An Assessment of the Significance of Factors Affecting the Occurrence of Rockburst Damage

By

Wei Duan

A thesis submitted to the Department of Civil and Resource Engineering in conformity with the requirements for the degree of

Masters of Philosophy

Feb 2016

Supervisors: Dr Johan Wesseloo

Prof Yves Potvin
Executive Summary

This thesis is concerned with the issue of rockburst damage in hard rock, mechanised underground mines. Specifically, given that a rockburst occurs, it quantifies the significance of the factors affecting the severity of damage, or how the variation in each contributing factor influences the likelihood of exceeding a certain damage severity.

A literature review was undertaken and it was shown that there was generally more than one factor controlling the stability of an excavation under dynamic loading. It was also shown that some factors are more significant than others at controlling the severity of damage. The lack of quantification on the weighting of factors controlling the stability of excavations was also seen in the Rockburst Damage Potential (RDP) method (Heal 2010). The Australian Centre for Geomechanics rockburst database was used to assess the weighting of factors controlling rockburst damage severity.

Factor analysis was first applied to explore the structure of the database, or how all variables associated with each damage case correlated with each other so that data reduction could be carried out. Stress factor, ground support, excavation span, geology factor, wall/back and Peak Particle Velocity (PPV) were determined to be potential factors controlling excavation stability. Rock Damage Scale (RDS) was selected as the most appropriate parameter to quantify damage severity.

Rock damage scale was regrouped into three categories based on its perceived operational implications: acceptable (R2), tolerable (R3) and intolerable (R4 and R5). Logistic regression was then used to model the probability of exceeding R2 and R3 severity damage. It was determined that ground support, geology factor and PPV are significant factors when predicting the probability of exceeding R2 severity damage. Stress factor and excavation span are additional significant factors predicting the probability of exceeding R3 severity damage.

The area under the receiver operating characteristic (ROC) curve was used in this study as a quantitative measure to assess the performance of the new regression models in comparison to the original RDP model. The inclusion of
factor weighting for the new model resulted in a 6.3 and 8.3% improvement for predicting a pair of positive and negative cases for exceeding R2 and R3 severity damage respectively over the original RDP models.

Following the goodness of fit test, the adjusted RDP method was applied to a series of rockburst case studies to assess its performance in a range of mining conditions and to assess how generalisable this method is at predicting rockburst damage. The performance of the adjusted RDP method during the case study was deemed to be adequate, although several issues were encountered and discussed.
Acknowledgements

To my principle supervisor, Dr Johan Wesseloo, also my mentor for the past four years, for his guidance and support in completing this research project during my time at the Australian Centre for Geomechanics and also afterwards in my career. To my co-supervisor, Prof Yves Potvin, for his generosity and patience in our endless discussion. The effort received will forever be remember and appreciated.

To the staff at the ACG, in particular Christine Neskudla for her support during my time there, Lindsey Macqueen, Maddie Adams and Garth Doig for their thorough and professional review work. To Paul Harris for his life-changing pieces of advice and his miraculous technical support during the project.

To my colleagues Kyle Woodward, Gerhard Morkel and Daniel Cummings-Potvin for their friendship and inspirational discussions. All of your brilliant ideas and suggestions have added a tremendous amount of value to the project.

To all the mining industry sponsors of the Phase 4 and Phase 5 of the Mine Seismicity and Rockburst Risk Management Project at the ACG, which this project is a part of. As major sponsors: Barrick (Australia Pacific) Ltd, BHP Billiton Olympic Dam, BHP Billiton Nickel West, Independence Group Lightning Nickel, Luossavaara-Kiirunavaara AB (LKAB), the Minerals Research Institute of Western Australia (MRIWA), Perilya Limited Broken Hill Mine, Vale Canada. As minor sponsors: Agnico-Eagle Canada, BCD Resources Tasmania Mine, Glencore Zinc Canada (Kidd Mine), Glencore Cosmos Nickel Australia, Glencore Nickel Rim South Mine Canada, Gold Fields Australia, Hecla USA, Kirkland Lake Gold, MMG Golden Grove, Newcrest Mining.

Finally, to the rest of my family and friends, in particular to Renae Berg and Zai Wickett, who stood by me. All of your support has made this and everything else possible. For this, I will remain forever grateful.
# Table of Contents

Executive Summary ................................................................................................................... i
Acknowledgements.................................................................................................................. iii
List of Figures ............................................................................................................................ ix
List of Tables ............................................................................................................................. xiii

1 Introduction ............................................................................................................................. 1
1.1 Defining the Rockburst Problem ......................................................................................... 1
1.2 Hazard and Risk associated with seismicity and rockburst ............................................ 2
1.3 Research hypothesis ............................................................................................................... 3
1.4 Proposed methodology ....................................................................................................... 4
1.5 Thesis Structure .................................................................................................................... 5

2 Literature Review ................................................................................................................... 7
2.1 Introduction ........................................................................................................................... 7
2.2 Studies aimed at quantifying the significance of factors affecting rockburst damage .... 8
2.3 Conclusions drawn from the literature ............................................................................... 14
2.4 Issues to be addressed in this thesis ............................................................................... 15

3 Multivariate Statistical Analyses .......................................................................................... 16
3.1 Introduction ........................................................................................................................ 16
3.2 ACG Rockburst Database ................................................................................................... 17
3.3 Factor Analysis ..................................................................................................................... 18
    3.3.1 General Description ...................................................................................................... 18
    3.3.2 Data preparation .......................................................................................................... 19
    3.3.3 Factor Extraction and Interpretation ............................................................................. 32
    3.3.4 Data Reduction ............................................................................................................ 36
3.4 Logistic Regression ............................................................................................................. 37
    3.4.1 General Description ...................................................................................................... 37
    3.4.2 Outcome variable regrouping ....................................................................................... 39
List of Figures

Figure 1-1 South African underground mining rock related fatality from 1984 to 2012 (Van Zyl & Adams 2013). .................................................................................................................................................................................................................................................. 2

Figure 2-1 A violent rockburst damage occurred to one side of an excavation wall while the other side appears to be intact (Ortlepp 1997). ........................................................................................................................................................................................................................................... 7

Figure 2-2 Cumulative percentage plot of estimated PPV parameter at the excavation boundary (Albrecht & Potvin 2005). ........................................................................................................................................................................................................................................... 11

Figure 3-1 Histogram of Stress Factor and Span. ............................................................................................................................ 22

Figure 3-2 Histogram of PPV and Failure Depth ........................................................................................................................................................................................................................................... 22

Figure 3-3 Scatter plot matrix for all continuous variables for linearity testing .......................................................................................... 23

Figure 3-4 Scree plot for determining the number of components to retain ........................................................................................... 33

Figure 3-5 Ground support performance at LaRonde Mine (Turcotte 2014). ........................................................................................................................................................................................................................................... 40

Figure 3-6 RDP fitted logistic regression lines. Reproduced from Heal (2010). Dashed lines are 90% confidence interval. ........................................................................................................................................................................................................................................... 41

Figure 3-7 Measured PPV vs Static Stress Drop for world wide database (Kaiser, McCreath & Tannant 1996). ........................................................................................................................................................................................................................................... 47

Figure 3-8 H-L contingency table plot for model R2 ........................................................................................................................................................................................................................................... 54

Figure 3-9 H-L contingency table plot for model R3 ........................................................................................................................................................................................................................................... 54

Figure 3-10 Plot of sensitivity vs 1-specificity for all possible cutting points values (Hosmer Jr, Lemeshow & Sturdivant 2013). ........................................................................................................................................................................................................................................... 57

Figure 3-11 ROC curve for model R2. Area under ROC = 0.767 ....................................................................................................................... 58

Figure 3-12 ROC curve for model R3. Area under ROC = 0.816 ....................................................................................................................... 58

Figure 3-13 Probability exceeding R2. Original Mode (Left) vs New Model (Right). .......................................................................................... 59

Figure 3-14 Probability exceeding R3. Original Mode (Left) vs New Model (Right). .......................................................................................... 60

Figure 3-15 Model R2 Sensitivity Chart ........................................................................................................................................................................................................................................... 61

Figure 3-16 Model R3 Sensitivity Chart ........................................................................................................................................................................................................................................... 62

Figure 3-17 Modelled Probability vs Stress Factor ........................................................................................................................................................................................................................................... 63

Figure 3-18 Modelled Probability vs Support Capacity ........................................................................................................................................................................................................................................... 63

Figure 3-19 Modelled Probability vs Excavation Span ........................................................................................................................................................................................................................................... 64

Figure 3-20 Modelled Probability vs Geology Factor ........................................................................................................................................................................................................................................... 64

Figure 3-21 Modelled Probability vs PPV ........................................................................................................................................................................................................................................... 65

Figure 3-22 Rock Damage Scale vs Probability of Exceeding Damage Severity. RDS are offset by 0.1. .................................................................. 66

Figure 3-23 EVP new vs PPV. Background are coloured by probability of exceeding R2. Cases exceeded R2 are marked using red spheres and cases which did not are marked using white triangles. EVP values are randomly offset with a mean of 0.2 for a better scattering. .................................................................. 67
Figure 3-24  EVP new vs PPV. Background is coloured by probability of exceeding R3. Cases which exceeded R3 are marked using red spheres and cases which did not are marked using white triangles. .................................................................68

Figure 3-25  Probability Exceeding R2 vs Probability Exceeding R3. Cases with probability exceeding R3 greater than R2 are highlighted using Red Cross marker. Cases with probability exceeding R3 less than R2 are highlighted using Green Sphere marker. ..................................................71

Figure 3-26  Span vs Stress factor illustrating applicable zones. Invalid cases are highlighted using red cross and valid cases using green sphere. ..............................................................................72

Figure 4-1  Kidd mine stress values vs Distance away from excavation centroid. Red: 95% confidence interval. Green: median. Blue: Mean. Grey dash: standard deviation. ....................................................76

Figure 4-2  Stress vs Distance from excavation centroid. The markers are coloured by residual sum of the two fitted lines. ..................................................................................................77

Figure 4-3  Excavation span fitting illustration (Heal 2010). ..............................................................................80

Figure 4-4  Mine A offset fault illustration (plan view). The faults shown are for illustration purposes only.................................................................83

Figure 4-5  Mine A Mag-Time chart. Local magnitude is shown and it approximately equals to Richter magnitude. ..................................................................................................84

Figure 4-6  Mine A rockburst damage.........................................................................................................................85

Figure 4-7  Mine A Map3D model illustration.............................................................................................................86

Figure 4-8  Mine A Map3D model sigma 1 stress contour along damaged drives ......................................................86

Figure 4-9  Mine A survey coloured by excavation span. .........................................................................................88

Figure 4-10 Mine A survey coloured by PPV. .............................................................................................................89

Figure 4-11 Mine A rockburst RL715 HW shoulder bulking. ..................................................................................90

Figure 4-12 Mine A rockburst RL715 FW wall bulking. ..........................................................................................91

Figure 4-13 Mine A rockburst RL715 FW wall bulking, location B looking south behind failed surface support ........................................................................................................91

Figure 4-14 Mine A rockburst RL715 FW lower wall damage ..................................................................................92

Figure 4-15 Mine A rockburst RL730 HW shoulder bulking. ..................................................................................95

Figure 4-16 Mine A rockburst RL730 FW lower wall ejection. ...............................................................................95

Figure 4-17 Mine A rockburst RL730 offset zone shoulder bulking. .....................................................................96

Figure 4-18 Mine A rockburst RL730 offset zone wall collapse. .........................................................................97

Figure 4-19 Mine B active faults in damage vicinity (plan view) ...........................................................................99

Figure 4-20 Mine B rockburst damage illustration. Drive is coloured by damage severity. Blasted stope is coloured in transparent pink.................................................................100

Figure 4-21 Mine B rockburst location calculated by monitoring system. The grid spacing is 200 m. ..............101

Figure 4-22 Mine B rockburst Magnitude and Time chart. Local magnitude is shown which approximately equal to Richter scale magnitude. ................................................................101

Figure 4-23 Mine B drives coloured by nearby stress conditions. The mined out zone resulted in a stress shadow as highlighted in blue.........................................................102

X
Kidd Mine 2011 dynamic support system example.

Figure 4-24 Mine B survey coloured by excavation span. ................................................................. 104
Figure 4-25Mine B geological structures illustration. The lithology contact is highlighted using red
dashed line. .................................................................................................................................................. 104
Figure 4-26 Mine B survey coloured by estimated PPV. ................................................................. 105
Figure 4-27 Mine B RL1120 intersection wall ejection. ................................................................. 106
Figure 4-28 Mine B RL1120 FW drive east wall collapse. Looking south east. .............................. 107
Figure 4-29 Mine B RL1120 FW drive east wall collapse. Looking south west. ............................. 107
Figure 4-30 Mine B RL1120 FW drive east wall ejection. Looking east. ......................................... 108
Figure 4-31 Mine B RL1120 FW drive east wall bulking. Looking north west................................. 108
Figure 4-32 Mine B RL1150 FW drive roof bulking and ejection. ..................................................... 111
Figure 4-33 Mine B RL1150 FW intersection roof bulking. ............................................................ 112
Figure 4-34 Mine B RL1150 FW intersection wall bulking. ............................................................ 112
Figure 4-35 Kidd Mine location and a bird eye view of the mine. .................................................... 115
Figure 4-36 Kidd Mine strong North-South trending faults. ........................................................... 116
Figure 4-37 Stop blast on 7300 level prior to the occurrence of rockburst ........................................ 117
Figure 4-38 Kidd Mine 2009 Rockburst Magnitude-Time chart. Magnitude shown is ESG Local
Magnitude (approx 1 lower than Richter scale) ...................................................................................... 117
Figure 4-39 Kidd Mine 2009 survey coloured by observed damage severity. .................................. 118
Figure 4-40 Kidd Mine 2009 rockburst sigma 1 stress. ................................................................. 119
Figure 4-41 Kidd Mine 2009 rockburst dynamic support system example. ....................................... 121
Figure 4-42 Kidd Mine 2009 survey coloured by excavation span. .................................................. 122
Figure 4-43 Kidd Mine 2009 rockburst survey coloured by estimated PPV value............................ 123
Figure 4-44 Kidd 2009 rockburst 6700 level 01S drive pillar ejection. ............................................. 124
Figure 4-45 Kidd 2009 rockburst 6800L 74XC & DD intersection fall of ground............................... 126
Figure 4-46 Kidd 2009 rockburst 6800L 01S & 74XC intersection fall of ground............................... 126
Figure 4-47 Kidd 2009 rockburst 6800L 74XC rebar protruding vertically. ........................................ 127
Figure 4-48 Kidd 2009 rockburst 6900L 82XC fall of ground. Seismic rupture is denoted as SR1.......... 129
Figure 4-49 Kidd 2009 rockburst 6900L 82XC lower wall shakedown ............................................. 130
Figure 4-50 Kidd 2009 rockburst 7000L 82XC wall ejection. .......................................................... 132
Figure 4-51 Kidd 2009 7000L rockburst 01S shoulder ejection. ....................................................... 133
Figure 4-52 Kidd 2009 rockburst 7100L 84XC intersection collapse. ............................................. 135
Figure 4-53 Kidd 2009 rockburst 7100L 84XC intersection back seismic rupture. ............................ 136
Figure 4-54 Strong seismic response within vicinity of seismic ruptures in the south end between 6800L
and 7500L ................................................................................................................................................. 138
Figure 4-55 Kidd 2011 rockburst location coloured by RDS and blast location................................. 139
Figure 4-56 Kidd 2011 rockburst Magnitude-Time chart. Magnitude shown is ESG local magnitude
(approx. 1 less than Richter scale) ........................................................................................................ 139
Figure 4-57 Kidd Mine 2011 rockburst survey coloured by sigma 1 stress. Looking North East .......... 140
Figure 4-58 Kidd mine 2011 dynamic support system example..................................................... 142
Figure 4-59  Kidd 2011 rockburst survey coloured by excavation span. Looking North East. .........................143
Figure 4-60  Kidd 2011 rockburst seismic ruptures. Looking North East. .................................................144
Figure 4-61  Kidd Mine 2011 rockburst survey coloured by PPV plot ..............................................................145
Figure 4-62  Kidd 2011 rockburst 7000L 01S and S46 intersection .................................................................146
Figure 4-63  Kidd 2011 rockburst 7000L 01S and S46 intersection roof bulking .............................................146
Figure 4-64  2011 Kidd Mine rockburst 7000L broken straps and ejected debris ..............................................147
Figure 4-65  2011 Kidd Mine rockburst 7100L 84XC intersection prior to damage. Photo is looking North West and 84XC is situated behind the red truck. ........................................149
Figure 4-66  2011 Kidd Mine rockburst 7100L 84XC prior to damage. Photo is looking North East. .............150
Figure 4-67  2011 Kidd Mine rockburst 7100L 84XC intersection damage. Looking North West ................150
Figure 4-68  2011 Kidd Mine rockburst 7100L 84XC damage. Looking North East .................................151
Figure 4-69  2011 Kidd Mine rockburst 7300L S30XC wall bulking .................................................................153
Figure 4-70  2011 Kidd Mine rockburst 7300L S20XC roof wedge failure .......................................................154
Figure 4-71  2011 Kidd Mine rockburst 7400L S30XC wall damage ...............................................................156
Figure 4-72  2011 Kidd Mine rockburst 7400L fuel bay south wall damage ..................................................156
Figure 4-73  Mine A RL715 FW lower wall damage. Above the dash line, damage severity is lower while it is higher below the dash line. .................................................................162
Figure 4-74  Mine B RL1120 FW east wall bulking illustration ........................................................................163
Figure 4-75  Ground support rating comparison. Left is mine B RL1120 location D and Right is Kidd mine 2011 7000 level S46 location C. .................................................................164
Figure 4-76  Mine B RL1120 intersection wall ejection. Wall was supported with patterned Garford dynamic solid bolt ........................................................................................................165
Figure 4-77  Mine B RL1120 location B on left and Kidd mine 2009 6800L location A on right. For mine B, the height of the wedge is taller than the end of the bolt. For Kidd mine, the end of the rebar was still seen grouted to rock debris .........................................................166
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 3-1</td>
<td>Factor analysis sample size adequacy (Comrey &amp; Lee 1992).</td>
<td>21</td>
</tr>
<tr>
<td>Table 3-2</td>
<td>Square Multiple Correlation for all variables prior to outlier removal.</td>
<td>24</td>
</tr>
<tr>
<td>Table 3-3</td>
<td>Multivariate outlier cases with MD² significance less than 0.001.</td>
<td>27</td>
</tr>
<tr>
<td>Table 3-4</td>
<td>Correlation matrix for factorability assessment. Correlation strength greater than 0.3 are</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>highlighted in bold.</td>
<td></td>
</tr>
<tr>
<td>Table 3-5</td>
<td>Factor loading index interpretation (Comrey &amp; Lee 2013).</td>
<td>30</td>
</tr>
<tr>
<td>Table 3-6</td>
<td>Variable SMC value for outlier among variable removal. Produced following outlier cases</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>removal.</td>
<td></td>
</tr>
<tr>
<td>Table 3-7</td>
<td>Factor loading matrix for outlier variable screening. Significant variables with loading number</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>absolute value greater than 0.32 are highlighted in bold.</td>
<td></td>
</tr>
<tr>
<td>Table 3-8</td>
<td>Extracted factors, corresponding eigenvalues and variance percentage accounted for.</td>
<td>33</td>
</tr>
<tr>
<td>Table 3-9</td>
<td>Rotated factor loading matrix for interpretation. All loading number greater than 0.32 are</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>highlighted in bold.</td>
<td></td>
</tr>
<tr>
<td>Table 3-10</td>
<td>Rock Damage Scale classification regrouping (Mikula 2013).</td>
<td>39</td>
</tr>
<tr>
<td>Table 3-11</td>
<td>Acceptable vs Unacceptable full model variable significance test.</td>
<td>44</td>
</tr>
<tr>
<td>Table 3-12</td>
<td>Log likelihood comparison of reduced models for R2 model.</td>
<td>45</td>
</tr>
<tr>
<td>Table 3-13</td>
<td>PPV fractional polynomial result. Model R2.</td>
<td>46</td>
</tr>
<tr>
<td>Table 3-14</td>
<td>R2 model coefficients and confidence interval.</td>
<td>47</td>
</tr>
<tr>
<td>Table 3-15</td>
<td>R3 model full model variable significance test.</td>
<td>48</td>
</tr>
<tr>
<td>Table 3-16</td>
<td>Log likelihood for full model and reduced model. Model R3.</td>
<td>49</td>
</tr>
<tr>
<td>Table 3-17</td>
<td>Stress factor fractional polynomial result. Model R3.</td>
<td>49</td>
</tr>
<tr>
<td>Table 3-18</td>
<td>Excavation span fractional polynomial result. Model R3.</td>
<td>49</td>
</tr>
<tr>
<td>Table 3-19</td>
<td>PPV fractional polynomial result. Model R3.</td>
<td>50</td>
</tr>
<tr>
<td>Table 3-20</td>
<td>R3 model variable coefficients and confidence interval.</td>
<td>51</td>
</tr>
<tr>
<td>Table 3-21</td>
<td>Contingency table for Hosmer and Lemeshow test. R2 model.</td>
<td>53</td>
</tr>
<tr>
<td>Table 3-22</td>
<td>Contingency table for Hosmer and Lemeshow test. R3 model.</td>
<td>53</td>
</tr>
<tr>
<td>Table 3-23</td>
<td>Hosmer and Lemeshow significance test results. A significance value of greater than 0.05</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>suggests an acceptable calibration.</td>
<td></td>
</tr>
<tr>
<td>Table 3-24</td>
<td>Area under ROC curve qualitative interpretation (Hosmer Jr, Lemeshow &amp; Sturdivant 2013).</td>
<td>57</td>
</tr>
<tr>
<td>Table 3-25</td>
<td>Base parameter for plotting sensitivity chart.</td>
<td>61</td>
</tr>
<tr>
<td>Table 4-1</td>
<td>Examples of E2 classification.</td>
<td>79</td>
</tr>
<tr>
<td>Table 4-2</td>
<td>E4 geology factor rating (Heal 2010).</td>
<td>81</td>
</tr>
<tr>
<td>Table 4-3</td>
<td>Modified RDS classification (Heal 2010).</td>
<td>82</td>
</tr>
<tr>
<td>Table 4-4</td>
<td>Mine A rock UCS values.</td>
<td>86</td>
</tr>
<tr>
<td>Table 4-5</td>
<td>Mine A ground support systems E2 rating.</td>
<td>87</td>
</tr>
</tbody>
</table>

xiii
Table 4-6  Mine A rockburst RL715 RDP analyses summary

Table 4-7  Mine A rockburst RL730 RDP analyses summary

Table 4-8  Mine B support systems summary

Table 4-9  Mine B rockburst RL1120 RDP analyses summary

Table 4-10 Mine B rockburst RL1150

Table 4-11 Intact rock strength in MPa used for RDP model (Tannant, Martin & Kaiser 1997)

Table 4-12 Kidd Mine 2009 E2 classification

Table 4-13 Kidd Active Structures (Cooper 2012)

Table 4-14 Kidd 2009 rockburst 6700 level O1S RDP analyses summary

Table 4-15 Kidd 2009 rockburst 6800L 74XC RDP analyses summary

Table 4-16 Kidd 2009 rockburst 6900L 82XC RDP analyses summary

Table 4-17 Kidd 2009 rockburst 7000L RDP analyses summary

Table 4-18 Kidd 2009 rockburst 7100L RDP analysis summary

Table 4-19 Kidd 2011 rockburst support classification

Table 4-20 2011 Kidd Rockburst 7000L RDP analyses summary

Table 4-21 2011 Kidd Mine rockburst 7100L RDP analyses summary

Table 4-22 2011 Kidd Mine rockburst 7300L RDP summary

Table 4-23 2011 Kidd Mine rockburst 7400L RDP analyses summary

Table 4-24 Case study summary. Probabilities highlighted with red are conservative and yellow are optimistic. Good model performance are highlighted in green, fair in yellow and poor in red.

Table 4-25 Rock damage scale (Heal 2010)
1 Introduction

1.1 Defining the Rockburst Problem

In literature, the term ‘rockburst’ is used to describe a wide range of occurrences. This word first introduced by mining engineers, was often used to refer to large seismic events that occurred in underground mines and resulted in damage to an excavation (Gibowicz 1990). Damage to the tunnel, in this study, is defined as damage done to the rock mass and ground support system. Damage could exist in three distinct damage mechanisms, according to Kaiser, McCreath and Tannant (1996): bulking, ejection and rockfall.

Despite decades of collaboration and research, no widely accepted definition for the term ‘rockburst’ exists (Gibowicz 2009). In this thesis, the definition proposed by Ortlepp and Stacey (1994) will be adopted. The authors defined rockburst as:

“Damages that occurred in a tunnel as results of a seismic event, or which is directly associated with a seismic event”.

The earliest disastrous event that might be classified as a ‘rockburst’ possibly occurred at Altenberg tin mine in 1640 (Ortlepp 2006). The event was so severe that it was felt in Dresden, 45 km away. Extensive mine collapse did not allow the mine to reopen until 1860. In Australia, the earliest documented rockburst disaster can be traced back to 28th August 1917, where a reported seismic tremor led to multiple injuries and took the life of miner John Flannigan, at the Great Boulder Proprietary Mine (Kalgoorlie Miner 1917).

In recent years, rockburst has been reported from many countries, including South Africa (Ortlepp 1997), Chile (Orrego, Cuello & Rojas 2011), Russia (Kozyrev et al. 2013), Canada (Simser, Joughin & Ortlepp 2002) and China (Gong et al. 2012). Stacey (2013) concluded that rockburst is now a worldwide problem affecting both the underground mining and civil engineering projects.

Despite decades of research in mining-induced seismicity and associated rockburst, factors affecting their occurrences are not yet well understood (Heal
The relatively frequent occurrence of rockbursts represents a significant risk, both to personnel safety and profitability of mining operations.

There have been several rockburst related fatalities in recent years worldwide, including Australia (Melick 2006), Sweden (Sjöberg et al. 2011) and USA (Breland et al. 2011). In South Africa, rockburst risks are more severe; rockburst related fatalities are reported every year in significant numbers. This is shown in Figure 1-1.

The severity of rockburst risk was further highlighted by the recent closure of BHP Billiton’s Perseverance Mine, which was due to unmanageable seismic risks (Ker 2013).

1.2 Hazard and risk associated with seismicity and rockburst

The effect and implication of rockbursts from a mining operational perspective can vary depending on the circumstances. The consequences could range from being as minor as requiring no immediate action, up to as severe as write-off of reserve, permanent mine closure and even multiple fatalities. A seismically active mine may experience combinations of the above effects.

The pervasiveness of rockburst issues in many current underground mining operations suggests that they are still a major ground control challenge. Recent history in Australia has shown that the consequences of rockburst related fatalities have much greater effect and impact on the mine operation than other
fatalities. Common fatal accidents in an underground mine would generally result in the mine shutting down or part of it closing for a few days or weeks, at the most. The two most recent fatal accidents related to rockburst that occurred in Australia (Beaconsfield mine and Big Bell mine) have resulted in over a year of mine closure with mining methods re-engineered (Potvin & Wesseloo 2013a).

In the above case, the financial loss associated with seismicity and rockburst fatalities is far greater than any other type of fatality that could occur on a mine. This implies that rockburst and seismicity remain one of the most significant risks to the viability of seismically active mines.

Several seismic and rockburst risk management approaches are available today and are currently utilised by mines (Hudyma & Potvin 2009; Potvin & Wesseloo 2013a; Potvin 2009). Underpinning all these approaches, effective seismic monitoring and analysis are the key.

The Rockburst Damage Potential (RDP) method proposed by Heal, Potvin and Hudyma (2006), based on the Australian Centre for Geomechanics (ACG) rockburst database and further developed in Heal (2010), is an empirical index used in seismically active mines to evaluate rockburst damage potential. The index comprises of five factors accounting for the effect of local stress condition, ground support, excavation span, geology and the intensity of ground motion. The method combined these factors into a single rating value, RDP, through a multiplication relationship. However, by combining all five factors into one single index, the weighting of each variable relative to the resulted damage was not explicitly accounted for. This may potentially lead to a less than optimum analysis result.

1.3 Research hypothesis

This thesis is concerned with the variables from the ACG rockburst database used by RDP method. More specifically, it is concerned with the statistical significance or weighting of each predictor variable used, with respect to the severity of rockburst damage, or how effective each variable is at improving forecast of rockburst damage severity (RDS).

It is hypothesised that each variable associated with rockburst damage used in RDP method affects the severity of observed damage to various degrees, and
some of the variables are more influential than others. Consequently, an improvement in rockburst damage forecast may be achievable through recognising the weighting of each variable during damage assessment process.

This thesis assesses the statistical significance of each variable with respect to the RDS. If successful, it will provide a better understanding of the causes of rockburst damage occurring in an excavation subjected to dynamic loading and lead to an improved hazard assessment.

1.4 Proposed methodology

It is proposed that the ACG rockburst database be analysed in this study to determine the weighting of factors with respect to damage severity.

In order to assess the significance of factors affecting rockburst damage, variables representing damage severity and variables potentially affecting damage severity had to be identified from within the database.

The factor analysis (FA) technique was applied first to explore the underlying structures of the database and to determine the cross correlation between variables. A clear understanding of correlations among variables helped in statistically identifying outcome variables and potential predictor variables. Once they were identified, data reduction was carried out by selecting the most appropriate outcome variables and eliminating irrelevant variables from subsequent analysis.

Logistic regression was then used to determine the significance of factors in forecasting damage severity. The significance of variables in this study is defined as the ability of a variable to improve the forecast outcome. Logistic regression models were built to forecast the likelihood of exceeding designed RDS. Significant variables for each model were determined using the Wald and Log likelihood test. Linearity assumption was then checked for all continuous predictor variables using the fractional polynomial technique. Once all significant variables were determined, the goodness of fit (GOF) of the models was then assessed using the area under the Receiver Operating Characteristic (ROC) curve and Hosmer-Lemeshow (HL) method.
The significance of different variables affecting rockburst damage was then illustrated through plotting sensitivity of the forecasted likelihood of damage with respect to percentage change in input variables, while holding other variables constant.

To validate the damage forecasting performance of the derived regression models, a series of case studies consisting of more recent rockburst cases was carried out. The variable weight was validated through evaluating the performance of the logistic regression models on the newly collected rockburst cases.

1.5 Thesis structure

This thesis is structured as following:

Chapter 1 Introduction

This chapter described the rockburst phenomenon and defines the focus of this research and thesis hypothesis.

Chapter 2 Literature Review

This chapter reviews available literature on factors affecting RDS in underground mine excavations with specific focus on the study of factor weighting. This chapter builds the case and identifies the gap for the need of a statistical assessment of the significance of factors used to forecast damage.

Chapter 3 Multivariate Statistical Analyses

This chapter documents the steps in applying FA and logistic regression modelling to quantify the significance of factors affecting the severity of rockburst damage. The coefficient or weighting of the predictor variables are illustrated at the end of this chapter using a series of charts and plots.

Chapter 4 Case Study

This chapter documents the case studies carried out validating the performance of the regression models. The case study consists of four rockburst cases collected from three mine operations which the author had visited. The performance of the regression models is evaluated and discussed at the end of this chapter.
Chapter 5 Conclusion

This chapter summarises the findings resulted from this study and addresses the necessity of future work that needs to be carried out to further the understanding of rockburst damage causes.
2 Literature Review

2.1 Introduction

The sudden and often violent failure of rock occurring in underground mine excavation accompanying rockburst poses significant risk to the profitability of the operation, and to the safety of personnel and equipment. An example of violent rockburst damage is shown in Figure 2-1. Before 1993, rockburst was the first or second greatest contributor of fatality in South Africa (Gibowicz 2009).

![Figure 2-1](image.jpg) A violent rockburst damage occurred to one side of an excavation wall while the other side appears to be intact (Ortlepp 1997).

There are a wide range of practices and strategies for managing seismic and rockburst risks that are currently accepted and implemented in the mining industry. Based on discussion by Potvin and Wesseloo (2013a), the management of seismic risk could be broadly grouped into three categories:

- Seismic hazard reduction
- Personnel exposure reduction
- Rockburst damage potential reduction
Seismic hazard reduction generally involves implementing long-term strategies such as mining geometry and mining method changes. Although it is likely the most effective reduction method, it is difficult to achieve, time consuming and costly (Potvin & Wesseloo 2013a). Reduction of the exposure of personnel to rockburst damage hazard generally involves managing the time and duration of personnel working in hazardous areas.

Damage potential reduction generally involves implementing short- to mid-term strategies such as upgrading ground support and pre-conditioning (Potvin & Wesseloo 2013a). A dynamic yielding support system is commonly used in mines to reduce potential rockburst damage hazard, which could then result in less time lost and disruption to production.

Due to current limited understanding of the problem, which does not allow a deterministic support design, an empirical approach is often preferred (Potvin & Wesseloo 2013b). This approach involves quantifying factors affecting rockburst damage and comparing them to observed damage severity.

The objective of this chapter is to present a literature review on factors affecting rockburst damage in underground mine excavations. More specifically, the focus is on the studies of significance of influence of factors affecting rockburst damage.

2.2 Studies aimed at quantifying the significance of factors affecting rockburst damage

The influence of in-situ stress variation on the severity of rockburst was noticed in the Lucky Friday Mine rockburst study (Whyatt, Williams & Blake 1993). Three severe rockbursts were encountered during three consecutive development rounds, resulting in approximately 300 tonnes of displaced rock. It was concluded after the stress measurement campaign that the localised nature of the stress field coupled with strong, brittle, sulphide-altered quartzite strata was likely the dominant driving factor of these rockburst damages. The effect of other factors was not reported during this study.

The effect of localised stress variation on rockburst damage was also noted during a deep civil tunnelling project in Sweden (Martna & Hansen 1986). It was observed that in sections of the tunnel with high rock stresses, rockbursting and
rock instability accompanied by rock noise have occurred in a more frequent and violent manner. The dominant effect of in-situ stress on rockburst damage in this case is more evident, as excavation dimension and ground support were relatively consistent throughout the entire tunnel development.

A theoretical explanation of this effect was provided by Kaiser, McCreath and Tannant (1996). They suggested that larger in-situ stress creates a greater fracture depth, in which the fractured rock can be mobilised or even ejected under large dynamic loading.

During a ground support evaluation study, Morissette, Hadjigeorgiou and Thibodeau (2014) noted that at Creighton mine, despite being at a greater depth and with higher stress condition, they did not encounter more severe damage than in Copper Cliff and Coleman mines. This was interpreted as the result of an effective support system that has evolved over time. In this particular case, dynamic support was used to ‘offset’ the adverse effect of high stress. However, no quantitative assessment on the influence of high stress was mentioned or provided.

The presence of certain geological features was also observed to be dominant in some cases. During an investigation of a magnitude 3.6 rockburst in a deep South African gold mine, Durrheim et al. (1997) observed that rockburst damage was closely associated with the up-dip side of the excavation. It was concluded that this was due to the more inherently unstable orientation of the bedding relative to the sidewall of the excavation, and up-dip sidewall being significantly higher due to geology and development technique, resulting in an unstable structure configuration. The effect of geological features was determined to be the dominant factor causing damage in this case.

The influence on RDS from local geology was further studied by Reddy and Spottiswoode (2001) through conducting a rockburst simulation blast experiment. The aim was to study the influence of local geology and rock mass characteristics on deformation during a rockburst caused by controlled blast. They concluded that mining-induced fractures had the largest influence at this particular site and suggested that geological weakness could play a larger role at lower stress environment. Although Reddy and Spottiswoode (2001)
identified geological weakness as the most influential factor in determining final damage severity, the conclusion, however, was largely qualitative.

The presence of local active faults can also have a dominant effect on the resulted rockburst damage. In a case study conducted by Yao et al. (2010), rockburst damage was frequently observed around identified geological faults. In subsequent excavation stability assessment, they placed a greater emphasis on excavation located adjacent to seismically active structures. Although local stress condition and excavation dimension were also considered during the campaign, the significance of all factors affecting damage was only assessed qualitatively.

The prominent effect of mine faults on rockburst damage was also evident in a case study reported by Slade (2004). It was observed during the study that all damages were restricted to areas adjacent to large-scale faults. Following the study, one of the ‘high risk’ areas was determined to be drives located within 10 m from mine faults.

As seen from the above studies, rockburst damage is often dependent on several factors, and the influence of individual factors can vary. The subsequent damage likelihood assessment was often carried out qualitatively without explicitly quantifying the relative significance of factors that may affect excavation stability.

Durrheim et al. (1995) identified several more factors affecting RDS, such as mining geometry relative to geological structures, type of support system installed and pillar dimensions. It was concluded that local rock conditions and the support system play the most important role in determining the severity of damage sustained during a rockburst.

In an attempt to identify factors controlling the stability of an excavation subjected to dynamic loading, Albrecht and Potvin (2005) proposed a methodology which aims to maximise the separation of two cumulative plots of damage and no damage cases. This is also graphically illustrated in Figure 2-2.
This approach was applied for Big Bell Mine case study to identify significant factors affecting RDS. It was concluded that estimated peak particle velocity (PPV) at the boundary of the excavation is the most significant parameter affecting damage in the back, followed by drive orientation relative to foliation, major principle stress and span of excavation (Albrecht & Potvin 2005). These four factors are conceptually similar to some of the factors used in a later study by Heal, Potvin and Hudyma (2006). No quantitative study on significance between each factor contributing towards rockburst was performed.

The influence of dynamic loading induced by seismicity was also observed to be dominant in other studies. Gay (1993) noted that the general damage severity of rockburst increased with the magnitude of the seismic event. In another study, Lenhardt (1988) observed a profound influence of the distance and magnitude of rockburst on subsequent damage. It was possible to correlate damage severity to seismic event magnitude in spite of the interference of other factors such as geology, mining geometry and support types.

More conveniently, ground motion estimated using seismic event magnitude and distance from damage locations was frequently used to assess the damage potential. McGarr (1983) noted that it is best correlated with observed damage.

Although several studies completed in the past have attempted to relate ground motion to damage severity (Owen & Scholl 1981; Langefors & Kihlström 1978; St John & Zahrah 1987), in the complex mining environment where the variations in rock mass condition, geology, excavation dimension and ground
support are greater, the influence of other factors simply cannot be ignored. This is supported by the following literature.

Based on rockburst data from Creighton mine, Jesenak, Kaiser and Brummer (1993) attempted to relate RDS solely from estimated ground motion. Although some correlations were observed, they concluded that the remaining variation was likely due to other factors affecting damage, such as mining stress and geology. No further study quantifying the significance of these factors was carried out.

In another study, Liang, Hadjigeorgiou and Thibodeau (2011) analysed rockburst data collected from Vale’s Coleman and North Mine in Canada using multivariate statistic techniques. The authors first applied principle component analysis (PCA) to explore the general structure in the data, then projection to latent structures technique to study the correlation between damage-contributing variables and damage variables.

Through the analysis of Coleman mine data, Liang, Hadjigeorgiou and Thibodeau (2011) showed that:

- Deeper and wider excavations were likely to experience more severe damage
- More factors other than ground support control the severity of damage
- Damage severity represented using tonnage displaced is highly correlated with proximity to geological contact and structure

This study identified several factors and their relation with respect to damage severity. The presence of local geological structure and contacts was determined to be a strong factor influencing final damage severity in both case studies. However, its strength of association with respect to damage severity compared with other factors such as stress and excavation span was not quantitatively investigated.

Ground support upgrade has been used to ‘offset’ the influence of other adverse conditions such as high stress variation, large excavation span and large expected dynamic loading. This is shown in several studies previously discussed (Yao et al. 2010; Slade & Ascott 2007; Morissette, Hadjigeorgiou &
It is often seen that the ground support selection for rockburst conditions was carried out without assessing the weighting of factors relative to damage severity; that is, how significant a predictor variable is with respect to predicting damage severity.

The lack of quantification on the weighting between factors can also be seen in the Rock Damage Potential (RDP) method proposed by Heal, Potvin and Hudyma (2006).

Heal, Potvin and Hudyma (2006) combined five factors identified affecting rockburst damage into one single index RDP through a multiplication relationship to evaluate the likely rock damage severity. The RDP index comprising of five factors is shown in Equation 2.1. A more detailed description of RDP can be found in Appendix A.

\[
RDP = \frac{E_1 (\text{Stress Factor})}{E_2 (\text{Ground Support})} \times \frac{E_3 (\text{Span})}{E_4 (\text{Geology})} \times ppv
\]  

(2.1)

Where:

\( E_1 \): The ratio of \( \sigma_1 \) induced principle stress over intact rock Uniaxial Compressive Strength (UCS) expressed in percentage \( \left( \frac{\sigma_1}{\text{UCS}} \times 100 \right) \)

\( E_2 \): The support dynamic capacity in kJ/m\(^2\)

\( E_3 \): This factor indicates the maximum span of the section of excavation in metres

\( E_4 \): Geology factor accounts for the presence of unfavourable geological structures

\( PPV \): Estimated ground motion intensity for damaged location in m/s

The major principle stress was determined through numerical modelling of the damage site, and UCS value of rock mass was determined through rock sample testing (Heal 2010). The ground support capacity for five different support systems was determined through reviewing literature, laboratory testing and validation using rockburst simulation blast. The span of the excavation was determined through measurement on mine survey. The geology factor values were chosen arbitrarily based on preliminary investigation of the data and from
experience. Maximum ground motion was estimated from the measured event magnitude and calculated distance from damage site.

Logistic regression models were then fitted to the rockburst database using the single predictor variable RDP in an attempt to separate damages of various severities. Although the weighting within some of the factor was quantified prior to logistic regression fitting, the weighting between factors was not explicitly quantified during fitting because they were combined into one single predictor index.

It can be seen from Equation 2.1 that one-unit change (or 1% change) in each of the factors has an equal amount of influence on the predicted damage severity (RDP). However, this is not necessary the case, as suggested in the previous section of literature review, where some factors were stated to be more dominant in influence than others. The omission of factor weighting in the rockburst damage assessment process does not allow allocation of greater emphasis for factors that are potentially more influential, resulting in a less than optimum rockburst damage prediction.

2.3 Conclusions drawn from the literature

Through literature review on factors affecting rockburst damage in underground mine excavation, there is consensus on several findings. The following conclusions can be drawn:

- The effect of any individual factor affecting RDS cannot be sufficient enough to be related to the potential of level of damage
- The presence of unfavourable geology, local stress conditions, excavation span and estimated ground motion are common factors observed to affect the occurrence and severity of rockburst damage
- The strength of association between these factors and damage severity varies from case to case. One factor that is influential in one case study may not be in another
The assessment of the significance of factors affecting rockburst damage was often carried out qualitatively rather than quantitatively.

The literature review has also shown that little attention has been given to the study on the strength of association of factors affecting RDS, and how sensitive the resulting damage would be to changes in those contributing factors is unknown. During several excavation stability studies reviewed, the significance of factors affecting damage was often carried out qualitatively.

One of the reasons for the lack of quantitative assessment is that the assessment of rockburst damage is a highly complex and multi-dimensional problem, as discussed by Potvin and Wesseloo (2013b). The stability of an excavation does not only depend on one factor; it often depends on various factors. Another contributing cause is that some, if not all, of the factors such as the effect of geology and damage severity are often difficult to quantify numerically.

Nevertheless, a quantitative assessment of the significance of factors affecting rockburst damage will provide further insights into its occurrence and will also improve future excavation stability assessment, potentially resulting in more accurate damage forecast.

2.4 Issues to be addressed in this thesis

This study aims to investigate the weighting of factors affecting the stability of excavation under dynamic loading. That is, how sensitive the forecasted RDS is relative to the changes in each of the factors used in damage severity prediction. The analyses, which include a multivariate statistic component and a case study component, are carried out using the Australian Centre for Geomechanics rockburst database and a series of newly collected rockburst cases respectively.

This study will assist in understanding the relative significance of factors affecting rockburst damage in a more quantitative way. It could also potentially improve the damage forecast accuracy of the RDP method.
3 Multivariate Statistical Analyses

3.1 Introduction

The literature review has identified the lack of quantitative assessment on the strength of influence or weighting of factors affecting RDS. In keep with the objective of this thesis, the weighting of factors affecting rockburst damage is quantified in this chapter using multivariate statistical techniques.

Multivariate statistical techniques are used in this thesis, as the problem of rockburst damage is multi-dimensional and related to more than one parameter. Rockburst damage occurrence and severity are dictated by more than one variable, as suggested in the previous chapter. Bivariate analyses of damage severity criteria and predicting variable are unable to account for the complexity of the problem and capture the ‘whole picture’; therefore, its use may not be appropriate.

At this point, it is important to distinguish between predictor variables (independent variables or IV) and outcome variables (dependent variables or DV), often referred to in discrimination regression analyses. Tabachnick and Fidell (1996) defined independent variables (IV) as the differing conditions to which researchers expose subjects, or characteristics the subjects themselves bring, into the research situation. IV are often considered as predictor variables, as they predict or cause the dependent variable or outcome variable.

To maintain simplicity, only the most adequate outcome variable will be selected and used to quantify damage severity. There are a total of 13 variables in the ACG rockburst database. It is important to determine and distinguish between predictor variables and outcome variables, and to understand the correlation between variables. FA is the first technique used in this study to achieve this objective.

Once potential predictor variables and outcome variables are determined, regression modelling is then used to determine the relationship between the two. The GOF of the logistic regression model is rigorously tested to ensure that the model can effectively describe the observed dataset. Once the model fit is
deemed to be adequate, the weighting between variables affecting rockburst damage is then interpreted.

Although the two proposed multivariate statistic techniques were also used by Heal (2010), their applications here have very different emphasis and are used to achieve different research outcomes. Their application here is concerned with exploring the underlying structure within the database, and quantifying the weighting of factors affecting RDS so that a probabilistic estimate of an excavation exceeding different damage severity could be achieved.

3.2 ACG rockburst database

The Australian Centre for Geomechanics rockburst database used for this study contains 254 damage locations resulted from 83 rockburst cases collected from thirteen Australian and Canadian mines. The thirteen mines, all of which are underground, hard rock, mechanised and metalliferous, cover a wide range of geological settings and mining methods. Thirteen excavation-specific variables associated with each damage location were collected, of which some are qualitative and others are quantitative.

The dynamic loading resulting from a seismic event is often quantified using maximum ground motion expressed using PPV. Previously in the work undertaken by Heal (2010), PPV was estimated from seismic event magnitude and distance from damage site to seismic event using the far-field scaling law relationship provided by Hedley (1992). This relationship is shown in Equation 3.1.

\[
PPV = \frac{1.4 \times 10^{(M_R/2)}}{R}
\]

(3.1)

Where:

\[M_R = \text{Richter Scale Magnitude}\]

\[R = \text{Distance to event hypocentre}\]

However, the use of far-field scaling law to estimate ground motion has been criticised in a recent study by Kaiser and Cai (2013b). It was argued that a large portion of the cases in the database are within the near-field of the seismic event and that the use of far-field scaling law equation may result in
overestimated and unrealistic ground motions. The actual ground motion values at the damage locations are expected on average to be significantly lower than those estimated using far-field scaling law.

It was also argued that the scaling law, which is to be used for design purposes only, provides an upper bound value to the field-observed ground motions with a 90 to 95% confidence limit of not exceeding (Kaiser & Cai 2013b). In reality, the ground motion experienced at damage sites is likely to be lower than anticipated. In this study, a confidence limit level of 50% is selected to provide a more realistic and reasonable estimate of ground motion at damage sites.

In order to saturate the near-field ground motion, the scaling law provided by Potvin, Wesseloo and Heal (2010), as shown in Equation 3.2, is used to estimate the ground motion at damage location.

\[
PPV = \frac{C \cdot 10^{ \frac{1}{2} (M_R + 1.5) } }{R + r_o}
\]

Where: 
- \(C\): It is a constant depending on static stress drop. A value of 0.1 is used, which corresponds to 50% confidence limit at less or equal to 5 MPa static stress drop
- \(M_R\): Richter Scale Magnitude
- \(R\): Distance to event hypocentre
- \(r_o\): Seismic source radius

A more detailed description of the database and how parameters associated with each damage case were derived can be found in Appendix B.

3.3 Factor Analysis

3.3.1 General Description

Factor analysis or principle component analysis is a common multivariate statistic technique applied to a single set of variables where researchers are interested in discovering the underlying correlations among them (Tabachnick & Fidell 1996). The underlying correlations among variables are often referred to as factors or components. They are commonly used to summarise patterns of correlations among observed variables, and to reduce a large number of
observed variables down to a smaller number while maintaining sufficient amount of variance.

Variables that are more correlated with each other, but more independent of others, are grouped together to form factors or components. Each factor or component is representative of an underlying structure in a database.

FA, frequently used in psychological and social sciences studies, has been seen applied in the field of rockburst damage study. It has been used in recent years to study the underlying relationships among variables associated with rockburst damage occurrences (Morissette, Hadjigeorgiou & Thibodeau 2011; Morissette, Hadjigeorgiou & Thibodeau 2012; Morissette, Hadjigeorgiou & Thibodeau 2014; Liang, Hadjigeorgiou & Thibodeau 2011; Morissette, Hadjigeorgiou & Thibodeau 2013).

In this study, FA is used to explore the pattern among variables to help identify and distinguish between predictor variables, outcome variables and ‘noise’ variables so that a subsequent data reduction is possible.

The analysis process and results are presented here in three sections: data preparation, factor extraction and interpretation, and data reduction. Part of the data preparation was carried out using the software mXrap developed by ACG (Australian Centre for Geomechanics 2015), and the remaining analyses were carried out using statistical software package SPSS (Field 2013).

3.3.2 Data preparation

Prior to factor extraction, a series of checks and diagnostics must be applied to ensure that all analysis assumptions and prerequisites are met. This step is also essential to ensure the accuracy of the result and appropriateness of applying such a method.

PPV estimated from seismic event magnitude and distance between the event and damage location is a widely accepted parameter used to capture the dynamic loading induced by the remote seismic event for ground support selection and rockburst risk assessment (Morissette, Hadjigeorgiou & Thibodeau 2012). Therefore, to simplify the database and avoid potential bias introduced by including these two variables, seismic event magnitude and distance are omitted from further analyses, and only PPV is retained.
The understanding of the term ‘tonnes’, frequently used to quantify RDS, seems to vary between mine site practitioner and researchers. It is commonly seen that mine site practitioners define ‘tonnes’ as the weight of rock ejected into the excavation, whereas researchers define ‘tonnes’ as the weight of rock displaced (contained and ejected) as a result of rockburst.

RDS, which acts like a summary index of damage severity, is determined through assessing tonnage displaced or ejected, fracture density of failed rock and support system state. Therefore, the inclusion of tonnes is redundant. For this reason, tonnage is excluded from subsequent analyses.

Sample size adequacy

Sample size required for a FA depends on the strength of the correlation among variables (Tabachnick & Fidell 1996). A smaller sample size is required if the correlation among variables is strong, and a larger size is required if correlation is weak. Analysis results tend to be less reliable when estimated from an insufficient size sample, and an adequate size sample is ensuring the reliability of the result.

There seems to be no general agreement on the minimum sample size required for a reliable FA in statistical literature. Gorsuch (1983) and Kline (1979) recommended that the minimum number of cases to use for FA should be at least 100. Cattell (1978) recommended a minimum number of at least 250 to be used. Comrey and Lee (1992) offered a rough rating scale for adequate sample size in FA. This is shown in Table 3-1. Tabachnick and Fidell (1996) provided a rule of thumb that it is comforting to have at least 300 cases for FA. These recommendations were made specifically for the field of epidemiology study. Due to a general lack of such guidelines in other fields, Comrey and Lee’s (1992) guideline will be used in this study.

Although more data is always desirable, the current sample size of 254 meets the minimum requirement of a FA for all above recommendations. Therefore, sample size is adequate.
Table 3-1  Factor analysis sample size adequacy (Comrey & Lee 1992).

<table>
<thead>
<tr>
<th>Minimum number of cases</th>
<th>Qualitative scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Poor</td>
</tr>
<tr>
<td>200</td>
<td>Fair</td>
</tr>
<tr>
<td>300</td>
<td>Good</td>
</tr>
<tr>
<td>500</td>
<td>Very good</td>
</tr>
<tr>
<td>1000</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

b  Normality testing

Multivariate normality is the assumption that all variables, and all combinations of them, are normally distributed (Tabachnick & Fidell 1996). The analysis results will be enhanced if variables are normally distributed; if the variables are not, the results will be degraded.

However, as long as PCA and FA are used descriptively as convenient ways to summarise the relationship in a large set of observed variables, assumptions regarding to variable distribution are not enforced (Tabachnick & Fidell 1996). For this reason, variable normality will not be assessed.

c  Linearity testing

The assumption of linearity is that there is a linear relationship between two variables (Tabachnick & Fidell 1996). PCA and FA are based on Pearson correlation coefficient and do not reflect non-linear relationships. Analyses are degraded when linearity assumption fails and variable scale transformation is required.

Since the nature of this analysis is exploratory, which relaxes strict linearity assumption, only linearity among pairs of continuous variables is assessed through inspection of scatter plot. If both variables are normally distributed and linearly related, the scatter plot is oval-shaped. If two variables are non-linearly related, the scatter plot is curved.

The histograms for all continuous variables are plotted in Figure 3-1 and Figure 3-2.
It could be seen from above figures that there is some skewness in distribution for span, PPV and failure depth. Scatter plot matrixes for all continuous variables are constructed and shown in Figure 3-3.
It can be seen from the Figure 3-3 that the majority of charts exhibit a random scatter pattern with no distinctive correlation. This indicates that the correlations among variables are weak in this data set. Nevertheless, no scatter plot displays a visible curvature, suggesting that linearity assumption among continuous variables is adequate for this study.

- **Multicollinearity and Singularity**

Multicollinearity and singularity are problems with a correlation matrix that occur when variables within the dataset are extremely correlated with each other (Tabachnick & Fidell 1996). With multicollinearity, the variables are highly correlated ($R^2>0.9$); with singularity, variables are redundant since one is a linear combination of the others.

For the purpose of FA, extreme multicollinearity and singularity introduce bias into analysis results and dictate the real result (Tabachnick & Fidell 1996). When determinant of the correlation matrix approaches zero, multicollinearity and singularity may exist. Further investigation of squared multiple correlation (SMC) for each variable may confirm the existence of multicollinearity or singularity.
SMC for each variable is calculated where it serves as an outcome variable with all other variables as predictor variables. It is a measure of how well the variable can be represented with the remaining variables in the data set. If SMC is one, singularity exists; if SMC exceeds one, multicollinearity is present. The default of many statistical programs for detecting extreme multicollinearity ranges from 0.99 to 0.9999, and it was advised by Tabachnick and Fidell (1996) that the researcher should take control of adjusting the tolerance level. For this study, a SMC threshold of 0.99 is selected as the minimum cut-off threshold for detecting extreme multicollinearity. A threshold of 0.99 was selected as conservative measure of detecting multicollinearity.

A preliminary FA run is carried out and the determinant of the correlation matrix is calculated to be 0.053. This indicates that multicollinearity or singularity may exist among variables. The SMC for each variable are calculated to further test their existence. The SMC for all variables are shown in Table 3-2.

<table>
<thead>
<tr>
<th>Variable</th>
<th>SMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress Factor</td>
<td>0.803</td>
</tr>
<tr>
<td>Support Capacity</td>
<td>0.765</td>
</tr>
<tr>
<td>Excavation Span</td>
<td>0.455</td>
</tr>
<tr>
<td>Geology Factor</td>
<td>0.279</td>
</tr>
<tr>
<td>RDS</td>
<td>0.902</td>
</tr>
<tr>
<td>SDS</td>
<td>0.858</td>
</tr>
<tr>
<td>Density</td>
<td>0.187</td>
</tr>
<tr>
<td>Failure Depth</td>
<td>0.678</td>
</tr>
<tr>
<td>Wall(0)/back(1)</td>
<td>0.464</td>
</tr>
<tr>
<td>PPV</td>
<td>0.146</td>
</tr>
</tbody>
</table>

As it can be seen from above table that no SMC values equal to one, which indicates that singularity does not exist. SMC of one variable is greater than 0.9, suggesting the existence of some multicollinearity. However, no extreme multicollinearity exists and, for the purpose of this study, some multicollinearity can be tolerated. Therefore, multicollinearity and singularity do not pose any concern in this study.
Outlier cases in data is a pervasive problem in most data analysis, as they often lead to results that do not generalise due to the results being overly determined by the outliers (Tabachnick & Fidell 1996). In multivariate analyses, they are cases that have unusual pattern of scores. Their individual values may be within the expected range, but when two or more variables are considered together, they then become apparent.

The Mahalanobis Distance (MD) technique has many different uses in multivariate statistical analysis (De Maesschalck, Jouan-Rimbaud & Massart 2000). It is used in this study to detect multivariate outliers. MD is a multidimensional version of the standardized z score, which is defined as the number of standard deviation an observation of datum is above the sample mean.

Mahalanobis distance squared ($D^2$) measures the distance of a case from the multidimensional centroid of the entire data set. Distribution of $D^2$ follows a chi-square distribution with the degrees of freedom equal to the numbers of variables included in the calculation. Conservatively speaking, a case is a multivariate outlier if the probability or significance associated its $D^2$ is 0.001 or less (Meyers, Gamst & Guarino 2006).

MD is computed for all 254 damage cases in the database, including 10 variables. These variables are stress condition, ground support, excavation span, geology factor, RDS, Support Damage Scale (SDS), failure depth, density, PPV and wall/back. Chi-square significance with the degrees of freedom equal to 10 was computed for $D^2$ index, and all cases with significance equal or less than 0.001 were filtered out for further investigation.

A total number of five cases were detected to be multivariate outlier. These cases together with their ten variable values are listed in Table 3-3. It is important to investigate the causes why these cases were rendered as outliers so that the unreliable variables can be identified. The potential variables which rendered them as outliers are summarised as following:

1. BMS 3a: Failure depth is overestimated and geology is not correctly assigned.
2. BMS 3b: Damage severity was underestimated.

3. BMS 4a: Cause of damage is unknown and it may be pre-existing; it was assumed that the 2.7 event is the cause.

4. BMS 15a: Damage occurred within a large open stope, not within the scope of this study of regular supported drives.

5. Kanowna Belle 4a: Damage was not documented in damage report.

In summary, all five cases are a result of inconsistent interpretation or samples from data population for different scopes of study. The interpretation inconsistency was likely due to insufficient data available in the damage report and where educated assumptions had to be made.

Due to the small number of outlier cases presented in the database and lack of detailed rockburst report for improved re-interpretation, removal of these cases is chosen to minimise the influence of outliers.
Table 3-3  Multivariate outlier cases with MD² significance less than 0.001.

<table>
<thead>
<tr>
<th>Mine</th>
<th>No</th>
<th>Stress Factor</th>
<th>Support Capacity</th>
<th>Span</th>
<th>Geology Factor</th>
<th>RDS</th>
<th>SDS</th>
<th>PPV</th>
<th>Failure Depth</th>
<th>Density</th>
<th>Wall/Back</th>
<th>MD</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMS</td>
<td>3A</td>
<td>67</td>
<td>10</td>
<td>11</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>0.11</td>
<td>6</td>
<td>4300</td>
<td>1</td>
<td>49.46</td>
<td>0</td>
</tr>
<tr>
<td>BMS</td>
<td>3B</td>
<td>67</td>
<td>25</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0.11</td>
<td>1</td>
<td>4300</td>
<td>1</td>
<td>30.77</td>
<td>0.0006</td>
</tr>
<tr>
<td>BMS</td>
<td>4A</td>
<td>76</td>
<td>10</td>
<td>6</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>0.25</td>
<td>5</td>
<td>4300</td>
<td>1</td>
<td>36.28</td>
<td>0.0001</td>
</tr>
<tr>
<td>BMS</td>
<td>15A</td>
<td>50</td>
<td>10</td>
<td>30</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>0.21</td>
<td>3</td>
<td>4300</td>
<td>1</td>
<td>64.25</td>
<td>0</td>
</tr>
<tr>
<td>K3</td>
<td>4A</td>
<td>71</td>
<td>10</td>
<td>20</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>0.28</td>
<td>5</td>
<td>2800</td>
<td>1</td>
<td>38.38</td>
<td>0</td>
</tr>
</tbody>
</table>
A large data set is factorable only if there are several sizable correlations (Tabachnick & Fidell 1996). If no significant correlation among variables exists, the use of FA may not be appropriate.

The factorability is first checked through inspecting the correlation matrix. The correlation matrix is simply a linear regression of one variable against another presented in matrix form. This is shown in Table 3-4. If a data set is factorable, several correlations within the correlation matrix should be in excess of 0.3 (Tabachnick & Fidell 1996).

Kaiser’s measure of sampling adequacy is also used to further confirm the data set’s factorability. A Kaiser’s measure value of minimum 0.6 is recommended if a data set is factorable (Kaiser 1974).

As it could be seen from the Table 3-4, four pairwise correlations have $\text{R}^2$ values greater than recommended minimum of 0.3, which indicates that there are sufficient number of correlations in the data set for FA to be applied. The Kaiser measure of sampling adequacy is calculated to be 0.622, which is greater than recommended value of 0.6, further supporting the hypothesis. Therefore, factorability of the data set is adequate for this study.
Table 3-4  Correlation matrix for factorability assessment. Correlation strength greater than 0.3 are highlighted in bold.

<table>
<thead>
<tr>
<th></th>
<th>Support Capacity</th>
<th>Excavation Span</th>
<th>Geology Factor</th>
<th>RDS</th>
<th>SDS</th>
<th>Density</th>
<th>Failure Depth</th>
<th>Wall(0)/Back(1)</th>
<th>PPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress Factor</td>
<td>0.314</td>
<td>-0.274</td>
<td>0.136</td>
<td>-0.080</td>
<td>-0.013</td>
<td>-0.094</td>
<td>0.056</td>
<td>-0.075</td>
<td>-0.099</td>
</tr>
<tr>
<td>Support Capacity</td>
<td>0.052</td>
<td>-0.083</td>
<td>-0.253</td>
<td>-0.222</td>
<td>-0.060</td>
<td>0.001</td>
<td>0.213</td>
<td>0.136</td>
<td></td>
</tr>
<tr>
<td>Excavation Span</td>
<td>-0.063</td>
<td>0.106</td>
<td>0.053</td>
<td>0.080</td>
<td>0.140</td>
<td>0.087</td>
<td>0.098</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geology Factor</td>
<td>-0.297</td>
<td>-0.265</td>
<td>-0.092</td>
<td>-0.243</td>
<td>-0.088</td>
<td>-0.085</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RDS</td>
<td></td>
<td></td>
<td></td>
<td>0.881</td>
<td>0.182</td>
<td>0.640</td>
<td>-0.041</td>
<td>0.195</td>
<td></td>
</tr>
<tr>
<td>SDS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.132</td>
<td>0.576</td>
<td>-0.085</td>
<td>0.187</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.013</td>
<td>0.040</td>
<td>0.081</td>
</tr>
<tr>
<td>Failure Depth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.131</td>
<td>0.105</td>
<td></td>
</tr>
<tr>
<td>Wall(0)/Back(1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.010</td>
</tr>
</tbody>
</table>
Outliers among variables are those variables in the data set that are unrelated to other variables and the first few factors extracted (ranked by variance accounted for). In other words, these variables are independent from the remaining variables in the database and, therefore, can be considered as ‘noise’ and excluded from subsequent analysis. Factors extracted that rely on these variables are often unreliable since they account for little variance and are often defined by just one or two variables (Tabachnick & Fidell 1996).

The SMC values of variables and factor loading index are commonly used to screen for these variables. The factor loading indexes are indications of the strength of association between variable and the extracted factor. It varies from 0 to 1. The greater the loading number, the more the variable is a pure measure of the factor. Comrey and Lee (2013) provided a guide of interpreting factor loading index, which is shown in Table 3-5. Percentage of variance denotes the variance of the data variable shares with the factor.

<table>
<thead>
<tr>
<th>Factor Loading Index</th>
<th>% of variance</th>
<th>Qualitative Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 0.71</td>
<td>50</td>
<td>Excellent</td>
</tr>
<tr>
<td>&gt; 0.63</td>
<td>40</td>
<td>Very good</td>
</tr>
<tr>
<td>&gt; 0.55</td>
<td>30</td>
<td>Good</td>
</tr>
<tr>
<td>&gt; 0.45</td>
<td>20</td>
<td>Fair</td>
</tr>
<tr>
<td>&gt; 0.32</td>
<td>10</td>
<td>Poor</td>
</tr>
</tbody>
</table>

Outlier variables generally have low SMC values, as they are not well related to other variables in the data set and not correlated with first few factors extracted. From Table 3-6, assuming a SMC cut-off of 0.5, three variables were identified to be potentially variable outliers: geology factor, density and span.
Following identifying three potential outlier variables, a preliminary FA run was carried out using a principle component extraction technique followed by the Varimax rotation technique. Three components were extracted and deemed to be significant with eigenvalue greater than 1, based on eigenvalue criterion (Kaiser 1960). The factor loading matrix is shown in Table 3-7.

### Table 3-6 Variable SMC value for outlier among variable removal. Produced following outlier cases removal.

<table>
<thead>
<tr>
<th>Variable</th>
<th>SMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress Factor</td>
<td>0.764</td>
</tr>
<tr>
<td>Support Capacity</td>
<td>0.798</td>
</tr>
<tr>
<td>Excavation Span</td>
<td>0.470</td>
</tr>
<tr>
<td>Geology Factor</td>
<td>0.311</td>
</tr>
<tr>
<td>RDS</td>
<td>0.903</td>
</tr>
<tr>
<td>SDS</td>
<td>0.862</td>
</tr>
<tr>
<td>Density</td>
<td>0.414</td>
</tr>
<tr>
<td>Failure Depth</td>
<td>0.740</td>
</tr>
<tr>
<td>Wall/back</td>
<td>0.589</td>
</tr>
<tr>
<td>PPV</td>
<td>0.647</td>
</tr>
</tbody>
</table>

### Table 3-7 Factor loading matrix for outlier variable screening. Significant variables with loading number absolute value greater than 0.32 are highlighted in bold.

<table>
<thead>
<tr>
<th>Variable</th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
<th>PC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress Factor</td>
<td>0.034</td>
<td>0.201</td>
<td><strong>0.847</strong></td>
<td>-0.078</td>
</tr>
<tr>
<td>Support Capacity</td>
<td>-0.157</td>
<td><strong>0.790</strong></td>
<td>0.331</td>
<td>0.197</td>
</tr>
<tr>
<td>Excavation Span</td>
<td>0.094</td>
<td>0.243</td>
<td><strong>-0.619</strong></td>
<td>0.138</td>
</tr>
<tr>
<td>Geology Factor</td>
<td><strong>-0.431</strong></td>
<td>-0.266</td>
<td>0.209</td>
<td>-0.104</td>
</tr>
<tr>
<td>RDS</td>
<td><strong>0.914</strong></td>
<td>-0.193</td>
<td>-0.052</td>
<td>0.165</td>
</tr>
<tr>
<td>SDS</td>
<td><strong>0.888</strong></td>
<td>-0.217</td>
<td>0.032</td>
<td>0.157</td>
</tr>
<tr>
<td>Density</td>
<td>0.045</td>
<td>-0.131</td>
<td>-0.190</td>
<td><strong>0.599</strong></td>
</tr>
<tr>
<td>Failure Depth</td>
<td><strong>0.833</strong></td>
<td>0.193</td>
<td>0.013</td>
<td>-0.093</td>
</tr>
<tr>
<td>Wall(0)/back(1)</td>
<td>0.064</td>
<td><strong>0.673</strong></td>
<td>-0.311</td>
<td>-0.188</td>
</tr>
<tr>
<td>PPV</td>
<td>0.131</td>
<td>0.154</td>
<td>0.011</td>
<td><strong>0.778</strong></td>
</tr>
</tbody>
</table>

A principle component extraction technique is used here, as it is a commonly used factor extraction technique (Tabachnick & Fidell 1996). It aims to extract maximum variance from the data set with each component. Varimax is a commonly used orthogonal rotation technique. It maximises the interpretability of the extracted components. Regardless of the extraction technique used and
in practice, the results share remarkable similarities, and differences are often slight (Velicer & Jackson 1990).

Using a minimum loading number cut-off of 0.32, geology factor is deemed to be significantly associated with the first factor and therefore unlikely to be a variable outlier. From a practical engineering perspective, geology was frequently seen to be a dominant factor controlling the excavation stability in rockbursting conditions. Therefore, it cannot be excluded from subsequent analysis.

Density, on the other hand, is only associated with the fourth extracted component, which accounts for 10% of the total variance in the data set. This suggests that it is largely irrelevant to other variables or components in the data set. Practically speaking, density was not seen to be significantly related to resulted RDS. Therefore, it is excluded from further analysis.

It could be seen from the above table that span is only associated with the third extracted factor, suggesting that it may be an outlier variable. However, large excavation spans are frequently seen associated with severe rockburst damages; therefore, it cannot be excluded from this study.

Geology factor and span are retained; density is omitted from subsequent analysis.

3.3.3 Factor Extraction and Interpretation

Following data preparation, a final run of factor extraction was carried out using a principle components extraction method and the Varimax rotation technique. Nine variables were used in this run: stress condition, ground support capacity, excavation span, geology factor, rock damage scale, SDS, failure depth (t), wall/back and PPV.

The extracted component and their associated eigenvalues and variance are shown in Table 3-8. Eigenvalue for a component indicates the amount of variance it explicitly accounts for among all components extracted.
Latent Root Criterion (or Eigenvalue criterion) specifies that factors with an eigenvalue greater than 1 should be retained for interpretation (Meyers, Gamst & Guarino 2006). Based on this criterion, three components should be retained for interpretation.

Scree plot is also used here to confirm the number of components to be retained for interpretation. The number of components to retain for interpretation on a Scree plot is determined through inspecting the descending slope. The number is where the slope of the curve flattens out. Scree plot is shown in Figure 3-4.

<table>
<thead>
<tr>
<th>Component</th>
<th>Eigenvalue</th>
<th>% of Variance</th>
<th>Cumulative%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.668</td>
<td>29.642</td>
<td>29.642</td>
</tr>
<tr>
<td>2</td>
<td>1.409</td>
<td>15.659</td>
<td>45.301</td>
</tr>
<tr>
<td>3</td>
<td>1.347</td>
<td>14.962</td>
<td>60.263</td>
</tr>
<tr>
<td>4</td>
<td>0.990</td>
<td>10.996</td>
<td>71.260</td>
</tr>
<tr>
<td>5</td>
<td>0.875</td>
<td>9.726</td>
<td>80.985</td>
</tr>
<tr>
<td>6</td>
<td>0.798</td>
<td>8.866</td>
<td>89.851</td>
</tr>
<tr>
<td>7</td>
<td>0.427</td>
<td>4.750</td>
<td>94.601</td>
</tr>
<tr>
<td>8</td>
<td>0.375</td>
<td>4.166</td>
<td>98.767</td>
</tr>
<tr>
<td>9</td>
<td>0.111</td>
<td>1.233</td>
<td>100.000</td>
</tr>
</tbody>
</table>

Figure 3-4  Scree plot for determining the number of components to retain.
Based on Scree plot, a total of three components to retain seems to be reasonable, since component 4 indicates a sharper decline in slope from component 3. Based on the two criterion, three components are retained for interpretation.

The rotated factor loading matrix of the three components is given in Table 3-9. The three factors account for a total of 60% of the total variance in the data set, which is considered to be acceptable according to the recommended value of between 50 to 75% (Tabachnick & Fidell 1996).

<table>
<thead>
<tr>
<th></th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress Factor</td>
<td>0.027</td>
<td>0.167</td>
<td>0.875</td>
</tr>
<tr>
<td>Support Capacity</td>
<td>-0.140</td>
<td>0.807</td>
<td>0.324</td>
</tr>
<tr>
<td>Excavation Span</td>
<td>0.097</td>
<td>0.276</td>
<td>-0.640</td>
</tr>
<tr>
<td>Geology Factor</td>
<td>-0.429</td>
<td>-0.285</td>
<td>0.191</td>
</tr>
<tr>
<td>RDS</td>
<td>0.932</td>
<td>-0.157</td>
<td>-0.070</td>
</tr>
<tr>
<td>SDS</td>
<td>0.910</td>
<td>-0.183</td>
<td>0.003</td>
</tr>
<tr>
<td>Failure Depth</td>
<td>0.797</td>
<td>0.172</td>
<td>0.041</td>
</tr>
<tr>
<td>Wall(0)/back(1)</td>
<td>-0.003</td>
<td>0.631</td>
<td>-0.190</td>
</tr>
<tr>
<td>PPV</td>
<td>0.267</td>
<td>0.298</td>
<td>-0.185</td>
</tr>
</tbody>
</table>

One should be cautious when interpreting total variance accounted for by the extracted factors. Total variance can be interpreted as all variation introduced by all variables in the data set, variance accounted for measuring the amount of variation ‘captured’ by the extracted correlation among variables (called component or factor). Total variance accounted for should be treated as a prerequisite criterion rather than a GOF indicator during analysis and interpretation.

As previously explained, factor loading numbers in Table 3-9 are representations of correlation between variables and extracted components. The greater the loading number, the more the variable is a pure measure of the component. The extracted three components are interpreted separately based on the variables they are significantly related to.
Component 1 is positively correlated with RDS, SDS and failure depth, and negatively correlated with geology. From a practical engineering standpoint, this component can be interpreted as a representation of general damage severity since it is strongly correlated with three damage severity variables. This positive loading number for RDS, SDS and failure depth confirms the statistical similarities among them, of which one should be selected as an outcome variable.

The negative weak correlation of geology to component 1 suggests that there is an inverse relationship between geology and damage severity, and geology may be the most significant predictor variable. This is intuitively correct since the presence of unfavourable geology (low value) is frequently observed to be associated with severe damages.

Component 2 is well represented with ground support and wall/back. This component can be interpreted as ground support capacity difference between wall and back.

The positive loading numbers for wall/back and support capacity suggest that for damage occurred in the back (value equals to 1), ground support capacity was generally higher. This observation may be largely due to the installation of high static capacity support tendons in the back of drives, such as rebar and cable bolt.

Component 3 is well represented with stress condition, ground support capacity and excavation span. Since stress condition has the highest loading index, this component can be interpreted as a characteristic of damage location in a high stress condition.

The positive loading number for support capacity and stress condition suggests that wherever rockburst damage is observed in high stress conditions, excavation is more likely to be supported with a higher capacity support system.
The negative loading number for excavation span suggests that damage occurred in high stress conditions is generally associated with smaller excavation span. This may appear to be counter-intuitive since larger excavation in high stress conditions will be more vulnerable than smaller excavations. However, this observation may be due to the excavations in high stress conditions being generally smaller than in low stress conditions, which resulted in more small span damage cases collected.

### 3.3.4 Data Reduction

In Section 3.3.2, density of rock was removed as an outlier among variables. It was found that density of rock is not significantly associated with other variables in the data set or the significant factor extracted.

PCA suggests that rock damage scale (RDS), SDS and failure depth are statistically all closely correlated with each other and can be used to represent damage severity. Since all three variables are statistically similar, it is then counter-intuitive to include all three variables in subsequent analysis. For the purpose of quantifying rockburst damage and damage likelihood forecast, one outcome variable that can appropriately capture the overall severity is sufficient.

RDS is a categorical index that quantifies the general severity of damage, which includes tonnes displaced, extent of the damage and state of the support system. SDS is a categorical index similar in concept to that of RDS. However, its use is only concerned with the general state of the support system at damaged locations and does not reflect the overall damage severity such as failure depth. SDS is redundant in the presence of RDS since RDS already contains a support damage component. A detailed classification table for both indexes can be found in Appendix C.

Failure depth at a damage location is determined predominantly through physically measuring the depth of failure during rehabilitation. In cases where physical measurements are not possible, educated guesses had to be made based on the degree of bulking, which introduces a certain level of subjectivity. Ambiguity can also occur when failure depths of two damage locations are the same and when rock is contained at one location but not at the other. For instance, damage with 0.5 metres of failure depth with rock ejected into the
excavation would have a higher severity than a damage location of 0.5 metres of failure depth with rock contained by support system. For the above concerns, failure depth is also not a good parameter to quantify damage severity.

Since RDS already has a component quantifying support damage severity, which makes SDS redundant in the presence of RDS, RDS is selected in this study as the parameter to use to quantify damage severity.

In summary, RDS is selected as the most appropriate outcome parameter out of four variables representative of damage severity. Rock density is deemed to be independent from other variables in the database and excluded from subsequent analysis. The event magnitude and distance to event are excluded from further analyses, and PPV is retained as the only parameter to represent dynamic loading.

Six potential damage contributing factors remain and are used in the next analysis for regression modelling. They are stress factor, support capacity, excavation span, geology factor, PPV and wall/back.

3.4 Logistic Regression

3.4.1 General Description

Regression models have become an integral component of many modern data analyses concerned with describing the relationship between a dependent variable and one or more predictor variables (Hosmer & Lemeshow 2000).

While many regression models are available, logistic regression modelling is used here to delineate between different severities of damage with all factors used as individual predictor variables. It is used here because of its superior ability to deal with problems of binary or categorical outcomes than other type of regression technique (Karp 1998). Its probabilistic nature is also more suited to the study of rockburst problems due to its high complexities.

A logistic regression model allows one to predict a discrete outcome such as group membership from a set of variables that may be continuous, discrete, dichotomous or a mix (Tabachnick & Fidell 1996). A logistic regression model utilises a non-linear transformation, called the link function, to convert a linear combination of predictor variables to a probability scale of positive outcome.
occurring (0 to 1). The linear combination of the predictor variables relationship is illustrated using Equation 3.3 and logit transformation using Equation 3.4.

\[
z = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots + \beta_i X_i = \alpha + \sum_1^i \beta_i X_i
\]  

(3.3)

\[
p = \frac{1}{1+e^{-z}}
\]  

(3.4)

Where:

- \( z \) is the linear combination of all predictors
- \( \alpha \) is the regression constant
- \( \beta \) are the regression coefficients for variables
- \( X \) are the predictor variables
- \( p \) is the estimated probability value

The value of coefficient \( \beta \) determines the relationship between predictor variables and outcome variables (Peng, Lee & Ingersoll 2002). When \( \beta \) is greater than zero, larger values of predictor variables are associated with a higher probability of truth occurring. Conversely, if \( \beta \) is less than zero, larger values of predictors are associated with a lower probability of truth occurring.

Another cumulative Gaussian probability model transformation is also available. The choice of which link function to use depends on the underlying relationship between the outcome variable and the predictors (Peng et al. 2002). However, the standard and Gaussian transformations are very similar in shape, with the Gaussian models giving similar values to the standard model over the region of most interest (0.1 to 0.9), but being more difficult to calculate (Lloyd 1999). For these reasons, the standard model is used in this study in preference over Gaussian models.

The application of logistic regression frequently seen in medical and health science studies has expanded into geotechnical engineering in recent years. During a rock mass cavability study, Mawdesley, Trueman and Whiten (2001) incorporated two predictor variables through logistic regression analysis to delineate between different zones of stability. In a study of coal mine roof support design, Lawrence (2009) utilised three predictor variables in logistic regression to solve for the stable-failure boundary. In another study of roof
stability study, Palei and Das (2009) applied the same regression modelling technique with seven variables to delineate between accidents of different severity.

This section documents the steps of building the logistic regression models. Firstly, outcome variables are grouped into three categories based on their corresponding operational implications. The number of logistic regression models required is then determined. Following the model building, the GOF is tested through assessing the models’ calibration and discrimination abilities. Once the fitted models were deemed to be adequate, the variable coefficients or weighting of variables can then be interpreted.

3.4.2 Outcome variable regrouping

Rock Damage Scale was determined in the previous section as the most appropriate parameter available in the database to quantify damage severity. Although RDS classification describes the observed physical rockburst damage in detail, its implications on an operational level are not explicitly specified. That is, the impact associated with different severities of damage on the operation is not well specified.

This effect can be seen from a ground support study carried out by Mikula (2013), where the five-class RDS was grouped into three categories based on operational implications. This grouping technique is illustrated in Table 3-10.

<table>
<thead>
<tr>
<th>RDS</th>
<th>Tonnes Displaced</th>
<th>Rating</th>
<th>Operational Implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Nil</td>
<td>Acceptable</td>
<td>Damage is sufficiently limited that it does not need repair</td>
</tr>
<tr>
<td>R2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3</td>
<td>&lt;10</td>
<td>Tolerable</td>
<td>Damage requires a level of repair or rehabilitation, however, effort and cost can be tolerated</td>
</tr>
<tr>
<td>R4</td>
<td>&lt;100</td>
<td>Intolerable</td>
<td>Damage is extensive that effort and cost would be high</td>
</tr>
<tr>
<td>R5</td>
<td>&gt;100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Depending on exposure, these may also translate into risk to personal.

Mikula (2013) noted during the rockburst damage study that the original RDS classification possesses little meaning on a practical level and R3 was the most severe damage that could be economically rehabilitated. For this reason, RDS
regrouping was carried out so that it could be interpreted and understood from an operational perspective.

A similar grouping approach was also adopted in a rockburst damage study by Turcotte (2014), where the damage severity variable RDS was grouped into three categories based on the tonnage displaced value: low zone (less than 1 tonne), transition zone (1 to 10 tonnes) and high zone (over 10 tonnes). This is shown in Figure 3-5.

![Figure 3-5](image)

*Figure 3-5  Ground support performance at LaRonde Mine (Turcotte 2014).*

In order to assign RDS a more practical interpretation, the same regrouping technique used by Mikula (2013) is also adopted in this study. Three outcome groups are used for subsequent analysis: acceptable (R1 & R2), tolerable (R3) and intolerable (R4 & R5).

One other reason for regrouping the outcome variable down to three categories is due to the uncertainties lying within the causes leading to the difference in damage severity. That is, it is not known whether the minor difference in damage severity, i.e. between R4 and R5, was a result of difference in the five predictor variables used. These variations in observed damage severity may also be due to other factors that were not explicitly accounted for in this study, such as support installation quality and corrosion. Therefore, it is
counter-intuitive to demand a ‘high resolution’ result while providing the model with only a few variables with unknown predictabilities or relevance.

The last reason that the regrouping of outcome variables was adopted in this study is due to insufficient sample size of R5 cases. An insufficient sample size for one particular outcome can often result in an unstable estimate of coefficients and an overestimated confidence interval, sometimes even resulting in failure to converge for a maximum likelihood estimate. During the fitting of a logistic regression model to separate R5 scale damage from the remaining cases, only 27 cases of R5 scale cases were available in the total 254 damage cases. This resulted in poorly estimated variable coefficients and large estimated confidence intervals, as shown in Figure 3-6.

![Fitted Logistic Regression Lines](image)

*Figure 3-6  RDP fitted logistic regression lines. Reproduced from Heal (2010). Dashed lines are 90% confidence interval.*

It can be seen from Figure 3-6 that the fitted logistic regression line for R5 (solid red) is considerably far from the R3 and R4 lines. The 90 percentile interval for R5 (dashed red) is significantly larger than those of R3 and R4, and indicates an overestimated confidence interval.

Due to these concerns discussed above, the outcome variable RDS is regrouped to a three-class outcome based on the operational implications. Two
LR models are required to separate three outcome categories. The first LR model (model R2) is fitted to separate acceptable cases and unacceptable cases (tolerable & intolerable), which yields the probability of exceeding R2 damage severity. The second LR model (model R3) is fitted in order to separate tolerable cases (acceptable & tolerable cases) and intolerable cases, which yields the probability of exceeding R3 damage severity.

3.4.3 Logistic Regression Model Fitting

The logistic regression model building process based on Hosmer Jr, Lemeshow and Sturdivant (2013) can be broadly grouped into four steps: predictor variable selection, predictor variable linearity testing, interaction assessment and model GOF assessment. This section presents the results and discusses the findings of the first two steps. The GOF assessment is presented in Section 3.4.4.

Following variable selection, one crucial assumption of linearity has to be verified. The linearity assumption in logistic regression is that all predictor variables are related linearly to the outcome variables (Harrell 2001). If a non-linearity component is found, appropriate transformation of the variable guided by subject knowledge is then required. Of several linearity testing techniques available, a fractional polynomial technique first introduced by Royston and Altman (1994) is used here for its simplicity and ease of understanding.

Due to the complexity and current poor understanding of the rockburst damage problem, it is unlikely that the five predictor variables are able to reliably and accurately predict its occurrences. For this reason, unjustifiable variable scale transformation is avoided in this study to reduce overfitting and to ensure the robustness of the model.

Fractional polynomial determines the exponent value of a continuous variable, which yields the best model fitting by a search through a small but reasonable set of possible exponent values. The approach can be generalised using the following Equation 3.5:

\[
g(x, \beta) = \beta_0 + \sum_{j=1}^{J} \beta_j F_j(x) \tag{3.5}
\]

Where:
$\beta$ denotes the vector of model coefficients

$J$ denotes degree of correlation between variable $x$ and outcome variable $g$

$F_j(x)$ denotes particular type of power function

Royston and Altman (1994) recommended a set of powers that are commonly observed [-2, -1, -0.5, 0, 0.5, 1, 2, 3]. Zero denotes log transformation. Implementation of the method requires, for $J = 1$ (first degree of polynomial function), fitting eight models; that is, one model for each recommended exponent value. For $J = 2$ (second degree of polynomial function), 36 models are required for each continuous variable. In most applied statistic settings, an adequate transformation may be found if $J = 1 \text{ or } 2$ is used (Hosmer & Lemeshow 2000; Royston & Altman 1994).

Due to the current limited understanding of scale effect of factors affecting damage, complex correlations (second degree or higher) between predictor variables and damage severity cannot be explained using scientific reasoning. In addition, the inclusion of more complex terms than are necessary or the use of more complicated approaches than are necessary often result in overfitting (Hawkins 2004). Overfitted models may produce results that are more optimistic than reality. Therefore, to maintain simplicity and avoid overfitting, only first degree correlation is assessed.

Interactions among variables play an important role in logistic regression modelling building (Hilbe 2009). Interaction is the effect that the levels of one predictor influence the response differently of another predictor. For example, consider the continuous predictor excavation span and categorical variable geology. It is likely that the scale effect of span varies for different values of geology. In other words, the effect of the excavation span on the probability of exceeding a certain level damage severity may be different for different geology factor values. However, due to the current lack of work carried out to study such an effect, interaction is not explicitly investigated here to ensure simplicity of the model and ease of interpretation.

With six potential predictor variables remaining, a backwards variable selection process is adopted, wherein all variables are entered into the model and
insignificant variables are removed individually and stepwise. A final model is determined when changes in GOF are significant with the further reduction of variables.

The model building process results are presented in two separate sections, one for each model. Model R2 delineates between acceptable (R2) and unacceptable damages (R3 & R4 & R5), model R3 delineates between tolerable (R2 & R3) and intolerable damages (R4 & R5).

a Acceptable vs Unacceptable

Following the data reduction described in Section 3.3, remaining variables that are to be used for damage prediction are stress condition, ground support capacity, excavation span, geology condition, PPV and wall/back.

The first step in model building is to select significant predictor variables. Backwards variable selection is used here to screen for any variable that does not significantly contribute towards R2 damage prediction. A full model comprising of all variables is firstly run and the Wald statistic is computed as a first pass to screen for insignificant variables. The full model variable coefficients ($\beta$) together with standard error (S.E.), the Wald statistic, the degrees of freedom (df) and the Wald significance (p or Sig.) are presented in Table 3-11.

Table 3-11 Acceptable vs unacceptable full model variable significance test.

<table>
<thead>
<tr>
<th>Variable</th>
<th>b</th>
<th>S.E.</th>
<th>Wald</th>
<th>df</th>
<th>p</th>
<th>Exp(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress Factor</td>
<td>0.011</td>
<td>0.009</td>
<td>1.525</td>
<td>1</td>
<td>0.217</td>
<td>1.011</td>
</tr>
<tr>
<td>Ground Support</td>
<td>-0.283</td>
<td>0.069</td>
<td>16.930</td>
<td>1</td>
<td>0.000</td>
<td>0.754</td>
</tr>
<tr>
<td>Excavation Span</td>
<td>0.036</td>
<td>0.060</td>
<td>0.356</td>
<td>1</td>
<td>0.551</td>
<td>1.037</td>
</tr>
<tr>
<td>Geology Factor</td>
<td>-2.766</td>
<td>0.619</td>
<td>19.967</td>
<td>1</td>
<td>0.000</td>
<td>0.063</td>
</tr>
<tr>
<td>Wall/Back</td>
<td>-0.110</td>
<td>0.306</td>
<td>0.129</td>
<td>1</td>
<td>0.719</td>
<td>0.896</td>
</tr>
<tr>
<td>PPV</td>
<td>3.587</td>
<td>1.283</td>
<td>7.824</td>
<td>1</td>
<td>0.005</td>
<td>36.139</td>
</tr>
<tr>
<td>Constant</td>
<td>3.414</td>
<td>0.979</td>
<td>12.165</td>
<td>1</td>
<td>0.000</td>
<td>30.401</td>
</tr>
</tbody>
</table>

The Wald test is calculated by dividing the variable coefficient by its standard error, and it is also a z statistic. It is often used as first pass to screen for insignificant predictor variables. An insignificant Wald test score (significance >
suggests that the variable is not significant in contributing towards damage prediction.

The Wald test score for stress condition, span and wall/back variable suggests they are not significant predictors for separating R2 damages away from more severe damage (R3, R4 and R5). In other words, the occurrence of R2 scale rockburst damage is somewhat insensitive to changes in stress condition, excavation span and whether damage is in the roof or wall.

However, the Wald score has been criticised for being too conservative (Harrell 2001; Tabachnick & Fidell 1996). To further test this hypothesis, span is removed from the full model and model fitting is re-run. Log likelihood is then computed for the reduced model for comparison against the full model. The same approach is repeated for stress condition and wall/back, and all three variables simultaneously. The difference of $-2 \times \log \text{likelihood}$ between models can be approximated using a chi-square distribution with the degrees of freedom equal to the difference in number of variables. The significance test results are presented in Table 3-12.

It could be seen from the results that by removing stress condition, span and wall/back from the full model, model prediction is not significantly affected. In other words, all three variables separately or together do not significantly contribute towards R2 damage prediction and can be omitted from the full model.

<table>
<thead>
<tr>
<th></th>
<th>$-2 \times \log \text{likelihood}$</th>
<th>D</th>
<th>df</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full model</td>
<td>289.16</td>
<td>0</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Without stress</td>
<td>290.70</td>
<td>1.54</td>
<td>5</td>
<td>0.21</td>
</tr>
<tr>
<td>condition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Without span</td>
<td>289.52</td>
<td>0.36</td>
<td>5</td>
<td>0.55</td>
</tr>
<tr>
<td>Without wall/back</td>
<td>289.29</td>
<td>0.13</td>
<td>5</td>
<td>0.72</td>
</tr>
<tr>
<td>Without all 3</td>
<td>291.04</td>
<td>1.88</td>
<td>3</td>
<td>0.60</td>
</tr>
</tbody>
</table>

The second step in logistic regression model building is the assessment of linearity assumption between continuous predictor (PPV for this model) and outcome variable.
Fractional polynomial is applied in this study to achieve this objective. Rather than attempting all recommended exponent values and to maintain simplicity, only four exponent values are tested for each continuous variable, namely 0 (Log), 0.5 (square root), 2 (square) and 3 (cube). This is due to the current lack of understanding on the scale effect of factors affecting the rockburst damage likelihood. Once non-linear components between predictor variables and outcome variables are found, an appropriate variable scale transformation is carried out guided by subject knowledge.

The Log likelihood value is computed for each exponent value run and is afterwards compared to the linear model for assessing significance of change. A chi-square significance value is then computed for log likelihood values of all runs that have shown improvement over the linear model (decrease in log likelihood value). A significant result for an exponent value suggests that relation between that particular variable is better modelled using such exponent value power relation.

The fractional polynomial analysis results for PPV in model R2 are presented in Table 3-13. J denotes degree of polynomial, df denotes the degrees of freedom, \( \Delta \) denotes change in log likelihood value over the linear model, p denotes the significance and Exponent denotes the exponent value used.

<table>
<thead>
<tr>
<th>df</th>
<th>(-2 \times \text{Log likelihood})</th>
<th>D</th>
<th>p</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>J=1</td>
<td>6</td>
<td>288.31</td>
<td>2.73</td>
<td>0.10</td>
</tr>
<tr>
<td>J=1</td>
<td>6</td>
<td>289.61</td>
<td>1.43</td>
<td>0.23</td>
</tr>
<tr>
<td>Linear</td>
<td>5</td>
<td>291.04</td>
<td>0</td>
<td>Linear</td>
</tr>
<tr>
<td>J=1</td>
<td>6</td>
<td>292.99</td>
<td>-1.95</td>
<td>Square</td>
</tr>
<tr>
<td>J=1</td>
<td>6</td>
<td>293.74</td>
<td>-2.70</td>
<td>Cube</td>
</tr>
</tbody>
</table>

It can be seen from the above tables that no significant non-linearity was found with PPV based on a significance level of 0.05. However, it could be seen from the result that log transformation of PPV is only marginally insignificant, with a significance level of 0.098. This suggests that PPV is, to some degree, better correlated with damage likelihood in logarithmic scale. Through reviewing past literatures, it had been frequently, if not exclusively, seen that PPV is plotted on a log scale or used as a logarithmic parameter. A good example can be seen
from the work carried out by Kaiser, McCreath and Tannant (1996), as shown in Figure 3-7.

The data population can be better approximated using a normal distribution in log scale on Y axis. For these reasons, log transformed PPV is used in the following logistic regression modelling.

The final logistic regression model fitting is carried out with three remaining variables. The variable coefficient, standard error, odd ratio and 95% confidence interval estimated using the bootstrap method with 1000 samples are shown in Table 3-14.

![Figure 3-7 Measured PPV vs Static Stress Drop for world wide database (Kaiser, McCreath & Tannant 1996).](image)

<table>
<thead>
<tr>
<th>Variable</th>
<th>b</th>
<th>S.E.</th>
<th>Odd ratio</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support Capacity</td>
<td>-0.257</td>
<td>0.075</td>
<td>0.773</td>
<td>-0.426</td>
<td>-0.143</td>
</tr>
<tr>
<td>Geology Factor</td>
<td>-2.653</td>
<td>0.649</td>
<td>0.070</td>
<td>-4.067</td>
<td>-1.557</td>
</tr>
<tr>
<td>Ln (PPV)</td>
<td>0.652</td>
<td>0.209</td>
<td>1.920</td>
<td>0.248</td>
<td>1.095</td>
</tr>
<tr>
<td>Constant</td>
<td>5.864</td>
<td>1.067</td>
<td>352.088</td>
<td>4.224</td>
<td>8.425</td>
</tr>
</tbody>
</table>

Bootstrap, introduced by Efron and Tibshirani (1986), is a general purpose technique for obtaining estimates of the properties of statistical estimators without making assumptions about the distribution giving rise to the data. It is to repeatedly simulate a sample of size $n$ from the data set, computing statistic of interest, and assess how the statistic behaves over certain repetitions.
Therefore, the bootstrap quartiles are better estimates than confidence intervals, which are based on a normality assumption.

The negative coefficients for the support capacity and geology factor suggest that they are adversely related to RDP; the positive coefficient for PPV suggests that it is positively related to damage potential.

The final logistic regression model for predicting the probability of unacceptable damage or damage severity exceeding R2 occurring is illustrated in Equation 3.6:

\[
p = \frac{1}{1+e^{-(5.864-0.257 \times E2-2.653 \times E4+0.652 \times \ln(PPV))}} \tag{3.6}
\]

Where:

- E2: dynamic capacity of support system
- E4: geology factor
- PPV: peak estimated ground motion in m/s

\[b\] Tolerable vs Intolerable (R3 Model)

An initial full model run is firstly carried out to screen for insignificant predictor variables. The variable coefficients, the standard error, the Wald statistic, the degrees of freedom and the significance are shown in Table 3-15.

<table>
<thead>
<tr>
<th>Variable</th>
<th>(\beta)</th>
<th>S.E.</th>
<th>Wald</th>
<th>df</th>
<th>Sig</th>
<th>Exp(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress Factor</td>
<td>0.036</td>
<td>0.011</td>
<td>11.053</td>
<td>1</td>
<td>0.001</td>
<td>1.037</td>
</tr>
<tr>
<td>Support Capacity</td>
<td>-0.411</td>
<td>0.083</td>
<td>24.273</td>
<td>1</td>
<td>0.000</td>
<td>0.663</td>
</tr>
<tr>
<td>Excavation Span</td>
<td>0.221</td>
<td>0.070</td>
<td>10.015</td>
<td>1</td>
<td>0.002</td>
<td>1.247</td>
</tr>
<tr>
<td>Geology Factor</td>
<td>-3.658</td>
<td>0.696</td>
<td>27.597</td>
<td>1</td>
<td>0.000</td>
<td>0.026</td>
</tr>
<tr>
<td>PPV</td>
<td>3.605</td>
<td>1.220</td>
<td>8.733</td>
<td>1</td>
<td>0.003</td>
<td>36.796</td>
</tr>
<tr>
<td>Wall/Back</td>
<td>-0.060</td>
<td>0.326</td>
<td>0.034</td>
<td>1</td>
<td>0.855</td>
<td>0.942</td>
</tr>
<tr>
<td>Constant</td>
<td>1.385</td>
<td>0.994</td>
<td>1.944</td>
<td>1</td>
<td>0.163</td>
<td>3.996</td>
</tr>
</tbody>
</table>

As seen from above table, five variables are significant predictors and cannot be omitted from the full model based on the Wald statistic. The Wald statistic for the wall/back is insignificant, suggesting that damages occurring in the back/wall do not result in significant difference in damage severity.
To further test this hypothesis, log likelihood is then computed for the reduced model without wall/back variable and is used to compare with the full model. Test results are shown in Table 3-16.

**Table 3-16 Log likelihood for full model and reduced model. Model R3.**

<table>
<thead>
<tr>
<th></th>
<th>$-2 \times \text{Log likelihood}$</th>
<th>$\Delta$</th>
<th>df</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full model</td>
<td>254.459</td>
<td>0</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Reduced model</td>
<td>254.492</td>
<td>-0.033</td>
<td>5</td>
<td>0.86</td>
</tr>
</tbody>
</table>

The removal of the wall/back variable from the full model did not yield significant difference in predicting power of the model, suggesting that the wall/back variable is not a significant predictor; therefore, it is removed from the full model.

Following variable selection, linearity for all continuous variables within the model is checked using a fractional polynomial technique. The same approach of using only four exponent values is applied to three continuous variables in this study, namely stress factor, excavation span and PPV. The significance test results for three tests are presented in Table 3-17, Table 3-18 and Table 3-19.

**Table 3-17 Stress factor fractional polynomial result. Model R3.**

<table>
<thead>
<tr>
<th>Stress</th>
<th>df</th>
<th>$-2 \times \text{Log likelihood}$</th>
<th>$\Delta$</th>
<th>p</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>J=1</td>
<td>6</td>
<td>259.638</td>
<td>-5.146</td>
<td></td>
<td>Log</td>
</tr>
<tr>
<td>J=1</td>
<td>6</td>
<td>257.143</td>
<td>-2.651</td>
<td></td>
<td>Sqrt</td>
</tr>
<tr>
<td>Linear</td>
<td>5</td>
<td>254.492</td>
<td>0</td>
<td></td>
<td>Linear</td>
</tr>
<tr>
<td>J=1</td>
<td>6</td>
<td>249.539</td>
<td>4.953</td>
<td>0.03</td>
<td>Square</td>
</tr>
<tr>
<td>J=1</td>
<td>6</td>
<td>246.079</td>
<td>8.413</td>
<td>0.004</td>
<td>Cube</td>
</tr>
</tbody>
</table>

**Table 3-18 Excavation span fractional polynomial result. Model R3.**

<table>
<thead>
<tr>
<th>Span</th>
<th>df</th>
<th>$-2 \times \text{Log likelihood}$</th>
<th>$\Delta$</th>
<th>p</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>J=1</td>
<td>6</td>
<td>252.628</td>
<td>1.864</td>
<td>0.17</td>
<td>Log</td>
</tr>
<tr>
<td>J=1</td>
<td>6</td>
<td>253.412</td>
<td>1.08</td>
<td>0.30</td>
<td>Sqrt</td>
</tr>
<tr>
<td>Linear</td>
<td>5</td>
<td>254.492</td>
<td>0</td>
<td></td>
<td>Linear</td>
</tr>
<tr>
<td>J=1</td>
<td>6</td>
<td>257.17</td>
<td>-2.678</td>
<td></td>
<td>Square</td>
</tr>
<tr>
<td>J=1</td>
<td>6</td>
<td>259.909</td>
<td>-5.417</td>
<td></td>
<td>Cube</td>
</tr>
</tbody>
</table>
Table 3-19 PPV fractional polynomial result. Model R3.

<table>
<thead>
<tr>
<th>PPV</th>
<th>df</th>
<th>$-2 \times \text{Log likelihood}$</th>
<th>$\Delta$</th>
<th>p</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>J=1</td>
<td>6</td>
<td>251.804</td>
<td>2.688</td>
<td>0.10</td>
<td>Log</td>
</tr>
<tr>
<td>J=1</td>
<td>6</td>
<td>252.861</td>
<td>1.631</td>
<td>0.20</td>
<td>Sqrt</td>
</tr>
<tr>
<td>Linear</td>
<td>5</td>
<td>254.492</td>
<td>0</td>
<td></td>
<td>Linear</td>
</tr>
<tr>
<td>J=1</td>
<td>6</td>
<td>257.506</td>
<td>-3.014</td>
<td></td>
<td>Square</td>
</tr>
<tr>
<td>J=1</td>
<td>6</td>
<td>259.138</td>
<td>-4.646</td>
<td></td>
<td>Cube</td>
</tr>
</tbody>
</table>

Both square and cube transformations of the stress factor variable yielded significant results, suggesting that the stress variable is better modelled using non-linear scale.

Kaiser, McCreath and Tannant (1996) hypothesised that a high stress condition is likely to induce a deeper depth of fracturing and potentially increase the quantity of rock that can be mobilised during rockbursting. Through case studies of tunnel spalling, Martin, Kaiser and McCreath (1999) demonstrated that depth of spalling or fracture was linearly related to increasing the stress to strength ratio. Since volume of displaced rock is more representative of RDS, which is more linearly related to square depth or cube depth, a square or cube transformation of the stress factor is then justifiable. A square transformation is used in order to avoid amplifying uncertainty and dependency of prediction on the stress factor.

A log transformation for the excavation span variable returned a significance level of 0.17, suggesting that there is an insignificant amount of non-linearity between span and rockburst damage likelihood. Since its significance level is lower than that of PPV, and to avoid over fitting, scale effect and transformation of excavation span are not further investigated in this study.

A log transformation of PPV for model R3 yielded a comparable significance level to model R2, suggesting the non-linear effect for PPV remains true for model R3. To maintain consistency, a log transformation of PPV is also adopted in model R3.

The final run is then carried out with the remaining five predictor variables. The variable coefficients, standard error, odd ratio and confidence interval estimated using the bootstrap sampling method are shown in Table 3-20.
Table 3-20  R3 model variable coefficients and confidence interval.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\beta$</th>
<th>S.E.</th>
<th>Odd ratio</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Stress Factor)$^2$</td>
<td>4.104E-04</td>
<td>1.022E-04</td>
<td>1.000</td>
<td>2.200E-04</td>
<td>6.472E-04</td>
</tr>
<tr>
<td>Support Capacity</td>
<td>-0.443</td>
<td>0.084</td>
<td>0.642</td>
<td>-0.642</td>
<td>-0.307</td>
</tr>
<tr>
<td>Excavation Span</td>
<td>0.240</td>
<td>0.071</td>
<td>1.271</td>
<td>0.106</td>
<td>0.427</td>
</tr>
<tr>
<td>Geology Factor</td>
<td>-3.950</td>
<td>0.725</td>
<td>0.019</td>
<td>-5.841</td>
<td>-2.668</td>
</tr>
<tr>
<td>ln(PPV)</td>
<td>0.828</td>
<td>0.230</td>
<td>2.288</td>
<td>0.424</td>
<td>1.333</td>
</tr>
<tr>
<td>Constant</td>
<td>4.607</td>
<td>1.070</td>
<td>100.137</td>
<td>2.693</td>
<td>7.113</td>
</tr>
</tbody>
</table>

The final logistic regression model for estimating the probability of an excavation suffering intolerable rockburst damage (exceeding R3) is illustrated in Equation 3.7:

$$p = \frac{1}{1+e^{-(4.607+4.104\times10^{-4}\times E1^2-0.443\times E2+0.24\times E3-3.95\times E4+0.828\times \ln(PPV))}}$$

(3.7)

Where:

- $E1$: $\sigma1$ principle stress over rock UCS in %
- $E2$: support system capacity
- $E3$: excavation span in metres
- $E4$: geology factor
- PPV: peak estimated ground motion in m/s

3.4.4 Verifying the logistic regression model

A critical step following the building of a logistic regression model is to assess the appropriateness of the model, which involves evaluating its GOF, or how well the model describes the observed data (Hosmer, Taber & Lemeshow 1991). GOF is an issue that considers how well a given model, considered by itself, fits the data, rather than whether or not the model is more appropriate than another model (Kleinbaum & Klein 2010).

A well-fitted logistic regression model should have the ability to effectively delineate between true positive and true negative over a wide range of probability cutting points. That is a probability value where below which is considered a negative occurrence and above which a positive occurrence. In
the sense of rockburst damage, a true positive may be considered as damage that exceeded expected damage severity, and a true negative may be considered as damage that did not. Without this important step, any inferences drawn from the development of the model or subsequent prediction may be misleading or totally incorrect.

Two major components of assessment of GOF are calibration and discrimination (Harrell 2001). Calibration is a measure of how well predicted probability agrees with actual observed probability or ratio of truth occurring. When the average estimated probability within subgroups of a prospective population sorted by predicted probability matches the proportion that actually sustains unacceptable severity of damage, it could be said that the model is well calibrated.

Discrimination is a measure of how well the model can separate cases that do and do not sustain an unacceptable severity of damage. If the predicted probabilities for true cases are all higher than false cases, it could be said that the model can discriminate perfectly, even if the predicted probability does not match the proportion with true population (Cook 2007).

\[ \text{Calibration Assessment} \]

The HL method is one of the most important logistic regression fit statistics, together with a related table of deciles (Hilbe 2009). Hosmer and Lemeshow (1980) and Lemeshow and Hosmer (1982) proposed the GOF assessment technique based on grouping according to estimated probabilities. The data set is divided into groups based on two available grouping strategies: percentile and fixed value strategies. The HL GOF statistic, \( \hat{C} \), is obtained by calculating the Pearson chi-square statistic from the \( g \times 2 \) table of observed and expected frequencies as a measure of the overall correspondence of counts, with \( g \) denoting number of groups.

Theoretically, observed and expected counts should be close. Therefore, a closer ‘gap’ between observed and expected counts indicates a better calibration.

Hosmer and Lemeshow (1980) demonstrated through simulations that \( \hat{C} \) is well approximated by the chi-square distribution with \( g - 2 \) degrees of freedom.
Based on the $\hat{\mathcal{C}}$ distribution, a HL statistic with a $\rho$-value greater than 0.05 is considered an acceptable fit. The lower the HL statistic, the less variance in fit, the greater the $\rho$-value, and better in fit.

A percentile grouping strategy is generally preferred and usually with $g = 10$ groups. These groups are often referred to as the deciles of probability. The deciles of probability, also called contingency table for the two models, are shown in Table 3-21 and Table 3-22.

<table>
<thead>
<tr>
<th>Group</th>
<th>Acceptable Cases</th>
<th>Unacceptable Cases</th>
<th>Total Cases</th>
<th>Expected %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Expected</td>
<td>Observed</td>
<td>Expected</td>
</tr>
<tr>
<td>1</td>
<td>22</td>
<td>21.662</td>
<td>3</td>
<td>3.338</td>
</tr>
<tr>
<td>2</td>
<td>19</td>
<td>17.284</td>
<td>6</td>
<td>7.716</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>15.760</td>
<td>14</td>
<td>9.240</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>14.635</td>
<td>11</td>
<td>11.365</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>12.185</td>
<td>7</td>
<td>12.815</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>10.427</td>
<td>16</td>
<td>14.573</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>8.826</td>
<td>17</td>
<td>17.174</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>6.405</td>
<td>21</td>
<td>18.595</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>4.718</td>
<td>18</td>
<td>19.282</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>3.098</td>
<td>21</td>
<td>19.902</td>
</tr>
</tbody>
</table>

The contingency tables are also graphically illustrated in Figure 3-8 and Figure 3-9.
Regions of estimated probability where the model does not perform satisfactorily are shown in the above table and charts. Deciles with large numbers of discrepancies between observed and expected cases can be regarded as regions of poor model performance. It is noticeable from the contingency table plot that certain regions of predicted probability are uncertain.
due to a lack of cases, such as above 80% for model R3 and below 30% for model R2.

For model R2, one region of poor model performance can be seen from the contingency table plot between 30 and 60%, indicated by a large discrepancy between observed and expected number of cases. These regions of poor fit are likely due to the lower number of predictor variables used (3 in model R2 as oppose to 5 in model R3). It is also possibly due to outlier cases in the database or cases that cannot be well described by the predictor variables used. Considering the complexity of the rockburst damage problem, poor model fit while using only three predictor variables is not surprising.

The calibration of model R3 compared with model R2, as can be seen from Figure 3-8 and Figure 3-9, is improved. However, one region of poor fit is still relatively distinct for model R3 at around 40%.

When discussing approaches of dealing with outlier cases in logistic regression, Jennings (1986) stated the following:

‘Fitting the true model to the censored data will produce estimates of \( \beta \) that are biased. The censoring prevents us from finding the correct systematic component event asymptotically. Under this definition, outliers are necessary for logistic regression estimation.’

These outliers in the database are potentially drawn from a population of potentially different mechanism rockburst damages. By removing these outliers, the fitted regression models are biased, as the remaining data is no longer representative of the true rockburst damage population. Regression models fitted to such biased data, although producing a better GOF since biased data is more ‘homogeneous’, are less robust because they only describe one subgroup of the true sample population. For this reason, these outliers in regions of poor fit are necessary in order to maintain the robustness of the regression model and will not be investigated further.

Due to the limited availability of rockburst data, the effect of certain regions of factor values may be uncertain. For instance, the effect of a stress factor value of below 20 and greater than 90 is uncertain due to a lack of damage cases reported in those regions, as shown in Figure 3-1. This region of uncertainty
also applies to the estimated probability of exceeding a certain level of damage severity. It can be seen in Figure 3-9 that there is a lack of damage cases with estimated probability of exceeding R3 greater than 80%, which resulted in poor confidence in calibration of probability values in that region. Therefore, caution should be taken when operating in these regions of uncertainties in future studies.

The HL significance tests for both models are then computed based on the contingency table, and the results are shown in Table 3-23.

<table>
<thead>
<tr>
<th></th>
<th>Chi-square</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptable model (Model R2)</td>
<td>12.354</td>
<td>8</td>
<td>0.136</td>
</tr>
<tr>
<td>Tolerable model (Model R3)</td>
<td>11.033</td>
<td>8</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Despite the presence of regions of poor model performance, the insignificant values for both models, as shown in above table, suggest that the overall calibration for both models are acceptable for the purpose of this study.

**b Discrimination Assessment**

Discrimination is most often measured by the area under the ROC curve, also called the c statistic (Cook 2007). The ROC curve and c statistic are functions of sensitivity and specificity for a wide range of probability cutting values. A probability cutting point is defined as a probability where below which is considered a negative occurrence and above which is considered a positive occurrence.

Sensitivity is defined as the ability of the model to successfully predict the positive occurrence, and specificity is defined as the ability of a model to successfully predict the negative occurrence. A perfect model, by definition, has 100% sensitivity and specificity, and a model with low sensitivity or specificity is less desirable.

The ROC curve is the plot of sensitivity versus one minus specificity, over all possible cutting points as shown in Figure 3-10. The ROC methodology is based on statistical decision theory and was originally developed in the context of electronic signal detection and problems with radar in the early 1950s (Zweig
& Campbell 1993). It has since become the standard for evaluating a fitted model’s discrimination ability.

![Figure 3-10 Plot of sensitivity vs 1-specificity for all possible cutting points values (Hosmer Jr, Lemeshow & Sturdivant 2013).](image)

The area under the ROC curve, which ranges from 0.5 to 1, provides a summary measure of the model’s ability to delineate between cases that experience outcome versus those that do not (Hosmer Jr, Lemeshow & Sturdivant 2013). The value can be interpreted as the probability of the model successfully classifying a pair of true positive and true negative cases. As the discrimination ability increases, the area under the curve increases from 0.5 to its theoretical maximum of 1.

A guideline was provided by Hosmer Jr, Lemeshow and Sturdivant (2013) to describe qualitatively the discrimination ability of a fitted model, and this is shown in Table 3-24.

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROC = 0.5</td>
<td>No discrimination ability, might as well flip a coin</td>
</tr>
<tr>
<td>0.5 &lt; ROC &lt; 0.7</td>
<td>Poor discrimination, not much better than coin toss</td>
</tr>
<tr>
<td>0.7 &lt; ROC &lt; 0.8</td>
<td>Acceptable discrimination</td>
</tr>
<tr>
<td>0.8 &lt; ROC &lt; 0.9</td>
<td>Excellent discrimination</td>
</tr>
<tr>
<td>ROC &gt; 0.9</td>
<td>Outstanding discrimination</td>
</tr>
</tbody>
</table>

Table 3-24  Area under ROC curve qualitative interpretation (Hosmer Jr, Lemeshow & Sturdivant 2013).
Based on such classification, an area cut-off value of 0.7 is selected in this study as the minimum criterion for a model with sufficient discrimination ability. The ROC curves for the models are plotted in Figure 3-11 and Figure 3-12.

**Figure 3-11 ROC curve for model R2. Area under ROC = 0.767.**

**Figure 3-12 ROC curve for model R3. Area under ROC = 0.816**

The area under the ROC curve for model R2 is 0.767, which can be classified as acceptable; for model R3, it is 0.816, which can be marginally classified as excellent.
The GOF for both models is deemed to be acceptable for the purpose of this study. Both models possess sufficient discrimination ability to delineate between cases that do not exceed a certain level of damage severity, and cases that do exceed a certain level of damage severity.

3.5 Forecast Improvement

The area under the ROC curve, or the $c$ statistic, is again used in this section to provide a quantitative measure of improvement of the new model over the original RDP model. The $c$ statistic is computed for the two RDP models and is used to compare the two new models formulated in this study. The ROC plots for the models are shown in Figure 3-13 and Figure 3-14.

The area under the ROC curve suggests that the discrimination ability for both models improved with the inclusion of factor weighting. As shown in above figures, the green curve is higher along the diagonal line than the red curve, which suggests that the improvement of discrimination ability is over a wide range of probability cutting points. Since the area under ROC curve can be interpreted as a probability of correctly classifying a pair of a true positive case and a true negative case, the improvements in forecasting probability for exceeding R2 and R3 severity damage are 6.3 and 8.3% respectively.

![ROC Curve](image1.png)  ![ROC Curve](image2.png)

*Figure 3-13 Probability exceeding R2. Original Mode (Left) vs New Model (Right).*
It is demonstrated in this section that the inclusion of factor weighting produced considerable improvement in rockburst damage severity forecast.

3.6 Regression Model Interpretation

In keeping with the objective of this thesis, the factor weighting of each regression model is interpreted in this section. Since the weighting of factors is different for each model, their interpretation is carried out separately.

Some assumptions are made prior to assessing how sensitive the likelihood of exceeding certain severity damage is, relative to change in each factor used.

Firstly, for interpretation purposes, it is assumed that all factors used are continuous, and one-unit change for each factor makes sense. The second assumption made is that the interaction effect among factors is negligible. That is, the scale effect of one variable is independent on the value choice of another variable. This assumption is for simplicity’s sake, as there has been minimum work done on such effect. In future studies, when more and higher quality data is available, the interaction effect should be investigated and taken into account if found to be significant.

In this study, the weighting of factors is interpreted by assessing the sensitivity of damage likelihood relative to the changes in one input factor while holding the value of remaining factors constant. A set of base case parameters must be
determined for both models. The base case parameter values were chosen close to their median value and are representative of a moderately vulnerable excavation. The base case parameters are shown in Table 3-25.

Table 3-25 Base parameter for plotting sensitivity chart.

<table>
<thead>
<tr>
<th>Stress Factor</th>
<th>Support Capacity</th>
<th>Excavation Span</th>
<th>Geology Factor</th>
<th>PPV</th>
<th>Exceeding R2</th>
<th>Exceeding R3</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>8</td>
<td>6.5</td>
<td>1</td>
<td>0.5</td>
<td>66.8%</td>
<td>39.5%</td>
</tr>
</tbody>
</table>

The sensitivity charts for the base case are illustrated in Figure 3-15 and Figure 3-16.

Figure 3-15 Model R2 Sensitivity Chart.
It can be seen from the charts that, based on the slope of each curve, the geology, stress and ground support factors are more dominant factors controlling the likelihood of exceeding a R3 severity damage than span and PPV factors. Since all five factors used have different value ranges (ratio of largest possible value over smallest possible value), a sensitivity chart alone cannot effectively illustrate the influence of factors on modelled probability.

To alternatively illustrate the effect of factors used on estimated probability over the entire range of factor values, the two modelled probabilities and factor histogram are plotted against each factor for the base case in Figure 3-17, Figure 3-18, Figure 3-19, Figure 3-20 and Figure 3-21. The probability of exceeding R2 severity damage was not plotted for the stress factor and excavation span, as they are insignificant predictors for the R2 model. In other words, changes in the stress factor and excavation span have a negligible effect on the probability of exceeding R2 severity damage.

Figure 3-17 shows that the change in probability exceeding R3 is, according to expectation, increasing. The increase in probability is accelerating as the stress factor gets higher. This is likely due to rock mass around excavation deteriorating more rapidly at higher stress conditions. Due to the limited data for a stress factor greater than 85, the trend and extrapolated model beyond this region is less reliable.
Figure 3-18 shows the modelled probabilities as a function of support capacity. The probabilities, as expected, are inversely related to support capacity. The modelled R3 probability decreases quickly, with capacity exceeding 10, and eventually flattens off. The database lacks data beyond the region of E2 of 15, and firm conclusion with respect to this region cannot be made.

Figure 3-19 shows the probability of exceeding R3 severity damage as a function of span. The probability increases rather linearly in comparison to
previous factors. The probability saturates when span exceeds 12 m, which may be due to the lack of data in that particular region.

Figure 3-19 Modelled Probability vs Excavation Span.

Figure 3-20 shows the modelled probabilities as a function of the geology factor. The probability is inversely related to the geology factor, as per definition. Similar to previous factors, the lack of data for category value of 1.5 compromises the reliability of the model for data for that particular region.

Figure 3-20 Modelled Probability vs Geology Factor.

Figure 3-21 shows the two probabilities as a function of the PPV factor. The rate of probability increase is linearly related to the logarithmic scale of the PPV factor.
factor, which results in the model being more sensitive to lower PPV than higher.

The above charts demonstrate the lack of cases with extreme factor value, which reduces the model confidence in those regions. Caution should be taken when extreme factor values are used.

To graphically visualise the regression models’ ability to separate damage cases in the database of different damage scales, the RDS is plotted against the probability of exceeding damage severity for the two models in Figure 3-22.
Figure 3-22 Rock Damage Scale vs Probability of Exceeding Damage Severity. RDS are offset by 0.1.

It can be seen from Figure 3-22 that damage cases with high damage severity, in particular R5, generally score a higher probability than lower damage scale cases. This suggests that both models possess sufficient discrimination abilities.

However, it is difficult to visualise the separation in Figure 3-22, since all damage cases are stacked. Alternatively, all cases in the database are plotted in an Excavation Vulnerability Potential (EVP) new versus PPV chart with the background coloured by the probability of exceeding modelled damage severity. These are shown in Figure 3-23 and Figure 3-24.

EVP in the original RDP work done by Heal (2010) is an index that combines all four excavation specific factors through a multiplicative relationship, as shown in Equation 3.8:

\[
EVP = \frac{E_1}{E_2} \times \frac{E_3}{E_4}
\]

(3.8)

Where:

- **E1**: The ratio of \( \sigma_1 \) principle stress over rock mass UCS expressed in percentage (\( \frac{\sigma_1}{UCS} \times 100 \))
- **E2**: The support dynamic capacity in kJ/m²
- **E3**: This factor indicates the maximum span of the section of excavation in metres
\( E4 \): The geology factor accounts for the presence of unfavourable geological structures

In this study, a new interpretation of EVP is introduced, which combines all four factors using an additive relationship. The new EVP is illustrated in Equation 3.9:

\[
EVP_{new} = \alpha_1 E1 + \alpha_2 E2 + \alpha_3 E3 + \alpha_4 E4
\]  

(3.9)

Where:

\( E1 \): The ratio of \( \sigma_1 \) principle stress over rock mass UCS expressed in percentage \( (\frac{\sigma_1}{UCS} \times 100) \)

\( E2 \): The support dynamic capacity in \( \text{kJ/m}^2 \)

\( E3 \): This factor indicates the maximum span of the section of excavation in metres

\( E4 \): The geology factor accounts for the presence of unfavourable geological structures

\( \alpha \): Factor coefficients

*Figure 3-23 EVP new vs PPV. Background are coloured by probability of exceeding R2. Cases exceeded R2 are marked using red spheres and cases which did not are marked using white triangles. EVP values are randomly offset with a mean of 0.2 for a better scattering.*
Figure 3-24 EVP new vs PPV. Background is coloured by probability of exceeding R3. Cases which exceeded R3 are marked using red spheres and cases which did not are marked using white triangles.

For model R2, EVP new calculation only contains ground support and geology factors, which are both categorical in nature. This resulted in a limit of 15 values for EVP. For this reason, a random value with a mean of 0.2 is added to R2 EVP new calculation to improve scatter for a clearer visualisation of data. For model R3, EVP new calculation contains all four factors, of which two are continuous factors. This resulted in a much more diverse EVP value range for model R3 and a more evenly distributed scatter, as shown in Figure 3-24.

It can be seen from both figures that cases which exceeded design damage severity (red spheres) are generally located towards the top right side of the chart, and cases which did not are generally located at the bottom left side of the chart. This is particularly evident for model R3, where a large proportion of negative cases (white triangles) are located within a probability range of less than 40%; a large proportion of positive cases (red spheres) are located in regions greater than 40%.

It is also noticeable through visual inspection of the charts that certain probability regions in both models lack cases compared with other regions. For instance, the probability region between 10 and 20% for model R2 and greater than 80% for model R3. As discussed in Section 3.4.4, this may result in uncertainty in the performance of the model in those probability regions.
Nevertheless, the new EVP approach provides a probabilistic assessment of rockburst damage given to a set of excavation specific parameters over a range of possible ground motions. Although there are no cases in the database with PPV greater than 1.7 m/s, the probability envelope can still be extrapolated beyond 1.7 m/s with reasonable confidence since log scale PPV is used.

3.7 Discussion

3.7.1 Delineate the Occurrence of Rockburst Damage

Logistic regression is a technique used to discriminate between two categories of binary or dichotomous outcome variables, such as between damage cases (1) and non-damage cases (0).

In rockburst damage study, the main objective is to estimate the probability of an excavation experiencing rockburst damage exceeding a certain level of severity. In other words, given an excavation of known specification and a certain level of dynamic loading, what is the probability of such an excavation suffering rockburst damage exceeding a certain severity?

This problem can be broadly classified into two different components: probability of experiencing damage and probability of damage exceeding a certain level of severity. An example for estimating the probability of experiencing R2 damage severity is illustrated in Equation 3.10.

\[
p(RDS > R2) = p(Severity > R2) \times p(Damage occurring)
\]  

(3.10)

The occurrences of rockburst damage are predominately controlled by dynamic loading. Wherever there is no dynamic loading, there will not be rockburst damage. On the other hand, the RDS, as demonstrated in the previous chapter, is dictated more by the geological condition, ground support and stress condition surrounding the excavation, and less by PPV or dynamic loading.

This difference in factor weighting suggests that the occurrence of rockburst damage and severity of rockburst damage would more likely be two issues different in nature. Therefore, the problem requires separate regression models during analysis. For these reasons, it is necessary to separate rockburst damage forecast into two different components in future study: damage occurrence and damage exceeding certain severity.
Non-damage locations or R0 scale damage were not recorded during the data collection step, and all cases in the database are damages with severity greater than or equal to R2. The fitting of a logistic regression model to such data set resulted in one crucial assumption being made, which is that rockburst damage has already occurred. As a result, the probability modelled in this study should be interpreted as follows:

“Given the specification of the excavation and level of dynamic loading, and rockburst damage has already occurred, what is the probability of rockburst severity exceeding R2 or R3?”

This assumption made the second component of Equation 3.10 redundant (probability of damage occurring = 1), which results in a conservative probability estimate. This issue is particularly apparent for excavations at a greater distance away from the seismic source where dynamic loading is low (low probability of experiencing damage). The true probability of such excavation experiencing greater than R2 scale damage would be much less than the modelled probability.

Due to the lack of non-damage data, this issue cannot be further investigated in this study. However, this problem should be quantified in the future once a sufficient quantity of data becomes available.

3.7.2 Higher Probability of Exceeding R3 Damage than R2

By definition, for the same excavation, the probability of exceeding R3 damage should be less than that of exceeding R2 damage. However, this assumption is not true for some damage cases, as shown in Figure 3-25.
A total number of 18 damage cases out of 249 cases were found to have probability of exceeding R3 damage greater than R2. This phenomenon is a result of both stress condition and excavation span being insignificant predictors for modelling the probability exceeding R2. And an increasing stress condition or excavation span will result in higher probability exceeding R3, while the probability exceeding R2 will remain effectively constant.

The fact that stress condition and excavation span are significant predictors in modelling R3 probability, but not for modelling R2 probability, suggests that the damages observed, despite variations in severity, are to some degree different in nature. In other words minor severity damages, whose occurrence is governed by a different set of predictors than severe damages, are to some degree different in nature than severe damage.

Heal (2010) stated the following:

‘A stiff and competent rock mass is often associated with strain bursting and these are typically smaller rockburst, involving lower quantity of rock displacement or ejection. The largest damage typically comes from cases where major structure is present or where there is a significant zone of rock mass fracturing around the excavation.’

The above statement suggests that rockburst damages associated with strain burst are generally less severe than those associated with a fault slip type of
rockburst. It also suggests that a strain burst type of rockburst generally occurs in a different geological setting than that of a fault slip type. Therefore, it is likely that R2 damages in the database are likely strain burst in nature, whereas more severe damages are more likely fault slip in nature. This hypothesis is also supported by Kaiser and Cai (2013a).

The 18 cases with a probability of exceeding R3 higher than R2 are likely associated with a fault slip type of rockburst and occurred in highly stressed large excavations. However, the lack of available information associated with each rockburst case does not allow its mechanism to be accurately determined. Nevertheless, the inclusion of rockburst mechanism as a predictor in the future may help in offsetting the modelled probability exceeding R2.

In the meantime, one should be cautious when evaluating RDP in high stress and large excavation where probability exceeding R3 is likely to be higher than R2. To assist in identifying the invalid zone, the validity boundaries for different geological factors with respect to stress condition and excavation span are graphically illustrated in Figure 3-26.

![Figure 3-26 Span vs Stress factor illustrating applicable zones. Invalid cases are highlighted using red cross and valid cases using green sphere.](image)

3.8 Summary

In this chapter, multivariate statistic techniques were used to investigate the underlying correlations among variables in the database. It was determined that
RDS is the most appropriate parameter within the database to quantify damage severity, stress condition, support capacity, excavation span, and the geology; PPV and the wall/back are potentially damage contributing factors.

The RDS was then regrouped to a three-category index based on the corresponding operational implications. Two logistic regression models were then fitted to the data set to provide a probabilistic approach of assessing anticipated damage severity. During the model building stage, a non-linear component was found with the stress condition and PPV. A scale transformation was subsequently carried out to rectify the issue. The GOF for the two regression models was rigorously tested and the fit of both models was deemed to be satisfactory.

Following regression modelling, the factor coefficient or factor weighting was interpreted using sensitivity charts assuming a base. It was found that the geology and ground support factors are dominant in affecting damage exceeding R2 severity. The stress condition, ground support and geology factors were found to be dominant factors contributing to rockburst damage exceeding R3 severity.

The improvement in damage forecast of the new model was then compared to the original RDP model through the use of the area under the ROC curve. It suggests that the model discrimination ability improved for both models at 6.3 and 8.3% respectively, for correctly classifying a pair of true positive and true negative cases.

The conditionality of the regression models was also discussed at the end of this chapter, which highlighted the need for more comprehensive data for future studies. The applicability of the model, which can result in invalid forecasted probabilities, was also discussed at the end of this chapter.
4 Case Studies

4.1 Introduction

The previous chapter addressed the issue of lack of quantification on factor weighting used in the RDP method. The weighting of the factors affecting rockburst damage severity was quantified through reapplying logistic regression technique with all predictors in an additive relationship.

However, a common concern in the application of regression analyses is that the effectiveness of the regression model degrades when used on a different set of data (external data) drawn from the study sample population (Charlson et al. 1987; Vergouwe et al. 2005), also known as the generalisation problem (Justice, Covinsky & Berlin 1999).

If this is the case, the regression model is expected to work better for the data from which the model was derived than for any other data. This is because each regression model is mathematically optimised to fit the data which it was built upon (also called internal data). Therefore, any performance indicators measured on the same data sample used to fit the model is biased in favour of the regression model.

The usefulness of the regression models depend on their generalisability (Terrin, Schmid & Griffith 2003). As a consequence, Giancristofaro and Salmaso (2003) recommend obtaining some quantitative and objective measures of how well the regression model performs on a separate data sample not used for model building (also called external dataset) to determine its generalisability. If the performance of the regression model drops off significantly, then the regression model can be said to be sample specific and to have no generalisability, and is thus of limited scientific application (Giancristofaro & Salmaso 2003).

In this chapter, an external dataset consisting of four rockburst cases collected from three different mines is used to validate the performance of the regression models developed in Chapter 3. This chapter documents RDP model building steps, model performance evaluation and discusses some of the issues encountered during the study.
In compliance with the confidentiality agreement between the Australian Centre for Geomechanics and project sponsors, sensitive information such as the mine name, location and detailed mine plan for two of the three mines are censored in this study to protect the interest of the mine operators. The mines are simply referred to as mine A, mine B and Kidd mine.

4.2 RDP Factors

There are five factors used in the adjusted RDP method: E1 stress factor, E2 ground support factor, E3 excavation span, E4 geology factor and PPV factor. This section aims to describe these factors in detail and how their ratings were derived when applied to the case studies.

4.2.1 E1 stress factor

Stress factor is defined as the major principle stress at the damage location over the intact rock UCS expressed in percentage, as shown in Equation 4.1. The major principle stress in the database was evaluated using numerical modelling, considering only the effect of nearby stopes and other large excavations while excluding the effect of the drive itself.

\[
\text{Stress factor} = 100 \times \frac{\sigma_1}{UCS}
\]  

Where:

\( \sigma_1 \): the total maximum principle stress in the vicinity of the area being evaluated in MPa

\( UCS \): the intact unconfined (or uniaxial) compressive strength in MPa

For mine A, the major principle stress was derived using elastic numerical modelling. For mine B and Kidd mine, the major principle stress was derived from elasto-plastic numerical model.

For elasto-plastic numerical models, the modelled plastic behaviour of rock around the drive excavation resulted in a lower stress environment due to load shedding. This effect is not consistent with the original stress factor definition (Heal 2010), as the stress value in the vicinity of the drive is low and not representative of the stress environment of the region. The extent of drive scale
effect must be determined and minimised to maintain consistency with the definition of stress factor.

To determine the extent of drive scale effect, stress values were grouped into bins of 1 m distance away from excavation from centroid. The mean, median, standard deviation and 95 percentile values for each bin for Kidd Mine model are plotted against distance in Figure 4-1.

![Figure 4-1 Kidd mine stress values vs distance away from excavation centroid. Red: 95% confidence interval. Green: median. Blue: mean. Grey dash: standard deviation.](image)

To determine the extent of the drive scale effect in a more robust approach, piecewise linear least square fitting was performed for mean stress values. For this approach, two linear functions are fitted to the mean stress curve in an attempt to find the partition point along the curve. For each point along the curve, a residual sum of square is calculated. The point with the lowest residual was chosen as the partition point and extent of the drive scale. This is shown in Figure 4-2.
The sum of residual suggests that the partition point or extent of the effect is at 7 m away from excavation centroid. Therefore, the stress values less than 7 m away from the excavation centroid are not used for building the RDP model.

Since the stress condition greater than 7 m away from excavation centroid exhibited little variation, a maximum distance of 15 m away from centroid was chosen arbitrarily as outer boundary.

For elasto-plastic numerical models, the stress value average of six months prior to the rockburst and six months after was used for the major principle stress extraction as an approximation for the stress condition at the time when damages were observed.

4.2.2 E2 ground support factor

The ground support rating used for RDP model is loosely based on the support system capacity expressed in terms of kJ/m². It is used to reflect the overall support system capacity rather than the capacity of individual support elements.

Using rockburst simulation blast experiments, Heal (2010) derived the capacity expressed in kJ/m² of five commonly used ground support systems. These capacities were then used to define E2 ratings for similar support systems. In subsequent case studies, Heal (2010) determined E2 rating through classifying
ground support systems into one of the five existing rating categories. The five E2 categories together with ground support examples from the past case studies are shown in Table 4-1.
Table 4-1 Examples of E2 classification.

<table>
<thead>
<tr>
<th>E2</th>
<th>Rockbolt</th>
<th>Surface</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>None</td>
<td>Spot bolting</td>
<td>Spot bolting with split sets or solid bar bolts, minimal surface support.</td>
</tr>
<tr>
<td></td>
<td>Gewibar</td>
<td>W-strap</td>
<td>Pattern approx 1 m by 1 m. Standard support (a)</td>
</tr>
<tr>
<td></td>
<td>Split set</td>
<td>None</td>
<td>Pattern bolting with split bolt (b) (c)</td>
</tr>
<tr>
<td></td>
<td>Point anchor bolts</td>
<td>None</td>
<td>Pattern bolting with 2.4 m point anchor bolts (c)</td>
</tr>
<tr>
<td></td>
<td>Split set and point anchor bolts</td>
<td>None</td>
<td>Pattern bolting with split set and point anchor bolts (c)</td>
</tr>
<tr>
<td></td>
<td>Split set and cable bolt</td>
<td>None</td>
<td>Pattern bolting with split set and unplated cable bolt (c)</td>
</tr>
<tr>
<td>5</td>
<td>Pattern bolting</td>
<td>Mesh or fibrecrete</td>
<td>Pattern bolting with split sets or solid bar reinforcement with mesh or 50 mm fibrecrete.</td>
</tr>
<tr>
<td></td>
<td>Gewibar and split sets</td>
<td>Mesh</td>
<td>Mixed pattern of 50% Gewibar plus 50% split set with weld mesh (a)</td>
</tr>
<tr>
<td></td>
<td>Split set</td>
<td>Mesh</td>
<td>Beaconsfield standard support (d)</td>
</tr>
<tr>
<td></td>
<td>Split sets</td>
<td>Mesh and fibrecrete</td>
<td>SLC and HWL hanging wall drives (e)</td>
</tr>
<tr>
<td>8</td>
<td>Pattern bolting with second pass of pattern bolting</td>
<td>Mesh or fibrecrete</td>
<td>Pattern bolting with split sets with mesh or 50 mm fibrecrete, plus an additional pass of pattern reinforcement, such as solid bar bolts.</td>
</tr>
<tr>
<td></td>
<td>Split sets and Posimix bolts</td>
<td>Mesh</td>
<td>Beaconsfield reinforced support 1 (d)</td>
</tr>
<tr>
<td></td>
<td>Split sets and modified cone bolt</td>
<td>Mesh</td>
<td>Beaconsfield reinforced support 2 (d)</td>
</tr>
<tr>
<td></td>
<td>Split sets and Gewis</td>
<td>Mesh and fibrecrete</td>
<td>SLC crosscuts and footwall drives (e)</td>
</tr>
<tr>
<td></td>
<td>Split sets and Securabolls</td>
<td>Mesh and fibrecrete</td>
<td>Permanent infrastructure support (e)</td>
</tr>
<tr>
<td>10</td>
<td>Pattern bolting and pattern cable bolts</td>
<td>Mesh or fibrecrete</td>
<td>Pattern bolting with split sets or solid bar reinforcement, with mesh or 50 mm fibrecrete. Plus pattern cable bolting.</td>
</tr>
<tr>
<td></td>
<td>Gewibar, split sets and cable bolt</td>
<td>Mesh</td>
<td>Patterned Gewibar, split sets and cable bolt. Cable bolt pattern 2 m by 1.5 m, twin strand bulbed (a)</td>
</tr>
<tr>
<td></td>
<td>Gewibar, split sets and cable bolt</td>
<td>Mesh and fibrecrete</td>
<td>Patterned Gewibar, split sets and cable bolt. 75 mm fibrecrete added to surface support (a)</td>
</tr>
<tr>
<td></td>
<td>Gewibar, cable bolt and split sets</td>
<td>Mesh and straps</td>
<td>3 m unplated grouted cable bolt, plain strand with single bulb at toe (a)</td>
</tr>
<tr>
<td></td>
<td>Gewibar, cable bolt and split sets</td>
<td>Mesh, strap and fibrecrete</td>
<td>100 mm fibrecrete is added to surface support on top of previous support standard (a)</td>
</tr>
<tr>
<td></td>
<td>Split sets, modified cone bolt and cable bolt</td>
<td>Mesh</td>
<td>Beaconsfield reinforced support (d)</td>
</tr>
<tr>
<td></td>
<td>Split sets, Securabolls and cable bolts</td>
<td>Mesh and fibrecrete</td>
<td>Perseverance intersection standard (e)</td>
</tr>
<tr>
<td>25</td>
<td>Pattern dynamic support</td>
<td>Dynamic surface support</td>
<td>Pattern bolting with dynamic ground reinforcement such as cone bolts, with a dynamic resistant surface support system.</td>
</tr>
<tr>
<td></td>
<td>Split sets, Securabolls and cable bolts</td>
<td>Mesh, fibrecrete, heavy gauge mesh and shotcrete arches</td>
<td>Perseverance rehab standard (e)</td>
</tr>
<tr>
<td></td>
<td>Rebar and modified cone bolt</td>
<td>Chain link mesh and straps over fibrecrete</td>
<td>1 m by 1 m pattern modified cone bolt. Straps over chain link mesh over fibrecrete (f)</td>
</tr>
<tr>
<td></td>
<td>Split set and dynamic cable bolt</td>
<td>Straps over weld mesh over fibrecrete</td>
<td>Patterned split set and 6m Garford dynamic cables. Straps over weld mesh over 50 mm fibrecrete (g)</td>
</tr>
</tbody>
</table>

Reference: (a) Mt Charlotte (Heal 2007b), (b) Kanowna Belle (Heal 2010), (c) Broken Hill (Heal 2010), (d) Beaconsfield (Heal 2007a), (e) Perseverance (Heal 2010), (f) Brunswick Mining Services (Heal 2010), (g) Junction (Heal 2010).

As shown in above table, dynamic support rating of E2 = 25 was only assigned to support systems that have dynamic support tendons and compatible surface
support systems. A support system with dynamic tendons without a compatible surface support system will result in a lower E2 rating, as the dynamic tendon capacity is often unattainable due to the weak surface support.

The ground support ratings for the case studies presented later in this thesis were assigned through selecting the rating of a similar support system shown in Table 4-1.

4.2.3 E3 excavation span

Excavation span was thought to have a direct influence on the depth of failure for gravity related falls of ground and dynamic rock mass failures (Heal 2010). The span for the RDP method was derived by simply fitting the largest circle that can be drawn internally to the excavation survey, as illustrated in Figure 4-3. This task was performed using mXrap software on mine drive 3D survey files (Australian Centre for Geomechanics 2015).

![Figure 4-3 Excavation span fitting illustration (Heal 2010).](image)

4.2.4 E4 geological factor

The use of geology factor in RDP models is to account for the adverse influence of specific rock mass features such as seismically active structures, which may enhance damage potential or significantly increase failure depth (Heal 2010). A
three-category classification system was proposed to account for this effect, and it is shown in Table 4-2.

<table>
<thead>
<tr>
<th>E4</th>
<th>Description</th>
</tr>
</thead>
</table>
| 0.5 | Seismically active major structures  
Major structural features such as faults, shears or discrete contacts intersect the location and act as a potential failure surface promoting rock mass failure. |
| 1 | Unfavourable rock mass/no major structure  
The orientation of the rock mass discontinuity fabric may promote or enhance rock mass failure. Generally, this factor is applied when there are local cases in which the rock mass discontinuities promoted falls of ground much larger than would be expected. |
| 1.5 | Massive rock mass/no major structure  
The rock mass is essentially massive or non-persistent rock mass discontinuities may exist, including possible minor blast related fracturing. There are no major structures such as faults or shears, which may promote or enhance rock mass failure. |

Seismically active structures can be defined through analysing seismic monitoring data if available. Provided that the source location accuracy is adequate, clusters of seismic events generally align on these active features exhibiting strong spatial relationship (Heal 2010).

4.2.5 PPV factor

PPV factor is the estimated ground motion at the damage site as a result of the rockburst. It is the only factor used in RDP to account for dynamic loading. In the original RDP method, PPV factor is estimated using the far-field scaling law with 90 to 95% confidence of not exceeding. As discussed in Section 3.2, PPV factor for this case study is estimated using the near-field saturation scaling law with 50% confidence of exceeding, as shown in Equation 4.2.

\[
PPV = \frac{C \cdot 10^{0.5(M_R + 1.5)}}{R + r_o}
\]  

(4.2)

Where:  
- \(C\): It is a constant depending on static stress drop. A value of 0.1 is used, which corresponds to 50% confidence limit at less or equal to 5 MPa static stress drop  
- \(M_R\): Richter Scale Magnitude
\(R\): Distance to event hypocentre

\(r_o\): Seismic source radius

4.2.6 Rock Damage Scale

The rock damage severity observed following rockbursts is quantified using the modified RDS classification described in Heal (2010). It is shown in Table 4-3.

<table>
<thead>
<tr>
<th>RDS</th>
<th>Rock mass damage</th>
<th>Support damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>No damage, minor loose</td>
<td>No damage</td>
</tr>
<tr>
<td>R2</td>
<td>Minor damage, less than 1 t displaced</td>
<td>Support system is loaded, loose in mesh, plates deformed</td>
</tr>
<tr>
<td>R3</td>
<td>1-10 t displaced</td>
<td>Some broken bolts</td>
</tr>
<tr>
<td>R4</td>
<td>10-100 t displaced</td>
<td>Major damage to support system</td>
</tr>
<tr>
<td>R5</td>
<td>100+ t displaced</td>
<td>Complete failure of support system</td>
</tr>
</tbody>
</table>
4.3 Mine A 2013 Rockburst Case Study

4.3.1 Mine A Description

Mine A is a gold mine located within the Archaean Norseman-Wiluna Belt in the Eastern Goldfields Province of the Yilgarn Craton in Western Australia. The mineralisation is hosted in a thin and laminated quartz vein within a biotite rich structure. To the east of the structure is an andesite unit and to the west is volcanogenic sediment at the base of a gabbro unit. The orebody dips approximately 65° to the west and has a horizontal average width of 60 cm.

The deepest stope mined at mine A reaches a depth of approximately 730 m below surface. The Ground Control Management Plan (GCMP) document indicates that the major principle stress is horizontal and parallel to the orebody. Previous stress measurement at the mine indicates a north west horizontal virgin stress of approximately 50 MPa at a depth of 600 m. The minor principle stress is sub vertical. The ratio of major principle stress over minor principle stress is estimated to be 1.8, which is considered to be average for this region.

A series of parallel faults cut across the orebody, offsetting the mineralisation. The mineralisation is broken up by the series of faults within the offset zone, which result in ore loss in the vicinity. Poor ground condition is also encountered north of the offset zone. Two parallel faults were modelled in the numerical model, and they are illustrated in Figure 4-4.

![Figure 4-4 Mine A offset fault illustration (plan view). The faults shown are for illustration purposes only.](image-url)
4.3.2 Rockburst Description

Following the final blast of a mining panel at a depth of approximately 700 m, a rockburst of $M_R$ 1.7 occurred less than 1 second following the blast in the footwall 6 m away from the blast. There was an elevated seismic activity rate with the largest aftershock reaching $0 M_R$, 22 minutes following the main event. Seismic activity rate returned to near background level approximately 5 to 6 hours following the blast. The seismicity magnitude time chart is shown in Figure 4-5.

![Magnitude-Time Graph](image)

*Figure 4-5  Mine A Mag-Time chart. Local magnitude is shown and it approximately equals to Richter magnitude.*

Damage was observed on the two levels below the blasted stope and all damages are within a radius of 60 m away from the event hypocentre. Approximately 100 m of drives were damaged as a result of the rockburst. The majority of the damage was observed in the lower wall below the mesh line in the FW side of the drive. Damage severity for mine A rockburst ranges from cracks in the fibrecrete, to collapse of an entire wall located in the offset zone (red excavation illustrated in Figure 4-6). The two levels (which are named by their depth below surface) coloured by RDS together with blast and main event are illustrated in Figure 4-6.
4.3.3 RDP Model Building

   a  E1 Stress Factor

For mine A, sigma 1 principle stress was derived using Map3D elastic numerical modelling. The general layout of the model is shown in Figure 4-7. The modelled features are mined out stopes (blue), non-damage excavations (orange), unfavourable faults (purple) and blasted stope (yellow). The damaged drives coloured in green are not modelled and the stress values for damage locations were queried along the green drives. The modelled sigma 1 stress in cross-section view along damage locations is shown in Figure 4-8. The induced stress at the damage location is estimated to be 60 MPa near the blasted stope brow on RL715 and 55 MPa elsewhere.
At mine A, three rock types are encountered. In the FW, a weaker, crystal-rich and fragmental andesite unit is generally seen. In the HW, a higher strength Gabbro and Sediment unit is generally seen. The rock strength parameters are summarised in Table 4-4.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>UCS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gabbro</td>
<td>140</td>
</tr>
<tr>
<td>Sediment</td>
<td>185</td>
</tr>
<tr>
<td>Andesite</td>
<td>70</td>
</tr>
</tbody>
</table>
**b) E2 Ground Support**

A Garford dynamic solid bolt, which is frequently seen used in Australian underground mines, is a resin based rock bolt that relies on a sliding anchor near the toe of the bolt to absorb energy during failure. A Garford dynamic solid bolt is used as the primary dynamic support tendon at mine A and mine B.

The support systems used for the mine A rockburst study are summarised in Table 4-5. The entries highlighted in bold and italic are the descriptions for each capacity category.

<table>
<thead>
<tr>
<th>E2</th>
<th>Rockbolt</th>
<th>Surface</th>
<th>Comments</th>
<th>No. cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>None</td>
<td>Spot bolting</td>
<td>Spot bolting with split sets or solid bar bolts, minimal surface support.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spot bolting</td>
<td>Fibrecrete (75 mm)</td>
<td>Lower wall support</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>Pattern bolting and pattern cable bolts</td>
<td>Mesh or fibrecrete</td>
<td>Pattern bolting with split sets or solid bar reinforcement, with mesh or 50 mm fibrecrete. Plus pattern cable bolting.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Garford dynamic solid bolt</td>
<td>Mesh embedded fibrecrete (100 mm)</td>
<td>Ore drive wall support</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Friction Bolt Garford dynamic solid bolt</td>
<td>Mesh over Fibrecrete (75 mm)</td>
<td>Ore drive shoulder support</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Friction Bolt Garford Cable</td>
<td>Mesh over Fibrecrete (75 mm)</td>
<td>Ore drive back support</td>
<td>2</td>
</tr>
</tbody>
</table>
4.3.4 E3 Span

The drive survey coloured by excavation span for mine A is shown in Figure 4-9.

![Figure 4-9 Mine A survey coloured by excavation span.](image)

4.3.5 E4 Geology Factor

For mine A, there are no major active structures within the vicinity of the rockburst locations. The offset zone, shown in Figure 4-4, was formed as a result of a series of small faults. The ground condition within the zone is generally poor. Therefore, observed damages located in the offset zone will be assigned an unfavourable geology factor of 0.5 and the remaining damages will be assigned an average geology factor of 1.

4.3.6 PPV

For the mine A rockburst study, the seismic event location was manually processed and the location was insensitive to small changes in the P and S wave phase picks. The location is approximately 5 m south of the blasted stope. The drive survey coloured by estimated PPV values is illustrated in Figure 4-10.
4.4 Performance Evaluation

As discussed in Section 3.7.2, some cases may exceed model’s applicability and result in $P_{R2}$ being less than $P_{R3}$, which is fundamentally invalid as per definition that $P_{R2}$ must be greater or equal to $P_{R3}$. For all case studies presented here, $P_{R2}$ is assumed to equal to $P_{R3}$ when case exceeds model’s applicability.

4.4.1 RL715 Damage Study

There was damage occurring across on RL715 from the intersection up to the brow of the blasted stope. The majority of the damage observed on this level was restricted to the FW, in particularly the lower wall. The damages observed on this level were mostly shakedown of small blocks in the FW lower wall, bulking behind the fibrecrete in the FW and HW shoulder. No fall of ground was seen on this level. An example of damage observed in the HW shoulder is shown in Figure 4-11, the FW in Figure 4-12 and the FW lower wall in Figure 4-14.

The damage observed in the HW was mostly restricted to the shoulder. At location A, cracks with a size of up to 5 cm were seen together with minor bending in the cable plate. Bulking up to 10 cm was observed over an area of 3 m by 1.5 m and less than 1 tonne of material was contained. Based on the
RDS classification shown in Table 4-3, a RDS rating of R2 was given to this location.

![Figure 4-11 Mine A rockburst RL715 HW shoulder bulking.](image)

On the FW side, all damages in the wall were observed within close proximity to the blasted stope. At location B, Garford dynamic solid bolt plates were frequently seen pulling through the fibrecrete embedded mesh, as shown in Figure 4-13. The embedded mesh suffered extensive necking where bulking was severe. The block size of the failed rock was mostly small with a median size of approximately 10 cm. Through visual estimation, approximately 10 tonnes of material was displaced at this location. Based on the RDS rating system, either a rating of R3 or R4 can be assigned to this location.
Lower wall failure on the FW side was frequently seen below the mesh line. At location C, fibrecrète was frequently seen ejected together with large blocks of rock into the excavation. Approximately 1 tonne of material was displaced and a RDS rating of R2 was assigned to location C.
Figure 4-14 Mine A rockburst RL715 FW lower wall damage.

a  Assessment of E1 stress factor

The modelled sigma 1 stress values for these damage locations is approximately 55 MPa, as shown in Figure 4-8. The rock type at locations B and C is andesite with a UCS value of 70 MPa, and sediment at location A with a UCS value of 185 MPa. The calculated stress factor is approximately 30 for location A, 80 for B and C.

b  Assessment of E2 ground support factor

Location A was supported with patterned cable bolts, split set bolts and mesh over fibrecrete. Although dynamic support tendons are used at this location, the lack of compatible surface support does not warrant the use of an E2 rating of 25. Based on Table 4-1, an E2 rating of 10 can be assigned. Location B was supported with patterned Garford dynamic bolts, split set bolts and mesh embedded fibrecrete. Although dynamic support tendons are used, only an E2 rating of 8 was assigned due to the use of weak surface support. Location C located below mesh line was supported with only fibrecrete, and a support rating of 2 was assigned.

c  Assessment of E3 excavation span

The excavation span based on fitting circles to the survey file is 3.2 m for A, 3.6 m for B and 3.3 m for C.
d **Assessment of E4 geology factor**

No unfavourable geological structures are within close proximity to the observed damage and an average geological factor rating of 1 was assigned to the above cases.

e **Assessment of PPV**

These damage locations are relatively close to the observed seismic event location at 50 m. The event magnitude is 1.6 and the estimated PPV factor value is 0.15 m/s for A and B, and 0.08 m/s for location C, as shown in Figure 4-10. The RDP analyses for the three locations are summarised in Table 4-6.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>30</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>E2</td>
<td>10</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>E3</td>
<td>3.2</td>
<td>3.6</td>
<td>3.3</td>
</tr>
<tr>
<td>E4</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PPV</td>
<td>0.14</td>
<td>0.15</td>
<td>0.08</td>
</tr>
<tr>
<td>P_{R2}</td>
<td>34%</td>
<td>48%</td>
<td>74%</td>
</tr>
<tr>
<td>P_{R3}</td>
<td>1%</td>
<td>30%</td>
<td>74%</td>
</tr>
<tr>
<td>RDS_{Observed}</td>
<td>R2</td>
<td>R3/R4</td>
<td>R2</td>
</tr>
</tbody>
</table>

f **Performance evaluation**

The adjusted RDP method performed well for location A and has a fair performance at location B; however, for location C, the method incorrectly predicted the observed damage severity.

Damage similar to location A was widely observed during the mine A case study. The model suggests a fairly high probability of 48% for experiencing damage levels greater than R2 and 30% greater than R3. With the experienced damage level at R3/R4, the model performance is classified as fair. The surface support suffered extensive failure, as bolt plate was seen pulled through where severe bulking was seen. The Garford dynamic bolts, however, were mostly intact.
At location C, the modelled probability suggests the most likely damage severity is greater than R3 while the observed severity is R2. It should be noted, however, that the RDP calculation at that location is applicable for the limited section between the floor and the start of the mesh where $E2 = 2$ is applicable. The damage that occurred is quite extreme for the whole section but not extensive, as it is limited in space. Taking this into account, the high level of damage predicted by the model is a fair result since the experienced damage is severe but limited in its failure volume due to the geometric constrains.

### 4.4.2 RL730 Damage Study

There was a wider spread of damages observed on RL730, which is located below RL715. The support system used on this level is identical to the one used on RL715.

An example of HW shoulder damage (location A) is shown in Figure 4-15, FW lower wall damage (location B) in Figure 4-16, offset zone shoulder damage (location C) in Figure 4-17 and offset zone wall collapse (location D) in Figure 4-18.

Damage in the HW shoulder was consistently observed on this level beneath the blasted stope. At location A, bulking up to 30 cm was observed over an area of 5 m by 1.5 m. Cracks up to 10 cm in fibrecrete and plate bending of the cable bolt were also seen throughout this damage location. Approximately 5 tonnes of material was contained at this location and based on the scale presented in Table 4-3. A RDS rating of R3 was assigned.
The damage observed in the FW lower wall was similar to the ones observed on RL715, but more severe. At location B, damage was observed mostly below the mesh line. Large pieces of fibcrete were seen ejected into the excavation for more than 20 m along the FW. Approximately 10 tonnes of material was ejected from the lower wall along this location. Based on RDS classification, a RDS rating of R3 was assigned. The failed rock mass was highly foliated and several sets of distinctive joint sets were visible. Floor heave up to 1 m on the FW side was also seen accompanying severe lower wall damage.
In the offset zone, cracks in the fibrecrete were more frequently seen around the perimeter of the excavation up to the collapse of the wall. At location C, large slabs of fibrecrete formed and were contained by the mesh. Bulking exceeding 30 cm was seen at this location, as well as severe bending of the cable bolt plate. Approximately 5 tonnes of material was displaced at this location, of which most was contained. A RDS rating of R3 was assigned to location C, according to Table 4-3.

![Figure 4-17 Mine A rockburst RL730 offset zone shoulder bulking.](image)

A wall collapse was seen in the offset zone at location D involving up to 100 tonnes of material from the shoulder down to floor level. A RDS rating of R5 was assigned. The ejected rock was mostly small in size and slabby. The failed support system was ejected into the excavation together with the rubble. The failure depth likely exceeded length of the support tendons.
a Assessment of E1 stress factor

The modelled sigma 1 stress at these locations is approximately 55 MPa, as shown in Figure 4-8. Locations A, C and D are located in the HW sediment with UCS value of 185 MPa. Location B is located in the FW andesite with an UCS value of 70 MPa. The calculated stress factor is approximately 30 for A, C and D, 80 for location B.

b Assessment of E2 ground support

Locations A and C were supported with mesh over fibrecrete, patterned cable bolts and split set bolts. Based on the support classification Table 4-1, an E2 rating of 10 was assigned. Location B was supported with fibrecrete in the lower wall where damage occurred and an E2 rating of 2 was assigned. Location D was supported with patterned Garford dynamic bolts, split set bolts and mesh embedded in fibrecrete. Due to a lack of dynamic tendon compatible surface support (no straps or other techniques to improve the dynamic capability of the surface support (refer to Table 4-1)), an E2 rating of only 10 was assigned to D.

c Assessment of E3 excavation span

All four damage locations are located in the drive with an average span factor of between 3.5 and 4.6 metres.
d Assessment of E4 geology factor

Locations C and D are located within the offset zone, where highly foliated rock mass and the presence of offset faults were encountered. An unfavourable geological factor of 0.5 was assigned to C and D. An average geological factor of 1 was assigned to A and B.

e Assessment of PPV

All above locations are approximately 40 m away from the event location. As shown in Figure 4-10, a PPV factor value of 0.08 m/s was estimated for both locations. The RDP analyses for the above locations are summarised in Table 4-7.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>30</td>
<td>80</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>E2</td>
<td>10</td>
<td>2</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>E3</td>
<td>4.6</td>
<td>4.3</td>
<td>3.5</td>
<td>3.9</td>
</tr>
<tr>
<td>E4</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>PPV</td>
<td>0.07</td>
<td>0.08</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>P_{R2}</td>
<td>25%</td>
<td>79%</td>
<td>59%</td>
<td>70%</td>
</tr>
<tr>
<td>P_{R3}</td>
<td>1%</td>
<td>79%</td>
<td>7%</td>
<td>15%</td>
</tr>
<tr>
<td>RDS_{Observed}</td>
<td>R3</td>
<td>R3</td>
<td>R3</td>
<td>R5</td>
</tr>
</tbody>
</table>

f Performance Evaluation

The adjusted RDP method correctly predicted the observed damage severity for locations A and C, but not for B and D. The forecasted probability suggests that the damage severity at B is most likely R4 or R5, while the observed damage severity is R3. However, it should be noted that the R3 rating is a result of the limited volume of the damage that occurred (according the Table 4-3). Whilst the damage in this area was limited in volume, it was quite severe and was accompanied with floor heave of 1 m. The area to which the RDP rating P_{R2} = P_{R3} = 79% was applicable was limited to the lower 0.5 m height of the wall, which geometrically constrained the volume of the total failure size. Recognising these factors, the very high predicted rock burst damage
probability and the severe damage that was experienced, although limited in size, constitutes a good outcome.

The result suggests that the damage severity at location D has 15% chance exceeding R3, while the observed damage severity was classed as R5. The expected damage severity was less than the experienced damage. Although a fairly high probability was assigned to the probability of experiencing damage greater than R2, this is regarded as a fair outcome.

4.5 Mine B 2014 Rockburst Case Study

4.5.1 Mine B Description

Mine B is an underground gold mine located within the Boorara Domain of the region Yilgarn Craton in Western Australia. The mineralisation is hosted in sedimentary volcanoclastic and conglomeratic rocks, separated into HW and FW by a major south south-east dipping zone of structures. The deposit is mined using sub-level open stoping in an interval of 30 m.

A number of major structures exist throughout the mine. They are generally orientated north-east and steeply dipping towards south-west. They generally span through hundreds of metres over numerous levels. An example of the structures mapped at Mine B is shown in Figure 4-19.

![Mine B active faults in damage vicinity (plan view).](image)

Mine B operates at a relatively high mining depth with the deepest stope mined approximately 1200 m below surface. Several acoustic emission stress
measurement campaigns have been carried out in the past and the results suggest a sub-horizontal major principle stress of 80 MPa striking north-west at a depth of 1200 m. The minor principle stress is sub-vertical and is approximately 35 MPa at a depth 1200 m.

4.5.2 Rockburst Description

A rockburst of 2.6 Mr took place less than 1 second following a stope blast in the lower mining block on RL1120 at 18:24:09 on the 10th Jan 2014. The event occurred immediately after the blast and was subsequently recorded together with the event in the same wave form. Approximately 35 m of excavation were damaged on two levels above and below the blasted stope. All damages were observed within a distance of 80 m away from the blast. The survey coloured by damage severity is shown in Figure 4-20.

The location of the main event is located further into the HW away from mine developments. The event triggered 19 sensors in the mine; however, only five sensors captured the wave form of the event and were used for the calculation for the event location. The location calculated by the monitoring system is illustrated in Figure 4-21.

The large distance between the event location and the damage location, coupled with the fact that only five sensors were used for event location, resulted in low confidence in the location accuracy. It is regarded as very
unlikely for an event at the calculated location to result in damage at the 
damage location. It is more likely that the event location was close to the blast. 
For the purpose of this study, the location was assumed to be at the blast 
location.

![Diagram](image1)

Figure 4-21 Mine B rockburst location calculated by monitoring system. The grid spacing is 200 m.

The rockburst triggered a large seismic response in the region. A large jump in 
seismic activity rate was observed immediately following the rockburst, as 
illustrated in Figure 4-22. The activity rate returned to near background level 
approximately 12 hours following the rockburst.

![Diagram](image2)

Figure 4-22 Mine B rockburst Magnitude and Time chart. Local magnitude is shown which 
approximately equal to Richter scale magnitude.
4.5.3 RDP Model Building

\( a \) E1 Stress Factor

The drive survey coloured by the sigma 1 stress value used for the mine B case study is shown in Figure 4-23.

![Figure 4-23 Mine B drives coloured by nearby stress conditions. The mined out zone resulted in a stress shadow as highlighted in blue.](image)

All observed damage occurred in the FW sediment with an estimated UCS value of approximately 140 MPa.

\( b \) E2 Ground Support

The ground support systems used for mine B are similar to that of mine A. The standard support system consists of patterned split set bolts, Garford dynamic solid bolt in the wall and roof, mesh over fibrecrete in the roof and mesh embedded in fibrecrete in the wall. In addition to the above support elements, the dynamic support system consists of reinforced mesh and straps.

For intersections, cable bolt is installed in addition to the standard support system. The ground support systems used at mine B and their capacity ratings are shown in Table 4-8.
### Table 4-8  Mine B support systems summary.

<table>
<thead>
<tr>
<th>E2</th>
<th>Rockbolt</th>
<th>Surface</th>
<th>Comments</th>
<th>No. cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Pattern bolting</td>
<td>Mesh or fibrecrete</td>
<td>Pattern bolting with split sets or solid bar reinforcement with mesh or 50 mm fibrecrete.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Split set</td>
<td>Mesh over fibrecrete (100 mm)</td>
<td>Standard mine support</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Pattern bolting and pattern cable bolts</td>
<td>Mesh or fibrecrete</td>
<td>Pattern bolting with split sets or solid bar reinforcement, with mesh or 50 mm fibrecrete. Plus pattern cable bolting.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Garford dynamic bolt, split set</td>
<td>Mesh over fibrecrete (100 mm)</td>
<td>Reinforced support standard</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Garford dynamic bolt, split set, Garford cable bolt</td>
<td>Mesh over fibrecrete (100 mm)</td>
<td>Dynamic support standard for large excavation</td>
<td>1</td>
</tr>
<tr>
<td>25</td>
<td>Pattern dynamic support</td>
<td>Dynamic surface support</td>
<td>Pattern bolting with dynamic ground reinforcement such as cone bolts, with a dynamic resistant surface support system.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Garford dynamic bolt, split set</td>
<td>Mesh over fibrecrete (100 mm), strap</td>
<td>Dynamic support standard</td>
<td>4</td>
</tr>
</tbody>
</table>

**E3 Span**

The drive survey coloured by excavation span for mine B is shown in Figure 4-24.
**E4 Geology Factor**

The influence of unfavourable geological features at mine B is ambiguous and subject to interpretation. There are series of north trending structures observed on this level, as shown in Figure 4-25. These structures were interpolated based on either observation during development or measured seismicity clustering. Due to the short spacing and the large number of interpolated structures, it is uncertain which of these structures is active or has potential to generate damaging seismicity.

**Figure 4-24 Mine B survey coloured by excavation span.**

**Figure 4-25 Mine B geological structures illustration. The lithology contact is highlighted using red dashed line.**
Two of these interpolated structures are in close proximity to the observed damage. In addition to the two structures, a contact between two lithology units is also in close proximity to damages observed. Due to the poor understanding of the unfavourable geological features, all damage locations intersecting these active structures or lithology contacts were assigned with an unfavourable E4 rating of 0.5.

As discussed in previous sections, the seismic event location, for the purpose of this case study, was assumed to be the location of the blast. The PPV factor was then calculated based on the blast location. The survey drives coloured by estimated PPV for mine B are shown in Figure 4-26.

![Figure 4-26 Mine B survey coloured by estimated PPV.]

4.6 Performance Evaluation

4.6.1 RL1120 Damage Study

Damage was observed on RL1120 level along FW drive east. All damages were observed in the wall, shoulder and roof. Unlike the previous case study where the lower wall suffered severe damage, the lower wall at mine B only suffered minor damage.

HW shoulder ejection was observed at location A at a three-way intersection on FW drive east, as shown in Figure 4-27. Approximately 2 tonnes of material was
ejected into the excavation, which were mostly slabs of fibrecrete. The mesh was torn open and at least four split set plates were stripped off. There was approximately 30 cm of bulking in the shoulder over an area of 5 by 2 m. An estimated 10 tonnes of material was contained by the support system. Several Garford bolts pulled through surface support and the bolt plate showed little signs of bending. A RDS rating of between R3 and R4 was assigned to this location.

More damage was observed further east from the intersection at the corner of the FW drive east. Over 100 tonnes of material was displaced at location B with maximum failure depth exceeding the length of Garford bolt (2.4 m). A R5 rating was assigned to B. The area beyond this location, however, suffered minimum damage.

A large rock wedge of approximately 2 by 1.5 by 1.5 m was seen lying against the FW, as shown in Figure 4-28. Two Garford dynamic bolts previously supporting the wedge were seen protruding through the wedge pointing upwards. One of the bolts snapped close to the toe of the bolt. Large amounts of debris with sizes up to 0.5 m were seen to the east of this large wedge. At least 12 Garford bolts have failed (see Figure 4-29).
Damage was also observed on the east wall of this location at location C. Large slabs of fibrecrete were ejected into the excavation from the wall and approximately 2 tonnes of material was displaced. The mesh embedded in fibrecrete was torn around the edge. Both split sets and Garford plates pulled through the surface support. An estimated 5 tonnes of material was displaced and a R3 rating was assigned to location C.
At location D, bulking up to 20 cm was observed over an area of 5 by 3 m in the wall with approximately 5 tonnes of material contained. Large cracks in fibcrete (up to 10 cm in width) were seen in the wall, and surface support was loaded. However, the wall remained intact and only minor rehab is required to render the excavation back to safe working condition. An RDS rating of between R2 and R3 was assigned to location D.
a  **Assessment of E1 stress factor**

The modelled sigma 1 principle stress at location A is 120 MPa and 80 MPa at locations B, C and D, as shown in Figure 4-23. Location A is closer to the mined out stope; therefore, it experiences a more elevated stress condition than other locations. All above damages occurred in the FW sediment with an UCS value of 140 MPa. The calculated stress factor is approximately 85 for location A, 60 for B, C and D.

b  **Assessment of E2 ground support**

The support system at locations A, B and C consists of patterned Garford dynamic bolts, split set bolts and mesh over fibcreete or mesh embedded in fibcreete. Since no dynamic bolt compatible surface support was used at these locations, an E2 rating of 8 was assigned based on the support classification shown in Table 4-1.

In addition to the support standard described above, the support system at D received an upgraded surface support of reinforced mesh and straps. The E2 rating can then be rated as a dynamic of 25.

c  **Assessment of E3 excavation span**

The excavation span at A, B and C was relatively large at approximately 9 m, and 5.6 m at D.

d  **Assessment of E4 geology factor**

Location A intersects two active structures and was assigned an unfavourable geological factor of 0.5. Locations B, C and D intersect a lithology contact and were also assigned an unfavourable geological factor of 0.5.

e  **Assessment of PPV**

Location A is located approximately 50 m away from the assumed seismic event with an estimated PPV factor of 0.17 m/s, as shown in Figure 4-26. Locations B, C and D are located approximately 80 m away from the assumed event location with an estimated PPV factor of 0.11 m/s. The RDP analyses for above locations are summarised in Table 4-9.
Table 4-9 Mine B rockburst RL1120 RDP analyses summary.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>85</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>E2</td>
<td>10</td>
<td>10</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>E3</td>
<td>8.2</td>
<td>9.1</td>
<td>9.1</td>
<td>5.6</td>
</tr>
<tr>
<td>E4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>PPV</td>
<td>0.17</td>
<td>0.11</td>
<td>0.11</td>
<td>0.12</td>
</tr>
<tr>
<td>P_{R2}</td>
<td>84%</td>
<td>63%</td>
<td>72%</td>
<td>4%</td>
</tr>
<tr>
<td>P_{R3}</td>
<td>84%</td>
<td>51%</td>
<td>72%</td>
<td>1%</td>
</tr>
<tr>
<td>RDS_{Observed}</td>
<td>R3/R4</td>
<td>R5</td>
<td>R3</td>
<td>R2/R3</td>
</tr>
</tbody>
</table>

**Perform Evaluation**

The method performed well for locations A and C, and fair for D. The severity of damage at location B is extreme and the failure depth at some places exceeded the support tendon embedment depth. The support system anchor depth was therefore too short and the capacity of the system was not properly mobilised. The E2 rating was assessed under the assumption that the support system was able to fully mobilise its capacity. At location B, however, this was not the case. Under these conditions, more severe damage than the expected damage level is expected. The unexpectedly large failure depth may be a result of several factors. The explicit evaluation of the probable failure depth and the associate anchor length required for the support system to function as design is not in any way incorporated in the RDP system. However, further investigation of this issue is outside the scope of this study.

4.6.2 RL1150 Damage study

There was more damage observed on RL1150 along the lithology contact in FW drive east. The majority of the damage was observed in the roof and some in the HW.

The roof suffered extensive damage between the two three-way intersections on FW drive east, as shown in Figure 4-32. At location A, damage was well contained and only minor bulking was observed. Less than 1 tonne of material was displaced and a RDS rating of R2 was assigned.
At location B, approximately 100 tonnes of material was dislodged from the roof of the drive. A R5 rating was assigned to location B. The ejected material appears to be highly jointed and foliated. Upon close inspection, a minimum of five Garford bolts have failed and several Garford dynamic bolts have pulled through the surface support.

To the east of B, more damage was observed at location C in the roof of the intersection, as shown in Figure 4-33. Bulking up to half a metre was observed over an area of 5 by 3 m. Approximately 5 tonnes of material was dislodged from the back of the intersection and another 10 tonnes of material contained. A RDS rating of R4 was assigned to location C. Similar to the previous damage location, the ejected material at this location is highly foliated and slabby with average size of less than 10 cm.
Damage was also observed in the HW location D, as shown in Figure 4-34. Cracks up to 10 cm were seen from shoulder level down to floor level. The wall bulked approximately 30 cm at some places, resulting in minor damages to the surface mesh. All material was sufficiently contained by the support system and a RDS rating of R2 was assigned to location D.

Assessment of E1 stress factor

The modelled sigma 1 stress value at locations A and B was approximately 80 MPa, as shown in Figure 4-23. The sigma 1 stress value at C and D was
approximately 95 MPa. The rock type at all locations is sediment with an UCS value of 140 MPa. The calculated stress factor value is approximately 60 for A and B, 70 for C and D.

b  Assessment of E2 ground support

The support system at A, B and D consists of patterned Garford dynamic bolts, split set bolts and mesh over fibrecrete. Dynamic rock bolts were used here without compatible surface support elements such as straps. This often leads to premature surface support failure resulting in lower attainable overall capacity. Therefore, an E2 rating of 10 was assigned to A, B and D. At location C, which is located in the roof, additional patterned cable bolts were used. Since the surface support is not reinforced, the same E2 rating 10 was assigned.

c  Assessment of E3 excavation span

The span at A and B was approximately the same size as the development profile of 5.5 m. Locations C and D were located in an intersection with span value of 8.6 m.

d  Assessment of E4 geology factor

All damages observed on this level were adjacent to the lithology contact, which was thought to be unfavourable. Therefore, an E4 rating of 0.5 was assigned to all four locations.

e  Assessment of PPV

All damage locations on this level were approximately 70 m away from the assumed event, which resulted in an estimated PPV factor of 0.1 m/s, as shown in Figure 4-26. The RDP analyses for these damage locations are summarised in Table 4-10.
Table 4-10 Mine B rockburst RL1150.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>60</td>
<td>60</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>E2</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>E3</td>
<td>5.4</td>
<td>6</td>
<td>8.6</td>
<td>8.6</td>
</tr>
<tr>
<td>E4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>PPV</td>
<td>0.12</td>
<td>0.11</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$P_{R2}$</td>
<td>64%</td>
<td>63%</td>
<td>61%</td>
<td>61%</td>
</tr>
<tr>
<td>$P_{R3}$</td>
<td>32%</td>
<td>33%</td>
<td>59%</td>
<td>59%</td>
</tr>
<tr>
<td>RDS_{Observed}</td>
<td>R2</td>
<td>R5</td>
<td>R4</td>
<td>R2</td>
</tr>
</tbody>
</table>

**f Performance Evaluation**

The adjusted RDP method performed well for location C, correctly predicting observed damage severity, but less satisfactorily for A, B and D.

The failure depth at location B likely exceeded the embedment length of support system. The extreme failure depth at B, similar to previous cases, indicates the high complexity of rockburst damage and may suggest the true dynamic loading is higher than expected. The excavation conditions at locations A, C and D are comparable to the condition at B; however, the observed severity varied largely across all four locations. This suggests that either a critical damage predicting factor was not accounted for by the method or one of the factors used was incorrectly estimated.
4.7 Kidd Mine 2009 Rockburst Case Study

4.7.1 Kidd Mine Description

Kidd Mine is a base metal mine located approximately 27 km north of the city of Timmins in Ontario, Canada (Figure 4-35). The deposit was first discovered in November 1964, and mining commenced in late 1966. The mine is currently operating at a significant depth, with the deepest stope mined some 2895 m below surface. The mine has a long history of seismicity and rockbursting dating back as early as in the mid-1980s (Counter 2012).

![Kidd Mine location and a bird eye view of the mine.](image)

The orebodies and their host rocks dip 70° to 80° east, plunge between 60° and 70° north, and are overturned. There are multiple distinct, south dipping brittle faults defined by up to 2.5 cm of gouge or 8 to 12 cm of brecciated material. They strike east southeast and dip 75° to 88° south southwest with a sinistral reverse dip slip movement involving appropriately 200 m of vertical displacement, and up to 100 m of left lateral strike slip.

The three strongest of these structures in the current mining vicinity are the North F, the North G and the North H faults, as illustrated in Figure 4-36 (Cooper 2012). The North G faults and other similar south dipping structures have been the source for numerous large seismic events and rockbursts in the past (Counter 2009). Numerous damaging events that occurred in the lower
part of the mine are believed to be associated with these south dipping structures.

4.7.2 Rockburst Description

Following the final slot blast of the GW5 stope on 7300 level (Figure 4-37) at the end of night shift on 5th January 2009, there was an increase in the rate of seismic events followed by a gradual decay, as shown in Figure 4-38. Similar decay behaviour of seismic response following production blasts is frequently seen at Kidd mine.

Approximately 24 hours following the stope blast, a 3.3 $M_R$ (Local Magnitude = 2.3) seismic event occurred. The seismic monitoring system located the event north of the stope on the North G fault near 7100 level, approximately 61 m above 7300 level. The main event was followed by a 1.2 $M_R$ event on 6900 level and a 0.6 $M_R$ event on 6800 level.
The seismic activity rate returned to near background level around the 10th of January. The seismic system indicated that the entire block from 6000 level to 7800 level showed an increase in seismicity following the main event, possibly as a result of joints or faults adjusting to the new stress regime.
The rockburst damage affected up to 1500 m of development spreading across seven levels. The observed damage ranges from shake down, new fractures in rock mass to collapse of intersection. Most of the severe damage was restricted to between 10 to 20 m away from a rupture formed during the main event, which is referred to as the seismic rupture in this study. Elsewhere, damage was generally well contained by the ground support system. All significant rock damages (RDS>R1) observed following the 2009 rockburst coloured by RDS are illustrated in Figure 4-39.

![Figure 4-39 Kidd Mine 2009 survey coloured by observed damage severity.](image)

4.7.3 RDP Model Building

a  E1 Stress Factor

For Kidd Mine, non-elastic numerical model was available and used to derive principle stress values. The drive survey coloured with sigma 1 stress is illustrated in Figure 4-40.
Five different rock types were seen at Kidd Mine (Tannant, Martin & Kaiser 1997). Their names and corresponding strength parameters are summarised in Table 4-11.

Table 4-11  Intact rock strength in MPa used for RDP model (Tannant, Martin & Kaiser 1997).

<table>
<thead>
<tr>
<th>Rock Unit</th>
<th>UCS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andesite-diomite</td>
<td>130</td>
</tr>
<tr>
<td>Greywacke</td>
<td>160</td>
</tr>
<tr>
<td>Talc-carbonate</td>
<td>65</td>
</tr>
<tr>
<td>Rhyolite</td>
<td>110</td>
</tr>
<tr>
<td>Massive sulphide</td>
<td>150</td>
</tr>
</tbody>
</table>

b  E2 Ground Support Factor

There are large differences between the ground support used in previous case studies and the Kidd Mine case study, which can be generally attributed to the different mining practices in Canada and Australia. For example, a split set or friction bolt is used in Canada only to secure mesh. In Australia, they are used as first pass primary ground support tendons.

For the Kidd Mine 2009 rockburst case, support systems without either rock bolts or surface support were assigned a rating of 2. A dynamic support rating of $E_2 = 25$ was only assigned to excavations where high capacity rock bolts such as modified cone bolt, and reinforced surface support such as additional...
straps on top of existing mesh and fibrecrete, are used. The support systems in this case study are summarised in Table 4-12.

Table 4-12  Kidd Mine 2009 E2 classification.

<table>
<thead>
<tr>
<th>E2</th>
<th>Rockbolt</th>
<th>Surface</th>
<th>Comments</th>
<th>No. cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>None</td>
<td>Spot bolting</td>
<td>Spot bolting with split sets or solid bar bolts, minimal surface support.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rebar</td>
<td>None</td>
<td>Lower wall</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>Fibrecrete</td>
<td>Lower wall</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>Pattern bolting</td>
<td>Mesh or fibrecrete</td>
<td>Pattern bolting with split sets or solid bar reinforcement with mesh or 50 mm fibrecrete.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rebar</td>
<td>Fibrecrete</td>
<td>Old standard support</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Rebar and cable bolt</td>
<td>Fibrecrete</td>
<td>Old intersection support</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>Pattern bolting with second pass of pattern bolting</td>
<td>Mesh or fibrecrete</td>
<td>Pattern bolting with split sets with mesh or 50 mm fibrecrete, plus an additional pass of pattern reinforcement, such as solid bar bolts.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rebar</td>
<td>Mesh</td>
<td>New standard support</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Rebar</td>
<td>Mesh over fibrecrete</td>
<td>Reinforced standard support</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>Pattern bolting and pattern cable bolts</td>
<td>Mesh or fibrecrete</td>
<td>Pattern bolting with split sets or solid bar reinforcement, with mesh or 50 mm fibrecrete. Plus pattern cable bolting.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rebar and cable bolt</td>
<td>Mesh over fibrecrete</td>
<td>Intersection standard support</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Rebar and cable bolt</td>
<td>Mesh</td>
<td>Intersection standard support</td>
<td>1</td>
</tr>
<tr>
<td>25</td>
<td>Pattern dynamic support</td>
<td>Dynamic surface support</td>
<td>Pattern bolting with dynamic ground reinforcement such as cone bolts, with a dynamic resistant surface support system.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rebar and cone bolt</td>
<td>Mesh over fibrecrete, straps</td>
<td>Dynamic support system</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Rebar and cone bolt</td>
<td>Mesh and straps</td>
<td>Dynamic support system</td>
<td>2</td>
</tr>
</tbody>
</table>

For Kidd Mine 2009 rockburst, five damage locations were supported with a dynamic support system with an E2 rating of 25. The support tendon consists of patterned rebar and modified cone bolt. The surface support consists of
0 gauge straps (diameter = 8.25 mm) on top of standard mesh (aperture = 100 mm, diameter = 4.9 mm) and approximately 75 mm of fibrecrete. The dynamic support system is also shown in Figure 4-41. The bolt capacity, overall bolt density and surface support used for Kidd dynamic support system are all comparable to the dynamic support example cases described in Table 4-1; therefore, the assignment of $E_2 = 25$ is reasonable.

\[ \text{Figure 4-41 Kidd Mine 2009 rockburst dynamic support system example.} \]

\[ \text{c E3 Excavation Span} \]

The level survey coloured by span for Kidd 2009 RDP model is shown in Figure 4-42.
For Kidd mine, actual measurements of displacement along these structures are taken regularly to monitor the response of a geological structure to nearby mining. This approach allows the ‘activeness’ of structures to be numerically quantified and then compared. These structures ranked by rate of movement in response to mining are given in Table 4-13.

Table 4-13 Kidd Active Structures (Cooper 2012).

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>North F</td>
</tr>
<tr>
<td>2</td>
<td>North G</td>
</tr>
<tr>
<td>3</td>
<td>North H</td>
</tr>
<tr>
<td>4</td>
<td>North I</td>
</tr>
<tr>
<td>5</td>
<td>Gouge fault 4</td>
</tr>
<tr>
<td>6</td>
<td>North G splay</td>
</tr>
<tr>
<td>7</td>
<td>North K</td>
</tr>
</tbody>
</table>

All rock damages located with 10 m to these structures, which also have shown signs of movement following failures, are assigned with an unfavourable E4 factor of 0.5. All damages located further away from these structures are assigned with an average E4 factor of 1. All damages located at a distance
away from above structures, which occurred in massive rock with no unfavourable geological features, are assigned with an E4 factor of 1.5.

PPV Factor

The Kidd Mine survey coloured by estimated PPV factor for the 2009 rockburst case is illustrated in Figure 4-43.

4.8 Performance Evaluation

4.8.1 6700L 01Dr South Damage Study

The damages observed on 6700 level are restricted to the intersection highlighted in Figure 4-44, adjacent to the North G fault, which was thought to be the cause of the rockburst. Large slabs of fibrecrete were ejected 5 m away from the nose of the pillar at Location A. A minimum of 10 tonnes of material was displaced at this location and a RDS rating of R4 was assigned.

At location B where bulking was observed, approximately 2 tonnes of material was ejected into the excavation and another 5 tonnes contained by the support system. A RDS rating of R3 was assigned to location B.
a  Assessment of E1 stress factor

The modelled sigma 1 stress condition is approximately 125 MPa for A and 130 MPa for B, shown in Figure 4-40. Both damage locations occurred in andesite with an UCS value of 130 MPa. The calculated stress factor is approximately 95 for A and 100 for location B.

b  Assessment of E2 ground support

Both damage locations were supported with patterned rebar and mesh over fibrecrcte. Based on the E2 rating example shown in Table 4-1, an E2 rating of 8 was assigned to both locations.

c  Assessment of E3 excavation span

Location A is in a three-way intersection with a span of 6.5 m. Location B is further up from A with a span of 4.5 m.

d  Assessment of E4 geology factor

Both locations intersect the North G fault, which was an active structure, and an unfavourable geological factor of 0.5 was assigned to both locations.

Figure 4-44 Kidd 2009 rockburst 6700 level 01S drive pillar ejection.
Assessment of PPV

Both locations are approximately 200 m away from event location, with an estimated PPV factor of 0.12 m/s, as shown in Figure 4-43. A summary of RDP analyses for the two damage locations is shown in Table 4-14.

Table 4-14  Kidd 2009 rockburst 6700 level 01S RDP analyses summary.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>95</td>
<td>100</td>
</tr>
<tr>
<td>E2</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>E3</td>
<td>6.5</td>
<td>4.5</td>
</tr>
<tr>
<td>E4</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>PPV</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>(P_{R2})</td>
<td>94%</td>
<td>93%</td>
</tr>
<tr>
<td>(P_{R3})</td>
<td>94%</td>
<td>93%</td>
</tr>
<tr>
<td>RDS(_{\text{Observed}})</td>
<td>R4</td>
<td>R3</td>
</tr>
</tbody>
</table>

Performance Evaluation

The adjusted RDP method performed well for location A, but less satisfactorily for B. Locations A and B share remarkable similarity in excavation condition, support system and dynamic loading quantified using PPV. However, the observed difference in damage severity is significant. This suggests that either the dynamic loading or excavation vulnerability was not appropriately captured using the five factors.

4.8.2 6800L 74XC Damage Study

The damage observed on 6800 level was mostly restricted to along 74XC.

The back of the intersection to the west of 74XC (location A) had failed to depth in excess of 4 m, and over 100 tonnes of material was displaced from the back. A RDS rating of R5 was assigned to location A. This is illustrated in Figure 4-45.

Adjacent to this at location B, severe bulking occurred with approximately 10 tonnes contained by the support system. A RDS rating of between R3 and R4 was assigned.
Further east from locations A and B, fall of ground was observed again at location C (68-01 Dr. So. Intersection with 68-74 and 76 XCs) with over 100 tonnes of material ejected from the back. A RDS rating of R5 was assigned to location C. A large number of rebar bolts were seen protruding vertically on top of the failed debris, as shown in Figure 4-47. The height of the pile has exceeded the original height of the excavation and beyond the failure was not accessible.
A new and not previously known seismic rupture was mapped following the rockburst. This rupture dips at 65 degrees to the north north west and can be observed from 6800L down to 7100L. This newly formed rupture is closely spatially associated with most of the severe damage observed for the 2009 case study. The collapse of the intersection to the east of 74XC illustrated in Figure 4-46 is located on the seismic rupture.

\[ a \] Assessment of E1 stress factor

Prior to the occurrence of the rockburst, there were signs of extreme compressive stress oriented in a north-south direction in the back and frequent fibrecrêute failures were seen. The modelled sigma 1 stress is approximately 165 MPa at locations A and B, 135 MPa at location C, shown in Figure 4-40. The rock type at all three locations is andesite with UCS of 110 MPa. The calculated stress factor is approximately 150 for A and B, and 125 for C.

\[ b \] Assessment of E2 ground support factor

Locations A and C were supported with patterned rebar, twin strand plain cable bolts (unplated) and standard mesh. Based on the E2 classification shown in Table 4-1, a rating of 10 was assigned. Location B was supported with patterned rebar and mesh, which resulted in an E2 rating of 8.
c  Assessment of E3 excavation span

All three locations are located at intersections, and a large intersection is experienced. The approximated span for three locations is 7.5 m.

d  Assessment of E4 geological factor

All three locations were located adjacent to the North G fault and the North I fault, and intersect the newly formed seismic rupture. Therefore, an unfavourable geological factor of 0.5 was assigned to all locations.

e  Assessment of PPV

The above locations were located approximately 150 m away from the event location with PPV factor value of 0.15 m/s. The new RDP analyses summary for these locations is shown in Table 4-15.

Table 4-15  Kidd 2009 rockburst 6800L 74XC RDP analyses summary.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>150</td>
<td>150</td>
<td>125</td>
</tr>
<tr>
<td>E2</td>
<td>10</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>E3</td>
<td>7.3</td>
<td>7.3</td>
<td>7.7</td>
</tr>
<tr>
<td>E4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>PPV</td>
<td>0.15</td>
<td>0.15</td>
<td>0.14</td>
</tr>
<tr>
<td>(P_{R2})</td>
<td>100%</td>
<td>100%</td>
<td>99%</td>
</tr>
<tr>
<td>(P_{R3})</td>
<td>100%</td>
<td>100%</td>
<td>99%</td>
</tr>
<tr>
<td>RDS_{Observed}</td>
<td>R5</td>
<td>R3/R4</td>
<td>R5</td>
</tr>
</tbody>
</table>

f  Performance Evaluation

The adjusted RDP method performed well for A and C. For location B with \(P_{R3} \sim 100\%\), the result is conservative and fair.

Despite the method performing well for locations A and C, it was noted that the stress factor used in this case study was much higher than the largest value in the original ACG database (E1=95). Since the square scale of stress factor is used, the use of extreme stress factors quickly exceeded the model's applicability and resulted in saturated probability forecast.
It was also noted that the failure depth at A and C likely exceeded the maximum support system embedment depth. As discussed in the previous case studies, such a situation would not allow the full dynamic capacity of the support tendons to be mobilised, and the assigned E2 rating of 10 is likely overestimated.

4.8.3 6900 L 82XC

Most damages observed on 6900 level were minor in comparison to the damages observed in above levels. The mine standard support system of rebar, mesh over fibrecrete was sufficient to contain majority of the damages.

There was approximately 15 tonnes of material ejected from the back at location A in 82XC, as illustrated in Figure 4-48. The ejected rock was mostly slabby of approximately 20 cm in size or less. Bulking of more than half a metre was seen in the back over an area of 5 by 5 m and a RDS rating of R4 was assigned to location A.

Further back the drive along 82XC, expulsion of rock from the lower wall below mesh line was frequently seen, as illustrated in Figure 4-49. Only 1 tonne of material at location B was locally ejected from near the floor (where support is minimal) and a RDS rating of R2 could be assigned. However, the entire wall to a depth of several metres was damaged, and required extensive scaling or shotcrete application, followed by installation of new tendons, mesh and strap.
support throughout the damaged area. Therefore, the “outcome” was in line with an R4 level of repair, and a RDS rating of R4 could also be assigned.

![Image](image-url)

*Figure 4-49 Kidd 2009 rockburst 6900L 82XC lower wall shakedown.*

a **Assessment of E1 stress factor**

The modelled sigma 1 stress is 140 MPa for location A and 130 MPa at B, as shown in Figure 4-40. Sulphide with UCS of 150 MPa was encountered at both locations. The calculated stress factor is approximately 95 for A and 85 for B.

b **Assessment of E2 ground support factor**

Location A was supported with patterned twin strand plain cable bolts (unplated) and rebar, and mesh over fibrecrete. The E2 rating based on the support classification table is 10 for A. Location B, which is in the lower wall, was supported with spot bolting, resulting in an E2 rating of 2.

c **Assessment of E3 excavation span**

The estimated span value is 7.2 m at A and 5.3 m at B.
d Assessment of E4 geology factor

Location A intersects the North K fault, which was considered as active at the time of the rockburst. Therefore, an unfavourable geological factor of 0.5 was assigned to A. Location B was not adjacent to any major structures and an average geological factor of 1 was assigned.

e Assessment of PPV

Both locations are approximately 150 m away from the seismic event; however, they are close to the rupture itself. Therefore, a saturated PPV value of 0.55 m/s is used. The new RDP analyses for the two damage locations are summarised in Table 4-16.

Table 4-16 Kidd 2009 rockburst 6900L 82XC RDP analyses summary.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>95</td>
<td>85</td>
</tr>
<tr>
<td>E2</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>E3</td>
<td>7.2</td>
<td>5.3</td>
</tr>
<tr>
<td>E4</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>PPV</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>(P_{R2}) (%)</td>
<td>96</td>
<td>97</td>
</tr>
<tr>
<td>(P_{R3}) (%)</td>
<td>96</td>
<td>97</td>
</tr>
<tr>
<td>RDS_{Observed}</td>
<td>R4</td>
<td>R2/R4</td>
</tr>
</tbody>
</table>

f Performance Evaluation

The adjusted RDP model performed well for locations A and for B. However, this case shed lights on the issue of applying RDS to classify rockburst damage severity, which does not account for the extent of the damage in space. This has resulted in differences in determined damage severity ratings.

4.8.4 7000 01 South Drive & 82XC Damage Study

There was a significant amount of damage observed on 7000 level, mostly to the south end. This level was in the process of a support upgrade prior to the occurrence of the rockburst and a large proportion of the drives were supported with high capacity dynamic support.
Over 100 tonnes of material was ejected into the excavation at location A in 82XC, approximately 10 m behind the service lift, shown in Figure 4-50. The ejection ruptured the surface support of mesh over fibcrete and straps. Large numbers of modified cone bolts failed in necking. The failed rock was mostly in the form of pulverised rock with an average size of 5 cm. A RDS rating of R5 was assigned to location A.

Significant damage was also observed at the intersection with S46, shown in Figure 4-51. The dynamic support system which included additional straps and modified cone bolts was installed up to location B, illustrated using a red dotted line. The support system at C failed completely and at B only suffered minor bulking. Over 10 tonnes of material was displaced at C and the support system suffered complete failure. Location C was assigned with a RDS rating of R4 due to the severe damage to the support system. Less than 1 tonne of material was displaced at B and all was well contained resulting in a RDS rating of R2.
a  Assessment of E1 stress factor

The modelled sigma 1 stress is approximately 135 MPa at location A and 120 MPa for locations B and C, as shown in Figure 4-40. The rock type encountered at all three locations was andesite with an UCS value of 130 MPa. The calculated stress factor is approximately 100 for A, 95 for B and C.

b  Assessment of E2 ground support factor

The ground support at location A consists of patterned rebar and modified cone bolts, mesh over fibcrete with 0 gauge straps. The surface support is compatible with the dynamic bolt used; therefore, an E2 rating of 25 was assigned to A. The support system at B is essentially the same as A, but without the fibcrete, a rating of 25 was also assigned to B. At location C, support consists of only patterned rebar over mesh and, based on the E2 classification table, an E2 rating of 8 was assigned.

c  Assessment of E3 excavation span

The estimated span at location A is 5.2 m, 4.5 m at B and 7.1 m at C.
d Assessment of E4 geology factor

All above damage locations intersect the seismic rupture created during the rockburst; therefore, an unfavourable geological factor of 0.5 was assigned to all cases.

e Assessment of PPV

All damage locations are located approximately 50 m away from the event. However, due to the close proximity of these locations to the rupture, a saturated PPV factor of 0.55 m/s is used. The RDP analyses summary for the three locations is shown in Table 4-17.

Table 4-17 Kidd 2009 rockburst 7000L RDP analyses summary.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>100</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>E2</td>
<td>25</td>
<td>25</td>
<td>8</td>
</tr>
<tr>
<td>E3</td>
<td>5.2</td>
<td>4.5</td>
<td>7.1</td>
</tr>
<tr>
<td>E4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>PPV</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>P_{R2}</td>
<td>9%</td>
<td>9%</td>
<td>98%</td>
</tr>
<tr>
<td>P_{R3}</td>
<td>3%</td>
<td>2%</td>
<td>98%</td>
</tr>
<tr>
<td>RDS_{Observed}</td>
<td>R5</td>
<td>R2</td>
<td>R4</td>
</tr>
</tbody>
</table>

f Performance Evaluation

The new RDP model performed well for locations B and C, but less satisfactorily for A, failing to predict the severity of the observed damage. The failure depth at A is estimated to have mostly exceeded some of the bolts with a length of 2.2 m. Some bolts necked while others stayed intact.

As previously discussed, the extreme failure depth does not allow the design capacity of the support system to be reached. This in turn suggests that the E2 rating of 25 for the support system is likely overestimated and a longer support length would be beneficial in achieving a higher dynamic capacity.
4.8.5 7100 01S & 84XC Intersection Damage Study

More damage was observed on this level. Some minor shakedown was observed in most of the level below the mesh line in the lower wall. The back of the intersection of 84XC (location A) collapsed up to a depth of 3 metres and over 100 tonnes of material was displaced from the back, as shown in Figure 4-52. A RDS rating of R5 was assigned to location A.

![Figure 4-52 Kidd 2009 rockburst 7100L 84XC intersection collapse.](image)

The north end of the failure was well defined by the newly formed seismic rupture (Counter 2012), which was seen extending from 6800 level down to 7100 level. The seismic rupture had shown signs of large movement and lateral displacement, which may have contributed towards the intersection collapse. A close-up look at the back of the collapsed intersection is shown in Figure 4-53.
a  Assessment of E1 stress factor

The modelled sigma 1 stress at location A is approximately 105 MPa and the rock type is andesite with a UCS value of 130 MPa, as shown in Figure 4-40, which resulted in a calculated stress factor of 80.

b  Assessment of E2 ground support factor

The support system at this location consists of patterned rebar, twin strand plain cable bolts (unplated) and fibrecrete as surface support. Due to the weak surface support used, a support rating of 5 was assigned.

c  Assessment of E3 excavation span

This location has suffered damage previously, and the excavation span was estimated to be 9.2 m.

d  Assessment of E4 geology factor

Location A intersects the newly formed seismic rupture; therefore, an unfavourable geological factor of 0.5 was assigned.
Location A is approximately 50 m away from the event, which resulted in an estimated PPV factor of 0.5 m/s, as shown in Figure 4-43. The RDP analysis for this location is summarised in Table 4-18.

Table 4-18  Kidd 2009 rockburst 7100L RDP analysis summary.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>80</td>
</tr>
<tr>
<td>E2</td>
<td>5</td>
</tr>
<tr>
<td>E3</td>
<td>9.2</td>
</tr>
<tr>
<td>E4</td>
<td>0.5</td>
</tr>
<tr>
<td>PPV</td>
<td>0.5</td>
</tr>
<tr>
<td>PR2</td>
<td>98%</td>
</tr>
<tr>
<td>PR3</td>
<td>98%</td>
</tr>
<tr>
<td>RDS&lt;sub&gt;Observed&lt;/sub&gt;</td>
<td>R5</td>
</tr>
</tbody>
</table>

The new RDP model correctly predicted the occurrence of rockburst damage to exceed R3 severity. Similar to the severe damages observed in the first case on 6700L, the damage observed at this location was also located relatively close to the seismic rupture formed and the seismic rupture.

The failure depth at this location again exceeded the length of grouted rebar, leaving cable bolts as the only support tendon with sufficient embedment. Such a situation when failure depth exceeds a maximum embedment length is not accounted for when assessing an E2 rating for a support system. It is also unknown what factor or condition can result in such extreme failure depth.
4.9 Kidd Mine 2011 Rockburst Case Study

4.9.1 Rockburst Damage Description

A 3.3 M<sub>r</sub> rockburst took place in the south end of the HW on the seismic rupture formed in the 2009 rockburst. The event was heard and felt throughout the mine, and was felt locally at the town of Timmins, 27 km away. This event is comparable in mechanism and magnitude to the 2009 rockburst.

Following the blast of GW4 stope on 7300L on the 9<sup>th</sup> September 2011, there was an increase in local seismic activity rate in the south end of the mine between 6800L and 7500L. The seismic response prior to the large event exhibited strong spatial correlation with the seismic ruptures formed in previous large rockbursts, as illustrated in Figure 4-54. The seismic events are coloured by apparent stress, which was a significant parameter used for re-entry analysis at Kidd Mine.

![Figure 4-54 Strong seismic response within vicinity of seismic ruptures in the south end between 6800L and 7500L.](image)

Approximately four days following the stope blast at 7:59:50 on the 13<sup>th</sup> September, a 3.3 M<sub>r</sub> rockburst occurred in the southern HW on 6900L. The seismic event location, damage location coloured by RDS, seismic ruptures and previous stope blasts are illustrated in Figure 4-55. There was an elevated seismic activity rate following the rockburst, and it returned to background level approximately 24 hours after the main event. The magnitude-time chart for the seismic events, 1 week prior to 1 week after the main event, is shown in Figure 4-56.

138
In comparison to the 2009 rockburst, the quantity and severity of damage of the 2011 rockburst is significantly reduced. For the 2011 rockburst, damage was observed from 6900L down to 7500L. The damage severity ranges from shakedown of small blocks to a large volume of ejection from wall. However, no collapse of intersection was observed following the 2011 rockburst. It was thought that the reduction in damage severity was likely due to the upgraded dynamic ground support system extensively used prior to the 2011 event (Counter 2011).
4.9.2 RDP Model Building

This section describes the steps in building the RDP model for all damage locations observed from 6900L to 7500L.

\( a \) E1 Stress Factor

For the Kidd Mine 2011 rockburst study, the sigma 1 stress value was derived from elasto-plastic numerical models in the same way as for the Kidd Mine 2009 rockburst study. The drive survey coloured by sigma 1 stress values used for 2011 rockburst study is shown in Figure 4-57.

![Figure 4-57 Kidd Mine 2011 rockburst survey coloured by sigma 1 stress. Looking North East.](image)

There are no new rock types in the additional levels included in this study. The same UCS values listed in Table 4-11 are also used for the 2011 rockburst study.

\( b \) E2 Ground Support

There are minor differences in the ground support system used for the 2011 rockburst than the 2009. Most of the differences are associated with the new dynamic support tendons that were adopted during the ground support upgrade campaign leading up to the 2011 rockburst.
Since 2009, Kidd Mine had implemented new rock bolts in the high dynamic support standards. Super Swellex bolts (Atlas Copco 2015) of 3.8 m in length were extensively used in the rehabilitation process, particularly when highly fractured ground was encountered. Such ground condition does not allow the installation of resin based tendons, as drill hole overbreak and collapse often result in great difficulty during installation.

The support systems used for the 2011 rockburst are summarised in Table 4-19. The entries highlighted in bold and italic are the descriptions for each capacity category. This is followed by each support system used.

<table>
<thead>
<tr>
<th>E2</th>
<th>Rockbolt</th>
<th>Surface</th>
<th>Comments</th>
<th>No. cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>None</td>
<td>Spot bolting</td>
<td>Spot bolting with split sets or solid bar bolts, minimal surface support.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rebar</td>
<td>None</td>
<td>Wall spot bolting.</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>Fibrecrete</td>
<td>Lower wall support</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>Pattern bolting</td>
<td>Mesh or fibrecrete</td>
<td>Pattern bolting with split sets or solid bar reinforcement with mesh or 50 mm fibrecrete.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rebar</td>
<td>Fibrecrete</td>
<td>Old mine support standard</td>
<td>12</td>
</tr>
<tr>
<td>8</td>
<td>Pattern bolting with second pass of pattern bolting</td>
<td>Mesh or fibrecrete</td>
<td>Pattern bolting with split sets with mesh or 50 mm fibrecrete, plus an additional pass of pattern reinforcement, such as solid bar bolts.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rebar</td>
<td>Mesh over fibrecrete</td>
<td>Reinforced support standard</td>
<td>1</td>
</tr>
<tr>
<td>25</td>
<td>Pattern dynamic support</td>
<td>Dynamic surface support</td>
<td>Pattern bolting with dynamic ground reinforcement such as cone bolts, with a dynamic resistant surface support system.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rebar, Modified cone bolt</td>
<td>Mesh over fibrecrete, straps</td>
<td>Dynamic support standard for intact ground.</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Rebar, Super Swellex</td>
<td>Mesh over fibrecrete, straps</td>
<td>Dynamic support standard for broken ground.</td>
<td>12</td>
</tr>
</tbody>
</table>

Most damage locations supported with dynamic support (E2 = 25) in this study have previously suffered rockburst damages. In the following rehabilitation
process, a dynamic support system was often installed on top of the pre-existing support system. The previous support system standard was not accounted for in the evaluation of the E2 rating and only the new support system was accounted for.

When rating the support system capacity, the connection between the rock bolt and surface support is assumed to be compatible in capacity to both rock bolt and surface support. An example of the dynamic support standard \((E2 = 25)\) prior to damage is shown in Figure 4-58. This location was supported with patterned rebar and Super Swellex, mesh over a minimum 100 mm of fibrecrete and 0 gauge straps.

![Image](image_url)

*Figure 4-58 Kidd mine 2011 dynamic support system example.*

**c E3 Excavation Span**

The excavation span for the Kidd Mine 2011 study was derived in the same way as the 2009 study, using the same set of survey files. The drive survey coloured by the excavation span for 6900L to 7500L is shown in Figure 4-59.
**d E4 Geology Factor**

E4 geology factor is determined in the same way as the 2009 rockburst study.

In addition to the seismically active structures listed in Table 4-13. Three seismic ruptures (SR) are also included in the 2011 geology factor rating process. They are Seismic Ruptures 1 (SR1), formed during 2009 January rockburst, Seismic Rupture 1A (SR1A), formed as a result of several smaller seismic events with magnitude of greater than 0 M$_r$ prior to 2011 rockburst, and Seismic Rupture 2 (SR2), formed during the 2009 June rockburst.

SR1 and SR1A, mapped following the January and June 2009 rockburst, as shown in Figure 4-60, are thought to be closely related to the 2011 rockburst (Counter 2011). It also intersects two of the most severely damaged locations.
PPV for the 2011 rockburst was estimated using the same approach as the 2009 rockburst study. The location of rockburst for 2011 is higher in elevation than that of 2009. The hypocentre of the 2011 rockburst is located further away from the severe damage observed (RDS>R3) and it is higher in elevation than all damages observed in 2011. The drive coloured by estimated PPV is shown in Figure 4-61.
4.10 Performance Evaluation

4.10.1 7000L S46 XC Damage Study

The damages observed on 7000L following the 2011 rockburst were mostly restricted to the south end of the level, similar to the 2009 rockburst. The north wall of the intersection (location B) between S46XC and 01S drive was damaged, as shown in Figure 4-62. The displaced material measured by drilling during repair was approximately 2 m deep, over an area of 60 m², which resulted in a total of 600 tonnes. Therefore, an RDS rating of R5 was assigned to location B.

Over 10 tonnes of rock was ejected into the excavation from lower wall (Location A) accompanied by some floor heave. The largest rock debris ejected measures 0.5 by 0.5 by 0.5 m. The support system at location A suffered severe damage and a RDS rating of R4 was assigned.
Large bulking up to 30 cm over an area of 3 by 3 m was observed in the back of the intersection at location C. Multiple bolt plates were stripped off the Super Swellex bolts (highlighted in red circles in Figure 4-63). Up to 5 tonnes of material was displaced and contained in the roof and a RDS rating of R3 was assigned.

This damage location was supported with patterned self-drilling rebar and Swellex bolts, straps and mesh over fibrecrete at all three cases. Higher capacity dynamic rock bolts, such as the cone bolt, were not used due to the
poor ground condition. The damage at this location was generally well contained in the wall and roof by the support system. Pieces of a strap originating from the lower wall can be seen lying on the floor together with rock debris up to half a tonne in weight, shown in Figure 4-64.

![Figure 4-64 2011 Kidd Mine rockburst 7000L broken straps and ejected debris.](image)

(a) **Assessment of E1 stress factor**

The modelled sigma 1 stress at this location is approximately 140 MPa, and the rock type is andesite with a UCS value of 130 MPa, as shown in Figure 4-57. The calculated stress factor for all three damages is 105.

(b) **Assessment of E2 ground support factor**

The support at these locations consists of patterned rebar and Super Swellex, straps and mesh over fibcrete. Since both dynamic support tendons and compatible surface support were used, an E2 rating of 25 was assigned.

(c) **Assessment of E3 excavation span**

This case is located at a two-way intersection and a span of 7.1 m was estimated.
d  **Assessment of E4 geology factor**

This location is assigned with an unfavourable geological factor, as it is located between two seismic ruptures.

e  **Assessment of PPV**

This location is approximately 60 m away from the event location. However, due to the close proximity of these locations to the seismic rupture, a saturated PPV factor of 0.55 m/s is used. The RDP analyses summary for the three locations is shown in Table 4-20.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>105</td>
<td>105</td>
<td>105</td>
</tr>
<tr>
<td>E2</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>E3</td>
<td>7.1</td>
<td>7.1</td>
<td>7.1</td>
</tr>
<tr>
<td>E4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>PPV</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>P_{R^2}</td>
<td>9%</td>
<td>9%</td>
<td>9%</td>
</tr>
<tr>
<td>P_{R^3}</td>
<td>6%</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>RDS_{Observed}</td>
<td>R4</td>
<td>R5</td>
<td>R3</td>
</tr>
</tbody>
</table>

f  **Performance Evaluation**

The method performed well for location C, correctly predicting the observed damage severity, but less satisfactorily for locations A and B. Considering that the support systems and excavation specifications are comparable between all three locations (all three cases have identical ratings but different observed outcomes), it is possible that the geometry constraints, as previously discussed, contributed to the difference in performance of the system.

4.10.2  **7100L 84XC Intersection Damage Study**

The largest quantity and most severe rock damages for the 2011 case study was observed on 7100L, at the intersection with 84XC and along 84XC crosscut. Previously, the back of the intersection collapsed up to a depth of 3 metres during the 2009 rockburst (shown in Figure 4-52 and Figure 4-53). The
previous damage can be attributed to the formation of the SR1, which was seen defining the north extent of the damage.

A shotcrete post was also constructed to support a wedge formed along the SR1 on the north east corner of the intersection, as shown in Figure 4-65. For the purpose of comparison, a photo of 84XC prior to the rockburst is shown in Figure 4-66.

Figure 4-65. 2011 Kidd Mine rockburst 7100L 84XC intersection prior to damage. Photo is looking North West and 84XC is situated behind the red truck.
Following the rockburst, the roof of the intersection was seen displaced southerly, relatively close to the base of the post, which resulted in large shearing movement in the shotcrete post (shown in Figure 4-67). The west wall of the intersection or location A suffered severe ejection in the lower half of the wall, with failure depth up to 2 m. Swellex bolts were broken and ejected into the excavation together with straps. The furthest ejection was approximately 6 m away. Approximately 50 tonnes of material was displaced at this location and a RDS rating of R4 was assigned to A.
Along 84XC, there was more severe damage. The crosscut appeared to have been sheared with up to half a metre of displacement of the back to the south relative to the floor. The reinforced dynamic support system in the wall suffered severe damage; however, it remained mostly in place with no catastrophic failure.

Approximately 50 tonnes of material was displaced on each side of the wall (location B) for approximately 30 m, most of which was contained. This is shown in Figure 4-68. A RDS rating of R4 was assigned to location B. The roof (location C) only suffered minor bulking with cracks occasionally seen, resulting in a RDS rating of R2.

![Image](image.jpg)

*Figure 4-68 2011 Kidd Mine rockburst 7100L 84XC damage. Looking North East.*

**a  Assessment of E1 stress factor**

The modelled sigma 1 stress is approximately 110 MPa for above locations, as shown in Figure 4-57. The rock type is andesite with an UCS value of 130 MPa. The calculated stress factor is approximately 85 for above locations.

**b  Assessment of E2 ground support factor**

The above locations were supported with a mixed of patterned twin strand plain cable bolts, rebar, self-drilling rebar, Swellex bolts, strap, fibocrete, mesh and chain link mesh. Since both dynamic support tendons and compatible surface support were used, a dynamic E2 rating of 25 was assigned.
c  **Assessment of E3 excavation span**

The span at location A is approximately 9.2 m, and 5.2 m for B and C.

d  **Assessment of E4 geology factor**

All locations are within a radius of 10 m away from the seismic ruptures formed during previous rockbursts; therefore, an unfavourable geological factor of 0.5 was assigned to all above cases.

e  **Assessment of PPV**

The seismic event location is over 100 m away from the above damage locations. However, due to the close proximity of these locations to the seismic rupture, a saturated PPV factor of 0.55 m/s was used. The RDP assessment for the three distinct locations is summarised in Table 4-21.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>85</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>E2</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>E3</td>
<td>9.2</td>
<td>5.2</td>
<td>5.2</td>
</tr>
<tr>
<td>E4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>PPV</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>(P_{R2})</td>
<td>9%</td>
<td>9%</td>
<td>9%</td>
</tr>
<tr>
<td>(P_{R3})</td>
<td>3%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>RDS(\text{Observed})</td>
<td>R4</td>
<td>R4</td>
<td>R2</td>
</tr>
</tbody>
</table>

f  **Performance Evaluation**

The three locations were the most severe damages observed following the 2011 rockburst. They are within close proximity to SR1 and SR1A, formed during previous rockbursts. The deformation observed at these damage locations is a strong indicator that there was a large displacement along these structures during the event.

The method performed adequately only for location C, but poorly for A and B. The severe deformations observed at these locations suggest that the dynamic loading on this level is extreme.
It was also noted in this case study that the mechanism of damage on this level appears to be different than in previous cases. The large degree of deformation observed on this level suggests high complexity associated with rockburst damage and raises the question of whether this mechanism of dynamic loading can be captured with the PPV factor.

4.10.3 7300L Damage Study

The damage observed on 7300L and on levels below was minor in severity and restricted only to the abandoned drives. The ground support systems in these areas were not brought up to dynamic support standard prior to the damaging event.

On 7300L, further bulking up to 30 cm over an area of 5 by 2 m was observed at location A on the north east wall of S30XC near the intersection, shown in Figure 4-69. Approximately 5 tonnes of material was bulked and a RDS rating of R3 was assigned to location A. At location B, further wedge failure was observed in the back of the S20XC, as shown in Figure 4-70. The support system consisting of rebar and fibrecrete failed completely. Approximately 10 tonnes of material was displaced from the roof and a RDS rating of R4 was assigned.

![Figure 4-69 2011 Kidd Mine rockburst 7300L S30XC wall bulking.](image)
Assessment of E1 stress factor

The modelled sigma 1 stress at these locations is approximately 170 MPa, and the rock type is rhyolite with UCS value of 110 MPa, as shown in Figure 4-57. The calculated stress factor value is approximately 155 for above locations.

Assessment of E2 ground support factor

Above locations were supported only with patterned rebar and fibcrete. Based on the support classification table (Table 4-1), an E2 rating of 5 was assigned.

Assessment of E3 excavation span

Location A is in a four-way intersection with a span of 10.3 m. Location B has a span of 6.2 m.

Assessment of E4 geology factor

The above locations are not within close proximity to any active structures, and an average geological factor of 1 was assigned.
**Assessment of PPV**

Locations A and B were approximately 150 m away from event location, resulting in an estimated PPV factor of 0.15 m/s, as shown in Figure 4-61. The RDP analyses summary for the two locations is summarised in Table 4-22.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>155</td>
<td>155</td>
</tr>
<tr>
<td>E2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>E3</td>
<td>10.3</td>
<td>6.2</td>
</tr>
<tr>
<td>E4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PPV</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>P_{R2}</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>P_{R3}</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>RDS_{Observed}</td>
<td>R3</td>
<td>R4</td>
</tr>
</tbody>
</table>

**Performance Evaluation**

The adjusted RDP method performed well for location B, but less satisfactorily for A. For both cases, the results have been conservative. The modelled probability saturated due to the extreme stress factor used. This case again demonstrated the uncertainty of the model when using extrapolated stress factors values.

**4.10.4 7400L Damage Study**

Similar to 7300L, the damage observed on 7400L was mostly restricted to the abandoned drives in the south end of the level.

Minor expulsion of rock and fibrecrete was observed in the wall near the entrance to the 74-S30XC at location B, as illustrated in Figure 4-71. Approximately 20 cm thick of rock failed around the rebar over an area of 4 by 2 m and was ejected into the excavation. An estimated 2 tonnes of material was displaced at this location. Due to the damage severity to the support system, a RDS rating of R3 was assigned to location B.
Adjacent to this location at location A, the wall was supported with a dynamic support system which suffered minimum damage, as shown in Figure 4-71. A RDS rating of R2 was assigned to location A.

Further damage was observed in the fuel bay behind the fuel tank in the south wall. Damage has been previously reported at this location. Further bulking of the rock mass and deterioration of the support system were seen. Large cracks developed across the entire wall, which can be seen in Figure 4-72. A RDS rating of R2 was assigned to location C.
a Assessment of E1 stress factor

The modelled sigma 1 stress is approximately 165 MPa at locations A and B, and 110 MPa at C, as shown in Figure 4-57. The encountered rock type is rhyolite at all three locations, with an UCS value of 110 MPa. The calculated stress factor is approximately 150 for A and B, 100 for C.

b Assessment of E2 ground support factor

The support system at location A consists of patterned modified cone bolt and rebar, straps over mesh. Based on the support classification table shown in Table 4-1, an E2 rating of 25 was assigned. The support system at locations B and C consists of only patterned rebar and fibrecrete, resulting in an E2 rating of 5.

c Assessment of E3 excavation span

The span is estimated to be around 5.2 m at locations A and B, and 8.9 m at C.

d Assessment of E4 geology factor

No active geological structures or other unfavourable features were observed at the above locations within a distance of 50 m, and the rock appears to be massive. Therefore, a good geological factor of 1.5 was assigned.

e Assessment of PPV

Locations A and B are approximately 170 m away from the event and C is 250 m. The estimated PPV factor value for A and B is 0.12 m/s and 0.08 m/s respectively, as shown in Figure 4-61. The RDP analyses summary for these locations is shown in Table 4-23.
### Table 4-23 2011 Kidd Mine rockburst 7400L RDP analyses summary.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>150</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>E2</td>
<td>25</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>E3</td>
<td>5.2</td>
<td>5.2</td>
<td>8.9</td>
</tr>
<tr>
<td>E4</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>PPV</td>
<td>0.12</td>
<td>0.12</td>
<td>0.08</td>
</tr>
<tr>
<td>(P_{R2})</td>
<td>3%</td>
<td>99%</td>
<td>66%</td>
</tr>
<tr>
<td>(P_{R3})</td>
<td>3%</td>
<td>99%</td>
<td>66%</td>
</tr>
<tr>
<td>(R_{\text{DSo}})</td>
<td>R2</td>
<td>R3</td>
<td>R2</td>
</tr>
</tbody>
</table>

### f Performance Evaluation

The adjusted RDP method performed well for location A, but overly conservative for B and C. The difference in damage severity at locations A and B reflected the benefits of higher support capacity for containing rockburst damage.

The above cases may indicate that the uncertainty associated with a stress factor well outside of the original empirical range results in unrealistic forecast results and that caution should be taken when these values are used.

### 4.11 Case Study Summary

The performance of all case studies is summarised in Table 4-24. The performance rating for the two models is based on the discrepancy between predicted probability and observed damage severity. Since it was difficult to quantify the damage severity numerically, the performance rating was simplified down to three ratings: good (green), fair (yellow) and poor (red).

The conservative probabilities that forecast more severe damage than observed are marked with ‘cons’. The over-optimistic probabilities that forecast less severe damage than observed are marked with ‘opt’. The conservative forecasts are more tolerable than optimistic forecasts, as optimistic forecasts could result in catastrophic results.

The performance of the R2 model for the four case studies varied. The R2 model performance for mine A, mine B and Kidd 2009 can be regarded as
good, correctly predicting the majority of the cases. However, its performance was poor for the Kidd mine 2011 study, with 45% of cases being over-optimistically forecasted. Upon close inspection, the optimistic probabilities forecasted for the Kidd 2011 case studies are all associated with the use of dynamic support rating (E2 = 25).

The performance of the R3 model is not as good as the R2 model. Apart from for mine B and Kidd 2009, the performance of the R3 model is poor for all other two case studies, with the majority of cases being over-optimistically forecasted. For mine A, the complexity of the rockburst mechanism may have contributed towards the poor performance. For the Kidd mine 2011 study, the use of extreme stress factors and dynamic support rating likely contributed towards the poor R3 model performance.

Overall, the performance of the adjusted RDP method varied on the external case studies. The good performance of the method on some of the new case studies suggests that the adjusted RDP method can be generalisable; however, the generalisability does not apply to some specific situations, such as when complex rockbursts were encountered. The discussion below provides some insight into where the method can be further investigated to improve its generalisability.
Table 4-24 Case study summary. Probabilities highlighted with red are conservative and yellow are optimistic. Good model performance are highlighted in green, fair in yellow and poor in red.

<table>
<thead>
<tr>
<th>Level</th>
<th>Location</th>
<th>RDS</th>
<th>P2 (%)</th>
<th>R2 Model Performance</th>
<th>P3 (%)</th>
<th>R3 Model Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine A</td>
<td>RL715</td>
<td>A</td>
<td>R2</td>
<td>34 Good</td>
<td>1</td>
<td>1 Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>R3/R4</td>
<td>48 (cons) Fair</td>
<td>30 (cons)</td>
<td>30 (cons) Fair</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>R2</td>
<td>74 (opt) Poor</td>
<td>74 (opt)</td>
<td>74 (opt) Poor</td>
</tr>
<tr>
<td></td>
<td>RL730</td>
<td>A</td>
<td>R3</td>
<td>25 (cons) Fair</td>
<td>1 (cons)</td>
<td>1 (cons) Fair</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>R3</td>
<td>79 Good</td>
<td>79 (opt)</td>
<td>79 (opt) Fair</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>R3</td>
<td>59 Good</td>
<td>7 Good</td>
<td>7 Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
<td>R5</td>
<td>70 Good</td>
<td>15 (cons)</td>
<td>15 (cons) Poor</td>
</tr>
<tr>
<td>Mine B</td>
<td>RL1120</td>
<td>A</td>
<td>R3/R4</td>
<td>84 Good</td>
<td>84</td>
<td>84 Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>R5</td>
<td>63 Good</td>
<td>51</td>
<td>51 Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>R3</td>
<td>72 Good</td>
<td>72 (opt)</td>
<td>72 (opt) Fair</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
<td>R2/R3</td>
<td>4 (cons) Fair</td>
<td>1</td>
<td>1 Good</td>
</tr>
<tr>
<td></td>
<td>RL1150</td>
<td>A</td>
<td>R2</td>
<td>64 (opt) Fair</td>
<td>32 (cons)</td>
<td>32 (cons) Fair</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>R5</td>
<td>63 Good</td>
<td>33 (cons)</td>
<td>33 (cons) Fair</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>R4</td>
<td>61 Good</td>
<td>59</td>
<td>59 Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
<td>R2</td>
<td>61 (opt) Fair</td>
<td>59 (opt)</td>
<td>59 (opt) Poor</td>
</tr>
<tr>
<td>Kidd 2009</td>
<td>6700L</td>
<td>A</td>
<td>R4</td>
<td>94 Good</td>
<td>94</td>
<td>94 Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>R3</td>
<td>93 Good</td>
<td>93 (opt)</td>
<td>93 (opt) Poor</td>
</tr>
<tr>
<td></td>
<td>6800L</td>
<td>A</td>
<td>R5</td>
<td>100 Good</td>
<td>100</td>
<td>100 Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>R3/R4</td>
<td>100 Good</td>
<td>100 (opt)</td>
<td>100 (opt) Fair</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>R5</td>
<td>99 Good</td>
<td>99</td>
<td>99 Good</td>
</tr>
<tr>
<td></td>
<td>6900L</td>
<td>A</td>
<td>R4</td>
<td>96 Good</td>
<td>96</td>
<td>96 Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>R2/R4</td>
<td>97 (opt) Poor</td>
<td>97 (opt)</td>
<td>97 (opt) Fair</td>
</tr>
<tr>
<td></td>
<td>7000L</td>
<td>A</td>
<td>R5</td>
<td>9 (cons) Poor</td>
<td>3 (cons)</td>
<td>3 (cons) Poor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>R2</td>
<td>9 Good</td>
<td>2</td>
<td>2 Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>R4</td>
<td>98 Good</td>
<td>98</td>
<td>98 Good</td>
</tr>
<tr>
<td></td>
<td>7100L</td>
<td>A</td>
<td>R5</td>
<td>98 Good</td>
<td>98</td>
<td>98 Good</td>
</tr>
<tr>
<td>Kidd 2011</td>
<td>7000L</td>
<td>A</td>
<td>R4</td>
<td>9 (cons) Poor</td>
<td>6 (cons)</td>
<td>6 (cons) Poor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>R5</td>
<td>9 (cons) Poor</td>
<td>6 (cons)</td>
<td>6 (cons) Poor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>R3</td>
<td>9 (cons) Poor</td>
<td>6</td>
<td>6 Good</td>
</tr>
<tr>
<td></td>
<td>7100L</td>
<td>A</td>
<td>R4</td>
<td>9 (cons) Poor</td>
<td>3 (cons)</td>
<td>3 (cons) Poor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>R4</td>
<td>9 (cons) Poor</td>
<td>1 (cons)</td>
<td>1 (cons) Poor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>R2</td>
<td>9 Good</td>
<td>1</td>
<td>1 Good</td>
</tr>
<tr>
<td></td>
<td>7300L</td>
<td>A</td>
<td>R3</td>
<td>100 Good</td>
<td>100 (opt)</td>
<td>100 (opt) Fair</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>R4</td>
<td>100 Good</td>
<td>100</td>
<td>100 Good</td>
</tr>
<tr>
<td></td>
<td>7400L</td>
<td>A</td>
<td>R2</td>
<td>3 Good</td>
<td>3</td>
<td>3 Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>R3</td>
<td>99 Good</td>
<td>99 (opt)</td>
<td>99 (opt) Fair</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>R2</td>
<td>66 (opt) Fair</td>
<td>66 (opt)</td>
<td>66 (opt) Poor</td>
</tr>
</tbody>
</table>
4.11.1 Rock Damage Severity Quantification

The severity of rockburst damage in this study was quantified using the modified Rock Damage Scale shown in Table 4-25.

Table 4-25: Rock damage scale (Heal 2010).

<table>
<thead>
<tr>
<th>RDS</th>
<th>Rock mass damage</th>
<th>Support damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>No damage, minor loose</td>
<td>No damage</td>
</tr>
<tr>
<td>R2</td>
<td>Minor damage, less than 1 t</td>
<td>Support system is loaded, loose in mesh, plates</td>
</tr>
<tr>
<td></td>
<td>displaced</td>
<td>deformed</td>
</tr>
<tr>
<td>R3</td>
<td>1 – 10 t displaced</td>
<td>Some broken bolts</td>
</tr>
<tr>
<td>R4</td>
<td>10 – 100 t displaced</td>
<td>Major damage to support system</td>
</tr>
<tr>
<td>R5</td>
<td>100+ t displaced</td>
<td>Complete failure of support system</td>
</tr>
</tbody>
</table>

As it can be seen from Table 4-25, the RDS rating for a damage location is assessed based on the rock mass damage volume as well as support damage severity. However, during the rating process, the extent of the damage location was not explicitly accounted for.

In the case for damage observed for mine A RL715 FW lower wall, described in Section 4.4.1 and shown in Figure 4-73, the damage severity quantified using tonnes displaced may be low due to smaller volume of rock displaced. However, the RDS rating will be higher if the tonnage was assessed for the entire lower wall along this drive, as the total tonnage is proportional to the length of the tunnel being assessed. In other words, damage severity varies from location to location and it may be better assessed using tonnes displaced per area (or volume).
This variation in determined damage severity rating in turn has an implication on the performance evaluation of the RDP method. For the case shown in Figure 4-73, the RDS rating not accounting for the damage extent (only accounting for total displaced tonnes) is estimated to be R2. Considering that the estimated probability of experiencing R4 and R5 severity is 74%, the RDP performance is poor. However, if the severity rating accounts for the damage extent (i.e. displaced tonnes per unit area), the estimated damage severity will be much higher, which returns a good RDP model performance. As demonstrated, the inability of the RDS rating system to account for damage extent remains an issue that should be investigated in the future.

As shown in Table 4-25, the rock damage severity rating assessment was carried out based on both rock tonnages displaced and support condition. However, the study has shown that this approach may not always produce consistent results, as rock damage and support damage are not always proportional and closely correlated.

In the case of mine B RL1120 FW east location D described in Section 4.6.1 and shown in Figure 4-74, the tonnage displaced and contained by the support system was estimated to be around 10 tonnes. Based on the rock mass damage description, the RDS rating would be between R3 and R4. The support system at this location remained intact with minimum damage. The RDS rating based on support damage alone for this location would be R2, which is much lower than the rating based on rock mass damage.
The discrepancy in determined rock damage severity subsequently has an implication on the performance evaluation of the adjusted RDP model. For the case described above, the forecasted damage severity was R2. Therefore, the model performance would have been adequate if the observed severity was assessed based on support damage. The result will be fair or even poor if it was assessed based on rock mass damage.

Further study is required to fine-tune the rockburst damage assessment to account for the issues outlined above so that a more consistent damage severity rating can be achieved.

4.11.2 Ground Support Capacity Assessment

It was found during the study that the current E2 support rating assessment approach has many uncertainties and that a confident and reliable dynamic support rating is difficult to determine.

The first notable issue associated with the current E2 rating approach is that it cannot account for the difference in dynamic support components used. In other words, the current approach regards all dynamic support tendons as the same and assigns them with the same E2 rating. For instance, the E2 rating for Kidd mine 2011 7000L S46 location C is the same as for mine B RL1120 location D \( (E2 = 25) \). However, the ground support components used at the two locations are vastly different, as shown in Figure 4-75.
For the mine B, shown on the left, the support tendons used are a mixture of friction bolts and Garford dynamic solid bolts. For the Kidd mine on the right, the support tendons are a mixture of grouted rebar and Super Swellex friction bolts. The dynamic support tendon used at the two locations are different in mechanism, length and dynamic capacity based on lab tests. There are insufficient evidence and data to suggest that the dynamic capacities of the two systems are comparable.

It is also noticeable in Figure 3-18 that the number of damage cases with a support capacity rating greater than 10 is lower than cases with capacity less than 10. This in turn may have resulted in the uncertainty in the reliability of the ground support rating of 25.

Another difficulty encountered during this study was that some support systems cannot be easily classified into the existing five classes of support ratings. Subject to interpretation, one support system can be assigned with more than one E2 rating.

In the case for mine B RL1120 intersection wall ejection, as shown in Figure 4-76, the wall was supported with Garford dynamic solid bolts with a pattern of 1.5 by 1.5 m, spot bolting of friction bolts and mesh over fibrecrete. Since there were two passes of bolting, including a pass of solid bolt with compatible surface support, the E2 support rating for this particular location
based on Table 4-1 can be assigned with a rating of 8. The dynamic solid bolt used at this location, however, has a much higher dynamic capacity than the standard rebar described in the $E2 = 8$ category. As a result, the overall dynamic capacity of this support system is higher than an $E2$ rating of 8. However, the support system at this location cannot be assigned with an $E2$ rating of 10 as there is no cable bolt as required by $E2 = 10$. This has resulted in uncertainty in the $E2$ rating for this particular location.

With the increasing number of new dynamic support tendons available in the market, the $E2$ rating does not sufficiently cover the different options available and needs to be extended.

Another issue noted during the study is that the current support rating process does not account for the length of the support tendons. It has been seen during the study that the rock failure depth exceeded the maximum length of the support tendons.

For instance, the rock failure depths at mine B RL1120 FW drive east location B and Kidd mine 2009 6800L location A both exceeded the length of the support tendons, as shown in Figure 4-77. Since the failure depth exceeded the maximum embedment length of the support tendon, the actual support capacity will not likely be mobilised during failure and, in effect, will be much lower than
the value assigned through the E2 rating (as it assumes a depth sufficient to mobilise the capacity).

Overall, the current support rating E2 approach was found difficult to apply, resulting in uncertainty in determining RDP ratings. Further study is required to improve the ground support rating E2.

4.11.3 Rockburst Damage Complexity

This study has demonstrated that rockbursts can be very complex in nature. The resulted rockburst damage is generally associated with many factors, some of which are excavation-specific while others are not.

For Kidd mine, severe rockburst damage observed generally exhibited a strong spatial association to the newly formed seismic rupture. In other words, the seismic rupture, to a certain degree, defined the rockburst damage. The dynamic effect of the active structures, however, cannot be effectively captured using the estimated PPV factor.

4.11.4 Future Focuses

Based on the findings from this study, three main future study focuses are determined. They are:
1. Quantifying rockburst damage
   a. Account for the extent of damage when assessing damage severity
   b. Put more emphasis on evaluating performance of support systems when assessing damage severity

2. Quantifying support capacity
   a. A more up to date support capacity rating that includes more recent support systems
   b. Account for the rock failure depth and its implications on the overall support capacity

3. Investigating rockburst complexity
   a. Investigate the occurrence of rockburst damage (damage versus no damage, as discussed in Section 3.7)
   b. Investigate further the rockburst complexity and mechanism, which were significant factors affecting damage severity for the Kidd mine case study
5 Summary and Conclusion

It was shown in the literature review that the phenomenon of rockburst damage is complex and governed by multiple factors. According to literature, peak ground motion, geological features and ground support systems are dominant factors controlling the excavation stability following damaging seismic events. It was also identified that there was a lack of quantification on the weighting between key factors controlling the stability of an excavation, or how influential each factor was compared with others relative to the likelihood of damage.

The Australian Centre for Geomechanics Rockburst Database was used in this study to quantify the weighting of factors contributing towards the occurrence of certain severities of damage. Firstly, FA was applied to the database to explore the underlying structure of the database and to reduce the database dimension. Logistic regression modelling was determined to be the most appropriate technique to quantify the relationship between factors controlling excavation stability and damage severity.

Two regression models were built to quantify the probability of exceeding R2 severity cases and R3 severity cases. It was noted that ground support, geology factor and PPV are significant factors affecting the occurrences of R2 severity cases. Stress factors and excavation spans are two additional significant factors affecting the occurrence of R3 scale damages.

The improvement in classifying a pair of true positives and true negative cases of the new regression models with factor weighting are 6.3 and 8.3% more accurate than the original RDP models. The factor weighting was interpreted using sensitivity charts for both models assuming a base case scenario. It was noted that stress factor, ground support and geology factor are dominant factors controlling the likelihood of experiencing damage exceeding a certain severity.

A series of case studies were conducted to test the generalisability of the adjusted RDP method and to determine how well the method performs in a rockbursting environment outside of the original database. Despite the several issues encountered, the case study has demonstrated the potential value as a damage predictor, in empirically quantifying rockburst severity. Future studies to
improve the parameters used to quantify rockburst damage, support capacity and to better understand rockburst mechanisms are required to improve the method.
Reference

Albrecht, J & Potvin, Y 2005, 'Identifying the factors that control rockburst damage to underground excavations', Sixth International Symposium on Rockburst and Seismicity in mines.


Australian Centre for Geomechanics, mXrap, Australian Centre for Geomechanics. Available from: <http://mxrap.com/>.

Brelan, RB, Rogers, SP, Chaix, B, Tyrna, P & Palmer, K 2011, Report of Investigation Underground Metal Mine: Fatal Fall of Roof Accident, Mine Safety and Health Administration, Vacaville, California.


Cooper, G 2012, Strong Influential Geological Structure, ed.^eds Email W Duan, Kidd Creek Mine, Timmins, Ontario.


Heal, DP 2007b, *KCGM Mt Charlotte Mine Analysis of Recent Seismic Activity*, Australian Centre for Geomechanics, Perth, Australia.


Kalgoorlie Miner 1917, 'Sensational mining fatality, severe earth tremor causes fall of rock on Great Bounder mine, one man killed, others injured', *Kalgoorlie Miner*.


Ortlepp, WD 2006, 'A review of the contribution to the understanding and control of mine rockbursts', in *6th International Symposium on Rockbursts and Seismicity in Mines*, 20, Australian Centre for Geomechanics, Perth, Australia.


Potvin, Y & Wesseloo, J 2013a, 'Improving Seismic Risk Management in Hardrock Mines', *8th Rockburst and Seismicity in Mines*.


Slade, J & Ascott, B 2007, 'Impact of rockburst damage upon a narrow vein gold deposit in the eastern goldfields, Western Australia', in Challenges in Deep and High Stress Mining, eds Y Potvin, J Hadjigeorgiou & TR Stacey, Australian Centre for Geomechanics, Perth.


Tannant, DD, Martin, CD & Kaiser, PK 1997, Site Characterisation of the 6800 to 7800 Mining Block, Geomechanics Research Centre, Sudbury, Canada.


Turcotte, P 2014, 'Practical applications of a rockburst database to ground support design at LaRonde Mine', Deep and High Stress Mining.


An Assessment of the Significance of Factors Affecting the Occurrence of Rockburst Damage

APPENDICES

Wei Duan
University of Western Australia
Feb 2016

Supervisors: Dr Johan Wesseloo
Prof Yves Potvin
Appendix A

Rock Damage Potential is an index scale developed by Heal (2010) to describe the likely severity of rockburst damage given the occurrence of seismic event and combines the five factors (stress, span, geology, ground support, expected PPV) using a multiplication relationship. The support design is carried out by altering the support system rating (E2) to reduce the expected damage to an acceptable level.

*Excavation Vulnerability Potential (EVP)*

Excavation vulnerability potential is proposed as an index to empirically quantify the effect of local site condition on rockburst damage. It utilizes four site specific variables (stress, ground support, span, geology) which are not related to the source of the seismic event (Heal, 2010).

- **E1: Stress Factor**
  
  It is defined as the ratio of principle stress over rockmass UCS value expressed in percentage ($\frac{\sigma_1}{UCS} \times 100$).

  The rockburst case study Dan Heal conducted has demonstrated that the static stress condition surrounding an excavation contribute to the level of damage caused by seismic event.

  Maximum principle stress can be evaluated using numerical modelling. The E1 factor is to provide the estimated stress condition near the excavation opening rather than a precise measurement. Therefore, a numerical model which considers the effect of nearby stopes and other large excavations should be sufficient enough for E1 estimation.

- **E2: Ground Support Factor**
The ground support capacity of kJ/m$^2$ is used here as the basis for the Ground Support Factor E2. It has been simplified into five general categories. The capacity factor is estimated for the overall support system rather than summing up capacity of individual element within the system.

An E2 value of 2 indicates spot bolting of split sets. An E2 value of 25 represents pattern bolting with dynamic ground support such as Garford yielding bolts. A detailed description of ground support classification is given in Table 1.
<table>
<thead>
<tr>
<th>E2</th>
<th>Classification</th>
<th>Surface Support</th>
<th>Reinforcement</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Low</td>
<td>None</td>
<td>Spot bolting</td>
<td>Spot bolting with split sets or solid bar bolts, minimal surface support</td>
</tr>
<tr>
<td>5</td>
<td>Moderate</td>
<td>Mesh or fibcrete</td>
<td>Pattern bolting</td>
<td>Pattern bolting with split sets or solid bar reinforcement, with mesh or 50 mm fibcrete</td>
</tr>
<tr>
<td>8</td>
<td>Extra bolting</td>
<td>Mesh or fibcrete</td>
<td>Pattern bolting with a second pass of pattern bolting</td>
<td>Pattern bolting with split sets with mesh or 50 mm fibcrete. Plus an additional pass of pattern reinforcement, such as solid bar bolts.</td>
</tr>
<tr>
<td>10</td>
<td>High static strength</td>
<td>Mesh or fibcrete</td>
<td>Pattern bolting and pattern cable bolts</td>
<td>Pattern bolting with split sets or solid bar reinforcement, with mesh or 50mm fibcrete. Plus pattern cable bolting.</td>
</tr>
<tr>
<td>25</td>
<td>Very high dynamic capacity</td>
<td>Dynamic surface support</td>
<td>Pattern dynamic support</td>
<td>Pattern bolting with dynamic ground reinforcement such as cone bolts, with a dynamic resistant surface support system.</td>
</tr>
</tbody>
</table>

- **E3: Span Factor**

  This factor indicates the maximum span of that section excavation opening. The span of an excavation has a direct influence on the failure probability and depth as shown in the rockburst database (Heal, 2010). The span calculation for an excavation section simply attempts to fit the largest circle that can be drawn internally to the excavation 2D or 3D survey.
An illustration of span relative to the floor string in 2D is given in Figure 1.

**Figure 1 Span Factor Illustration (Heal, 2010).**

- **E4: Geology Factor**

This factor accounts for the presence of unfavourable geological structures such as seismically active faults, schistosity, fractures within the rockmass etc. The presence of such structures is likely to promote the rockmass failure during a dynamic event (Heal, 2010). The E4 classification and description is listed in Table 2.
<table>
<thead>
<tr>
<th>E4</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td><strong>Seismically active major structure</strong>&lt;br&gt;Major structural features such as faults, shears or discrete contacts intersect the location and act as a potential failure surface promoting rockmass failure.</td>
</tr>
<tr>
<td>1</td>
<td><strong>Unfavourable rock mass / No major structure.</strong>&lt;br&gt;The orientation of the rock mass discontinuity fabric may promote or enhance rockmass failure. Generally, this factor is applied when there are local cases in which the rockmass discontinuities promoted falls of ground much larger than would be expected.&lt;br&gt;Example: A heavily jointed, blocky rock mass with kinematically unstable rock mass blocks. The rock mass is prone to deeper than normal gravity driven failure mechanisms.</td>
</tr>
<tr>
<td>1.5</td>
<td><strong>Massive rock mass / No major structure.</strong>&lt;br&gt;The rock mass is essentially massive or non-persistent rock mass discontinuities may exist, including possible minor blast related fracturing. There are no major structures such as faults or shears, which may promote or enhance rock mass failure.</td>
</tr>
</tbody>
</table>

Two factors were identified to be related: damage initiation and depth of failure.

And the empirical EVP index proposed make use of these two factors:

- **Damage Initiation Factor:** $\frac{E_1}{E_2}$
  
  The damage initiation factor accounts for the parameters that are responsible for the initiation of the dynamic rockmass failure. The higher in-situ ground stress within the rockmass will increase the likelihood of rockmass failure during a dynamic event. More competent ground supports will strength the rockmass, reducing the likelihood and severity of rockmass failure during a dynamic event (Heal, 2010).

- **Depth of Failure Factor:** $\frac{E_3}{E_4}$
The depth failure factor accounts for local site conditions that may enhance the depth of failure induced by dynamic event. The larger span or unfavourable geological conditions contribute towards large zones of failure or unstable zones, while smaller span or favourable geological condition help reducing the likelihood of large scale failures from occurring. EVP index is proposed as the product of Damage Initiation Factor and Depth of Failure Factor (Heal, 2010).

The Excavation Vulnerability Potential (EVP) is the product of Damage Initiation Factor and Depth of Failure Factor.

\[
\text{EVP} = (\text{Damage Initiation Factor}) \times (\text{Depth of Failure Factor})
\]

\[
= \frac{E_1}{E_2} \times \frac{E_3}{E_4}
\]

**Rock Damage Potential**

Rock Damage Potential (RDP) is the product of EVP and Peak Particle Velocity (PPV).

\[
\text{RDP} = \text{EVP} \times \text{PPV}
\]

After the application of logistic regression on the rockburst damage case history data, both EVP and RDP indexes were determined between all different rockburst damage levels. The RDP damage threshold can be seen in Figure 2.
Figure 2 shown is derived from actual rockburst database which consist of real rockburst damage reported from mines across the world such as Australia, Canada etc. The RDP has shown that, in general, an increasing level of rockburst damage potential is associated with:

- Increase in-situ stress.
- Decrease in the capacity of support.
- Increase excavation span.
- Less favourable geology condition.
- Increase in PPV.

The 50% value on each curve in Figure 2 represents the index where higher RDS level is more probable than the lower RDS. These values are shown in Figure 3.
The RDP index is a statistically defendable measure of an excavation’s proneness to rockburst damage (Heal, 2010). Combined with existing seismic hazard and exposure risk assessment measures, reasonably reliable and straightforward expected rockburst damage could be forecasted.
Appendix B

ACG Rockburst Database

The ACG rockburst database was collected from 13 Australian and Canadian mines. A total of 83 rockburst events were collected comprising 254 damage cases. The time span varies from 1993 to 2004. The rockburst information and damage cases are summarised in Table 3.

Table 3  Rockburst database summary (Heal, 2010).

<table>
<thead>
<tr>
<th>Operation</th>
<th>Location</th>
<th>History</th>
<th>Case No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barkers</td>
<td>Western Australia</td>
<td>10</td>
<td>23</td>
</tr>
<tr>
<td>Big Bell</td>
<td>Western Australia</td>
<td>9</td>
<td>39</td>
</tr>
<tr>
<td>Black Swan</td>
<td>Western Australia</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Brunswick</td>
<td>New Brunswick, Canada</td>
<td>15</td>
<td>24</td>
</tr>
<tr>
<td>Craig</td>
<td>Ontario, Canada</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Darlot</td>
<td>Western Australia</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>Junction</td>
<td>Western Australia</td>
<td>16</td>
<td>40</td>
</tr>
<tr>
<td>Kanowna Belle</td>
<td>Western Australia</td>
<td>5</td>
<td>34</td>
</tr>
<tr>
<td>Mt Charlotte</td>
<td>Western Australia</td>
<td>8</td>
<td>29</td>
</tr>
<tr>
<td>Broken Hill</td>
<td>New South Wales, Australia</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>Perseverance</td>
<td>Western Australia</td>
<td>7</td>
<td>23</td>
</tr>
<tr>
<td>Strzelecki</td>
<td>Western Australia</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Thayer Lindsley</td>
<td>Ontario, Canada</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

A total of 12 quantitative variables are available in the database including stress factor (E1), ground support capacity (E2), excavation span (E3), geological condition (E4), rock damage scale (RDS), support damage scale (SDS), displaced tonnes, event magnitude (ML), distance from damage site to event, failure depth (t), rock density and failure position (wall=0/back=1).
Appendix C

Rock damage scale is used in the original RDP index to quantify overall damage severity. It was originally introduced by Kaiser et al. (1992). Heal (2010) used an altered version of the original RDS scale since number of cases had tonnage displaced in excess of 1000 tonnes and above. The altered version of the index is given in Table 4. The original Rock Damage Scale classification is given in Table 5. The original support damage classification is given in Table 6.

<table>
<thead>
<tr>
<th>RDS</th>
<th>Damage description</th>
<th>Support damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>No damage, minor loose</td>
<td>No damage</td>
</tr>
<tr>
<td>R2</td>
<td>Minor damage, less than 1 t</td>
<td>Support system is loaded, loose in mesh, plates deformed</td>
</tr>
<tr>
<td>R3</td>
<td>1-10 t displaced</td>
<td>Some broken bolts</td>
</tr>
<tr>
<td>R4</td>
<td>10-100 t displaced</td>
<td>Major damage to support system</td>
</tr>
<tr>
<td>R5</td>
<td>100+ t displaced</td>
<td>Complete failure of support system</td>
</tr>
<tr>
<td>Damage Level</td>
<td>General Description</td>
<td>Rock mass / Excavation Damage</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>R0</td>
<td>Conditions unchanged</td>
<td>No new damage due to rockburst</td>
</tr>
</tbody>
</table>
| R1           | Excavations undamaged but first signs of distress detectable | Rock shows fresh but minor, small fractures and cracks (possibly behind ‘loose’)
Small shards of rock may have been displaced |
| R2           | Slight damage to excavations Only ‘loose’ displaced | Slight sloughing from back and walls of unsupported excavations
(only ‘loose’ rock displaced, little freshly broken rock)
Small shards and a few chunks of rock displaced in supported excavations (possibly retained by mesh)
Rock mass shows only minor new fracturing |
| R3           | Minor damage to excavations ‘Loose’ displaced and new rock failure | Unsupported drifts sustain damage with <200 kg of rock displaced from either a fall of ground or due to newly generated fracturing of rock (spalling)
In drifts supported with only rock bolts and mesh, small to large pieces and occasional blocks (totaling < 1000 kg) of rock dislodged
Moderate new bagging of mesh by fractured and displaced rock
Clear evidence of newly fractured rock, possibly displaced violently |
| R4           | Moderate to considerable damage to excavations Violent displacement of ‘loose’ and freshly broken rock | Unsupported drifts sustain damage at multiple locations
Drifts supported with only rock bolts and mesh are damaged with substantial rock displaced (<10000 kg) but are still passable
Rock is heavily fractured and displaced violently |
| R5           | Serious or severe damage to excavations Opening collapsed | Unsupported drifts completely closed
Drifts supported with only rock bolts and mesh heavily damaged and unpassable
Substantial amounts of rock displaced (> 10000 kg)
Rock is highly broken and fractured |

Notes: 1) The damage indicators listed in this table describe damage that is new and was caused by the rockburst. If the observer cannot ascertain that the damage was inflicted by the rockburst then the damage should be ignored for the purposes of damage classification.
2) The mass of displaced rock serves only as a rough guide and should not be used alone to establish the degree of rockburst damage. Other qualitative descriptions are equally important when deciding on the degree of damage.
3) One or more damage scales may be observed in the same area and should be recorded separately.
4) ‘Loose’ is rock that could be scaled down by hand without much effort
Table 6  Support Damage Scale (Kaiser et al., 1992).

<table>
<thead>
<tr>
<th>Damage Level</th>
<th>General Description</th>
<th>Support Damage</th>
<th>Shotcrete Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0</td>
<td>Conditions unchanged</td>
<td>No new damage or loading</td>
<td>No new damage or loading</td>
</tr>
<tr>
<td>S1</td>
<td>Support undamaged but first signs of distress detectable</td>
<td>No damage to any support component</td>
<td>Shotcrete shows new cracks, very fine or widely distributed</td>
</tr>
<tr>
<td>S2</td>
<td>Slight damage to support Loading clearly evident but full functionality maintained</td>
<td>Plates and wooden washers on some rock bolts are deformed, showing loading Individual strands in mesh broken Mesh bagged but retains material well</td>
<td>Shotcrete cracked, minor flakes dislodged Shotcrete is clearly taking load from broken rock mass (mostly drummy)</td>
</tr>
<tr>
<td>S3</td>
<td>Moderate damage to support Support shows significant loading and local loss of functionality; retaining function primarily lost (except in laced or shotcreted areas)</td>
<td>Plates, wooden washers, and wood blocking on rock bolts are heavily deformed, showing significant loading; bolt heads may be &quot;sucked&quot; into rock Mesh torn near bolt heads with some strands broken and mesh torn or opened at overlapping edges Moderate bagging of mesh and isolated failures of rock bolts Cable lacing performs well</td>
<td>Shotcrete fractured, often debonded from rock and/or reinforcement Major flakes possibly dislodged Holding elements mostly intact</td>
</tr>
<tr>
<td>S4</td>
<td>Substantial damage to support More extensive loss of retaining and holding functions (except for lacing systems)</td>
<td>Mesh is often torn and pulled over rock bolt plates; if it did not fail, it is substantially bagged (at capacity) Many rock bolts failed Rock ejected between support components Cable lacing is heavily loaded with bagged mesh</td>
<td>Shotcrete heavily fractured and broken, often separated from the rock mass with pieces lying on the ground or hanging from reinforcement Connections to holding elements often failed or holding elements failed locally</td>
</tr>
<tr>
<td>S5</td>
<td>Severe damage to support Support retaining, holding, and reinforcing functions failed</td>
<td>Most ground support components broken or damaged Most rock bolts fail and rock peels off cable bolts Shotcrete non-functional Mesh without cable lacing heavily torn and damaged Cable lacing systems heavily stressed and often failed</td>
<td>For damage level S5, shotcrete fails to be functional and the left-hand column applies</td>
</tr>
</tbody>
</table>

Notes: 1) The damage indicators listed in this table describe damage that is new and was caused by the
rockburst. If the observer cannot ascertain that the damage was inflicted by the rockburst then the damage should be ignored for the purposes of damage classification.

2) One or more damage scales may be observed in same section and should be recorded separately.

3) Rock and support damage levels need not correspond.

4) Because the function of shotcrete support is somewhat different and more complex than for other support systems, a separate column of indicators is provided over the range of S0 to S4. It is important to record where shotcrete is present and when it has been used to determine the support damage level.

5) Failure of rock bolt applies to failure of nut, plate, anchor or shank.