Fredrica Ferrari, Klaus Thoeni, Anna Giacomini and Cedric Lambert

A new rockfall hazard assessment methodology for open-pit coal mines

Rockfalls represent a serious hazard in open pit-mines, threatening human lives, machinery and portal structures located at the toe of highwalls. This hazard can have significant financial consequences should the production be temporarily stopped for safety issues. Results from the ACARP C19026 rockfall netting project and field observations suggest that a more effective approach to rockfall hazard management is required for safe mining operations.

In this paper, a new qualitative rockfall hazard procedure specifically designed for coal mining environments developed within the current ACARP project C23026 is presented. The methodology intends to be a simple and quick tool for identifying the most dangerous highwall sections. The use of this methodology provides practitioners with a more rigorous guidance on rockfall management strategies, and the industry with the ability to generate hazard zoning maps that can be updated on a regular basis. The methodology uses *in situ* observations (and records of past rockfall events when available) for the definition of three hazard levels (i.e. low, medium and high) defined on the basis of the expected rockfall energy at the base of a highwall and the rockfall frequency, evaluated through the state of activity of the highwall. As a result, the sections with a high level of hazard, which require a further strict quantitative assessment, are quickly identified. The methodology will provide greater confidence in locating personnel, machineries, and structures over the working areas at the toe of highwalls.

Keywords: Rockfalls, hazard, qualitative methodology, surface mining, evolving rockfall hazard assessment.

INTRODUCTION

Rockfalls consist of the detachment of a rock (or a few single rocks) from a vertical or sub-vertical cliff, followed by a rapid motion downward characterised by free falling, bouncing, rolling and sliding phases (Varnes, 1978). Due to the high motion velocities, which render any warning equipment useless, rockfalls are one of the major hazards in open-pit mines. Rockfalls can cause serious injuries to personnel or even fatalities, as well as damage to machinery and structures. Therefore, an appropriate hazard assessment methodology is necessary to efficiently control the rockfall hazard.

A simple and effective way for reducing potential damages caused by rockfalls consists in identifying different hazard levels and the corresponding protection actions or measures to put in place (Cascini, 2008). Qualitative and quantitative methods are used for this purpose. The former describe the hazard by means of ranked attributes or classes; they are usually considered quick and easy to use and are suitable for hazard mapping of large areas. The quantitative methods use numerical probability analyses to define the level of hazard. They require a significant amount of data collection, resulting in quite laborious and time-consuming methodologies, mainly applicable to very restricted areas. It follows that in large coal mine sites, it is advisable to perform first a qualitative assessment for the identification of the most hazardous areas where a second more robust quantitative analysis should then be conducted.

Over the last two decades, several qualitative and quantitative methodologies were proposed in order to assess the rockfall hazard along road-cuts and mountain slopes (Abbruzzese & Labiouse, 2014; Corominas & Mavrouli, 2011; Lambert & others, 2012; Mazzoccola & Sciesa, 2001; Pierson & others, 1990; Rouiller & others, 1998). A few methods were developed for assessing general open-pit mine slope stability, but none of these methods focuses especially on rockfall hazard. They encompass the Slope Stability Assessment (Jhanwar, 2012), the Risk Rating System (Canbulat & others, 2013), and the Mine Slope Instability Index (Naghadehi & others, 2013). The ROFRAQ method (Rockfall Risk Assessment for Quarries) developed by Alejano & others (2008) deals with rockfalls in ornamental quarries and it represents the scientific basis of the more recent QuaRRi method (Peila & others, 2011). In both methods, predisposing factors, instability mechanisms, triggering causes, slope rockfall history, trajectory modelling and expositional factors are taken into account to assess the rockfall hazard and risk. The approach results quite detailed and unsuitable for a quick qualitative hazard assessment, as it requires *in situ* measurements, hydro-meteorological data and numerical modelling of potential block trajectories.

The new Evolving Rockfall Hazard Assessment (ERHA) methodology presented in this study was developed in order to provide the coal mine industry with a quick and rigorous tool able to identify different hazard levels at the bottom of highwalls. The method involves a first assessment for the identification of the most hazardous areas that can evolve towards a second quantitative analysis when deemed necessary. In the first step, hazard zoning maps from simple *in situ* observations can be generated. The qualitative step of the ERHA and the definition of the hazard level are described in the following. Finally, an example of application of the proposed methodology to an Australian highwall section is reported.

ERHA METHODOLOGY

The first qualitative step of the ERHA methodology differentiates levels of hazard as function of the geo-structural and geometrical features of the highwall. The hazard classification is inspired by the Swiss code, being one of the most well-established and most widely accepted natural hazard assessment guideline (Raetzo & others, 2002). The code relies on a matrix diagram (Figure 1) which defines three levels of hazard (i.e. low, medium and high) on the basis of the rockfall probability and intensity. The former is given by the expected rockfall frequency (i.e. probability of occurrence of rockfall events), the latter by the kinetic energy (Lateltin & others, 2005). Both probability and intensity are subdivided into three classes: low, medium and high. In quantitative approaches, the rockfall probability and intensity are generally determined by means of site-specific historical databases and trajectory simulations, respectively. Nevertheless, these methods cannot always cope with rockfall hazard in open-pit mine sites, where accurate databases of past rockfall events are seldom included in the current practice. Therefore, it is herein proposed to adapt the probability (x-axis of the Swiss matrix) and intensity (y-axis) evaluation process to the mine site conditions and to routinely available data.

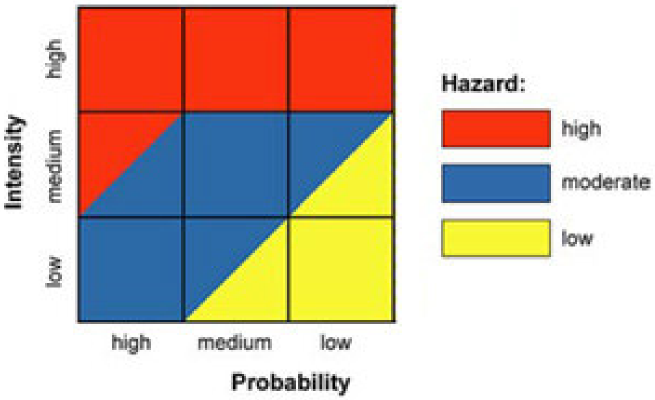


Figure 1: Swiss matrix for defining hazard levels in function of probability and intensity classes (modified after Lateltin & others, 2005).

Evaluation of the rockfall probability (frequency)

In the qualitative assessment, the rockfall frequency is characterised by the state of activity of the highwall and it represents the predisposition of a slope, in this case a highwall, to be affected by rockfall occurrence: the higher the state of activity, the higher the likelihood of rockfall events or the higher the susceptibility of the highwall to rockfall events.

The state of activity of a highwall is obtained by applying a rating approach based on *in situ* observations. It accounts for the rock mass geological structure (i.e. fracturing degree of the rock mass), the potential for instability mechanisms (due to undercutting, block toppling or sliding), the slope performance (deviation from the slope design), as well as signs of recent block detachments. All these parameters can be easily observed and quickly rated as shown in Table 1.

The fracturing degree, evidences of undercutting, block sliding and toppling, as well as the slope performance parameters are rated using a binary classification system. In order to get the final score for each parameter, the rating (0 or 1) is multiplied with the corresponding weight. The weighting system is defined according to the significance of each parameter in the hazard assessment. The sum of the scores ranges from 0 to 11 and defines a preliminary class of state of activity: low (from 0 to 3), medium (4 to 7) or high (8 to 11).

The final class of state of activity is determined by taking into account the presence of obvious signs of activity given by recent block detachments. If no signs of activity are observed, the final state of activity class remains unchanged. Otherwise, the preliminary state of activity class is changed according to Table 2.

Table 1: Parameters and scores for evaluating the state of activity.

Parameter	Description	Rating	Weight	Score
Fracturing degree	Massive rock mass structure	0	3	…
	Blocky or very blocky	1		
Undercutting	Homogenous weathering	0	2	…
	Presence of ledges, overhangs	1		
Block sliding	Block sliding is unlikely	0	2	…
	Block sliding is likely	1		
Block toppling	Block toppling is unlikely	0	1	…
	Block toppling is likely	1		
Slope performance	Good (close to slope design)	0	3	…
	Bad (deviation from design)	1		
			Σ	…

Table 2: Identification of the final class of state of activity

Preliminary class	Without signs of activity	With signs of activity
Low	Low	Moderate
Moderate	Moderate	High
High	High	High

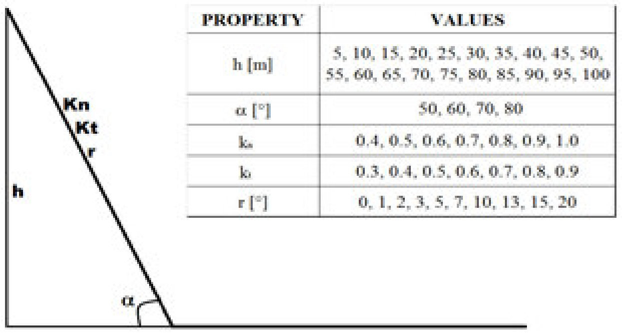
Evaluation of intensity and stand-off distance

The rockfall intensity is given by the kinetic energy reached by a potential unstable block at the toe of the highwall. Therefore, the rockfall intensity depends on the mass of the block (block volume and lithology-specific density), its initial position (or falling height) and the energy dissipation along its path (due to impacts with the surface or mitigation measures installed on the wall). Two possible scenarios can be considered. If a potential unstable block is clearly visible on the highwall, its own dimensions and source location are taken into account. Alternatively, the representative characteristics of the highwall section are considered, the block volume is estimated from the mean joint set spacing and the maximum fall height is taken as equal to the slope height.

A sensitivity analysis was conducted to estimate the dissipation of energy during the block fall. The influence of site specific features on the values of kinetic energy was investigated by means of 2D rockfall simulations performed with the software Rocfall 4 (Rocscience, 2009). The initial conditions, block mass and its release position, were maintained constant throughout all the simulations. The initial fall was assumed as a ledge failure. The outcropping material properties and the slope geometry were varied.

As observed by Giacomini & others (2012) coal mine highwalls are typically made of a succession of sandstone, mudstone and siltstone layers and they are generally steeper than 45º. Therefore, most of the energy dissipation takes place at impact with the rock surface and it varies as function of the block and the surface properties. Based on these observations, the simulations were conducted varying the values of the coefficient of restitution k_n and k_t from 0.4 to 1 and from 0.3 to 0.9 respectively (Turner & Schuster, 2012). Various slope heights and slope inclinations were also considered. The slope height *h* was varied from 5 to 100 m, with 5 m steps, and the slope angle α from 50° to 80°, with 10° steps. Finally, ten different values were taken into account for the standard deviation of the roughness (*r*). The configurations for the sensitivity analysis are summarised in Figure 2.

A total of 39,200 stochastic simulations were performed, each stochastic simulation corresponding to a particular combination of parameters presented in Figure 2. The resulting kinetic energies at the bottom of the highwall and the horizontal distances of the first impact location were analysed. As suggested by well-established methodologies and guidelines (Abbruzzese & others, 2009; Pierson & others, 2001; Rouiller & Marro, 1997), the 90th percentile of the energy and the 95th percentile of the distance were taken into account instead of the maximum values, as it was observed that the latter determine extreme unfavourable conditions that are unlikely to happen.



PROPERTY	VALUES
h [m]	5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100
α [°]	50, 60, 70, 80
k_n	0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0
k_t	0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
r [°]	0, 1, 2, 3, 5, 7, 10, 13, 15, 20

Figure 2: Sketch of the slope profile and the input values used in the simulations. ***h*** *is the slope height,* ***α*** *the slope angle,* ***kn*** *the normal restitution coefficient,* ***kt*** *the tangential one, and* ***r*** *the standard deviation of slope roughness.*

The results show that the energy dissipation is mainly controlled by the slope angle, followed by the standard deviation of slope roughness and the restitution coefficients (Ferrari & others, 2015). The energy dissipation increases by decreasing the slope angle, the roughness or the restitution coefficients. As example, the results obtained from a 50m high highwall with a roughness standard deviation of 10° are displayed in Figure 3. For instance, for the slope angle 70°, the ratio between the 90th percentile of energy and the potential energy (*mgh*) is between 72% and 95%. This means that the dissipation of energy for this slope geometry is between 5% and 28% of the potential energy.

The horizontal impact locations at the bottom of the pit are mainly controlled by the slope height (i.e. fall height), the standard deviation of roughness and the slope angle. In this case, the restitution coefficients revealed to play a secondary role. The horizontal distance increases by increasing the fall height and the slope roughness, due to the presence of irregularities in the slope profile.

In the analysis, the minimum, mean and maximum values of the 90th percentile of energy and the 95th percentile of distance were identified for each slope's geometry. Then, linear regression coefficients were calculated to relate the slope geometry to the expected 90th percentile of energy at the base of the highwall (Figure 4) and to the 95th percentile of the horizontal impact location (Figure 5). In order to consider all the possible combinations of restitution coefficients, both maximum and mean values were taken into account to define a confidence interval for the estimation of the energy and the distance of the first impact.

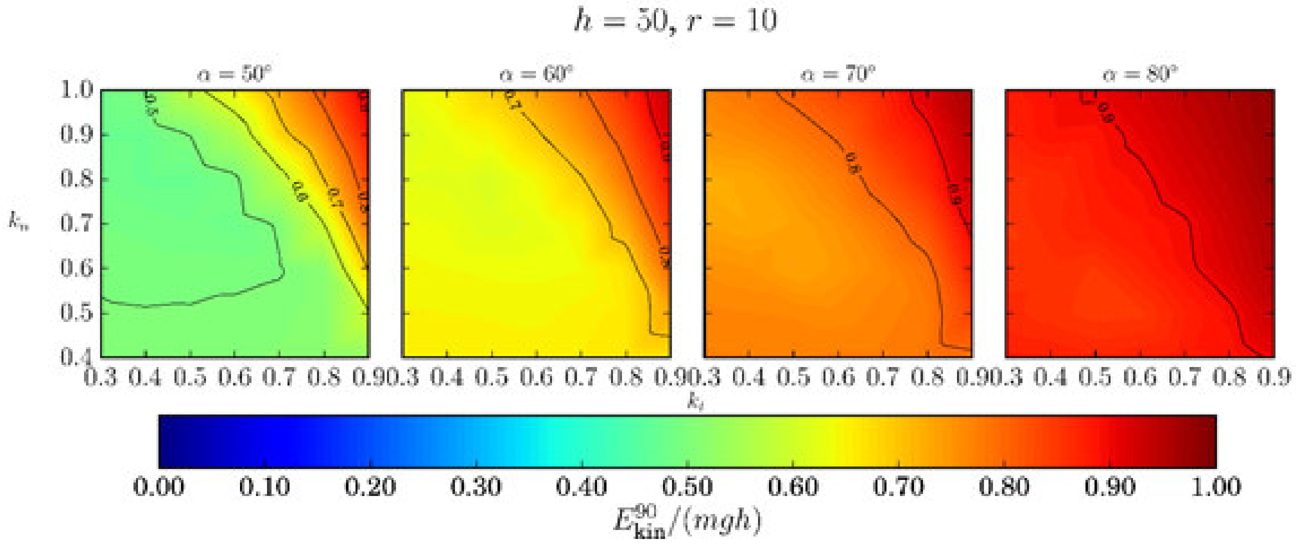


Figure 3: Results for h = 50 m and r = 10°. Each plot has a different slope angle (α). In each plot, the ratio of the 90th percentile of energy and the potential energy is displayed in function of all combinations of k_n and k_t.

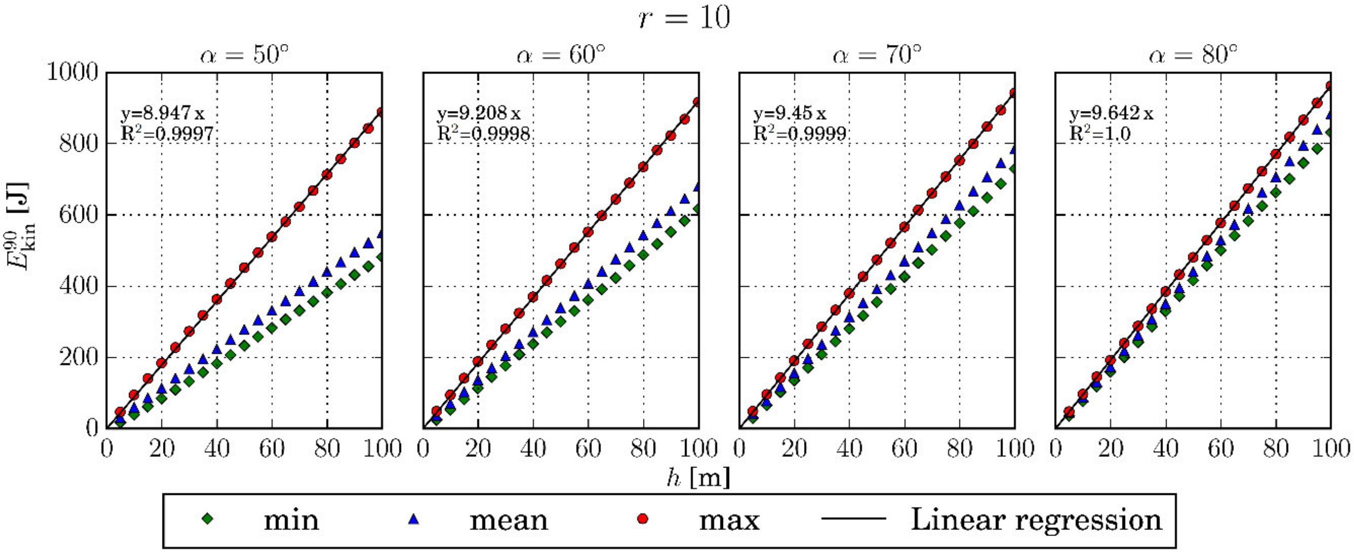


Figure 4: Results for r = 10°. Linear regression relating the slope height (h) to the 90th percentile of energy. The minimum, mean and maximum values were calculated considering all the possible combinations of restitution coefficients.

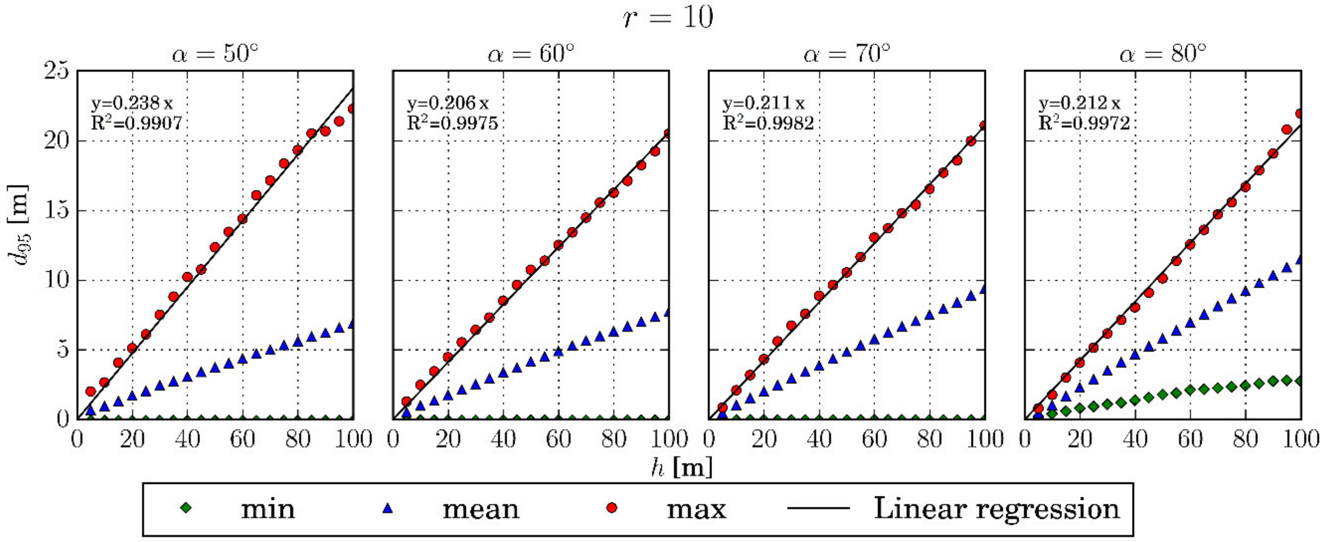
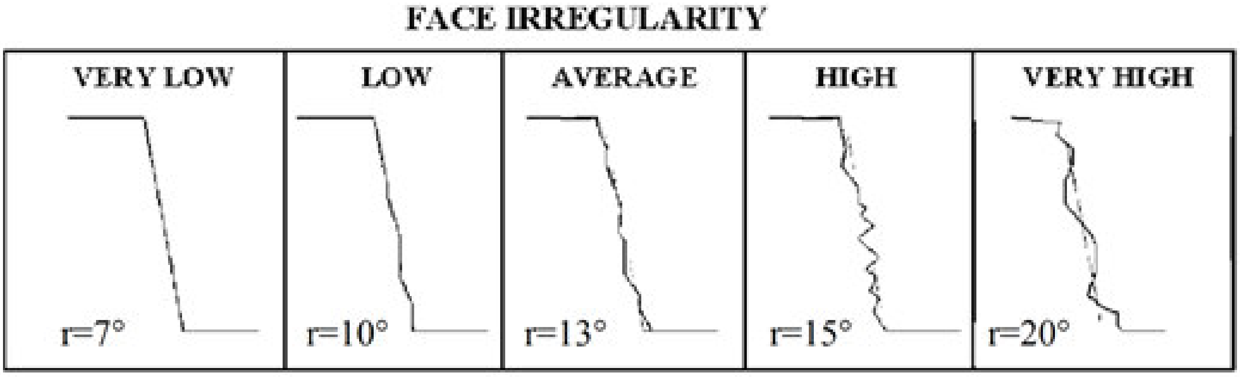


Figure 5: Results for r = 10°. Linear regression relating the slope height (h) to the 95th percentile of distance. The minimum, mean and maximum values were calculated considering all the possible combinations of restitution coefficients.



VERY LOW.- More than 80% of half-barrels related to blast-hole length are observed in the slope face.

LOW.- Between 40 and 80 % of half-barrels can be observed in the slope face.

AVERAGE.- Between 10 and 40 % of half-barrels can be observed in the slope face. A shotcrete layer up to 20 cm is enough to give a locally smooth face.

HIGH.-A shotcrete layer between 20 and 50 cm is needed to give a locally smooth face. Maximum depth of overhangs is 0.5 m.

VERY HIGH.- Overhang depth over 0.5 m.

Figure 6: Classes of slope roughness with corresponding values of roughness standard deviation (modified from Alejano & others, 2008).

The estimation of the value of the standard deviation of the roughness for a given slope is not immediate. In fact, this estimation is very difficult and subjective; hence, it does not satisfy the requirements of a qualitative methodology. To overcome this problem, the face irregularity scoring approach of the ROFRAQ methodology was adopted (Alejano & others, 2008). This allows a quick estimation of the slope roughness and the association to a corresponding class through a visual comparison between the investigated slope and the five sketch profiles reported in Figure 6.

In order to correlate the classes of slope roughness to the value r of the simulations, a survey was conducted among 27 geotechnical engineers and geologists using about 30 different pictures of various highwall sections. For each picture, a class of roughness was estimated (according to Figure 6) and compared to the r value calculated from the corresponding detailed highwall profile. This allowed attributing a range of r values to each class and checking the subjectivity of the method. With the aim to be on the safe side, the maximum r was chosen for each class.

Finally, the regression coefficients calculated for the rockfall energies (Table 3) and the stand-off distances (Table 4) were assigned to each roughness class using the matrix presented in Table 3 and Table 4 for the 90th of energy and the 95th percentile of the first impact distance respectively.

As a result, for a given slope geometry and block characteristics, a rapid estimation of the expected ranges of kinetic energy at the bottom of a highwall and horizontal distance are achievable by using the following equations:

$$E_{kin}^{90} = Rc_E * h * m$$

$$d_{95} = Rc_d * h$$

Where Rc_E and Rc_d are the regression coefficients of energies and first impact distances respectively, h is the fall height of the block (measured from the toe of the highwall) and m the estimated block mass. Both Rc_E and Rc_d can be easily determined from the slope angle and the roughness class (Table 3 and Table 4).

The range of the estimated energy is used for defining the level of rockfall hazard. The horizontal distance provides useful information about the expected location of the first impact at the toe of a highwall and, hence, about the recommended stand-off distance.

Finally, specific values for the definition of the intensity classes (i.e. low, medium, and high) have to be introduced. In the original Swiss matrix (Lateltin & others, 2005), these values were established for land-use planning purposes. In ERHA these boundaries are adapted to the open-pit mine environment and they are chosen according to the impact resistance of PPE helmets [0.05kJ] (Standards Australia & Standard New Zealand, 1997), the falling object protective structures (FOPS) of machinery [11.6kJ] (ISO 3449:2005) and concrete portal structures [300kJ] (Figure 7).

Table 3: Regression coefficients for the 90th percentile of energy, given the slope angle and the class of roughness.

α \ r	VERY LOW	LOW	AVERAGE	HIGH	VERY HIGH
50°	5.29 ÷ 8.62	5.53 ÷ 8.95	5.78 ÷ 9.12	5.93 ÷ 9.14	6.30 ÷ 9.36
60°	6.59 ÷ 8.96	6.81 ÷ 9.21	7.00 ÷ 9.35	7.15 ÷ 9.39	7.46 ÷ 9.54
70°	7.66 ÷ 9.22	7.86 ÷ 9.45	8.05 ÷ 9.53	8.19 ÷ 9.60	8.43 ÷ 9.66
80°	8.69 ÷ 9.60	8.84 ÷ 9.64	8.97 ÷ 9.68	9.04 ÷ 9.71	9.18 ÷ 9.73

Table 4: Regression coefficients for the 95th percentile of first impact distance given the slope angle and the class of roughness.

α \ r	VERY LOW	LOW	AVERAGE	HIGH	VERY HIGH
50°	0.034 ÷ 0.134	0.072 ÷ 0.238	0.120 ÷ 0.346	0.154 ÷ 0.424	0.249 ÷ 0.626
60°	0.040 ÷ 0.122	0.080 ÷ 0.206	0.128 ÷ 0.307	0.161 ÷ 0.381	0.248 ÷ 0.529
70°	0.053 ÷ 0.133	0.095 ÷ 0.211	0.140 ÷ 0.275	0.172 ÷ 0.347	0.250 ÷ 0.470
80°	0.072 ÷ 0.142	0.116 ÷ 0.212	0.158 ÷ 0.295	0.186 ÷ 0.347	0.256 ÷ 0.431

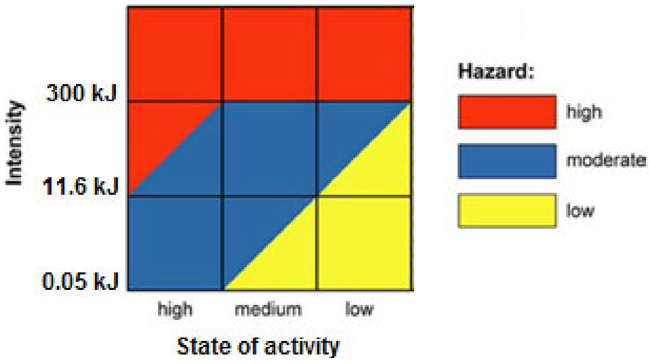


Figure 7: Matrix for defining hazard levels in Evolving Rockfall Hazard Assessment

Individuation of the hazard class

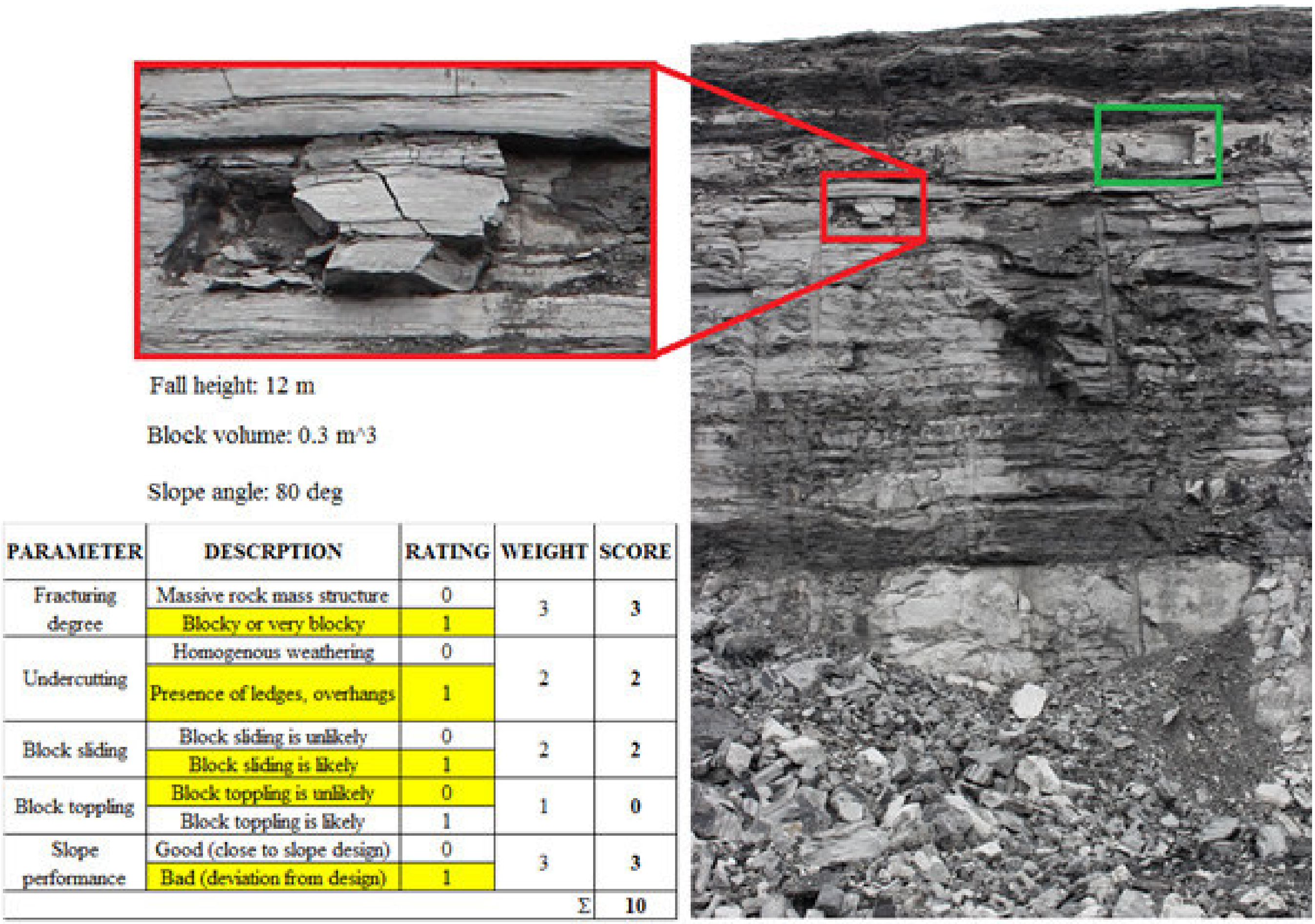
Once the classes for probability (i.e. state of activity) and intensity (i.e. energy) have been identified, the hazard level can be established according to Figure 7. For high hazard level, a strict quantitative assessment is required in order to define with more detail safety zones, zones at risk of impact, and zones where mitigation measures are requested. For moderate hazard level, further investigations may be suggested as function of the working activity expected at the areas at the bottom of the highwall. Slopes with low hazard level do not require further investigations.

APPLICATION

An example of the application of the new qualitative ERHA to a coal mine highwall located in the Hunter Valley is described herein.

The evaluation of the state of activity was performed by observing the highwall section and choosing the most appropriate rating for each parameter listed in Table 1. At least three main joint sets are identified in the outcropping rock mass and, hence, the rock mass has a blocky structure according to the Geological Strength Index classification system (Marinos & others, 2003). It is also observed that the instability mechanisms that could more often lead to a block failure are mainly related to undercutting (free fall of blocks) and block sliding, as one discontinuity set is almost parallel to the highwall face. No block toppling, generally associated to a steep discontinuity set with dip direction opposite to the rock wall dip, was considered as instability mechanism for this case. Finally, the slope performance was rated as 'bad', due to the evident presence of overhangs and loose material and semi-detached blocks on the wall. As a result, the assessment gives a state of activity score of 10 (Figure 8) and it indicates a preliminary high class of activity. This is confirmed by the presence of several blocks at the bottom of the highwall and several areas of the rock surface with evident signs of rockfall activity.

The evaluation of the intensity class requires the identification of a potential unstable block and the estimation of its fall height and mass. A block located at a height of about 12m and with a mass of about 660kg was identified (Figure 8). Then, the regression coefficients Rc_E and Rc_d were calculated knowing the slope angle and the class of roughness. The former is equal to 80°, and the latter resembles the sketch profile of the average roughness class (Figure 6). This leads to ranges for Rc_E and Rc_d of 8.97 ÷ 9.68 and 0.158 ÷ 0.295, respectively. These ranges of regression coefficients (from Table 3 and Table 4) were determined considering the mean and maximum values of both energy and distance. It follows that the expected 90th percentile of energy at the bottom of the highwall ranges from 71kJ to 77kJ, falling within the medium intensity class (Figure 7). Contextually, the expected



Fall height: 12 m

Block volume: 0.3 m^3

Slope angle: 80 deg

PARAMETER	DESCRPTION	RATING	WEIGHT	SCORE
Fracturing degree	Massive rock mass structure	0	3	3
	Blocky or very blocky	1		
Undercutting	Homogenous weathering	0	2	2
	Presence of ledges, overhangs	1		
Block sliding	Block sliding is unlikely	0	2	2
	Block sliding is likely	1		
Block toppling	Block toppling is unlikely	0	1	0
	Block toppling is likely	1		
Slope performance	Good (close to slope design)	0	3	3
	Bad (deviation from design)	1		
			Σ	10

Figure 8: Photo of the highwall section. The red rectangle indicates a potential unstable block, the green rectangle indicates a recent block detachment. On the left, some block and slope features are reported, together with the table for the state of activity assessment.

horizontal distance of the first impact location ranges from 1.9m to 3.5m.

The high state of activity class combined with the medium intensity class defines in the hazard matrix a moderate/high hazard level (Figure 1). Actually, the investigated highwall section has high rockfall activity and expected energies higher than the resistance of a FOPS. Therefore, further investigations, which also take into account the working activity at the base of the highwall, are necessary to guarantee the safety of the personnel.

CONCLUSIONS

A new rockfall hazard methodology, the Evolving Rockfall Hazard Assessment (ERHA), has been developed. The ERHA involves a first qualitative assessment for the identification of the most hazardous areas for which a second strict quantitative analysis is required.

This paper summarises the first qualitative step of ERHA. It is inspired by the well-established and widely accepted Swiss guidelines for rockfall hazard. These guidelines define the hazard level (i.e., low, moderate and high) taking into account the probability of occurrence and intensity of rockfalls along mountain slopes. Within ERHA, the probability of occurrence is defined by the evaluation of the highwall's state of activity through a rating based approach. It considers the geological structure, the potential failure mechanism, the slope performance and the presence of signs of rockfall activity. All parameters can be easily observed and quickly rated. The resulting score defines a probability class (i.e., high, medium or low).

The estimation of the intensity (i.e., kinetic energy) is based on a sensitivity analysis carried out through 2D rockfall simulations. Regression coefficients were computed in order to relate the slope geometry to the expected kinetic energy at the base of the highwall. Three energy classes are defined with boundaries (i.e., low, medium or high) chosen according to the mine environment.

Beyond the hazard level, the ERHA provides also an estimation of the expected location of the first impact, which is useful in defining the stand-off distance and, hence, in locating personnel, machineries, and structures.

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F. Ferrari[1], K. Thoeni[1], A. Giacomini[1] and C. Lambert[2]
[1]Centre for Geotechnical and Materials Modelling, The University of Newcastle, Newcastle, Australia
[2]Golder Associates (NZ) Limited, Christchurch, New Zealand