A Study of Damage Profiles Behind Blasts

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Abstract
Blasting is usually required to produce easily-excavated broken rock, while leaving surrounding rock masses as undamaged and stable as possible. In mining applications, it is common to utilise production blasting in the centre of an open pit, and specially developed limits blast designs when blasting adjacent to the excavation perimeter. In open pit blasting, limits blast designs generally include pre-splitting, trim blasts, or buffer blasts, all of which are designed to limit, or eliminate, damage beyond the designed pit wall. This paper reports on the findings of a study of the profile of damage in rock masses surrounding blasts, determined by a combination of vibration monitoring, displacement monitoring using extensometers, and video inspection of open holes drilled at various distances behind blasts. The results obtained suggest that the profile of damage may extend for the full depth of the bench, for distances of up to 12 to 15 metres behind blasts. This suggests that entire berms may be affected by blasting, displaying loss of friction and cohesion along joint and fracture planes. The study has considered production blasts and trim blasts with small diameter blastholes and pre-splits.

Common Types of Wall Blasting

It is common to observe in open pit mining that blasts fired against pit walls are different from production blasts fired in either ore or waste material in the centre of the pit. The differences between production blasts and wall blasts can be many and varied, depending on the size of mine and available resources, but the common feature of wall blasts is that they are intended to reduce the extent and degree of damage so that the rock mass composing the pit walls is as undamaged and undisturbed as practical.

Most open pit designs today aim to produce pit slopes as steep as possible in order to minimise strip ratio and optimise mining costs. Some of today’s pits are being designed with a maximum working depth in the range of 800 to 1000 metres, and depths up to 400 metres are common. Blasting practices are commonly identified as having the potential to exert a major influence on the ability to ensure safe working conditions whilst permitting development of the pit to maximum designed slope angles.

Intuitively, it seems unreasonable to expect that any blasting operation can provide well fragmented material in front of blastholes, while at the same time not causing any damage to the rock behind the blastholes. Some degree of damage behind blastholes would seem inevitable, irrespective of the type of cautious blast fired, and probably irrespective of the rock strength. Since the stability of pit slopes is very dependent on joint properties, and since any disturbance to the surrounding rock will cause the in-situ joint properties to be degraded, it seems appropriate to investigate the profile of damage behind some of the different types of blasts used to form pit slopes.

Trim Blasting
Trim blasting is defined in this paper as being a blast specifically designed to reduce the impact of blasting on the pit wall, and possessing the following important characteristics:
1. narrow width of blast, typically comprising no more than 4 rows of blastholes parallel to the pit wall;
2. length of blast typically at least several times greater than the width;
3. a free face, with all loose material completely removed so that unimpeded forward movement of the burden material can occur;
4. reduced charge weight in blastholes, especially those drilled closest to the pit wall.

It is clear from these general guidelines with respect to trim blasting that it is widely considered that charge confinement plays a major role in determining the extent and degree of damage behind blasts, as does the level of induced vibration in the pit wall. However, confinement is a poorly defined concept for which there are no known mathematical descriptors or units of measurement. As such, different people have different concepts of the term and factors affecting it. Factors considered to affect confinement include depth of charge burial (stemming height), burden and spacing dimensions (powder factor), amount of sub-drill, delay timing, density of rock, the number of rows of blastholes, and the distance to the free face. Some of these factors are frequently overlooked when designing trim blasts. Issues commonly not given appropriate consideration with respect to trim blast design include:

1. the use of small diameter holes or simply the use of a reduced charge weight – are they equivalent?
2. the most appropriate powder factor – should it be less than, greater than, or equal to the powder factor used in production blasting?
3. initiation timing and initiation direction – how do delay timing and initiation sequence affect overbreak and damage?
4. The use or elimination of sub-drill - what is the impact of sub-drilling in terms of wall damage?
5. the use or elimination of stemming in trim blast holes – how does stemming affect wall damage?

**Buffer Blasting**

This is also commonly called cushion blasting or modified production blasting, and usually involves modifying the back one or two rows of blastholes nearest to the pit wall. Except for the modified blasthole rows, the blast is the same as a production blast, and avoids the need for a separate dedicated trim blast. The back rows are typically modified in the some or all of the following ways:

1. reduced blasthole or charge diameter;
2. reduced spacing and/or reduced burden;
3. inclined to be parallel, or sub-parallel, to the designed bench face angle (batter angle);
4. reduced depth to help form a relatively low batter angle (vertical stab holes);
5. reduced sub-drill, and in some cases negative sub-drill (i.e. stand-off);
6. reduced stemming (in some case no stemming);
7. increased inter-row delay times.

Buffer blasts commonly contain many rows of blastholes containing standard production charges, as well as one or more rows of holes for which the charge configuration has been modified. Buffer blasting therefore clearly places less emphasis on reducing confinement (i.e. less emphasis on promoting movement of burden material away from the back rows of
blastholes), but shares a common focus with trim blasting of reducing vibration levels by reducing the size of charges placed near to the pit walls.

While buffer blasting is clearly the mine-preferred method for forming pit walls, there is little information available to indicate, in quantitative terms, the relative merits of trim blasting and buffer blasting. Trim blasting suffers the major disadvantage of requiring shovels or excavators to take a second pass of an area in order to complete the excavation of blasted material.

**Pre-Splitting**

Many operations conduct pre-splitting as a matter of course prior to blasting against pit walls with either trim blasting or buffer blasting practices. Pre-splitting is widely perceived to produce cleaner and safer walls, but is also considered expensive, often difficult to implement, and frequently difficult to schedule. Although pre-split designs generally share a common design feature of close-spaced holes, there is a great deal of variability and uncertainty with respect to other critical design characteristics including:

1. hole diameter – this affects the cost of dedicated drilling equipment, flexibility of use for other drilling requirements, spacing and number of holes required, the ability to drill inclined holes, and the ability to drill in wet ground;
2. amount of charge and method of charge distribution in the holes (continuous decoupled charges, or air decked toe charges);
3. use or elimination of stemming;
4. optimum spacing between holes;
5. placement and charging of back row trim/buffer/production blastholes with respect to the pre-split line;
6. scheduling of the pre-split firing – ahead of, and separate from the adjacent trim/buffer blast, or at the same time.

More and more, mines prefer to use large diameter holes for pre-splitting, even though the benefits in terms of increased spacing are probably outweighed by the higher cost of drilling, and the loss of flexibility with regard to hole inclination. Coal mines, where pre-split holes may be up to 80 metres deep, clearly have no practical alternative but to use large diameter pre-split blastholes. There is a strong perception that pre-splitting introduces a barrier between subsequent trim/buffer/production blastholes and the pit wall, preventing or impeding the transmission of cracks, block movement, and gas flows into the wall.

**Vibration and Charge Confinement as Damage Mechanisms**

All blast designs specifically developed to provide maximum protection to the pit wall, focus on either issues of charge confinement, or peak vibration, or both. Numerous researchers have attributed measured damage to peak levels of induced vibration, though the most notable of these studies may be the work reported by Holmberg and Persson (1979), in which the onset of blast-induced cracking was related to peak levels of vibration. Building on the study by Holmberg & Persson, LeJuge et al (1994) undertook perhaps the first comprehensive study of damage in terms of vibration, gas pressure influences, and bench dilation measurement, presenting some innovative techniques for quantification of gas pressure influences. The conclusions reached by LeJuge et al (1994) highlight the prominent roles of both vibration and gas pressure in determining the extent and degree of damage.
behind blasts. In more recent studies utilising perhaps the clearest and least ambiguous measurement of damage yet undertaken by any research group, Ouchterlony (1999) reports that damage around blastholes increases with increasing burden, hinting at an effect of confinement in addition to vibration level and charge concentration. Bulow and Chapman (1994) conclude their study of limits blast design optimisation by saying that the effects of vibration and gas pressure have equal impact in terms of damage to pit walls. Floyd (1999) focuses his study of damage behind blasts almost entirely on issues of charge confinement, and McKenzie (1999) reviews the role of gas pressure in dilating joints and fractures behind blast patterns, relating the impact of high pressure gas flows through the rock fabric to issues of charge confinement. Importantly, the paper illustrates the effect of even low gas pressures on the stability of rock blocks located behind blastholes, in the area commonly required to act as a stable and long-standing catchment berm.

Bickers et al (2001) conclude that the use of trim blasting to achieve design pit slope at Mt Whaleback is both technically and operationally appropriate. Trim blasthole diameter at Mt Whaleback is adjusted according to the local geotechnical conditions. However, in what might be considered a controversial finding, Brent et al (2001) report that increased charge confinement, through increased burdens or apparent burdens (due to ‘choking’) at the Fimiston Gold Mine, did not result in increased vibration levels, or increased gas penetration. They concluded that no increased damage to pit walls would be caused by replacing narrow, free-face trim blasting with ‘choked’ buffer blasting. These conclusions, however, were strongly based on the results of monitoring single blastholes fired with variable burden to a free face, and it is also noted that the “trim” blasts and production blasts utilised the same pattern size, explosive type, and blasthole diameter. The work reported by Grohs & Marton (2001) also appears at odds with the results reported by Brent et al.

Of particular significance to the issue of damage behind blasts is the role of powder factor. In terms of practical implementation of effective wall blast designs, it must be recognised that blasting against pit walls must always be considered to have two equally-important objectives – protection of the wall and diggability of the muckpile. Either without the other can not constitute successful cautious blasting, and the factor having the controlling influence on diggability is powder factor. Bulow and Chapman (1994) conclude that vibration damage is proportional to powder factor, whereas LeJuge et al (1994) conclude that powder factor is not a reliable indicator of damage, and further assert that improved results in terms of wall stability are generally obtained from the use of relatively high powder factors which prevent unnecessary confinement at the back of trim blasts. In his review of the role of gas pressure on damage behind blasts, McKenzie (1999) observed that no researchers involved in the study of gas pressure influences had found or suggested a link between gas penetration and powder factor. In his study of overbreak control, Floyd (1999) asserts that energy factors should be maintained relatively high to avoid over-confinement of charges near to the pit wall. McKenzie et al (1995) conclude that powder factor did not appear to play a major role controlling damage at Chuquicamata, though note that charge distribution did appear to be an important factor.

Detailed studies of the role of pre-splitting in controlling damage to pit walls are relatively few. Ouchterlony (1999) reports that the pre-split blasting at Aitik Copper Mine with decoupled and unstemmed holes forces pressurised blast fumes into the rock forming the pit wall, for distances of at least 6 metres. His study also reported that, once formed, the pre-split plays an important role in preventing blast fumes and vibrations from passing, but that significant bench dilation extends well behind the pre-split as a result of both the pre-split
blasting itself and of subsequent production and trim blasting. Ouchterlony also asserts that
dilation should be considered as damage, irrespective of its cause. LeJuge et al (1994) also
reported measurable damage in the form of dilation and gas flow from pre-split charges, and
concluded that the pre-split does not markedly attenuate vibration (after measuring vibration
levels on either side of a pre-split line), and that although the pre-split is effective in terms of
preventing gas flow from nearby production and trim blasting into the rock mass behind the
pre-split line, it is ineffective in terms of limiting bench dilation. The conclusion with
regards to vibration transmission across a pre-split is in accordance with the results of a
specific investigation by the USBM (Devine et al, 1965).

Evaluation of Blasting Impact

Based on a review of hard factual literature, it appears there is no clear consensus on how to
design and implement the most effective wall control blasts. In recent studies, an
examination of the different profiles of damage behind production blasts and trim blasts was
used as the basis for comparing the effectiveness of various techniques to limit damage to pit
walls. Production blasts utilised 229 mm diameter blastholes with 400 to 1000 kg of
explosive per hole (average 540 kg) while trim blasts utilised various hole diameters (127 to
229 mm) and charge weights in the range 140 to 540 kg (average 420 kg). The study
included the following means of assessing the impact of the different blast types on the pit
wall:

1. peak particle velocity measured using geophones and accelerometers bonded to
   the top of concrete-filled holes, located over the range 10 to 500 metres behind
   blast patterns;
2. bench displacement measured using survey instrumentation to determine
   displacement of markers, anchored at depths varying from 10 metres to 3 metres
   below the bench surface, and at distances ranging from 6 metres to 20 metres
   behind blastholes;
3. surveying of surface cracking;
4. video inspection of open holes, before and after blasting, drilled at distances
   between 4 and 13 metres behind blasts.

The study has provided some indications of how damage is distributed vertically and
horizontally in the bench behind blasts. The measurement methods are sufficiently simple to
implement to enable on-going measurement by mine-site personnel. The studies conducted
to date, while not complete in terms of comparing all of the potential wall blast designs, allow
clear conclusions to be drawn regarding the impacts of production and trim blasting on pit
walls, while providing geotechnical engineers with valuable information regarding the
volume of rock behind blasts which has been detrimentally affected by blasting. It is noted
that all measurements were made prior to excavation, so any subsequent excavation-related
movements are unaccounted for, and future studies need to address the effects of measured
damage in terms of time-dependent berm failures.

Vibration Measurement

The vibration measurement campaign included the use of accelerometers for very near-field
monitoring and geophones in the medium to far-field. Where the ground movement induced
by the blast was expected to exceed 2 mm, accelerometers were utilised, otherwise
geophones were preferred due to lower cost and ease of use. Most monitoring was conducted
in the range 10 to 50 metres, but some blasts were monitored at distances of up to 500 metres.
Figure 1 presents the vibration data for the monitored blasts, with the measurements
separated for production blasting and trim blasting. The figure indicates no significant difference in terms of vibration attenuation conditions for the trim and production blasts, suggesting that the presence of a free face, and the practice of firing narrow trim blasts, do not produce any significant reduction in peak vibration levels.

Adjacent to many of the nearer vibration monitoring stations were located open holes for video camera analysis. This analysis was undertaken specifically to obtain visual confirmation and evidence of damage in the form of cracking appearing directly after blasting. In all cases, video analysis was conducted as quickly as practical after blasting and always within 24 hours and well before the muckpile had been excavated. A subjective rating was made by an experienced geotechnical engineer of the degree of damage observed during the video analysis. The engineer also recorded the depth within the hole at which the damage was observed. Relating the observed subjective rating to vibration levels produced the graph shown in Figure 2.

*Figure 1. Peak vector sum vibration levels for production and trim blasting.*
The conclusions drawn from Figure 2 were:

- Observable damage, in the form of new or open cracks, appears to commence at around 200 mm/s;
- Once levels increase to around 400 mm/s, observable damage can become intense.

Notably, damage in the inspection holes was observed over the full depth of the holes, representing the full depth of the bench being blasted. To minimise damage to berms, vibration levels need to be maintained below 400 mm/s, and preferably below 200 mm/s. With large diameter blastholes, normal blasthole charge weights, and normal stand-off distances from the designed pit wall, this level of control can not be achieved, suggesting that in this situation, small diameter blastholes, or at least small explosive charges, are an essential component of effective wall formation.

**Movement Measurement**

Movement was measured in all directions using standard mine survey instrumentation. Whereas previous studies by LeJuge et al (1994), and Ouchterlony (1999) focused primarily on vertical movement and joint and fracture dilation, this study considers that any movement within a catchment berm will result in a loss of joint strength, and therefore a reduction in wall stability. It is noted that the dominant direction of movements varied in the study from vertically up, to vertically down, to sidewards. Whereas the observation of a vertically downward movement was initially perplexing, it can be readily explained in situations where the dominant direction of muckpile movement is forward, towards the pit. The observed downward movement could be a release-of-load response, or a sliding action along downwardly inclined joints permitted by the presence of a power trough or simply a reduction in horizontal confinement stresses. It is a clear signal that movement itself is an early indicator of a loss of joint strength and block stability.
Figure 3 shows the movement data, again divided into measurements made behind trim blasts and measurements made behind production blasts. The measurements made to date suggest a clear distinction between the worst case movements behind production and trim blasts.

Following the assertion that movement must inevitably result in a loss in joint strength and block stability, there seems to be a convincing trend that production blasting generally produces a greater degree of damage to the surrounding rock mass than does trim blasting – the movements are less, and extend for considerably shorter distances behind back row blastholes. The very high powder factors used in some of the production blasts also appear to result in a greater degree of damage, though there is inadequate data available to make this a solid conclusion at this early stage. There is also inadequate data to comment on whether the movement versus distance trend is linear or otherwise – the displayed lines are presented only as trend indicators.

![Figure 3. Movement measurements made behind trim and production blasts.](image)

To examine the profile of damage with depth, this study examined those blasts for which movement monitoring was simultaneously conducted both at the surface and at depth. Movement markers were grouted at a maximum depth of 10 metres below bench surface – using approximately 1 metre of concrete to anchor the PVC pipe in the hole. In all cases, movement was observed to be greatest at the surface and least at depth, with the further trend that both surface and at-depth movements decreased with increasing distance behind the nearest row of blastholes. The raw data trend is shown in Figure 4, and it is also noted that the dominant direction of movement was vertically upwards, representing overall dilation of the bench surrounding the blast. It is clear that substantial movement is occurring to considerable depth below the bench surface, behind both trim blasts and production blasts.
By grouping measurements at the same site, and considering the ratio of measured movement at depth to total surface movement, it is possible to gain a limited insight into how relative movement varies with depth below the bench surface (Figure 5). The diagonal line in this figure illustrates a trend where movement varies linearly with depth, all the way to the base of the bench. There is the general observation that, at half bench height, measured movement is approximately half of the total surface movement. Assuming that movement below the bottom of the blasthole is unlikely, it seems reasonable to assume that movement extends all the way to the base of the bench. This is supported by the observation that the borehole video camera analysis at no time detected any shearing of observation holes. It also suggests that, over any 1 metre interval, movement is more or less constant throughout the bench.

Figure 4. Movement measurements as a function of depth below bench surface.
Figure 5. Relative movement as a function of bench height (Note: the labels associated with each data point indicate the distance behind the blast at which the measurements were made).

At distances of up to 10 metres behind blasts (both production and trim), movements still appear to extend all the way to the bottom of the bench.

Work by Schamaun (1983), suggested a damage profile resembling an inverted cone, as did McKenzie et al (1995), and Scherpenisse (1994). Floyd (1999) postulated a conical damage profile in which damage at the base of the bench extended only very short distances behind blastholes, whereas the damage profile at the surface extended as much as 10 metres behind a trim blasthole. If the damage zone extends all the way to the base of the bench, for distances of 10 or 12 metres behind blastholes, the repercussions in terms of ground support and the volume of rock associated with potential berm failures, could be very significant. On the basis of the observations made to date, it appears reasonable to interpret the damage profile behind blasts as being of a shape similar to that illustrated in Figure 6. This shape is similar to the contours formed by applying vibration contours using the near-field vibration equation proposed by Holmberg & Persson (1979). The use of a vibration-based model to predict the limit of cracking is further supported by Olsson et al (2001) who concluded that cracking in rock is caused by shock.
Figure 6. Possible damage profile around production and trim blastholes.

Conclusions

The study conducted to date, and the conclusions reached to date, should be regarded as preliminary only – the amount of data available is still very limited. More compelling conclusions will only come from a much more extensive study, and one in which strict quality control is exerted over the process of design implementation. However, the results obtained to date suggest that the data required to make meaningful comparisons between different types of blasts against pit walls, and their impact in terms of damage to berms, may not be difficult to obtain, nor difficult to interpret. Similarly, decisions regarding the potential benefits or otherwise of changing blasthole diameter, powder factor, or explosive type when blasting near to pit walls, and the value of pre-splitting, can be relatively easily evaluated over a series of blasts. Such a program would not require expensive instrumentation and would appear to be within the capabilities of mine technical personnel. General trends coming from early analysis suggests:

1. trim blasts utilising smaller diameter holes, no more than 4 rows of blastholes, and a clean free-face, appear to produce significantly less damage (i.e. a more narrow damage zone) to berms than production blasts, especially where production blasting is utilising high powder factors to promote high mill or excavator productivity;
2. both trim blasts and production blasts cause damage to surrounding rock masses, and the damage may be extending to the full depth of the bench. Observable surface damage may extend deep into the bench;
3. It is not yet possible to say whether the primary source of observed damage is vibration or gas pressure, though the profile of damage appears more consistent with expected vibration contours.

To date, no direct comparison has been made between trim blasts and modified production (i.e. buffer, cushion or choked) blasts. If the modified production blasts utilise the same
diameter of charge as production blastholes, adjacent to the pit wall, damage is likely to be greater than that from smaller diameter blastholes.

References


