



With Compliments

The Use of Blast Timing to Improve Slope Stability

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1. Abstract

The release of energy during blasting produces reactive forces, which cause the deterioration of the remaining rock face. Pre-splitting and trim blasting are the key techniques adopted to protect final rock faces, and success is greatly affected by the timing of these holes. The theoretical requirements for these techniques are sometimes counter to each other, and an understanding of mechanisms is needed for good timing design.

Split timing, while needing instantaneous firing, should not produce excessive reactionary forces in the back wall. Trim blasting should proceed so as to protect the split surface and trim any frozen rock from it. Detonator timing precision is crucial in determining the extent of control over results, and the full potential of damage control can only be accessed through harnessing the accuracy of digital delay detonators.

2. Introduction

The linkage between slope stability and blasting practice is a complex one, related to geological conditions, the needs of the excavation, the scale of operations and the economics of the situation. However, intelligently applied blasting procedures will always serve to reduce the extent of backbreak and to leave the final rock mass in a more stable condition. The ideal outcome is to leave a solid wall of rock delineated by the barrels of the blastholes, from the top of the bench to its toe, with neither serious cracking of the face nor unbroken rock stuck against it after the main blast. When this target is not met, what has to be decided is (a) the reason for the failure, and (b) whether the need is sufficiently great for extra effort and expense towards improving it in the next blast.

The most common approach to final limit blasting is to specify presplitting techniques for the final wall, with trim blasting of the rock burden in front, so as to protect it from damage by heavily charged production holes. Presplitting provides a preferential fracture plane behind the blast to terminate cracks growing from the blastholes, while trim blasting reduces the rate of energy release against the final wall.

However, even when these well known techniques are applied, slope failures and back damage can persist. The key parameters within the control of the blasting engineer are, type and amount of energy in the hole, drilling pattern, hole depth, hole diameter, hole angle, bench geometry and blast timing. This last parameter, which is the most readily addressed, is the focus of this article.

3. Effect of Blast timing on rock behind the burden

Blast damage is created by the transfer of explosive energy into the rock mass. Two distinct mechanisms operate, creating quite different kinds of damage

1. Strain waves and expanding gases of detonation, leading to crushing and crack development as portrayed in Figure 1. The time frame for these phenomena is over within a few milliseconds.
2. Inertial mechanisms leading to ground shift, as portrayed in Figure 2. Since ground mass reaction is relatively slow (face velocities are typically in the range of 8 to 30 m/s) the time frame for these mechanisms lasts for tens, and even hundreds of milliseconds: in effect for the duration of the whole blast event.

Remedial steps must counter both mechanisms. Unfortunately, methods that benefit the mechanisms of Figure 1 sometimes exacerbate those of Figure 2. For example, the most

common approach to achieving a smooth final wall is by presplitting. This harnesses a well understood and widely publicised mechanism of favourable stress alignment which arises when all the blastholes in a line are fired simultaneously: tensile crack development between the holes is favoured, while tensile crack development perpendicular to the row of holes is suppressed (Figure 3).

However, as indicated in Figure 3, when holes are fired simultaneously, even if the charge in the holes is greatly reduced compared to normal blasting, a massive, low frequency, lateral impulse is delivered to the surrounding block of ground. The body of rock is thrust back by the sustained pressure of explosive gases expanding into the forming split. As this pressure is released, the whole body, in which the joints have been loosened and the bedding uplifted, slumps back. A split has been formed, but the quality of the rock is no longer what it was. It has been shaken and dislocated by high vibration levels, the upheaval of the surface, and sometimes, significant forward movement of the whole block of ground between the presplit holes and the nearest free face. Holes that may have been drilled in this block will tend to be closed by shearing (Figure 4).

The lateral impulse of splitting also has particular potential to upset joint integrity in the block ahead of the split. Previously intact ground may now be able to shift during the production blast, and even lead to sympathetic detonation if explosives gas stream through the loosened joint planes. Moreover, the creation of the split may not achieve its aim of preventing damage when the buffer blast is taken, since the split itself presents a free face to which the back holes can break. If the split is tightly closed, then the compressive and shear stress waves (and to some extent even the tensile waves) from these holes will cross the split with little attenuation. If the split has created a gap, then the solid wall is impacted by the reactionary thrust of fragmenting rock from the back holes.

Trim blasting is undertaken to reduce the energy released close to this split plane and therefore minimises the impact across the plane: however, lack of appreciation of the mechanisms at work can still result in poor outcomes.

To summarise, it is not unusual to find that presplitting and trim blasting, which are the normal methods adopted for limiting back damage and promoting slope stability, do not, on their own deliver what is required. Even where the barrels of split blastholes are left after the blasting, these sometimes collapse some time after exposure, and what was thought to be solid rock begins to slide off the face. The problem facing the blasting engineer is therefore both

- to create a preferential split at the back wall so as to provide a clean break between damaged and undamaged rock, and
- to reduce energy flow into the back wall.

While much can be done to address this problem in terms of the drilling and loading of holes, blast timing plays a very key role in controlling the release of energy, and enabling blast layouts to deliver sound back walls. The following assumes that everything has been done to limit damage in terms of the hole spacing and depth, and the loading of holes.

4. Options for reducing damage

Clearly, damage is maximised when the maximum amount of explosive is detonated at the same instant. Timing is the key to controlling both the rate at which the available energy is released, and the direction of thrust of the blast. Thus the need is to monitor

- Rock conditions and how these need to be addressed to prevent slope failure,
- The amount of explosive detonating in any given time window, and
- The direction in which the rock mass is loaded.

The worst conditions are when the rock mass is (a) generally very incompetent and liable to collapse into the open pit under its own weight, (b) strong, but intersected by pronounced off-vertical slips and joints running parallel to and out of the face. Under both of these conditions, normal controlled blasting measures tend to give disappointing results.

The issues that need to be faced are, (a) the technical requirements of the blasting, (b) the ability of the available explosives initiation systems to deliver these.

4.1 Technical Requirements

In optimising back wall conditions, the key is to record as closely as possible what is done and the results achieved. This information is crucial in applying principles of blasting to improve the results. So far as blasting results are concerned, the simplest tools are photography and vibration monitoring. High vibration levels are a direct symptom of blast energy channelled into the wall, and even quite simple capture systems set up consistently behind the wall will provide useful information on success in protecting the wall. If at all possible, proper slope stability ground movement monitors should be deployed and examined after each blast.

4.1.1 Pre Splitting

Splitting is highly desirable but not always possible, especially where the desired split plane is within 20 degrees of a major joint or slip plane. When conditions are difficult, the engineer needs to improve the distribution of energy along the split plane. This requires adoption of increasingly light and more decoupled charges, and closer spacing of blastholes. However, to reduce the vibration level in the rock mass, timing may need to be introduced to reduce the explosive mass firing instantaneously.

The simplest approach is to break up the split blast into groups of simultaneously firing holes, each group separated by a short delay, only long enough for the strain waves from the previous group to disperse. This can be determined by monitoring, but typically 17 to 25ms is more than adequate.

Where there are decks within the blastholes, these need to be fired simultaneously.

By "simultaneously", is meant, "within one millisecond", since co-operation of the strain waves is crucial and it has been widely demonstrated that the quality of split is greatly reduced when the timing between holes is in excess of 1ms. This is to some extent scale dependent, but a good rule.

4.1.2 Trim Blast timing

In keeping with the need to reduce the energy transfer across the split plane, trim holes usually have reduced drilling patterns and charge masses, and are timed to achieve single hole firing. Where decking is introduced, it is conceivable to introduce timing between the decks, but this is fraught with problems in terms of preventing some decks from dislodging or desensitising those around them. The rough rule is that at least 8ms is needed between shots for them not to reinforce each other in creating vibration, however, if the holes are physically well separated from each other (by 100 hole diameters or more), the travel time and buffering of any intervening broken rock tends to negate this requirement.

Since the impact of the developing inertial thrust of a trim (or production) blast is substantial, it is important to arrange it to be parallel, rather than perpendicular to the final split surface. This is achieved by developing the firing sequence with shorter delays perpendicular to the split, and longer delays parallel to it. The length of the delays is dependent on the conditions prevailing and the available delays and systems, but a good starting point is to have say 42ms delays running back towards the split, and 75 or 100ms delays running parallel to the face (See Figure 5). This deflects the thrust of the blast along, rather than into the split, which reduces the impact. A real benefit of this is that any rock sticking to the split becomes sheared off by the movement of the trim blast, leaving a clean face.

The time per metre of face traversed by the blast is controlled by the delay across the front of the blast, and is a useful measure of the thrust on the back wall: say the hole spacing is 5m, and 75ms delays are used between these. This gives $(75/5)$ or 15ms per metre of face. If 25ms delays are used, the rate is $(25/5)$ or 5ms per metre of face, and if the final row is shot with detonating cord with velocity of 6000m/s, the time between holes is $(5/6000)$ or 0.833ms, which works out to $(0.833/5)$ or 0.167 ms per metre of face. These changes represent quantum leaps in the thrust delivered and the extent of potential damage. Some idea of the actual power being delivered can be derived by dividing the mass of explosive per hole by the delay per square metre of face, and multiplying by 3 (assuming a nominal energy delivery of 3 MJ/kg). The results report in MJ per ms per square metre. This is material for further comment, but illustrates the principle. Figure 6 portrays how for a particular blast layout, increasing the delay across the face reduces the rate at which energy release takes place opposite the split. Clearly, short delays result in very high release rates, which are likely to be detrimental to the condition of the finished wall.

The delay of holes from the free face towards the split needs to be sufficient to allow relief of burden, that is to permit the tightest holes, against the split, to move their rock burden outwards from the split. Although shorter timing between these holes is effective in directing the thrust beneficially, tight confinement of the inmost holes can lead to excessive thrust. It is permissible to delay the back holes by an extra period in order to achieve better relief, but this has to be considered in relation to the overall design and constraints.

4.2 Capability of Explosives Initiating Systems

By far the majority of initiating systems currently available are based on shock tube systems with pyrotechnic timing. Pyrotechnic delays are exceptionally robust and simple to use, but suffer from intrinsically restricted precision: this has an important effect on blasting results, since it removes the ability to predict the achieved interval between shots. Basically, the average nominal delay will be achieved, but scatter will be distributed within a range of about + 5 to 9 percent of the in hole nominal delay.

Typically, in-hole detonators for opencast mining conditions have delays of 500 to 800ms, with surface timing units providing the inter-hole and inter-row delays. These will result in a normally distributed system scatter of + 30ms (which will vary from batch to batch). This means that, if the surface delay is say, 42ms, then a few shots can fire out of sequence, and some can fire as much as 70ms apart. This phenomenon is well understood, but there was nothing much that could be done until recently. The consequences have been a tendency toward inconsistent blasting results, which again is half expected, owing to the vagaries of geology. However, with the introduction of electronic digital delay detonators, a new window of capability has opened up.

Where splitting is concerned, in almost every explosives conference there are papers demonstrating that even quite small deviations from instantaneous firing result in split surfaces which are rougher, with increased scalloping of the wall. Typically, such papers call for holes to fire within 1ms of each other. Normally, the use of detonating cord, which fires at velocities in excess of 6000m/s, or 0.17ms per metre, is the best way to achieve this: holes are frequently less than 2m apart which means that they fire within 0.4ms of each other, while in-hole delay detonators usually have scatter over a range of 30ms or more. The greatest hole spacing encountered for splitting is about 5m, and even with this, detonating cord will deliver a delay of only 0.9ms. The significant scatter achieved with in-hole delay detonators is clearly unacceptable, so the only options are for detonating cord initiation, or for zero delay detonators in the hole with detonating cord on surface.

However with digital delay detonators, the split holes can be fired without the noise and performance loss associated with detonating cord, and if desired, these can be fired as the last holes after the trim shot.

What we have found with these accurate systems is that much of the prevailing wisdom around delays can be rewritten: present guidelines have developed from studies in which significant delay scatter was intrinsic, and wide variation in results is factored into recommendations. With tight control of timing, we have found that much shorter delays are not only possible, but also desirable for reducing backbreak, enhancing fragmentation and controlling movement. It is gratifying to note that precise timing brings consistent and reasonably predictable blasting results, with much enhanced control of backbreak.

5. Conclusion: Blast timing for slope stability

The timing needed to deliver a stable slope is highly dependent on the conditions and needs at the site, but the general principles given above are the correct starting point.

Firstly, the geometry of blasting needs to favour energy release away from the critical final wall. Timing influences this by directing the ground reaction of both trim and production blasting away from the back wall. Line blasting parallel to the wall is entirely inappropriate, and is likely to cause not only loosening of previously tight joints, but the freezing of significant volumes of cracked rock against the split. We have proven time and again that where blast progression is toward a site, vibration levels can be double the levels on the opposite side, with propagation away from the site.

Secondly, the packets of explosive energy released need to be appropriate to the conditions. Not only should the loading in each hole be addressed, but serious attention must be given to achieving a delay long enough for the strain waves from neighbouring holes to disperse individually.

Thirdly, the precision of the timing system is crucial in achieving consistent results. With pyrotechnic timing systems, the lack of precision demands that fairly long inter-hole delays are employed in order to avoid crowding or out of sequence shots. Long delays can result in ground movement interfering with the functioning of holes around each shot, and in excessive fracture and movement between shots. Digital electronic timing is indispensable for achieving strong, consistent final wall conditions without compromising production blasting.

Fourthly, the close monitoring of blasting results is crucial to achieving sound designs for each domain of final limit blasting. Photographs are the simplest and most convincing proof of what is achieved, but need to be filed for easy reference and must show the extent of deterioration with time. Together with these are required the blasting parameters, geological analysis and any meaningful records of vibration levels behind the wall.

It is not always appreciated that changing any one parameter in a blast can have serious implications for other parameters and blast results. The task must be approached holistically, so that broad input and learning can be achieved.

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