SSIM 2023 – PM Dight (ed.)
© 2023 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-6-5
doi:10.36487/ACG_repo/2335_43

A qualitative rockfall hazard screening tool for open pit mining

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Abstract

Rockfall is a key focus for geotechnical risk management and operational safety in the current mining environment. Due to limited site records and variability in rockfall conditions and outcomes, risk assessments are ideally completed by experienced practitioners who can make sound judgement calls. The reality in an operational space is that these assessments are often undertaken by site staff that are junior or inexperienced. This may result in a site operating at a higher than acceptable risk level due to rockfall.

The development of a qualitative rockfall hazard screening tool for a benched mine slope is outlined in this paper. It is intended to be quick and easy, providing a structured, repeatable framework to assess rockfall hazard. The tool acts as a guide to assist staff in making important judgement calls about rockfall hazard in the field.

The tool utilises a rating system to assess factors contributing to the intensity and likelihood of a rockfall occurring. Intensity factors include block size, block weight, slope height and geometry, all of which influence possible impact energy. Likelihood factors include slope geometry features, accumulation of loose material and batter condition. All ratings have been calibrated to conditions at a case study site utilising field trials and extensive sensitivity rockfall modelling. Once all factors have been assessed in the field and office, the intensity and likelihood factor totals are compared to a hazard matrix which allocates a rockfall hazard level for that slope.

Applications for this tool include routine slope hazard assessments in active working areas, providing semi-qualitative hazard information for risk assessments and generating rockfall hazard maps for communication to site staff. While this tool was developed for a specific case study site, it can be readily modified and calibrated for other sites.

Keywords: *rockfall, open pit mining, hazard assessment*

1 Introduction

Rockfalls are hazardous events that occur commonly in steep slopes, whether they are natural or excavated. A rockfall event consists of the detachment of a rock block from a slope followed by a rapid downward motion characterised by freefall, bouncing, rolling and/or sliding motions (Figure 1: Ritchie 1963; Pierson et al. 2001; Varnes 1978). Factors that cause or contribute to rockfall include:

- Unfavourably orientated geological structures (discontinuities).
- Poor blasting practices.
- Water, either through adverse groundwater conditions or poor surface water management.
- Weathering and vegetation.

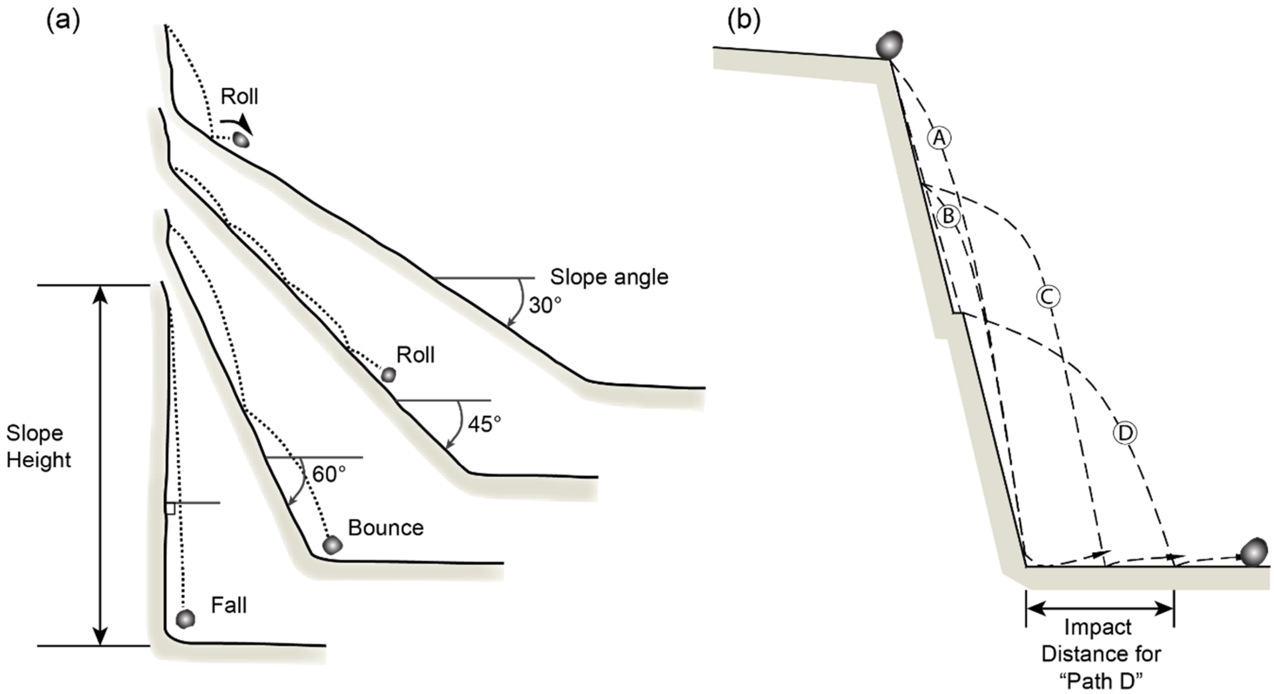

Figure 1 Rockfall (a) travel modes (after Ritchie 1963) and (b) paths (after Pierson et al. 2001)

In a mining environment, rockfalls present a constant risk to personnel, light vehicles and other equipment. Quantifying this risk relies on an accurate assessment of the rockfall hazard, which is often difficult due to a range of variables that influence rockfall trajectories. Rockfall risk assessments are ideally undertaken by an experienced geotechnical practitioner, however, they are often completed by young or inexperienced site personnel. This can result in a site operating at a higher than acceptable risk level due to mischaracterisation of the rockfall hazards.

This paper presents a qualitative rockfall hazard screening tool (QRHST) for benched mine slopes. The tool is intended as a guide to assist operational geotechnical personnel in the consistent identification and characterisation of rockfall hazards around an open pit.

The QRHST utilises an intensity–likelihood hazard assessment matrix to characterise and assess the rockfall hazard level for a given slope. The tool comprises:

1. Ratings to factors that influence the intensity of the rockfall hazard.
2. Ratings to factors that influence the likelihood of the rockfall hazard.
3. Rating factors summed (individually for intensity and likelihood), with the resultant intensity factor rating and likelihood factor ratings being assigned a hazard level.
4. Ratings levels plotted on a hazard matrix to assess the overall slope rockfall hazard level. Each hazard level correlates to specific follow-up actions including risk assessments for high hazard slopes.

It is important to note that the inputs and ratings for the tool presented in this paper have been calibrated for the conditions of a case study site (referred to as 'Site'). The Site is a hard rock, open cut mine, with the dominant rock types being shale and breccia. Three main slope types are present at the Site: benched final highwall, benched inter-stage cutback and footwall. Benched inter-ramp heights are typically up to 200 m. The tool presented in this paper is calibrated specifically to address these conditions, however, the framework and logic underpinning the results could be readily calibrated to other sites and conditions.

2 Existing rockfall hazard rating systems and site requirements

Characterising and defining a rockfall hazard is critical in risk assessments aimed at keeping people and equipment safe. Rigorous rockfall assessments are not common in the mining industry, and operational rockfall management on mine sites is often reactive and unstructured.

There are numerous published rockfall risk and hazard assessment methods covering applications from civil to transport, natural slopes and mining. Three notable existing rockfall hazard rating systems are summarised here. Note that while this is not an exhaustive list, it provides a good idea of the range of existing methods.

2.1 Rockfall hazard rating system

This system was developed in the 1980s by the Oregon Department of Transportation and published by Pierson et al. (1990). The rockfall hazard rating system is a two-phase process divided into a preliminary rating phase and a detailed rating phase. The preliminary phase qualitatively rates different factors to determine the hazard/risk to the assessed roadway. The preliminary rating phase assigns a slope as one of three classes:

- Class A: moderate to high risk: source of rockfall is obvious, a small roadside ditch, history of frequent rock on the roadway; requires immediate detailed assessment.
- Class B: low to moderate risk: rockfall is possible, frequency is low enough or roadside ditch is large enough to restrict nearly all rockfall from reaching the roadway; to be evaluated in more detail as time and funding allow.
- Class C: low or non-existent risk: unlikely that a rock will fall or, if a rock should fall, it is unlikely to reach the roadway; no further attention is required.

2.2 Swiss system

The Swiss guidelines (Federal Office of Planning et al. 1997) assess rockfall hazards according to their onset probability/return period (failure likelihood) and intensity represented by the kinetic energy of the falling blocks (failure magnitude). They define three hazard ratings from low to moderate to high. The intensity of rockfall is obtained from rockfall trajectory simulations. The intensity limits are based on the impact energy that can be resisted by different types of building wall construction. The probability class limits are apparently equivalent to those established for snow avalanches and floods in Switzerland. While the term 'return period' is normally applied to recurring processes (like floods and earthquakes), the Swiss have used it as a relative term for rockfalls. The only reference they make to estimating probability is by 'taking into account traces of former events', which is assumed to mean it is based on observational evidence of past rockfall.

2.3 Qualitative evolving rockfall hazard assessment for highwalls

This rating system was developed by Ferrari et al. (2017) for open cut coal mine highwalls. The intensity versus likelihood framework was inspired by the Swiss system but has been modified to better represent mining conditions and considerations. Notably, the intensity energy thresholds have been modified to be relevant to mining environments. These are:

- 0.05 kJ: the rating for a typical personal protective equipment hard hat.
- 11.6 kJ: the impact resistance of falling object protective systems.
- 300 kJ: the impact resistance for infrastructure such as concrete portals.

Also, the likelihood return period has been replaced with the concept of 'state of activity'. This method is intended for use in the field and rates several factors to provide an overall hazard rating, either low, moderate or high. While this method accounts for many factors relating to the mining environment, it is specifically developed for coal highwalls, which are of significantly different character to the benched slopes at the Site.

2.4 Site requirements

The three existing rockfall hazard/risk assessment methods outlined above provide good systems for environments such as civil, roads, natural slopes and coal mines. They do not provide a direct solution for the conditions at the Site, however, and as such, a site-specific rockfall hazard assessment system was developed: the QRHST.

There are three key characteristics of the Site that may promote increased rockfall trajectories and require specific consideration in the QRHST. These are:

- Slopes are typically benched.
- Inter-stage mining results in reduced catch capacity due to blast spillage and increased rockfall source material.
- Design conformance is variable due to geological structure, blasting and excavation execution.

These have been considered in the QRHST, along with a range of other factors that influence rockfall trajectories and contribute to the rockfall hazard.

3 Qualitative rockfall hazard screening tool

3.1 Overview

The QRHST utilises a rating system to assess factors contributing to the intensity and likelihood of a rockfall occurring. Intensity factors include block size, block weight, slope height and geometry, all of which influence the possible impact energy. Likelihood factors include slope geometry features which may promote rocks to progress further down the slope and/or runout onto the floor, accumulation of loose material and batter condition (i.e. the presence of unstable rockfall source material).

The QRHST template provides a framework for a quick and easy assessment of these factors, which are assigned ratings based on certain criteria. All ratings have been calibrated to site conditions utilising field trials, parameter back-analysis and extensive sensitivity rockfall modelling. Once all factors have been assessed in the field and office, the intensity and likelihood factor ratings are summed, with the resultant total intensity factor rating and likelihood factor rating being assigned a hazard level following the rating scale in Figure 2. These are then compared to a hazard matrix, which allocates a rockfall hazard level for that slope. The hazard levels correlate to specific actions that should be completed if access is required below the rockfall hazard.

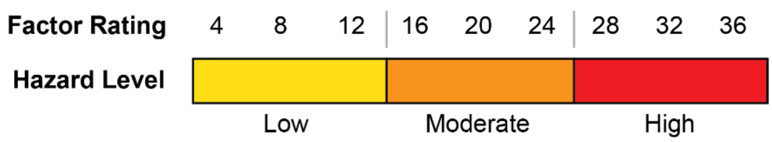

Figure 2 QRHST factor hazard rating scale

3.2 Rockfall field trials and modelling parameter back-analysis

Rockfall field trial campaigns were conducted to collect controlled empirical data across a range of block sizes to allow calibration of rockfall modelling input parameters. Rocks were dropped from two locations, which were considered a good representation of the different highwall slope conditions at the mine site. A range of shapes and weights were used for the trials, with more than 50 rocks dropped between the two campaigns. The resulting back-analysed rockfall parameters are listed in Table 1.

Table 1 2D Rigid body rockfall modelling parameters

Slope material	Coefficient of normal restitution	Coefficient of tangential restitution	Friction angle (°)	Slope roughness
Batter	0.58 ± 0.12	0.85 ± 0.12	30 ± 3	0 ± 1.5
Berm	0.31 ± 0.12	0.65 ± 0.12	34 ± 3	0 ± 1.5
Rill	0.26 ± 0.12	0.50 ± 0.12	40 ± 3	0 ± 1.5

All rockfall modelling undertaken for the QRHST calibration in this paper utilises the 2D rockfall modelling software RocFall2, developed by Rocscience Inc. (2022). Rigid body analyses are undertaken, which consider the shape of the rock. The analysis method was consistent with that used for the field trial back-analysis and utilised the site-calibrated rigid body input parameters.

3.3 Assessed factors and ratings

The first section of the QRHST is subdivided into intensity factor ratings and likelihood factor ratings. A summary of all QRHST factors and ratings is provided in Section 3.4.1 of this paper.

3.3.1 Intensity factors

Intensity in this study is defined by impact energy. Impact energy is dependent on block size (mass) and trajectory (fall height). In general, larger rocks and larger fall heights will have higher associated energies than smaller rocks and smaller fall heights. It is important to note that variation in slope shape (such as that shown schematically in Figure 3) and slope angle can influence the trajectories also. For example, a steep slope with poorly formed benches can promote rocks to jump large distances and, as a result, impact with higher energies. With this in mind, the QRHST assesses four primary factors that influence impact energy. These are:

1. Block size/weight.
2. Slope height.
3. Slope angle.
4. Slope shape.

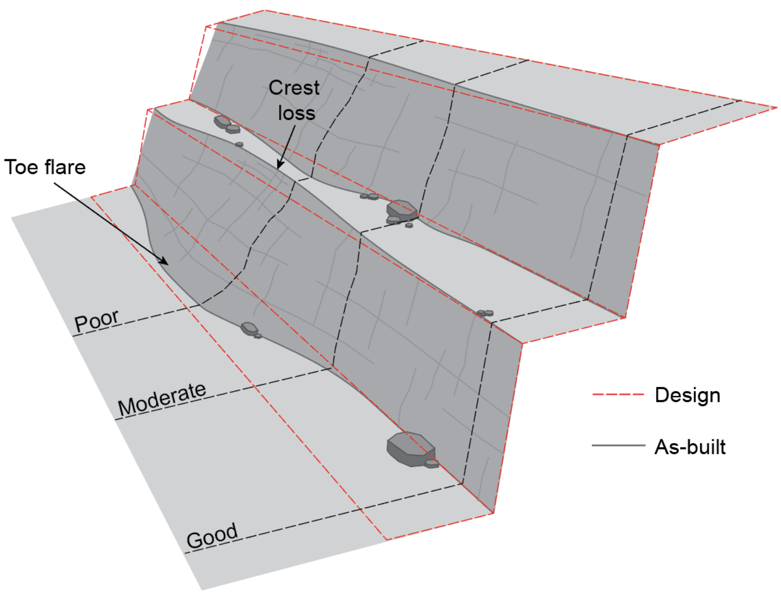

Figure 3 Schematic slope illustrating variations in slope shape relative to the design profile. These differences are typically due to blasting, excavation and geological factors

Rockfall modelling was conducted to assess the influence and relative weighting of each factor with regard to impact energies. 2D rigid body modelling was undertaken in the RocFall2 software. The site-calibrated modelling parameters in Table 1 were used. Several benched and unbenched slope profiles with slope angles between 25° and 62° were assessed, representing the possible range of slope conditions that could be anticipated at the site. The intensity results were categorised using three energy thresholds defined by Ferrari et al. (2017), which are listed in Section 2.3.

Rockfall modelling impact energy results are summarised in Figure 4. The 90th percentile translational kinetic energy was chosen for the assessment as the maximum energy often represents extreme, unrealistic conditions (Ferrari et al. 2017). The results were subdivided into combinations of the four intensity factors (e.g. 1–5 kg rocks falling from a 50 m-high, 48° slope, Figures 4 and 5). An energy rating was assigned to each combination, considering the energy intensity thresholds of 0.05, 11.6 and 300 kJ. An example showing some of the combinations of intensity factors and resultant energy (i.e. modelled hazard range) is shown in Figure 5.

An iterative comparison between the modelling results and qualitative rating system was then undertaken to refine the rating system values for each factor. Due to the range of factors and the way in which they are combined, the individual ratings are non-unique solutions. However, the overall results compared to the modelled results were considered a good fit. Note that the values with the highest difference relative to the energy thresholds are typically unbenched 62° slopes greater than 50 m in height. These scenarios are considered highly unlikely at the Site. Each of these unlikely cases also overestimates the hazard level slightly, which may be considered conservative/favourable in those circumstances.

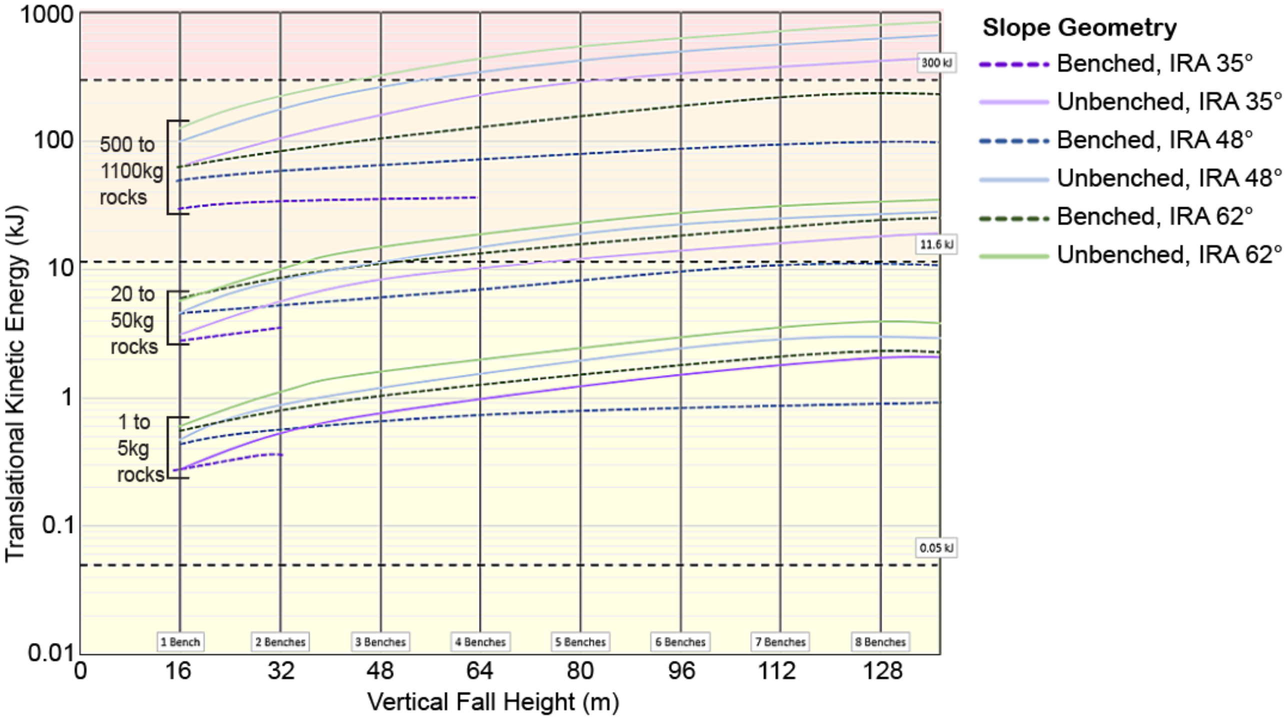

Figure 4 Intensity factor rockfall sensitivity modelling results. The three energy thresholds of 0.05, 11.6 and 300 kJ are annotated as dashed lines and hatched from yellow to red. IRA = inter-ramp angle

	QRHST Factor Combination Ratings				Hazard Rating Calibration		
	Rock Size	**Slope Height**	**Slope Shape**	**Slope IRA**	**Modelled Hazard Rating Range**	**QRHST Rating**	**Correlation**
Factors	1 to 5	<50	Benched	35	Low	**4**	✓
Rating	**1**	**1**	**1**	**1**	0-14		
Factors	1 to 5	<50	Benched	48	Low	**6**	✓
Rating	**1**	**1**	**1**	**3**	0-14		
Factors	1 to 5	<50	Benched	62	Low	**9**	✓
Rating	**1**	**1**	**1**	**6**	0-14		
Factors	1 to 5	<50	Unbenched	35	Low	**9**	✓
Rating	**1**	**1**	**6**	**1**	0-14		
Factors	1 to 5	<50	Unbenched	48	Low	**11**	✓
Rating	**1**	**1**	**6**	**3**	0-14		
Factors	1 to 5	<50	Unbenched	62	Low	**14**	✓
Rating	**1**	**1**	**6**	**6**	0-14		
•••							
Factors	20 to 50	>80	Unbenched	35	Moderate	**18**	✓
Rating	**5**	**6**	**6**	**1**	14-26		
Factors	20 to 50	>80	Unbenched	48	Moderate	**20**	✓
Rating	**5**	**6**	**6**	**3**	14-26		
Factors	20 to 50	>80	Unbenched	62	Moderate	**23**	✓
Rating	**5**	**6**	**6**	**6**	14-26		

Figure 5 Examples of parts of the intensity factor assessment and rating calibration

3.3.2 Likelihood factors

Likelihood relates to factors promoting block detachment and/or block propagation down the slope. Four likelihood factors have been included in the QRHST:

1. Slope design conformance.
2. Rill accumulation on berms.
3. Loose material at crest (e.g. blasted stocks or fill) and hang-ups on pit or bench crests.
4. Batter condition.

3.3.2.1 Slope design conformance

Bench geometries are typically designed to control rockfall and, as such, the design geometry for slopes is typically favourable in terms of rockfall retention and risk mitigation. Variation from this design profile is common, however, and occurs due to several factors including geological structure, poor blasting and excavation practices. These factors can result in crest loss, flattening of the batter face angle, and reduced catch capacity and launch features, all of which promote higher rockfall trajectories.

Rockfall analyses were conducted to understand the impact of different levels of conformance to enable the design of rockfall trajectories. A representative slope from the Site was used for 2D rockfall modelling. The modelling methodology follows that described in earlier sections of this paper. Four slope scenarios were run for a five-bench-high slope:

1. Design Case A (85° batter face angle, 7 m berm width, 16 m bench height).
2. Case A with 10% berm width reduction.
3. As-built example for Case A, with a roughly 50% berm width reduction.
4. As-built example for Case A which represents a roughly 75% berm width reduction.

The as-built scenarios also represent reduced batter face angles (73° to 67°). The results of these analyses are shown in Figure 6. The modelled slope geometries represent a range of geometrical differences between an ideal design case (1) and poor design conformance cases (3 and 4). The results were used to interpolate the runout distances for 20%, 30% and 40% berm width reduction cases (Figure 6).

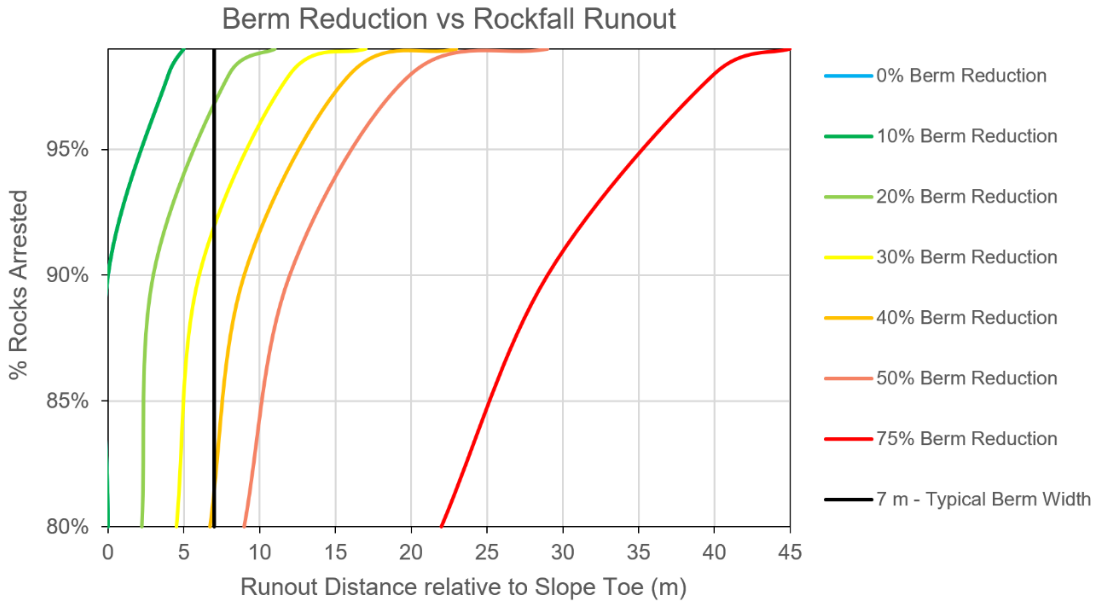

Figure 6 Slope design conformance rockfall modelling results

To determine rating thresholds for the QRHST, the percentage of rocks arrested was assessed relative to a typical berm width of 7 m. This distance was chosen considering the element at highest risk, which is typically drill and blast crews drilling and loading wall control and buffer rows proximal to the slope. The low to moderate threshold chosen was 98% rocks arrested within 7 m, which corresponds to approximately 15% crest loss (Figure 6). A lower value of 85% was chosen for the moderate to high threshold, corresponding to approximately 50% crest loss.

3.3.2.2 Accumulation of loose material on berms

A large number of historic rockfalls at the Site occur below an inter-stage cutback where blast spillage has covered the majority of the slope as illustrated in Figure 7. The spillage material (rill) elevates the rockfall hazard by:

- Reducing the slope catch capacity.
- Increasing the amount of rockfall source material on the slope.
- Forming ski ramp launch features (noting that there may also be a degree of energy absorption when impacting the rill material).

Rockfall analyses were completed to assess the impact of varying levels of rill accumulation on rockfall trajectories and runout distances. Three accumulation scenarios were modelled: 0% (i.e. clean benches), 50% and 100% rill accumulation.

Rockfall analysis results are presented in Figure 8. The results show that the difference between 0% and 50% rill accumulation is relatively minor in terms of rockfall propagation down the slope. Results for 100% accumulation (full benches), however, had a dramatic increase in the percentage of rocks that propagate down the slope. These results were used to inform the QRHST rating thresholds and relative weighting for rill accumulation on benches.

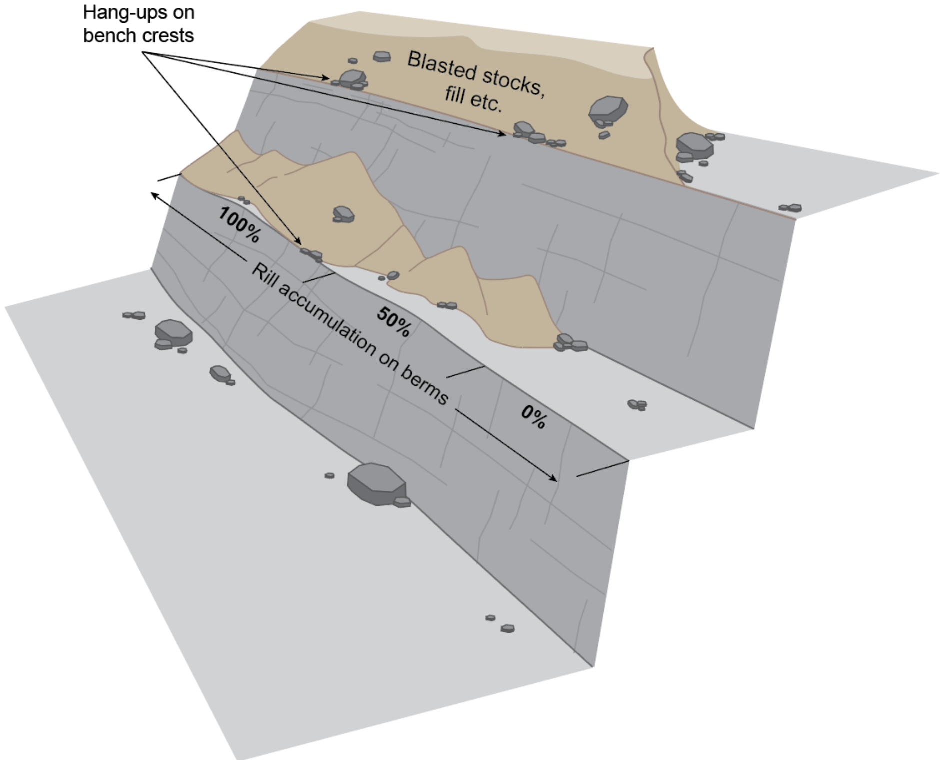

Figure 7 Schematic slope showing varying degrees of rill accumulation on berms, discrete hang-ups on bench crests and loose material (blasted stocks) at the crest

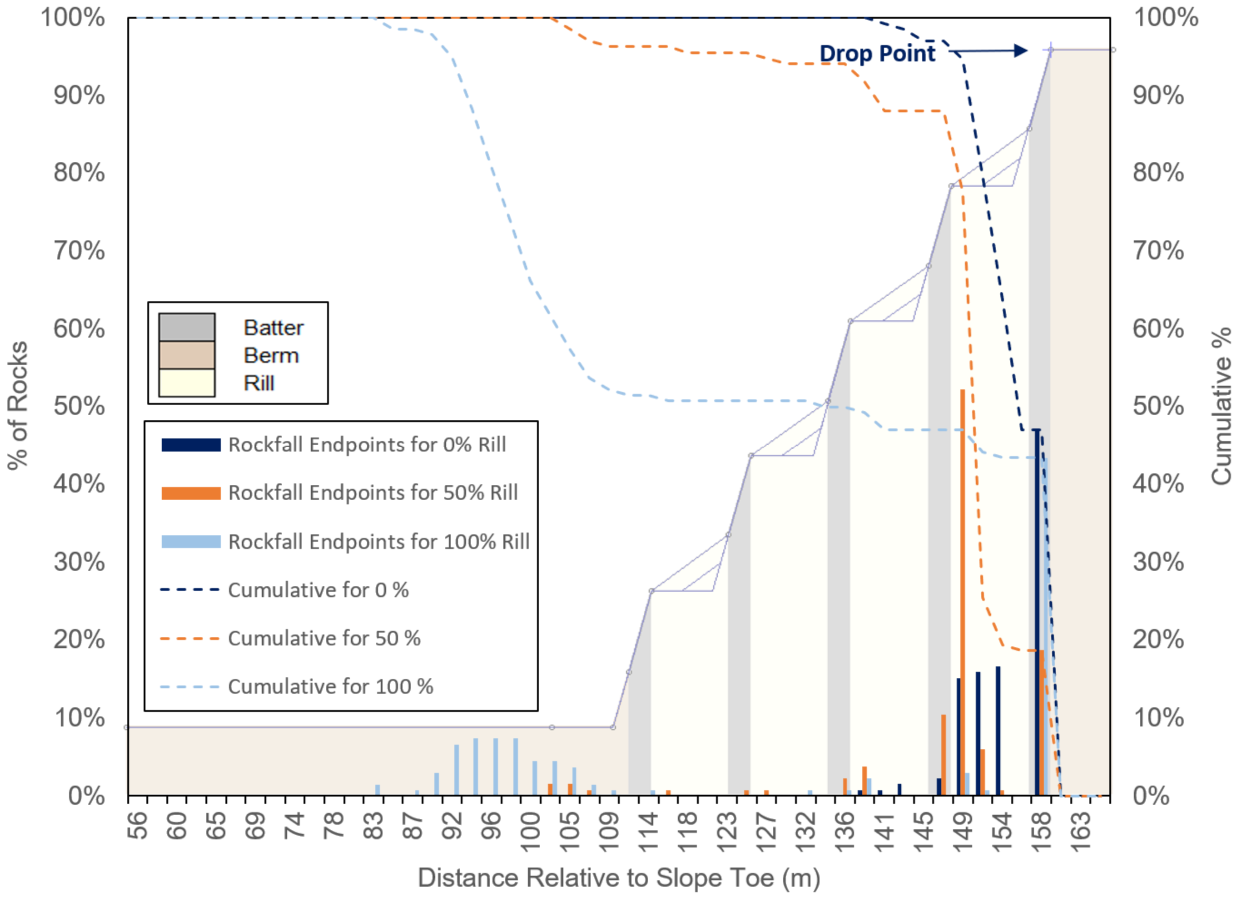

Figure 8 Rill accumulation rockfall modelling results

3.3.2.3 Presence of loose material and/or hang-ups at crest

Loose material at the pit crest, such as blasted stocks or fill such as that shown schematically in Figure 7, presents an increased source of potentially unstable blocks. This type of material is also recharged periodically during pit crest blasts, meaning a higher frequency of unstable blocks that have not had a chance to detach during other pit blasts and/or rainfall events. These features are common in inter-stage cutback mining and result in a higher risk to operations below due to rockfall.

The ratings for both loose material at the crest and discrete hang-ups are nominal values chosen with a degree of judgement and consideration of the Site historical rockfall register. Loose material at the crest and discrete observed hang-ups have been included as separate sections in the QRHST template for ease of assessment. To ensure that they are not over-represented in the overall likelihood rating, however, their combined scores are weighted evenly with other factors.

3.3.2.4 Batter condition

Batter condition refers to the likelihood a block will detach from a batter. Factors that promote blocks detaching from batters are:

- Blast damage (dilation of fractures and loose blocks).
- Poor scaling (loose blocks).
- Rock mass condition (block size): Ferrari et al. (2017) use geological strength index for this aspect. Conditions at the Site are typically ‘blocky’ and this factor does not have much variation at the site.
- Structure (unstable blocks due to structural orientations).

Similar to those of the loose crest material and hang-ups, rating thresholds for batter condition are based on judgement and consideration of site conditions. The rating categories consider a combination of the factors listed above. It is noted that rockfalls occurring due to blocks detaching from batter faces represent a very low number of reported rockfalls at the Site.

3.3.3 Overall rating calibration

Once all factors had been assessed and preliminary ratings and thresholds assigned, a further overall calibration was undertaken to ensure that QRHST-assessed hazard levels were appropriate and consistent across a range of conditions. To do this, a number of case studies from the Site were assessed using the QRHST. Assessed slopes included a range of clean to rill-filled slopes, good to poor design conformance, and different heights and slope angles. Ratings were modified to ensure that all slopes were assigned an appropriate overall hazard level. This final calibration was to ensure that the tool does not underestimate the rockfall hazard but is also not overly conservative, which would place undue constraints on operations.

3.4 Qualitative rockfall hazard screening tool framework and methodology

3.4.1 Section 1: field observations

Section 1 of the QRHST, shown in Figure 9, comprises the initial qualitative assessment of the intensity and likelihood factors. The assessment is intended to be undertaken both in the field and in the office using a combination of field observations, drone photographs and 3D survey scans. Each factor has a description to assist the assessor in assigning consistent ratings. Further guidance is provided in the form of reference diagrams on the reverse side of the template. The descriptions and reference material are intended to ensure that assessment results are relatively consistent, regardless of the person undertaking the assessment. These also prompt less experienced staff to ensure all important factors are assessed so that the rockfall hazard is not underestimated.

1. Field Observations					
Factor		Description of Field Observation	Class	Rating	Field Rating
A. Intensity	A1. Maximum Possible Rock Weight	The estimated weight of the largest possible unstable block.	< 20 kg	1	
			21 to 200 kg	5	
			201 to 600 kg	10	
			> 601 kg	16	
	A2. Slope Height	Slope height in metres.	0 to 48 m	1	
			49 to 80 m	4	
			> 81 m	6	
	A3. Slope Shape	Unbenched footwall slope (< 25° slope angle).	Unbenched Footwall	1	
		Benched slope with good design conformance.	Well formed benches	1	
		Benched slope with moderate design conformance.	Moderately formed benches	4	
		Benched slope with poor design conformance.	Poorly formed benches	6	
	A4. Slope Angle	Inter-ramp angle (measured from toe to toe in degrees).	0° to 35°	1	
			36° to 45°	3	
			46° to 60°	6	
B. Likelihood	B1. Slope Design Conformance	Good design conformance. Crest loss is minimal with up to 15% berm width reduction. Toe flare is minimal. No launch features present.	Good design conformance	1	
		Moderate design conformance. Crest loss is moderate with between 15-50% berm width reduction. Toe flare may be present. Minor launch features are observed.	Moderate design conformance	8	
		Poor design conformance. Crest loss high with >50% reduction in berm width. Toe flare may be present. Significant launch features observed.	Poor design conformance	14	
	B2. Rill Accumulation on Berms	Estimated percentage of rill accumulation on slope berms.	0% accumulation	0	
			50% accumulaton	3	
			100% accumulation	9	
	B3. Loose Material at Crest (e.g. blasted stocks or fill).	Loose material present at the pit crest. This may include blasted stocks, emplaced fill etc.	No material present	0	
			Material present	4	
	B4. Hang-ups on Pit and/or Bench Crests	Observed discrete loose, unstable blocks located on the pit/ bench crests.	None observed	0	
			Several blocks observed	3	
			Numerous blocks observed	5	
	B5. Batter Condition	Good condition. Wall scaled. The rockmass condition is tight, with little dilation and low level of loose blocks observed on the batter face. Pre-split barrels are visible for full height of batters.	Clean batter	1	
		Moderate condition. The rockmass is dilated between 5-10 mm. A moderate level of loose blocks are observed on the batter faces. Structural orientations potentially result in unstable blocks.	Some unstable blocks observed on batter	4	
		Poor condition. The rockmass is dilated >10 mm. A high level of loose blocks are observed on the batter face. Structural orientations result in unstable blocks.	Numerous unstable blocks observed on batter	8	

Figure 9 Field observations section of the qualitative screening tool template

3.4.2 Section 2: factor hazard rating

The QRHST utilises an intensity–likelihood hazard rating system, as is widely used in other rockfall hazard assessment methods. Section 1 of the QRHST assigns a numerical rating for each individual factor influencing the rockfall hazard. The individual ratings are then summed separately for intensity and likelihood in Section 2 of the tool template, and compared to a numerical hazard rating scale (Figure 10) that assigns a hazard category of low, medium or high for each.

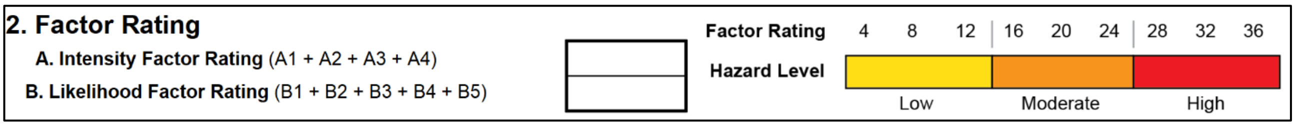

Figure 10 Factor rating section of the qualitative screening tool template

3.4.3 Section 3: hazard matrix and actions

The assessed hazard levels for intensity are plotted on the Y-axis and likelihood plotted on the X-axis of the hazard matrix, Figure 11, to determine the overall slope hazard level due to rockfall. The slope hazard level, whether low, moderate or high, correlates to specific actions to be taken should access be required at the base of the slope.

Low hazard slopes do not require any further investigation unless work is to be undertaken on foot at the base of the slope. Common site safety procedures, such as take 5s and job safety analyses are likely appropriate prior to entry. The moderate category represents rockfall hazards of possible high intensity, low likelihood to low intensity, and high likelihood. In these cases, and with the elevated rockfall hazard, a qualitative risk assessment is required prior to work being undertaken at the base of the slope. In these risk assessments, the ratings from the QRHST will assist with hazard definition. Lastly, for high hazard slopes, a detailed quantitative risk assessment is required prior to accessing and undertaking work at the base of the slope, as these cases represent a much higher or even unacceptable risk to operations.

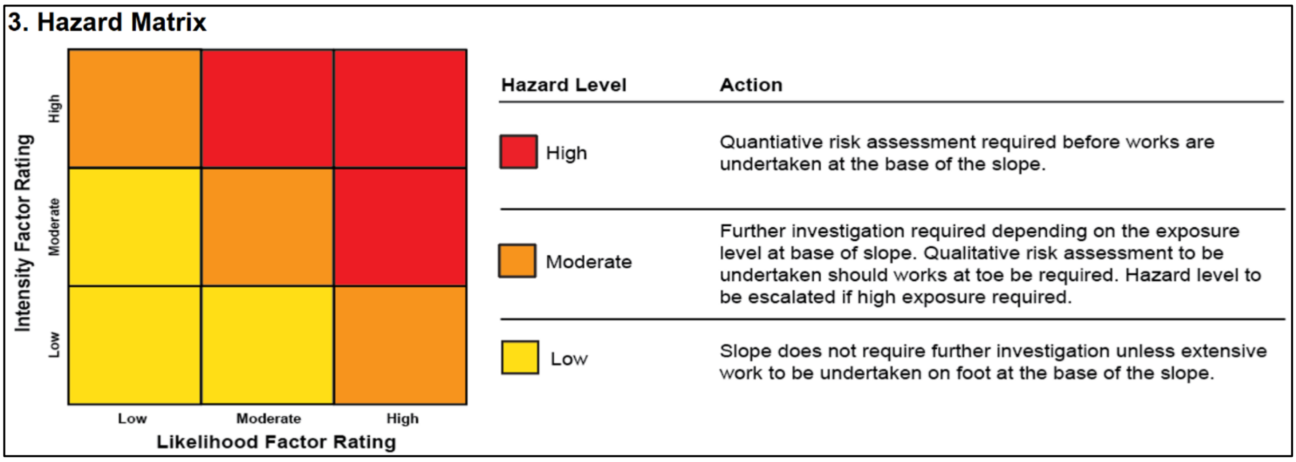

Figure 11 Hazard matrix section of the qualitative screening tool template

3.5 Applications for the QRHST

Applications for the QRHST include routine slope geotechnical hazard assessments in active working areas, providing semi-qualitative hazard information for risk assessments and generating rockfall hazard maps for communication to site staff.

While it is more appropriate for site geotechnical staff to undertake the assessments, the QRHST framework and prompts would assist experienced site staff, such as supervisors, to undertake rockfall hazard assessments.

4 Discussion

The QRHST has been developed utilising data and analyses that are readily collected and undertaken on mine sites. To ensure that the tool captures site-specific conditions, calibration of rockfall modelling parameters is essential. It is relatively rare that a site rockfall register has sufficient information from which rockfall modelling parameters can be calibrated. Rockfall field trials, though uncommon in the current mining industry, provide a good way of acquiring an empirical dataset from which this calibration can be undertaken.

Utilising site-specific rockfall modelling parameters ensures that the results and ratings that form the basis of the QRHST capture site conditions and hazards appropriately.

The QRHST is intended as a guide to assist inexperienced staff make important judgement calls about rockfall hazard in the field but cannot account for all possible occurrences of rockfall and influencing factors. It should be noted that it is possible for rockfall events to occur that exceed the assumptions in the tool as many of the factors and ratings are assessed considering probabilities.

It is important to understand that the QRHST assesses hazard rather than risk. The tool is developed as an initial rockfall hazard identification and classification tool. The intent is that risk assessments will be undertaken as required for moderate to high hazard level slopes identified by the QRHST. These risk assessments would consider factors relating to the proposed task to be undertaken below the rockfall hazard, including temporal factors (exposure time) and vulnerability. These factors have not been incorporated into the QRHST.

Two other notable factors are not considered by the qualitative screening tool. The first is fragmentation, which can lead to elevated rockfall trajectories. Review of published literature indicates that both the occurrence and possible outcomes of fragmentation are difficult to predict (Giacomini et al. 2009; Guccione 2020; Gili et al. 2022). As such, this phenomenon cannot be captured effectively by the QRHST and remains as a residual risk. The second factor is transient factors that may trigger rockfall events, such as rainfall, blasting, seismicity and machinery. These factors are often controlled by other existing site procedures, such as rainfall trigger action response plans, blast exclusions, and exclusion zones proximal to – and under – working machinery. These factors could be incorporated into the QRHST if required.

5 Conclusion

This paper presents a QRHST for benched slopes in open pit mines. The tool provides a quick, relatively easy to complete and repeatable framework to assist site staff in making important judgement calls regarding rockfall hazard. The parameter ratings were calibrated with extensive rockfall sensitivity analyses using site-specific modelling parameters from field trials. While the tool has been developed for a specific site, the logic and framework could be readily recalibrated to other sites.

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