an indication that a zone of fracturing is forming in situ, or it may simply be due to scatter in microseismic event location, or a combination of the two. The groups of events are alternated with zones of low event density, creating ‘bands’. The bands were identified visually by time slicing through the microseismic databases.

Three of these obvious cases found were from Mine A, one from Mine B and one from Mine C. The cases spanned a large range of time periods (from weeks to years) and appeared ahead of and parallel to both the crown and periphery of caves. There were also times at which the cave appeared to propagate via a diffuse cloud of events, which is discussed further in Section 4.2.4.

4.2.3.1 Case 1

Case 1 took place in the crown of Block 1 of Mine A. The banding of events took place over approximately six weeks, during a time period in which the cave development was mature. The 3D view of the events in this time period is given in Figure 4.4. The magnitude time chart in Figure 4.5 shows the temporal context of these events.
Figure 4.4  Events in time period for Case 1, highlighted in orange. All events shown in grey.

Figure 4.5  Magnitude time chart for Mine A, Lift 1. Time period for Case 1 shown in orange, all other events in grey. Cumulative number of events shown as red line.
The banding of events in Case 1 is illustrated in Figure 4.6, where the events are coloured by date to show the progression through time and the bands are highlighted in red. The vertical extent of this banding behaviour was approximately 60 m. The position of the banding with respect to the cave geometry (as interpreted by site personnel), is shown in Figure 4.7. From this figure, it appears that the bands are sub-parallel to the cave which is expanding upwards away from the undercut through this banding behaviour.

Figure 4.6  Case 1 - bands of microseismicity at Mine A, undercut level shown in blue and production level shown in purple. Events coloured by date. In B, bands highlighted in red.
Case 2 also took place in the crown of Lift 1 of Mine A. The banding of events took place over approximately 6 weeks, during an early period in cave development. The 3D view of the events in this time period is given in Figure 4.9 and the magnitude time chart in Figure 4.8 shows the temporal context of these events within Lift 1.
Figure 4.8  Events in time period for Case 2, highlighted in orange. All events shown in grey.

Figure 4.9  Magnitude time chart for Mine A, Lift 1. Time period for Case 2 shown in orange. Cumulative number of events shown as red line.
The banding of events in Case 2 is shown in Figure 4.10, where the events are coloured by date to show the progression through time and the bands are highlighted in red. The banding was present over a total extent of approximately 70 m. The position of the banding with respect to the cave geometry (as interpreted by site personnel), is shown in Figure 4.10. From this figure, it appears that the cave is expanding upwards sub-vertically through this banding behaviour.

Figure 4.10  Case 2 - bands of microseismicity at Mine A, undercut level shown in blue. Events coloured by date. In B, bands highlighted in red.
Figure 4.11  Banding of events shown with cave shape for this time period, as interpreted by site personnel (Case 2, Mine B)

4.2.3.3 Case 3

Case 3 took place in the periphery of Lift 2 of Mine A. The banding of events took place over approximately 11 weeks, during the early to middle period of cave development. The 3D view of the events in this time period is given in Figure 4.12 and the magnitude time chart in Figure 4.13 shows the temporal context of these events within Lift 1.
Figure 4.12  Events in time period for Case 3, highlighted in orange. All events shown in grey.

Figure 4.13  Magnitude time chart for Mine A, Lift 2. Time period for Case 3 shown in orange. Cumulative number of events shown as red line.
The banding of events in Case 3 is shown in Figure 4.14, where the events are coloured by date to show the progression through time and the bands are highlighted in red. The cave appears to be expanding upward and outward in the periphery. The bands had a total lateral extent of approximately 45 m. The position of the banding with respect to the cave geometry (as interpreted by site personnel), is shown in Figure 4.15. From this figure, it appears that the cave is expanding laterally outwards through this banding behaviour. It is important to note that the events in Case 3 are located close to the extraction level of Block 1, placing the events close to the cave interaction zone.

Figure 4.14  Case 3 - bands of microseismicity at Mine A, undercut levels shown in blue and production levels shown in purple. Events coloured by date. In B, bands highlighted in red.
4.2.3.4 Case 4

Case 4 took place in the periphery of Mine B. The banding of events took place over approximately 12 weeks, during the latter period of cave development, when the cave was breaking through to the SLC above. The 3D view of the events in this time period is given in Figure 4.16 and the magnitude time chart in Figure 4.17 shows the temporal context of these events within Lift 1. While the events in Case 4 are temporally related to blasted, there is no evidence to suggest that the pattern in location (i.e. the banding behaviour) was due to blasting, as the undercut blasts progressed outwards in a smooth pattern without jumps.
Figure 4.16  Events in time period for Case 4, highlighted in orange. All events shown in grey.

Figure 4.17  Magnitude time chart for Mine B. Time period for Case 4 shown in orange. Cumulative number of events shown as red line.
The banding of events in Case 4 is shown in Figure 4.18, where the events are coloured by date to show the progression through time and the bands are highlighted in red. The bands expand the cave outwards over time, increasing the lateral extents of the cave. No cave interpretations were available for Mine B; however, the position of the banding with respect to the blasts is shown for reference in Figure 4.19. It appears that the cave is expanding laterally outwards through this banding behaviour.

Figure 4.18  Case 4 - bands of microseismicity at Mine B, undercut level shown as black lines. Events coloured by date. In B, bands highlighted in red.
Figure 4.19    Banding of events shown with blasts for this time period (Case 4, Mine B)

4.2.3.5 Case 5

Case 5 took place in crown of Mine C. The banding of events took place over nearly 18 months, during a later period of cave development. This is a significantly longer time period than any of the other four cases. The 3D view of the events in this time period is given in Figure 4.20 and the magnitude time chart in Figure 4.21 shows the temporal context of these events within this orebody of Mine C.
Figure 4.20  Events in time period for Case 5, highlighted in orange. All events shown in grey.

Figure 4.21  Magnitude time chart for Mine C. Time period for Case 5 shown in orange. Cumulative number of events shown as red line.
The banding of events in Case 5 is shown in Figure 4.22, where the events are coloured by date to show the progression through time and the bands are highlighted in red. The crown of the cave progresses vertically upwards in a single large ‘jump’. No cave interpretations were available for Mine C; however, the position of the banding with respect to the blasts is shown for reference in Figure 4.23. It appears that the cave is expanding laterally outwards through this banding behaviour.

Figure 4.22  Case 5 - bands of microseismicity at Mine C, development shown as black lines. Events coloured by date. In B, bands highlighted in red.
4.2.3.6 Progression over time

The bands of events move outwards over time, indicating that the cave is expanding outwards and thus that the formation of the bands is part of the cave propagation and expansion process. This is illustrated for Case 4, in the cave periphery of Mine B in Figure 4.24. It can be seen that the first two bands formed almost simultaneously (Figure 4.24A) and the third band formed after the first two bands had almost finished forming (Figure 4.24B). The fourth band formed while the third was still active (Figure 4.24C) and the fifth while the fourth was still active (Figure 4.24D). This kind of overlapping progression through time, where the new zone of events began forming as the previous zone was still active, was common to all cases except for Case 5. This can be seen in the figures in which the events are plotted by time (Figure 4.6, Figure 4.10, Figure 4.14 and Figure 4.22).
4.2.4 Diffuse microseismicity

The pattern of bands of microseismicity was not always observable in all locations and times in the mines examined. The propagation of the cave could also, at times, appear to have been via a diffuse cloud of events, as illustrated for Mine B in Figure 4.25.
There are a number of potential reasons for the lack of consistency in the observability of the banding phenomenon:

- One of the possibilities is that the specific conditions necessary for it to occur are not always being met throughout the period of cave propagation and that the cave may be expanding through different mechanisms at different times.

- Another possibility is that the fractures are spaced so closely that the location accuracy of the microseismic monitoring system is not sufficient to resolve the bands of events, resulting in a sparse cloud instead of a tight band.

- A third potential reason is that parallel fracturing could form a beam ahead of the cave surface, which subsequently fails, creating microseismic events in between the bands. This would result in the volume ahead of the cave filling with events, creating a diffuse cloud.
• It is also possible that the at least some diffuse microseismicity is due to a Duplancic style of caving and that both banding and Duplancic behaviour are occurring in the same mine at different times.

### 4.2.5 Examination of source parameters in bands

A study of the microseismic source parameters of the events was conducted in order to determine if source parameters could be used to distinguish differences in mechanism between the bands and surrounding events or to help reveal the location of otherwise ‘hidden’ bands. The distribution of source parameters of each band was compared with that of events in the same vicinity, but outside of the bands. Figure 4.26 and Figure 4.27 give examples from Case 1 of the volumes used for analysis of the events inside of the bands and outside of the bands respectively.

![Figure 4.26 Volumes used for bands in Case 1](image)
The source parameter distributions examined were:

- Seismic energy
- Seismic moment
- Apparent stress
- Energy index
- Corner frequency
- S:P wave energy ratio
- Static stress drop
- Frequency-moment
- Time of day (diurnal analysis)

The full results of the analysis of these source parameters for all of the cases can be found in Appendix H.
The analysis results indicated that there are not any specific source parameters that could be used to reveal the presence of banding of events or the source mechanism of the bands. For some of the source parameters in some of the cases, the distribution of the events outside of the bands was almost indistinguishable from that of the events within the bands, as shown in Figure 4.28.

![Graph showing moment distributions for events outside of bands (shown in purple) and bands (shown in other colours) for Case 1](image)

**Figure 4.28  Moment distributions for events outside of bands (shown in purple) and bands (shown in other colours) for Case 1**

For other source parameters and cases, the events outside of the bands had distributions which deviated significantly from that of the bands. However this deviation was not consistent between cases. An example of this inconsistency in deviation is shown in Figure 4.29, in which the events in the bands have a lower S:P wave energy ratio than the events outside of the bands (shown in purple) and Figure 4.30 where the bands have a higher S:P wave energy ratio. The differences between distributions of source parameters between the events inside and outside of the bands were inconsistent and as a result none of the source parameters examined were suitable for use as indicators of banding of events, nor as indicators of the mechanism of failure within the bands.
Figure 4.29  S:P Wave Energy ratio distributions for events outside of the bands (shown in purple) and bands (shown in other colours) for Case 4

Figure 4.30  S:P Wave Energy ratio distributions for events outside of the bands (shown in purple) and bands (shown in other colours) for Case 2
4.2.6 Investigating Potential Alternative Explanations for Event Banding

It could be argued that the bands of events observed are not a genuine expression of the cave propagation and instead could be a result of either geological influence, or an artefact of the microseismic monitoring system due to poor configuration. These hypotheses were investigated to determine if they could be confirmed or rejected.

4.2.6.1 Geology

All three study sites have detailed geological models which include features which could influence the location of microseismicity. Based on consultation with site personnel and examination of the geological models, there is no reason to believe that these bands of microseismicity are a result of geology (faults, contacts, intrusions, lithology, etc.). In Case 5, the cave had not propagated beyond the maximum elevation shown in Figure 4.22. A geotechnical borehole was drilled in order to investigate the reason for the banding behaviour. No evidence of a large structure was found to suggest that the ‘jump’ in microseismicity was due to a geological feature.

There was no evidence found in any of the cases supporting the hypothesis that the banding behaviour was a result of geological influence.

4.2.6.2 Potential microseismic monitoring system artefact

To investigate the potential for system artefacts at Mine A, the sensors used in the location of each event were analysed. This data was not available for Mines B and C. The volumes mentioned previously in Section 4.2.5 were used for this analysis.

As detailed in Section 4.2.1, the relative proportions of sensor use allow us to see which sensors are used more and less often in event location. These relative proportions are given in Figure 4.31, Figure 4.32 and Figure 4.33 for Cases 1, 2 and 3. The events outside of the bands are shown in purple, and each of the bands is given in the other colours. The events outside of the bands have similar proportional use of each sensor to the events inside of the bands. As the events were processed using the same combinations of sensors, the ‘jumps’ cannot be attributed to systematic location bias resulting from the inclusion or exclusion of different sensors.
Figure 4.31  Relative proportion of sensor use per band (Case 1, Mine A). Events outside bands in purple.

Figure 4.32  Relative proportion of sensor use per band (Case 2, Mine A). Events outside bands in purple.
As previously mentioned in Section 4.2.1, CQI was also used to evaluate sensor configuration at Mine A. Figure 4.34, Figure 4.35 and Figure 4.36 give the cumulative distributions of CQI for Cases 1, 2 and 3 respectively. The events outside of the bands are shown in purple, and each of the bands is given in the other colours. The events outside of the bands have a similar and, at times, worse distribution of CQI with the vast majority of events exceeding the minimum of 0.3 suggested by Mendecki et al. (1999). This indicates that the banding of events was not due to poor configuration quality. One exception was the band shown in orange in Figure 4.34, which has a significantly worse distribution of CQI. This is likely due to the fact that the events did not form a very tight band, with few events in this area. This band is shown in 3D by the orange volume in Figure 4.26.
Figure 4.34  Cumulative distribution of CQI per band (Case 1, Mine B). Events outside bands in purple.

Figure 4.35  Cumulative distribution of CQI per band (Case 2, Mine B). Events outside bands in purple.
Figure 4.36  Cumulative distribution of CQI per band (Case 3, Mine B). Events outside bands in purple.

Figure 4.37 shows the change in the number of active sensors and the average log(CQI) over time for Mine A. Sensors were deemed to be active if they were used in the processing of at least 10 events in a month. The time period for each of the three cases are indicated as dashed lines on the chart. It is clear that the three cases all happened at times when both the number of active sensors and average log(CQI) were relatively high, indicating that the sensor array had a good 3D configuration necessary for quality event locations.
Figure 4.37  Active sensors and average log(CQI) over time (Mine A). Time periods for Cases 1, 2 and 3 shown as green, purple and pink dashed lines respectively.

To assess the system configuration quality for Mines B and C, CQI was calculated on a grid for a local magnitude -1.0 event (methodology detailed in Section 4.2.1). Isosurfaces for different values of CQI at Mine B are shown in Figure 4.38. Based on the analysis, the area in which the event banding took place is in the range of $1 < \text{CQI} < 2$. This is significantly higher than the minimum of 0.3 suggested by Mendecki et al. (1999).
Isosurfaces for different values of CQI at Mine C are shown in Figure 4.39. Based on the analysis, the area in which the event banding took place is in the range of $0.6 < \text{CQI} < 1$. This is again significantly higher than the minimum of 0.3 suggested by Mendecki et al. (1999).
From the analyses conducted, there is no evidence to support the hypothesis that the phenomenon observed of bands of events was created as an artefact due to bias of the microseismic monitoring system.

4.3 Open Hole Video Camera Monitoring

Video camera surveys of open holes were reviewed to investigate the failure mechanisms and fracturing ahead of the cave back in the field. The amount of information on fracturing that can be obtained from open hole monitoring is inherently limited by the small diameter of the holes (in comparison to the size of the cave), orientation of the borehole and potential issues in the quality of the image. This limits observations to obvious examples of fracturing (i.e. significant shear causing misalignment of the borehole). Open holes, despite the limitations, often provide the only available visual observations ahead of the advancing cave back.
Videos from two mines, Mine A and Mine B, were used in this analysis. Only videos from a single hole were available for Mine A; however, there were 70 video surveys for this hole, allowing for a good dataset over time. The open hole is shown in Figure 4.40, with the microseismic events to indicate the geometry of the cave. The undercut and extraction levels of both blocks are shown in grey and the level from which the hole was drilled is given in blue.

Figure 4.40  3D view of open hole at Mine A facing two different directions. Events shown in grey.
Mine B had four holes intersecting the cave. However, there were limited video surveys available and the videos available often showed little fracturing. Hence, the datasets obtained were limited. In particular, the data from Hole 1 was too limited to allow any conclusions, while the conclusions made from Holes 2 and 3 were limited. These holes are shown in Figure 4.41, along with the microseismic events to indicate the position of the cave. Hole 1 terminated just short of the bands of events highlighted in Case 4 of Section 4.2.3. This, coupled with the lack of data for Hole 1, meant that this example of banding of events could not be investigated using video camera data.

Figure 4.41 3D view of open holes at Mine B facing two different directions. Events shown in grey.
4.3.1 Methodology

The videos of the monitoring holes were reviewed and the depth of the cave back, when visible, was recorded. An example of the cave back from the videos is given in Figure 4.42. At times the hole was blocked by rocks or because the shear movement along a fracture had made it impossible for the camera to pass. These locations were recorded as dislocations and are illustrated in Figure 4.43A and Figure 4.43B respectively. Significant shear movement along fractures were also recorded, an example of which is given in Figure 4.44. Due to limitations with a video down a single linear borehole, fractures that form in extension are virtually impossible to identify and, as such, were not included in the analysis.

![Figure 4.42](image1.png) Example of cave back in open hole video

![Figure 4.43](image2.png) Examples of dislocations through shearing of the hole (A) and rocks blocking the borehole (B)
To make conclusions about the caving behaviour, the open hole video camera readings were examined along with the events which were within 25 m of the borehole. An example of the events within 25 m of Hole 2, Mine B is shown in Figure 4.45.
The elevation of the readings from the video camera surveys were examined along with the events on a date-elevation scatterplot. The median elevation of events in a 7 day time window, centred on the current date, was also plotted. The scatterplots allowed for observation of how the cave was progressing upwards and the fracturing ahead of the cave over time.

4.3.2 Mine B

4.3.2.1 Hole 1

Hole 1 only intersected the cave for a short length and had few video surveys. As a result, very few observations could be made and those that could be made were a long distance from the cave, as shown in Figure 4.46. Due to the lack of data, no conclusions could be made using Hole 1.

![Figure 4.46 Open hole video readings from Hole 1 (Mine B)](image)

4.3.2.2 Hole 2

Hole 2 also had a limited dataset; however, the readings made were within the caving area. A 3D view of the readings from Hole 2 can be seen in Figure 4.47.
An elevation-date scatterplot is given in Figure 4.48. While the small number of readings limits the value that can be extracted, it is interesting to note that there are some events occurring below the cave back, illustrated in purple in Figure 4.48B. While there are relatively few events below the cave in Hole 2, there are more in other holes from Mine B. There are a number of potential explanations for the events being located here. These include poor location of the events, events occurring within the caved zone due to comminution, or that a beam has formed creating a cave back under which the solid beam is failing.

Despite three cave back readings from Hole 2, there were no observations of shear damage ahead of the cave back. This indicates that there is no significant, continuous increase in damage close to the cave back.
Figure 4.48  Open hole video camera readings and events over time (Mine B, Hole 2)
4.3.2.3 Hole 3

As shown in Figure 4.49, only a single reading could be made for hole 3, again limiting the number of conclusions that can be made.

![Figure 4.49 Open hole video readings from Hole 3 (Mine B)](image)

The single reading for Hole 3 is the cave back and, as shown in purple in Figure 4.50, there are a more significant number of events which occurred beneath the cave back. There was also no shear damage ahead of the cave back to indicate that the damage profile is continuous.
Figure 4.50  Open hole video camera readings and events over time (Mine B, Hole 3)

4.3.2.4 Hole 4

The readings for Hole 4 are shown in Figure 4.51. As can be seen, Hole 4 has the largest number of readings for Mine B.
Despite multiple readings of dislocations, there was only a single reading of the cave back for Hole 4. Due to the limited number of readings of shear failure, along with the single cave back reading, it is not possible to ascertain the fracturing profile with any confidence. There is, however, another example of a number of events locating underneath the cave back (shown in purple in Figure 4.52).
Figure 4.52  Open hole video camera readings and events over time (Mine B, Hole 4)
4.3.3 Mine A

4.3.3.1 Hole 1

The readings from the single available hole at Mine A, along with the events and the hole itself, can be seen in 3D in Figure 4.53.

Figure 4.53 Open hole video readings from Hole 1 (Mine A)

Figure 4.54 shows the elevation of the open hole video camera readings, along with the events and median elevation of events over time. There are three distinct time periods with different caving activity, labelled with numbers on the figure.
In Period 1, the early period of cave development, there are multiple readings of the cave back, as shown in Figure 4.55. The cave back advances slowly in this period, with a moderate number of events locating above the cave back. There are few shear fractures ahead of the cave in this period and no indication of a continuous damage profile ahead of the cave. The microseismicity in this period was strongly related to blasting. The data makes it unclear as to what caving mechanism is occurring during Period 1; however, it could be attributed to localised rock mass degradation due to stress change from undercut blasting.
The caving behaviour in Period 2 (seen in Figure 4.56) showed a significant change from Period 1. The cave back could not be identified in this period due to a number of dislocations in the borehole. If the change in elevation of the events and dislocations is used as a proxy for the change in elevation of the cave, it is clear that the cave back progressed upwards at a far more significant rate than in Period 1. Over Period 2, the proxy for cave movement advances by about 170 m in 11 weeks (approx. 2.3 m/day), compared to a cave advance of about 40 m in 11 months during Period 1 (approx. 0.1 m/day). Another significant change in this time period is that there are very few microseismic events occurring, despite the rapid cave growth. This suggests that the cave is growing via a mechanism which involves less fracturing of rock such as banding behaviour. While it is not always clear due to the time between readings and the dislocations, it appears that the cave may be progressing through a series of large jumps of 30 - 80 m in height, with very little shear damage in the intervals between jumps. Based on these observations, it appears that the cave is most likely propagating via a banding mechanism.
There were a number of trial stopes present in the area through which the cave propagated in Period 2. These stopes may have contributed to the lack of seismicity and potential ‘jumps’ in the cave back, however, as can be seen in Figure 4.57, the height of the stopes is small (approximately 40 m) in comparison to the change in cave elevation over this period. As a result, it is likely that the stopes were a small contributor, but not the controlling factor in cave behaviour during Period 2.
The caving propagation in Period 3 exhibits a change from that of Period 2. There are a significant number of shear fractures, whose frequency increase closer to the dislocations. There are also significantly more events than in Period 2. All of this behaviour, highlighted in blue in Figure 4.58, correlates well with the Duplancic conceptual model of caving.

At the beginning of Period 3, there appears to be a transition in mechanism from the banding behaviour of Period 2 to the Duplancic behaviour of Period 3 (highlighted in red in Figure 4.58). There is an increase in the number of events and shear fractures close to the dislocations, indicating a shift towards a Duplancic mode of failure. The upward progression of the dislocations also appears to progress as a smoother, continuous progression that one would expect from the Duplancic conceptual model.
Figure 4.58  Open hole video camera readings and events over time (Mine A, Hole 1, Period 3)

Figure 4.59 gives a moving average of fracture frequency for increasing distance to the dislocation, which is the maximum accessible depth of the hole at that time. The large maximum in fracture frequency near the dislocation, along with the smooth decline with increasing distance from the dislocation indicates that the damage profile is continuous and matches well with the Duplancic conceptual model of caving.
4.3.4 Open hole video camera monitoring summary

Mine B

While there was limited data available for Mine B, there were multiple examples of events locating below the cave back, indicating a caving mechanism not captured by the Duplancic model. There were no indications that the damage profile is continuous, however the limited number of observations of shear fractures makes it difficult to determine definitively.

Mine A

There was only a single hole available for analysis at Mine A. There were three distinct periods with different caving behaviour. Table 4.1 summarises the mechanisms interpreted from observations from the video camera surveys of Hole 1.
Table 4.1  Summary of caving mechanisms for Mine A, Hole 1

<table>
<thead>
<tr>
<th>Period</th>
<th>Interpreted Caving Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Localised rock mass degradation due to stress change from undercutting</td>
</tr>
<tr>
<td>2</td>
<td>Banding style behaviour</td>
</tr>
<tr>
<td>3</td>
<td>Duplancic style behaviour</td>
</tr>
</tbody>
</table>