The Application of Electronic Monitors to Understand Blast Movement Dynamics and Improve Blast Designs

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ABSTRACT: Blasting is a critical process at most hard-rock mines that affects almost every other stage of the operation but the detailed dynamics are not well understood. One reason for this is the difficulty of measurement and this lack of data has lead to myths and conflicting theories. The University of Queensland developed an electronic blast movement monitor primarily as a grade control tool but it quickly became apparent that its accuracy and ease of data collection presented an opportunity to quantify 3-dimensional blast movement and therefore extend the understanding of blast movement dynamics. This paper summarises six years of research by quantifying relationships and describing blast movement dynamics. For example, it examines the movement dynamics in all regions of the pattern including the confined and unconfined front edges; formation of the power trough; movement around initiation centrelines; and muckpile swell. The profile in most areas of the muckpile is D-shaped, with the maximum horizontal displacement occurring in the mid-elevation of the bench, but a notable exception is the power trough, where the lower part of the bench moves forward and the upper part of the bench drops down into the void. Superior knowledge of blast dynamics can be applied to improve blast designs. The paper compares free-faced and buffered blasts, demonstrates that bench height has negligible effect on movement and why echelon initiation is preferred for optimal grade control. Finally, blast movement monitoring has been used to scrutinise design aspects such as sub-drill, electronic delay detonators, explosive performance and pattern geometry.

1 INTRODUCTION

Blasting is a pivotal process in most mining operations. It is the practical link between geology and production that affects almost every process that follows it, as Mine to Mill® research throughout the 1990s demonstrated. Considerable research has been done in the area of blast optimisation but this has had a strong emphasis on production and safety, such as fragmentation, diggability, vibration and damage, but this is in the Mining Engineering discipline. However, blasting also has a significant impact on grade control due to the movement of the rock, but blast movement, and blast dynamics in general, is not well understood.

It is somewhat surprising that in a mature industry, such a critical process is not understood better. One could sight various reasons for this lack of awareness but arguably, the main reason is that until recently there was no reliable, accurate and practical method to routinely measure blast movement. There have been isolated investigations by individuals at sites and a handful of researchers with varying success (eg. Gilbride et al, 1995, Taylor et al, 1996, Harris et al, 1999 & 2001). Most of this work involved ad-hoc visual targets such as sand bags, chains, plastic pipe and various other items but none fit the criteria of being reliable, accurate and practical. Consequently, reliable blast movement data has been sparse.

The Julius Kruttschnitt Mineral Research Centre of the University of Queensland developed an electronic blast movement monitor during 2002-2003, primarily as a grade control tool but it quickly became apparent that this presented a unique opportunity to quantify 3-dimensional blast movement and therefore extend the understanding of blast movement dynamics. With support from Barrick Gold Corporation, the author then led a research project to continue development of the system and investigate blast movement dynamics and grade control. The data and experience gathered over six years of R&D and consulting is unprecedented in the field of blast movement. The dataset currently includes 1500 movement vectors from 28 sites around the world and covering most of the practical range of blasting conditions (eg. powder factors from 0.36 kg/m³ to 1.7 kg/m³; rock densities up to 3.2 g/cm³; bench heights from 5 m to 15 m and all methods of initiation).

This paper only summarises the more important results because there is far too much information to
include everything that the measurements have revealed about blast dynamics.

2 BACKGROUND

2.1 Blast Movement Measurement

The benefits of measuring blast movement to reduce ore loss and dilution have been recognised by many people for many years and various methods have been used with limited success. Most use *ad-hoc* visual targets such as pipe, chain, rope and coloured sandbags. The disadvantages of these methods include:

- poor recoveries;
- labour intensive;
- have to be excavated before their position is known;
- some only provide 2-dimensional movement.

Electronic methods promise to alleviate some of the shortcomings of the visual methods, especially the last two items. Again, several techniques have been tested including ground penetrating radar, magneto-metry, metal detection and recently, RFID tags. Most suffer from limited range, which means the targets must be placed close to the surface or indeed, on the surface, which is inherently inaccurate due to movement dynamics as explained in Figure 1.

![Figure 1 - Illustration of why near-surface movement is not useful for grade control purposes or blast dynamics research](image)

2.2 Description of Blast Movement Monitor System

The Blast Movement Monitor (BMM®) system was developed and patented by the University of Queensland and commercialised under licence by Blast Movement Technologies. The system consists of directional transmitters placed within the blast volume prior to blasting which are then located after the blast with a special detector and the data is processed with purpose-designed software. The complete system is explained below.

- The Activator is a remote control that switches each transmitter on and programs it as required.
- A number of BMM®’s are then installed in dedicated drill holes within the blast and surveyed.
- A special detector is used to locate each BMM® after the blast and determine its depth.
- The included software calculates the 3-dimension movement vector of each BMM®. The data is archived in a database for future reference.
- Ore boundaries can be redefined within 1-2 hours of the blast to reflect the measured movement so that the material can be transported to the correct location.

Accuracy is proportional to the depth and at typical depths is about 0.1 – 0.2 m in horizontal and vertical displacements.

3 BLAST MOVEMENT DYNAMICS

3.1 Mechanisms

There are several basic concepts that must be kept in mind to understand blast dynamics and optimise blast design. A simplistic understanding of blasting leads to poor design decisions, especially in critical areas such as limits (or buffer) blasts.

The explosive is a source of energy that is distributed in space and time – it is not a point source. Individual holes are linear sources, typically in the lower half of the bench and initiation usually starts at the bottom. At the scale of the whole blast, holes release their energy at discrete times. The basic physics involved are:

- Upon detonation, each discrete element of the explosive exerts a force equally in all directions on the adjacent rock. The rocks with least resistance will begin to move. These rocks in turn act on neighbouring rocks which results in bulk movement of the rock mass.
- The rock moves in the direction of the dynamic free face in its area of influence – *The path of least resistance*. This is approximately perpendicular to the initiation timing contours.
- The rock at the top of the bench is not directly pushed by the explosive but instead is either indirectly moved by collisions from other rocks or dragged along by the friction from the moving rocks below. The further a rock is above the explosive column, the less energy it will receive and therefore the less distance it will move. Hence, the D-shaped vertical profile with greater movement of the rock mass.
- The path of least resistance.

The D-shaped vertical profile with greater movement of the rock mass.
3.2 Movement in Various Regions of the Blast

A blast consists of a number of regions or zones where movement is different due to the different dynamics in each. The main ones are the front, the back and close to the centerline of initiation. Each of these extend for about 2-3 hole spacings and the remainder is termed the body of the blast.

3.2.1 Body

The body of the blast is everywhere that is not influenced by any edge effects and the movement in this region is regarded as normal or typical for that particular blast. Horizontal displacement is directly related to powder factor and has been measured up to 40 m (not face throw). The characteristics of the movement in the body of a blast are:

- The horizontal displacement changes with depth as per the characteristic D-shaped profile.
- The direction is approximately perpendicular to the timing contours.
- The inclination is positive (upward). It is close to horizontal at the bottom of the bench and increases progressively through the bench. This increasing inclination is illustrated in Figure 2 and Figure 3 where the points 3 & 4 represent body movement.

3.2.2 Front

The front edge is defined as the boundary adjacent to the ignition point in the direction of movement – it could be a buffered or clean face. Note that a centre-lift blast has two “fronts” in the centre of the pattern but this is a special case that is discussed in Section 3.2.4.

Figure 2 and Figure 3 illustrate the conceptual movement vectors for buffered and free-face blasts respectively. Points 3 & 4 represent typical movement of the body of the blast in the upper and lower bench. They are provided to compare and contrast the movement at the front. More detailed dynamics of buffered and free-faced blasts are provided in Section 3.3.

For a buffered blast, the movement at position ① is less than the corresponding body movement at ③. The 3D distance is less, but the inclination is greater as it moves towards the free surface. The vertical displacement is likely to be greater, depending on the depth. At position ②, the movement is greater than the corresponding body movement at ④ because of the partial free-face provided by the power trough.

For a free-faced blast, the movement in the body and the back are essentially the same as for a buffered blast (see Section 4.2) but the front face movement is different. Provided there is sufficient energy to move the face burden, movement at position ① is considerably greater than the corresponding body movement at position ③ and potentially downward (depends on the initial height). The movement at position ② is almost certainly downward as it falls behind the lower bench and the distance is likely to be greater than the corresponding body movement at ⑤.

3.2.3 Back

The back of the blast is defined as the edge(s) opposite to the direction of movement, typically characterised by a vertical face along the back edge where the surface of the muckpile is below bench height – referred to as the power (or energy) trough. One of the most satisfying achievements from the research is the quantification of the dynamics that forms the power trough. Figure 4 is a diagram to help with the explanation and the numbers of the following points relate to the corresponding numbers in the diagram.

1. The movement follows the D-shaped profile throughout most of the muckpile until a few rows before the back edge where the dynamics begins to change. In the front and body regions, the upper bench moves forward and upward.
2. When the explosive in the last row detonates, it pushes the rock forward the same as for the body region, but...
3. There is no rock moving forward from behind the last row to move and support the upper bench at ③ and this rock drops down into the void.
Figure 4 - Diagram of the dynamics that forms a power trough

Figure 5 is a graph derived from measured data, showing the movement of a vertical stack of rocks (non-filled points) that are near the back of a pattern, which end up rotating to a lateral orientation. Note that this is not the final muckpile surface because part of adjacent slices of rock will lie over this slice. Measurements and observation demonstrate that the surface of the power trough is the original bench surface.

- Initiation starts at one end of the centreline and progresses along the centreline and away from it, in a sequence determined by the initiation timing.
- When the first hole initiates, the only broken rock is in front of it, so the rock moves forward. This applies for every hole along the centreline. The confinement, however, is greater than an equivalent echelon blast because rock is moving towards the centreline ahead of the centreline holes initiating.
- Under these confined conditions, the rock’s normal forward motion is restricted and it will seek a less restrictive path – upwards.
- As the rock close to the centreline moves upwards, this creates a path for neighbouring rock and since movement starts at the bottom, the newly broken rock pushes under the rock in the forward direction, lifting it further.
- Basic collision motion or fluid motion will also dictate that the rock will move upward and forward because it has nowhere else to go due to the confinement from other rock moving towards the centreline from the other side. Consider two streams of water on a hard surface that flow together at an angle.

3.2.4 Centreline

The typical muckpile from a V-initiated blast is characterised by a ridge along the centreline of the initiation. A good blast with appropriate burden and spacing and energy containment will result in consistent bulk movement of the rockmass. Once in motion, it can be thought of as a fluid to understand certain aspects of the dynamics. To understand the dynamics in the centreline region, it helps to break down the events.

Figure 6 is a diagram of the influence on the movement that the firing angle has. The blue dashed lines represent timing contours and the dashed arrows are typical movement vectors that would result in the body of the blast. When the angle is greater (flatter V), the rock tends to flow forward during the collision close to the centreline and move further than the typical body movement. It probably takes some curved path but we actually measure the final vector as indicated. This effect is more pronounced closer to the centreline. When the angle is small enough (tighter V), measurements indicate that the rocks do not flow further forward but rather collide and move upward. In practice, however, the movement is usually erratic close to the centreline due to random collisions; and more so for tighter angles, to the point where it is almost chaotic.

Figure 6 - The influence of angle to movement close to the centreline
Figure 7 shows two V-initiated patterns from the same bench. The pattern on the left has timing contours at an acute angle to the centreline and the movement is chaotic close to the centreline. Compare this to the blast on the right that has a flat V and the movement is consistent throughout. The surface profiles of the muckpiles were as expected – the first one steep and the second one flatter. The second blast is much easier to accurately account for blast movement and therefore would result in less ore loss and dilution, regardless of monitoring. The details of this project can be seen in Adam & Thornton (2004).

3.3 Anatomy of Blast Movement

3.3.1 Buffered Blast

Figure 8 shows the plan and elevation from a buffered blast that illustrates many of the blast dynamics concepts discussed above. Table 1 is a summary of the movement and the important data are the Initial Depth, Horizontal Displacement and Vertical Displacement. The bench height is 10 m. Initiation is from the southeast corner (near post-blast BMM “A”), timed as an echelon. There are blasted muckpiles along the eastern and southern edges, both with a power trough. After the blast, there was a deep power trough along the north-eastern edge.

- BMM 1 is close to the front and 7.2 m deep. The confinement of the muckpile in front has offered some buffering when compared with BMM 2 (similar depth at the back). The muckpile in front prevents forward movement of the first row but the rock has to go somewhere with the force of the explosive pushing it. The closest free face is the surface, so it moves upward as evidenced by the greater inclination and vertical displacement and smaller horizontal displacement than BMM 2.

- BMM 2 is 7 m deep and even though it is only just in front of the last row, it moved 8.4 m at 7.5 degrees above horizontal. There are ample measurements to prove that the horizontal movement of the lower bench towards the back is representative of body movement and indeed often the greatest movement of the blast.

- BMM 3 is in a similar position to BMM 2 with respect to the back row, but it is only 1.8 m deep. It moved down 2.2 m and forward 1.7 m. This is the power trough dynamics. The elevation view in Figure 8 clearly demonstrates the relative motion at these two levels. BMM 2 has moved well past BMM 3 so most of the rock that was underneath BMM 3 is no longer there. BMM 3 has been dragged forward but falls into the void left by the rock below.

- BMM 4 is at a similar depth to BMM 3 but close to the front edge. The power trough was estimated to be 3 – 4 m deep. The initial movement at the front of the lower bench is upward since it cannot go forward due to the muckpile in front (BMM 1). When the second row of holes detonates, the confinement is less than for the first row since that rock has already started moving upward, and the angle to get over the muckpile in front is less. This rock pushes up and forward, pushing the rock ahead of it. Therefore, BMM 4 moves relatively steeply upward. The upper bench at the front is unconfined and pushed by the highly confined rock below, moves forward and up onto the back of the muckpile in front.
3.3.2 Free-Faced Blast
The dynamics of a free-faced blast are similar to that described above but the obvious difference is the confinement conditions at the front. Figure 9 is a photograph of a free-faced blast that shows the curved profile with more movement in the lower bench than the upper. All of the measurements to date suggest this basic shape is initially similar throughout the muckpile but at the front, there is no rock to support the mid-bench so it drops to the floor. Conversely, at the back, no rock is moving forward from behind the last hole, so it is the top that is unsupported and drops down. These mechanisms form the characteristic free-faced muckpile with a low-angled face and power trough at the back.

Below are results from two free-faced blasts. The first has all BMMs installed at approximately mid-bench to remove the influence of depth therefore it compares the movement at various distances from the free face. The second example shows the movement in the upper part of a 7.6 m bench.

### Blast FF1
Table 2 summarises the initial locations of the BMMs and their respective vector components. The bench height is 15 m. The plan of the pattern with the initiation timing contours and boundary conditions is shown in Figure 10. A horizontal perspective view of a monitored blast is shown in Figure 11.

BMMs 1 & 5 started close to the free face at depths of 7.7 m and 8.3 m respectively. BMM 1 was located just 1.2 m below the muckpile surface (point E) and BMM 5 was located just 1.0 m below the muckpile (point D). Where is the rock that was above these BMMs (the top of the free face)? The answer to this is not clearly defined from this test but measurements and observations by the author from many previous tests demonstrates that the top lags behind as the bottom half of the bench pushes forward. This is supported by the fact that BMM 5 was closer to the front and deeper than BMM 1 but was displaced further and ended up with less rock covering it.

### Table 2 - Summary of Movement for Blast FF1
<table>
<thead>
<tr>
<th>BMM #</th>
<th>Initial Depth (m)</th>
<th>Direction (deg)</th>
<th>Hoz. Dist (m)</th>
<th>Vert. Dist (m)</th>
<th>3D Dist (m)</th>
<th>Incl’n (deg)</th>
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<tbody>
<tr>
<td>1</td>
<td>7.7</td>
<td>191</td>
<td>40.0</td>
<td>-4.7</td>
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<td>2</td>
<td>7.9</td>
<td>192</td>
<td>19.5</td>
<td>1.0</td>
<td>19.5</td>
<td>3.0</td>
</tr>
<tr>
<td>3</td>
<td>8.2</td>
<td>190</td>
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<td>14.1</td>
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<tr>
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<td>209</td>
<td>12.7</td>
<td>2.4</td>
<td>12.9</td>
<td>10.5</td>
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<tr>
<td>5</td>
<td>8.3</td>
<td>204</td>
<td>38.5</td>
<td>-4.4</td>
<td>38.7</td>
<td>-6.5</td>
</tr>
</tbody>
</table>
Blast FF2
This is a free-faced trim blast. All BMMs were installed in the upper half of a 7.6 m bench. The relationships between depths and displacement of the three BMMs along the free-face demonstrate that the top of the bench is left behind as the bottom moves forward. Figure 12 and Figure 13 are plan and elevation views respectively that show these relationships.

- BMM #297 and #335 were approximately mid-bench level and moved approximately horizontally 10 m and 12 m respectively.
- BMM #297 was installed 3.1 m deep and was located with 2.1 m of cover;
- BMM #335 was installed 3.0 m deep and located with 1.4 m of cover.
- BMM #347 was installed 1 m deep and its horizontal displacement was just 2.5 m and still had about 1 m of cover.
- BMM #305 is in the back corner and moved straight down, which is the extreme power trough dynamics.

<table>
<thead>
<tr>
<th>BMM #</th>
<th>Initial Depth</th>
<th>Direction Hoz. Dist</th>
<th>Vert. Dist</th>
<th>3D Dist</th>
<th>Incl’n (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (296)</td>
<td>3.0</td>
<td>131</td>
<td>0.7</td>
<td>-1.2</td>
<td>1.4</td>
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<tr>
<td>2 (347)</td>
<td>1.0</td>
<td>76</td>
<td>2.5</td>
<td>-3.0</td>
<td>3.9</td>
</tr>
<tr>
<td>3 (339)</td>
<td>1.0</td>
<td>122</td>
<td>2.0</td>
<td>-3.2</td>
<td>3.8</td>
</tr>
<tr>
<td>4 (315)</td>
<td>3.5</td>
<td>144</td>
<td>1.6</td>
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</tr>
<tr>
<td>5 (297)</td>
<td>3.1</td>
<td>144</td>
<td>10.2</td>
<td>-0.7</td>
<td>10.2</td>
</tr>
<tr>
<td>6 (313)</td>
<td>3.6</td>
<td>155</td>
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<td>6.1</td>
<td>7.3</td>
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<td>12.1</td>
</tr>
<tr>
<td>8 (305)</td>
<td>2.8</td>
<td>111</td>
<td>0.0</td>
<td>-3.2</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Figure 12 - Measured movement vectors of blast FF2

3.4 Vertical Profile

The general shape of the vertical profile results from the fact that the energy is concentrated at the bottom of the bench. The horizontal movement is typically D-shaped with the minimum at the surface, increasing to a maximum close to the top of the explosive column and decreasing again close to the bottom of the bench. There is not enough data from the sub-drill region to completely understand movement close to the bottom of the hole but some relevant data is presented in Section 4.3 and there are examples of typical data in Section 4.4.

To reinforce the data, there have been a number of occasions when pin-flags or other similar markers have been used to mark the pre-blast position of a BMM monitoring hole and after the blast, these markers have remained standing in the muckpile and representing the post-blast location of the collar of the monitoring hole or surface movement. Figure 14 is a photograph that was taken while the BMMs were being located. The dirty yellow flag in the middle is the pre-blast pin-flag as it was found after the blast. The white pin-flag on the right is where the BMM was located after the blast. The surveyor is standing at the original location of the hole collar. The three points are approximately collinear.

Figure 14 - Photograph showing the difference between surface and mid-bench displacement

The old saying that a photo is worth a thousand words is certainly true of Figure 14. It clearly demonstrates why surface movement is not a good indicator of bulk muckpile movement. Surface displacement underestimates the actual bulk displacement by about 50% (which could be many metres). Figure 15 is a diagram showing the move-
ment in cross-section. The BMM was installed 6 m deep in a 10 m bench, about 2 m below the top of the explosive column (left circle) and the right circle is its approximate final location. The surface moves more steeply upward and less horizontally than the mid-bench, producing the characteristic D-shaped vertical profile.

The practice of using polypipe as movement indicators is akin to surveying the middle pin-flag in Figure 14 so for single-pass excavation, polypipe (or any other surface measurement) is not representative of the bulk movement of the muckpile. This research has also demonstrated that the movement close to the surface is more variable due to the extra degree of freedom, which increases the error for grade control.

There are three possible scenarios for swell and all are plausible (Figure 16). One could argue that the swell is greater in the lower part of the bench because fragmentation is greater adjacent to the explosive. Equally, one could argue that the swell is greater close to the surface because the rocks are less constrained so there will be greater vertical movement; and indeed the vertical movement does increase closer to the surface. Regardless of the swell profile, the surface will experience the greatest vertical movement because it is the accumulation of all of the gaps below it. However, this does not necessarily equate to greater swell close to the surface. In reality, there is a combination of the two so one could argue that swell is approximately uniform.

![Figure 15 - Diagram showing the displacement in section](image)

![Figure 16 - Diagram showing possible scenarios of uniform or non-uniform swell with depth](image)

3.5 Muckpile Swell

The uniformity of swell with depth has reconciliation implications for sites that excavate a bench in multiple passes. If the swell in not uniform vertically, it can alter the post-blast elevation of the original sub-bench levels even though the surface heave could be the same in both cases. Muckpile swell is caused by dilation of the rockmass, i.e., gaps between the fragmented blocks. In simplistic terms, swell is a function of fragmentation and movement. Smaller fragmentation produces more gaps and more movement potentially results in greater gaps between rocks.

There is generally insufficient data at a full range of depths to define the relationship and typically, the approximation is done by manually drawing a line from the average muckpile heave to approximately zero at the bottom of the hole. A steeper relationship equates to less dilation of the muckpile. A straight line passes through the centre of the data (Figure 17) at most sites, which indicates uniform swell. The curved relationship shown in Figure 18, indicates less swell in the upper part of the bench. There are other blasts where the relationship appears to curve the other way, which indicates more swell at the top than bottom. The measured data supports the theory that the conflicting mechanisms that cause non-uniform swell usually cancel one another out but under certain circumstances, one or the other can dominate and produce non-uniform swell.
4 PRACTICAL APPLICATIONS FROM THE UNDERSTANDING OF BLAST MOVEMENT DYNAMICS

4.1 Initiation Sequence

There are two main aspects to blast initiation: the delay times and the initiation sequence. The properties of the rockmass will dictate how soon it begins to move and therefore the optimum delay times. This will not form part of this discussion. As for initiation sequence, there are 3 main configurations – echelon, V, and centre (also known as drop-cut, diamond, centre-lift, paddock) and these are illustrated in Figure 19. The best configuration for grade control is the echelon because it maximises the percentage of the blast that will move consistently. For example, it is better to have 5 m of consistent displacement everywhere rather than 2 m of random movement everywhere. The objective is to minimise the error of defining and excavating post-blast ore blocks.

The greatest difference of horizontal displacement at different depths occurs in the power trough region, followed by the centreline regions; both are also more variable than the body of the blast. A “V” is two echelons back-to-back and a centre-lift is essentially four echelons. Each sub-echelon is smaller and so there is less distance for the movement to settle to “normal” plus the number of centrelines and power troughs doubles from the preceding one.

The biggest problem in terms of grade control is not with tracking the movement but the fact that there is inherent dilution in these regions caused by the different displacement at different depths. That is, ore can be pushed under waste and vice versa. The movement could be measured with sufficient monitors but it is not feasible to excavate the 3-dimensional contacts and dilution is inevitable. Cratering and stemming ejection is also more likely in areas of high confinement (e.g. centrelines) because the energy will take the path of least resistance – upward. The initiation point of a centre-fired blast is surrounded by intact rock so confinement must be greater than if the initiation point is adjacent to a broken muckpile (buffered).

Figure 20 is a diagram of a pattern that has a blasted muckpile to the south and all other edges are unblasted. It was initiated in the centre because the shotfirer believed that a centre-lift provided better relief and less movement than firing into a muckpile, which is not the case. The various movement regions have been overlaid. The percentage of the blast that moves normally is quite small. Compare this to an alternative tie-up using a V-initiation offset to one side and firing into the broken muckpile (Figure 21). The point of initiation is three holes in from the hard edge which provides sufficient relief so as not to overly damage the adjacent bench. The result is very different with about 50% of the blast that would settle into consistent movement and the buffered region across the front is actually beneficial for grade control. If the pattern had two free faces, then it could be initiated as an echelon and there would not be any centreline region – the best scenario.
4.2 Free-Face vs Buffer Blasting

The different dynamics at the front of buffered and free-faced blasts, is described in Section 3.3. However, for patterns large enough to have a significant body section (away from edge effects), the movement in the body of free-faced and buffered blasts are similar. Figure 22 plots powder factor against the average mid-bench horizontal displacement in the body of all blasts. This data supports the observed dynamics that the front face confinement has little influence on the movement away from its area of influence. The influence of the free face diminished as the distance from the face increases and becomes negligible at a relatively short distance (2-3 burdens), which is also reported by Taylor and Firth (2003).

There are various reasons why sites may plan to blast with clean or buffered faces but this is beyond the scope of this paper. However, in terms of blast movement and hence grade control, there is little difference.

4.3 Sub-drill

One of the side-benefits of precise blast movement monitoring is that it scrutinises many aspects of the blast design and sub-drill is one such design parameter. Sub-drill is defined as the distance from the designed floor level to the toe of the blast hole. Blasting principals state that sub-drill is necessary to break the bench between blast holes because the rock will break at some angle from the toe of the hole and the depth is chosen so this breakage coalesces at or above the level of the floor.

The optimum sub-drill is difficult to determine and in the author’s experience, site typically use floor conditions as a gauge. However, blast designers will react to isolated instances of toe by increasing sub-drill whereas the likely cause of the toe is more likely quality control – poor drilling and/or loading of individual holes, insufficient sub-drill will cause toe everywhere. Excessive sub-drill is not only an unnecessary expense (drilling and explosive) but
it unduly damages the next bench which causes drilling problems and therefore potentially, the accuracy of hole placement.

Movement is a sure indicator of breakage so if there is movement between the blast holes at the floor level then the rock must be broken. The objective is therefore to achieve minimal movement at the floor level and blast movement monitoring enables quantification of this. Figure 23 shows the horizontal displacement at various depths for a blast in a 5 m bench with 140 mm diameter blast holes and 0.7 m sub-drill. There is significant horizontal displacement just above the bench and in fact, there is little difference between the mid-bench and floor displacement.

The consequences of these results are that both sites have ample sub-drill and it also indicates that the breakage mechanism at the bottom of the bench may need to be reviewed, particularly for blast design education purposes. The rockmass appears to be almost shearing between holes, rather than the classic cratering mechanism, which is the mechanism that a company supplying an accessory air decking system claims to instigate. However, there is not enough data to know how common this is.

4.4 The Effect of Bench Height

It is commonly believed that higher benches will move more than a similar blast in a shorter bench. This is a reasonable assumption in the absence of data since this is true of objects thrown from different heights above the ground – a common particle motion problem. This is because the higher object will take longer before it hits the ground and therefore travel further. However, rocks in a muckpile do not behave this way because most do not end up at floor level – they move forward and upward, then stop, supported by rocks below. The exception to this is the free face region.

It is difficult to test this in practice because mines usually use one bench height for the whole pit but there has been a couple of opportunities to directly compare different bench heights. The results from these sites suggest that there is negligible difference in the horizontal movement for different bench heights. When the movement mechanism is understood, it makes sense that the bench height is irrelevant. Note that the bench height does have an influence on the energy distribution and this affects the uniformity of movement – vertically and horizontally.

Figure 24 shows the results from a site that blasts 6.1 m (20 ft) benches in the ore zone and 12.2 m (40 ft) benches while stripping waste. The red circles are from a single 12.2 m blast. The blue dashed line is the estimated average profile for the 6.1 m bench. The red dotted line is the expected profile for a 12.2 m bench with the explosive distribution shown at the right. The maximum average displacement is similar for both but a greater percentage of the higher bench is moving the same amount due to the better energy distribution and so will result in less ore loss and dilution than the smaller bench (more vertical error). Ironically, the lower benches are used in the belief that it improves grade control. From a blasting and production perspective, a better solution would be to split-bench the ore zones, although there are sampling issues.

Figure 25 is from another site where one of the objectives was to compare of 5 m and 10 m benches. The powder factor of the 10 m blast was less than that of the 5 m blast (0.61 kg/m$^3$ compared to 0.67 kg/m$^3$). Considering the variation in the movement and the different powder factor, again it appears that bench height has negligible effect on the maximum average horizontal displacement. The better energy distribution in the 10 m bench produces a more uniform profile and therefore from a displacement perspective, a single 10 m bench should give more uniform movement than two equivalent 5 m benches.

Figure 26 is a graph of Powder Factor and Horizontal Displacement. The results for all benches less than 10 m high are indicated by the square points. The fact that they lie on either side of the linear trend line gives some statistical weight to the argument that bench height does not affect horizontal displacement in the body for the muckpile. This may not be the case for the front of a free-faced blast because the rocks do fall to the floor level.
4.5 Grade Control

The research has contributed to open pit blasting by helping to develop a practical tool for measuring blast movement then using it to improve understanding of blast dynamics. However, these achievements would be of largely academic interest without taking the final step of using this technology and knowledge to account for blast movement as part of the grade control process.

Ore loss occurs when it is misclassified as waste and sent to the waste dump. Similarly, dilution occurs when waste is designated as ore and sent to the concentrator. Therefore if ore polygons are excavated in their original location, ore loss occurs forward of the leading ore/waste boundaries and dilution occurs at the trailing boundaries. In many operations, ore and waste materials cannot be identified visually or by associated rockmass structure and for these, the only way to account for blast-induced movement is to measure it.

Below is a case study that dates back to the early research of the blast movement monitor. It is included here because it demonstrates how inappropriate measurements and lack of knowledge about blast dynamics led to incorrect assumptions that had a detrimental impact on grade control. The initial publication of the work (Thornton et al., 2005) focused on the measurement and grade control aspects but below is a summary from a blasting perspective...with the benefit of hindsight and further experience.

Case Study: Blasting was conducted on a 10 m bench that was mined in two 5 m passes (split-benching or flitch mining).

What went wrong?

− The mine had done some measurements with polypipe and concluded that the movement of the top flitch was about 2 m. Apparently, few reliable measurements were obtained for the bottom flitch.
− The geologists thought the top of the blast moves more than bottom so concluded that blast movement was not an issue.
− Polypipe measures the surface movement (ref. Figure 15) and Figure 27 shows that indeed the surface displacement is about 2 m. However, the mid-bench displacement averages about 9 m (up to 15 m).
− In certain areas of the pit, mineralisation was perpendicular to the firing direction. The width of the ore zones is comparable to the horizontal displacement so it was possible to send entire ore blocks to the waste dump (Figure 28).
− Therefore, the measurement method provided misleading data, which when combined with an incorrect assumption of muckpile dynamics, led to a false sense of security.

The site eventually adopted blast movement monitoring as standard practice to translate ore polygons according to the measured movement vectors supplemented by knowledge of muckpile dynamics.

4.6 Other Applications

The preceding sections have discussed some of the many ways that blast movement monitoring and/or knowledge of blast dynamics can lead to improved blast designs and productivity. As the technology is used more widely, people are thinking of new ways to use it to solve various blasting related problems. Below is a brief summary of more applications.
− Blast design implementation – blast movement can be used as a quality control gauge. There is a direct relationship between quality of implementation and movement variation. For example, a single hole out or place or stemming ejection can be seen as a different movement vector.
− Pattern geometry – The shape and aspect ratio of a pattern affects the movement.
− Edges – movement rotates towards free faces such as pit edges. The face burden influences the movement of the face at different levels.
− Blast performance – Blast movement monitoring will establish a range of normal values under certain conditions. Statistical outliers indicate unusual behaviour by definition and should be investigated. For example, lack of movement has identified issues with explosive performance and loading practices.
− Limits blasting – to minimise damage to a blast boundary, the rock must move away from it to provide a path of least resistance for the energy.
− Computer modelling – Development of muckpile movement models has been hampered in the past by a lack of good data for calibration and validation. The BMMs provide a quick and easy way to scrutinise existing muckpile movement models. However, the measured movement is highly variable and will present a challenge to accurately model detailed movement. This is potentially unsurmountable due to limitations of the initial conditions.
− Confirm collapse of underground workings – When blasting to collapse old underground workings, it may be important to know for certain that the rock has indeed collapsed before sending machinery and personnel into a hazardous zone. The blast movement monitors can measure the vertical displacement.

5 CONCLUSIONS

The primary motivation for developing the blast movement monitoring system was for a grade control tool to reduce ore loss and dilution. However it has enabled a new insight into blast dynamics that
has dispelled some myths and should result in improved blast designs. A summary of the main finding are:

- In the body of the blast:
  - The lower bench moves more than the upper bench. The profile is D-shaped, increasing with depth through the stemming column, reaching a maximum at about the top of the explosive column and stays reasonably constant until close to the bottom of the hole where it decreases.
  - The inclination of movement is almost horizontal at the bottom of the bench and increases steadily as it gets closer to the top.
  - Swell is approximately uniform throughout the depth of the bench.
  - Body movement is similar for free-faced and buffered blasts.
- The front of the blast can be either free-faced or buffered.
  - In the case of a free-faced blast, the bottom half of the bench moves considerably more than the equivalent body movement and more than the top. The upper bench moves forward but falls in behind the lower bench.
  - In the case of a buffered front face, material in the lower bench and close to the front moves less than the equivalent body movement and it moves more steeply upward as it pushes up towards the unconfined surface. Depending on the depth of the power trough of the adjacent blast, the upper bench is likely to move further forward than the equivalent body movement as it is pushed up onto the adjacent muckpile.
- At the back of the blast, the dynamics of the lower bench is the same as for the body of the blast but the top of the bench drops downward into the void left by the lower bench since no material is coming from behind to support and move the upper bench. This creates the power trough along the back edges.
- Movement close to any centrelines of surface timing is more variable than in the body, often to the point of being chaotic. The rock typically flows forward and upward creating the classic ridge along the centreline. Material does not flow across the centreline.
- Movement is typically close to perpendicular to the timing contours. However this can be influenced by various things such as proximity to open faces; proximity to the timing centreline; and stemming ejection or cratering.
- The sequence of initiation affects the movement, which in turn affects the accuracy of grade control. The best method is the echelon and benches should be planned to maximise the number of echelon-initiated patterns.
- Bench height has little, if any, influence on horizontal displacement in the body of the blast.

- BMMs have proven to be useful for scrutinising blast design and implementation such as:
  - The effectiveness of sub-drill;
  - Blast performance by comparing the movement to other similar blasts;
  - Overall productivity – movement is necessary to efficiently excavate hard rock; and
  - Effective limits blasting.
- This research has provided knowhow and technology that can be used for calibration and validation of blast movement models.

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