NOVA

University of Newcastle Research Online

nova.newcastle.edu.au

Spadari, M., Kardani, M., De Carteret, R., Giacomini, A., Buzzi, O., Fityus, S., Sloan, S. W.,
"Statistical evaluation of rockfall energy ranges for different geological settings of New South
Wales, Australia". Originally published in Engineering Geology Vol. 158, p. 57-65 (2013).

Available from: <http://dx.doi.org/10.1016/j.enggeo.2013.03.007>

Accessed from: <http://hdl.handle.net/1959.13/1041261>

Statistical evaluation of rockfall energy ranges for different geological settings of New South Wales, Australia.

Spadari M.^a, Kardani M.^a, De Carteret R.^a, Giacomini A.^a, Buzzi O.^a, Fityus S.^a, Sloan S.W.^{a,b}

^a: Centre for Geotechnical and Materials Modelling, The University of Newcastle, Callaghan, NSW, Australia.

^b: ARC Centre of Excellence for Geotechnical Science and Engineering, The University of Newcastle, Callaghan, NSW, Australia.

Corresponding Author: Spadari M. Tel + 61249216141, Fax: +61249216991, email: Michele.Spadari@newcastle.edu.au. Centre for Geotechnical and Materials Modelling, University Drive, 2308, Callaghan, NSW.

1. Abstract

Structures used in rockfall protection are designed on the basis of the expected impact energy. This quantity is usually assessed using commercial lumped mass models that stochastically predict possible block trajectories on a given slope. In New South Wales, Australia, it is estimated that rockfall hazard involves values of energy which are much lower than those in Europe, Canada or the USA. However, this view has not been supported by any systematic study across the whole state. Such a study is presented in this paper. It applies to the five geological situations that are the most prone to rockfall in eastern Australia. Previous experimental findings, relating to block size distribution or

restitution coefficients (reviewed herein), have been used to perform this statistical analysis. A newly formulated lumped mass model, which incorporates a relationship between the normal restitution coefficient and the impact angle, allows the adoption of normal restitution coefficients in excess of unity for impact angles lower than 20 degrees. The results confirm that in three out of the five geological situations, the 95th percentile of impact energy is lower than 200 kJ, and less than 2000 kJ for the other two situations.

Keywords: rockfall, hazard, impact energy, block size, lumped mass

2. Introduction

As for any engineered structure, the design of rockfall protection structures requires the determination of a design load: in this situation it is the impact energy which must be withstood. Prediction is usually achieved using numerical codes such as CRSP (Jones et al., 2000) or Rocfall (Stevens, 1998) that predict the possible trajectories of a large number of boulders for a given slope in a stochastic manner. These codes provide the statistical distribution of total energy of the blocks at a specified location along the slope. Energy prediction is usually a one-off task, carried out for a specific slope where rockfall has been identified as a possible hazard (Pierson, 1993; Fell et al., 2008). In some cases where attention is focused on hazard mapping, larger areas are considered (Ayala et al., 2003; Chau et al., 2003; Cascini et al., 2005; Mazengarb, 2005; Chiessi et al., 2010) but the statistical assessment of impact energy is seldom applied to whole geological areas.

It is clearly recognised that the magnitude of rockfall energy is a function of the geology of the area, since this affects the shape and steepness of slopes, the sizes and shapes of

boulders and the material constituting the slopes (Ritchie, 1963; Bozzolo and Pamini, 1986; Azzoni et al., 1992; Giani, 1992; Azzoni and de Freitas, 1995; Giani et al., 2004; Vandewater et al., 2005). Rockfall energies can reach very high values, as is evident in the recent development of high capacity barrier systems: 5000 kJ (Trad et al., 2011), 7000 kJ (Maccaferri, 2007) and 8000 kJ (Geobrugg, 2011). However, in many places worldwide, the rockfall hazard involves much lower values of energy. Muraishi et al. (2005) surveyed 607 rockfall events in Japan, of which 68% involved energies less than 100 kJ. Similarly, there are regions of Australia where a rockfall hazard does exist but involves relatively low levels of energy (Young, 1983; Gordon, 1999; Dahlhaus and Miner, 2000; Dutton and Stocker, 2001; Kotze, 2007; Hunter et al., 2011). This is particularly the case in New South Wales, where the nature of the geological environments (Fityus et al., 2012) is inherently different from the mountainous areas of Europe or Northern America. Although this fact is recognised (for example, by the roads authority; Buzzi et al., 2012), the range of possible impact energies in New South Wales has never been quantified. Consequently, the applicability of proprietary systems, which have been developed for other geographical regions, to Australian rockfall hazard situations is unclear.

The purpose of this paper is to quantify the likely rockfall hazard characteristics which are typical of the major geological regions of New South Wales. These can be used to develop a series of standard protection structure designs which are generally suitable for particular geological settings. Rockfall analyses have been performed for a large number of characteristic slopes, coming from five different geological settings prone to rockfall in New South Wales, using a statistical approach. Experimental data, gathered from previous studies in these settings (Spadari et al., 2011; Fityus et al., 2012) were used as inputs for a new lumped mass numerical model, developed for the purpose of the study. This model is

based on the same physical principles as most other lumped mass models, but incorporates the possibility of using restitution coefficients greater than unity and defines a relationship between k_n and the impact angle. It is shown that these features prove necessary to achieve meaningful results in the environments tested. As a result of the study, statistical distributions of the likely impact energy have been produced for five different geological situations which are prone to rockfall hazards. Such statistical data is useful for the pre-design of a range of standard interception structures, on the basis of the accepted level of risk in a specific geological setting. It also quantifies the difference in the rockfall hazard between New South Wales, Australia, and other locations where significant rockfall developments have previously taken place (such as Europe, Canada and the USA).

3. Characteristics of rockfall prone settings in New South Wales

3.1 Definition of the relevant geological situations

As indicated by Branagan and Packham (1967), the East Coast of New South Wales, along the Great Dividing Range, is where the rockfall hazard is the most significant. This is mostly due to the geomorphological characteristics of the region: hilly to mountainous areas, moderate to steep slopes, and the presence of rocky outcrops and rock debris. In contrast, the inland regions are generally flatter and less problematic in terms of rockfall. In addition, the East Coast has seen a progressive urbanization over the past decades, which has increased the exposure to the rockfall risk.

In this study, four distinct geological settings have been proposed (Figure 1) on the basis of characteristics that are relevant to the rockfall issue. These are outlined on the simplified geological map in Figure 1, and comprise:

HERE FIGURE 1 (one and a half column width)

The Sydney Basin Sandstones (denoted SBS), of predominantly Triassic age, comprising thickly-bedded sandstones in a relatively undeformed sedimentary basin setting. These mostly occur as the Narrabeen and Hawkesbury sandstones (Herbert and Helby, 1980);

The Palaeozoic Fold Belts (Lachlan and New England), comprising sequences of sedimentary and volcanic rocks, affected by moderate tectonic deformation (Branagan and Packham, 1967). From a rockfall perspective, two significant and distinctive lithologies, representing two different geological situations, are recognised: the Fold Belt Sandstones (denoted FBS), and the Fold Belt Volcanics (denoted FBV). These each occur as tilted, moderately to thickly bedded units, but with distinctly different fracture and weathering characteristics. They can be mapped at the local scale but cannot be distinguished on the scale of a regional map (Figure 1);

Tertiary flood basalts (denoted B), in horizontally layered flows, which characteristically occur as capping layers along the Great Dividing Range (Johnson et al., 1989);

Granites (felsic granitoids, denoted G), which are mostly of Palaeozoic or early Triassic age and which occur as intrusions throughout the Palaeozoic fold belts. (Johnson, 2004).

This study will focus on the five different situations presented above: FBS, FBV, G, B and SBS, noting that two different situations are recognised in the Palaeozoic fold belt setting. Note that it is not the purpose of this paper to discuss the geology of these settings, and the reader is referred to Fityus et al. (2012) for more details.

Although the different settings differ in terms of slope geometry, slope material, restitution coefficients, block material and block dimensions, it has been found that the distribution of block size is the main difference between the settings (see section 3.2). This characteristic significantly affects the outcomes in terms of impact energy, as is shown in the results section. The other characteristics all have a minor influence: all the slopes tested were slightly vegetated and covered with sparse debris yielding similar values of restitution coefficients (Spadari et al., 2011). In addition, the natural variability of the restitution coefficients masks the effect of the block material. Finally, the survey of the slopes showed that no typical geometry (angle and length) could be associated to a given setting (see section 2.3).

3.2 Statistical distribution of block sizes in the different settings

The block mass strongly affects the impact energy, i.e. the block's kinetic energy, which is composed of a translational component and a typically smaller rotational component. It is hence of prime importance to rigorously and accurately characterise the size or mass of the

potentially unstable blocks for a given site. In a previous study, Fityus and co-workers (2012) surveyed block populations for different geological environments and correlated the size of the blocks to the geology of the area (e.g. lithology, structure, weathering). Around 600 blocks were measured yielding frequency distributions of block size in four of the five geological situations considered here (SBS, FBS, B, FBV). A frequency distribution, based on 642 size measurements taken in granitic regions, has since been derived to account for the remaining situation (G). Figure 2 shows the distributions of the average block dimension, taken as the average value of the three dimensions for the five studied situations.

HERE FIGURE 2 (small column size)

3.3 Selection of slopes for rockfall simulations

In order to obtain a representative assessment of typical energy values for the different geological areas, rockfall analyses were performed for a large number of realistic slope profiles. The slopes modelled come from the slope hazard database of the local state road

authority (Roads and Maritime Services, formerly known as the Roads and Traffic Authority). Suitable natural slopes with potential for rockfall (either cuttings or natural slopes above a roadway) were identified by reviewing 3,838 entries located within the selected geological settings. Any natural slope with an angle lower than 15 degrees was excluded, as experience from rockfall field tests has shown that rock rolling cannot be sustained on such slopes, regardless of the geological situation (Spadari et al., 2011). Cuttings without significant natural slopes above them were also excluded. This was justified because existing cuttings can be specifically engineered to mitigate rockfall hazards. In this paper, attention is focused on the rockfall hazard associated with natural slopes including those above cuttings.

In the best case, database records included the location, the slope height, the slope angle, the block size, the vegetation, sketches of the site in both plan and cross-section and previous rockfall history. However, many of the entries were not sufficiently documented to allow them to be reliably modelled. At the end of the process, a total of 211 suitable slopes were selected: 92 slopes in the Sydney Basin Sandstones, 22 slopes in the Fold Belt Sandstones, 22 slopes in the Basalts, 51 slopes in the Granites and 24 slopes in the Fold Belt Volcanics. Figure 3 shows that a diverse range of scenarios, in terms of slope angle and length, was covered.

HERE FIGURE 3 (small column size)

These slopes were then used to produce two-dimensional profiles used for the rockfall analysis.

4. Program for rockfall simulations and preliminary results

Most lumped mass models deal with impacts between the rocks and the slope using so-called restitution coefficients (Piteau and Clayton, 1976; Wu, 1985; Hungr and Evans, 1988) in a stochastic manner. This aims to reproduce the natural variability of the phenomenon that stems from local effects related to slope roughness, block angularity, rotation of the block, impact angle. However, none of the available simulation programs can accommodate values of normal restitution coefficient k_n greater than unity, despite data from field tests which suggests such values are realistic (Spadari et al., 2011; Azzoni et al., 1992). Also, the dependence of k_n on the impact angle (Bourrier et al., 2009) is usually not accounted for.

To overcome these limitations, a code, NURock, was developed at the University of Newcastle to analyse rockfall trajectories and predict impact energy. NURock is based on similar physical principles to the two most commonly cited lumped mass codes, namely CRSP (Jones et al., 2000) and Rocfall (Stevens, 1998). In these codes, the trajectory of the block is represented by a series of parabolic curves (free flight) and interactions with the slope surface (impacts or sliding). The slope is defined as a 2-dimensional profile made up

of straight line segments, with particular properties (k_n , k_t , roughness and friction angle) assigned to each segment. The initial conditions (translational velocity, rotational velocity and height of the starting point) can be defined by the user, as can the block properties (shape, dimensions and density). The number of simulations per run can be set by the user to allow for statistical analysis. Some features of the NURock code will be detailed in the following sections, but it is not the purpose of this paper to present the code comprehensively.

4.1 Formulation of impact

The impact phenomenon is modelled via the restitution coefficients k_n and k_t and by quantifying the energy dissipation upon impact. The coefficients are defined as the ratios between the normal and tangential components of the block velocity, before and after the impact, respectively. This definition is the most commonly adopted in rockfall simulation programs. The normal component of velocity after impact (V_{NA}) is directly proportional to the normal velocity before impact (V_{NB}) with a coefficient equal to k_n :

$$V_{NA} = k_n \cdot V_{NB} \quad (1)$$

As an alternative to Equation 1, NURock allows for the use of a scaling relationship reducing the normal restitution coefficient as a function of the normal velocity (Equation 2):

$$V_{NA} = \frac{k_n \cdot V_{NB}}{1 + \left(\frac{V_{NB}}{9.144} \right)^2} \quad (2)$$

This approach is used in other rockfall analysis codes (Jones et al., 2000; Stevens, 1998) and is based on experimental observations on bouncing blocks. It accounts for the fact that the normal restitution coefficient tends to decrease as the block velocity pre-impact increases (Pfeiffer and Bowen, 1989). As a result, the “effective” normal restitution coefficient is lower than the original k_n value measured in the field. Unlike in commercial codes, there is no upper bound for k_n in NURock. However, allowing $k_n > 1$ requires checking that there is no kinetic energy increase but only dissipation upon impact, as happens in reality. The code includes a verification algorithm that is detailed in a following section.

When Equations 1 or 2 are used, a degree of randomness is added to account for the variability arising from local effects, which are neglected in the case of idealized slope profiles. This is achieved by randomly increasing the slope angle (α) by an angle θ . The maximum variation (θ_{max}) is defined, according to Pfeiffer and Bowen (1989), as:

$$\theta_{max} = \tan^{-1}(S/R) \quad (3)$$

where S is the surface roughness and R is the rock radius (Figure 4). This directly impacts the trajectory of a block.

HERE FIGURE 4 (small column size)

Another novel feature is the implementation of a relationship between k_n and the impact angle θ . This relationship (Equation 4) has been derived from test results on natural slopes in the studied areas and for impact angles lower than 30 degrees (Spadari et al., 2011 - Figure 5) It can be activated by the user in addition to equations 1 or 2 and it is only taken into account when the impact angle is smaller than 30 degrees: otherwise, the program will calculate the normal velocity post-impact using equations 1 or 2 only. The natural variability of k_n is accounted for in Equation 4 via a random variation of ± 0.5 within the predictive confidence interval of 90% over the samples provided:

$$k_n = -0.04\theta + 1.8 + \Delta \quad \text{with } \Delta \in \{-0.5, 0.5\} \quad (4)$$

where θ is expressed in degrees. The variation Δ means that a number with two decimal places is randomly chosen so that any value within such interval can be assumed.

HERE FIGURE 5 (small column size)

The post-impact tangential velocity can be calculated in either of two ways: through the definition of k_t (Equation 5) or by using a function based on the balance of energy (Equation 6 - Stevens, 1998).

$$V_{TA} = k_t \cdot V_{TB} \quad (5)$$

$$V_{TA} = \sqrt{\frac{r^2(I \cdot \omega_B^2 + m \cdot V_{TB}^2) \cdot F_1 \cdot F_2}{I + m \cdot r^2}} \quad (6)$$

In Equations 5 and 6, V_{TB} and V_{TA} are the tangential components of velocity before and after impact respectively, r is the block radius, ω_B is the angular velocity before the impact, m is the rock mass, I is the moment of inertia of the block, and F_1 and F_2 are scaling factors accounting for the loss of energy upon impact and defined by Jones et al. (2000) as:

$$F_1 = k_t + \frac{1 - k_t}{\left(\frac{V_{TB} - r \cdot \omega_B}{6.31}\right)^2 + 1.2} \quad (7)$$

$$F_2 = \frac{k_t}{\left(\frac{V_{NB}}{76.2 \cdot k_n}\right)^2 + 1} \quad (8)$$

where the velocity is expressed in m/s. The choice between Equations 5 and 6 is left to the user. In this study, Equation 6 was used to calculate the post-impact tangential velocity, as the use of constant restitution coefficients may lead to the unrealistic arrest of blocks along the slope (see Bourrier and Hungr, 2011).

4.2 Energy check

As alluded to previously, high values of k_n , if combined with high values of k_t , could result in the creation of energy upon impact, which is not physically acceptable. Laboratory testing (Buzzi et al., 2012) showed that, while high k_n values are realistic, they are associated with low k_t so that energy is always dissipated at impact.

Consequently, an iterative control routine that checks for energy dissipation and corrects the post-impact velocity accordingly has been implemented. The experimental results obtained by Spadari et al. (2011) indicate that, for impact angles lower than 30 degrees, about 14 to 34% of the total kinetic energy (sum of translational and rotational energy) is lost upon impact. If, at some point in the simulations, total energy is greater after impact (i.e., energy is created) due to an inappropriate combination of k_n and k_t , the subroutine randomly chooses a value of energy dissipation within the range 14%-34% and reduces the tangential component of velocity so that the target energy dissipation is met.

4.3 Formulation for sliding and rolling

Rolling and sliding are captured in a common approach in NURock, similarly to the basic physical principle of an object sliding along an inclined plane with a given friction. Indeed,

the two phenomena can be formulated in the same way, as the friction force on the block, tangential to the slope surface, T is given by:

$$T = N \cdot \delta \quad (9)$$

where N is the force acting perpendicular to the slope surface, and δ is either the friction coefficient μ or the rolling coefficient ν . Depending on the ratio of δ to $\tan(\alpha)$, where α is the slope angle, a block in a rolling/sliding phase can accelerate ($\delta < \tan(\alpha)$), decelerate ($\delta > \tan(\alpha)$) or maintain its speed ($\delta = \tan(\alpha)$).

The rolling/sliding algorithm is activated when the block's total velocity after an impact is lower than a threshold value fixed by the user. Sliding is also activated if, at the beginning of the simulation, the block remains in contact with the slope after a small time increment (i.e. the block velocity is parallel to the slope).

4.4 Parameters required for the rockfall simulations

As for similar lumped mass models, the data required to run the analysis include the geometrical description of the slope, the location of the analysis points, the initial velocities, the block's size/shape and the parameters describing the slope/block interaction (restitution coefficients, rolling coefficient, friction coefficient and roughness).

Simplified geometries, consistent with the RTA Guide to Slope Risk Analysis (2001), were used for this study and these included features such as the length and angle of the slopes. Since this work focuses on rockfalls associated with natural slopes, and not from cuttings,

the velocity and bouncing height were only determined for all the blocks at the end of the natural slopes above roads, assuming that this is where a protection structure would be located.

In terms of initial conditions, the release point for the blocks was set between 0 and 1 m above the slope with an initial horizontal velocity of 2 m/s, a nil vertical velocity and a nil angular velocity. These values were chosen in order to simulate realistic onset conditions for blocks toppling on the type of slopes considered. The influence of the initial velocity on the distribution of velocity at the bottom of the slope was assessed and is presented in section 3.5.

The mean block size was defined from the distribution presented in section 3.2 and density values were ascribed on the basis of the lithology. As per most of the lumped mass models, the blocks were assumed to be spherical.

Although pertaining to different geological situations, all the slopes considered were characterised by the presence of slightly vegetated soil with the occurrence of low rock outcrops and scattered rock debris. Consequently, it was decided to allocate identical values of the restitution coefficients for the five geological situations. Indeed, k_n and k_t were found to be mostly dependent on the slope characteristics (ie, vegetation, soil, rock etc.) rather than lithology (Spadari et al., 2011). The tangential restitution coefficient was taken as 0.73, the average value of the experimental results of obtained by Spadari et al. (2011), while the relationship described in Equation 4 was used for the normal restitution coefficient for impact angles lower than 30 degrees. For higher impact angles, a value of 0.8 was adopted. Indeed, for impact angles higher than 30 degrees, k_n is considered

unlikely to be greater than unity and the average value of the normal restitution coefficients below unity (Spadari et al., 2011) was deemed representative of the slope material considered.

A value of 30 degrees was chosen for the friction angle, yielding a friction coefficient μ of 0.57. The same value was taken for the rolling coefficient, blending the two phenomena into one. This allowed consistent simulation of the arrest of rocks on low inclination slopes and a rolling/sliding behaviour on steeper slopes. The value of the rolling coefficient used for the simulations is higher than the average experimental value (about 0.35) determined by Spadari et al. (2011), but is consistent with the value commonly adopted in previous studies (Jones et al., 2000; Stevens, 1998). The threshold velocity for sliding was estimated to be 1 m/s from field observations. Higher values would predict that a large number of blocks would slide down to the bottom of the slope, which was not observed experimentally.

Finally, typical slope roughness values (S) were estimated from observations made for slopes within the different geological settings during *in situ* testing activities. Table 1 provides a summary of all the parameters used for this study.

Table 1. Parameters used for the simulations performed. S is the slope roughness.

Geological Situation	Mean Block Radius (m)	Block Density [kg/m ³]	Slope Material	S [m]	k_n	k_t	μ and ν
SBS	0.45	2450	Slightly	0.06	Eq. (4) for impact angles < 30° and 0.8 above	0.73	0.57
FBS	0.27	2450	vegetated soil	0.03			
B	0.15	2900	with sparse debris and	0.05			
G	0.45	2650	occasional	0.30			
FBV	0.23	2650	rock outcrops	0.05			

4.5 Influence of the initial velocity

Like other lumped mass simulation codes, NURock requires an initial block velocity to be specified. A range of initial horizontal velocity values were tested in a series of simulations, performed on a representative slope, characterised by an average inclination of 30 degrees and length of 150 m. The result of this preliminary analysis (Figure 6) shows that the initial horizontal velocity has little influence on the 95th percentile of the velocity at the bottom of the slope, at least in the range tested (0 to 5 m/s). This range is deemed reasonable to represent onset conditions for these situations.

HERE FIGURE 6 (small column size)

4.6 Influence of k_n values greater than unity

The reliability of the predictions from the NURock code was tested in a preliminary study, prior to undertaking the simulations for this research. This aimed at checking the influence of k_n values greater than unity on the rockfall motion predictions and the validity of the relationship between k_n and the impact angle. Figure 7 compares some experimentally

measured velocity results for Fold Belt sandstone blocks, with the envelopes of maximum velocity obtained by NURock using values of k_n lower than one or possibly larger than one. Although the results are not directly comparable since the NURock analysis is stochastic, they confirm that using Equation 4 (i.e. allowing values of k_n possibly larger than one) does not cause over-prediction of the block velocity. In fact, Equation 4 gives a better match between the predicted and observed results, while the maximum velocities obtained without Equation 4 are lower bounds on the experimental results.

HERE FIGURE 7 (small column size)

4.7 Significance of block size for the trajectory

The energy of a block is a function of its mass and its velocity. A stochastic approach to determine likely block energies would conduct a large number of simulations on blocks with a size distribution derived from the relevant geological situation, such as is shown in Figure 2. The velocity determined for each simulated block could then be combined with its mass to estimate its energy.

The size of each block should affect its falling motion and trajectory. In a lumped mass model, however, the size and shape have limited direct importance, since the specific kinematics of individual fragments are not considered directly. To consider the importance of size in lumped mass model predictions, a series of simulations using different sized blocks was carried out on ten different slopes with a broad range of inclinations (from 20 to 35 degrees) and lengths (between 15 and 210 m). Figure 8 shows the results for only one slope, but similar results were obtained for all simulations. It can clearly be seen that, in terms of both the average and standard deviation, the velocity and bouncing height are largely independent of the block radius, and hence of the block mass. Indeed, the block mass only appears in the calculation of the tangential velocity (Equation 6) and its influence in determining the velocity after the impact is minor.

This is a significant outcome, as it allows all NURock analyses to be carried out for a single (in this case average) block size for each geological situation. This then allows the distribution of the impact energy to be obtained directly from the predicted velocity and the distribution of the block masses. The approach is described in greater detail in the following section.

HERE FIGURE 8 (side by side, small column size)

5. Methodology to determine the distribution of impact energy in each geological situation

In the following, each geological situation is characterised by a subscript sit , with $sit \in \{FBS, FBV, SBS, G, B\}$. Also, each situation is characterised by a number of slopes, equal to N , and a data distribution of block radius, denoted $DD(R_{sit})$, that can be used to produce a distribution of the block mass $DD(m_{sit})$.

The preliminary study (section 3.7 and Figure 8) suggested that, for a given slope, the effect of block radius on the distribution of velocity and bouncing height is minor and can be neglected. Consequently, the N slopes belonging to situation sit were analysed with the mean block radius pertaining to the particular geology (see Table 1). For each slope i within situation sit , 1000 block trajectories were obtained using the NURock code. As a result, a distribution of impact velocities $DD(V_{i,sit})$ at the bottom of the slope was obtained, from which a 95th percentile value was determined. This latter is noted $V95_{i,sit}$. Tests were also carried out with higher numbers of runs: since the results did not show noticeable differences in terms of the 95th percentile values, 1000 was deemed to be an appropriate number of runs for this study.

The distribution of impact energy for the slope i of the situation sit is noted $(DD(E_{i,sit}))$ and was estimated by combining the distribution of block mass $DD(m_{sit})$ and $V95_{i,sit}$.

$$DD(E_{i,sit}) = \frac{1}{2} \cdot DD(m_{sit}) \cdot V95_{i,sit}^2 \quad (10)$$

Once the energy distributions for the N slopes were known, the distribution of the impact energy of the situation sit was then estimated as:

$$DD(E_{sit}) = \sum_{i=1}^N DD(E_{i,sit}) \quad (11)$$

In this study, only translational energy is considered (Equation 10). The rotational component has been neglected for a number of reasons. First, it has been experimentally found that rotational energy represents only 10 to 15% of the total energy (Spadari et al., 2011) and can therefore be neglected without introducing unacceptable error. Second, its calculation is plagued by the need to estimate the block's angular momentum resulting in a higher degree of error than for the translational component. Finally, the practical consequences of rotational energy are the so-called “saw effect” (local damage of the mesh due to sharp edges of a rotating block) and the possibility that the block can climb up the protective structure. The rotational energy does not load the barrier in the manner it is designed for, or by which it is tested: i.e. translational impact, usually imposed through simple free fall (EOTA, 2008). Note, however, that rotational energy does influence the trajectory of the block to a significant extent and is therefore accounted for when presenting the 95th percentile of the bouncing height. This latter was calculated in a similar way to the 95th percentile of velocity.

6. Results

Figure 9 presents the cross-section of a typical slope showing the different block trajectories predicted by the NURock analysis. The analysis point is at the top of the cutting, where a barrier would have to be installed to protect the road and users from the rocks falling from the slope above. The velocities and bouncing heights determined at the analysis point are used to produce statistical distributions similar to the one shown in Figure 10, according to the approach described in the previous section. The cumulative distribution, displayed with the histogram of velocity, is used to determine the 95th percentile value (indicated by the arrow on the figure, showing a value slightly below 20 m/s).

HERE FIGURE 9 (small column size)

HERE FIGURE 10 (small column size)

HERE FIGURE 11 (side by side, small column size)

The 95th percentiles of the velocity and the bouncing height have been correlated to the slope angle for all the geological situations in Figure 11. The correlation is relatively insensitive to the geology since the slopes are all of the same type (slightly vegetated, with debris and occasional rocky outcrops) and because the block dimensions, which are inherent to the geology, do not significantly affect the velocity and the bouncing height. Unlike the slope length, the slope angle has a major influence on the results: the higher the slope angle, the higher the velocity and the bouncing height. Figure 11 can be used to estimate the velocity range for a given slope angle, regardless of the slope length. Obviously, these results apply for the conditions of the study, which are believed to be the most appropriate for the geological situations studied.

Finally, the probability distributions of impact energy for each one of the geological situations, obtained as per the methodology explained in section 4, are displayed in Figure 12. The curves shown are a best fit of the data obtained from the simulations. This choice was made for the sake of clarity. Higher values of impact energy are shown in Figure 12a, while lower values are presented in Figure 12b. As discussed previously, the specificity of the geological situation lies within the distribution of the block mass rather than within the block/slope interaction parameters. In addition, considering the 95th percentile of velocity as a critical value, instead of the whole distribution of velocity, means that the shape of the energy distribution directly reflects that of the block mass distribution. Hence, like the

block size distribution, it is more Lognormal-like than Gaussian. Also, the magnitude of energy increases with the range of the block size in the different geological situations.

The figures suggest that, for most cases, the magnitude of the impact energy which must be absorbed by a protective structure is relatively low: lower than 400kJ (average of about 200 kJ) for Sydney Basin Sandstones and Granites, and lower than 50 kJ for the Fold Belt Volcanics, Fold Belt Sandstones and Basalts. This research provides a general indication of the expected levels of energy for each geological situation, and confirms the fact that rockfall hazards associated with the geology of New South Wales are inherently different to those experienced in the mountainous areas of Europe, United States or Canada. To the authors' knowledge, these results are the first distributions of impact energy proposed for specific geological areas.

HERE FIGURES 12a AND 12b (small column size)

The 95th percentile of the impact energy from the distribution for each geological situation is presented in Table 2, together with the mean block radius. The values of the 95th percentile are still fairly low, at least for three out of the five geological situations.

Such data can be used to design standard barriers for use in the different geological situations on the basis of an accepted level of risk. Note that this would only be satisfactory to account for the general situation, and that site specific assessment should be used to confirm the assumptions made in this work. The values of the impact energy presented herein are not a substitute for a detailed rockfall analysis on a specific site.

Table 2. Mean block radius and 95th percentile of impact energy for different geological situations

Geological situation	Mean Block radius (m)	Impact energy 95th percentile [kJ]
SBS	0.45	1340
FBS	0.27	170
B	0.15	17
G	0.45	1770
FBV	0.23	165

7. Conclusions

This paper demonstrates, through a stochastic analysis conducted on more than two hundred representative slopes, how regionally-specific geological data can be used to formulate generalised design loadings for rockfall protection structures in different geological settings. This study employed previous experimental results characterizing the restitution coefficients and rolling coefficients of the different geological situations (Spadari et al., 2011) and statistical distribution of block sizes (Fityus et al., 2012) for five geological settings prone to rockfall in New South Wales, Australia.

A new lumped mass model, NURock, specifically developed for the purpose of the research, includes the possibility for the normal restitution coefficient k_n to be greater than unity. Furthermore, it also includes a relationship establishing the dependence of k_n on the impact angle. Some preliminary validation results, which compare NURock predictions with field measurement data, confirm that the inclusion of k_n values greater than unity leads to more realistic predictions of block motion.

The outcomes of the stochastic analysis of the slopes confirm that the rockfall hazard in New South Wales involves values of energy much lower than those typically encountered in the mountainous areas of Europe, USA or Canada. Indeed, for two out of five situations, the mean impact energy is only about 200 to 300 kJ, and for the other three, it is below 100 kJ. In this work, the 95th percentile of impact energy was suggested as a possible input value for design, although the results allow for values at any confidence level to be considered. The 95th percentile values are obviously higher than the mean values but still do not exceed 200 kJ for three of the studied situations (Basalts, Fold Belt Sandstones and Fold Belt Volcanics) or 2000 kJ for the other two (Granites and Sydney Basin Sandstones). The results presented here provide quantitative data that could be used as a basis to develop a range of standard protection structures for lower energy rockfall environments.

The analyses presented here have focused specifically on the geological settings of Eastern Australia, but their applicability extends beyond this. They are potentially useful for any environment of hilly terrain where source rocks detach from close to the ground surface and where the geological characteristics of the rocks are similar. More specifically, provided that the geological origin, subsequent tectonic history and surface environments

are similar, the results are generally applicable to any region where moderate rockfall hazards exist. The geological settings studied here are by no means unique to Eastern Australia, but are widespread throughout the world. A more detailed consideration of this is provided in Fityus et al. (2012).

8. Acknowledgement

The authors would like to thank the Australian Research Council and the Roads and Maritime Services of New South Wales for their financial support. They would also like to thank the University of Newcastle, for its support of the Priority Research Centre for Geotechnical and Materials and Modelling.

References

- Ayala, F.J., Cubillo, S., Álvarez, A., Domínguez, M.J., Laín, L., Laín, R., Ortiz, G., 2003. Large scale rockfall reach susceptibility maps in La Cabrera Sierra (Madrid) performed with GIS and dynamic analysis at 1:5,000. *Nat. Haz.* 30, 325–340.
- Azzoni, A., de Freitas, M., 1995. Experimentally gained parameters, decisive for rock fall analysis. *Rock Mech. Rock Eng.* 28(2), 111–124.
- Azzoni, A., Rossi, P.P., Drigo, E., Giani, G.P., Zaninetti, A., 1992. In situ observations of rockfalls analysis parameters, in: *Proceedings of the 6th international symposium on landslides*. Christchurch, pp. 307–314.
- Bourrier, F., Dorren, L.K.A., Nicot, F., Berger, F., Darve, F., 2009. Toward objective rockfall trajectory simulation using a stochastic impact model. *Geomorphol.* 110, 68–79.
- Bourrier, F., Hungr, O., 2011. Rockfall Dynamics: A Critical Review of Collision and Rebound Models, in: Lambert, S., Nicot, F. (Eds.), *Rockfall Engineering*. Wiley, pp. 175–209.
- Bozzolo, D., Pamini, R., 1986. Simulation of rock falls down a valley side. *Acta Mechanica* 63, 113–30.
- Branagan, D.F., Packham, G.H., 1967. *Field geology of New South Wales*. Science Press, Sydney.
- Buzzi, O., Giacomini, A., Spadari, M., 2011. Laboratory investigation on high values of restitution coefficients. *Rock Mech. Rock Eng.* 45(1), 35–43. DOI: 10.1007/s00603-011-0183-0

655 Buzzi, O., Spadari, M., Giacomini, A., Fityus, S., Sloan S.W., 2012. Experimental
656 testing of rockfall barriers designed for the low range of impact energy. Submitted to
657 Rock Mech. Rock Eng.

658 Cascini, L., Bonnard, Ch., Corominas, J., Jibson, R., Montero-Olarte, J., 2005.
659 Landslide hazard and risk zoning for urban planning and development, in: Hungr, Fell,
660 Couture, and Eberhardt (Eds.), Landslide Risk Management, Proceeding of the
661 International Conference on Landslide Risk Management, Vancouver, Canada. A.A.
662 Balkema Publishers, Taylor & Francis Group, London, pp. 199–235.

663 Chau, K.T., Wong, R.H.C., Lui, J., Lee, C.F., 2003. Rockfall hazard analysis for Hong
664 Kong based on rockfall inventory. Rock Mech. Rock Eng. 36(5), 383–408.

665 Chiessi, V., D'Orefice, M., Scarascia Mugnozza, G., Vitale, V., Cannese, C., 2010.
666 Geological, geomechanical and geostatistical assessment of rockfall hazard in San
667 Quirico Village (Abruzzo, Italy). Geomorphology 119(3–4), 147–161.

668 Dahlhaus, P.G., Miner, A.S., 2000. Estimating the occurrence of rockfalls in columnar
669 basalt, in: Proceedings of International Conference on Geotechnical & Geological
670 Engineering. Melbourne, Aust., pp. 19–24.

671 Dutton, A.J., Stocker, P.T., 2001. Rockfall Risk Assessment Burleigh Head National
672 Park. Australian Geomechanics 36(3), 43–48.

673 EOTA, 2008. Guideline for European technical approval of falling rock protection kits
674 (ETAG 027). February 2008, Brussels.

675 Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., Savage, W.Z., 2008.
676 Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning.
677 Eng. Geol. 102, 85–98.

678 Fityus, S.G., Giacomini, A., Buzzi, O., 2012. The significance of geology for the
679 morphology of potentially unstable rocks. Submitted to Eng. Geol.

680 Geobrigg, 2011. Declaration of conformity, Falling Rock Protection Barrier GBE-
681 5000A, No. 1301 – CPD – 0714, ETA – 11 / 0305.

682 Giani, G.P., 1992. Rock Slope Stability Analysis. Balkema, Rotterdam.

683 Giani, G.P., Giacomini, A., Migliazza, M., Segalini, A., 2004. Experimental and
684 theoretical studies to improve rock fall analysis and protection work design. Rock
685 Mech. Rock Eng. 37(5), 369–389.

686 Gordon, F.R., 1999. The Rockfall of Huzzas Cliff, Gracetown, Western Australia, in:
687 Proceedings, 8th Australia New Zealand Conference on Geomechanics. Hobart.

688 Herbert, C., Helby, 1980. A guide to the Sydney Basin. Bulletin 26. Dept Mineral
689 Resources. Geological Survey of NSW. D West, Government Printer NSW.

690 Hungr, O., Evans, S., 1988. Engineering evaluation of fragmental rockfall hazards, in:
691 Proceedings of the 5th International Symposium on Landslides. Lausanne, pp. 685–
692 690.

693 Hunter, A., Nicholson, T., Burgess, P., Brizga, V., 2011. Rockfall risk and remediation
694 on the Lake George escarpment. Australian Geomechanics 46(1), 1–12.

695 Johnson, D.P., 2004. The geology of Australia. Cambridge University Press,
696 Cambridge.

697 Johnson, R.W., Knutson, J., Taylor, S.R., 1989. Intraplate Volcanism in Eastern
698 Australia and New Zealand. Cambridge University Press, Sydney.

699 Jones, C., Higgins, J.D., Andrew, R.D., 2000. Colorado Rockfall Simulation Program
700 Users Manual for Version 4.0. Colorado Department of Transportation, Denver.

701 Kotze, G.P., 2007. An Assessment of Rockfall Frequency for the Coastal Cliff Lines of
 702 Pittwater Local Government Area, Sydney. *Australian Geomechanics* 42(1), 213–219.
 703 Maccaferri, 2007. Chapman’s peak drive, Cape Town, Western Cape. Case History.
 704 ZAF/CH/042: Eng-Rev 02, 2p.
 705 Mazengarb, C., 2005. The Tasmanian Landslide Hazard Map Series: Methodology;
 706 Record 2005/04, Tasmanian Geological Survey, Mineral Resources Tasmania,
 707 Department of Infrastructure, Energy & Resources, Hobart.
 708 Muraishi, H., Samizo, M., Sugiyama, T., 2005. Development of a flexible low energy
 709 rockfall protection fence. *Quarterly report of RTRI*, 46(3), 161–166.
 710 Pierson, L.A., Van Vickle, R., 1993. Rockfall Hazard Rating System: Participant’s
 711 Manual: Federal Highway Administration Publication SA-93-057.
 712 Piteau, D.R., Clayton, R., 1976. Description of the slope model computer rock fall
 713 program for determining rock fall distribution. D.R. Piteau and Associates.
 714 Pfeiffer, T., Bowen, T., 1989. Computer simulation of rockfalls. *Bull. Assoc. Eng.*
 715 *Geol.* 26(1), 135–146.
 716 Ritchie, A., 1963. Evaluation of rockfall and its control. *Highway Res. Rec.* 17, 13–28.
 717 RTA, 2001. Guide to Slope Risk Analysis Version 3.1 Roads and Traffic Authority,
 718 New South Wales, Australia (www.rta.nsw.gov.au).
 719 Spadari, M., Giacomini, A., Buzzi, O., Fityus, S., Giani, G.P., 2011. In situ rock fall
 720 testing in New South Wales, Australia. *Int. J. Rock Mech. Min. Sci.* 49, 84–93.
 721 doi:10.1016/j.ijrmms.2011.11.013
 722 Stevens, W., 1998. RocFall: a tool for probabilistic analysis, design of remedial
 723 measures and prediction of rock falls. M.A.Sc. thesis. Department of Civil
 724 Engineering, University of Toronto. Ontario, Canada.

725 Trad, A., Limam, A., Bertrand, D., Robit, P., 2011. Multi Scale Analysis of an
726 Innovative Flexible Rockfall Barrier, in: Lambert, S., Nicot, F. (Eds.), Rockfall
727 Engineering. Wiley, pp. 303–342

728 Vandewater, C.J., Dunne, W.M., Mauldon, M., Drumm, E.C., Bateman, V., 2005.
729 Classifying and assessing the geologic contribution to rockfall hazard. Environ. Eng.
730 Geoscience 11, 141–154.

731 Wu, S., 1985. Rockfall evaluation by computer simulation. Transportation Research
732 Record 1031, 1–5.

733 Young, R.W., 1983. Blockgliding in sandstones of the southern Sydney Basin, in:
734 Young, R.W., Nanson, G.C. (Eds.), Aspects of Australian sandstone landscapes.
735 Australian and New Zealand Geomorphology Group, Wollongong, pp. 31–38.

736

737

738