5 Discussion of Numerical Modelling

5.1 Introduction

The results of the physical model provided a unique opportunity for the testing, validation and improvement of numerical modelling approaches. Numerical models of physical modelling Test 4 were undertaken by staff from Itasca Consulting Group (Tryana Garza-Cruz, Lauriane Bouzeran and Matthew Pierce). The numerical models were performed before the materials testing of the physical modelling material was conducted and a number of assumptions on the strength of the material had to be made.

Comparing the results of the physical models with the numerical models highlights the different strengths and weaknesses of the approaches used and also reveals some interesting insights into the potential fracturing mechanisms. An in depth validation and subsequent improvement of the modelling approaches is outside the scope of the project.

5.2 Approaches used

Two different approaches were used: the Itasca Caving Algorithm approach and a Bonded Block Model (BBM) approach. The Itasca Caving Algorithm, developed as part of the International Caving Study and Mass Mining Technology projects, implements the CaveHoek constitutive model in a continuum-based software, along with a set of functions to control draw. The CaveHoek constitutive model involves using strain-softening and strain-dependent material properties to represent caving behaviour. More details on the Itasca Caving Algorithm can be found in Board & Pierce (2009). The BBM approach involves representing the rock mass as a series of tetrahedral blocks with bonds at the contacts between blocks. In this modelling approach, the material behaviour is not explicitly specified. Instead, the properties of the bonds are altered to change the emergent macro material properties and behaviour. More detail on the BBM approach can be found in Garza Cruz and Pierce (2014). The BBM models were implemented in the discontinuum code 3DEC (Itasca Consulting Group 2016a) and the Itasca Caving Algorithm models were implemented in the continuum code FLAC3D (Itasca Consulting Group 2016b).
5.3 Inputs

5.3.1 Stress, dimensions and boundary conditions

The same stress, dimensions and boundary conditions were used in both the 3DEC BBM models and FLAC3D Itasca Caving Algorithm models.

- Stress: The stresses were initialised to be equal to the theoretical stress distribution (as seen in Figure 3.3), with 80 g acceleration in the z-direction and 1 g in the y-direction. The non-body forces were applied on the boundaries of the sample.

- Dimensions: As 3DEC and FLAC3D are three-dimensional software packages, the dimensions of the samples and pistons could be represented exactly (see Section 3 for details).

- Boundary conditions: Four sides of the sample were fixed in the X and Y direction but free to move in the vertical direction. The top of the sample was free and the bottom of the sample completely fixed. The boundary conditions are shown in Figure 5.1 and Figure 5.2.

In both modelling approaches, the cave draw though piston retraction was implemented to represent the physical test, although this was done in different ways. The fundamental difference between the two approaches centres around the way the material behaviour is modelled.
Figure 5.1  Boundary conditions – Section view (from front/back)

Figure 5.2  Boundary conditions – Section view (from side)
5.3.2 3DEC – BBM model

- Elements: The elements were tetrahedral, with an edge length of 10 mm. A three-dimensional view of the elements in the BBM model, along with the co-ordinates system, is given in Figure 5.3.

![Tetrahedral elements in BBM model](image)

**Figure 5.3** Tetrahedral elements in BBM model

- Draw: The pistons were represented explicitly in the model and the data from the LVDTs attached to the pistons was used so that the exact movement of the pistons could be replicated numerically.

- Joints: The joints were modelled implicitly as part of the material. The joint pattern in the physical model was semi-random and it was assumed that the randomly assigned
variations in contact strength would result in a sufficient approximation of the joint pattern.

- Material properties: The same UCS values were used for the 3DEC model as the FLAC3D model (1 and 0.75 MPa). In the BBM approach, the material is made up of a series of blocks which are bonded by contacts. The micro scale bond and contact strengths are assigned values such that the emergent macro scale properties of the modelled material are equal to the assumed values. The emergent macro scale properties are usually determined through the use of a numerical simulation of a UCS test. The process of assigning micro scale properties requires the shape of the contact tensile strength distribution to be assumed. The material properties for the model are summarised in Table 5.1. The assumed distributions of contact tensile strength for both 3DEC models are given in Figure 5.4. An example of the element contacts coloured by tensile strength for Model 2 is given in Figure 5.5.

Table 5.1 Material properties: 3DEC – BBM models

<table>
<thead>
<tr>
<th></th>
<th>Model 1</th>
<th>Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Block Properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>400 kPa</td>
<td>400 kPa</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Density</td>
<td>1877 kg/m³</td>
<td>1877 kg/m³</td>
</tr>
<tr>
<td><strong>Contact properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal stiffness</td>
<td>7.25 GNm/m²</td>
<td>7.25 GNm/m²</td>
</tr>
<tr>
<td>Shear stiffness</td>
<td>3.62 GNm/m²</td>
<td>3.62 GNm/m²</td>
</tr>
<tr>
<td>Peak friction angle</td>
<td>30°</td>
<td>30°</td>
</tr>
<tr>
<td>Residual friction angle</td>
<td>30°</td>
<td>30°</td>
</tr>
<tr>
<td>Dilatancy angle</td>
<td>30°</td>
<td>30°</td>
</tr>
<tr>
<td>Peak tensile strength</td>
<td>Varied randomly based on distribution in Figure 5.4</td>
<td>Varied randomly based on distribution in Figure 5.4</td>
</tr>
<tr>
<td>Residual tensile strength</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Peak cohesive strength</td>
<td>2.5 x tensile strength</td>
<td>2.5 x tensile strength</td>
</tr>
<tr>
<td>Residual cohesive strength</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Emergent rock properties</strong></td>
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<td></td>
</tr>
<tr>
<td>UCS</td>
<td>0.75 MPa</td>
<td>1 MPa</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>325 MPa</td>
<td>325 MPa</td>
</tr>
</tbody>
</table>
The failure envelopes of the 10th, 50th and 90th percentiles of the tensile strength distribution are shown in Figure 5.6 (Model 1) and Figure 5.7 (Model 2). The tensile strength distribution is shown in pink for reference.
Figure 5.6  Failure Envelope: Model 1 – 0.75 MPa

Figure 5.7  Failure Envelope: Model 2 – 1 MPa
5.3.3 FLAC3D – Itasca caving algorithm model

- **Draw:** A low velocity was applied at the bottom of the sample at the position of each piston to simulate the movement of each piston. The magnitudes of the velocities applied were scaled to replicate the relative displacement of each piston measured by the LVDTs. The model geometry and simulated pistons are illustrated in Figure 5.8.

![FLAC3D model geometry and pistons](image)

**Figure 5.8** FLAC3D model geometry and pistons

- **Joints:** The joints were modelled implicitly as part of the material. They were taken into account through the use of a GSI of 90.

- **Material properties:** Two different assumed UCS values were tested. At the time of the numerical modelling, only the wet density of the sample was known and this value was used. The values of GSI, $m_i$, intact Young’s Modulus, Poisson’s ratio, critical plastic shear strain, residual cohesion and residual friction angle were assumed based on experience. The tensile strength of the material was assumed to be approximately 3% of the intact UCS. The values used for the two FLAC3D models are given in Table 5.2.
Table 5.2 Input parameters for Itasca Caving Algorithm – FLAC3D models

<table>
<thead>
<tr>
<th></th>
<th>Model 3</th>
<th>Model 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{CS_i}$</td>
<td>0.75 MPa</td>
<td>1 MPa</td>
</tr>
<tr>
<td>GSI</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>$m_i$</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Intact Young’s Modulus</td>
<td>325 MPa</td>
<td>325 MPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Density</td>
<td>1877 kg/m³</td>
<td>1877 kg/m³</td>
</tr>
<tr>
<td>Tensile Strength</td>
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<td>31 kPa</td>
</tr>
<tr>
<td>$U_{CS_{rm}}$</td>
<td>459 kPa</td>
<td>611 kPa</td>
</tr>
<tr>
<td>Critical plastic shear strain</td>
<td>2.8%</td>
<td>2.8%</td>
</tr>
</tbody>
</table>

5.4 Results

5.4.1 3DEC – BBM model

The results of the 3DEC BBM model using a UCS of 0.75 MPa are shown in Figure 5.9 and Figure 5.10. The shape of the failure zone in both BBM models matches that of physical modelling Test 4 relatively well. The lateral extents of the failed zone match the physical model particularly well. The vertical extents of the failure zone are somewhat smaller than those seen in the physical model and may be due to the high UCS value assumed in the numerical model. The numerical model indicates more small scale fracturing when compared with the larger fractures seen in the physical model. These smaller scale fractures appear to form in a ‘fracture zone’ which is parallel to the cave surface. Interestingly, the small fractures themselves appear to be oriented primarily in an orientation perpendicular to the cave surface. This contrasts with the larger fractures perpendicular to the cave seen in the physical model. The ‘fracture zones’ are at times alternated with zones with less damage, creating a discontinuous damage profile similar to that seen in the physical models. This is illustrated in Figure 5.13. The cave also appears to progress vertically through ‘jumps’ to successive damage zones in a manner similar to the physical model. The results of the 3DEC BBM model using a UCS of 1 MPa (shown in Figure 5.11 and Figure 5.12) show a similar caving behaviour to that of the 0.75 MPa model, albeit with slightly smaller failure zones. After querying the failure mode of the contacts, the model indicates that a large portion of the fractures created are nucleated in shear and subsequently propagate in tension. While the mode of fracture initiation in the physical models could not be determined with certainty, there were indications that the fractures formed and propagated in extension.
Figure 5.9  Results of 3DEC BBM Model 1: UCS = 750 kPa (part 1)  
NOTE: physical and numerical model results not to the same scale
Figure 5.10  Results of 3DEC BBM Model 1: UCS = 750 kPa (part 2)
NOTE: physical and numerical model results not to the same scale
Figure 5.11 Results of 3DEC BBM Model 2: UCS = 1 MPa (part 1)
NOTE: physical and numerical model results not to the same scale
Figure 5.12  Results of 3DEC BBM Model 2: UCS = 1 MPa (part 2)
NOTE: physical and numerical model results not to the same scale
Figure 5.13  Example of discontinuous damage in 3DEC model

5.4.2  FLAC3D - Itasca caving algorithm model

Figure 5.14 and Figure 5.15 give the z-displacement results of the FLAC3D models at different stages of cave propagation for the 0.75 and 1 MPa UCS models respectively. Based on visual observations, it appears that the geometry of the cave in the 0.75 MPa model matches better with the physical model than the 1 MPa model, however neither matches as well as the results of the 3DEC models. In both the 0.75 and 1 MPa FLAC3D models, the cave appears to stall towards the end of the test, which was not the case in the physical model. This may be attributed to the high assumed value of UCS used. No discontinuity is seen in the z-displacement results which may be attributed to the continuum code modelling approach not allowing discontinuous behaviour.

Interestingly, the plastic shear strain results (shown in Figure 5.16 and Figure 5.17) show shear localisation. Distinct shear bands form and propagate ahead of the cave. The shear bands form progressively, with multiple bands propagating simultaneously. The vertical extent of the shear bands is significantly larger than the parallel fractures seen in the physical model. While the shear bands do not explicitly represent failure in the models, this result does suggest that the Caving Algorithm model may be over-predicting the height of the failure zone. This over prediction cannot be regarded as indicative of the accuracy of the modelling process, as the match may be improved by using improved material parameters.
Figure 5.14  Z-Displacement - FLAC3D Caving Algorithm Model 3: UCS = 750 kPa
NOTE: physical and numerical model results not to the same scale
Figure 5.15  Displacement - FLAC3D Caving Algorithm Model 4: UCS = 1 MPa
NOTE: physical and numerical model results not to the same scale
Figure 5.16  Plastic shear strain - FLAC3D Caving Algorithm Model 3: UCS = 750 kPa
Both numerical approaches showed strengths and weaknesses when simulating the numerical test. In the 3DEC-BBM models, the fractures tended to concentrate in bands, creating discontinuous damage zones similar to the parallel fractures from the physical model. The cave also appeared to progress through ‘jumps’ to the next successive damage zone. The models were also able to recreate the cave shape relatively well, in particular the lateral extents of the cave. The size and orientations of the fractures created did not match as well with the physical model. The BBM models indicated smaller scale fracturing oriented primarily perpendicular to the cave back (concentrated into damage bands parallel to the cave back).

Figure 5.17  Plastic shear strain - FLAC3D Caving Algorithm Model 4: UCS = 1 MPa

5.5 Numerical modelling discussion and conclusions
The cave geometry in the FLAC3D-Itasca caving algorithm models did not match the physical model as well as the BBM. The caving process was more continuous, attributed to the bias towards continuum behaviour implicit in the continuum code FLAC3D. The models do, however, capture some of the discontinuous nature of the failure process from the physical models through the shear bands seen in the plastic shear strain plot. The shear bands formed simultaneously ahead of the cave in a manner similar to the physical model. While the FLAC3D software cannot explicitly model the formation of fractures, localised shear damage zones emerge in the model.

An important aspect of the comparison between in the physical and numerical models is in the underlying failure mechanisms. The material models used are based on Mohr-Coulomb/Hoek-Brown failure criteria. As such, they can only represent shear or tensile failure and are not capable of explicitly representing extensional failure. The failure mode seen in the Itasca Caving Algorithm – FLAC3D model, is more reminiscent of the shear bands formed in weak, low dilatancy materials described by Barton (1993) and Crook et al. (2003) (Figure 5.18).

![Figure 5.18](image)

**Figure 5.18**  Left: Failure zones from boreholes in sandstone (Addis et al. 1990) Centre: shear bands from borehole breakout in black shale (Meier et al. 2013) Right: Plastic shear strain from Itasca Caving Algorithm – FLAC3D model

Inspection of the failure mode of the element contacts in the BBM model revealed that the majority initiated in shear and propagated in tension. The fracture pattern observed resembles the fracture pattern of families of shear cracks creating spiral rupture surfaces seen in numerical models of a circular shaft by Lisjak et al. (2014). The fractures tend to develop at an angle of 45° to the maximum principal stress. The similarities between the two fracturing patterns are illustrated in Figure 5.19.
In contrast with this, the initiation and propagation mechanism of fracturing in the physical models appeared to be extension. The PIV results indicate that the direction of movement is perpendicular to the fracture orientations. Additionally, the fracturing pattern observed in the physical models is similar to the axial splitting in strong, brittle materials described by Crook et al. (2003). This mode of borehole breakout (illustrated in Figure 5.20) occurs through extensional fracturing. A number of studies detailed in the literature review (Chapter 2) describe similar fracture patterns forming in tension/extension. Unfortunately the frequency of photographs taken during the physical modelling was not fast enough to determine the fracturing mechanism with complete certainty.

The fracturing patterns of the shear bands in the continuum model and the fracture pattern emerging from the preferential fracture orientation in the BBM model is similar to the patterns...
observed for known shear failure mechanisms. The fracturing pattern observed in the physical model is more akin to that from known extensional fracturing. From the differences in the fracture patterns observed (illustrated in Figure 5.21), we can conclude that the numerical models may not be fully capturing the mechanism seen in the physical models and that the material models could be further improved by including failure through an extensional mechanism.

![Figure 5.21](image)

**Figure 5.21** Schematic of observed fracture patterns

It is important to note that adjusting or calibrating the model to improve the match between the numerical and physical models was outside the scope of the project. It is possible that some of the limitations of the model could be overcome with adjustment of the modelling approach, input parameters and material model used.
6 Development of Extended Conceptual Caving Model

The currently accepted conceptual model of caving, the Duplancic (2001) model, implies a continuous damage profile ahead of the cave. This thesis presents evidence from a number of different sources – including literature, physical modelling, microseismicity and open hole video camera monitoring – that the damage profile ahead of the cave can at times be discontinuous. This creates a requirement for an extension to the Duplancic conceptual model of caving.

As mentioned in Section 3.8, the samples tested as part of the physical modelling programme progressed both vertically and laterally via a series of ‘jumps’ to successive fractures parallel to the cave surface. For convenience, this mechanism of caving, consisting of a series of fractures ahead of and parallel to the cave back, will be referred to as fracture banding.

This chapter will explore the different characteristics of fracture banding and create an extended conceptual model of caving which can better account for this caving mechanism.

6.1 Fracture banding

6.1.1 Discontinuity of damage profile

Based on classical rock mechanics, one would expect increasing maximum principal stress and reducing confinement closer to the excavation surface (Kirsch 1898). Most failure criteria will predict continuously increasing damage under this stress regime. However, a number of authors have studied the process of zonal fracturing around deep mine tunnels and tabular stopes, which clearly have a discontinuous damage profile (Adams & Jager 1980; Shemyakin et al. 1986a, 1986b; Jia et al. 2012). Examples of this phenomenon are given in Figure 6.1 and Figure 6.2. The alternating pattern of fractured zones with unfractured zones closely resembles that of fracture banding. While the mechanism of failure in these cases may not be the same as that of fracture banding, the observations of a discontinuous damage profile lend credence to the idea that the damage profile around excavations can be discontinuous.
The mechanism of fracture banding was observed in all of the physical modelling tests which caved. An example of fracture banding occurring in Test 4 is shown in Figure 6.3. The cave surface at each point in the test is shown as a dashed green line and the previous cave surfaces are outlined in solid red lines. The cave ‘jumps’ to the next successive parallel fracture without any significant damage in between. The parallel fractures can also be seen forming ahead of the face (Figure 6.3D-F). This created a clearly discontinuous damage profile ahead of the cave, illustrated in Figure 6.4.
Figure 6.3  Example of cave propagation via fracture banding
The discontinuous damage profile of fracture banding bears strong resemblance to the results of many of the studies detailed in the literature review (Chapter 2). Panek (1981) and Sharrock et al. (2002) both observed a series of widely spaced fractures ahead of the cave boundary, implying a discontinuous damage profile. While there were a limited number of observations, Carlson and Golden (2008) also observed discontinuity in the damage in the cave periphery. There were also a number of studies using numerical modelling which gave results showing a discontinuous damage profile (Vyazmensky et al. 2007; Lisjak et al. 2012; Li et al. 2014), although they did not specifically mention the damage profile. Physical models of cave mining (McNearny & Abel 1993) and sinkhole propagation (Nishida et al. 1986) exhibited a series of fractures alternated with zones of minimal damage, again indicating a discontinuous damage profile.

A discontinuous damage profile was also revealed through the analysis of microseismicity given in Section 4.2. Multiple cases were found in which there was a series of zones of microseismic events alternated with zones with a lack of microseismic events. As mentioned previously in Section 4.2.3, it is unclear whether the banding behaviour presents itself as zones
because there are zone of fractures forming and coalescing, or if the bands are large individual fractures which present as zones due to scatter in source location. In the analysis of open holes (Section 4.3), there were observations that implied the cave was growing almost aseismically. This indicates that the cave may have been growing via a low energy release mechanism during this time period.

The analysis of open hole video camera monitoring also gave strong indications of a discontinuous damage profile, particularly at Mine A, where there was a period that included significant ‘jumps’ in the dislocations of the hole along with a lack of shear damage ahead of said dislocations (Section 4.3.3.1). This indicates that the elevation of the damage is ‘jumping’, creating a discontinuities damage profile.

Examples of some of the sources expressing discontinuous damage profiles in both caving and other mining contexts are shown in Figure 6.5. There are strong similarities in Figure 6.5A-D in the series of alternating fractures and undamaged zones ahead of the cave. The plan view of the cave in Figure 6.5E also bears a strong resemblance to the zonal fracturing around a tunnel in Figure 6.5G, as the series of fractures and unfractured zones take a circular shape around the excavation periphery.

The observations of a discontinuous damage profile ahead of the cave back detailed above are both numerous and from a diverse range of sources, lending credibility to the idea that the damage profile ahead of the cave in block caving mines can be discontinuous in some cases.
CAVING

Figure 6.5 Different examples of discontinuous damage profiles
The mechanism of fracture banding, illustrated in Figure 6.6, is a process whereby the cave propagates via a series of ‘jumps’ to successive fractures or fracture zones ahead of the cave.

Several fractures can form ahead of the cave back. The resulting damage profile is discontinuous, with peaks at the fractures or fracture zones. One would expect a gradual increase in damage between peaks, as the maximum and intermediate principal stresses increase and confinement is reduced closer to the cave back. The discontinuous damage profile of fracture banding is shown in Figure 6.7 and the continuous damage profile of the Duplancic conceptual model in Figure 6.8.
Figure 6.7  Illustration of discontinuous damage profile associated with fracture banding

Figure 6.8  Illustration of continuous damage profile associated with Duplancic conceptual model of caving
6.1.2 Timing of progression

When considering the progression of the parallel fractures/fracture zones in the fracture banding mechanism, the relative timing of the formation of these fractures needs to be investigated.

As the cave in the physical model expanded, the new parallel fracture would form ahead of the previous parallel fracture or cave back. However there were multiple instances where a fracture would form ahead of the cave back and a new fracture would subsequently form between the first fracture and the cave back. This is illustrated in Figure 6.9.

![Figure 6.9](image)

**Figure 6.9** Fracture forming ahead of cave back (A) and fracture being created between this fracture and the cave back in the next photograph (Test 2)
It is possible that a beam has formed between the parallel fractures and the cave back and the beam has subsequently failed in extension. This is further illustrated in Figure 6.10, where a potential beam has formed along with a crack which could be indicating failure of the beam. The findings of Szwedzicki et al. (2004) could provide support for this idea, as they found multiple breaks in TDR cables across a large area, suggesting that a beam may have formed over this area.

Figure 6.10  Potential beam from physical modelling (Test 5)
Due to the limits on the speed of the still camera (4 fps) and quality of the video cameras, the exact timing of events was often unclear and so it was difficult to determine if multiple parallel fractures were forming simultaneously.

Multiple bands were found to be active at the same time in the analysis of microseismicity (outlined in Section 4.2.3.6). At times, up to four bands had active microseismicity simultaneously. An example of the relative timing of the bands is shown in Figure 6.11. The peaks in activity rate differ for each band; however, there is still significant overlap in activity, indicating that one band is still active as another begins to form. This forms a repeating process where, as fractures or fracture zones mature, conditions change and new fractures begin to form.

![Figure 6.11 Activity rate of bands of microseismicity (Mine A – Case 1). Each band shown in a different colour](image)

From the evidence seen in the microseismicity, it can be concluded that the fractures or fracture zones created in fracture banding can be at different stages of maturity, but developing at the same time.
6.1.3 Shape

Another factor to assess as part of the caving mechanism of fracture banding is the shape of the fractures or fracture zones created.

The fractures created in the physical models are created in an orientation parallel to the cave back, at some distance from the boundary (as detailed in Section 3.8). As the cave boundary is curved, the fracture banding process creates a series of curved fractures.

A number of the examples from literature which showed a discontinuous damage profile had fractures which were aligned with the excavation surface. Panek (1981) found a roughly circular fracture zone around the periphery of the cave and posited that this would exist above the cave crown, while Sharrock et al. (2002) found fractures parallel to the excavation surface. The results of the numerical modelling studies (Vyazmensky et al. 2007; Lisjak et al. 2012; Li et al. 2014) and physical modelling (McNearny & Abel 1993; Nishida et al. 1986) also showed curved fractures created parallel to the cave surface.

The bands of microseismic events shown in Section 4.2.3 also follow the shape of the cave boundary. In Cases 1 and 5, in which the bands of events were in the crown of the cave, the shape bands are present as sub-horizontal and curved. Case 2 is in the crown of the cave, however the interpretation of the cave back from site indicates a very steep crown and the bands have a more vertical appearance, again lining up with the interpreted cave boundary. Cases 3 and 4 are in the cave periphery and the bands take a more vertical, linear shape as they follow the boundary of the cave.

Some examples from different sources of curved fractures in both the crown and periphery of the cave parallel to the excavation surfaces are shown in Figure 6.12 and Figure 6.13 respectively.
Figure 6.12  Examples of curved shape of fractures in crown of caves, fractures highlighted in red

Figure 6.13  Examples of curved shape of fractures in periphery of caves, fractures highlighted in red
As expressed by Panek (1981), the fractures should extend around the cave in three-dimensional space. The physical modelling conducted and most of the studies examined in the literature review were two-dimensional, not allowing any insight into the three-dimensional shape of the fracturing. The open hole video surveys, which give only linear data, also cannot give any insight. The results of the analysis of microseismic monitoring, while giving indications that the bands may exist as surfaces, are far from conclusive. More research on how the fractures develop in three-dimensions is needed.

There is significant evidence from multiple sources intimating that the fractures formed in the fracture banding process are created in an orientation parallel to the cave surface. In the crown of the cave this takes a sub-horizontal, curved character and in the cave periphery the fractures shift to a more vertical orientation.

### 6.1.4 Spacing

Fracture banding consists of a pattern of bands fractures or fracture zones, spaced by zones of undamaged rock mass. The spacing of these bands is an important aspect of fracture banding, as it can affect the rate of cave propagation and the primary fragmentation of the ore.

There was some small variation of the spacing of the fractures in the physical models. The variation between different tests was small; however, it was still larger than the spacing within each test, which was consistent. The spacing is illustrated in Figure 6.14 which includes arrows of equal length. The spacing between almost all of the fractures is approximately equal, with the final fracture being the only exception with a slightly shorter spacing.
Only two of the studies which described a discontinuous damage profile made specific mention of the spacing of the fractures. Panek (1981) and McNearny and Abel (1993) both made observations that the spacing of the fractures was consistent. While the spacing was not addressed, the figures given in a number of other studies also indicate a consistent fracture spacing (Nishida et al. 1986; Vyazmensky et al. 2007; Lisjak et al. 2012; Li et al. 2014). An example of the consistency of spacing seen in the literature is given in Figure 6.15.

Figure 6.15  Example of consistent spacing seen in literature. Spacing denoted by green arrows of equal length (after Nishida et al. 1986)
It is difficult to determine fracture spacing based on the analysis of microseismicity for a number of reasons. Cases 3 and 5 only included a single ‘jump’, giving only a single measurement of spacing. Another issue is that, as discussed in Section 4.2.3, the bands do not present as distinct lines, but as zones. This can make the edges of the zones and, in turn, the band spacing more difficult to distinguish.

The spacing between different bands within each case was relatively consistent. This is illustrated in Figure 6.16, where the spacing is indicated by green arrows of equal length. The one exception to this was in Case 4, in which the spacing did vary to some degree. This is shown in Figure 6.18, where the spacing between the first three bands was consistent (shown by green arrows of equal length), the next band had a wider spacing (shown by a blue arrow) and the final band had a tighter spacing (shown by a pink arrow).

The spacing of bands between different cases was also consistent, with the exception of Case 5 which had a much larger spacing. The development of Case 5 also took place over a much longer period of time. Approximate measures of spacing for each case are given in Table 6.1. While there is remarkable consistency in the spacing of Cases 1-4, more evidence would be needed to confirm that the spacing is a consistent characteristic of the phenomenon.

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<th>Case</th>
<th>Approximate Spacing (m)</th>
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<td>20</td>
</tr>
<tr>
<td>5</td>
<td>100*</td>
</tr>
</tbody>
</table>

* As only 2 bands were present, only a single ‘jump’ occurred, reducing the confidence in the spacing
Figure 6.16  Case 1 showing consistent spacing of bands. Spacing indicated by green arrows of equal length, bands highlighted in red.

Figure 6.17  Case 4 showing variation in spacing of bands with regular spacing (green arrows), wider spacing (blue arrow) and tighter spacing (pink arrow). Bands highlighted in red.
In the physical modelling results, some of the fractures terminated at the edge of the pistons, which could give the impression that the fracture banding phenomenon is created purely as an artefact of the testing approach. A more detailed analysis of the pictures does not, however, support this view. As shown in Figure 6.18, while there are some fractures that align with the edge of pistons (highlighted in red), there are also a number of fractures that do not (highlighted in orange). In the same test, there are also a number of fractures which appear to have initiated away from the pistons; however, the orientation of the fractures appears to deviate towards the edge of the pistons as they approach the bottom of the sample. This is illustrated in Figure 6.19 where the fracture orientations are influenced by the pistons only below the dashed red line. This confirms that, while it is possible that the piston width affected the specific point at which the fractures terminated, the series of fractures was not initiated due to the piston width.

![Figure 6.18](image_url) Fractures aligning with edge of pistons (solid red lines) and those that don’t (dashed orange lines). Physical modelling Test 6
Figure 6.19 Fractures initiating without influence of pistons and orientations deviating towards the edge of the pistons below dashed red line. Physical modelling Test 6

There are also a number of cases across multiple tests in which the bands of fractures formed at an elevation significantly above the ‘undercut’ and at a point in the testing when the ‘undercutting’ procedure would not influence the fracturing pattern evolved. An example of two such fractures is given in Figure 6.20.
Based on the results from the physical modelling, analysis of microseismicity and from literature it appears that the spacing of the fracturing is consistent under similar conditions.

6.1.5 Influence of mine scale geological features

Mine scale geological features, such as faults and contacts, can have a significant effect on the propagation of the cave, including propagation through fracture banding. Better understanding of the impact that these features have on cave growth allows for improved planning and operations of cave mining.

In the physical modelling, the large pre-existing fractures created discontinuities similar to these mine scale geological features. The pre-existing fractures bounded the extent of growth of the parallel fractures at times. This is illustrated in Figure 6.21 as the parallel fractures in red are bounded by the pre-existing fractures in blue. The areas in which the fractures did not cross the boundary are highlighted in orange.
6.2 Mechanism of fracture generation

Understanding the origin mechanism of the fractures created as part of fracture banding plays a significant role in the understanding of how the cave progresses and under which conditions fracture banding can occur.

The only method that could be used to determine the origin mechanism of the fractures from the physical modelling was the use of visual data. Based on observations from the raw photographs and the displacement vectors from the PIV, it appears that the first direction of movement was perpendicular to the fracture plane. This indicates that the source mechanism of the fractures is extensional. An example of this movement in the raw photographs and PIV results are shown in Figure 6.22 and Figure 6.23 respectively.
The DSLR camera could only take a maximum of four photographs per second. This interval was too large and the resolutions of the web cameras used were too low to determine the origin mechanism of the fractures with a high degree of confidence. A failure mechanism in which the fractures form in shear and subsequently open in extension cannot be ruled out; however, there is no evidence from the physical modelling that this is the case.

The fracture pattern generated in the physical model is similar to the axial splitting borehole breakout mechanism described by Crook et al. (2003). This mode of extensional failure was found by Crook et al. to occur in strong, brittle materials. The similarities between the fracture patterns are a further indication that the fractures generated in fracture banding are extensional.
The literature review details a number of authors that made observations of tensile and extensional fractures ahead of the cave (Heslop 1976; Panek 1981; Sharrock et al. 2002; Carlson & Golden 2008). Reyes-Montes et al. (2010a) and Tibbett et al. (2016) both discovered tensile fracturing sub-parallel to the cave back using a variety of methods, including analysis of microseismicity and numerical modelling. This is supplemented by Garza Cruz and Pierce (2014), who showed the development of tensile failure sub-parallel to the cave back in a numerical model simulating caving conditions. This evidence from the literature, along with that of the physical modelling, indicates that fractures with an extensional origin mechanism are occurring in caving mines.

The analysis of source parameters from the bands of microseismicity (Section 4.2.5) was inconclusive and could not be used in determining the origin mechanism of fracturing.

There are also a number of cases in the literature of indications of shear failure in caving, particularly from microseismic data, most notably the work of Duplancic (2001). Details of these cases are given in Section 2.3.

The results of the 3DEC-BBM model of the physical model indicated that the majority of fractures generated were initiated in shear and propagated in tension. It is important to note, however, that the material model used cannot explicitly simulate failure in extension.

The evidence presented indicates that both extensional and shear failure are present in caving mines. This conclusion is supported by the analysis of the open hole monitoring (Section 4.3). The monitoring, in particular that from Mine A, indicated that there were periods of caving with significantly different caving mechanisms, which may be linked to different origin mechanisms. In Period 3, there was an abundance of shear fractures forming, whereas in Period 2 there were almost no shear fractures observed.

### 6.3 Expanded conceptual model of cave propagation

From the discussion in Sections 6.1 and 6.2, we can determine with some certainty, particular aspects of fracture banding:

- The damage profile ahead of the cave can be discontinuous
- Multiple fracture bands can form at the same time, with new fracture bands being formed as the previous fracture bands mature
• The fracture bands created are parallel to the cave boundary
• The spacing of the fracture bands is generally consistent
• The progression of the cave is affected by mine scale geological features which can either expand, limit or deviate the propagation of the cave depending on the relative orientation and position of the feature and the cave

Figure 6.24 gives a schematic of a potential conceptual model of caving which better captures the phenomenon of cave growth through fracture banding. The damage profile ahead of the cave is discontinuous, with peaks in damage around the parallel fracturing. It is important to note that in these figures, the brown background colour represents the rock mass, which will include a number of in situ joints. Only significant fractures created as part of the cave propagation process are shown explicitly.

There are a number of factors regarding fracture banding which are still uncertain. The first is whether the bands are formed as single, large fractures as seen in the physical models, or as a zone of smaller fractures in which further failure and coalescence of fractures occurs, similar to the zones seen in the analysis of microseismicity. It is also possible that both of these cases are true and the form the bands take depends on the conditions ahead of the cave. An example of fracture banding shown as zones is illustrated in Figure 6.25.
Another unknown is the specifics of the evolution of the bands. It is possible that the evolution of the bands of microseismicity observed is due to parallel fractures forming simultaneously, as illustrated in Figure 6.26. The fractures further from the cave are only beginning to form, while the fracture closest to the cave is fully formed and becomes the subsequent cave back.

It is also possible that the parallel fracturing forms with little seismicity, and a beam is formed in between the parallel fracturing and the cave back. This beam then fails and significant
microseismicity is produced, creating bands of microseismicity as the cave expands and more beams fail. This is illustrated in Figure 6.27.

There is substantial evidence presented in this thesis based on a number of different sources that the caving mechanism of fracture banding is occurring in caving mines. There is also significant evidence given by Duplancic in the development of his conceptual caving model. It appears that both mechanisms of caving may occur in caving mines. In the analysis of open hole video camera monitoring (Section 4.3.3) there was an example of a change in caving mechanism from what appeared to be fracture banding to what appeared to be a Duplancic mode of caving. This implies that both fracture banding and Duplancic caving mechanisms can occur, even in the same mine. The change in caving mechanism is expected to be due to a change in a number of factors; however, determining these factors and their impact on the mechanism of caving is outside of the scope of this thesis and should be the subject of further studies. These factors likely include:

- Stress conditions ahead of the cave
- Rock mass quality
- Cave geometry
- Draw
- Rate of undercutting
- Mine scale geological features (faults, contacts etc.)

Figure 6.28 gives an extended conceptual model of caving which captures both the Duplancic mode of caving along with fracture banding. As indicated in the figure, caving behaviour can
change between continuous damage profile seen in Duplancic and the discontinuous damage profile of fracture banding. It is unknown whether this is a continuum with intermediate states, or whether the transition between the two is sharp (similar to the different modes of borehole breakout observed by Crook et al. (2003)). The only evidence observed indicating a continuum is the ‘transition period’ at the beginning of Period 3 from the open hole monitoring of Mine A (Section 4.3.3). The model shown in Figure 6.28 includes only that which is known about the different mechanisms of caving. Figure 6.29 gives a model which speculates on the factors which could influence the caving mechanism realised and the primary origin mechanism of the fracturing.

**Possible cave propagation mechanisms**

**Known model**

**Speculative model**

*Changes in:*
- Stress conditions
- Rock mass quality
- Cave geometry
- Draw
- Rate of undercutting
- Mine scale geological features
6.4 Other considerations

The large pre-existing fractures were also found to influence the direction of propagation of the cave. This is seen in Test 5, which began by propagating vertically towards the top of the sample (Figure 3.38) but, as the cave reached one of the diagonal pre-existing fractures, it deviated towards the right as shown in Figure 6.30.

![Figure 6.30 Deviation of cave due to pre-existing fractures (Test 5)](image)

There have been a number of studies investigating the effects of large scale geological features on caving (Vyazmensky et al. 2008, 2010; Elmo et al. 2010; Woodward 2011; Li et al. 2014). The results of these studies indicate that the cave growth in a particular direction can be extended or reduced depending on the feature orientation. If a feature intersects the cave, the cave development will be ‘bounded’ by the feature and the cave will deviate to follow the orientation of the feature (illustrated in Figure 6.31). If the feature comes close to the cave, the cave will ‘break-back’ to the feature (illustrated in Figure 6.32).
Figure 6.31  Illustration of cave bounded by intersecting discontinuity
The results of the physical model agree with the literature in that the cave will deviate to follow the orientation of major geological features, which can either expand or limit the propagation of the cave, depending on the relative orientation of the feature.
7 Thesis Conclusions

Within the mining industry, the Duplancic conceptual model of caving is generally accepted as an adequate conceptual model for cave growth. This model forms the framework for the interpretation of analysis and monitoring results in the industry. The Duplancic model was based on linear elastic numerical modelling and simple microseismic analysis of a single mine. More data and research has become available since Duplancic’s work, creating an opportunity for further investigation to extend or verify the original work. This thesis re-examines the Duplancic model from the perspectives of cave propagation mechanism and mechanism of fracture generation in order to extend the conceptual model of caving to account for all caving behaviour observed.

7.1 Mechanism of cave propagation

The Duplancic model implies that that the rock mass ahead of the cave back progresses continuously through each of the five zones in turn as the cave propagates vertically. The evidence presented in this thesis, however, indicates that this may not always be the case. The literature review revealed multiple studies identifying fractures parallel to the cave surface in different situations. These studies came from a wide variety of sources, including site observations, numerical modelling, physical modelling and analysis of microseismicity. The physical modelling programme conducted as part of this thesis showed the same form of caving behaviour. The cave was found to propagate via a series of fractures parallel to the cave surface, ‘jumping’ to the next parallel fracture to advance vertically, a caving mechanism termed fracture banding. This result was further verified by the field monitoring results. Observations were made at multiple caving mines of bands of microseismicity forming, separated by areas with little microseismicity. Review of open hole video monitoring in the crown of the cave showed a time period in which the cave may have progressed vertically through ‘jumps’. In this time period, little fracturing or microseismicity was observed between the discontinuities, indicating a low-energy caving mechanism such as fracture banding. Interestingly, the open hole video monitoring also revealed a period in which the cave progressed more gradually, with significant shear failure ahead of the cave back. The shear damage severity increased closer to the cave back, indicating a Duplancic style caving behaviour. This suggests that both caving mechanisms can occur in the same mine at different times.
Some key features of the fracture banding caving mechanism could be determined based on the research contained in this thesis:

- Multiple fracture bands can form ahead of the cave. A fracture band can form in between two other fracture bands. Multiple bands can form simultaneously.
- The shape of the fractures formed in the process of fracture banding is parallel to the cave surface, in both the crown and periphery of the cave.
- The spacing of the fracture bands is relatively consistent under similar conditions.

There are a number of features of fracture banding that are still to be determined, including:

- The specific effects of changes in mining conditions on which mechanism of cave propagation occurs.
- The exact spacing of fracture bands and which conditions affect the spacing.
- The specifics behind the vertical ‘jumps’ of the cave to successive parallel fractures. It is possible that the rock mass below the lowest parallel fracture becomes part of the caved zone as a block. It is also possible that a beam may be forming between the cave surface and the first parallel fracture, which then fails and becomes part of the caved zone.

Another area which requires further examination is the effect of faults on cave propagation. From the physical modelling it appeared that pre-existing fractures (analogous to faults) in some of the samples changed the way the cave grew, either limiting or expanding the cave geometry depending on the relative orientation of the fractures. The published literature agrees with the results seen in the physical model; however, this area is not the focus of this thesis and further research is required.

### 7.2 Mechanism of fracture generation

In the development of his conceptual model, Duplancic assumes that slip along pre-existing discontinuities will occur preferentially to intact rock failure, emphasising the role of shear failure over tensile/extensile failure. There is a compelling argument that this assumption may not always be valid. Multiple studies were found in the review of literature in which the primary mode of failure ahead of the cave was tensile or extensile. This includes a study which used a similar methodology to that used by Duplancic in the development of his model. Additionally,
the PIV results of the physical modelling point towards the fractures observed being extensile in nature. This is further cemented by the similarities between the fracture pattern seen in the physical model and examples of extensile fracturing from sources other than cave mining. As mentioned previously, the result of the open hole video monitoring revealed a period in which shear failure was not observed ahead of the cave. This implies that another failure mechanism (i.e. extension) was occurring. The shearing seen in a later period indicated that both fracture generation mechanisms can exist in caving mines at different times.

The numerical models were able to capture some of the banding nature of the fracturing seen in the physical model. There were some differences in the fracturing pattern, however, which indicated that the match between physical and numerical models could be further improved by including extensional failure in the material model.

Using source parameters of populations of microseismic events is a commonly used method for determining failure mechanisms in mining. Source parameters may not, however, be a reliable indicator of mechanism in caving mines. In the literature, the most commonly used parameter when trying to determine the mechanism of fracturing in caving mines using microseismicity was S:P wave energy ratio. However the verifications conducted in some of these studies indicate that S:P wave energy ratio is not a strong indicator of fracturing mechanism. Additionally, in cases of fracture banding, the source parameters of events inside of and outside of the bands was examined. The analysis did not reveal any patterns which could be used as indicators of event banding or the underlying fracturing mechanism of event banding.

7.3 Expanded conceptual model of cave propagation

From the aforementioned conclusions, it is clear that the Duplancic conceptual model cannot account for all of the caving behaviour seen in experiments and in caving mines. As such, an extended conceptual model of caving was proposed. This model can account for caving through both a continuous, Duplancic style mechanism along with a discontinuous, fracture banding style mechanism. It appears that changes in conditions will affect the caving mechanism produced. The specifics of whether the two mechanisms lie on a continuum or how the changing conditions affect the mechanisms was outside of the scope of this thesis and still unknown. Further research focusing on the impact of different factors on the mechanism produced could clarify the unknowns and produce a more robust conceptual model of caving.
7.4 Further Research

This thesis brings to light the importance of the fracture banding mechanism in caving; a previously unrecognised area of caving mechanics. The conceptual caving model created gives the industry a framework for interpreting results of monitoring and numerical modelling. There are, however, still many unknowns in the realm of caving mechanics. One significant area that needs to be addressed is the impact that different geological and mining factors have on the caving mechanism produced. This could be achieved using parametric studies of two-dimensional physical modelling, supplemented by three-dimensional physical models. Another approach could be to create physical models with different conditions, which could then be used to calibrate numerical models. The numerical models could, in turn, be used to conduct parametric studies to assess the impact of different factors on the caving process. Parameters that could be investigated include:

- In-situ stress magnitudes, gradients and stress ratios. In particular, using a liquid with a higher density in the bladders of the physical models could create a higher horizontal stress to approximate conditions often seen in Australian caving mines.

- The stress conditions ahead of the cave are likely to be very important in determining caving mechanism. Due to the difficulties of measuring this as part of a physical model, this would likely have to be investigated through use of a numerical model which has been calibrated to a physical model.

- Fracture density, length, orientation and strength. The fracture network in the physical models was chosen for practicality and simplicity to investigate the fracture banding phenomenon. However, the density, length and orientation of the fractures could be varied to investigate the effect that each of these have on the mechanism produced. Changes in the shear strength of the fractures could also have a strong impact on the caving mechanism, one would expect an increase in shear along these fractures with reduced shear strength.

- Undercutting procedure. There are a variety of different undercutting procedures that could be trialled using the test setup described in this thesis. There are a number of undercutting strategies employed by caving mines, all of which could impact cave propagation, particularly in the early stages of cave development.
The numerical modelling approaches shown in this thesis are simply two of many different approaches used throughout the industry to model caving. Physical models can be used as a way to validate and/or calibrate the efficacy of these approaches in describing cave propagation. Of particular use would be a ‘standard’ physical model of caving, which could be modelled numerically using different approaches to compare the results.

Unfortunately there was limited success in capturing the acoustic emission data from the physical modelling programme. Further research that can adequately capture acoustic emissions would provide researchers with an excellent tool to link field monitoring results to physical models. Using higher quality acoustic emission sensors and a denser array of sensors could improve on the results given in Cumming-Potvin et al. (2016).

It is important when conducting research to relate the findings from physical and numerical models to field observations. This helps to validate the results and can aid in the application of the results to operating mines.
8 References


Buckingham, E 1914, 'On physically similar systems; illustrations of the use of dimensional equations', *Physical Review*, vol. 4, no. 4, pp. 345–376.


Harris, PH & Wesseloo, J 2015, mXrap software, version 5, Australian Centre for Geomechanics, The University of Western Australia, Perth, https://mxrap.com

Hebblewhite, BK 2007, Management of Geotechnical Risks in Mining Projects, School of Mining Engineering, The University of New South Wales, Sydney.


Appendix A. Details of Geotechnical Centrifuge Facility

The centrifuge at the University of Pretoria Geotechnical Centrifuge facility is a C67-4 manufactured by Actidyn. It is a 150 g-ton centrifuge, meaning the centrifuge can spin one ton with enough acceleration to create a centripetal force which is 150 times that of the Earth’s gravity. The arm of the centrifuge is 2.04m long and the payload adds another 1.3m of length when extended. The maximum payload is 1500kg and the maximum velocity is 235 km/h. A picture of the centrifuge is seen in Figure A.1 and a schematic showing its dimensions in Figure A.2.

![Figure A.1 – Geotechnical centrifuge at University of Pretoria](image-url)
The centrifuge has a number of on-board acquisition systems, including:

- HBM QuantumX CX22 solid state computer
- Four HBM QuantumX MX410 amplifiers and an HBM QuantumX MX840A amplifier
- An HBM QuantumX MX878 signal generator
- An Ethernet connection via fibre optic rotary link
• Digidaq system modules, developed by The University of Western Australia (Gaudin et al. 2010). These modules allow for 8 channels of analog to digital conversion and storage on one board.

The centrifuge also has a number of control systems including water lines and configurable power supply lines. Digital still and video cameras can be placed in front of the model and the images/video transferred to a computer via Ethernet link. More information on the centrifuge facility can be found in Jacobsz, Kearsley and Kock (2014).
Appendix B. Testing Equipment Specifications

- **LVDTs**: Solartron 30mm AC LVDT
- **Pressure Transducer**: Bell & Howell Ltd Type: 4-305-0159-03MG (0-250 PSI)
- **Flow Restrictor**: Festo 6mm flow restrictor
- **Solenoid Valves**: SMC 1.6mm orifice VDW11-SG-2-M5-Q
- **DSLR Camera**: Canon EOS 100D with 40mm fixed lens
- **Webcam**: Microsoft LifeCam HD-3000
- **All piping**: Festo 6mm diameter
- **Pistons**: Festo DZF-50-100-P-A
Appendix C. Image Correction Procedure

The images were corrected in the GIMP software using the perspective tool. All images from each test were loaded as separate layers, so they could all have the same correction applied to them at the same time. The first step of the image correction involves adding guidelines to the image, shown in Figure C.1. Then the image is corrected so that the (straight) edges of the frame are aligned with the guidelines (Figure C.2). Then each layer of the corrected image is exported to a PNG format (Figure C.3). The corrected images can then be run through the PIV software.

![Step 1 of perspective correction – guidelines added to image](image-url)
The relative displacements were converted to absolute displacements using the known size of the frame.
Appendix D. Centrifuge Test Photographs

Test 1

Figure D.1 - Progression of Test 1 – Part 1
Figure D.2  Progression of Test 1 – Part 2
Test 2

Figure D.3  Progression of Test 2 – Part 1
Figure D.4  Progression of Test 2 – Part 2
Test 3

Figure D.5  Progression of Test 3 – Part 1
Figure D.6  Progression of Test 3 – Part 2
Test 4

Figure D.7  Progression of Test 4 – Part 1
Figure D.8  Progression of Test 4 – Part 2
Figure D.9  Progression of Test 5 – Part 1
FigureD.10  Progression of Test 5 – Part 2
Figure D.11  Progression of Test 5 – Part 3
Figure D.12  Progression of Test 5 – Part 4
Test 6

Figure D.13  Progression of Test 6 – Part 1
Figure D.14  Progression of Test 6 – Part 2
Figure D.15   Progression of Test 6 – Part 3
Test 7

Figure D.16  Progression of Test 7 – Part 1
Figure D.17  Progression of Test 7 – Part 2
Test 8

Figure D.18  Progression of Test 8 – Part 1
Figure D.19  Progression of Test 8 – Part 2
Appendix E. PIV calculation method and displacement results

The PIV software returns the location of the patch (x, y co-ordinates) at each frame (photograph). These results were exported from Matlab and all further calculations and visualisation was done in the mXrap software (Australian Centre for Geomechanics 2016). The vector plots presented in Figure E.1 through Figure E.20 were created simply by creating a vector from the original patch position to the patch position in the current frame. This vector is shown as an arrow and its length scaled for clarity. The displacement plots seen in Section 3.8 were created by calculating the total displacement from the original position of the patch to the current position. This was simply calculated by finding the distance (in mm) between a point between one frame and the previous frame.

The points seen in the displacement plots are the patch locations coloured by displacement. The colour of the surface behind the points was smoothed by a calculation on a regular grid with a spacing of 2mm x 2mm. The total displacement on each of those grid points was calculated by an inverse distance squared weighted average of the closest 5 patches (with a maximum of 2mm between the grid point and the patch centroid). The grid point displacement equation is:

\[
D_G = \frac{\sum_n \left(1 - \left(\frac{u}{u_{max}}\right)^2\right) \times D_n}{n_{max}}
\]

Where;

- \( n \): 1 – \( n_{max} \), with \( n_{max} \) capped at 5
- \( u \) = the distance from patch \( n \) to the grid point
- \( u_{max} = 2 \text{mm} \)
- \( D_n \) = the total displacement value for patch \( n \) at the given frame
- \( D_G \) = the total displacement value for grid point \( G \) at the given frame
Figure E.1  Test 1 PIV vector plot (part 1)
Figure E.2    Test 1 PIV vector plot (part 2)
Figure E.3  Test 1 PIV vector plot (part 3)
Figure E.4 Test 1 PIV vector plot (part 4)
Figure E.5  Test 2 PIV vector plot (part 1)
Figure E.6  Test 2 PIV vector plot (part 2)
Figure E.7  Test 2 PIV vector plot (part 3)
Figure E.8  Test 2 PIV vector plot (part 4)
Figure E.9   Test 4 PIV vector plot (part 1)
Figure E.10  Test 4 PIV vector plot (part 2)
Figure E.11  Test 4 PIV vector plot (part 3)
Figure E.12  Test 4 PIV vector plot (part 4)
Figure E.13 Test 5 PIV vector plot (part 1)
Figure E.14  Test 5 PIV vector plot (part 2)
Figure E.15  Test 5 PIV vector plot (part 3)
Figure E.16  Test 5 PIV vector plot (part 4)
Figure E.17  Test 6 PIV vector plot (part 1)
Figure E.18 Test 6 PIV vector plot (part 2)
Figure E.19  Test 6 PIV vector plot (part 3)
Figure E.20  Test 6 PIV vector plot (part 4)
Appendix F. Examples of Parallel Fractures From Centrifuge Tests

In all tests in which the cave did not immediately stall, the caving mechanism of fracture banding was displayed. Examples of the parallel fracturing from each test are given in Figure F.1 through Figure F.5. The top half of the figures (labelled A) are shown without annotation, and the bottom half (labelled B) have annotations in red to highlight the parallel fractures. In tests two and five, some of the pre-existing fractures showed significant shear movement. These pre-existing fractures are highlighted by dashed blue lines in Figure F.2 and Figure F.4 for clarity.
Figure F.1 Parallel fractures ahead of the cave, highlighted in red (test one)
Figure F.2  Parallel fractures ahead of the cave and on the cave periphery highlighted in red, along with pre-existing fractures highlighted in blue (test two)
Figure F.3  Parallel fractures ahead of the cave, highlighted in red (test four)
Figure F.4 Parallel fractures ahead of the cave and on the cave periphery highlighted in red, along with major shear discontinuities highlighted in blue (test five)
Figure F.5  Parallel fractures ahead of the cave and on the cave periphery, highlighted in red (test six)
Appendix G. Details of Study Site Microseismic Systems

As mentioned in Section 4.2.1, the microseismic events used in the analyses were first passed through a basic quality filter. The following events were filtered out of the databases:

- Events tagged as outliers by the site
- Events tagged as blasts in the waveform processing software
- Events outside of a given location range – a rectangular prism around the mine excavations
- Events with null values for local magnitude, seismic moment or seismic energy
- Events with an S:P energy ratio of exactly 1
- Events with an invalid date
- Events with parameters outside of the values listed in Table G.1.

**Table G.1 - Quality Filter Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Valid values (Mines A &amp; C)</th>
<th>Valid values (Mine B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Magnitude</td>
<td>$-8 &lt; M_L &lt; 8$</td>
<td>$-5 &lt; M_L &lt; 4$</td>
</tr>
<tr>
<td>Seismic Energy</td>
<td>$E_n &lt; 10^{14}$</td>
<td>$E_n &lt; 10^{14}$</td>
</tr>
<tr>
<td>Seismic Moment</td>
<td>$M_o &lt; 10^{14}$</td>
<td>$M_o &lt; 10^{14}$</td>
</tr>
<tr>
<td>Number of sensors used in processing</td>
<td>$N &gt; 4$</td>
<td>$N &gt; 4$</td>
</tr>
</tbody>
</table>

The following figures show the microseismic monitoring systems over time in each of the study mines. In Mine A, data on which sensor was used in the processing of each event was available. Sensors were classed as active if they were used in the processing of at least 10 events in the specified time period and partially active if they were used in the processing of 1-10 events. The figures for Mine B and Mine C simply show the sensors which were installed at a given point in time.
Figure G.1  Microseismic system and events at Mine A from January-2013 to June-2013
Figure G.2  Microseismic system and events at Mine A from July-2013 to December-2013
Figure G.3  Microseismic system and events at Mine A from January-2014 to July-2014
Figure G.4  Microseismic system and events at Mine A from June-2014 to December-2014
Figure G.5  Microseismic system and events at Mine A from January-2015 to July-2015
Figure G.6  Microseismic system and events at Mine A from July-2015 to December-2015
Figure G.7  Microseismic system and events at Mine A from January-2016 to July-2016
Figure G.8  Mine B microseismic monitoring system at 2009-01-01. Events for 2008-07-01 to 2009-01-01 shown in grey.
Figure G.9  Mine B microseismic monitoring system at 2009-07-01. Events for 2009-01-01 to 2009-07-01 shown in grey.
Figure G.10  Mine B microseismic monitoring system at 2010-01-01. Events for 2009-07-01 to 2010-01-01 shown in grey.
Figure G.11  Mine B microseismic monitoring system at 2010-07-01. Events for 2010-01-01 to 2010-07-01 shown in grey.
Figure G.12  Mine C microseismic monitoring system at 2013-01-01. Events for 2012-07-01 to 2013-01-01 shown in grey.
Figure G.13  Mine C microseismic monitoring system at 2013-07-01. Events for 2013-01-01 to 2013-07-01 shown in grey.
Figure G.14  Mine C microseismic monitoring system at 2014-01-01. Events for 2013-07-01 to 2014-01-01 shown in grey.
Figure G.15  Mine C microseismic monitoring system at 2014-07-01. Events for 2014-01-01 to 2014-07-01 shown in grey.
Figure G.16  Mine C microseismic monitoring system at 2015-01-01. Events for 2014-07-01 to 2015-01-01 shown in grey.
Figure G.17  Mine C microseismic monitoring system at 2015-07-01. Events for 2015-01-01 to 2015-07-01 shown in grey.
Figure G.18  Mine C microseismic monitoring system at 2016-01-01. Events for 2015-07-01 to 2016-01-01 shown in grey.
Appendix H.  Source Parameter Charts from Examples of Banding

Given below are the source parameter charts described in Section 4.2.5. Events in each band are shown in a different colour, events outside of the bands are shown in purple.

Case 1

Figure H.1  Volumes used for bands in Case 1
Figure H.2  Volume used for events outside of bands in Case 1

Figure H.3  Energy distributions for bands in Case 1
Figure H.4   Moment distributions for bands in Case 1

Figure H.5   Apparent Stress distributions for bands in Case 1
Figure H.6  Energy Index distributions for bands in Case 1

Figure H.7  Corner Frequency distributions for bands in Case 1
Figure H.8  S:P Wave Energy ratio distributions for bands in Case 1

Figure H.9  Static Stress Drop distributions for bands in Case 1
Figure H.10  Frequency-Moment distributions for bands in Case 1

Figure H.11  Diurnal chart for bands in Case 1
Case 2

Figure H.12  Volumes used for bands in Case 2

Figure H.13  Volume used for events outside of bands in Case 2
Figure H.14   Energy distributions for bands in Case 2

Figure H.15   Moment distributions for bands in Case 2
Figure H.16  Apparent Stress distributions for bands in Case 2

Figure H.17  Energy Index distributions for bands in Case 2
Figure H.18   Corner Frequency distributions for bands in Case 2

Figure H.19   S:P Wave Energy ratio distributions for bands in Case 2
Figure H.20  Static Stress Drop distributions for bands in Case 2

Figure H.21  Frequency-Moment distributions for bands in Case 2
Figure H.22  Diurnal chart for bands in Case 2

Case 3

Figure H.23  Volumes used for bands in Case 3
Figure H.24  Volume used for events outside of bands in Case 3

Figure H.25  Energy distributions for bands in Case 3
Figure H.26  Energy distributions for bands in Case 3

Figure H.27  Apparent Stress distributions for bands in Case 3
Figure H.28  Energy Index distributions for bands in Case 3

Figure H.29  Corner Frequency distributions for bands in Case 3
Figure H.30  S:P Wave Energy ratio distributions for bands in Case 3

Figure H.31  Static Stress Drop distributions for bands in Case 3
Figure H.32  Frequency-Moment distributions for bands in Case 3

Figure H.33  Diurnal chart for bands in Case 3
Case 4

Figure H.34  Volumes used for bands in Case 4

Figure H.35  Volume used for events outside of bands in Case 4
Figure H.36  Energy distributions for bands in Case 4

Figure H.37  Moment distributions for bands in Case 4
Figure H.38  Apparent Stress distributions for bands in Case 4

Figure H.39  Energy Index distributions for bands in Case 4
Figure H.40  Corner Frequency distributions for bands in Case 4

Figure H.41  S:P Wave Energy ratio distributions for bands in Case 4
Figure H.42  Static Stress Drop distributions for bands in Case 4

Figure H.43  Frequency-Moment distributions for bands in Case 4
Figure H.44  Diurnal chart for bands in Case 4
Case 5

Figure H.45   Volumes used for bands in Case 5

Figure H.46   Volume used for events outside of bands in Case 5
Figure H.47  Energy distributions for bands in Case 5

Figure H.48  Moment distributions for bands in Case 5
Figure H.49  Apparent Stress distributions for bands in Case 5

Figure H.50  Energy Index distributions for bands in Case 5
Figure H.51  Corner Frequency distributions for bands in Case 5

Figure H.52  S:P Wave Energy ratio distributions for bands in Case 5
Figure H.53  Static Stress Drop distributions for bands in Case 5

Figure H.54  Frequency-Moment distributions for bands in Case 5
Figure H.55  Diurnal chart for bands in Case 5