Experimental study on rockfall drapery systems for open pit highwalls

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A B S T R A C T
This study presents in situ experiments carried out at an open cut mine in New South Wales (Australia). The research intends to improve the current knowledge on drapery systems for rockfall hazard management in mining environments. Blocks were released from the top of two different sections of the highwall: with and without a rockfall drapery system installed on the highwall. The trajectories of the blocks were recorded by using synchronised stereo pairs of high speed cameras. Velocities were derived from the trajectories and used to gather rockfall motion parameters (restitution coefficients) and various energies.

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1. Introduction

Rockfall represents a significant safety hazard in mining environments around the world. It is the cause of serious injuries or fatalities to personnel and can damage infrastructure and machinery. Moreover, it can result in major financial losses when production is temporarily stopped for safety reasons. The hazard associated with rockfall events needs to be rigorously managed in both surface and underground operations. Indeed, a reliable approach for designing slopes, portals, roads and ramps depends critically on suitable rockfall protection systems.

Over the last three decades rockfall has been widely studied for roads and highways [1–4], but it is only recently that it has been accounted for in the context of open pits, quarries, [5–8] and underground mines [9,10]. Data collected from worldwide databases show that rockfall is one of the most serious causes of injury in mining operations [8,10–16] and several fatal events have been recorded since the mid 1990s.

Rockfall in underground mines is mainly related to roof or rib failure and inadequate examination/maintenance [10]. The situation is different in open pit mines, where rockfall is generally associated with geological features, weathering of the rock surfaces, blast-induced fracturing, and machinery activity on top of crests and along roads at the bottom of highwalls.

In open pit mining, rockfall has been the topic of a number of studies [17–19] which have proposed various approaches for safe and cost effective remediation solutions. These have resulted in different protective measures being suggested, either to prevent rockfall or to control its consequences. These measures include active systems designed to prevent instability (e.g. wire anchors, rock bolts) and passive systems that control the dynamic motion of the blocks (e.g. benches, catch ditches [20–21], flexible catch fences [22–28], attenuator systems [29–32]). Drapery systems [29], placed against the rock surface and combined with face bolting, fall within these two categories. They directly act on the stability of the blocks, but also control their fall should failure occur. Such systems are common practice within Australian open cut mines.

In surface mining, draperies are used to prevent rocks from impacting directly onto the concrete culverts used as portal structures for underground access. However, blocks can still fall under the net and land on top of the portals and/or in their vicinity. This represents a serious hazard for highly-worked areas at the bottom of the highwalls, and a proper prediction of the block trajectories and velocities is of prime importance in assessing and mapping the residual rockfall hazard.

Even though drapery systems have been used for several years as a rockfall protective measure, it is only recently that their design and field-testing have been addressed in the scientific literature. In particular, [33] and [34] compared the performance of hexagonal wire mesh, ring nets and cable net drapery systems
used for slope protection along North American state highways. The performance of wire mesh and cable net systems were also numerically investigated by [35], where a finite element model was calibrated from the experimental results in [33] to better understand the influence of mesh weight, the friction interface between the rock and the mesh, and the accumulation of debris on the system behaviour. The study in [29] developed a full scale test procedure to evaluate the behaviour of different types of drapery mesh panels, and 6 m × 6 m wire meshes or cable net panels connected to a rock mass were tested under a force of 200 kN using an hydraulic jack. These results showed the need for a better understanding of the overall behaviour of the drapery system, with a specific focus on the design procedures and installation methods. However, as far as the authors are aware, results for rockfall tests involving drapery systems have been rarely addressed in the scientific literature [31].

For the first time, full-scale tests of rockfall impacting on drapery in a surface mine have been performed and the results are presented in this paper. The experiments were carried out at an open cut mine in New South Wales (Australia) and recorded by using synchronised stereo pair high speed cameras. Two series of tests were performed at two different locations and compared: one with drapery on the highwall and one without. Three-dimensional (3D) block trajectories were reconstructed by using stereo-photogrammetry, which has seldom been used for rockfalls [36,37]. Block velocities were measured and used to infer the restitution coefficients and the impact energy on the portals.

The study, funded by the Australian Coal Association Research Program (ACARP), was carried out with the objective of improving the current knowledge on drapery systems for rockfall hazard management in mining environments and to assess the residual hazard. Important information on the type of motion, trajectory, arrest zones and potential impacting energy were gathered and observations for protection system optimisation were collected. These data are crucial for the safe and effective design of portals and roads in open cut mines.

2. Experimental testing

2.1. Experimental site

Two series of full scale rockfall tests were carried out at the Beltana mine (owned by Xstrata Coal), one of the most productive longwall thermal coal mines in Australia, located in the Hunter Valley in New South Wales (Australia) near Singleton.

Beltana longwall operations commenced in 2003, with the construction of portals to provide an entrance to the underground long wall for workers and machinery, as well as access for electricity, ventilation air, water, communication systems and coal conveyors. In 2004, a rockfall control system was installed to minimise the risk of falling blocks and to protect personnel and equipment working at the base of the wall. The system, placed over the highwall on top of each portal, consisted of four mesh strips of flexible draping (a double twist type from Maccaferri Pty Ltd). The strips, each 4 m wide, were clamped together along their long edges, anchored at regular intervals at the top of the highwall 5 m behind the crest, and restrained by a single cable, threaded through the bottom edge of the drape and anchored at each end. The drapery was combined with rock bolts drilled into the face to stabilise parts of the highwall.

The global height of the highwall varies between 40 m and 50 m and its slope is around 70°. Two testing sites were chosen around three portal entries at the south-eastern end of the highwall (Fig. 1a) over a length of 200 m where mining operations are no longer occurring. In consequence, the experimental programme was conducted without affecting mine operations or exposing mine personnel to any risk.

The first site (Fig. 1b), referred to as “Site 1—drapery”, was located in correspondence to the first portal, where the highwall is 39 m high from the top of the portal and a drapery system is installed on the rock surface. The drapery, after more than six years of use, is still in good condition without evidence of serious damage along his length or near the clamping connecting the 4 strips of mesh. Two berms are located at the bottom of the highwall at 10 and 15 m from the base of the highwall. The second testing site (Fig. 1c), referred to as “Site 2—no drapery”, is located 207 m North-West of “Site 1—drapery”, in front of a large mud-filled depression. No rockfall protection system is installed on this part of the highwall. The location of the second site was mainly driven by safety considerations. Indeed, the mud depression was used as a capture area for the blocks.

For the purpose of the study, a simplified geological profile of the two sections has been considered in which seven different layers of material were identified. The top of the highwall, referred to as the Denman formation [38], was subdivided into three main layers: sandstone, mudstone and mudstone-debris. The latter were located at the bottom of the previous layer. A thin layer of coal was identified in the middle of the highwall immediately underneath the Denman formation, followed by a succession of interbedded layers of sandstone and mudstone and then mudstone and siltstone. A layer of massive sandstone was identified again at the bottom of the highwall. In both sites, a substantial amount of debris was located on top of the portal for “Site 1—drapery” and above the mud depression in “Site 2—no drapery”.

A detailed geostructural survey of the highwall was performed in [39]. The in situ block size distribution of unstable blocks was also carried out and reported in [40].

2.2. Testing set up

Thirteen concrete blocks whose shapes were in accordance with EOTA [41] were cast in the Laboratory of the Centre for Geotechnical and Materials Modelling at the University of Newcastle. The block size, about 30 cm in the largest dimension, was chosen on the basis of data related to previous rockfall events [39]. The blocks weighed 44.5 kg. All blocks were painted in yellow with a unique black pattern on each of the six square faces in order to determine their rotational movement during the fall (Fig. 2a). A 60 t crane with a man basket was positioned at the top of the highwall adjacent to the testing sections and used to release the blocks (Fig. 2b).

A detailed inspection of the mesh was carried out on site 1 before testing and a suitable location was identified to insert the blocks under the net. This was achieved by cutting a few diamonds in the mesh without damaging the entire strip. Note that the blocks were not recovered after the tests for safety reasons.

The objective of the study was to record and reconstruct the motion of each block using stereo-photogrammetry. As far as the authors are aware, this technique has only used before in [36]. Two sets of stereo-pair video cameras were used, where each set covered about 30 m of the highwall. The first set of stereo-pair cameras (Canon EOS 7D, 60 fps, 720 × 1280 pixel, 45 mm focal length) captured the top of the highwall whereas the second set (Optronics CR600, 500 fps, 1024 × 1024 pixel, 35 mm focal length) was used for the bottom section of the highwall. The two camera pairs had an overlap of about 10 m along the highwall height [42], allowing the recording of the full fall of the block from the starting point to the bottom of the highwall. Unlike the set up used by [36], each pair of cameras was synchronised, which reduced the error in capturing the motion.
Two additional high speed video cameras (Phantom v9.1, 1000 fps, 1632 × 1200 pixel, and Phantom Miro eX-series, 500 fps, 800 × 600 pixel) with different lenses were used to capture details of the block fall along the highwall such as bouncing on the highwall face and final impacts at the bottom of the highwall. All cameras were set up in front of the highwall at a distance of 40 to 50 m.

Ten control points, placed on each test section of the highwall, provided a scale for the photogrammetry and allowed a referenced tracking of the 3D motion of the block over the entire height of the highwall. These control points were surveyed by electronic theodolite [42].

2.3. Testing programme

Table 1 summarises the details of the two series of tests carried out in “Site 1—drapery” and “Site 2—no drapery”. A total of fifteen tests were completed in the testing programme, with thirteen man-made blocks and two natural blocks found on site.

In the first series, six concrete blocks were released between the drapery installed above the first underground portal entry and the highwall surface (tests T01–T06). The blocks were released from position A between the mesh and the highwall. Seven concrete blocks and two natural sandstone blocks, collected from

the base of the highwall at the bottom of testing “Site 1—drapery”, were released from the top of the testing “Site 2—no drapery”. The blocks were released from two different positions, B1 and B2: 4 concrete blocks (tests T07–T10) were released from position B1, and 3 concrete blocks (tests T11–T13) and two sandstone blocks, N1 and N2, were released from position B2 (tests TN1–TN2). The additional position B2 was chosen because of adverse safety conditions for the man basket in position B1. Three concrete blocks were then released from the same position B2 in order to obtain comparable results between tests performed with concrete and natural blocks. Blocks N1 and N2 were measured and painted before the tests.

The average vertical drop measured from the release point A was 38.3 m in test T01 in “Site 1—drapery”, and 43.6 m and 41.3 m from point B1 and B2 respectively in tests T08 and T11 in “Site 2—no drapery” (Fig. 3).

3. Data analysis procedure

3.1. Highwall representation

Digital images of the highwall were collected and processed by the software package Sirovision (http://www.sirovision.com/)
The module Siro3D [43,44] was used to create a georeferenced 3D model of the highwall. Two overlapping stereo-pairs of images of each section of the highwall were used to build two 3D models corresponding to “Site 1—drapery” and “Site 2—no drapery”. A point cloud of the georeferenced 3D model was then exported and further processed with the open-source software Meshlab (http://www.meshlab.sourceforge.net/) [45] to get an accurate 3D surface representation with triangular elements.

### 3.2. Block trajectories

The sequences of images collected during the tests by the two sets of stereo-pair cameras were analysed with the photogrammetry software package ‘VMS—Vision Measurement System’ (http://www.geomsoft.com) [46] to obtain the 3D coordinates of the blocks during their motion. These coordinates were used to infer blocks velocities.

Five points (on each block) were then utilised to identify the block position at each frame: a central point and four points around the block (upper side, lower side, left side and right side). An average of the five positions was then used to calculate the final coordinates \((x, y, z)\) of the block. Due to the considerable number of frames, only one in five frames was processed to reconstruct the trajectories.

Fig. 3 shows the trajectories of the concrete blocks recorded during tests T01 (“Site 1—drapery”, initial position A), test T08 (“Site 2—no drapery”, initial position B1) and test T11 (“Site 2—no drapery”, initial position B2). The field of overlap of the two sets of stereo-pairs of cameras can be observed: blue and red trajectories correspond to the top (Canon) and bottom (Optronics) parts of each section respectively. Due to the different resolutions of the stereo-pair cameras a difference in accuracy (around ±15 to ±19 mm in “Site 1—drapery” and ±18 to ±21 mm in “Site 2—no drapery”) was observed for the trajectory in the overlap zone.

### 3.3. Translational and angular velocities

The three components of the block translational velocities \((v_x, v_y, v_z)\) were computed by using the 3D coordinates of the block

<table>
<thead>
<tr>
<th>Testing site</th>
<th>Rockfall mesh</th>
<th>No of blocks</th>
<th>Test</th>
<th>Block material</th>
<th>Dropping position</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>6</td>
<td>T01–T06</td>
<td>Concrete A</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>4</td>
<td>T07–T10</td>
<td>Concrete B1</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>3</td>
<td>T11–T13</td>
<td>Concrete B2</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2</td>
<td>TN1–TN2</td>
<td>Sandstone B2</td>
<td>194 and 157.5</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. (a) Photograph of some of the blocks used for the testing showing the different patterns on each side. (b) Crane and man basket used to release the blocks from the top of the highwall.

Fig. 3. 3D views of the concrete block trajectories: the blue trajectory corresponds to the top section and the red to the bottom section. “Site 1—drapery”, test T01 under the net, initial position A (left). “Site 2—no drapery”, tests T08 initial position B1 and T11 initial positions B2 (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).
trajectories determined in the previous step. The travel distance \((\Delta x, \Delta y, \Delta z)\) between two frames was calculated for each Cartesian direction. Dividing these distances by the intermediate time interval \(\Delta t\) between two frames (i.e. frame rate) gives the average translational velocity components as:

\[
v_x = \frac{\Delta x}{\Delta t}, \quad v_y = \frac{\Delta y}{\Delta t}, \quad v_z = \frac{\Delta z}{\Delta t}
\]

Some noise was observed in the translational velocities, as shown in Fig. 8 in the results section. This is mainly related to the accuracy of the manual tracking of the position of the block which is limited to about one pixel in the analysis. One pixel in the images corresponds to about \((15 \times 15)-(26 \times 26)\) mm\(^2\) on the highwall depending on the distance of the camera to the wall. This results in a maximal positional error of about 15–26 mm. The measured 3D coordinates \((x, y, z)\) and the calculated travel distances \((\Delta x, \Delta y, \Delta z)\) are directly influenced by the positional error, as are the calculated velocities \((v_x, v_y, v_z)\). However, when comparing the field results to the theoretical predictions, good agreement was observed. Therefore, an average smoothing algorithm, based on a symmetric neighbourhood approach [47], was applied to the raw data in order to improve the results. The algorithm filters data by averaging a set of neighbouring data over a symmetric range. A 3D rotational motion involves three angular velocities \(\omega_x, \omega_y, \omega_z\). The angular velocities of each block before were accurately measured \((\text{if based on energy or velocity magnitude})\) or two \((\text{if based on velocity components})\) restitution coefficients. These latter quantify the decrease of velocity or the loss of kinetic energy upon impact \([1,3,48–51]\). If one coefficient only is used, it is required to assume the direction of rebound to model the trajectory. By contrast, using two distinct coefficients \((\text{i.e. normal and tangential restitution coefficients},\text{ denoted } k_n \text{ and } k_t)\) inherently captures the angle of rebound.

3.4. Rebound characteristics: pre/post impact velocities and restitution coefficients

One critical aspect of a rockfall modelling is the need to properly characterise the rebounds since they constitute a key source of energy dissipation. The most common approach is to use one \((\text{if based on energy or velocity magnitude})\) or two \((\text{if based on velocity components})\) restitution coefficients. These latter quantify the decrease of velocity or the loss of kinetic energy upon impact. Laboratory and in situ testing have been widely used to identify the factors influencing the restitution coefficients and to characterise them for a given site \([2,52–57]\). Estimating the restitution coefficients requires defining an average plane for each impact, which was achieved using the initial triangulation of the highwall (see Section 3.1). First, the impact point was located and the triangles interacting with the block were found. In most cases, three or four triangles were identified (Fig. 4a). The normal vector \(\mathbf{n}\) of the average impact plane \(P\) was defined by the average of the normal vectors of all triangles interacting with the block (Fig. 4b). The plane is defined by the normal vector \(\mathbf{n}\) and the point \(O\). The trajectory of the block just before and after impact remains in two planes perpendicular to plane \(A\). The incoming plane \(B\) and the outgoing plane \(B'\) are defined by the vector \(\mathbf{n}\) and the points \(P\) and \(P'\) of the incoming and outgoing trajectory respectively. The direction of the trajectory might change during impact due to block shape effects and real wall roughness (not the roughness represented by the triangles). As a result the outgoing plane \(B'\) is rotated of an angle \(\beta\) from the incoming plane \(B\).

The local coordinate system at the impact point \((\mathbf{t},\mathbf{s},\mathbf{n})\) was determined, where the vectors \(\mathbf{s}\) and \(\mathbf{t}\) are, respectively, orthogonal and coplanar to the incoming plane \(B\) and both are coplanar to the impact plane \(A\). Similarly, a local coordinate system at the impact point \((\mathbf{t},\mathbf{s},\mathbf{n})\) was calculated for the outgoing plane \(B'\). The local systems \((\mathbf{t},\mathbf{s},\mathbf{n})\) and \((\mathbf{t},\mathbf{s},\mathbf{n})\) were used for the calculation of the pre-impact velocity components \((v_{ix}, v_{iy}, v_{iz})\) and the post-impact velocity components \((v_{ix'}, v_{iy'}, v_{iz'})\).

\[
E_t = \frac{1}{2}mv^2
\]

where \(m\) [kg] is the mass of the block and \(v\) [m/s] represents the absolute total velocity. The rotational kinetic energy is defined as

\[
E_r = \frac{1}{2}I\omega^2
\]

where \(I\) [kg m\(^2\)] corresponds to the moment of inertia around the rotation axis and \(\omega\) [rad/s] is the angular velocity.

\[
E_r = \frac{1}{2}I\omega^2
\]

Fig. 4. (a) Impact surface (dashed line) and the triangles interacting with the block (pink). (b) Definition of the incident velocity \(v_i\) in the incoming plane \(B\) and the outgoing velocity \(v_o\) in the outgoing plane \(B'\). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Finally, the restitution coefficients were calculated as follows:

\[
k_n = \frac{v_{na}}{v_{nb}}; k_t = \frac{v_{ta}}{v_{tb}}
\]

(4)

where the subscripts \( n \) and \( t \) refer to the normal and tangential components of the velocity and the subscripts \( a \) and \( b \) refer to after and before impact, respectively. The restitution coefficients were calculated for all the different material layers identified in the highwall.

4. Results and discussion

4.1. Trajectories

Releasing the blocks under the drapery (test T01 to T06, “Site 1—drapery”) led to a relatively high number of impacts. Indeed, four to six impacts were recorded for each test, for a total of 30 impacts. For the entire series it was observed that the first two impacts took place on the Denman Formation surface and the last one on the muck pile on top of the culvert. Only a few blocks reached the berm located at the base of the highwall (about 10 m further). This final part of the trajectory was not considered in the analysis. A few impacts also occurred in the sandstone and mudstone layers. Only test T06 registered six impacts, with the fifth impact occurring on the layer of massive sandstone at the bottom of the highwall.

The photographic sequences were used to successfully reconstruct the block trajectories, as shown in Fig. 5a. Rockfalls are usually captured under one angle and the motion is assumed to be planar, but the current results clearly show that the blocks deviate from a planar trajectory. Stereo photogrammetry is hence necessary to accurately capture the three dimensional motion of the phenomenon and yields more realistic results. The trajectories measured were used to infer the position of the block, the restitution coefficients, the velocity and the impact angle. This latter is defined as the angle between the pre-impact velocity vector and the intersection of the average impact plane and the vertical plane including the pre-impact velocity vector. The maximum absolute velocity recorded was about 16.6 m/s (test T06) and the maximum impact velocity on top of the portal was about 14.5 m/s (test T02). Some issues occurred with data recording due to adverse weather conditions, and affected tests T03 and TN1. Consequently, the results (and trajectories) are incomplete for these tests.

No damage was observed to the drapery system as a result of the testing. All four strips of drapery remained clamped together forcing the blocks to fall between the highwall and the mesh.

2D rockfall simulations on two profiles from “Site 1—with drapery” and “Site 2—no drapery” exhibited similar trajectories [58]. The effect of drapery on the block trajectories can be analysed by comparing the test results between the two sites. Fig. 5b shows that the blocks tend to fall with only two or three impacts at most in the absence of drapery. Many of these impacts occurred at the top of the highwall (8 impacts in the Denman formation) with only one impact in mid-height observed during test T08 (interbedded sandstone/mudstone layer). About half of the blocks ended up in the mud depression and half in the debris at the bottom of the highwall. For these tests, the maximum velocity recorded was 28.4 m/s. This observation highlights the impact of the drapery on the trajectories: providing a geometrical constraint to the blocks close to the wall results in more impacts during the fall and hence more energy dissipation. The effect of the drapery on the trajectory can also be seen through the maximum jump distance \( D_{\text{max}} \) (m), measured orthogonal from the highwall. Table 2 summarises the characteristics of the blocks trajectory for all the tests.

Fig. 5. Reconstruction of block trajectories (a) for tests T01–T06 in “Site 1—drapery” and (b) for tests T07–T13 in “Site 2—no drapery”. The colour scale indicates the magnitude of the total velocity.

4.2. Velocity and impact energy

Fig. 6 shows smoothed velocities and measured vertical velocities. The measured vertical velocity \( v_z \) (grey line), theoretical free fall velocity (red line), and smoothed velocity (black line) are plotted versus time for test T08 (“Site 2—no drapery”). Similar noise was observed by [36]. The figure clearly shows the free fall phases and impact points, which are characterised by a loss of velocity. The smoothed data show good agreement with the theoretical evolution of speed in free fall. All results were processed in this manner before further data analysis.

The velocity profile can be turned into a translational kinetic energy profile (as a function of vertical distance travelled, Fig. 7) using the magnitude of velocity (as opposed to only the vertical
component). For the sake of clarity, not all test results are shown with attention being focused on the extreme cases: T01 and T06 (“Site 1—drapery”); T07 and T08 (“Site 2—no drapery”). These four tests correspond to the upper and lower bounds in terms of velocity (see Table 2). Test T08 was preferred to test T013 (which is the real lower bound) because it is the only test with an impact at mid height, and as such, it should be considered as a realistic scenario. Fig. 7 also indicates the zone of the debris material on top of the portal (dotted rectangle), which is useful to assess the efficiency of the drapery in reducing the impact energy on that structure. The likely impacting kinetic energy without drapery would range from 8 to 13 kJ, which can be reduced to less than 4 kJ with drapery.

In terms of portal design, it is interesting to also look at the impact zone and impact velocity (as opposed to kinetic energy only). These are represented in Fig. 8 for all test results. The drapery not only reduces the impact velocity, which is critical regarding concrete perforation issues, but also concentrates the blocks in a smaller zone, i.e. in the first 4 m of the portal which is 10 m long. Should an extra remediation method be used (e.g. attenuators), this seems required only on the first half of the structure. For completeness, the location of the final impact (taken from the highwall) and the block velocity at the bottom of the highwall, for tests performed in “Site 2—no drapery” is also
plotted in Fig. 8. These results show that a minimum restriction zone of about 12 m is necessary to limit rockfall hazard.

### 4.3. Rotational kinetic energy

Rotational energy was computed only at the impact points (pre and post impact). Before impact, the maximum rotational energy was estimated at 0.4 kJ and after impact at 0.9 kJ. The rotational component of the total kinetic energy was around 3% of the total pre-impact and 21% post-impact. It is assumed that the rotational component of energy is not an issue for a concrete portal, however, it can potentially cause some damage to the drapery (due to a sawing effect). The amount of rotational energy observed was not high enough for the blocks to damage the mesh.

Fig. 9a shows the variation of the rotational energy upon impact for all the tests with the concrete blocks. Thirty nine out of forty six impacts observed for the concrete blocks resulted in an increase of rotational energy for both sites, with and without drapery. Rotational energy was estimated at 0.4 kJ pre-impact and 0.9 kJ post-impact. The rotational component of the total kinetic energy was around 3% of the total before impact and 21% after impact. It is assumed that the rotational component of energy is not an issue for a concrete portal, however, it can potentially cause some damage to the drapery (due to a sawing effect). The amount of rotational energy observed was not high enough for the blocks to damage the mesh.

Fig. 9a shows the variation of the rotational energy upon impact for all the tests with the concrete blocks. Thirty nine out of forty six impacts observed for the concrete blocks resulted in an increase of rotational energy for both sites, with and without drapery. Fig. 9b and c shows the rotational energy upon impact as a function of the translational energy for all the tests. In “Site 1—drapery” the rotational energy represented less than 10% of the pre-impact translational energy and reached up to 90% of the post-impact translational energy. In “Site 2—no drapery” (Fig. 9c), the rotational energy remained below 0.16 kJ pre-impact and increased up to 0.84 kJ post-impact. Simultaneously, the translational energy was reduced from a maximum of 25 kJ down to a maximum of 5 kJ. This transfer of energy from translational to rotational energy at impact is a feature of rockfalls [56,57].

Between two impacts some of the rotational energy (up to 82%) was dissipated along the fall (Fig. 10). This was attributed to the block/mesh interaction, indeed, such loss of rotational energy was not observed in “Site 2—no drapery”.

The rotational energy dissipation along the mesh was calculated as the difference of rotational energy between two impacts $i$ and $i + 1$ as follows:

$$\Delta E_{rot} = E_{rot}^{i+1} - E_{rot}^{i}$$

where $E_{rot}^{i+1}$ is the pre-impact rotational energy at impact point $i+1$ and $E_{rot}^{i}$ is the post-impact rotational energy at impact point $i$. In Fig. 10, the $\Delta E$ values were normalised by the post impact rotational energy at impact point $i$, $E_{rot}^{i}$.

### 4.4. Energy balance

An energy balance after the last impact was also performed for the tests in “Site 1—drapery”. In the following, the physics definition of mechanical energy was adopted: it is the sum of the potential and the kinetic energy. Rotational energy is not accounted for in mechanical energy. Four different energies were calculated: the initial mechanical energy, $E_M$, equal to the potential energy at the beginning of the test, the total energy dissipated upon the impacts, $\Delta E_{imp}$, the total energy dissipated by the net during the fall, $\Delta E_{net}$, and the mechanical energy available after the last impact on the slope, $E_M$. $\Delta E_{imp}$ is obtained by summing the energy dissipated upon each impact of a fall, $\Delta E_{imp}$.
The mechanical energy after the last impact is by definition equal to the total kinetic energy after impact plus the potential energy computed from the elevation of the impact point. The principle of energy conservation along the fall then yields the following:

\[ E_{Mi} = E_{Mf} + \Delta E_{imp} + \Delta E_{net} \]  

(7)

The initial mechanical energy is equal to the mechanical energy after the last impact plus the energy dissipated during the impacts and the energy dissipated by the net. The ratio of each energy to the initial mechanical energy is shown in Fig. 11. It can be seen that 33% of the energy dissipation can be attributed to the mesh, representing 22% of the initial mechanical energy. On the average, each metre of mesh resulted in 0.12 kJ of energy dissipation.

4.5. Restitution coefficients

A total of 53 rebounds were recorded during the tests on the concrete and natural blocks and subsequently analysed. For 49 impacts it was possible to calculate the normal and tangential restitution coefficients according to the procedure defined in Section 3.4. Four impacts involved fragmentation of the rock surface. Hence it was not possible to measure the exact post impact velocities for the restitution coefficients calculation. Using the simplified geological description of Section 2.1, average values of restitution coefficients were attributed to different geological layers. Only the concrete blocks were considered in the calculation. Six impacts could not be attributed to a given geological layer with certainty and hence were not considered for the statistical calculations (see Table 3). Note that the average results for the two tests series were kept separate because the restitution coefficients depend on the impact angle, which is affected by the presence of the drapery (which is discussed further). Determining the restitution coefficients is crucial for an accurate estimate of the impact energy dissipation and the trajectory simulations, and the calculated values were used in a rockfall hazard assessment [40].

The values of restitution coefficients are mostly in accordance with typical values from the literature for these types of surfaces [1, 48] except for \( k_n = 1.14 \) in the Sandstone for “Site 1—drapery”. Values of \( k_n \) greater than unity have recently been recorded and explained in the literature [56, 57]. The result can be imputed solely to a low impact angle and the shape of the block. Indeed, the rotational component of energy, which can play a significant role [56], is marginal here. It is known that the lower the impact angle, the higher the role [51, 57, 59, 60] and this trend is confirmed by the present results (Fig. 12a). Fig. 12b clearly shows that the presence of the drapery strongly influences the distribution of the impact angles: 85% of the impacts occur with an angle lower than 30° in presence of the mesh but this is reduced to 60% without drapery. This translates to higher values of normal restitution coefficients (for the same material) as shown previously.

5. Conclusions

This study presents the results of in situ rockfall experiments conducted at the Beltana Mine (Xstrata Coal) in New South Wales.

### Table 3

<table>
<thead>
<tr>
<th>Material</th>
<th>Site</th>
<th>N. of impacts</th>
<th>( k_n )</th>
<th>St_dev</th>
<th>( k_t )</th>
<th>St_dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>Site 1</td>
<td>2</td>
<td>1.14</td>
<td>0.2</td>
<td>0.4</td>
<td>0.15</td>
</tr>
<tr>
<td>Mudstone</td>
<td>Site 1</td>
<td>5</td>
<td>0.61</td>
<td>0.16</td>
<td>0.78</td>
<td>0.11</td>
</tr>
<tr>
<td>Mudstone debris</td>
<td>Site 1</td>
<td>1</td>
<td>0.11</td>
<td>/</td>
<td>0.8</td>
<td>/</td>
</tr>
<tr>
<td>Coal</td>
<td>Site 2</td>
<td>1</td>
<td>0.41</td>
<td>/</td>
<td>0.64</td>
<td>/</td>
</tr>
<tr>
<td>Sand./Mud.</td>
<td>Site 1</td>
<td>6</td>
<td>0.71</td>
<td>0.33</td>
<td>0.83</td>
<td>0.11</td>
</tr>
<tr>
<td>Sand./Mud.</td>
<td>Site 2</td>
<td>10</td>
<td>0.61</td>
<td>0.29</td>
<td>0.75</td>
<td>0.17</td>
</tr>
<tr>
<td>Mud./Sand. Debris</td>
<td>Site 1</td>
<td>4</td>
<td>0.03</td>
<td>0.42</td>
<td>0.63</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>Site 2</td>
<td>5</td>
<td>0.22</td>
<td>0.08</td>
<td>0.4</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Site 2</td>
<td>4</td>
<td>0.13</td>
<td>0.05</td>
<td>0.15</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Fig. 10. Rotational energy dissipation \( \Delta E \) calculated as the difference between the pre impact rotational energy at impact \( i + 1 \) and the post impact rotational energy at impact \( i \) normalised to post impact rotational energy at impact \( i \) versus impacts.

![Fig. 10. Rotational energy dissipation ΔE calculated as the difference between the pre impact rotational energy at impact i + 1 and the post impact rotational energy at impact i normalised to post impact rotational energy at impact i versus impacts.](image)

Fig. 11. Energy balance after the last impact on the slope for each test in “Site 1—drapery”. Each bar shows the energy dissipated by the net, \( \Delta E_{net} \), the energy dissipated during the impacts, \( \Delta E_{imp} \), and the mechanical energy available after the last impact, \( E_{Mf} \), as a ratio of the initial potential.

![Fig. 11. Energy balance after the last impact on the slope for each test in “Site 1—drapery”. Each bar shows the energy dissipated by the net, ΔE_{net}, the energy dissipated during the impacts, ΔE_{imp}, and the mechanical energy available after the last impact, E_{Mf}, as a ratio of the initial potential.](image)
Two series of tests were conducted by releasing concrete blocks from the top of a highwall in a meshed and unmeshed area. In the first series of tests the blocks were released under a rockfall protection drapery system installed on the highwall surface above an underground entry. During the second series, tests were conducted by releasing the blocks from the top of a highwall section without a rockfall protection system. The blocks falls were recorded and their trajectories were reconstructed via stereo-photogrammetry. These trajectories were then used to infer the motion characteristics of velocity, energy and restitution coefficients.

The results showed that stereo-photogrammetry is a very useful tool for the computation of the 3D block trajectories. However, the resolution of the stereo-pair cameras and the identification of the coinciding pixel pair play a crucial role for the accuracy of the results. In this work, accuracy was improved by analysing five pixel pairs per frame and by smoothing the final data set.

Translational energy to rotational energy upon impact was quantified as well as the energy dissipated by the net. It was also observed that the mesh reduces the length of the impact zone by more than 60%. Indeed, the blocks land much closer to the highwall in presence of the drapery, which would have some implications on the design of complementary remediation measures (e.g. attenuators or energy absorption mats). Finally, the restitution coefficients were estimated for most of the geological layers of the highwall. These are necessary for further numerical 2D trajectory analysis with commercial codes such as CRSP [161] or RocFall [62], and for a comprehensive rockfall hazard analysis of the entire area at the bottom of the highwall.

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