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Full-scale experimental testing of dump-point safety berms in surface mining

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Abstract

Waste rock (muck) piles are used as energy absorption barriers in many surface mining applications, such as berms at dumping points and at the crest of slopes, and in windrows as traffic separators or edge barriers on haul roads. The height of safety berms and windrows is currently designed using rules of thumb, such as height equal to half the maximum wheel diameter. However, over the last few decades the dimensions of haul trucks have increased, and it is unclear if such rules of thumb are still applicable. This study, funded by the Australian Coal Association Research Program (ACARP), was carried out with the objective of improving the current knowledge on design and construction of dump-point safety berms in mining environments. Through full-scale experimental investigations on the dynamic impact of haul trucks on dump-point safety berms, significant data on berm design, construction materials, as well as principal berm characteristics were collected for the first time. The experimental findings suggested that the current rule of thumb might only be suitable for dump points where trucks travel at velocities lower than 10 km/h. They also found that, safety berms should be built using fresh, blocky, non-slaking waste rock materials and well maintained over their lifespan.

Keywords surface mining, berms, haul truck, mine-dump, full-scale tests.

Introduction

Safety berms as engineered barriers in surface mining

A safety berm is defined as “a pile or mound of material intended to assist in preventing mobile equipment from travelling over the edge of a bank” (Turin et al. 2001). In surface mining operations safety berms are utilised as visual and physical indications of where the edge of the haul road or dump crest is located, lateral restraints to prevent powered haul trucks from leaving the path of travel, or physical barriers to prevent vehicles backing over the crest of tip faces in waste dumps (Figure 1).

Constructed entirely of spoil (or waste rock) material, dump-point safety berms are generally not designed to indicate that the edge has been reached, but they should be considered as a safety extra and used for “spotting only” (May 1990; Turin et al. 2001).

Currently, dump-point berms are designed according to rules of thumb, e.g. the minimum height of the berm should be at least half the wheel diameter of the largest vehicle used in the mine site (MSHA 2001; Safe Work Australia 2011). Recent developments in the mining industry have led to increased haulage capacity through the introduction of ultra-class haul trucks. Haul road design and maintenance guidelines for safety berms, however, have not progressed equitably, and safety authorities are calling for a more rigorous design approach. Recently, the Mining and Quarrying Occupational Health and Safety Committee of South Australia (MAQOHSC 2009) and the Mines Inspectorate of Queensland (Queensland Government 2010) issued a newsletter and a safety alert that questioned the current rules of thumb, noting that safety berms needed to be designed to suit the nature of the material and the size of the machinery.

The importance of safety berms

Safety berms play a crucial role in preventing surface mining accidents involving haul trucks, in all major mineral industries, including coal, sand and gravel, crushed stone, metal and non-metal (May 1990; Groves et al. 2006). Dump-point accidents, involving the fall of large mining equipment over the edge and down the front slope of the waste dump or stockpile, also represent a major issue. Such accidents are more severe than the typical surface mining accidents and are responsible for a disproportionate share of the total fatalities and lost workdays in the mining industry.

The U.S. Bureau of Mines (May 1990) investigated the impact of dump-point accidents on the mining industry. Between 1983 and 1987, 103 accidents involving mobile equipment at dump points led to 4,821 lost workdays with 11 incidents resulting in fatalities. 80% of all dump point accidents were related to haul trucks, with the greatest percentage occurring in the coal industry where waste dumps and spoil piles are constructed with overburden materials (blasted rock). The study was extended for the period 1988-1997 by Turin et al. (2001). It was found that the two most common situations leading to fatal injuries were “travelled through a barrier” (30.8%; 8 fatalities) and “no barrier provided” (34.6%; 9 fatalities). Similar observations were made by Groves et al. (2007) for the period 1995-2004, where off-road ore haulage was the most common source of fatalities. They also pointed out that despite the record of progress that had been achieved in reducing mining injuries and fatalities, both the number and severity of haul truck related accidents occurring was still unacceptable. This remains the case, with more recent data published by Kecojevic and Zhang (2013) reporting 141 haul truck related fatalities in the U.S. for the period 1995-2011.

Md-Nor et al. (2008) used published data from the U.S. for the development of a risk assessment process for haul truck-related fatal accidents in mining. They analysed accidents

in the period 1995-2006. The recorded accidents were classified according to their hazard and severity, and the probability of each hazard was estimated. The hazard “failure to provide adequate berm at dump or haul road” was classified as “very likely” and with high severity. The importance of the haul road design standards and safety berms was also addressed in a study from South Africa (Thompson et al. 1998) where a haul road safety audit procedure was developed.

Noon and MacNeill (2008) compiled an international mining fatality database. The majority of the data was from 1980 to 2008. Its focus was on accidents from the U.S. and Australia. Between 1990 and 2006, the authors recorded 26 fatalities involving haul trucks in the coal mining sector globally, 13 of which involved inadequate or non-existence of safety berms. 30% involved the haul truck reversing over dump-point berms. When the data of the international mining fatality database is combined with more recent accident data from the U.S. and Australia gathered from the Mine Safety and Health Administration (MSHA) and the Minerals Industry Risk Management Gateway (MIRMGate) of the University of Queensland, it can be seen that one fatal accident per year was related to berms (roadside and dump-point combined) in the period 1990-2011. This highlights the importance of adequate safety berms in preventing fatal accidents.

Recent studies and current design

From the early ‘70s a few studies have been conducted in response to the significant number of recorded accidents in surface mining (Kaufman and Ault 1977; Wade 1989) and some useful practical information on maintenance, traffic controls, as well as suggested criteria for vehicle safety provisions have been provided. Most studies focussed on haul road berms and did not contain design and/or construction guidelines for dump-point berms. Nevertheless,

they addressed several important aspects of the safety berm design, such as construction materials and berm geometry that could as well apply to dump-point berms.

The height of the safety berm was considered the main factor in the design, and a rule of thumb was established. Kaufman and Ault (1977) suggested that the height of the berm should be equal to or greater than the rolling radius of the vehicle's tire in order to possess any measurable tendency to stop or redirect a haulage vehicle at impact. Interviews conducted with mine personnel at different mine sites across North America by Stecklein and Labra (1981) a few years later expressed a general consensus that this rule of thumb might have been inadequate, and a detailed study including full-scale and reduced scale physical testing and simple numerical modelling was carried out in order to provide more adequate guidelines. The full-scale tests involved driving a loaded 35 t single rear axle rear dump truck forward into triangular berms. However, even though the study did not specifically address impacts in backward motion as for dump point berms, it provided, for the first time, experimental data on construction materials, approach conditions and berms response upon impact. In particular, the authors concluded that to act as a restraint system, berms must be constructed to a height versus strength relationship (the greater the berm strength, the smaller the required berm height) and that the berm effectiveness is influenced by material composition and level of compaction introduced during the construction process.

More recently, Tannant and Regensburg (2001) recognised that the increases in truck size over the last decades played a crucial role in the design of a haul road. They recommended increases in the height of safety berms, requiring the ratio between berm height and the tire diameter to be about $3/4$, with all berms being greater than 1 m high regardless of tire size. Again, the guidelines addressed haul road berms only, but they highlighted the significance of the differences in spoil materials and berm geometries (triangular and trapezoidal shape) used in various mine sites.

In 2001, the U.S. Department of Labor's Mine Safety and Health Administration (MSHA) released the Dump-Point Inspection Handbook (MSHA 2001) in which strict procedures for the construction of dump-point berms were suggested. The handbook defines dump-point berms as a pile of material representing a visual indicator of the location of the dump point, or edge of the pile. In particular, their main function is to provide the driver with a "contact" point so that, if necessary, they can "feel" that the berm has been reached, and be substantial enough to impede equipment from going over the edge in the event of a misjudgement, operational error, or mechanical problem. In order to serve these functions, a dump berm height was suggested to be at least mid-axle height of the largest piece of equipment used in the dump area. However, the handbook outlined that while the adequacy of a berm is normally judged based on the mid-axle-height criterion, the latter only sets a minimum value for berm height, and the operators should realise that the effectiveness of a berm depends not just on its height but also on its thickness and firmness. In particular, earthen berms should be firm enough to avoid penetration by tires, and they should have a steep inside slope in order to resist the tires from climbing up and going over the berm. Additionally, the handbook provides suggestions on adequate maintenance and appropriate driving actions in order to mitigate and reduce the related hazard in surface mining operations. Finally, the guidelines suggest that the berm should have a sufficient base width to keep the heavy loading on the rear tires from getting too close to the edge of the pile where the slope could become unstable and the material could give way. For this purpose the base width of the dump berm should be at least the width that an axle-height berm would have if both its outside and inside slopes were at the material's angle of repose.

More recently, the Safe Work Australia (2011) code of practice adopted the MSHA approach, that a berm height must be at least half the diameter of the tire of the largest vehicle. The berm should be constructed as vertical as possible since steeper berms provide greater

restraint, as long as the berm has sufficient bearing strength. The berm height and slope, along with its width and firmness, were considered the main factors that influence berm performance.

Overall, safety berms are still designed using rules of thumb. There is common sense on what makes a berm effective, such as geometry, material, level of compaction and maintenance. It is well known that the height of the berm plays a crucial role, but there is no specific experimental evidence to inform designers about optimum berm geometries in specific applications.

This study

As far as the authors are aware, experimental data from full-scale testing to investigate the most significant factors influencing dump-point accidents involving haul trucks have never been published in the scientific literature. For the first time, rigorous full-scale tests of haul trucks impacting on dump-point berms have been performed. The testing procedure and the results are presented in this paper. The experiments were carried out at two open cut coal mines in Australia. Two series of tests were performed and results were compared in terms of truck fleets, truck motion, berm construction materials and berm geometry. Truck velocities and motions were recorded using digital cameras and berm deformations were measured by means of advanced photogrammetric surveys. The tests provided unique experimental evidence on the effect of dynamic impacts of trucks on dump-point safety berms to underpin useful recommendations for a better berm design.

Experimental procedure

Experimental facilities

Experimental full-scale tests were carried out in two open cut coal mines located in the Hunter Valley in New South Wales, Australia. Tests involved reversing different models of haul trucks, including the CAT 797F, CAT 793D and CAT 789D (Table 1), into berms constructed from mine spoil. All trucks were fully loaded during the testing. Tests were conducted only in backward motion and at low velocity in order to minimise the potential to damage the trucks. In addition, all tested berms were constructed on flat areas to eliminate the risk of the truck running over an edge. A first series of tests was conducted on a remedial dumpsite located within the Bulga Open Cut Mine Complex (Glencore-Xstrata) on October 2012 using a CAT 797F and a CAT 793D. In the following this site is referred to as Site A. The second series was undertaken in December 2013 at Drayton Mine (AngloCoal) using a CAT 789D. This site is referred to as Site B.

Berm materials and geometry

The tested berms were constructed following general surface mining construction practice, for which the material is first dumped on to the flat working area and then shaped into a berm by a dozer to form the sides and top surface (if safely accessible). The first series of tests at Site A consisted of testing a trapezoidal berm: the materials were initially dumped forming a triangular shape, and then shaped by the dozer to form a continuous isosceles trapezoidal berm. The berm was constructed in two sections containing spoil material with varying degrees of physical degradation and different amounts of handling, including some re-mined spoil. The first section was about 140 m long and it was constructed entirely from fresh mine spoil characterised as being quite blocky and solid. This section had an average height of 1.75 m and an average bottom and top width of 9.4 m and 4.4 m respectively (Figure 2a). The

second test section was 154 m long and was comprised entirely of re-mined spoil material, which was heavily degraded with high fines content. This section had an average height of 1.7 m and an average bottom and top width of 10.8 m and 5.7 m respectively (Figure 2b). Constructed heights were limited by the working constraints of the dozer. The average angles of repose for the first and the second section were of 36° and 34° respectively.

CAT 797F and CAT 793D dump trucks were used in the first series of tests. The height of the berm for both sections corresponds to about 50% of the wheel diameter of the CAT 793D (cf. Table 1), but only 40% of the diameter of the CAT 797F.

The second series of tests at Site B was carried out on two continuous triangular berms of different height. The first berm (Berm 1) had an average height and width of 3.2 m and 12.9 m respectively (Figure 3a). The berm was built by simply dumping the spoil material on the flat working area, without subsequent shaping by a dozer. The second berm (Berm 2) had an average height and width of 1.8 m and 5.4 m respectively (Figure 3b). This berm was built using a dozer and it corresponded to a realistic dump-point berm. Its height was about 50% of the wheel diameter of the CAT 789D (cf. Table 1) used for this series of tests. The average angles of repose for the first and the second section were 31° and 35° respectively. This difference can be attributed to the fact that only the second section was shaped on its sides by the dozer in the construction process. Greater berm heights were not achievable due to the working constraints of the dozer which was used to shape the berm. The berms were not compacted during the construction process. The material at site B comes from geologically weathered rock and it was characterised by a significant percentage of clay and very high fines content.

It is well established that there is a strong dependence of the material strength characteristics on the particle size and that an improvement of the spoil material gradation provides an

increase of shear strength (Fell et al. 2005; Williams and Kho 2013). Coal mine spoil material generally contains fines, gravels, cobbles and rocks or boulders of various sizes. Their mechanical behaviour and strength characteristics are governed by parent rock type, weathering/deterioration and mining activities/processes. The sedimentary overburden lithology contains sandstones, siltstones, mudstones, shales, laminites, cherts, and ironstones, but basalts, tuffs and igneous intrusions are also sometimes found (Fityus et al. 2008). The spoil texture and its strength are significantly influenced by the mining practices employed in overburden fragmentation (dozer ripping or blasting), overburden removal (dragline, shovel, excavator, or loader) and overburden placement (haul truck, dozer, dragline, or conveyor system).

Simmons and McManus (2004) provided a framework for the characterisation of spoil materials. The framework classifies any type of spoil into one of four categories through a visual-tactile method which considers four main physical attributes: predominant particle size, consistency, structure, and plasticity (Table 2). As the gradation improves, or as the proportion of larger particles increases, the friction angle also increases.

The particle size distribution (PSD) of all three spoil materials used to build the tested safety berms were determined by means of direct (sieving) and indirect (digital images) analysis. Figure 4 shows examples of digital images taken for each spoil material. In each photo, the reference scale objects (orange plastic balls with a diameter of 9.9 cm) were also included. The indirect PSD analysis was carried out for each test section by using the software package Split-Desktop (Split Engineering LLC, 2013). The fines content of each material was identified via laboratory sieving. The PSD results of the direct analyses were then combined with the average data of the indirect study (Figure 5).

Finally, the spoil materials used during the tests were classified according to the framework of Simmons and McManus (2004). The fresh and the re-mined materials used at Site A were classified as a Category 3 and a Category 2 spoil respectively. The weathered spoil material used at test Site B falls between Category 1 and 2, therefore it was classified as a Category 1.5 spoil.

Experimental setup

During each test series, the berms were divided into single test bays. Each bay was subjected to a single test. Typical test bays are shown in Figure 2 and Figure 3. The test bay width was determined based on the width of the approaching truck. Additional space between the tests was also used to avoid any influence between adjacent tests. Each test bay had a final width of around 14-18 m, allowing 8 and 9 tests to be conducted on the berm built with fresh and re-mined mine spoil respectively. This resulted in 17 tests conducted at Site A. Ten tests were conducted at Site B: 4 on Berm 1 and 6 on Berm 2.

Each test bay was marked out with spray paint and numbered signposts. Coloured sprayed lines on the ground indicated the approach conditions and helped direct the driver toward the berm. The impact of the truck on the berm was recorded by video cameras in order to measure the approach velocity of the truck, the vehicle-berm displacement and the wheel climb at impact. Reference targets were precisely positioned on both sides of each haul truck tray (Figure 6) so that the measured distances between these targets could be used as a reference scale for the video analysis. Targets on truck tires provided a visual of wheel spin.

Two Canon EOS D7 DSLR cameras (30 frames per second, 1920×1088 pixel image resolution) were used to record the motion of the truck. The cameras were positioned on the left (LHS) and right (RHS) hand sides of the truck at a determined safety distance of 20 m and normal to the truck's motion (Figure 6 and Figure 7). An additional camera was

positioned at the top of the berm a few metres from the impact zone. This camera was used for a qualitative assessment of the berm deformation of the top of the berm upon impact. Figure 7 shows a sketch of the testing area setup.

A photogrammetric survey was carried out to assess the deformation of the berm upon impact. For this purpose, ground control points were installed between the test bays and digital still images were collected before and after each test using a Panasonic Lumix LX5 (3776×2520 pixel image resolution). For each test, two sets of images were taken (Figure 8). The first set was collected at about 2-3 m walking distance from the berm, parallel to the berm's extension. The second set was collected from the deck of the truck, parked in front of the berm, at about 6-8 m from the berm. A multi-view reconstruction approach (Dall'Asta et al. 2013) was applied to reconstruct the surface of the berm before and after impact. Figure 8 shows an example of the results obtained with the multi-view reconstruction approach including the camera positions and the ground control points.

Table 3 and Table 4 show the detailed experimental program for the two test sites. A total of 27 tests were performed. The first test series carried out at Site A included 17 tests: 4 tests were conducted using a fully loaded CAT 793D haul truck and 13 tests using a fully loaded CAT 797F. The test series at Site B involved 10 tests carried out with a fully loaded CAT 789D. Both series included one test where the truck reversed into the berm multiple times at the same location. The multiple impact tests are Test 15 for Site A and Test 9 for Site B. All tests were carried out in backward motion, using approach velocities of around 7-10 km/h and approach angles of 90° or 75° to the axis of the berm. The approach conditions represent realistic scenarios for dump-point berms where truck drivers are supposed to reverse perpendicular to the safety berm. In practice the angle might vary in-between 90° and 75°. The approach velocities used during the tests are very close to the maximum reversing velocities of the truck.

In both cases, the truck driver was told to keep his foot on the accelerator to maintain a constant speed up to impact with the berm, and not to apply the brakes. However, once the driver felt the impact, he took his foot from the accelerator. Comments of the driver on how he felt the truck response upon impact were collected at the end of each test.

Data analysis

Video analysis

The open source video analysis and modelling tool Tracker (Brown, 2013) was used to analyse the video footage recorded during the tests. The tool combines videos with computer modelling and allows the tracking of position, velocity and acceleration of a moving object. In this research, the rear axle of the truck was tracked to determine the wheel climb of the truck in addition to its velocity and displacement. For each test, approach velocity and wheel climb were determined for each camera as a function of the time, as illustrated in Figure 9. The time was set so that the first contact with the berm was always $t = 1$ s. This information allowed the determination of the time from impact to zero velocity (i.e. impact duration), the impact velocity and the maximum wheel climb. In addition, the maximum horizontal wheel displacement, that is the horizontal displacement of the wheel from the first contact with the berm until the point of zero velocity in direction of the approach condition, was measured. Figure 10 shows the horizontal and vertical motion of the wheel during impact.

The video analysis was undertaken with the aim of identifying a relationship between approach velocity and subsequent wheel climb and horizontal wheel displacement. It is noted that in general the results for approach velocity and wheel climb were slightly different for camera LHS and RHS. In the case of approach velocity this was attributed to the difficulties of perfectly aligning both cameras with respect to the impact direction. An average value will

be presented in the following results analysis. In the case of the wheel climb, the difference between LHS and RHS were attributed to unevenness of the working area and to the rather random surface roughness of the safety berm. Therefore, average maximum values were calculated for an approach angle of 90° . For impacts with an approach angle of 75° the LHS wheels impacted the berm about half a second before the RHS wheels. In this case, due to the nature of the angled approach condition, the right wheel experienced negligible wheel climb and only the LHS maximum wheel climb and maximum horizontal wheel displacement were considered.

Photogrammetric analysis

The images collected during the tests were processed using the multi-view 3D reconstruction software PhotoScan (Agisoft LLC 2014). Around 50 images per test were used in this process in order to build one model. The final result was a 3D digital terrain model, for each test before and after the impact. The ground control points allowed the 3D models to be scaled and placed in a common reference coordinate system. A deviation analysis was carried out by comparing the two models and the deformation of the berm was assessed.

The open source 3D point cloud and mesh processing software CloudCompare (Girardeau-Montaut 2014) was used to perform a 3D deviation analysis and to obtain the maximum berm deformation resulting from the truck–berm interaction. The analysis consisted of calculating the distance between the 3D models generated from the images taken before and after the impact. The software calculates the distance between the two meshes normal to the surface and displays the results in the form of a colour coded 3D representation. Data were analysed in terms of tire penetration, i.e. absolute deformation normal to the berm surface, and in terms of vertical (z-direction) and horizontal (y-direction) berm deformation (Figure 11).

Results and discussion

Site A

Video analysis and photogrammetric survey data for the first test series at Site A are summarised in Table 3. In the following the most significant results are discussed.

The tests with an approach angle of 90° (perpendicular approach conditions) had impact velocities between 7.26 km/h (Test 7) and 10.24 km/h (Test 15(1)). The maximum wheel climb at first impact ranged from 0.31 m (Test 1, RHS) and 0.7 m (Test 3, LHS) whereas the maximum horizontal wheel displacement was between 0.99 (Test 10, RHS) and 1.75 m (Test 3, LHS). No major differences in maximum wheel climb or maximum horizontal displacement were observed between the two different spoil materials used in the tests. However, tests conducted on the well graded re-mined material provided more consistent results.

Measured tire penetration indicated (see Table 3) that the fresh material is stiffer and less prone to compaction under the action of the tires: the three tests carried out with an approach angle of 90° on the fresh material with the CAT 797F gave almost identical results for slightly different impact velocity values (Test 1, 2 and 3).

Impact velocities between 7.26 km/h (Test 7) and 8.09 km/h (Test 14) were used for the tests conducted with an approach angle of 75° as higher velocities could not be used for safety reasons. The maximum LHS wheel climb was between 0.41 m (Test 4) and 0.7 m (Test 17) whereas the maximum horizontal wheel displacement was between 1.08 m (Test 13) and 1.97 m (Test 17). This indicates that an angled approach condition generally results in a higher wheel climb and larger horizontal wheel displacement and, consequently, in a greater

berm deformation. Berm deformations for an angled approach were about 10% higher than those measured with perpendicular approach conditions (cf. Figure 13).

Figure 12 and Figure 13 show the results for two tests conducted with the two different approach conditions (90° and 75°). Both berms were built with re-mined material and the tests were conducted using a CAT 797F. It can clearly be seen that the angled approach resulted in a bigger horizontal displacement and a slightly higher wheel climb. Additionally, the angled approach induced significant bouncing of the truck body upon impact, as shown by the more pronounced hysteresis in Figure 12b compared to Figure 12a. For the 90° approach, the point where the maximum horizontal wheel displacement was reached coincides with the point of maximum wheel climb. This is not the case for the angled approach, where the point of maximum wheel climb is reached later due to the effects of tire compression and the resulting sidewise bouncing of the truck.

Test 15 was carried out on the re-mined material and it involved three successive impacts of the truck into the berm with an approach angle of 90° . The recorded impact velocities were 10.24, 7.88 and 8.51 km/h for the first, second and third impact respectively. Figure 14 shows the main results of the video analysis where the horizontal wheel displacement is plotted against the wheel climb. It can be seen that the maximum values were recorded at the last impact even though the impact velocity was almost 2 km/h lower than the one recorded at the first impact. In addition, a gradual decrease of the wheel climb was observed for a horizontal displacement up to 1.4 m (Figure 14). This latter was attributed to the compaction the material underwent during the multiple impacts: as the material was progressively compacted under the load of the truck tires, the berm height, and therefore the effectiveness of the berm, was reduced.

Site B

Data obtained from the video analysis and the photogrammetric analysis of the second series of tests conducted at Site B are summarised in Table 4.

The second series of tests allowed investigation of different berm heights. A large triangular berm (Berm 1) with an average height of 3.2 m and a small triangular berm (Berm 2) with an average height of 1.8 m were tested. The impact velocity was between 5.98 km/h (Test 9(1)) and 8.76 km/h (Test 3) for the tests at an approach angle of 90°. Comparable velocities were used for the angled approach tests, also. The maximum wheel climb for the perpendicular approach was very similar for both berm heights and varied between 0.23 m (Test 6) and 0.39 m (Test 3). Only Test 9 (multiple impacts) recorded much higher values of wheel climb and horizontal displacement, due to the multiple impacts.

For the truck impacting at an angle of 75°, the maximum wheel climb was considerably higher reaching values between 0.36 m (Test 10) and 0.59 m (Test 11). Generally, the maximum wheel climb was very similar for both berm heights, however, the horizontal wheel displacement was more significant for the smaller Berm 2 (Figure 15).

Tests conducted with comparable impact velocities on the two berm heights showed very similar absolute berm deformations (i.e., tire penetration). Test 2 on Berm 1, for example, had an impact velocity of 6.76 km/h and a tire penetration of 0.26 m. Test 8 on Berm 2, with impact velocity of 6.75 km/h, gave almost the same tire penetration (0.25 m). A similar tire penetration was observed for Test 3 and Test 7 carried out with higher approach velocity (around 8.5 km/h). This indicates that for both berms tested, they are sufficiently high that their height is no longer a factor in their response to impacts at the tested speeds, and that they exhibit similar compaction response during impact.

When comparing the two different approach conditions, generally the angled approach resulted in larger berm deformations. Figure 16 shows the comparison of the 90° and the 75° approach conditions: with similar impact velocities the angled approach resulted in an increase of berm deformation of around 30%.

One test with multiple impacts was carried out on Berm 2. The test (Test 9) involved three consecutive impacts into the berm at an approach angle of 90°. The impact velocities were 5.98, 9.40 and 7.15 km/h for the first, second and third impact respectively. Figure 17 shows the main results of the video analysis where the horizontal wheel displacement is plotted against the wheel climb. It can be seen that the maximum values were recorded at the last impact even though the impact velocity was more than 2 km/h lower than the one recorded at the second impact. In addition, up to a horizontal wheel displacement of about 1.3 m, the wheel climb decreased impact after impact. This can be attributed to the compaction of the material is undergoing during the subsequent impacts (cf. Figure 18).

Summary and comparison of results

Full scale experimental testing up to failure was not plausible because of safety issues and costs, and so, the “tendency” to potential failure must be inferred from the available data. A truck tends to rollover if the wheel climb is close to the berm height H (wheel climb / $H \approx 1$) and to punch through if the horizontal wheel displacement is greater than half the berm width, W , measured in direction of the approach condition (horizontal wheel displacement / $W/2 \geq 1$). In order to compare the results of the two series of tests in more detail in terms of performance for different geometries and materials, horizontal wheel displacement and wheel climb data are normalised with respect to half the berm base width and the berm height respectively. This representation, illustrated in Figure 19, allows consideration of the potential failure modes.

The diagrams in Figure 20 summarise the normalised horizontal wheel displacement and wheel climb for all tests with an approach angle of 90° . Comparing Figure 20a with Figure 20b, it can be seen that the results show a similar behaviour. However, tests on the re-mined material show significant variation in the normalised wheel displacement. This can be attributed to the significant variation in particle size. The high percentage of sand and gravel makes the material softer compared to the fresh spoil where cobbles and boulders dominate the behaviour (Figure 5) leading to a more significant resistance to the tire penetration. In both cases, the values do not exceed 0.4, which means that in all tests, the berms are far from failing. A different trend can be observed in Figure 20c-d, which summarises the results for Site B. In this case, the dominant displacement was the horizontal wheel displacement. For the smaller Berm 2, it can be seen that the berm was much closer to a punch through failure with a normalised horizontal wheel displacement bigger than 0.6. This highlights the weakness of berms built according to current rules of thumb using spoil of Category 1 and 2. The site interview with the truck driver conducted just after the test corroborated the observation: he expressed difficulty in detecting the instant of impact between rear wheels and berm. The consequence of this is that, in a real event at higher speed, he would have had less time to react and brake.

When comparing the multiple impact tests shown in Figure 14 and Figure 17, a similar behaviour is observed. However, a more significant effect of the three consecutive impacts was noticed on the material of Site B, where both horizontal wheel displacement and wheel climb increased for consecutive impacts (Figure 17). The third impact almost caused the truck to punch through and the berm height was reduced to about half of its initial height. This highlights the importance of regular maintenance and inspection since multiple impacts reduce the safety berm functionality especially in cases where spoil of Category 1 and 2 is used.

Figure 21 and Figure 22 summarise the results for the impacts at 90° and 75° respectively where normalised wheel climb and normalised horizontal wheel displacement are plotted against the impact velocity. The graphs highlight the different performance of the materials and geometries tested and the different behaviour of the three haul trucks used during the tests. Both normalised displacements (vertical and horizontal) increase with increasing impact velocity for most of the tests. Only the results for Berm 2 do not show this trend. This might be related to the fact that the impact was not really noticed by the truck driver which resulted in a reaction of the driver without a distinctive warning, i.e. the truck driver would still be applying pressure to the accelerator after the truck had touched the berm. It can also be seen that the normalised horizontal wheel displacements for Berm 2 were consistently higher than those measured for all other tests. This clearly indicates that Berm 2 was the weakest berm tested during the research with respect to punch trough failure (Figure 19).

Comparing the results for approach angle 90° and 75° it can be seen that the non-perpendicular approach generally gave higher values for both wheel climb and horizontal wheel displacement. This clearly makes angled approach conditions less favourable than perpendicular approach conditions. It is interesting to note that the CAT 793D gave higher values than the CAT 797F. This is not an expected result since it is a smaller truck.

Finally, the impact durations are also summarised in Table 3 and Table 4. The data represent the time from the first contact between truck and berm to the instant where the truck stopped. For most of the single impact tests this time was around 1.0 to 1.3 s. Only the multiple impacts at Site B showed longer impact times. This indicates that multiple impacts can considerably degrade the berm geometry and delay the response time of a driver in case of “hypothetical real event”. In order to retain its effectiveness and to give the truck driver a clear warning and a reasonable time to react or take action, a berm should be adequately maintained during its lifespan.

Conclusions

Safety berms are utilised as a restraint to prevent powered haul trucks from backing over an edge of a dump-point. Data from the literature have indicated that since 1990, an average of one fatal accident per year could be related to inadequacy of berms. Therefore, effective safety berms are crucial for a safe operation of haul trucks in a surface mine. The literature review showed that safety berms are designed using rules of thumb, and the most common of these specifies that the height of the berm should be at least half the wheel diameter of the biggest operating truck.

For the first time, experimental evidence of dynamic impacts of haul trucks running backwards into safety berms was collected. Full-scale experimental tests were performed at two different mine sites in NSW, Australia. The tests had the objectives to prepare dump-point safety berms according to current practices and to determine their effectiveness using different truck fleets and different approach conditions. The tests at Site A were carried out with berms constructed from fresh and re-mined mine spoil and impacted by a CAT 797F and a CAT 793D. The tests at Site B were conducted with berms made with heavily weathered mine spoil and impacted by a CAT 789D. In all cases, fully loaded trucks were run backwards into the safety berms with velocities of around 10 km/h.

The results showed that the fresh blocky mine spoil (Category 3) at Site A had more resistance than re-mined material (Category 2). Truck contacts with berms made of fresh blocky material are clearly noticed by truck drivers who, therefore, have more time to react. On the other hand, contacts with re-mined (Category 2) and weathered (Category 1.5) materials are less apparent to truck drivers, and they do not provide such an immediate or obvious warning. This clearly indicates that safety berms should be constructed from fresh blocky spoil materials.

Multiple impact tests showed that triangular berms built with weathered fine material have reduced resistance and their height can be progressively reduced during the impacts. This directs the focus on the berm construction method and on its maintenance. Berms tend to degrade during mining operations (e.g. repeated impacts and weathering), therefore, they need to be inspected regularly in order to maintain their design characteristics (i.e. shape and height).

The experimental tests clearly showed that angled approach conditions are less favourable than perpendicular approach conditions. Angled approaches resulted in more significant berm deformation. Therefore, such approach conditions should be avoided when planning and designing mining operations. Nevertheless, the experimental findings suggested that the current rule of thumb might still be suitable for dump points where trucks travel at velocities lower than 10 km/h perpendicularly to the berm. Results also indicated that the berm width plays a significant role in the berm performance. Whenever possible, trapezoidal berms should be employed in preference to triangular ones.

Finally, the comments of the truck drivers suggested that their response time in the case of a “hypothetical real event” plays a very important role and, therefore, truck drivers should be trained accordingly. Safety berms are generally not designed to stop a runaway truck but they are built to give drivers a visual and tactile indication of where the edge of dump is located.

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Figure 1: Ultra-class haul truck dumping material at a dump-site and safety berm positioned at the edge of the slope (arrow indicates safety berm).

(a)

(b)

Figure 2: Example of typical test bays for Site A: trapezoidal berm build out of (a) fresh spoil with average height of 1.75 m and (b) re-mined spoil with average height of 1.7 m.

(a)

(b)

Figure 3: Example of typical test bays for Site B with triangular berms: (a) Berm 1 with an average height of 3.2 m and (b) Berm 2 with an average height of 1.8 m.

Figure 4: Example of images used for the indirect particle size analysis (the scale reference objects are plastic balls with diameter of 9.9 cm): (a) fresh spoil Site A (Category 3), (b) re-mined spoil Site A (Category 2), and (c) weathered spoil Site B (Category 1.5).

Figure 5: Particle size distribution for the three different mine spoil materials.

Figure 6: Camera positions and truck with targets: (a) Site A with CAT 797F, the left hand side camera and the camera positioned on top of the berm; and (b) Site B with CAT 789D and all three cameras.

Figure 7: General sketch of the testing area setup.

Figure 8: Typical camera positions for photogrammetric survey: image set 1 taken from the ground and image set 2 taken from the truck.

Figure 9: Example of velocity and wheel climb data obtained from the video analysis (Site A Test 3).

Figure 10: Example of plot of the motion of the rear axle during impact where horizontal wheel displacement and wheel climb correspond to horizontal and vertical movement of the wheel respectively (Site A Test 3).

Figure 11: Scheme of the berm deformations measured with the photogrammetric survey.

(a)

(b)

Figure 12: Site A video analysis data for (a) Test 11 and (b) Test 14.

Figure 13: Example of measured berm deformation for Site A: (a) Test 11 with approach angle 90° and (b) Test 14 with approach angle 75°.

Figure 14: Site A Test 15: horizontal wheel displacement vs. wheel climb for the three consecutive impacts.

(a)

(b)

Figure 15: Site B video analysis data for (a) Test 2 and (b) Test 8.

Figure 16: Example of measured berm deformation for Site B: (a) Test 7 with approach angle 90° and (b) Test 11 with approach angle 75°.

Figure 17: Site B Test 9: horizontal wheel displacement vs. wheel climb for consecutive impacts.

Figure 18: Typical image of the berm at Site B after (a) one impact (Test 6) and (b) multiple impacts (Test 9).

Figure 19: General overview of the potential failure modes and effectiveness assessment applied in this study.

Figure 20: Comparison of perpendicular approach conditions: (a) Site A fresh material, (b) Site A re-mined material, (c) Site B Berm 1, and (d) Site B Berm 2.

(a)

(b)

Figure 21: Results for impact angle 90°: impact velocity vs. (a) normalised wheel climb and (b) normalised horizontal wheel displacement.

Figure 22: Results for impact angle 75°: impact velocity vs. (a) normalised wheel climb and (b) normalised horizontal wheel displacement.

Table 1: Specifications of truck fleets used during the testing.

	CAT 797F	CAT 793D	CAT 789D
Gross Vehicle Weight [t]	624	384	324
Maximum Payload [t]	363	218	181
Front Axle (loaded) [t]	208	127	107
Rear Axle (loaded) [t]	416	257	217
Overall Rear Tire Width [m]	9.53	7.61	6.93
Overall Length [m]	15.08	12.86	12.70
Tire Type	59/80R63	46/90R57	37.00R57
Tire Diameter [m]	4.02	3.58	3.42
Tire Width [m]	1.47	1.15	1.04
Top Speed Reverse (loaded) [km/h]	11.9	10.9	11.8

Table 2: Spoil characterisation framework (modified after Simmons and McManus, 2004).

CATEGORY	1	2	3	4
Description attributes	Fine-grained Clay-rich high plasticity	Fine-grained low plasticity with larger clast	Larger clast with fine matrix low plasticity	Large blocks, minor fines, minor slaking
Predominant Particle size	Clay	Sand	Gravel	Cobbles
Consistency: cohesive cohesionless	Soft to Firm Loose	Stiff Med. Dense	Hard Dense	XLS + rock Very Dense
Structure attributes	Matrix only	Matrix Supported	Framework supported	Framework only
Liquid Limit	High (>50)	Intermediate (35-50)	Low (20-35)	Not plastic (<20)

Table 3: Summary of testing program and results for Site A.

Test	Truck Type	Berm Material	Berm Geometry				Approach conditions		Results
			Average Height [m]	Average Base Width [m]	Average Top Width [m]	Angle of repose [°]	Approach Angle [°]	Impact Velocity [km/h]	Max. Wheel Climb [m]			Max. Horizontal Wheel Displacement [m]			Max. Horizontal Berm Deformation [m]	Max. Vertical Berm Deformation [m]	Max. Tire Penetration [m]	Impact Duration [s]						
										LHS	RHS	Mean	LHS	RHS	Mean										
1	CAT 797F	Fresh Spoil Site A (Spoil Category 3)	Trapezoid	1.7 5	9.4	4.4	36	90	8.20	0.47	0.31	0.39	1.30	1.05	1.18	0.29	0.28	0.31	1.03						
2								90	8.44	0.60	0.55	0.57	1.32	1.31	1.31	0.28	0.29	0.33	0.97						
3								90	9.78	0.70	0.57	0.64	1.75	1.58	1.67	0.25	0.26	0.29	1.20						
4								75	7.47	0.41	0.12	-	1.40	-	-	0.38	0.38	0.40	1.27						
5								75	7.26	0.51	0.08	-	1.27	-	-	0.31	0.30	0.34	1.30						
6								75	7.74	0.52	0.10	-	1.25	-	-	0.24	0.22	0.28	1.13						
7	CAT 793D							Re-mined Spoil Site A (Spoil Category 2)	Trapezoid	1.7	10.8	5.7	34	90	7.26	0.49	0.48	0.48	1.24	1.21	1.22	0.24	0.22	0.25	1.07
8														75	7.93	0.62	0.12	-	1.53	-	-	0.24	0.29	0.32	1.37
9	90	8.88	0.53	0.48	0.51	1.37	1.25							1.31	0.35	0.34	0.41	0.97							
10	90	8.83	0.55	0.46	0.50	1.20	0.99							1.09	0.21	0.23	0.25	0.90							
11	90	7.91	0.52	0.36	0.44	1.19	1.40							1.30	0.28	0.31	0.37	1.03							
12	75	7.81	0.56	0.36	-	1.25	-							-	0.27	0.32	0.33	1.13							
13	75	7.34	0.44	0.12	-	1.08	-							-	0.27	0.30	0.32	1.03							
14	75	8.09	0.56	0.13	-	1.48	-							-	0.41	0.37	0.45	1.27							
15(1)	90	10.24	0.63	0.56	0.59	1.59	1.69							1.64	0.46	0.48	0.51	1.10							
15(2)	90	7.88	0.52	0.43	0.47	1.18	1.37							1.27				1.00							
15(3)	90	8.51	0.68	0.58	0.63	1.32	1.46							1.39				1.07							
16	CAT 793D													90	8.41	0.55	0.43	0.49	1.63	1.70	1.66	0.35	0.34	0.37	1.30
17								75	7.93	0.70	0.03	-	1.97	-	-	0.48	0.46	0.56	1.63						

Table 4: Summary of testing program and results for Site B.

Test	Truck Type	Berm Material	Berm Geometry				Approach conditions		Results									
			Shape	Average Height [m]	Average Base Width [m]	Angle of repose [°]	Approach Angle [°]	Impact Velocity [km/h]	Max. Wheel Climb [m]			Max. Horizontal Wheel Displacement [m]			Max. Horizontal Berm Deformation [m]	Max. Vertical Berm Deformation [m]	Max. Tire Penetration [m]	Impact Duration [s]
									LHS	RHS	Mean	LHS	RHS	Mean				
1	CAT 789D	Weathered Spoil Site B (Spoil Category 1.5)	Triangle Berm 1	3.2	12.9	31	90	6.52	0.17	0.31	0.24	1.04	0.81	0.93	0.28	0.28	0.34	0.83
2							90	6.76	0.21	0.28	0.24	1.01	0.93	0.97	0.26	0.26	0.26	0.83
3							90	8.76	0.39	0.40	0.39	1.71	1.64	1.68	0.36	0.37	0.40	1.13
4							75	7.94	0.55	0.19	-	1.30	-	-	0.32	0.33	0.36	1.03
6			Triangle Berm 2	1.8	5.4	35	90	7.02	0.21	0.26	0.23	0.87	1.14	1.01	0.45	0.37	0.46	1.00
7							90	8.32	0.32	0.38	0.35	1.52	1.54	1.53	0.36	0.35	0.40	1.10
8							90	6.75	0.25	0.36	0.30	1.56	1.44	1.50	0.23	0.19	0.25	1.30
9(1)							90	5.98	0.52	0.44	0.48	1.66	1.91	1.78	0.46	0.55	0.56	1.70
9(2)							90	9.40	0.68	0.62	0.65	1.74	1.97	1.85				1.43
9(3)							90	7.15	0.90	0.75	0.83	1.95	2.45	2.20				2.30
10							75	5.54	0.36	0.06	-	1.20	-	-	0.30	0.30	0.31	1.27
11							75	8.99	0.59	0.01	-	1.97	-	-	0.52	0.60	0.61	1.43