ARTICLE IN PRESS

International Journal of Rock Mechanics & Mining Sciences ■ (■■■■) ■■■–■■■

Contents lists available at SciVerse ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

In situ rockfall testing in New South Wales, Australia

M. Spadari [a], A. Giacomini [a,*], O. Buzzi [a], S. Fityus [a], G.P. Giani [b]

[a] Centre for Geotechnical and Materials Modelling, The University of Newcastle, Callaghan, NSW 2308, Australia
[b] Department of Earth Sciences, State University of Milan, Italy

ARTICLE INFO

Article history:
Received 19 April 2011
Received in revised form
18 October 2011
Accepted 20 November 2011

Keywords:
Rockfall
Bouncing
Rolling
Restitution coefficient
Rolling coefficient
In situ testing

ABSTRACT

Despite the significance of rockfall hazards in Australia, this phenomenon is still poorly characterised in many regional environments. In particular, the relationship between slope/rock properties and rockfall motion parameters needs better definition. In the context of rockfall prediction, it is important to quantify the normal and tangential restitution coefficients (referred to as k_n and k_t) and the equivalent rolling coefficient (μ), which are site-specific. Several series of rockfall tests have been conducted in three different geological environments in New South Wales. The results of the tests show a large variability of the motion parameters, which is due to the natural variability of the blocks and to the randomness of the impact positions. Also, values of k_n consistently and systematically higher than the benchmark values from the literature have been inferred. Despite there being no clear correlation between the restitution coefficients and the rotational energy, rotational phenomena are believed to be at the origin of such results.

1. Introduction

Rockfall typically represents a severe safety hazard, not only in mountainous areas but also along coastal routes, road cuttings or quarry faces. A single event, even if small in proportions, can endanger human lives and lead to elevated costs, due to the need to maintain or rebuild protection structures. A rockfall event involves the fall, along a slope, of one or more rock blocks or fragments, with volumes typically ranging between 10^{-2} and 10^2 m^3 [1].

In order to efficiently design protection systems, the description of which is outside the scope of this paper, it is crucial to estimate the trajectory and the energy of the blocks during their fall, and more specifically, upon impact with an aforementioned structure. This requires simulation of the rockfall and determination of the motion characteristics, which are generally site-specific. Indeed, the geological and morphological features of the slope (e.g. material, roughness and inclination) and the characteristics of the blocks (e.g. material, shape and size) strongly influence the block's trajectory [2]. Simulation of rockfall is usually performed using analytical (based on the conservation of angular momentum) [3,4] and/or numerical models [1,5–9]. Commercial softwares such as RocFall [10] or Colorado Rockfall Simulation Program (known as CRSP, [7,11]) are now commonly used to quantify the rockfall hazard for the design of protective structures. Specifically, they are used to statistically estimate energies and trajectories so that particular areas exposed to different levels of risk can be identified.

The block motion during a fall can be described as a series or combination of different phases: free-falling, sliding, rolling and bouncing [3,4,12], some of which are accounted for in the commercial codes. Free-falling phases are usually separated by bounces during which energy dissipation occurs. Free-falling is well described by a ballistic trajectory and does not require the use of a descriptor of the rock/slope interaction. This is, however, not the case for bouncing and rolling.

Estimating the dissipation of energy during a bounce is a key factor in the calculation of the block's trajectory. To do this, Bozzolo and Pamini [3] and Azzoni and de Freitas [12] used a single restitution coefficient based on the mechanical analysis of the interaction between the slope and an ellipsoidal block. However, distinct normal and tangential restitution coefficients (k_n and k_t) are more commonly used (e.g. [5,7]) in order to account for impact mechanisms. The normal restitution coefficient has usually been associated with energy dissipation due to the elasto-plastic response of the surface material, and the tangential restitution coefficient with the frictional dissipation of energy and the roughness of the surface. The restitution coefficients are considered to be the most effective parameters for a rockfall simulation, entailing the influence of a larger number of impact parameters [2].

Rockfall events occurring on slopes with inclinations lower than 45° are more likely to be associated with rolling behaviour [13].

---

* Corresponding author. Tel.: +61 249216254; fax: +61 249216991.
E-mail addresses: anna.giacomini@newcastle.edu.au, anna.giacomini@libero.it (A. Giacomini).

1365-1609/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijrmms.2011.11.013

Please cite this article as: Spadari M, et al. In situ rockfall testing in New South Wales, Australia. Int J Rock Mech Mining Sci (2011), doi:10.1016/j.ijrmms.2011.11.013

Block rolling can result in kinetic energy loss (if a block decelerates) or gain (if a block accelerates). A rolling phase can be represented as a rapid succession of small bounces and aerial rotations [7] or, assuming that the block is a perfect cylinder travelling down a smooth plane, the rock/slope interaction can be described through a rolling coefficient, which expresses the potential resistance to rolling. The result can be kinetic energy dissipation or gain [2,14].

Over the last decades, investigations of rockfall motion characteristics have mainly been carried out by means of in situ rockfall tests on real slopes and restitution coefficients have been inferred for a wide variety of geomorphological environments [2,12–18]. Although in situ tests have proven to be the most appropriate way to assess the motion parameters, due to the site sensitivity, some have raised criticism about the reliability of the results. Paronuzzi [19] suggested that the choice of the blocks (too rounded or weathered) and the testing sites (particularly quarry faces, often used for in situ tests) could have affected the representativeness of most of the k_n values in the literature. A back analysis on a real rockfall event, performed by Paronuzzi, highlighted k_n values much higher than the benchmarks from the literature.

Some tests have also been carried out in the laboratory to investigate more fundamental aspects of rockfall with control over specific critical parameters. In particular, blocks with regular shapes and smooth slopes with constant steepness have been used to highlight the effect of the impacting angle or slope angle on the restitution coefficients and other motion parameters [20–24]. Undoubtedly, these controlled tests are useful to identify trends, but trends are difficult to extrapolate to real events because of the natural variability and randomness of a rockfall event in a natural situation.

The rockfall hazard has been investigated for different geological and morphological Australian environments [25–31]. However, its quantitative characterisation is still poor, mainly because the site-sensitivity requires an adequate database of motion parameters, which can only be acquired by means of in situ tests.

A better understanding of the rockfall hazard could lead to the design of protection structures (barriers) specifically adapted to the Australian environment whereas most of the current knowledge comes from research conducted in European or North American alpine areas. In these areas large blocks of rocks, or sections of rock mass can detach from high cliffs in steep, topographically-immature valleys, resulting in high values of impacting energies, which have biased evolutions in the analysis and design of protection structures. As a result, the existing literature is deficient in data of specific relevance to low and medium energy barriers (with design energy ranging from 4 to 100 kJ), which consequently tend to be overdesigned, in the context of the Australian environment.

This paper presents the results of four series of in situ rockfall tests performed on natural slopes with low inclination in different geological environments of New South Wales, Australia. This is the first time this type of tests and analysis has been carried out in Australia. The objective of these series of tests is to provide some quantitative data about rock slope interaction and rockfall motion characteristics for some typical geological situations of New South Wales. High definition cameras have been used to capture block motions and to quantify velocity and energy. As a result, the restitution coefficients (k_n and k_t), the equivalent rolling coefficient μ and the energy balance upon impact have been back-calculated. Although the values of the rolling coefficients and tangential restitution coefficients are in accordance with data from the literature, the normal restitution coefficients exhibit values above the upper bound commonly accepted. These results corroborate the outcomes from Paronuzzi [19] and the discussion proposes an explanation for the physical reasons of such findings and their significance for the design of the protection systems.

2. Experimental testing

2.1. Testing sites

New South Wales has a diverse geology that can be characterised into a number of distinctive settings [32]. Rockfall problems are typically uncommon over much of the inland, which is relatively flat and covered by recent sediments. Along the topographically-elevated eastern margin (Fig. 1), there are extensive regions of moderately deformed sedimentary rocks of Ordovician

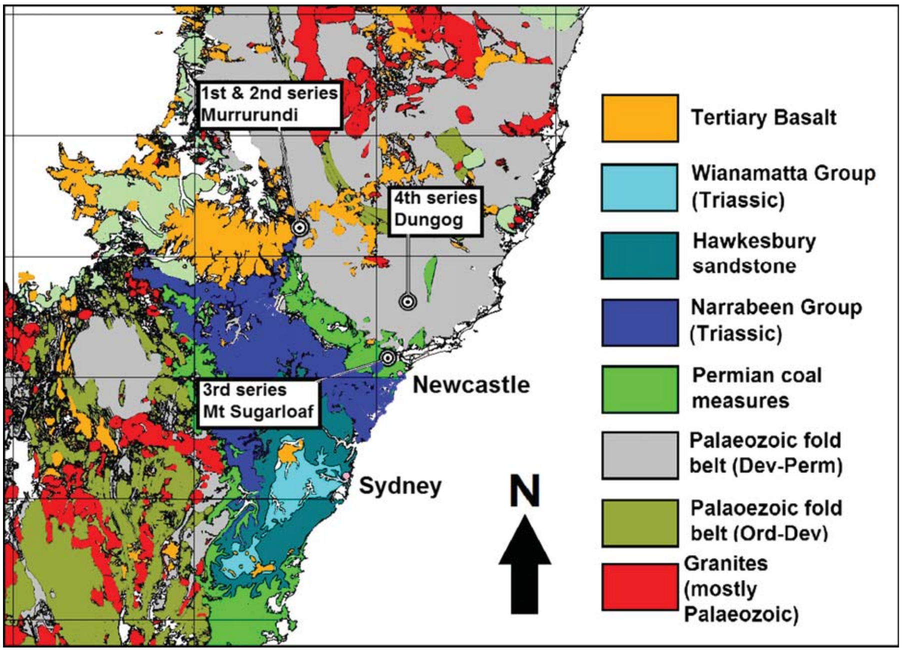

Fig. 1. Main geological areas related to rockfall hazard in New South Wales and locations where the rockfall tests were performed.

Please cite this article as: Spadari M, et al. In situ rockfall testing in New South Wales, Australia. Int J Rock Mech Mining Sci (2011), doi:10.1016/j.ijrmms.2011.11.013

to Carboniferous age in "fold belt" settings, which include some volcanics and localised metamorphics of relatively low grade. These are intruded by granitoids in many areas and they are overlapped in the central region by relatively undeformed sedimentary basin rocks of Permian and Triassic age, such as Narrabeen and Hawkesbury sandstones [33]. Tertiary basalts occur frequently as capping layers on the Great Dividing Range, which runs parallel and adjacent to the eastern seaboard (not shown here).

Several aspects were accounted for when selecting the geological areas of testing: (1) the geological features and their potential to produce a rockfall event, (2) the level of urban and economic development, which is a component of the concept of risk and (3) as the main task of this research is an investigation on low (4 kJ) and medium energy barriers (up to 100 kJ), the granites were not tested since they tend to form big, rounded boulders, and their associated rockfall behaviour is characterised by high impacting energies, even for low steepness slopes. On the basis of these considerations, three testing sites were identified as adequate and representative of the geological areas to which they belong.

2.1.1. *Murrurundi, Hunter Valley*

Two tests series were carried out on separate slopes in the upper Hunter Valley (Murrurundi, NSW) in an area characterised by deeply weathered Tertiary basalt rocks of the Liverpool Ranges. In this area, the basalts are dominantly alkali basalts and the slopes generally consist of slopewash and residual gravelly clays derived from underlying basalt parent rock [34]. Natural blocks outcropping in the area were used for the tests (the block characteristics are given together with the experimental programme). The results from these two series are presented together, since they belong to the same geological environment. The first slope considered was 19 m long, with average inclination around 22°, varying locally between 20° and 22.5° (Fig. 2(a)). The second slope was 27 m long, with an average inclination of 24.5° in the first 15 m and of 20° over the remainder of the slope (Fig. 2(b)).

2.1.2. *Mount Sugarloaf, Newcastle*

The third series of tests were performed on the slopes of Mount Sugarloaf, to the west of the city of Newcastle (NSW). This site is situated in the Triassic Narrabeen group, comprising undeformed, thickly-bedded quartz sandstones. This geological environment is representative of the Narrabeen group and the Hawkesbury sandstone, which are the predominant geologies of the greater Sydney region. The blocks tested consisted of sandstones and some pebbly sandstones/conglomerates. The slope used for the tests presented a layer of colluvial sandy soil with some outcropping rocks and low vegetation. Overlapping video cameras covered a 36 m long portion of the slope, with an inclination of 24° in the first part and 31° over the remainder of the slope (Fig. 2(c)).

2.1.3. *Dusodie, Dungog*

The fourth series of tests were conducted in an area of dipping volcanogenic, lithic sandstones of Carboniferous age from the Flagstaff formation, of the Gresford Block of the southern New England Fold Belt [35]. These occur extensively throughout the more heavily populated areas to the north of Sydney. The test site, at Dusodie near Dungog, comprised a grassy slope with scattered rock debris and occasional low outcrops of sandstone. The total length of the slope was around 80 m, with inclination increasing from 17° to 25° in the four identified sections (Fig. 2(d)).

Again, because the study is focused on low and medium energy barriers (typical values), blocks with masses lower than 500 kg and slopes with low inclinations (less than 35°) have been chosen for the three test sites.

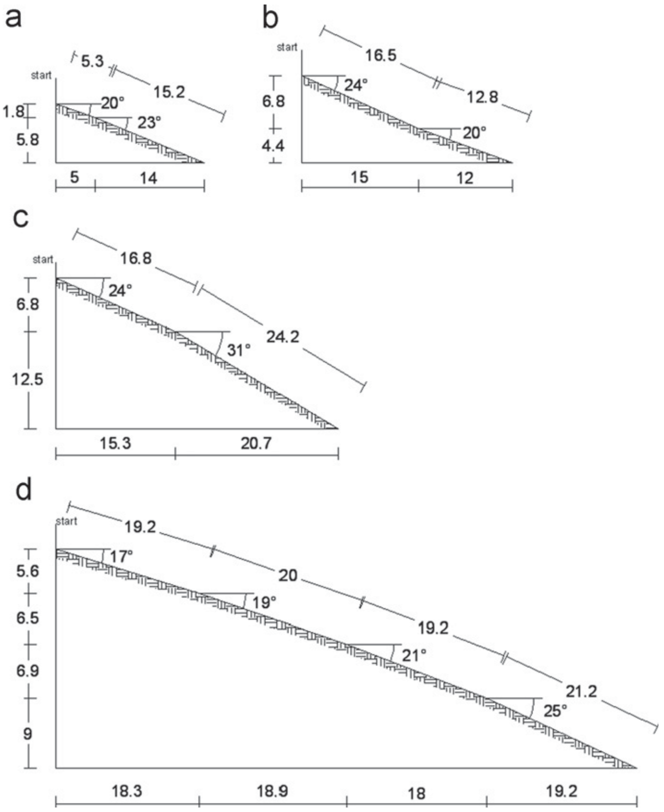

Fig. 2. Cross sections of the test sites for the four test series. First series (a), second series (b) were performed in Murrurundi; third series (c) were performed at Mount Sugarloaf; fourth series (d) were performed in Dungog. Lengths are in metres.

2.2. *Experimental setup and data acquisition*

In a manner consistent with many authors, the tests were conducted by recording the travel of the blocks down the slope using medium and high-speed cameras [2,12,14–18,36]. The photograph sequences allowed tracking of the blocks and determination of the motion and bounce characteristics. Up to four high-definition video cameras with a maximum speed of 50 frames per second were used. These were placed along the slope with overlapping fields of view as illustrated in Fig. 3(a), with one operator per camera. The sequences of photographs were analysed using the image tracking software TEMA 3.3, which can determine the position, speed and acceleration of a series of target points.

The blocks were spray-painted before testing to clearly identify the target points (typically, the centre of mass) and for a better identification of the faces during the fall (Fig. 3(b)). This was crucial for the estimation of the rotational energy of the blocks from the recorded images, as explained in the next section. The release of the block was manual.

2.3. *Calculations of the motion parameters*

The results of the tests will be discussed in terms of restitution coefficients, rolling coefficients, translational energy and rotational energy. The restitution coefficients, which quantify the energy dissipation upon an impact, are calculated as follows

$$k_n = -\frac{v_n^{post}}{v_n^{pre}}, \quad k_t = \frac{v_t^{post}}{v_t^{pre}} \tag{1}$$

Please cite this article as: Spadari M, et al. In situ rockfall testing in New South Wales, Australia. Int J Rock Mech Mining Sci (2011), doi:10.1016/j.ijrmms.2011.11.013

where k_n and k_t are the normal and tangential restitution coefficients, respectively, v_n^{pre}, v_n^{post} are the normal components and v_t^{pre}, v_t^{post} are the tangential components of the block's velocity, before and after the impact, respectively. This definition is the most commonly adopted in the literature (e.g. in [5,20,37]). Note that the high speed camera images reduce the 3D motion to a 2D analysis but this is not considered to be an issue as little deviation was observed from the expected, almost linear path.

The rolling coefficient μ, which finds its origin in tribology, is used to quantify the resistance to rolling or the amount of work required to make a block roll. The rolling coefficient as used in rock mechanics is a simplification of the real motion. The boulder is assumed to be a cylinder rolling down a smooth plane of inclination α [14]. For this configuration, and because of the amount of energy dissipated due to rolling resistance, a block having an initial velocity v_i (at a given point) has a velocity v_{i+1}, after having travelled an effective distance d, equal to:

$$v_{i+1} = \sqrt{v_i^2 + 2gd(\sin\alpha - \mu\cos\alpha)} \tag{2}$$

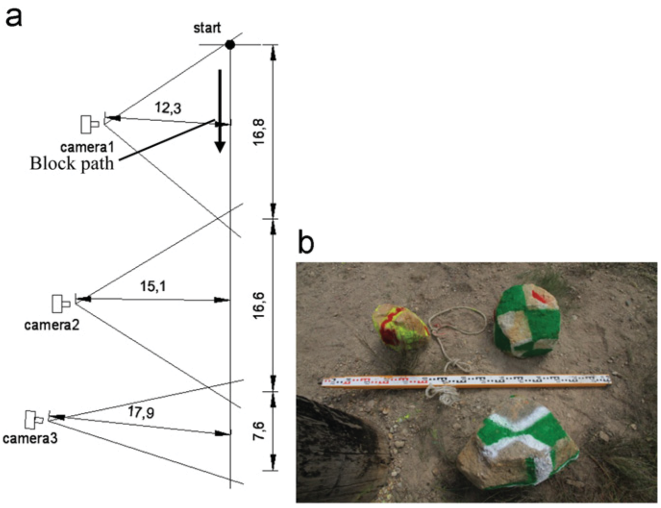

Fig. 3. Third series of tests: (a) plan of the site with camera positions (lengths in metres); (b) spray-painted sandstone and conglomerate blocks.

where α is the slope angle (considered as a constant along the section) and g is the acceleration due to gravity. The rolling motion along a slope section can then be described by the equivalent rolling coefficient μ:

$$\mu = tg\alpha + \frac{v_i^2 - v_{i+1}^2}{2gd\cos\alpha} \tag{3}$$

The rolling coefficient provides an evaluation of how the block tends to accelerate (if $\mu < \tan\alpha$, then $v_{i+1} > v_i$) or decelerate (if $\mu > \tan\alpha$, then $v_{i+1} < v_i$) along a slope with known inclination, over a certain distance. As with the restitution coefficients, different effects of the interaction between the block and the slope, such as friction and roughness, are included in derived values of μ. Two approaches have been followed to calculate the rolling coefficient [14]. These two methods consist of a regular measurement of the block's velocity along the slope (intervals of 8–12 frames) and of a curve fitting exercise between the experimental values and the theoretical curves coming from Eq. (2). The difference between the two methods lies within the way the rolling coefficient is allocated to the slope. In the first method, a single value is attributed to the whole slope whereas in the second method, the slope is divided in sub-sections having different rolling coefficients.

The effects of rotation on the block's motion during an impact have been investigated by assessing the rotational and translational energy before and after the impact. The total energy of the block, expressed in Eq. (4), is the sum of the translational (E_v) and the rotational (E_r) components:

$$E_t = E_v + E_r = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 \tag{4}$$

where m is the boulder mass, v is the velocity, I is the moment of inertia around the rotation axis and ω is the angular velocity. For each block an average moment of inertia has been considered in order to take into account the variations of the rotational axis during the fall. The angular velocity ω was calculated by evaluating the rotation of an axis on the block over a certain number of frames. The rotational energy was then estimated.

2.4. Experimental programme

The experimental programme is summarised in Table 1, presented below. Over the four series, the block mass and volume

Table 1
Summary of the testing programme.

1st series–(Liverpool Range) Alkali Basalts–21 blocks																					
Test no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
m (kg)	85	85	85	85	85	113	56	56	172	27	27	27	60	60	82	81	81	81	81	42	42
Slope angle	20°–22.5°																				
2nd series–(Liverpool Range) Alkali Basalts–19 blocks																					
Test no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19		
m (kg)	131	59	47	36	36	145	43	36	36	36	24	70	70	20	21	21	37	109	24		
Slope angle	24.5°–20°																				
3rd series-(Narrabeen) Quartz Sandstones+Conglomerates–13 blocks																					
Test no.	1	2	3	4	5	6	7	8	9	10	11	12	13								
m (kg)	72	60	76	62	66	129	29	57	57	24	116	196	160								
Slope angle	24°–31°																				
4th series-(Flagstaff Fm) Lithic Sandstones–40 blocks																					
Test no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
m (kg)	84	187	101	22	39	100	44	75	19	19	12	5	73	106	85	45	50	162	18	26	
Test no.	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	
m (kg)	97	375	58	212	22	25	47	76	26	294	140	34	31	62	97	14	47	39	30	24	
Slope angle	17°–25°																				

Please cite this article as: Spadari M, et al. In situ rockfall testing in New South Wales, Australia. Int J Rock Mech Mining Sci (2011), doi:10.1016/j.ijrmms.2011.11.013

ranged from 5 to 375 kg (mass measured on site with a portable scale) and 0.002 to 0.145 m^3, respectively. For all the series, the size of the boulders was representative of the typical dimensions related to the geology of the area.

In total, 93 tests were performed. Note that not every test gave conclusive results in terms of restitution coefficients or rolling coefficients. Some of the tests did not produce any bouncing at all, showing only a rolling behaviour, while for other tests the rock bounced several times. Moreover, in some tests the rotation of the block could not be clearly identified due to difficulties during the image processing. For these reasons, the number of results presented is different to the number of tests performed.

3. Results and discussion

3.1. Determination of the restitution coefficients

A total of 102 bounces from the four series were used to calculate the restitution coefficients, after the recorded images were deemed as suitably clear and consistent to support reliable interpretations. The calculations are based on the analysis of the image sequences, and more particularly, on the velocity estimates, pre and post impact. With a known photographic frame rate, the velocity is inferred from the distance covered by the centre of mass of the boulder over a given number of frames. Here, three frames have been used before impact and three after impact, for which the distance covered by a block typically ranges from 0.25 to 1.25 m. The accuracy of measurement ranges between 0.001 and 0.027 m (depending on the photograph resolution and on the position of the cameras), which yields errors between 0.1 and 10% in the measurement of distances. Image distortion has not been taken into account in the measurement.

The average values obtained for k_n and k_t over the four series are reported in Table 2 together with minimum, maximum and standard deviation. It can be seen that the tangential restitution coefficients are slightly higher but generally consistent (Fig. 4) with the benchmark from the literature [5,14–18,38,39], which for grassy surfaces covered with debris, have generally reported k_t values from 0.20 to 0.96.

However, the values for the normal restitution coefficients are significantly higher than the values normally reported and adopted [2]. In particular, average values greater than unity have been obtained for each of the four series. This could be considered abnormal as a k_n of one can be viewed as corresponding to a perfectly elastic shock. However, this pre-conceived idea is not reflected by the most commonly adopted definition for the restitution coefficients (Eq. (1)) since the normal and tangential components are uncoupled. When considering only the translational component of energy, which is generally the case, a perfectly elastic shock, i.e. no energy dissipation, would mean a ratio of total velocity post impact over total velocity pre impact v^{post}/v^{pre} equal to 1 (the upper bound considered in [4]). Such a value was never reached for any of the tests performed herein, meaning that in every case, translational energy was not conserved upon impact.

Table 2
Statistics of the restitution coefficients for the four series of tests.

Type of rock	Basalts (1st/2nd series)		Quartz sandstones (3rd series)		Lithic sandstones (4th series)	
Location	Murrurundi		Mount Sugarloaf		Dungog	
	k_n	k_t	k_n	k_t	k_n	k_t
Min	0.38	0.37	0.68	0.54	0.43	0.54
Max	1.98	0.94	1.79	0.93	1.85	0.96
Average	1.06	0.74	1.15	0.73	1.18	0.78
Standard deviation	0.41	0.14	0.28	0.13	0.32	0.09

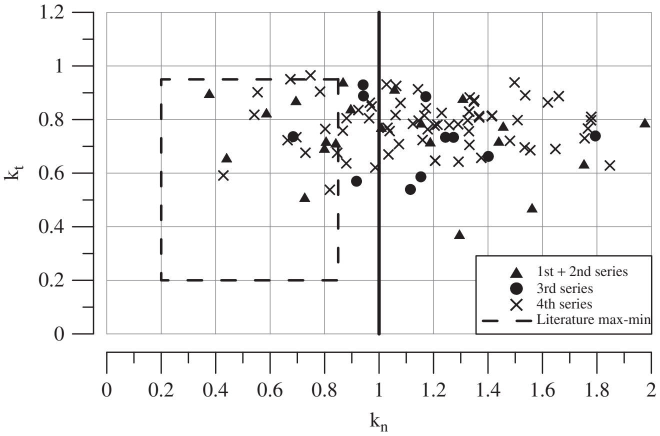

Fig. 4. Experimental values of restitution coefficients and minima/maxima from the literature for a similar type of slope (short vegetation with debris).

Table 3
Experimental restitution coefficients for the first, second and third series.

Weathered basalts (1st/2nd series)				Quartz sandstones (3rd series)	
k_n	k_t	k_n	k_t	k_n	k_t
0.38	0.90	1.56	0.47	0.68	0.74
0.59	0.83	1.30	0.37	1.24	0.73
0.81	0.72	0.73	0.51	1.12	0.54
1.98	0.79	1.44	0.72	1.27	0.73
1.46	0.78	0.69	0.87	1.40	0.66
0.90	0.84	1.15	0.79	0.94	0.93
0.87	0.94	0.44	0.66	0.94	0.89
1.01	0.77	0.80	0.69	1.55	0.71
1.31	0.88	1.19	0.72	1.17	0.85
1.06	0.91	1.75	0.63	1.15	0.59
		0.84	0.71	0.92	0.57

Table 4
Experimental restitution coefficients for the fourth series.

Sandstones (4th series)							
k_n	k_t	k_n	k_t	k_n	k_t	k_n	k_t
0.78	0.90	1.14	0.91	1.38	0.66	1.08	0.86
1.21	0.78	1.21	0.65	1.66	0.89	1.54	0.89
0.43	0.59	1.77	0.77	1.06	0.93	1.23	0.82
1.35	0.87	1.21	0.65	0.66	0.72	1.12	0.78
1.51	0.80	1.26	0.78	1.33	0.83	1.29	0.64
1.17	0.82	1.65	0.69	1.04	0.76	1.15	0.80
1.33	0.71	1.06	0.82	0.88	0.64	1.33	0.88
0.82	0.54	1.75	0.73	1.35	0.87	0.70	0.73
1.33	0.80	1.62	0.86	1.53	0.70	0.67	0.95
0.55	0.90	1.50	0.94	1.18	0.76	1.33	0.76
0.97	0.86	1.78	0.80	1.03	0.67	0.54	0.82
1.37	0.81	1.07	0.71	1.16	0.72	1.48	0.72
1.03	0.93	0.99	0.62	1.56	0.69	1.42	0.81
1.20	0.78	0.96	0.81	0.87	0.76	0.88	0.81
0.80	0.77	1.41	0.81	0.92	0.84	1.37	0.81
0.85	0.68	1.85	0.63	0.97	0.85	1.78	0.81
1.03	0.77	0.73	0.68	1.17	0.84	0.75	0.96
1.29	0.78	1.33	0.83				

Tables 3 and 4 report the k_n and k_t values for all the four series of tests. Fig. 4 shows the detailed results with k_t plotted as a

Please cite this article as: Spadari M, et al. In situ rockfall testing in New South Wales, Australia. Int J Rock Mech Mining Sci (2011), doi:10.1016/j.ijrmms.2011.11.013

function of k_n for the four series. It also shows the range of typical values from the literature that would be adopted for a slope covered by vegetation and debris. The results are extremely scattered with ranges of 0.37 to 0.96 for k_t and 0.38 to 1.98 for k_n. Performing the tests in a natural environment, using natural blocks, leads to a large and unavoidable variability (already assessable from the minima and maxima in Table 2). As already discussed, a significant number of k_n values are over unity and also, a large number of k_t values are very close to unity, which is equally unusual. Note that Paronuzzi [19] found that to reproduce an existing rockfall event, values of restitution coefficient greater than one had to be attributed to the slope and Bourrier et al. [24] predicted k_n values much higher than 1 for low incident angles using a stochastic impact model. However, we believe it is the first time values greater than one are consistently and systematically reported as a result of in-situ tests.

There is nothing to suggest that the measurements here were plagued with a systematic error that could explain these results. First, the methodology employed is common for rockfall testing. Second, the sensitivity of the coefficients to the number of frames used in their determination has been assessed, and the approach used was found to provide reliable results. This was done by considering the effect that a larger number of frames would have on the estimated velocities, given that the parabolic trajectory is being approximated by a linear tangent drawn from the point of impact (see Fig. 5). The effect is shown to be a systematic error to both the post and pre impact velocities so that, for greater than 3 frames, the effect is barely noticeable on the restitution coefficients. The error has been found to be consistently about 10% for 6, 9 and 12 frames. Fig. 5 also provides a visual evidence of k_n greater than one.

Azzoni et al. [18] have imputed high values of restitution coefficients to the combination of rolling and bouncing with high rotational moments (see Fig. 6). A similar configuration was described by Paronuzzi [19]. It is herein believed that it is a combination of rotational energy, block angularity and low impacting angle which is at the origin of such results. The configuration of the block at impact (i.e. the position of the centre of mass with respect to the impact point) is also believed to play a key role in the determination of k_n. The significance of all these parameters has been recently shown in [40]. Fig. 6 shows how a rotating, angular block can impact on an edge/point, causing it to flip and be catapulted away from the slope. As a result, the bouncing angle exceeds the impacting angle (Fig. 5) causing the post impact normal velocity to exceed its corresponding pre-impact value. The exact mechanism or combination of parameters leading to this outcome is currently under investigation. The variability of the block shape and of the trajectory explains the high variability of the results.

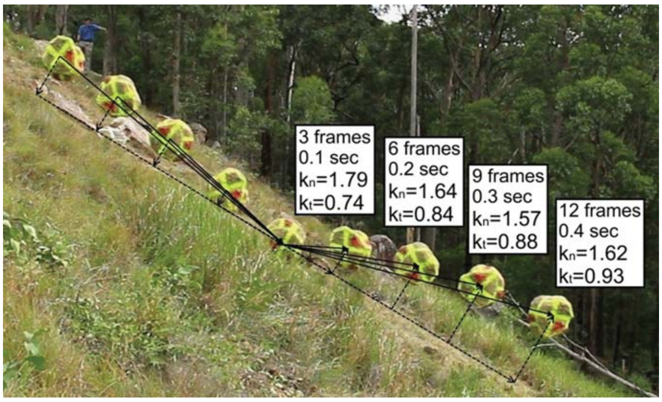

Fig. 5. Example of calculations of k_n and k_t using different frame intervals and visual evidence that the normal velocity post-impact is greater than the normal velocity pre-impact, i.e. $k_n > 1$.

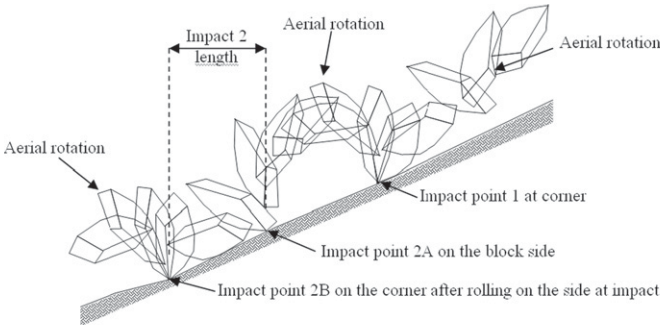

Fig. 6. Block no. 4, 2nd series: frame by frame analysis of two consecutive bounces with different impact dynamics (after [37]).

In an attempt to better understand the significance of the rotational energy on the restitution coefficients, Fig. 7 has been proposed. It shows the experimentally determined values of k_n and k_t as a function of the rotational energy pre-impact, for the tests where the latter parameter could be estimated. For the calculation of the rotational energy, an accurate estimation of the moment of inertia has been possible only for the blocks exhibiting a clearly recognisable shape (e.g. discs or spheres). When this was not possible, the blocks were considered as cuboids. The value of the moment of inertia was kept constant before and after the bounce: this is an accurate assumption for spherical and discoidal blocks and a reasonable approximation for cuboidal blocks (the change in the rotational axis is usually small and difficult to estimate accurately).

As previously described, the angular velocity estimation depends on the correct evaluation of the rotation of the block about an axis, over a certain number of frames: this estimation is therefore subject to the same kind of error highlighted for the translational velocity. Although the rotational energy evaluation is influenced by the calculations of the moment of inertia and the angular velocity of the block, the estimated variation of rotational energy during a bounce is considered reasonable. Unfortunately, the supposed influence of rotational energy on the restitution coefficients cannot be confirmed by Fig. 7 due to the high variability of the tests. No attempt has been made to sort the results according to the impact type in order to evidence a correlation.

3.2. Equivalent rolling coefficients

The rolling coefficients have been determined for a total of 23 blocks and the results are presented in Fig. 8 as a function of the slope angle. It can be seen that, similar to the restitution coefficient results, the rolling coefficient results are highly variable. Again, this is due to the inherent variability of a natural environment. The values here obtained are in relatively good accordance with those from the literature for similar types of slope [4,14].

Interestingly, the values of rolling coefficient available in the literature depend mainly on the type of slope and little on the block type. However, the underlying model used is that of a cylinder rolling on a plane. It follows that the further the block shape is from a cylinder, the less applicable is the model. This issue can be illustrated when applying two different approaches [14] to block number 3 of the fourth series (see Fig. 9). In the first approach a single μ value was used for the entire slope, whereas in the second method, different μ values were used corresponding to several sections along the slope. Fig. 9 shows the difference

Please cite this article as: Spadari M, et al. In situ rockfall testing in New South Wales, Australia. Int J Rock Mech Mining Sci (2011), doi:10.1016/j.ijrmms.2011.11.013

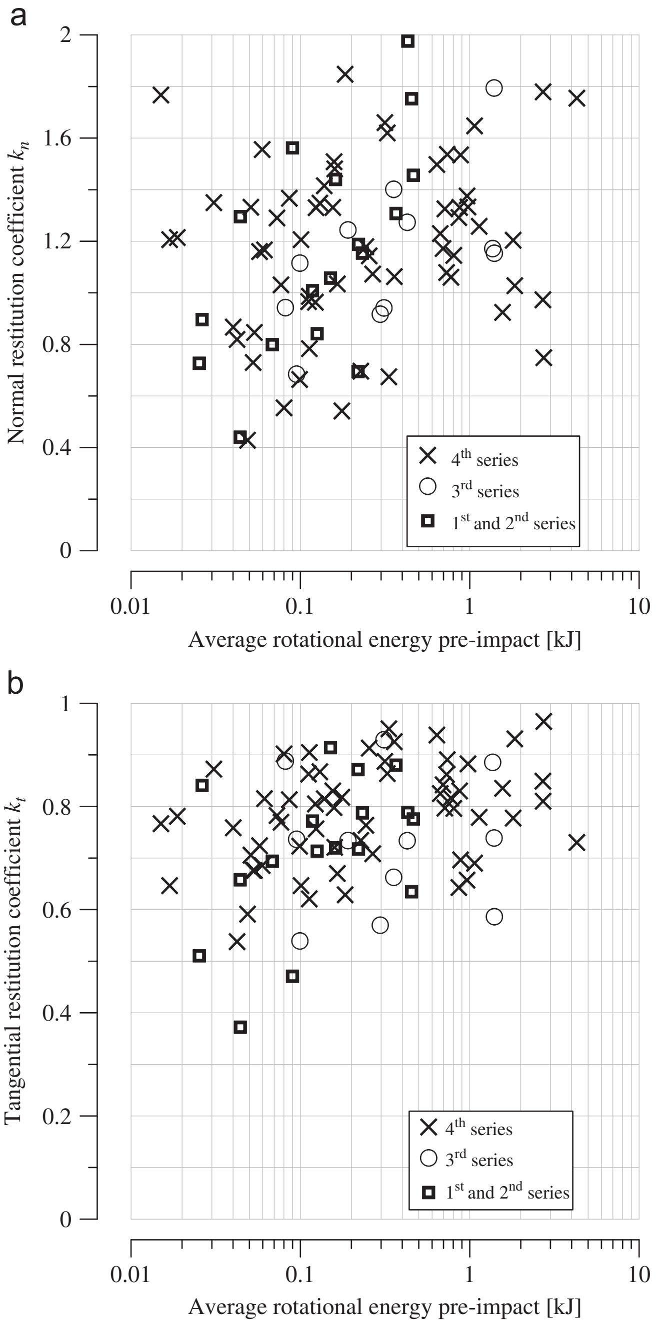

Fig. 7. k_n and k_t vs. rotational energy pre-impact for the four series of tests.

between the application of the two methods, considering a rolling coefficient value adjusted to obtain the highest correlation factor R^2. An R^2 of 0.238 was determined adopting a single value of μ for the entire trajectory whilst an R^2 of 0.609 was achieved when different μ values were assigned to each sub section. The better fit with the experimental data, achieved by subdividing the slope in sections and using multiple rolling coefficients, is in accordance with the findings of [14].

A single μ value tends to predict an increase of the block velocity towards the end of the slope, which is consistent with having a perfect cylinder on a 25° slope. The reality is quite different and highly variable, due to the natural irregularities of both the slope (especially in the last section) and the block (scattering of the data in Fig. 9). In that case, multiple rolling coefficients are better adapted.

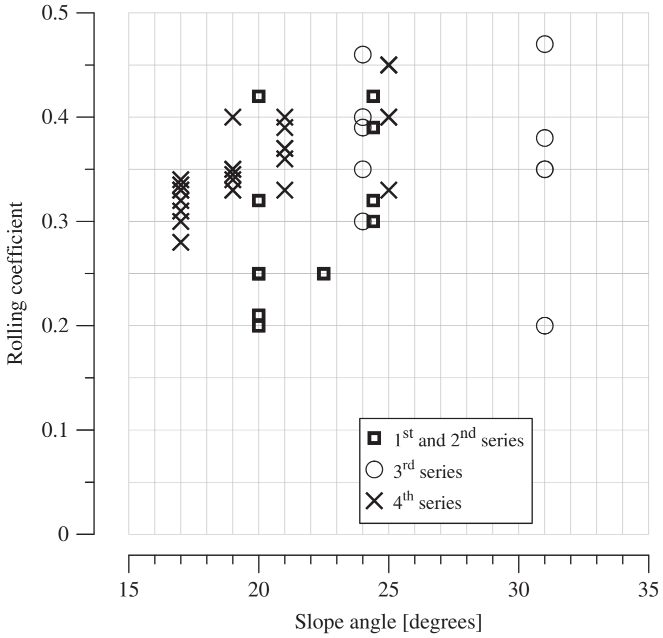

Fig. 8. Values of the rolling coefficients determined for the four series as a function of the slope angle. Values determined per section of slope.

A study of the match/discrepancy between the two methods for the 23 measurements showed that if the conditions are met to facilitate the sustained rolling of the block (i.e. rounded block and steep slope) then using a single rolling coefficient for the whole slope is a valid approach. On the contrary, if the rolling is impeded, e.g. by an angular block, a gentle slope or a varying roughness, then the block does not behave like an ideal cylinder but it decelerates. In that case, a different approach, where the rolling coefficient is increased to reflect the deceleration on a particular slope, must be employed. For the test site of Dungog, most of the blocks were angular and prismatic and the roughness was higher in the fourth section of the slope. However, one block, a rounded ellipsoid, did give consistent results for the two approaches (see Fig. 10). With such a round shape, the block could accelerate despite a relatively gentle slope (25°). For the tests of Mount Sugarloaf the slope was steeper (31°), and only one block did not accelerate, as predicted, when adopting a single μ value; this block was angular prismatic. All other blocks were rounder and a good match was found between the two approaches. In conclusion, it seems that in order to decide whether one or more rolling coefficient has to be used, one should start with a single value and qualitatively assess the block's motion (phases of acceleration and deceleration). If these phases are unlikely to occur, considering the slope angle and the blocks in presence, then several rolling coefficients might be considered.

3.3. Energy considerations

A further investigation has been conducted in order to quantify the variations of the different components of energy upon impact. To do so, the experimental values of rotational and translational energy were estimated before and after impact using Eq. (4) in Section 2.3. Although it has been confirmed that the translational energy always decreases upon impact (see Section 3.1), there is no certainty about the change in rotational energy upon impact. Fig. 11 shows the comparison between the variations in the total energy and in the translational energy (only) before and after an impact (each in terms of

Please cite this article as: Spadari M, et al. In situ rockfall testing in New South Wales, Australia. Int J Rock Mech Mining Sci (2011), doi:10.1016/j.ijrmms.2011.11.013

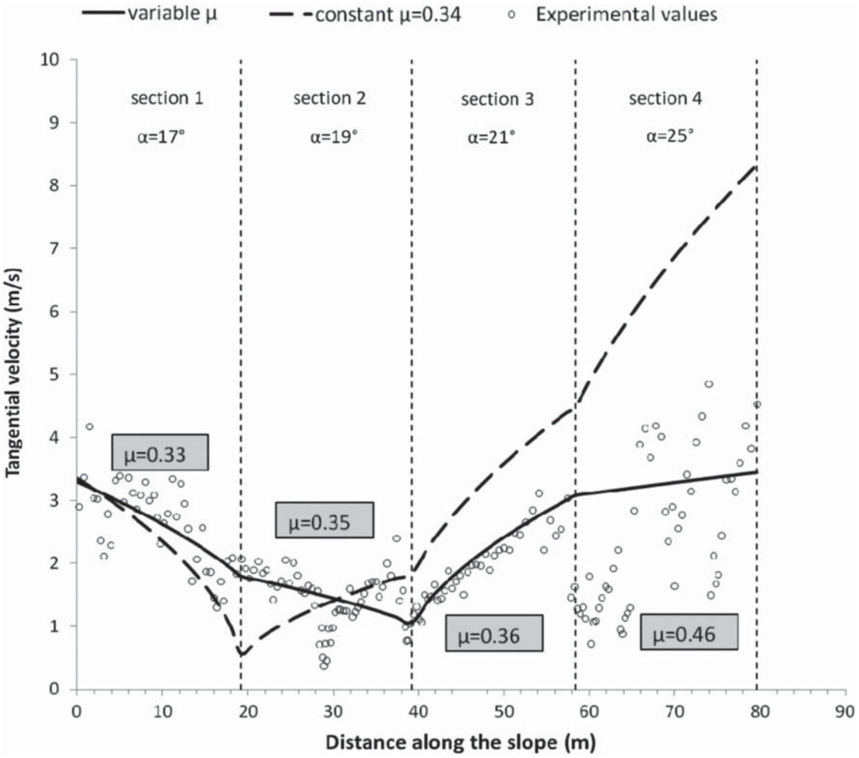

Fig. 9. Block no. 3, 4th series: comparison between experimental values and theoretical curves.

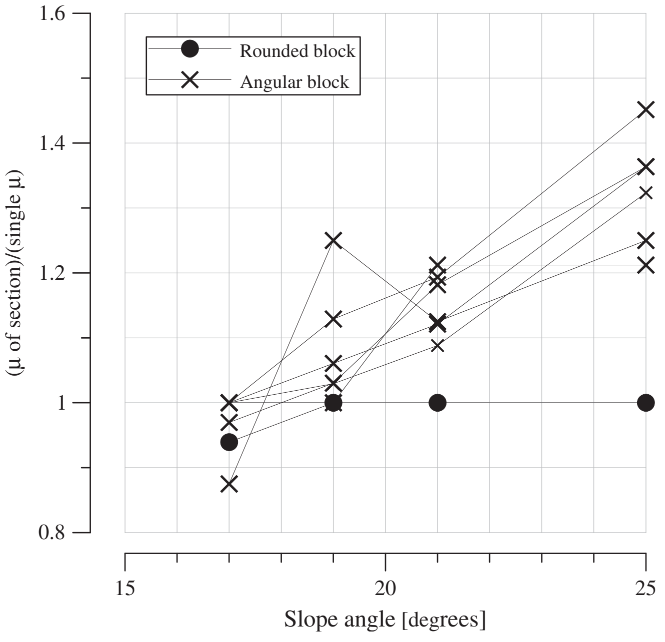

Fig. 10. Comparison of the two methods to determine the rolling coefficient: ratio of rolling coefficient per section over the single rolling coefficient value as a function of slope angle. Test site of Dungog, test where rolling occurred on the four sections.

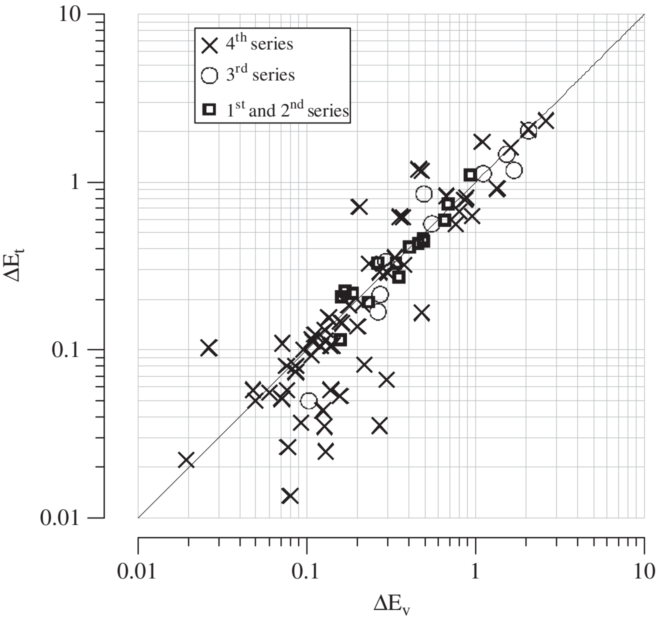

Fig. 11. Absolute values (in kJ) of variation of total energy vs. variation of translational energy upon impact. The diagonal line is the 1:1 line.

absolute values). In this figure, a point located on the 1:1 line represents a case where there is no change in rotational energy and the loss of total energy is equal to the loss of translational energy.

While a loss in total energy is always verified, the rotational energy may decrease (points above the 1:1 line) or increase after an impact (points below the 1:1 line). In 52 out of 88 cases, the rotational energy has increased after a bounce. However, for the tests performed, the gain in rotational energy does not compensate for the loss of translational energy. In the experience of the authors, and on the basis of the in situ tests presented here, the total energy always decreases during impact. This is confirmed by the tests presented in [40].

Please cite this article as: Spadari M, et al. In situ rockfall testing in New South Wales, Australia. Int J Rock Mech Mining Sci (2011), doi:10.1016/j.ijrmms.2011.11.013

4. Significance for rockfall modelling

An extensive discussion on the numerical modelling of the impact is beyond the scope of the paper; however, it is relevant to discuss the significance of the findings from this research for impact modelling. A more comprehensive discussion can be found in the recent review by Bourrier and Hungr [41].

The experimental data obtained from in situ testing was interpreted considering a lumped mass model. In particular, the normal restitution coefficient k_n was found to be consistently higher than unity, which can be explained by the angularity of the blocks, the effect of rotational momentum and low impacting angles, as shown in [40].

By nature, it is difficult for a lumped mass model to capture such effects [41] even though commercial codes like CRSP can capture the evolution of rotational energy throughout the fall. In fact, by scrutinising the energy balance (Section 3.3), it was found that an impact could lead to a loss or a gain of rotational energy, which could be reproduced by CRSP (not shown here for brevity). While a proper estimate of the total energy is possible, in the lumped mass models the lack of block shape and of proper contact description means that high bouncing angles, the so called saw effect [2], block fragmentation [42] or the possibility of the block "climbing" up the protective structure cannot be captured. In addition, commercial codes usually have an in-built upper bound of one for k_n, making it difficult to reproduce the blocks trajectories as observed in the field. To overcome such shortcomings, so called rigorous models, analytical or numerical, have been progressively developed [41]. These offer more options when trying to reproduce complex block shapes and block/slope interactions. Use of such models was not attempted in this study because of a lack of information about the block/slope contact (presence of vegetation) and an inadequate image frequency.

5. Conclusions

This paper presents the results of four series of rockfall tests performed at three different sites, which are considered representative of significant geological environments in New South Wales, Australia, particularly relevant for the rockfall issue. The tests were conducted following a methodology commonly used for this type of tests and attention was focused on determining the restitution coefficients, the rolling coefficient and both kinetic and rotational energy at impact. Although similar tests have already been conducted in Europe and in other countries, it is the first time such a characterisation of the rockfall motion is performed in Australia.

The results have shown a very high variability of the results due to the use of natural blocks in a natural environment. Nonetheless, some conclusions could be drawn. In particular, the values of the normal restitution coefficient have been found generally much higher than the benchmarks of the rockfall literature, with values up to 2. This is believed to be due to a combination of different parameters: high rotational energy pre-impact, low impacting angles and significant angularity of the blocks. Similarly, the tangential restitution coefficients have been found to be higher than the values usually adopted. Again, the rotational energy is believed to be responsible for this fact.

The values of the rolling coefficient were found to be in accordance with the outcomes from the literature and it is suggested that different approaches to determine them may be warranted in different conditions. In particular, the results suggest that in some situations it may be necessary to assign different rolling coefficient values to different sections of a slope in order to represent the overall rolling behaviour of a block. The usual approach of starting with a single rolling coefficient value may be adequate but one should qualitatively assess if the geo-morphological conditions are met to follow the resulting phases of motion. If not, the alternative approach of adopting several locally-applicable rolling coefficients might be more appropriate, particularly when angular blocks are likely to decelerate whilst rolling on gentler slopes.

References

[1] Agliardi F, Crosta G. High resolution three-dimensional numerical modelling of rockfalls. Int J Rock Mech Min Sci 2003;40:455–71.
[2] Giani GP. Rock Slope Stability Analysis. Rotterdam: Balkema, 1992.
[3] Bozzolo D, Pamini R. Simulation of rock falls down a valley side. Acta Mech 1986;63:113–30.
[4] Azzoni A, La Barbera G, Zaninetti A. Analysis and prediction of rockfalls using a mathematical model. Int J Rock Mech Min Sci 1995;32:709–24.
[5] Piteau DR, Clayton R. Description of the slope model computer rock fall program for determining rock fall distribution. DR Piteau and Associates, 1976.
[6] Descoeudres F, Zimmermann T. Three-dimensional dynamic calculation of rockfalls. In: Proceedings of the 6th International Congress on Rock Mechanics. Montreal: Balkema; 1987, p. 337–42.
[7] Pfeiffer T, Bowen T. Computer simulation of rockfalls. Bull Assoc Eng Geol 1989;26(1):135–46.
[8] Scioldo G. Rotomap: analisi statistica del rotolamento dei massi. Patron, Milano: Guida Informatica Ambientale; 1991.
[9] Guzzetti F, Reichenbach P, Wieczorek GF. Rockfall hazard and risk assessment in the Yosemite Valley, California, USA. Nat Hazards Earth Syst Sci 2003;3: 491–503.
[10] Stevens W. RocFall: a tool for probabilistic analysis, design of remedial measures and prediction of rock falls. MaSc thesis, University of Toronto; 1998.
[11] Jones C, Higgins JD, Andrew RD. Colorado Rockfall Simulation Program Users Manual for Version 4.0. Denver: Colorado Department of Transportation; 2000.
[12] Azzoni A, de Freitas M. Experimentally gained parameters, decisive for rock fall analysis. Rock Mech Rock Eng 1995;28(2):111–24.
[13] Ritchie A. Evaluation of rockfall and its control. Highway Res Rec 1963;17: 13–28.
[14] Giani GP, Giacomini A, Migliazza M, Segalini A. Experimental and theoretical studies to improve rock fall analysis and protection work design. Rock Mech Rock Eng 2004;37(5):369–89.
[15] Broili L. In situ tests for the study of rockfall. Geologia Applicata e Idrogeologia 1973;8:105–11.
[16] Bozzolo D, Pamini R. Modello matematico per lo studio della caduta dei massi. Lugano-Trevano: Laboratorio di fisica terrestre, Dipartimento della Pubblica Educazione; 1982.
[17] Fornaro M, Peila D, Nebbia M. Block falls on rock slopes—application of a numerical simulation program to some real cases. In: Proceedings of the 6th International Congress IAEG. Balkema; 1990, p. 2173–80.
[18] Azzoni A, Rossi PP, Drigo E, Giani GP, Zaninetti A. In situ observations of rockfalls analysis parameters. In: Proceedings of the 6th International Symposium on landslides, Christchurch. Balkema; 1992, p. 307–14.
[19] Paronuzzi P. Field Evidence and Kinematical Back-Analysis of Block Rebounds: The Lavone Rockfall. Northern Italy Rock Mech Rock Eng 2009;42:783–813.
[20] Wu S. Rockfall evaluation by computer simulation. Transportation Research Record 1985;1031:1–5.
[21] Chau KT, Wong RHC, Liu J, Wu JJ, Lee C. Shape effects on the coefficient of restitution during rockfall impacts. In: Proceedings of the 9th International Congress on Rock Mechanics, vol. 1. ISRM; 1999, p. 541–4.
[22] Chau KT, Wong RHC, Wu JJ. Coefficient of restitution and rotational motions of rockfall impacts. Int J Rock Mech Min Sci 2002;39:69–77.
[23] Labiouse V, Heidenreich B. Half-scale experimental study of rockfall impacts on sandy slopes. Nat Hazards Earth Syst Sci 2009;9:1981–93.
[24] Bourrier F, Dorren LKA, Nicot F, Berger F, Darve F. Toward objective rockfall trajectory simulation using a stochastic impact model. Geomorphol 2009;110: 68–79.
[25] Young RW. Blockgliding in sandstones of the southern Sydney Basin. In: Young RW, Nanson GC, editors. Aspects of Australian sandstone landscapes. Australian and New Zealand Geomorphology Group; 1983. p. 31–8.
[26] Cunningham DM. A rockfall avalanche in a sandstone landscape, Nattai North NSW. Aust Geogr 1988;19(2):221–9.
[27] Gordon FR. The Rockfall of Huzzas Cliff, Gracetown, Western Australia. In: Vitharana, Nihal Dhamsiri, Colman, Randal, editors. Proceedings of the 8th Australia New Zealand Conference on Geomechanics, Australian Geomechanics Society; 1999, p. 599–606.
[28] Dahlhaus PG, Miner AS. Estimating the occurrence of rockfalls in columnar basalt. Aust Geomech 2001;36(2):1–6.

Please cite this article as: Spadari M, et al. In situ rockfall testing in New South Wales, Australia. Int J Rock Mech Mining Sci (2011), doi:10.1016/j.ijrmms.2011.11.013

[29] Hendrickx M, Wilson R, Moon A, Stewart I, Flentje P. Slope hazard assessment on a coast road in New South Wales, Australia. In: Proceedings of the International Conference on Landslide Risk Management, Vancouver; 2005.

[30] Delaney M. Coastal cliff stability and regression in the Newcastle region. In: Geotechnical Challenges for Development in the Hunter Region (Part1). AGS, Aust Geomech; 2005, 40(1).

[31] Kotze GP. An Assessment of Rockfall Frequency for the Coastal Cliff Lines of Pittwater Local Government Area. Sydney Aust Geomech 2007;42(1):213–9.

[32] Branagan DF, Packham GH. Field geology of New South Wales. Sydney: Science Press; 1967.

[33] Herbert C, Helby R. A guide to the Sydney Basin. Bulletin 26. Dept Mineral Resources. Geological Survey of NSW. D West, Government Printer NSW; 1980.

[34] Fityus SG, Spadari M, Giacomini A, Buzzi O. The characteristics of rock fragments in the basalts of eastern Australia. In: Proceedings of the 11th International Congress IAEG. Auckland, New Zealand: CRC Press—Balkema; 2010, p. 2899–907.

[35] Roberts J, Engel B, Chapman J. Geology of the Camberwell, Dungog, and Bulahdelah 1:100,000 Sheets. Geological Survey of NSW. Sydney: Dept. Min. Res 1991.

[36] Giacomini A, Spadari M, Fityus S, Buzzi O. Experimental study on the rockfall motion characteristics in the basalt terrains of eastern Australia. In: Proceedings of the 11th International Congress IAEG. Auckland, New Zealand: CRC Press—Balkema; 2010, p. 2937–45.

[37] Hungr O, Evans S. Engineering evaluation of fragmental rockfall hazards. In: Proceedings of the 5th International Symposium on Landslides. Balkema; 1988, p. 685–90.

[38] Dorren LKA, Berger F. Putters US. Real size experiments and 3D simulation of rockfall on forested and non-forested slopes. Nat Hazard Earth Syst Sci 2006;6:145–53.

[39] Berger F, Dorren LKA. Objective comparison of rockfall models using real size experimental data. In: Disaster Mitigation of Debris Flows, Slope Failures and Landslides. Tokyo, Japan: Universal Academy Press Inc.; 2006, p. 245–52.

[40] Buzzi O, Giacomini A, Spadari M. Laboratory investigation on high values of restitution coefficients. Rock Mech Rock Eng 2011, doi:10.1007/s00603-011-0183-0.

[41] Bourrier F, Hungr O. Rockfall Dynamics: A Critical Review of Collision and Rebound Models. In: Lambert S, Nicot F, editors. Rockfall Engineering. Wiley; 2011. p. 175–209.

[42] Giacomini A, Buzzi O, Renard B, Giani GP. Experimental studies on fragmentation of rock falls on impact with rock surfaces. Int J Rock Mech Min Sci 2009;46:708–15.

Please cite this article as: Spadari M, et al. In situ rockfall testing in New South Wales, Australia. Int J Rock Mech Mining Sci (2011), doi:10.1016/j.ijrmms.2011.11.013