21. Blasting damage in rock

Introduction

The development of rock mechanics as a practical engineering tool in both underground and surface mining has followed a rather erratic path. Only the most naively optimistic amongst us would claim that the end of the road has been reached and that the subject has matured into a fully developed applied science. On the other hand, there have been some real advances which only the most cynical would discount.

One of the results of the erratic evolutionary path has been the emergence of different rates of advance of different branches of the subject of rock mechanics. Leading the field are subjects such as the mechanics of slope instability, the monitoring of movement in surface and underground excavations and the analysis of induced stresses around underground excavations. Trailing the field are subjects such as the rational design of tunnel support, the movement of groundwater through jointed rock masses and the measurement of in situ stresses. Bringing up the rear are those areas of application where rock mechanics has to interact with other disciplines and one of these areas involves the influence of blasting upon the stability of rock excavations.

Historical perspective

By far the most common technique of rock excavation is that of drilling and blasting. From the earliest days of blasting with black powder, there have been steady developments in explosives, detonating and delaying techniques and in our understanding of the mechanics of rock breakage by explosives.

It is not the development in blasting technology that is of interest in this discussion. It is the application of this technology to the creation of excavations in rock and the influence of the excavation techniques upon the stability of the remaining rock.

As is frequently the case in engineering, subjects that develop as separate disciplines tend to develop in isolation. Hence, a handful of highly skilled and dedicated researchers, frequently working in association with explosives manufacturers, have developed techniques for producing optimum fragmentation and minimising damage in blasts. At the other end of the spectrum are miners who have learned their blasting skills by traditional apprenticeship methods, and who are either not familiar with the specialist blasting control techniques or are not convinced that the results obtained from the use of these techniques justify the effort and expense. At fault in this system are owners and managers who are more concerned with cost than with safety and design or planning

engineers who see both sides but are not prepared to get involved because they view blasting as a black art with the added threat of severe legal penalties for errors.
The need to change the present system is not widely recognised because the impact of blasting damage upon the stability of structures in rock is not widely recognised or understood. It is the author's aim, in the remainder of this chapter, to explore this subject and to identify the causes of blast damage and to suggest possible improvements in the system.

A discussion on the influence of excavation processes upon the stability of rock structures would not be complete without a discussion on machine excavation. The ultimate in excavation techniques, which leave the rock as undisturbed as possible, is the full-face tunnelling machine. Partial face machines or roadheaders, when used correctly, will also inflict very little damage on the rock. The characteristics of tunnelling machines will not be discussed here but comparisons will be drawn between the amount of damage caused by these machines and by blasting.

Blasting damage

It appears to me, a casual reader of theoretical papers on blasting, that the precise nature of the mechanism of rock fragmentation as a result of detonation of an explosive charge is not fully understood. However, from a practical point of view, it seems reasonable to accept that both the dynamic stresses induced by the detonation and the expanding gases produced by the explosion play important roles in the fragmentation process.

Duvall and Fogelson (1962), Langefors and Khilstrom (1973) and others, have published blast damage criteria for buildings and other surface structures. Almost all of these criteria relate blast damage to peak particle velocity resulting from the dynamic stresses induced by the explosion. While it is generally recognised that gas pressure assists in the rock fragmentation process, there has been little attempt to quantify this damage.

Work on the strength of jointed rock masses suggests that this strength is influenced by the degree of interlocking between individual rock blocks separated by discontinuities such as bedding planes and joints. For all practical purposes, the tensile strength of these discontinuities can be taken as zero, and a small amount of opening or shear displacement will result in a dramatic drop in the interlocking of the individual blocks. It is easy to visualise how the high-pressure gases expanding outwards from an explosion will jet into these discontinuities and cause a breakdown of this important block interlocking. Obviously, the amount of damage or strength reduction will vary with distance from the explosive charge, and also with the in-situ stresses which have to be overcome by the high pressure gases before loosening of the rock can take place. Consequently, the extent of the gas pressure induced damage can be expected to decrease with depth below surface, and surface structures such as slopes will be very susceptible to gas pressure induced blast damage.

An additional cause of blast damage is that of fracturing induced by release of load (Hagan, 1982). This mechanism is best explained by the analogy of dropping a heavy steel plate onto a pile of rubber mats. These rubber mats are compressed until the momentum of the falling steel plate has been exhausted. The highly compressed rubber mats then accelerate the plate in the opposite direction and, in ejecting it vertically upwards, separate from each other. Such separation between adjacent layers explains the tension fractures frequently observed in open pit and strip mine operations where poor blasting practices encourage pit wall instability. McIntyre and Hagan (1976) report vertical cracks parallel to and up to 55 m behind newly created open pit mine faces where large multi-row blasts have been used.

Whether or not one agrees with the postulated mechanism of release of load fracturing, the fact that cracks can be induced at very considerable distance from the point of detonation of an explosive must be a cause for serious concern. Obviously, these fractures, whatever their cause, will have a major disruptive effect upon the integrity of the rock mass and this, in turn, will cause a reduction in overall stability.

Hoek (1975) has argued that blasting will not induce deep seated instability in large open pit mine slopes. This is because the failure surface can be several hundred metres below the surface in a very large slope, and also because this failure surface will generally not be aligned in the same direction as blast induced fractures. Hence, unless a slope is already very close to the point of failure, and the blast is simply the last straw that breaks the camel's back, blasting will not generally induce major deep-seated instability.

On the other hand, near surface damage to the rock mass can seriously reduce the stability of the individual benches which make up the slope and which carry the haul roads. Consequently, in a badly blasted slope, the overall slope may be reasonably stable, but the face may resemble a rubble pile.

In a tunnel or other large underground excavation, the problem is rather different. The stability of the underground structure is very much dependent upon the integrity of the rock immediately surrounding the excavation. In particular, the tendency for roof falls is directly related to the interlocking of the immediate roof strata. Since blast damage can easily extend several metres into the rock which has been poorly blasted, the halo of loosened rock can give rise to serious instability problems in the rock surrounding the underground openings.

Damage control

The ultimate in damage control is machine excavation. Anyone who has visited an underground metal mine and looked up a bored raise will have been impressed by the lack of disturbance to the rock and the stability of the excavation. Even when the stresses in the rock surrounding the raise are high enough to induce fracturing in the walls, the damage is usually limited to less than half a metre in depth, and the overall stability of the raise is seldom jeopardised.

Full-face and roadheader type tunnelling machines are becoming more and more common, particularly for civil engineering tunnelling. These machines have been developed to the point where advance rates and overall costs are generally comparable or better than the best drill and blast excavation methods. The lack of disturbance to the rock and the decrease in the amount of support required are major advantages in the use of tunnelling machines.

For surface excavations, there are a few cases in which machine excavation can be used to great advantage. In the Bougainville open pit copper mine in Papua New Guinea, trials were carried out on dozer cutting of the final pit wall faces. The final blastholes were placed about 19 m from the ultimate bench crest position. The remaining rock was then ripped using a D-10 dozer, and the final 55 degree face was trimmed with the dozer blade. The rock is a very heavily jointed andesite, and the results of the dozer cutting were remarkable when compared with the bench faces created by the normal open pit blasting techniques.

The machine excavation techniques described above are not widely applicable in underground mining situations, and consideration must therefore be given to what can be done about controlling damage in normal drill and blast operations.

A common misconception is that the only step required to control blasting damage is to introduce pre-splitting or smooth blasting techniques. These blasting methods, which involve the simultaneous detonation of a row of closely spaced, lightly charged holes, are designed to create a clean separation surface between the rock to be blasted and the rock which is to remain. When correctly performed, these blasts can produce very clean faces with a minimum of overbreak and disturbance. However, controlling blasting damage starts long before the introduction of pre-splitting or smooth blasting.

As pointed out earlier, a poorly designed blast can induce cracks several metres behind the last row of blastholes. Clearly, if such damage has already been inflicted on the rock, it is far too late to attempt to remedy the situation by using smooth blasting to trim the last few metres of excavation. On the other hand, if the entire blast has been correctly designed and executed, smooth blasting can be very beneficial in trimming the final excavation face.

Figure 1 illustrates a comparison between the results achieved by a normal blast and a face created by presplit blasting in jointed gneiss. It is evident that, in spite of the fairly large geological structures visible in the face, a good clean face has been achieved by the pre-split. It is also not difficult to imagine that the pre-split face is more stable than the section which has been blasted without special attention to the final wall condition.

The correct design of a blast starts with the very first hole to be detonated. In the case of a tunnel blast, the first requirement is to create a void into which rock broken by the blast can expand. This is generally achieved by a wedge or burn cut which is designed to create a clean void and to eject the rock originally contained in this void clear of the tunnel face.

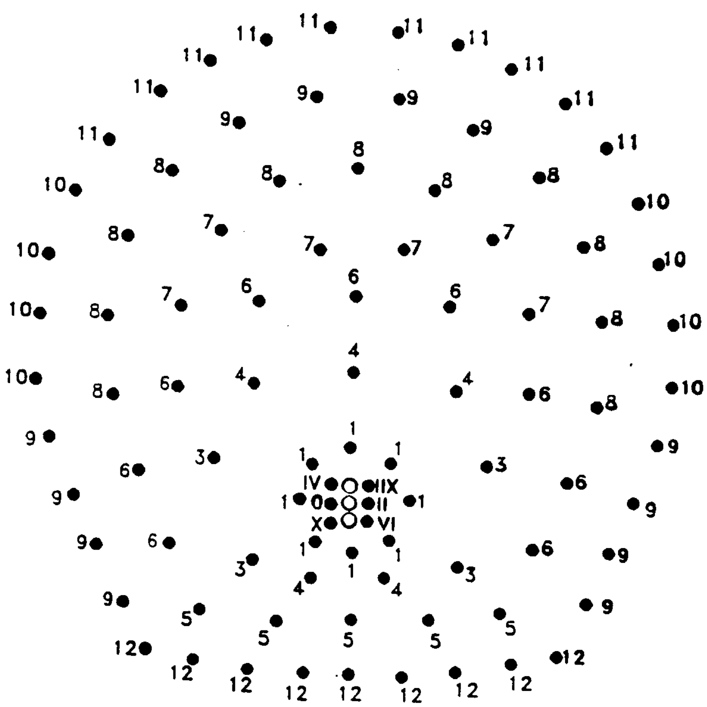
Figure 1: Comparison between the results achieved by pre-split blasting (on the left) and normal bulk blasting for a surface excavation in gneiss.

In today's drill and blast tunnelling in which multi-boom drilling machines are used, the most convenient method for creating the initial void is the burn cut. This involves drilling a pattern of carefully spaced parallel holes which are then charged with powerful explosive and detonated sequentially using millisecond delays. A detailed discussion on the design of burn cuts is given by Hagan (1980).

Once a void has been created for the full length of the intended blast depth or `pull', the next step is to break the rock progressively into this void. This is generally achieved by sequentially detonating carefully spaced parallel holes, using one-half second delays. The purpose of using such long delays is to ensure that the rock broken by each successive blasthole has sufficient time to detach from the surrounding rock and to be ejected into the tunnel, leaving the necessary void into which the next blast will break.

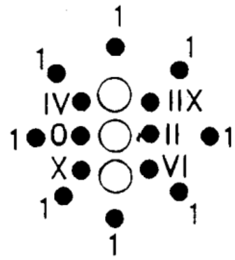
A final step is to use a smooth blast in which lightly charged perimeter holes are detonated simultaneously in order to peel off the remaining half to one metre of rock, leaving a clean excavation surface.

The details of such a tunnel blast are given in Figure 2. The development of the burn cut is illustrated in Figure 3 and the sequence of detonation and fracture of the remainder of the blast is shown in Figure 4. The results achieved are illustrated in a photograph reproduced in Figure 5. In this particular project, a significant reduction in the amount of support installed in the tunnel was achieved as a result of the implementation of the blasting design shown in Figure 2.

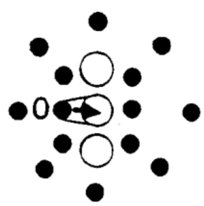


Holes	no	Dia mm	Explosives	Total wt. kg	Detonators
Burn	14	45	Gelamex 80, 18 sticks/hole	57	Millisec
Lifters	9	45	Gelamex 80, 16 sticks/hole	33	Half-sec
Perimeter	26	45	Gurit, 7 sticks/hole and Gelamex 80, 1 stick/hole	26	Half-sec
Others	44	45	Gelamex 80, 13 sticks/hole	130	Half-sec
Relief	3	75	No charge		
Total	96			246	

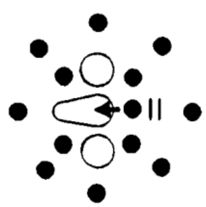
Figure 2: Blasthole pattern and charge details used by Balfour Beatty - Nuttall on the Victoria hydroelectric project in Sri Lanka. Roman numerals refer to the detonation sequence of millisecond delays in the burn cut, while Arabic numerals refer to the half-second delays in the remainder of the blast.



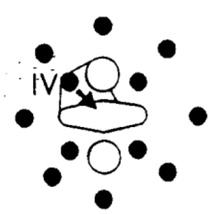
Layout of holes



Millisecond delay 0

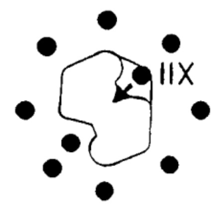


Millisecond delay II

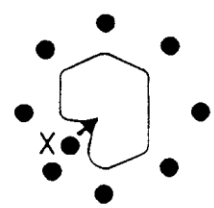


Millisecond delay IV

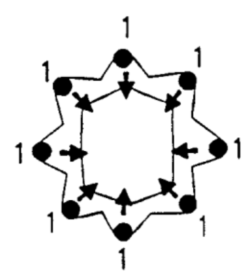
Milliscond delay VI



Millisecond delay IIX



Millisecond delay X



Half-second delay 1

Figure 3 Development of a burn cut using millisecond delays.

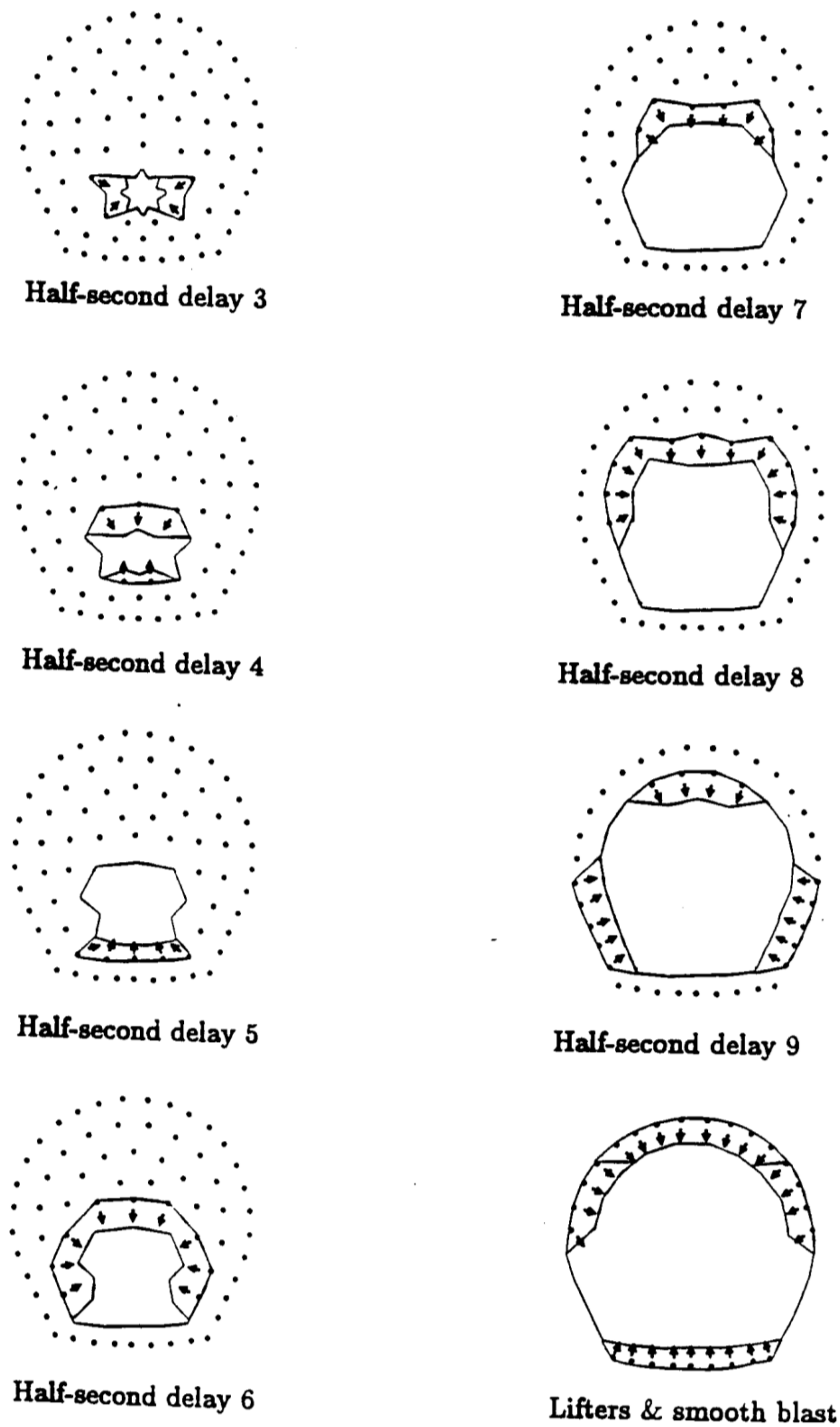


Figure 4: Use of half-second delays in the main blast and smooth blasting of the perimeter of a tunnel.

Figure 5: Results achieved using well designed and carefully controlled blasting in a 19 foot diameter tunnel in gneiss in the Victoria hydroelectric project in Sri Lanka. Note that no support is required in this tunnel as a result of the minimal damage inflicted on the rock. Photograph reproduced with permission from the British Overseas Development Administration and from Balfour Beatty - Nuttall.

A final point on blasting in underground excavations is that it is seldom practical to use pre-split blasting, except in the case of a benching operation. In a pre-split blast, the closely spaced parallel holes (similar to those numbered 9, 10 and 11 in Figure 2) are detonated before the main blast instead of after, as in the case of a smooth blast. Since a pre-split blast carried out under these circumstances has to take place in almost completely undisturbed rock which may also be subjected to relatively high induced stresses, the chances of creating a clean break line are not very good. The cracks, which should run cleanly from one hole to the next, will frequently veer off in the direction of some pre-existing weakness such as foliation. For these reasons, smooth blasting is preferred to pre-split blasting for tunnelling operations.

In the case of rock slopes such as those in open pit mines, the tendency today is to use large diameter blastholes on a relatively large spacing. These holes are generally detonated using millisecond delays which are designed to give row by row blasting.

Unfortunately, scatter in the delay times of the most commonly used open pit blasting systems can sometimes cause the blastholes to fire out of sequence, and this can produce poor fragmentation as well as severe damage to the rock which is to remain to form stable slopes.

Downhole delay systems which can reduce the problems associated with the detonation of charges in large diameter blastholes are available, but open pit blasting engineers are reluctant to use them because of the added complications of laying out the blasting pattern, and also because of a fear of cut-offs due to failure of the ground caused by the earlier firing blastholes. There is clearly a need for further development of the technology and the practical application of bench blasting detonation delaying, particularly for the large blasts which are required in open pit mining operations.

Blasting design and control

While there is room for improvement in the actual techniques used in blasting, many of the existing techniques, if correctly applied, could be used to reduce blasting damage in both surface and underground rock excavation. As pointed out earlier, poor communications and reluctance to become involved on the part of most engineers, means that good blasting practices are generally not used on mining and civil engineering projects.

What can be done to improve the situation? In the writer's opinion, the most critical need is for a major improvement in communications. Currently available, written information on control of blasting damage is either grossly inadequate, as in the case of blasting handbooks published by explosives manufacturers, or it is hidden in technical journals or texts which are not read by practical blasting engineers. Ideally, what is required is a clear, concise book, which sets out the principles of blasting design and control in unambiguous, non- mathematical language. Failing this, a series of articles, in similarly plain language, published in trade journals, would help a great deal.

In addition to the gradual improvement in the understanding of the causes and control of blast damage which will be achieved by the improvement in communications, there is also a need for more urgent action on the part of engineers involved in rock excavation projects. Such engineers, who should at least be aware of the damage being inflicted by poor blasting, should take a much stronger line with owners, managers, contractors and blasting foremen. While these engineers may not feel themselves to be competent to redesign the blasts, they may be able to persuade the other parties to seek the advice of a blasting specialist. Explosives manufacturers can usually supply such specialist services or can recommend individuals who will assist in improving the blast design. Incidentally, in addition to reducing the blasting damage, a well-designed blast is generally more efficient and may provide improved fragmentation and better muck-pile conditions at the same cost.

Conclusion

Needless damage is being caused to both tunnels and surface excavation by poor blasting. This damage results in a decrease in stability which, in turn, adds to the costs of a project by the requirement of greater volumes of excavation or increased rock support.

Tools and techniques are available to minimise this damage, but these are not being applied very widely in neither the mining nor civil engineering industries because of a lack of awareness of the benefits to be gained, and a fear of the costs involved in applying controlled blasting techniques. There is an urgent need for improved communications between the blasting specialists who are competent to design optimum blasting systems and the owners, managers and blasting foremen who are responsible for the execution of these designs.

Research organisations involved in work on blasting should also recognise the current lack of effective communications and, in addition to their work in improving blasting techniques, they should be more willing to participate in field-oriented programs in co-operation with industry. Not only will organisations gain invaluable practical knowledge but, by working side-by-side with other engineers, they will do a great deal to improve the general awareness of what can be achieved by good blasting practices.

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