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Natural slope hazard management and integration with mining operations

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Abstract

Exploration, resource definition, and active mining operations can be located in terrains that contain geohazards such as rockfalls or landslides from natural slopes. To mitigate risks associated with working within these environments, controls such as hazard rating sheets have been developed for use by field personnel that enable escalation of assessment and implementation of mitigation measures as may be required to manage the risk. Where these risks are present in active mining operations, assessment of the natural geohazards must be integrated with ground control management tools such as ground awareness training, trigger action response plans, and geotechnical hazard plans. This paper provides an example of a site-specific framework for natural slope hazard management in the Pilbara and how GIS-based susceptibility mapping and rockfall hazard rating field assessment sheets are integrated into the operations ground control management system.

Keywords: *natural slopes, landslides, rockfall hazard rating system, risk management*

1 Introduction

Mining and exploration activities are commonly located in environments where natural slope hazards exist in addition to typical pit slope and waste rock dump hazards. To effectively manage the risk, additional mitigating controls are required along with associated training and communication systems.

The Fortescue Metals Group (Fortescue) Solomon Hub is located in the Hamersley Range which is 60 km north of Tom Price in Western Australia. Operations have multiple operational, resource definition and exploration fronts that interact with natural slope environments. A large portion of the work areas at Solomon occur directly below an escarpment or within the accumulation zone of previous rockfalls (Figure 1). While the mining operational workforce are typically well-educated in pit slope ground awareness along with measures such as geotechnical hazard plans and mandated standard pit slope standoffs, awareness of natural slope systems is typically not part of previous requirements. Further, resource definition and exploration personnel typically work remote to mining operations and may not be captured by the ground awareness training program.

In response to recognition of this situation, Fortescue has developed a series of tools and procedures to manage exploration and mining activities exposed to natural slope hazards at Solomon. This paper outlines the overall rockfall hazard system including the purpose, main components, and steps for assessing the rockfall hazard. The main focus of this paper is on development of the natural slope assessment tool as a key part of the hazard management system including a summary of existing qualitative rockfall hazard rating systems, the approach used to design the Fortescue system, physical parameter classification, and rating of rockfall hazard. Some examples are presented showing application of the system and illustrating how the tools integrate with mine operations.

Figure 1 Natural escarpment, talus, and colluvial-alluvial slopes above an active mining area and historic exploration drill pads at the Solomon Hub

2 Fortescue natural slope hazard management

2.1 Background

At the corporate level, Fortescue has a generic list of 'contributing causes' to natural slope failure along with associated 'required controls' as shown in Table 1. This list provided the starting point for planning a work program to formulate a natural slope hazard management system and helped define the required system deliverables.

The program required development of the following key deliverables:

- Development of a GIS-based natural slope landslide susceptibility mapping system.
- Development of natural slope field assessment sheets.
- Development of a Bowtie and trigger action response plan (TARP).
- Development of natural slope orientated training packages.
- Integration of each of these tools with existing ground control management systems.

Table 1 Fortescue corporate list of causes and controls for natural slope failure

Contributing cause	Required controls
Geometrical changes	Controls for earthworks
Hydrogeological conditions	Controls for drawdown; seepage
Hydrology conditions	Controls for prolonged heavy rainfall
Natural processes	Controls for ongoing assessment – weathering, earthquake, freeze thaw
Erosion	Controls for surface water; services

The program focuses on rockfall hazards which are assessed as being the dominant natural slope landslide type at Solomon which threaten exploration and mining activities.

2.2 Steps for assessing rockfall hazard

A chart illustrating the workflow and decision points for assessing rockfall hazard from natural slopes at Solomon is presented in Figure 2.

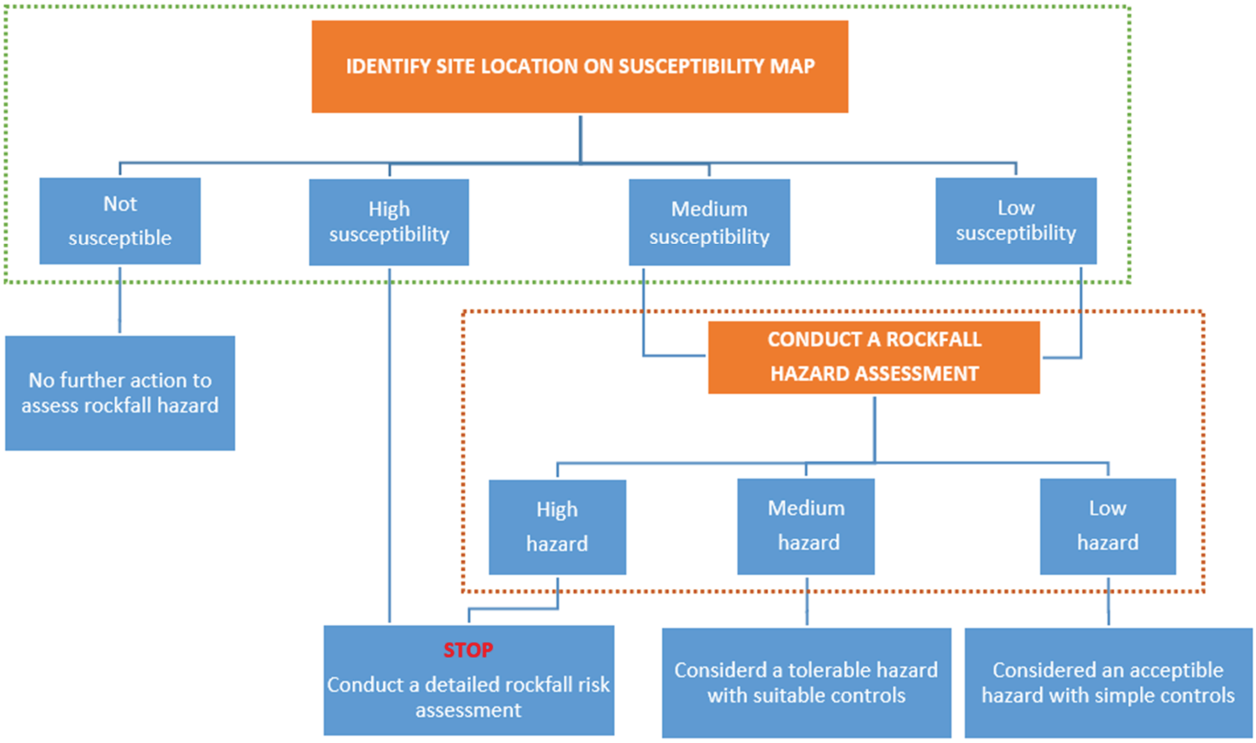


Figure 2 Flowchart for assessing rockfall hazard in natural slopes at Solomon

The system is designed to start at a high level and work towards the detail, where required. The steps are:

1. Determine the location of exploration activities on landslide susceptibility maps. These maps indicate the exposure of the location to a rockfall.
2. From the susceptibility maps, identify the exposure susceptibility for the activities.
3. If high susceptibility is indicated from the susceptibility map, conduct a detailed rockfall risk assessment, which should preferably be a quantitative assessment.
4. If medium or low susceptibility is indicated from the susceptibility map, conduct a rockfall hazard assessment for your site using the natural slope assessment tool.
5. If the rockfall hazard assessment returns a:
   a. Low hazard – this is considered to be an acceptable hazard with implementation of simple control measures.
   b. Medium hazard – this is considered to be a tolerable hazard with the implementation of suitable control measures.
   c. High hazard – this is considered to be an unacceptable hazard. The site requires a detailed rockfall risk assessment to better understand the risk prior to accessing the area for exploration activities. A detailed review of the risks should be undertaken by a person experienced and trained in quantitative landslide risk assessments. A detailed rockfall risk assessment involves mapping of the source rock mass and rockfall runout zone, often using drone images or photogrammetry in difficult to access areas. Numerical models are undertaken using site derived coefficients to evaluate exposure. Controls such as windrows, berms, or adjustment to mine designs can be assessed to ensure the risk to personnel and equipment are mitigated.

6. If 'not susceptible' is indicated from the susceptibility map, no further action is required to assess the rockfall hazard.
7. During exploration activities, follow the TARP guidelines for rockfall hazards for all susceptibility levels.

The two key components of the natural slope hazard management system are:

- The landslide susceptibility maps which are used to identify the exposure susceptibility for each worksite. This part of the workflow is outlined by the dashed green box in Figure 2.
- The natural slope assessment tool, which for Solomon is a rockfall hazard rating system and associated field assessment sheets. This part of the workflow is outlined by the dashed orange box in Figure 2.

The focus of this paper is on development of the rockfall hazard rating system. A mix of knowledge-based techniques were used to formulate GIS landslide susceptibility maps for Solomon. This included terrain mapping of geology and geomorphology, and linking this to an inventory/empirical approach to assess distribution of past and present landslides to predict future spatial occurrence of landslides. This methodology will be presented in a future publication.

2.3 Purpose of the natural slope assessment tool

Development of the rockfall hazard rating system placed particular emphasis on the following factors in the design of this tool.

- Be a rapid, high-level and simple exercise that can be undertaken in the field by exploration personnel who may not necessarily have the training or experience in landslide identification or risk management although it is expected that users of the system will have a general understanding of slope processes.
- Be qualitative in nature but still provide reliable outcomes.
- Identify high risk slopes that require a detailed assessment by people with the necessary background, experience, and training in slope hazards.
- Have a framework that can be potentially adopted for other Pilbara regions and/or other countries where Fortescue undertake exploration activities.

3 Existing qualitative rockfall rating systems

3.1 Previous systems

Qualitative rockfall hazard rating systems started to gained prevalence from the mid to late 1980s but particularly during the 1990s. Fundamentally there are two main approaches:

1. US based system – 'rockfall hazard rating system' (RHRS)
   a. First developed in the late 1980s for the Oregon Department of Transportation as first published by Pierson et al. (1990).
   b. Based on a Canadian railways system originally devised by Brawner & Wyllie (1976).
   c. Many US states have modified the RHRS to suit the geological, morphoclimatic and road conditions in their territory.
2. European based systems
   a. European countries often adopt the Swiss system published in 1997 by Lateltin (1997) and discussed in Raetzo et al. (2002).

b. There are other systems around Europe. In Italy, they have developed their own modification of the RHRS, referred to as mRHRS (Budetta 2004).

These RHRSs are briefly introduced to provide a flavour of what systems are available 'off the shelf'. The purpose is to illustrate there are no existing systems that fully met the needs of Fortescue and to show how ideas from existing systems were used to design the Fortescue RHRS.

3.2 US derived rockfall hazard rating system

3.2.1 Preliminary phase

Pierson et al. (1990) describe the RHRS as a two-phase process divided into a preliminary rating phase and a detailed rating phase. The preliminary rating groups sections of roads into three broad categories (Figure 3). The purpose of the preliminary rating is to identify those sections of road that require more detailed assessment.

The rating is a subjective assessment of the rockfall potential based on judgement by 'experienced and insightful' personnel. Data on historical rockfall activity is used as a supplement to the rockfall potential where clarification is required in the subjective assessment.

CRITERIA \ CLASS	A	B	C
ESTIMATED POTENTIAL FOR ROCK ON ROADWAY	HIGH	MODERATE	LOW
HISTORICAL ROCKFALL ACTIVITY	HIGH	MODERATE	LOW

Figure 3 Rockfall hazard rating system preliminary rating system (Pierson et al. 1990)

The rating classes in the preliminary RHRS are described by Pierson et al. (1990) as follows:

- Class A – moderate to high risk (in this context it is considered this is a classification of hazard not risk):
  - Source of rockfall is obvious, 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 allows.
- 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.

The 'estimated potential for rockfall on the roadway' considers the following factors after Pierson et al. (2005):

1. Estimated size of material (average and maximum block size of the rock that could be mobilised).
2. Estimated volume of material, in total and per event.
3. Amount of material available, as a qualitative descriptor (limited to plentiful).
4. Roadside ditch effectiveness, as a qualitative descriptor (poor to very good).

These four factors are recorded during a visual inspection of the slope.

The preliminary RHRS phase is similar to the approach to be adopted by the Fortescue system whereby it is a rapid field tool which filters the sites that require further, more detailed assessment.

3.2.2 Detailed phase

The detailed RHRS is based on the individual rating of around nine different parameters that are scored exponentially from 3 to 81, intended to represent a continuum from 1 to 100. The category scores are summed with the final score ranging between 9 and 900. Pierson et al. (1990) do not provide a classification of hazard based on the final score, but other literature such as Andrianopoulos et al. (2013) suggest a total score of less than 300 are low priority slopes and total scores greater than 500 require urgent action.

Parameters adopted in the RHRS based systems are listed in Table 2. Despite being labelled as a hazard rating system, these parameters are a mix of hazard and consequence. As such, this system estimates the degree of risk to vehicles on the road. That is to say that it is not an assessment of just the rockfall hazard.

Table 2 Detailed rockfall hazard rating system parameters

Hazard parameters	Consequence parameters
Slope height	Ditch effectiveness
Geologic characteristics	Roadway width
Block size	Average vehicle risk (probability of vehicle being in the hazard zone)
Climate and presence of water on the slope	Controls for ongoing assessment – weathering, earthquake, freeze thaw
Rockfall history	Percentage of decision sight distance

3.3 Swiss system

Swiss guidelines assess rockfall hazard according to onset probability/return period (failure likelihood) and intensity represented by the kinetic energy of the falling blocks (failure magnitude). They define three hazard ratings as shown in Figure 4.

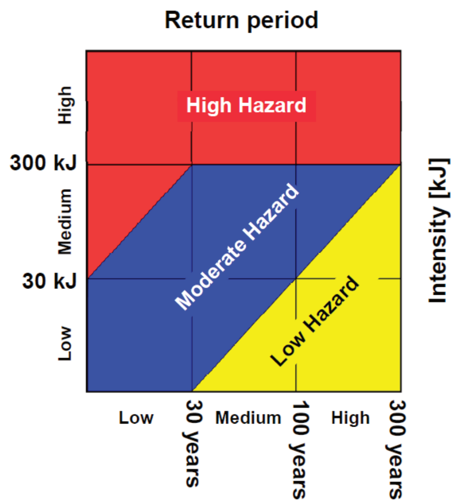


Figure 4 Swiss intensity-return period diagram defining hazard classification (Lateltin 1997)

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 used for recurring processes such as floods and earthquakes, for landslides, it is used in a relative context. The only reference they make to estimating probability is by 'considering traces or evidence of former events'. This is assumed to mean probability is estimated based on observed evidence of past rockfall.

3.4 Applicability to Fortescue requirements

Overall, the US derived RHRS is a relatively comprehensive qualitative system. However, the full preliminary-to-detailed approach does not directly satisfy the 'short and simple' objectives required for the Fortescue system. This is further complicated by the mixing of hazard and consequence parameters in the detailed phase and the focus on roads as the main element at risk. Similarly, the Swiss system does not incorporate important elements of the natural slopes at Solomon to help characterise the rockfall hazard.

Notwithstanding these limitations, some of the concepts and their derivatives from the RHRS and Swiss system have been used to develop the Fortescue natural slope assessment tool.

4 Development of Fortescue natural slope assessment tool

4.1 Background and approach to tool design

A sketch of the rockfall problem to be addressed by the Fortescue natural slope assessment tool is shown in Figure 5.

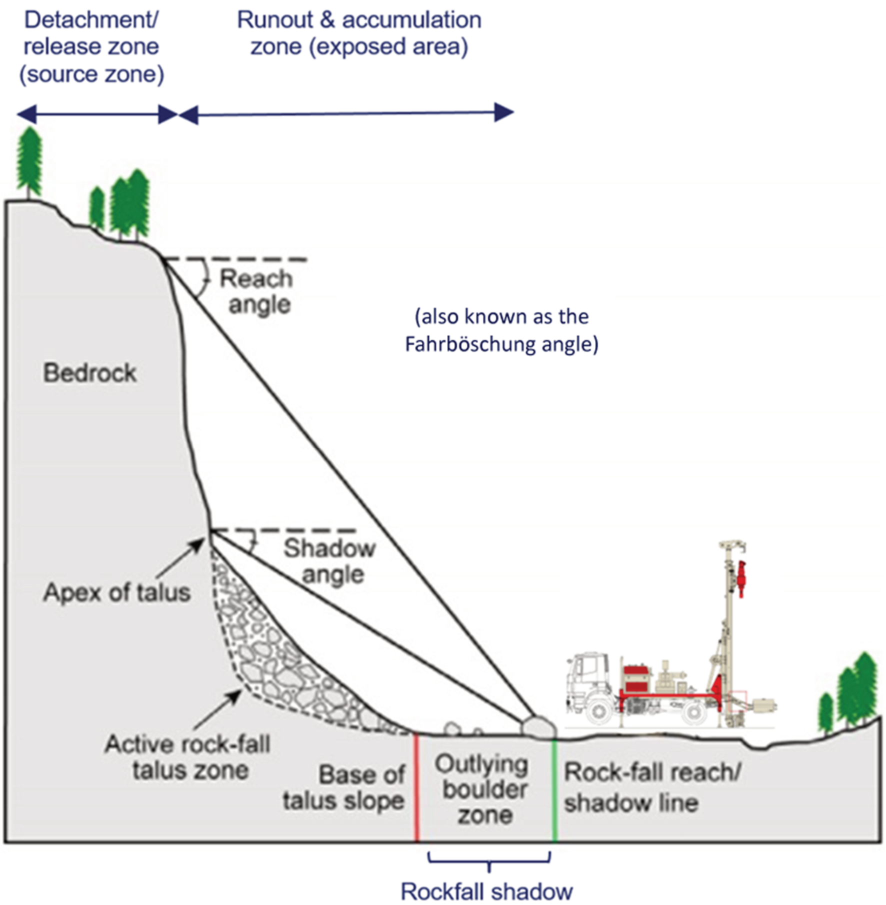


Figure 5 Schematic section of a typical slope at Solomon showing rockfall slope morphology and associated terms

The rockfall hazard that the slope represents to the drill pad can be expressed as:

Rockfall hazard = probability of rock detachment × probability of reach × intensity of rockfall

where:

probability of rock detachment = probability of spatial occurrence × probability of temporal occurrence.

These terms are explained as follows:

1. Likelihood
   a. Probability of rockfall detachment (product of two parameters)
      i. Probability of spatial occurrence controlled by the presence of potential sources zones in the slope.
      ii. Probability of temporal occurrence is a measure of approximately how long until the next detachment from the source zone occurs.
   b. Probability of reach is the trajectory and maximum runout of the falling rocks.
2. Intensity
   a. Magnitude of failure or the kinetic energy of the rockfall.

Observations that can be made in the field to infer these parameters are summarised as follows.

- Detachment source zones (spatial occurrence)
  - Do any blocks or areas of the rock mass on the slope look like they could detach or release?
  - Look for evidence of zones with a general loosened appearance, presence of dilated defects and fractures etc.
- Temporal source zone occurrence
  - Is there evidence of rockfall product/debris at the base of the slope?
  - Does the appearance of the rockfall blocks give an indication of the approximate age of movement (presence of fresh, slightly weathered/oxidised, or highly weathered surfaces on the displaced blocks, etc.), that is to say, is it recent or old?
- Reach exposed zone (runout or transit of rockfall blocks)
  - Where is the toe of the talus slope?
  - Where is the outside edge of the outlying boulder zone (rockfall shadow) marking the limit of the runout and accumulation zone?
- Intensity of rockfall
  - What is the size of the overall loosened/dilated zone in the slope?
  - What is the size of blocks in the loosened/dilated zone?
  - What is the size of displaced blocks in the runout and accumulation zone?

4.2 Parameter classification

The rockfall hazard equation and qualitative field observations of key physical parameters form the basis for the proposed Fortescue natural slope assessment system.

Classifications have been developed for the following parameters which can be assessed by simple observations of the slope in the field:

- Spatial occurrence probability (Table 3).
- Temporal occurrence probability (Table 4).
- Reach probability (Table 5).
- Intensity (Figure 6).

4.2.1 Likelihood

The field observations listed in Tables 3 to 5 are specific to the physical setting of the Pilbara landforms. Ratings for the first three parameters are based on an exponential scale, as per the RHRS, to accentuate the difference in the final score.

Table 3 Spatial occurrence probability ratings

Classification	Description of field observations		Rating
	Rock mass condition in source zone	**Detachment block development in source zone**	
Tight	Tightly interlocked, undisturbed rock mass with closed defects	No visible development of blocks that could detach	1
Partially loosened	Poorly interlocked, partially disturbed rock mass with defects/fractures open in the general range <10 mm with little or no dislocation of individual blocks	Some development of blocks which may conceivably detach	3
Loosened	Disconnected, disturbed rock mass with defects/fractures generally open >10 mm with in situ dislocation of individual blocks	Blocks clearly visible that could possibly or probably detach	9

Table 4 Temporal occurrence probability ratings

Classification	Description of field observations			Rating
	Rockfall scars in detachment source zone	**Evidence of past rockfall product in accumulation zone/exposed area**	**Condition of rockfall product in accumulation zone/exposed area**	
No apparent activity	No visible scars	No rockfall product is visible	No rockfall product	1
Past activity	Visible scars are degraded in appearance	Some accumulation of rockfall product at base of detachment zone	Surfaces of rockfall fragments are distinctly weathered	3
Recent activity	Visible scars are fresh in appearance	Significant accumulation of rockfall product at base of detachment zone	Surfaces of rockfall fragments are fresh or slightly weathered	9

Table 5 Reach probability ratings

Classification	Description of field observations		Rating
	If rockfall shadow is discernible	If rockfall shadow not obvious, use site angle (1)	
Beyond rockfall shadow	Substrate surface with outside rockfall shadow with no observable rockfall boulders	<25° minimum shadow angle	1
Rockfall shadow	Substrate surface covered discontinuously by scattered rock boulders that have rolled or bounced beyond the base of the talus zone	>25° minimum shadow angle	3
Talus zone	Cone or fan shaped accumulation of rock fragments below the detachment source slope	>35° minimum talus slope angle	9

(1) Angle from closest edge of worksite to apex of talus slope.

When assessing the reach probability, the idea is to recognise the following limits in the field:

- Edge of the talus slope from the shape of the terrain/ground surface.
- Edge of the rockfall shadow by identifying the farthest outlying block.

Where the rockfall shadow is not obvious in the field from the presence of an outlying boulder zone, the minimum shadow angle concept can be used. This is taken as 25° based on work by Evans & Hungr (1993).

The total score from the spatial and temporal occurrence and reach probability contribute to the rockfall likelihood assessment. The likelihood classification is presented in Table 6.

Table 6 Rockfall likelihood classification

Total score	Rockfall likelihood classification
3–7	Low
9–15	Medium
19–27	High

4.2.2 Intensity

The last of the four parameters in the rockfall hazard equation relates to rockfall intensity. For Solomon, this is based on the relationship between block size and slope height to infer the approximate kinetic energy of the falling block. Figure 6 presents the proposed rockfall intensity chart. Boundaries between intensity classes are based on the following criteria (Ferrari et al. 2017):

- Lower bound of the 'low intensity' is approximately equivalent to the impact resistance of a hard hat at 50 J, in accordance with Australia and New Zealand safety standards.
- Boundary between low and medium intensity is based on a kinetic energy limit of 11.6 kJ, which is the maximum resistance for 'falling object protective structures' of machinery.
- Boundary between medium and high intensity is set at 300 kJ, which corresponds to the impact energy that can be resisted by a reinforced concrete wall (Raetzo et al. 2002).

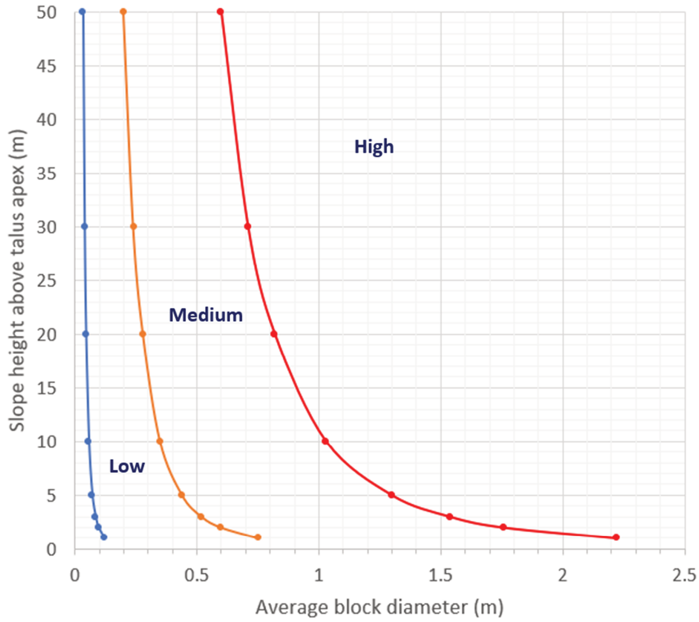


Figure 6 Rockfall intensity based on kinetic energy as controlled by block size and slope height

The intensity classification represents the energy of the falling block once it reaches the base of the source slope, or in other words, at the location of first impact on the talus slope. The kinetic energy of the falling block begins to dissipate on first impact. The travel distance from the first impact is then somewhat controlled by the rolling resistance on the talus slope, as estimated by the shadow angle which is equivalent to the energy line from the talus apex. As such, the intensity classification is a conservative estimate of the event magnitude, depending on the location of the exploration worksite on the slope.

4.3 Rating of rockfall hazard

The final rating of the rockfall hazard is based on the onset probability versus intensity matrix approach adopted by the Swiss. The recommended hazard rating system is shown as part of Figure 7, which includes the hazard matrix, likelihood classification and intensity chart.

The RHRS has been compiled into a field assessment sheet as presented in Figure 7. This provides descriptions of the rockfall likelihood field observations to assess spatial occurrence, temporal occurrence, and reach probability with fields for totalling the likelihood score and assessing the rockfall intensity. The final rockfall hazard ranking is then assessed from the hazard matrix using assessed likelihood and intensity decisions.

ROCKFALL HAZARD RATING SYSTEM

Fortescue The New Force in Iron Ore

Project: ____________ Location: ____________ Assessor: ____________ Date: ____________

Susc. Map Rating: ____________ Slope Stratigraphy: ____________

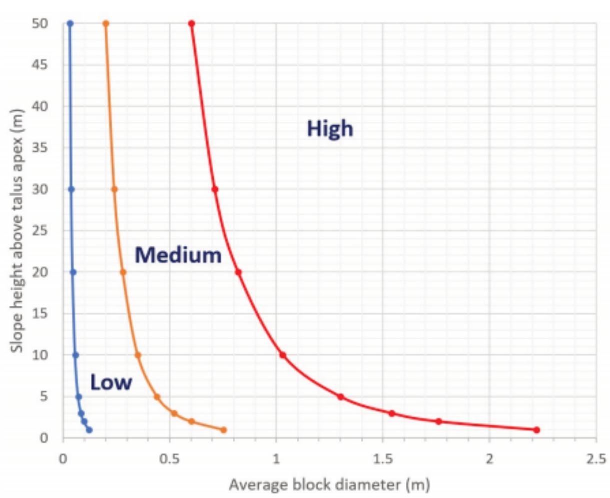
Parameter	Class	1. Rockfall Likelihood - Description of Field Observations			Rating
a. Spatial Occurrence - Block Detachment Potential		**Rock Mass Condition**	**Detachment Block Development**		
	Tight	Tightly interlocked, undisturbed rock mass with closed defects	No visible development of blocks that could detach		1
	Partially loosened	Poorly interlocked, partially disturbed rock mass with defects/fractures open in the general range < 10 mm with little or no dislocation of individual blocks	Some development of blocks which may conceivably detach		3
	Loosened	Disconnected, disturbed rock mass with defects/fractures generally open > 10 mm with in-situ dislocation of individual blocks	Blocks clearly visible that could possibly or probably detach		9
b. Temporal Occurrence - time to next detachment		**Rockfall Scars**	**Rockfall Product in Accum. Zone**	**Cond. of Rockfall Prod.**	
	No activity	No visible scars	No rockfall product is visible	No rockfall product	1
	Past Activity	Visible scars are degraded in appearance	Some accumulation of rockfall product at base of detachment zone	Rockfall fragment surfaces distinctly weathered	3
	Recent Activity	Visible scars are fresh in appearance	Significant accumulation of rockfall product at base of detachment zone	Rockfall fragment surfaces fresh or slightly weathered	9
c. Reach - trajectory and maximum runout of falling rocks		**Rockfall Shadow Discernible**	**Site Shadow Angle**		
	Beyond Rockfall Shadow	Substrate surface outside rockfall shadow with no observable rockfall boulders	< 25° minimum shadow angle		1
	Rockfall Shadow	Substrate covered discontinuously by scattered boulders that have rolled or bounced beyond base of talus zone	> 25° minimum shadow angle		3
	Talus Zone	Cone or fan shaped accumulation of rock fragments below the detachment source slope	> 35° minimum talus slope angle		9

a. Spatial Occurrence Rating	b. Temporal Occurrence Rating	c. Reach Rating	Likelihood Score

1. Rockfall Likelihood

Score:	3	5	7	9	11	13	15	19	21	27
Class:	low			medium				high		

2. Rockfall Intensity



3. Rockfall Hazard Matrix

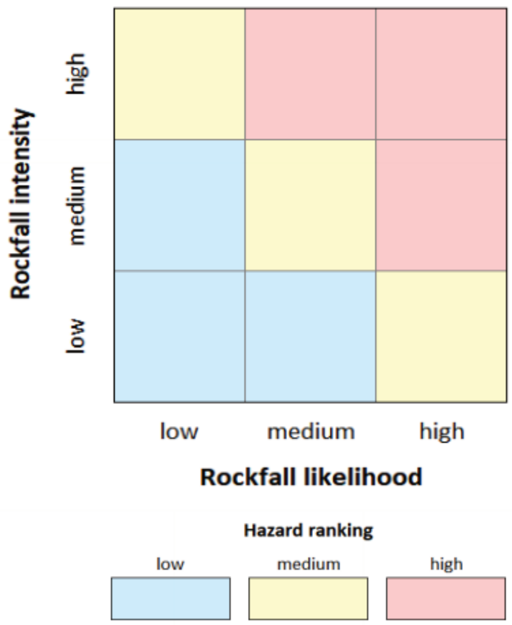


Figure 7 Fortescue rockfall hazard rating system field sheet

5 Implementation of Fortescue natural slope assessment tool

5.1 Example 1

Construction of an access ramp below a 25 m high escarpment and 50 m high talus slope is required to access future exploration and mining areas. Due to the steep nature of the terrain, it was not possible to avoid exposure to rockfall hazards during construction and operation.

Referring to the landslide susceptibility map, the planned construction falls within a medium and high susceptibility zone (Figure 8). The natural slope assessment tool was used to further define the area during early exploration and initial construction. The result indicated an overall high hazard category which is assessed as unacceptable without further controls. A full geotechnical assessment was carried out with rock mass mapping, rockfall reach, and back-analysis.

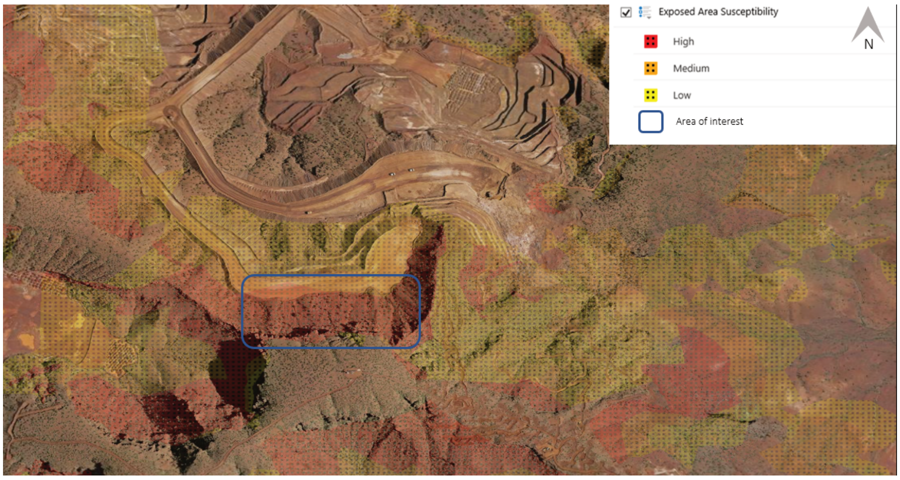


Figure 8 Landslide susceptibility map for Example 1 study area

Toppling has been assessed as the dominant failure mechanism generating rockfall detachment from the escarpment as controlled by a widely spaced, vertically jointed rock mass. This produces large rockfall blocks that have historically remained intact near the source at diameters greater than 1 m in size in the boulder zone (Figure 9).

Construction of a windrow on the exposure side is the primary control. Operation of the ramp occurs under the mining geotechnical TARP, which closely aligns with the Solomon mining area natural slope hazard: rockfall TARP.

Figure 9 Ramp under construction in the exposed zone below the escarpment slopes in the Example 1 study area

5.2 Example 2

Construction of resource definition road and drill pads was required below a 19 m high escarpment and talus zone ranging in height between 10 and 80 m (Figure 10). The area of interest falls just outside of the talus zone and within the outlying boulder zone. Modification of the slope is required as part of the access and drill pad construction which was considered as part of the assessment.

The expected failure mechanisms are a combination of toppling blocks and undercutting of the hard cap layer by weathering. Toppling blocks appeared to travel further downslope and posed the greatest risk to the work area.

The landslide susceptibility map placed the area of interest within the medium to high zone (Figure 11). On completion of the RHRS, the area was ranked as a high hazard.

A detailed rockfall assessment was undertaken prior to and during development of the area. Controls included construction of windrows, relocation of drill pads, and removing planned areas completely if no suitable controls could be found.

Figure 10 Access road and drill pads in the exposed zone in the Example 2 study area

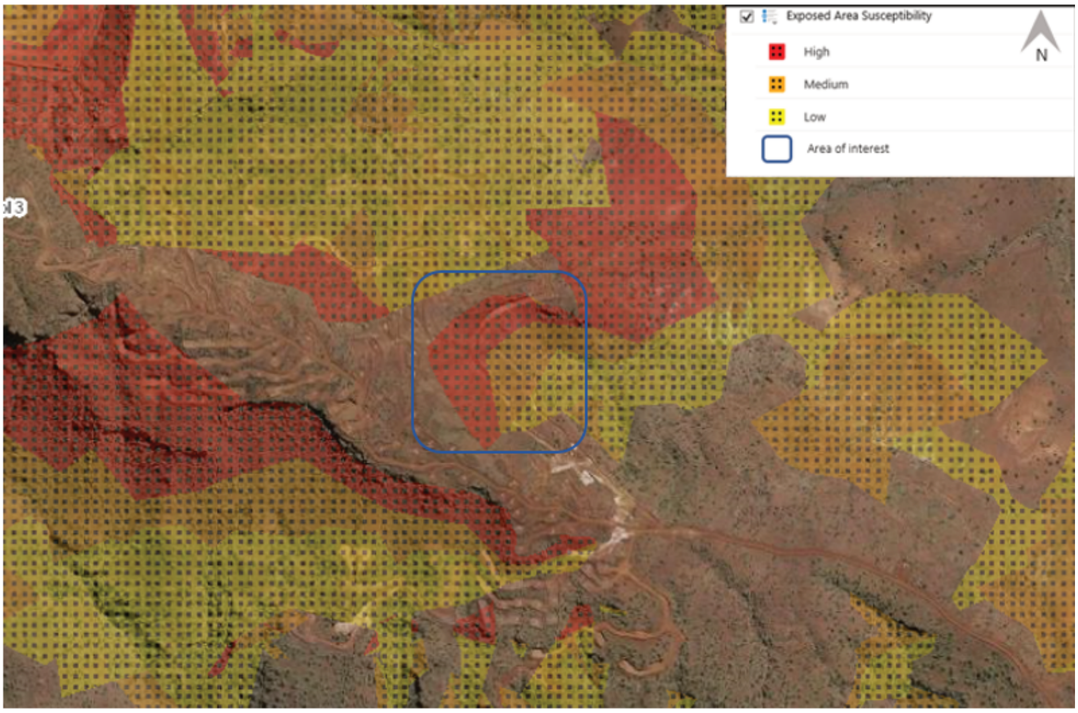


Figure 11 Landslide susceptibility map for Example 2 study area

5.3 Summary of Fortescue rockfall hazard rating system results for Examples 1 and 2

Ratings for the each of the rockfall parameters assessed for the two examples presented are provided in Table 7.

Table 7 Results of Fortescue rockfall hazard rating system for Examples 1 and 2

Example	Spatial occurrence	Temporal occurrence	Reach, max runout	Likelihood classification	Rockfall intensity	Rockfall hazard ranking
1	Loosened (9)	Recent activity (9)	Talus zone (9)	High (27)	High	High
2	Partially loosened (3)	Past activity (3)	Rockfall shadow (3)	Medium (9)	High	High

In summary the results show:

- Example 1
  - Likelihood classified as being 'high' based on a loosened rock mass in the detachment zone which shows recent rockfall activity with the site located in the talus zone in the exposed portion of the slope system.
  - Rockfall intensity ranked as being 'high' based on the height of the slope (25 m) and average block size diameter greater than 1 m.
  - Overall rockfall hazard ranked as being 'high'.
  - Rock mass mapping was carried out to characterise intact and failed block sizes and estimate coefficients for more detailed numerical rockfall modelling. This was used to ensure rockfall protection windrows were sized correctly to mitigate the risk.
- Example 2
  - Likelihood classified as being 'medium' based on partially loosened rock mass in the detachment zone which shows evidence of past rockfall activity with the site located in the rockfall shadow part of the exposed zone.
  - Rockfall intensity also ranked as 'high' based on the height of the slope (19 m) and average block size diameter greater than 1 m.
  - Overall rockfall hazard ranked as being 'high'.
  - Following the assessment of possible control measures, none were deemed adequate to mitigate the risk and hence drilling activities in this area were not progressed.

6 Conclusions

A bespoke RHRS has been developed for evaluation of natural slope hazards in Fortescue's Solomon mining area that interact with mining and exploration activities. The system is based on different levels of assessment; the first and broadest measure comprising landslide susceptibility maps, which indicate whether further evaluation is required.

For areas assigned as highly susceptible, a detailed quantitative risk assessment is to be carried out, while no further action is required for slopes assessed not to be susceptible to rockfall. For low or medium susceptible areas, a rockfall hazard assessment is to be undertaken using the natural slope assessment tool. The tool is based on concepts and their derivatives of the existing American and Swiss qualitative systems but modified to satisfy the 'short and simple' objective. It estimates the rockfall hazard using the product of probability of rock detachment and probability of reach (collectively this is defined as the likelihood) and rockfall intensity.

Simple slope observations that can be made in the field are presented as a series of classifications with qualitative descriptions to infer the rockfall likelihood (i.e. relating to spatial occurrence probability, temporal occurrence probability and reach probability) and the rockfall intensity. The final rating of rockfall hazard is assessed from the hazard matrix using the assessed likelihood and intensity decisions.

Areas returning a high hazard require a detailed rockfall risk assessment. This involves running numerical rockfall models to simulate and test rockfall protection to mitigate the risk to personnel and equipment. Areas that return a medium or low hazard are considered tolerable or acceptable with suitable controls put in place. Controls include removing the hazard, relocating the exposure site, engineering controls such as earth bunds, or administrative controls such as signage and training.

Acknowledgement

Permission from Fortescue Metals Group to publish this information is gratefully acknowledged.

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