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Case study: rockfall assessment and mitigation at the Newmont Boddington Gold mine

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Abstract

The risk of rockfall due to previously mined deteriorating pit wall conditions above operational areas of open pit mines is ever present. This paper presents a case study documenting rockfall assessment and subsequent mitigation measures after a rockfall event onto an operational ramp at the Newmont Boddington Gold (NBG) open pit mine. NBG is located two hours south of Perth, in Western Australia, and extracts over 90 Mt per year from operational pits. The South Pit has a current planned depth of over 650 m with a 36 m high and 15.2 m wide batter/berm configuration for an inter-ramp angle of 60.8°.

Information collected during unmanned aerial vehicle/rope access inspections and scaling works provided relevant data including block size and size distribution, enabling further assessment. Detailed rockfall assessment is undertaken using the 3D software Trajec3D™ to help gain a better understanding of how in situ pit conditions can influence the trajectory of falling rocks compared to 2D assessments. The work includes an assessment of object shape, assessment based on block size and size distribution, interpretation of rockfall source area, a step by step run through of modelling, and probabilistic interpretation of results including a sensitivity analysis based approach considering different potential particle size distributions. A Coefficient of Restitution is adopted from previous research. The paper also presents data assessment methodology used to interpret various aspects of model output data including gaining knowledge of linear and rotational energy and the interoperability and functionality of the Trajec3D and GEM4D™ software. The information is used to help assess the design criteria of a rock catch fence solution for this area of the pit. Rockfall assessment results are presented for both 'fence' and 'no fence' scenarios.

Keywords: *rockfall assessment, 3D software, Coefficient of Restitution, rock catch fence, open pit*

1 Introduction

The Newmont Boddington Gold (NBG) mine is located approximately 130 km south of Perth in Western Australia, Australia. The mining operation at NBG consists mainly of three open pits in an intrusive hard rock setting consisting of diorite/andesite criss-crossed by dolerite dykes. The operation extracts over 90 Mt per year. Current pit depths extend to approximately 500 m deep with planned pit extensions to reach over 650 m deep. Pit walls in hard rock have an inter-ramp angle of 60.8° with 36 m high benches blasted and excavated in three 12 m flitches. The top 12 m flitch has a batter face angle of 75°, while the lower two flitches have vertical batter angles. Berm width varies according to geology, however, generally design berm width is 15.2 m which affords for an amount of crest loss to occur as a result of blasting and excavation.

Rockfall occurred from a section of wall located approximately 90 m above a haul ramp in the S05 pit at Boddington at the beginning of the wet weather season in April 2020. As a result, assessment of the area included rockfall modelling and design of a rock catch fence solution. A brief overview of the scenario is offered within this case study along with a description of the rockfall assessment and the selected rockfall fence solution.

The section of wall that released rocks is in moderately weathered rock that has experienced deteriorating conditions over the last 3–4 years since the area was initially mined. An overhang had resulted along with accumulation of debris on the catch berm directly beneath.

In order to help prevent excessive damage to berm crests, pre-split blasting is undertaken for walls in hard rock in the NBG open pits. Although the design berm width is significant, localised crest loss can reduce achieved widths and may significantly impact the ability for berms to catch falling rocks. In this case, a shallow dipping sub-horizontal dolerite dyke caused difficulties during mining resulting in severe crest loss beneath and adjacent to the rockfall source. The damage occurred across the whole width of the berm, further accentuating the adverse conditions in this area of the pit.

After a period of wet weather, several rocks dislodged and travelled over two berms falling 90 m onto one of the main haul roads used to access the pit. A 50 kg rock fell into the middle of the haul road and was classified using Newmont's reporting system as a serious potential event (SPE). Figures 1 and 2 show close-up photos of the area of the rockfall and include additional details.

The following actions were undertaken as a result of the rockfall and SPE:

1. Initiate single lane running on haul road under area of concern.
2. Perform visual inspections of the source and deposition areas using drone video footage.
3. Scale area of pit wall consisting of the source of rockfall (rope access).
4. Perform rockfall assessment.
5. Assess requirement and suitability of potential long-term solutions.

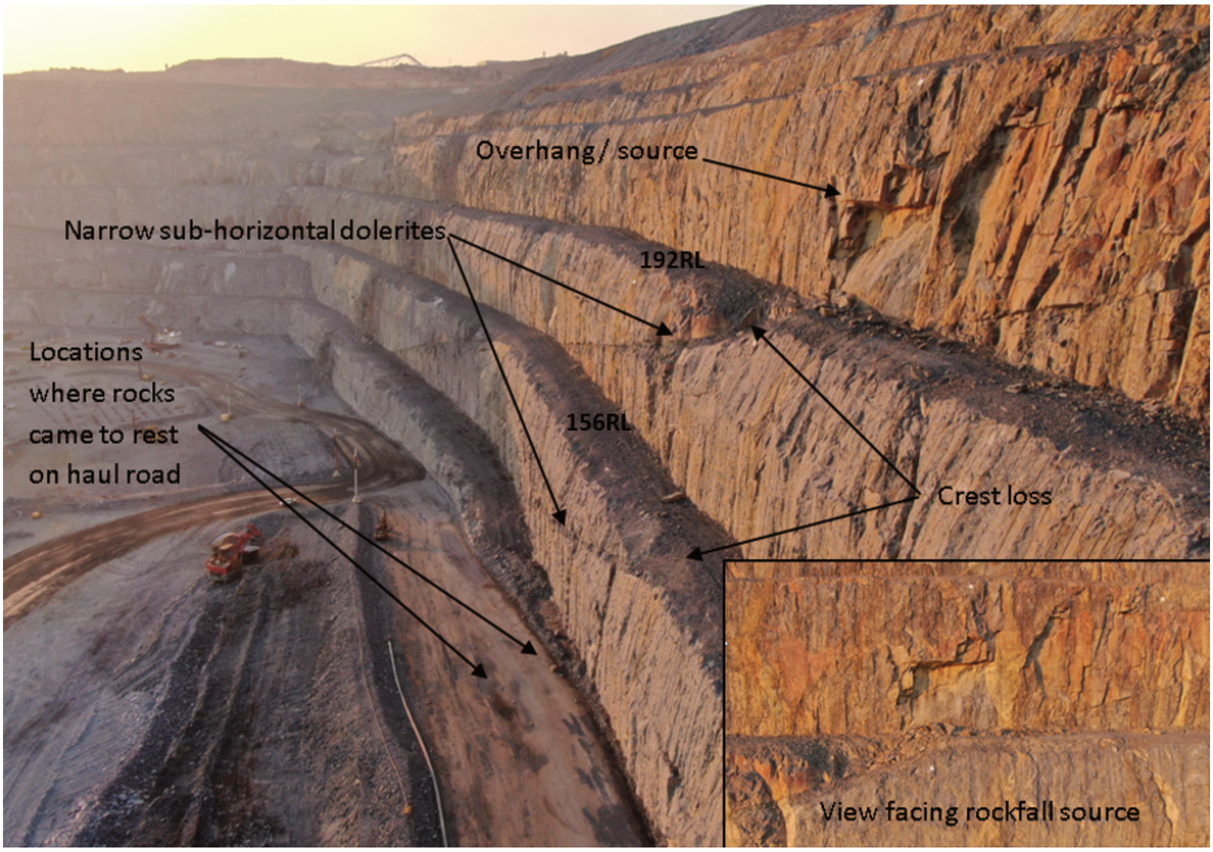


Figure 1 Source of rockfall and crest damage on berms below

Figure 2 View facing source of rockfall and showing accumulated debris beneath

During the course of the investigation, several potential solutions were considered as follows:

1. Increasing the frequency of scheduled inspections combined with manual scaling using rope access.
2. Installing a steel wire mesh drape over the affected area to help contain rockfall.
3. Constructing a rockfall fence on the berm above the haul road.

A decision was made to design and construct a rockfall fence due in part to access considerations related to construction and also related to future management of the area. Construction of a rockfall fence, for example, would allow an increased opportunity to conduct further manual scaling, should this be deemed appropriate. Scheduled visual inspections of the source area were also incorporated into the final solution.

2 Rockfall assessment

Various rockfall modelling software packages are currently available on the market. These traditionally have adopted a 2D approach to the problem, however, increasingly 3D options are becoming available. The authors believe that being able to incorporate 3D digital terrain models (DTMs) into rockfall modelling offers significant advantages over 2D modelling. This allows the user to investigate how more realistic terrain features may affect rockfall trajectories and influence rockfall mitigation solutions.

In this case, the Trajec3D software was selected for use. Trajec3D is a freely available rockfall analysis software tool developed by Basson (Basson 2012a), is easy to use, has good functionality, and allows importing DTMs including, for example, pit as constructed (ascon) DTM surfaces. This was particularly relevant for being able to assess how rockfall would be influenced by the 3D shape of the damaged section of berm under the rockfall source area. Trajec3D simulates rockfall trajectories while calculating freefall and pit wall interactions at short time-step intervals. The software provides output data in comma-separated values (CSV) file format for each individual falling object. Data streams include information related to geo-location, elevation, velocity, and both rotational and linear energy at selected user defined time-steps. CSV data can then be interrogated using Excel and also imported into GEM4D as a marker file for visualisation. GEM4D is software developed for interrogating and visualizing spatial and geotechnical information (Basson 2021). The various steps undertaken during the assessment are presented in the following section.

2.1 Determine likely block size/mass and shape

To determine likely block sizes, evidence of previous rockfalls generated by the source was scrutinised. This involved taking into consideration both recent and historic accumulation of rock debris. Visual inspections of the area were undertaken during inspection with aerial drones and also by personnel involved in the rope access scaling exercise. Various block sizes were interpreted for inclusion in the modelling. Figure 2 provides an example of imagery collected during inspection using the UAV drone.

In this case, the largest likely block was interpreted to be equivalent to 2.7 t (i.e. 1 m^3). Various other smaller block sizes were apparent during inspections, therefore, for the purpose of modelling, a variety of smaller sizes were considered. The smallest block size considered was 5 kg. Figure 6 presents a list of the various rock masses considered during the modelling exercise.

Block shapes were identified as generally tabular in nature although some variance was noted during observations.

2.2 Assess distribution of particle sizes

Field observations suggest that larger size rocks are not as easily caught on berms and can travel greater distances from pit walls. In order to gain a more robust understanding of the potential for rocks of different sizes to impact the haul road, an assessment of particle size distribution (PSD) was undertaken. Visual inspection was again used to help characterisation, however, some uncertainty was noted in this area. Therefore, different potential PSDs were also considered as part of a sensitivity analysis to assess any effect on the probability for modelled rocks to come to rest on the haul road. Generally, it was considered likely that for every large rock that fell, smaller rocks would also come loose as a result. Therefore, there would likely be more smaller rocks than larger rocks overall. This appeared to be corroborated by observations in the field. Assessed PSDs rated according to likelihood based on field observations are presented in Figure 7.

2.3 Determine coefficient of restitution, static and dynamic friction angles

Several variables are required to enable modelling using Trajec3D. These include the coefficient of restitution (CoR) and both static and dynamic friction angles which are properties of site-specific materials.

The CoR is a variable used to help describe and quantify the physical interaction between a falling object and the surface that it comes into contact with. It is the ratio comparing post- and pre-impact velocity of a falling object. A CoR of 1 indicates perfect preservation of velocity while a CoR of 0 indicates complete absorption of velocity. The CoR can be determined through recording trajectories during rockfall trials in the field or by other means such as recording bounce height of rocks dropped vertically from a known height and substituting values into Equation 1 below, as described by Basson (2012b).

$$C_R = \sqrt{\frac{h}{H}} \tag{1}$$

where:

C_R = coefficient of restitution.

H = bounce height.

H = drop height.

In this case, the geotechnical team at Boddington had previously undertaken work to calibrate a site-specific value for the CoR and determine appropriate friction angles. The methods used to determine the site specific CoR are described in detail within Basson et al. (2013). As a result of that study, a CoR of 0.1 was proposed as an upper limit for all rebound surfaces considered except for hard rock. Four rebound surfaces were considered in total; pit floor, haul road, catch berm and hard rock. Since the 2013 study, experience undertaking rockfall assessments and observing rockfalls on site has largely confirmed and validated the study results.

Static and dynamic friction angles refer to peak and post-peak friction characteristics of materials. Figure 3 shows a friction force diagram which illustrates the difference between static and dynamic friction. Guidance related to the choice of static and dynamic friction angles is offered in the *Trajec3D User Manual* (Basson 2015). The current study did not consider fall body interaction; therefore, static friction did not influence the outcome. A dynamic friction angle of 40 was selected in consideration of the hard rock environment and previous site experience.

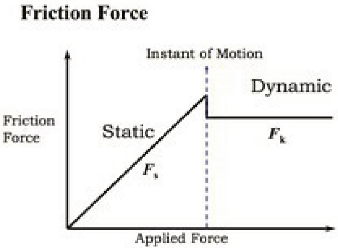


Figure 3 Friction force diagram illustrating difference between static and dynamic friction

2.4 Set up 3D surface model in Trajec3D

Trajec3D allows 3D surfaces to be imported as DXF files. Using GEM4D, the relevant section of the pit was cut out of the as-constructed pit surface using the 'rubber band' function, saved as a stand-alone DXF file and then imported into Trajec3D. Local geo-referencing is preserved during the process.

2.5 Selection of rock fence

In order to determine the effect of constructing a rock fence, engineering experience was used to select a 4 m high fence to incorporate and assess within the model. Selection of the location of the fence was done in order to maximise the amount of available berm floor between the pit wall and the fence. This helps to allow rocks to preferentially fall onto the berm rather than impact the fence. The fence is therefore utilised as a last resort to stop falling rocks from continuing to lower levels. The fence location must also consider the methods of installation, for example, construction teams must be able to drill and form foundation requirements at post locations.

Various fence configurations, energy ratings, and heights are available, however, it was not necessary to change the height of the fence during this study. A rigid post as opposed to a pivot post configuration was selected as this was determined to be adequate and is less complicated to install.

Within the Trajec3D model, the fence is considered a rigid body and objects will either be arrested or bounce back towards the slope on impact. In the field, the rock fence will be constructed of flexible steel mesh or a variation of this in order to absorb impact energy. This will result in a low 'bounce' factor, therefore, modelling the fence using a very low CoR is considered appropriate.

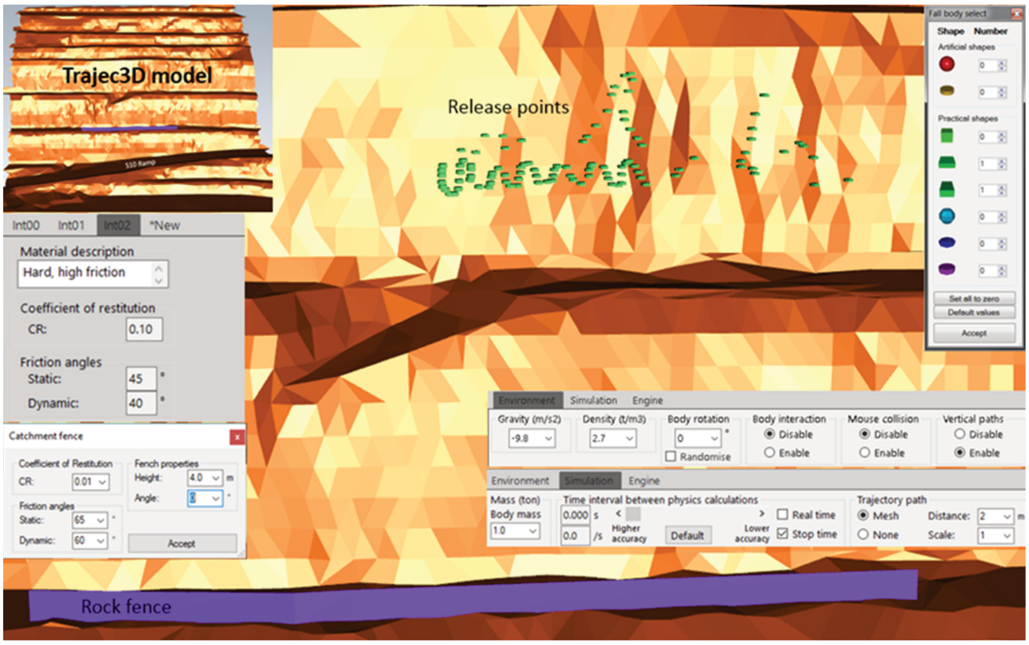
2.6 Undertake rockfall modelling using Trajec3D

Steps performed during the rockfall analysis were as follows:

1. Select shape of rocks according to field observations. In this case, generally tabular rock shapes were identified in the field and for every drop location two blocks were dropped, each slightly different rectangular shapes.
2. Select release points for rocks along the pit wall based on field observations. Similar release points for each rock mass category were used in order to allow like-for-like probabilistic comparison.

3. Perform analysis for various rock mass categories. In this case, 10 different masses were assessed. For each rock mass category, at least 200 rocks were dropped from similar release points to enable a statistical evaluation.
4. In Trajec3D, in the 'Simulation' tab under the 3D image, the highest level of simulation accuracy was selected. This provides the most detailed data.
5. After running the simulation, falling object trajectory data was exported in CSV file format.
6. In order to determine the effect of a catch fence, a 4 m high fence was modelled along catch berm below the source location. All modelling steps for each rock mass category were then repeated using similar release points to allow comparison to the base case 'no fence' scenario.

Figure 4 presents the model constructed in Trajec3D along with some of the associated input variables. Figure 5 provides an example of modelled trajectories for 1 t objects where a 4 m high catch fence is included.



Material description: Hard, high friction

Coefficient of restitution
CR: 0.10

Friction angles
Static: 45 °
Dynamic: 40 °

Catchment fence

Coefficient of Restitution
CR: 0.01

Friction angles
Static: 65 °
Dynamic: 60 °

Fench properties
Height: 4.0 m
Angle: 0 °

Fall body select: Artificial shapes 0, 0; Practical shapes 0, 1, 1, 0, 0, 0

Environment
Gravity (m/s2): -9.8
Density (t/m3): 2.7
Body rotation: 0 °
☐ Randomise
Body interaction: ● Disable ○ Enable
Mouse collision: ● Disable ○ Enable
Vertical paths: ○ Disable ● Enable

Simulation
Mass (ton) Body mass: 1.0
Time interval between physics calculations: 0.000 s; 0.0 /s; < Higher accuracy … Lower accuracy >
☐ Real time
☑ Stop time
Trajectory path: ● Mesh ○ None
Distance: 2 m
Scale: 1

Figure 4 Trajec3D model including settings, parameters, and release points on the as-constructed pit shell

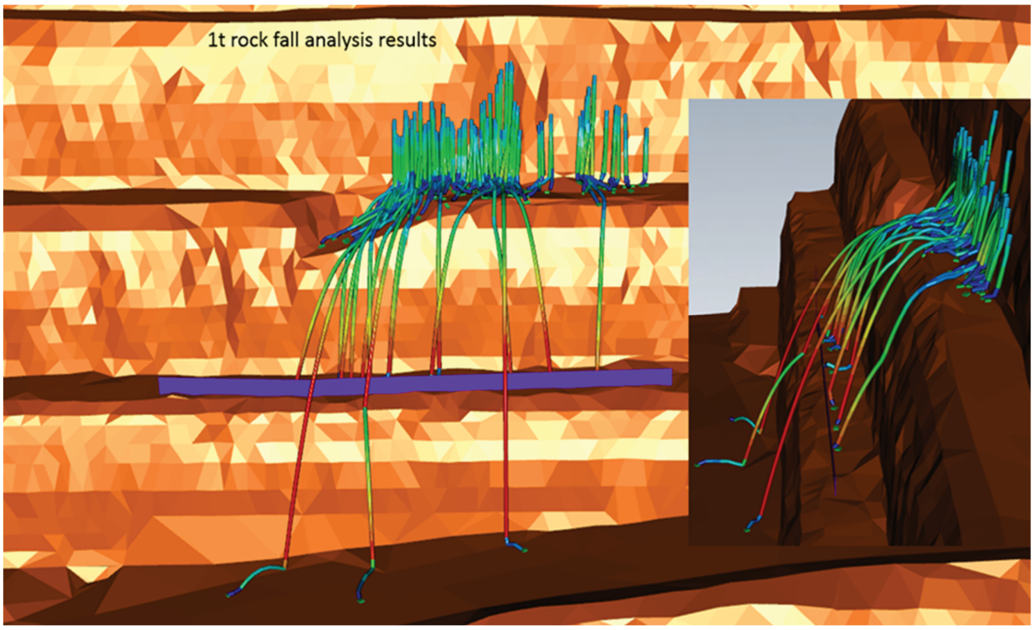
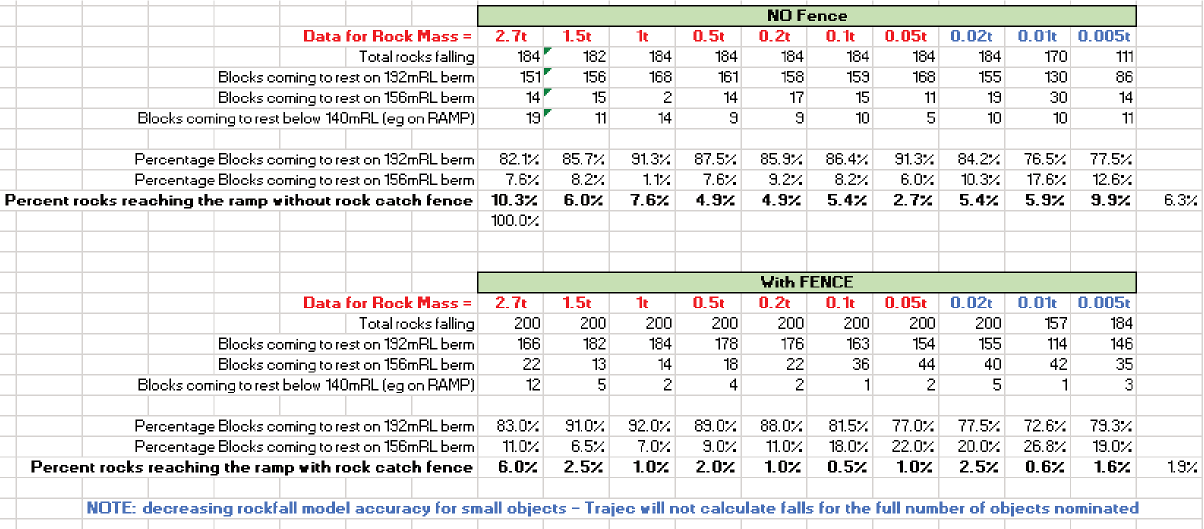


Figure 5 Example of Trajec3D visual representation of modelling results

3 Data assessment

3.1 Probability of rocks reaching haul road

In order to determine the probability of rocks reaching the haul road, rockfall data was isolated in MS Excel for objects falling below the lowest elevation of the berm directly above the ramp. Probabilities were calculated for each rock category and are presented in Figure 6.



	NO Fence										
Data for Rock Mass =	2.7t	1.5t	1t	0.5t	0.2t	0.1t	0.05t	0.02t	0.01t	0.005t	
Total rocks falling	184	182	184	184	184	184	184	184	170	111	
Blocks coming to rest on 192mRL berm	151	156	168	161	158	159	168	155	130	86	
Blocks coming to rest on 156mRL berm	14	15	2	14	17	15	11	19	30	14	
Blocks coming to rest below 140mRL (eg on RAMP)	19	11	14	9	9	10	5	10	10	11	
Percentage Blocks coming to rest on 192mRL berm	82.1%	85.7%	91.3%	87.5%	85.9%	86.4%	91.3%	84.2%	76.5%	77.5%	
Percentage Blocks coming to rest on 156mRL berm	7.6%	8.2%	1.1%	7.6%	9.2%	8.2%	6.0%	10.3%	17.6%	12.6%	
Percent rocks reaching the ramp without rock catch fence	**10.3%**	**6.0%**	**7.6%**	**4.9%**	**4.9%**	**5.4%**	**2.7%**	**5.4%**	**5.9%**	**9.9%**	6.3%
	100.0%										

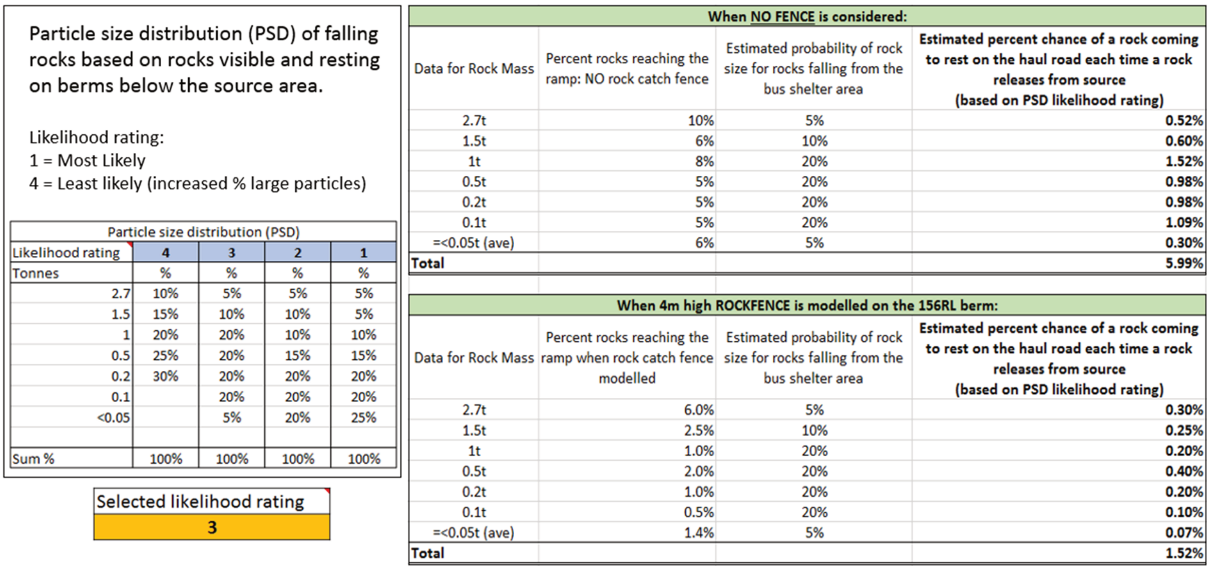
	With FENCE										
Data for Rock Mass =	2.7t	1.5t	1t	0.5t	0.2t	0.1t	0.05t	0.02t	0.01t	0.005t	
Total rocks falling	200	200	200	200	200	200	200	200	157	184	
Blocks coming to rest on 192mRL berm	166	182	184	178	176	163	154	155	114	146	
Blocks coming to rest on 156mRL berm	22	13	14	18	22	36	44	40	42	35	
Blocks coming to rest below 140mRL (eg on RAMP)	12	5	2	4	2	1	2	5	1	3	
Percentage Blocks coming to rest on 192mRL berm	83.0%	91.0%	92.0%	89.0%	88.0%	81.5%	77.0%	77.5%	72.6%	79.3%	
Percentage Blocks coming to rest on 156mRL berm	11.0%	6.5%	7.0%	9.0%	11.0%	18.0%	22.0%	20.0%	26.8%	19.0%	
Percent rocks reaching the ramp with rock catch fence	**6.0%**	**2.5%**	**1.0%**	**2.0%**	**1.0%**	**0.5%**	**1.0%**	**2.5%**	**0.6%**	**1.6%**	1.9%

NOTE: decreasing rockfall model accuracy for small objects – Trajec will not calculate falls for the full number of objects nominated

Figure 6 Calculated probability of rocks coming to rest on haul road based on Trajec3D modelling results

3.2 Sensitivity analysis based on likely particle size distribution

A sensitivity analysis was undertaken by varying the PSD of falling rocks. This produced results indicating minimal effect on probability of rocks reaching the haul road when PSD was varied within a reasonable range. The different PSDs considered resulted in calculated probability of rocks reaching the haul road ranging between 5.9 and 6.2% without a catch fence and between 1.5 and 2% with a catch fence. Figure 7 provides some of the details and an example of the sensitivity analysis calculations.



Particle size distribution (PSD) of falling rocks based on rocks visible and resting on berms below the source area.

Likelihood rating:
1 = Most Likely
4 = Least likely (increased % large particles)

Particle size distribution (PSD)				
Likelihood rating	4	3	2	1
Tonnes	%	%	%	%
2.7	10%	5%	5%	5%
1.5	15%	10%	10%	5%
1	20%	20%	10%	10%
0.5	25%	20%	15%	15%
0.2	30%	20%	20%	20%
0.1		20%	20%	20%
<0.05		5%	20%	25%
Sum %	100%	100%	100%	100%

Selected likelihood rating
3

When NO FENCE is considered:

Data for Rock Mass	Percent rocks reaching the ramp: NO rock catch fence	Estimated probability of rock size for rocks falling from the bus shelter area	**Estimated percent chance of a rock coming to rest on the haul road each time a rock releases from source (based on PSD likelihood rating)**
2.7t	10%	5%	**0.52%**
1.5t	6%	10%	**0.60%**
1t	8%	20%	**1.52%**
0.5t	5%	20%	**0.98%**
0.2t	5%	20%	**0.98%**
0.1t	5%	20%	**1.09%**
=<0.05t (ave)	6%	5%	**0.30%**
Total			**5.99%**

When 4m high ROCKFENCE is modelled on the 156RL berm:

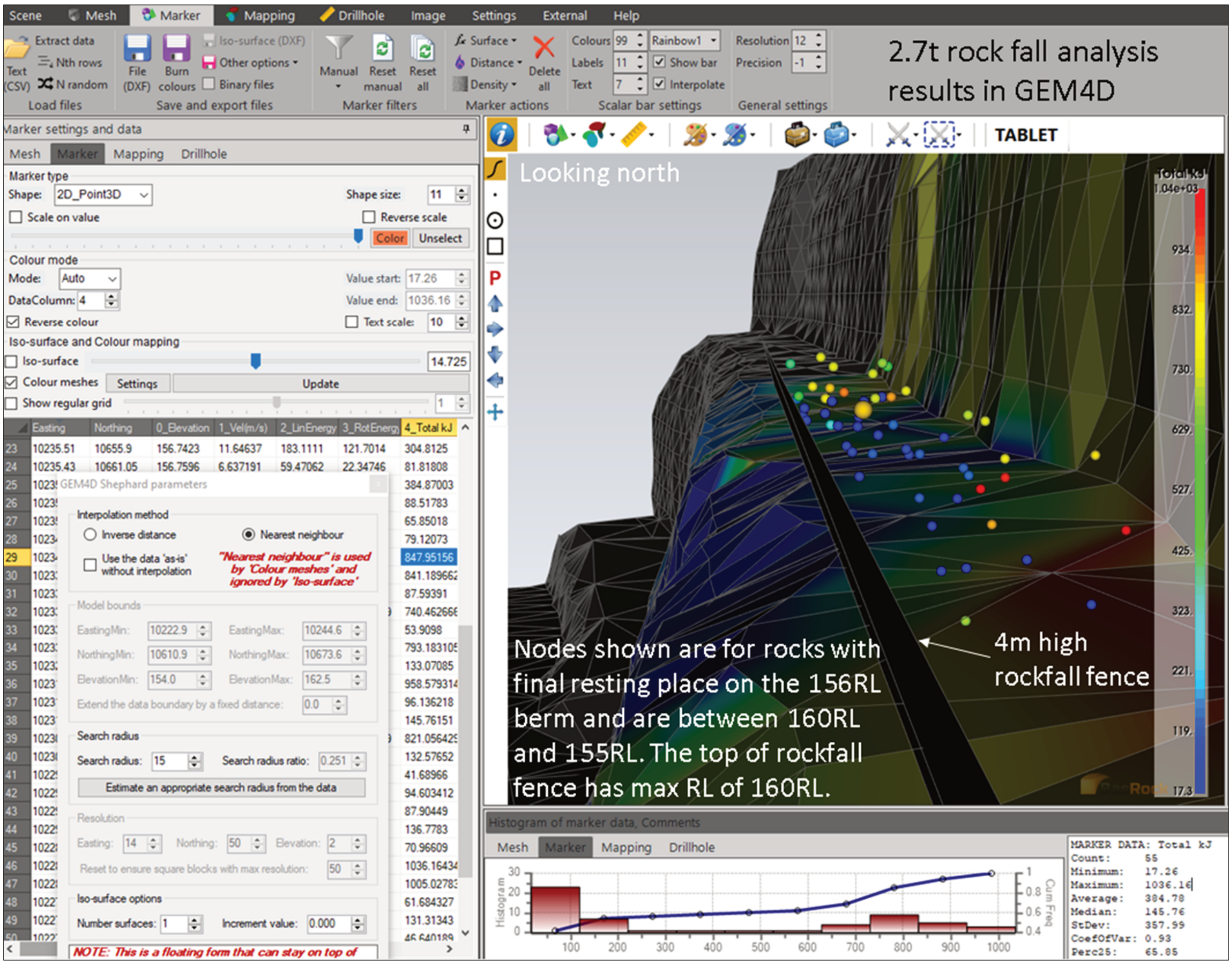
Data for Rock Mass	Percent rocks reaching the ramp when rock catch fence modelled	Estimated probability of rock size for rocks falling from the bus shelter area	**Estimated percent chance of a rock coming to rest on the haul road each time a rock releases from source (based on PSD likelihood rating)**
2.7t	6.0%	5%	**0.30%**
1.5t	2.5%	10%	**0.25%**
1t	1.0%	20%	**0.20%**
0.5t	2.0%	20%	**0.40%**
0.2t	1.0%	20%	**0.20%**
0.1t	0.5%	20%	**0.10%**
=<0.05t (ave)	1.4%	5%	**0.07%**
Total			**1.52%**

Figure 7 Sensitivity analysis to determine effect of particle distribution variation on rockfall assessment

3.3 Assessment of total energy

In Excel, linear and rotational energy data were combined for each data point to provide total energy. Since the dataset includes geo-referenced information to locate each time-step node, it is possible to observe total energy of nodes in proximity to the catch fence. This was done first in Excel and then the information was imported into GEM4D to enable spatial observation. To do this, the rendered Trajec3D output CSV file was imported as a marker file into GEM4D and the data column representing calculated 'Total energy' was selected. This displays node locations in 3D which are coloured according to energy rating shown on the legend provided. The pit surface was also coloured using the 'Nearest neighbour' option to represent proximity of node energy rating to the pit shell as shown in Figure 8. Modelled energy ratings were considered during the selection of an appropriate catch fence energy rating.

The highest energy ratings of rocks falling onto the 156RL berm resulted from the 2.7 t mass blocks that were modelled. A total energy of over 1,000 kJ was recoded on two occasions for rocks falling closer to the toe of the slope. Modelling results indicated a highest value of 1,036 kJ. The average total energy for 2.7 t mass blocks falling onto the 156RL berm was approximately 380 kJ with a standard deviation of about 350 kJ. Other rock mass categories below 2.7 t had significantly reduced total energy ratings. On the basis of the results, a 1,000 kJ rated fence was assessed to be suitable.



2.7t rock fall analysis results in GEM4D

Colours: 99 Rainbow1
Labels: 11 ☑ Show bar
Text: 7 ☑ Interpolate
Resolution: 12
Precision: -1

Marker type
Shape: 2D_Point3D
Shape size: 11
☐ Scale on value
☐ Reverse scale

Colour mode
Mode: Auto
DataColumn: 4
Value start: 17.26
Value end: 1036.16
☑ Reverse colour
☐ Text scale: 10

Iso-surface and Colour mapping
☐ Iso-surface 14.725
☑ Colour meshes
☐ Show regular grid 1

	Easting	Northing	0_Elevation	1_Vel(m/s)	2_LinEnergy	3_RotEnerg	4_Total kJ
23	10235.51	10655.9	156.7423	11.64637	183.1111	121.7014	304.8125
24	10235.43	10661.05	156.7596	6.637191	59.47062	22.34746	81.81808
25	1023						384.87003
26	1023						88.51783
27	1023						65.85018
28	1023						79.12073
29	1023						847.95156
30	1023						841.189662
31	1023						87.59391
32	1023						740.462666
33	1023						53.9098
34	1023						793.183105
35	1023						133.07085
36	1023						958.579314
37	1023						96.136218
38	1023						145.76151
39	1023						821.056429
40	1023						132.57652
41	1022						41.68966
42	1022						94.603412
43	1022						87.90449
44	1022						136.7783
45	1022						70.96609
46	1022						1036.16434
47	1022						1005.02783
48	1022						61.684327
49	1022						131.31343
50	1022						46.640189

GEM4D Shephard parameters

Interpolation method
○ Inverse distance
● Nearest neighbour
☐ Use the data 'as-is' without interpolation
"Nearest neighbour" is used by 'Colour meshes' and ignored by 'Iso-surface'

Model bounds
EastingMin: 10222.9
EastingMax: 10244.6
NorthingMin: 10610.9
NorthingMax: 10673.6
ElevationMin: 154.0
ElevationMax: 162.5
Extend the data boundary by a fixed distance: 0.0

Search radius
Search radius: 15
Search radius ratio: 0.251

Resolution
Easting: 14
Northing: 50
Elevation: 2
Reset to ensure square blocks with max resolution: 50

Iso-surface options
Number surfaces: 1
Increment value: 0.000

NOTE: This is a floating form that can stay on top of

Looking north

Nodes shown are for rocks with final resting place on the 156RL berm and are between 160RL and 155RL. The top of rockfall fence has max RL of 160RL.

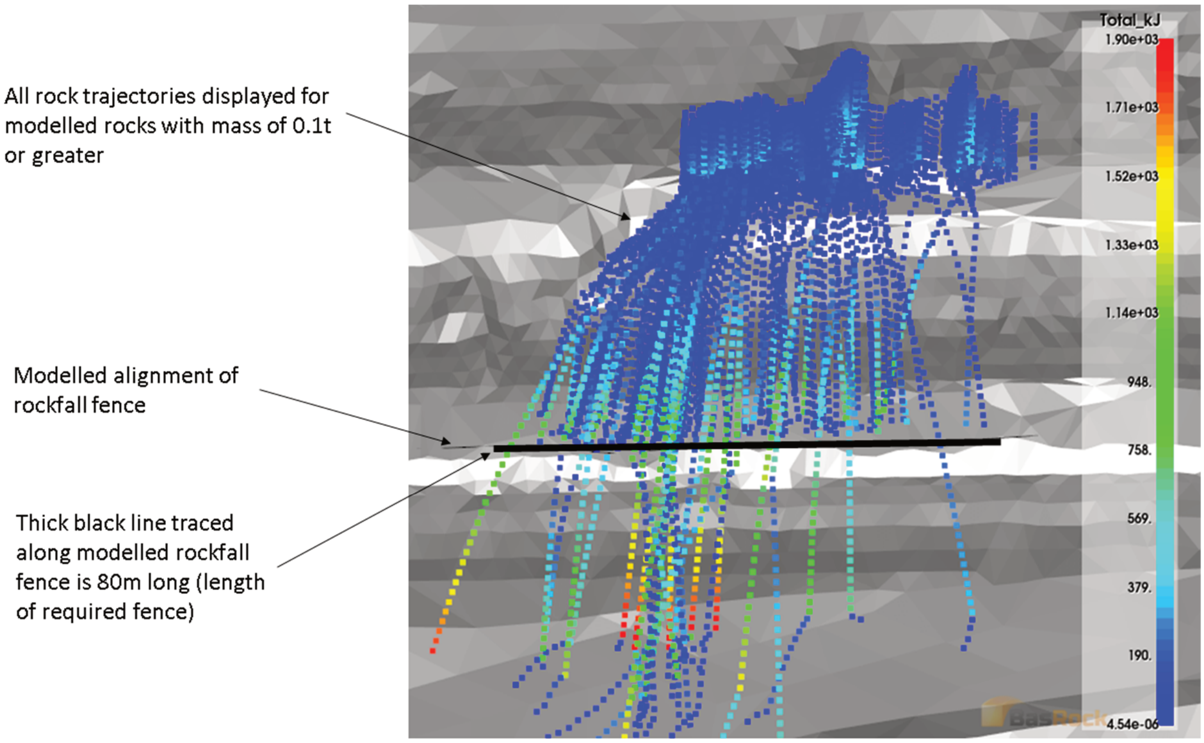
4m high rockfall fence

```
MARKER DATA: Total kJ
Count:      55
Minimum:    17.26
Maximum:    1036.16
Average:    384.78
Median:     145.76
StDev:      357.99
CoefOfVar:  0.93
Perc25:     65.85
```

Figure 8 Total energy ratings at modelled Trajec3D nodes represented in GEM4D with 'nearest neighbour' colouration on pit shell

3.4 Assessment of required rock catch fence length

To assess the length of required catch fence, data for all rock mass categories was combined in Excel and imported into GEM4D as a marker file. Once this data was represented visually, the information was then used to determine the most effective length of catch fence by measuring as appropriate using the measurement tool within GEM4D. The fence length was selected so that it extended to sufficiently provide a barrier for modelled potential rock trajectories. Figure 9 illustrates how this was done.



All rock trajectories displayed for modelled rocks with mass of 0.1t or greater

Modelled alignment of rockfall fence

Thick black line traced along modelled rockfall fence is 80m long (length of required fence)

Figure 9 Assessment of required length of catch fence by importing Trajec3D data as a marker file in GEM4D

4 Conclusion

Field observations were very important in determining and characterising inputs used in rockfall modelling, for example, likely rock size, size distribution, and suitable location of the rock fence. The versatility of Trajec3D was also key to undertaking the detailed rockfall assessment. Trajec3D enabled bespoke modelling using the as-constructed pit shell and provided node data that could be further assessed using Excel and imported into GEM4D. Visual and tabular data representation capabilities offered within GEM4D were used to help interpret and better understand modelling results and assess requirements of the catch fence solution.

Once fence construction is complete, single lane running will no longer be required along this section of the haul road. In addition to the catch fence solution, other ongoing methods of rockfall mitigation for this location will include scheduled periodic visual inspections using drone imagery and additional inspection and controlled scaling using rope access techniques, should this be required.

Based on site experience, the selected solution as presented in this paper is considered to be adequately robust and conservative to help address other variables that may have the potential to affect rockfall trajectories. These include potential variations in the CoR, friction angles, and block shapes. Site practitioners are encouraged to undertake appropriate levels of assessment considering local conditions.

Acknowledgement

The author thanks Frans Basson for the creation of the Trajec3D software and accompanying technical research and software user guidance. The author also thanks the wider geotechnical team at Boddington for their inputs.

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