In Situ Experiments of Rockfall in an Open Pit Coal Mine

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Abstract

Rockfalls are a significant safety hazard in mining environments that need to be rigorously managed, in particular when designing portal entries for punch longwalls. In situ experiments were carried out at a mine in New South Wales (Australia) to improve management of the rockfall hazard at the base of the highwall. Concrete blocks were released from the top of the highwall. Block sizes were defined according to records of rockfall events and results of polyhedral modelling of the highwall.

The tests were carried out on two different sections of the highwall: the first section was draped with a netting protection system whereas the second section had no protection system (net) installed. In the first section, the blocks were released behind the net in order to be able to investigate the effect of the net on the block trajectory and the energy dissipation. Direct comparison was made with the section where no net interfered with the rockfall.

The tests were repeated several times and were recorded by using high speed cameras. Analysis of the rockfall images and videos allowed for the gathering of information on the motion type, trajectories, arrest zones and potential impacting energy. Particular emphasis was given to the analysis of the residual hazard once a protection system is in place. This is of particular importance for giving recommendations for optimising the protection system which then helps to provide greater confidence in the safety of portal installations.

1 Introduction

Rockfall events pose a significant risk in open cut and underground mines around the world, being responsible for a substantial number of fatalities and serious injuries, infrastructure damage and financial loss, e.g., when production is temporarily stopped for safety reasons. The hazard needs to be rigorously managed to reduce the risk to the employees and infrastructure through a reliable approach to the design of the portals, roads and ramp locations, by employing adequately designed rockfall protection systems such as rockfall netting, face bolting and portal protection structures. Rockfall has been widely studied for roads and highways (Pfeiffer & Bowen 1989, Giani 1992, Agliardi & Crosta 2003, Dorren 2003) but it is only recently that it has been accounted for in the context of open pits and quarries (Alejano et al. 2007, Alejano et al. 2008, Peila et al. 2011).

The installation of restraining nets combined with face bolting is a common practice to mitigate rockfall hazards in Australian open cut mines. This type of protective system can be considered as a hybrid between active and passive systems (Bertolo et al. 2009). The net is placed against the rock surface and its action consists of limiting the possible trajectories of the rock fragments, and in particular it prevents them from falling directly onto the concrete culverts used as portal structures for access to underground workings. However, the system does not totally eliminate the rockfall hazard as blocks can still detach and fall down between the net and the highwall, landing in highly worked areas in the vicinity of the portals. Some typical examples are shown in Figure 1. Whilst rockfall hazards are most significant for portals built into highwalls, they are also significant in most areas of the mine.
It is of prime importance to be able to predict likely trajectories and velocities of rocks behind rockfall protection nets in order to properly map and assess the residual rockfall hazard. There are currently no design guidelines, recommendations or even empirical models to address this safety issue in Australia. Such documents for open cut mining are long overdue. Draped nets are commonly used around the world to protect roads and infrastructure from falling rocks. In international literature there have been a number of reports on full scale field tests on rockfall fences (Smith & Duffy 1990, Gerber & Haller 1997, Peila et al. 1998, Peila et al. 2006, Hearn et al. 1992, Hearn et al. 1995, Gottardi et al. 2009) and hybrid drapery systems (Boettihcr et al. 2011, Glover et al. 2010, Geobrugg 2010) since the early 1990s. However, only a few research articles have addressed both design and field testing of netting systems so far (Bertolo et al. 2009, Maccaferri 2008, Sasiharan et al. 2006).

The aim of this study is to improve the current knowledge and understanding of the application of wire mesh drapery systems for rockfall hazard management in mining environments. Through field tests, data collection and data analysis, the research describes the principal characteristics of a rockfall event along an open cut highwall. The study will be then combined with numerical analysis to highlight fundamental characteristics of rockfall in a mine site such as run-out distances, velocities and kinetic energy achieved during the fall. This information will allow for assessing the residual hazard associated to netting protective solutions.

2 Experimental testing

2.1 Testing site

Experimental tests were carried out at the Beltana mine (XstrataCoal) in New South Wales (Australia). The mine, located in the Hunter Valley near Singleton, is one of the most productive longwall coal mines in Australia. Several years ago, in the development of underground access through the open cut highwalls, a rockfall control system was installed to protect personnel and equipment working at the base of the wall (http://www.stornoway.com.au). A system combining flexible draping of a double twisted Maccaferri rockfall mesh (http://www.maccaferri.com.au) over the highwall face with rock bolts drilled into the face was installed to minimise the risk of falling blocks. The 16 m wide wire mesh drapes are made of four individual 4 m wide mesh strips, clamped together along their long edges. Each drape is anchored at regular intervals on the top of the highwall 5 m behind the crest, and the bottom is restrained by a single cable, threaded through the bottom edge of the drape and anchored only at the end.
The highwall is around 1.4 km long, over 40 m high and it slopes at around 70°. It mainly consists of horizontal layers of interbedded sandstone and mudstone and some thin (<300 mm) layers of coal. The mine operations in this area have already been completed, and therefore, it was possible to conduct the tests without affecting mine operations or exposing mine personnel to risk. For this study, only 200 m at the southeaster end of the highwall are considered. Three abandoned underground portal entries are located in this area, each with a draped netting rockfall protection system installed on the highwall, as shown in Figure 2.

A geostructural study of the highwall to map the main structures of the rock mass, to analyse their characteristics and to assess the size distribution of the potentially unstable blocks through numerical analysis was carried out and reported previously (Thoeni et al. 2011). In addition, data on recent rockfall events and associated information on rock material characteristics and block dimensions were collected for comparison with the numerical results.

2.2 Experimental set-up and data acquisition

2.2.1 Experimental set-up

Thirteen concrete blocks, with shapes according to EOTA (2008), were made in the laboratory of the Centre for Geotechnical and Materials Modelling of The University of Newcastle. The blocks, with a width of 30 cm and a mass of 44.5 kg, were painted yellow with a unique black pattern on each of the 6 main faces so that its rotational movement could be determined from high speed images taken during the fall. The geometry of the block is shown in Fig. 3a and a typical block is shown in Fig.3b.

A 60 tonne all-terrain crane with a man basket (Fig. 4) was used to release the blocks from the top of the highwall. The crane was positioned on a road on the top of the highwall adjacent to the sections selected for the tests. A detailed inspection of the mesh was previously carried out in order to find a suitable location to insert the blocks under the net.

The blocks were released manually at the top of the highwall at two different sections: the first section with drapery above the first portal and the second section without any netting. A safety berm was located 10 m from the base of the highwall at the bottom of the first section to catch the rocks that arrived there. There was no safety berm at the base of the highwall in the second section, but instead there was a large mud-filled depression which captured the blocks upon impact. For each section, all blocks were released from the same position in order to reproduce the tests and obtain comparable data. Radio communication was used to coordinate the tests.
Figure 3.  (a) Technical drawing showing the dimensions of a block (in mm). (b) Photograph of a block used for the testing showing the different patterns on each side.

Figure 4.  (a) Crane and (b) man basket used to release the blocks from the top of the highwall.

2.2.2 Data acquisition

The motion of each of the blocks down the highwall was recorded using high speed video cameras. In rockfall experiments, cameras are usually set up on an axis orthogonal to the expected plane of the boulder’s trajectory and two-dimensional video processing is used to analyse the data. In this case cameras could only be set up on the road in front of the highwall at a safe distance of about 50 m from the highwall. Stereo-photogrammetry was used for the test so that three-dimensional information could be captured. Using images captured from videos instead of photo stills tends to lower the resolution of the images, and consequently, the fall along the highwall
was divided into two sections (top and bottom) captured by separate, closely-positioned cameras to increase the accuracy of measurement.

Two sets of stereo-pair cameras were set up on the road to record the blocks. Two Canon EOS 7D SLR cameras and two high-speed Optronics CR600 video cameras were used to record the motion of the block at the top section and at the bottom section of the highwall, respectively. The details of the cameras are shown in Table 1. In order to capture the entire fall of the blocks along the highwall, the two sets of cameras were overlapped by about 10 m as shown in Figure 5. Each stereo-pair of cameras was synchronised using synch-cables. For safety reasons the cameras were triggered remotely. Two additional high speed cameras were used to capture some local details such as bouncing on the highwall face and the final impact. However, the data of these two cameras have not been included in the current work.

![Figure 5](image.png)

**Figure 5.** Picture showing the locations and the parts covered by the stereo-pair cameras used for the stereo-photogrammetry. The line indicates the field of view for each stereo-pair.

<table>
<thead>
<tr>
<th>Details of the cameras used in the experiments.</th>
<th>Canon EOS D7</th>
<th>Optronic CR600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame rate (frame per second)</td>
<td>60</td>
<td>500</td>
</tr>
<tr>
<td>Resolution (pixels)</td>
<td>720 x 1280</td>
<td>1024 x 1280</td>
</tr>
<tr>
<td>Lenses</td>
<td>Canon EFS 15-85mm</td>
<td>Nikkor 35mm F2D</td>
</tr>
<tr>
<td>Focal length (mm)</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>Field of view (horizontal x vertical)</td>
<td>19 x 28°</td>
<td>23 x 29°</td>
</tr>
</tbody>
</table>
Stereo-photogrammetry was used to track the changing position of the blocks and to determine their motion and bounce characteristics. Ten control points were placed on each test section of the highwall (Figure 6) to provide scale for the photogrammetry and allow each section to be measured on the same reference system. This allows tracking of the three-dimensional motion of the block over the entire height of the highwall. The control points were placed in such a way that each camera pair could see at least 6 of them. The coordinates of the control points were measured by using a Trimble M3 electronic theodolite. The photogrammetry software package ‘VMS – Vision Measurement System’ (http://www.geomsoft.com) was used to analyze the sequences of photographs collected by the stereo-pair cameras. This software is designed for video sequencing and thus the three-dimensional coordinates of a block during its motion down the highwall can be easily measured. From this, the speed and acceleration of the block can be determined.

Each of the stereo-pair cameras covers about 30 m of the highwall, which implies that each pixel in the images represents about 25 mm on the highwall. The operator of the photogrammetry software also has to determine the position of the centroid of the rotating block on each pair of images in order to track the position of the block. Since the position of the block in each frame of the video sequence has to be measured “manually” (by clicking on the points) the expected accuracy for its position is about 25-50 mm in each frame of the video sequence. However, the accuracy also depends on the velocity of the block. The initial velocity of the block has a movement of around 50 mm when measured at 60 frames per second, and therefore, the estimates of the initial velocities will contain large errors in comparison to the rest of the test.

Figure 6. Pictures showing the two sections used for the testing and the control points used to provide scale for the stereo-photogrammetry. (a) Test 1 under the net, (b) Test 2 without net.
2.3 Experimental program

All thirteen concrete blocks were released from the highwall over two consecutive days. The blocks were not recovered after the tests for safety issues.

On the first day of testing, 6 concrete blocks were released under the netting above the first portal entry. The section above the first underground portal entry was chosen for this series of tests since the rockfall protection drapery installed there was in better condition compared to those above the other entries. Potentially, the most difficult task was to release the block between the highwall and the netting.

On the second day, 7 concrete blocks were released on top of another section of the highwall, without any drapery installed or an underground portal entry at the bottom of the highwall, as indicated in Figure 2. The blocks were released from the man basket in two different positions, chosen in order to increase the bounces off the wall.

In the following, to limit the length of the paper, only the results obtained for one test under the net (Test 1) and one test without net (Test 2) are presented and analysed.

3 Results and observations

For the tests performed under the net above the first portal, several impacts of the blocks between the net and the rock surface were typically observed and there was no damage evident to the drapery. All blocks reached the base of the highwall and impacted on the muck pile which is located on the top of the concrete culvert of the underground entry. Some blocks continued after this to reach the safety berm located 10 m out from the base of the highwall. However, these parts of the trajectory were outside the field of view that could be captured by the stereo-pair high speed cameras. By contrast, the blocks dropped down the undraped section of the highwall recorded fewer bounces (typically only one or two) and impacted further from the base of the wall.

Figure 7 and Figure 8 show different views of the trajectory of the block during Test 1 and Test 2. The overlap of the stereo-pair cameras (Fig. 5) can be easily seen from the trajectories. The blue trajectory corresponds to the top section captured by the Canon cameras, whereas the red trajectory corresponds to the bottom section captured by the Optronics cameras. The block trajectory determined from each pair of cameras in the overlap zone is not exactly the same. This is due to the different resolution of the stereo-pair cameras, which results in a different accuracy, and to the manual procedure of tracking the block. However, a good agreement in the shape of the path is observed.

By comparing the trajectories of Figure 7 with Figure 8 it can be seen that the net strongly influences the bounce height – measured perpendicular to the face – by controlling the motion of the block and guiding the blocks to the bottom of the highwall. The maximum bounce height for Test 2 without a net is around 10 m whereas it is only around 1.5 m for Test 1 with the net.

Furthermore, five impacts were observed for the block between the rock surface and the protection system during the fall in Test 1: four impacts on the highwall and one final impact on the muck pile at the base of the highwall. Test 2 shows two impacts on the highwall and one final impact about 10 m from the base of the highwall. Both trajectories have almost a two-dimensional behaviour. A few small curves were observed in the motion of the block of Test 1 under the net.

As shown in Figs. 7-8 the vertical distance measured from the point where the block was released to the final impact is 31.1 m for the test with the net and 48.1 m for the test without the net.
Figure 7. Different views of the block trajectory for Test 1 under the net (the blue trajectory corresponds to the top section captured by the Canons and the red to the bottom section captured by the Optronics).

Figure 8. Different views of the block trajectory for Test 2 without the net (the blue trajectory corresponds to the top section captured by the Canons and the red to the bottom section captured by the Optronics).
Figure 9. Measured vertical velocity of the block vs. time for Test 1 (orange and blue line), theoretical vertical velocity vs. time (dotted red line) and filtered vertical velocity vs. time (black line).

Figure 10. Measured vertical velocity of the block vs. time for Test 2 (orange and blue line), theoretical vertical velocity vs. time (dotted red line) and filtered vertical velocity vs. time (black line).
The vertical velocity of the blocks for both the tests was analysed. Vertical velocity vs. time is plotted in Figure 9 and Figure 10, for Test 1 and Test 2 respectively. In the diagrams the theoretical vertical velocity corresponding to the free-fall motion of the block under gravity (the red dotted lines) and the vertical velocity derived from the measured data (orange and blue lines) are shown. The latter, obtained separately for the top and bottom section of the highwall, showed some noise due to the manual tracking procedure of the block with the photogrammetry software. In order to show the clear trend of the vertical velocity, this problem has been solved, firstly, by tracking several points with the photogrammetry software and averaging the coordinates in order to get the coordinates of the centre of the block. Secondly, a moving average filter has been applied to the results where each data point was computed using the previous four data points (black line).

The individual impacts and the resulting decrease of velocity caused by the impact can clearly be seen in Figs. 9-10. In addition, a very good agreement between the theoretical free-fall motion and the recorded data is observed in both cases. In Test 1, the maximum recorded vertical velocity of the block is 15 m/s, corresponding to the velocity of the block just before impact on the muck pile on top of the portal, at the base of the highwall. The total travel time of the block is 4.4 s. In Test 2, the maximum vertical velocity is 23.5 m/s and the total travel time of the block is 4.1 s.

By comparing the results of the two different tests it can be seen that not only the bounce height is reduced by the net but also the velocity of the block. Furthermore, the test where blocks were dropped down behind the net shows more impacts than the test without the net. In addition, it was observed that the net prevents the block primary from rotating. While the block is rotating very fast after impact during Test 2, this is not the case for Test 1 where the block almost slides down along the net once it has impacted on the net.

4 Conclusions

This paper presents the first results of in situ rockfall experiments conducted at the Beltana Mine (XstrataCoal) in New South Wales (Australia). Two series of tests were carried out by releasing concrete blocks from the top of a highwall and recording the block trajectories with high speed cameras. 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. The second series of tests were conducted by releasing the blocks from the top of a highwall section without a rockfall protection system.

Results of one test from each series are presented and discussed. Three-dimensional trajectories and vertical velocity data for each test are analysed. The strong influence of the net on the bounce height of the blocks and in the reduction of velocity at the bottom of the highwall is clearly observed. Therefore, the net plays a key role in the residual hazard assessment of a portal entry for underground mining. The vertical velocity is not reduced drastically by the net and the final velocity of the block behind the net at the top of the muck pile is larger than expected. Therefore, muck piles at the bottom of the highwall and especially at the top of an underground entry are confirmed as also playing a crucial role in the residual hazard management.

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6 References


