THE USE OF A COMPUTER TO DESCRIBE BLASTING

By

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ABSTRACT

The first production stage in any mining operation is the breaking of whole rock into fragments small enough for loading and subsequent handling. This primary fragmentation is most frequently accomplished with blasting. The maximum fragment size and the fragment size distribution have an influence on the subsequent loading, handling and crushing costs.

It is assumed that total rock fragmentation in practice is a result of an interacting array of radial cracks from various blastholes. The representation for the basic pattern of radial cracks emitted from a particular blasthole is first described. A model is then developed simulating the interaction between blastholes at various burdens and spacings, and in simultaneous and delayed modes. The resultant picture is analysed and a fragment size distribution calculated. Methods of incorporating the existing faults in the rock are also discussed.

Finally application of this model to various facets of mining are considered.

INTRODUCTION

Blasting is often described as an art rather than a science. It is an apparently simple operation which consists of drilling holes in a pattern, charging them with explosives, stemming the holes and then detonating the holes in a given order. In spite of this apparent simplicity, the practical problem of relating explosive properties, the pattern and firing order used and the rock properties to the blasting results, particularly fragmentation, is still obscure. Part of the difficulty lies in the speed at which the transient processes which give the observed results take place. It is impossible in practice to observe the processes occurring in the interior of the rock mass. Another difficulty in understanding the complete blasting process lies in the large number of possible variables, many of which may be inter-related.

This paper discusses a method of simulating blasting and the effect that changes in blasting have upon fragmentation. It should be pointed out that good fragmentation by itself is not sufficient. The muck pile has also to be heaved into a configuration suitable for loading by a particular piece of equipment and subsequent processing. Methods of predicting heave have been described elsewhere (Harries 1973). It is also required that blasting should not unduly weaken the walls of the excavation or cause excessive vibration. The overall objective is to find the method of blasting which will give the lowest overall mining cost.

This paper will discuss the reasons for using a digital simulation of blasting, the mechanism of blasting assumed in the simulation and the parameters necessary to simulate the

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mechanism and the algorithm which describes the interaction of the parameters. The results of the simulation and some applications are then discussed.

THE METHODS

There are three distinct methods by which fragmentation can be studied:

1. Using the actual operation as the model.
2. Using scale models.
3. Digital simulation.

The actual situation is often too large for experimentation. Measurements are difficult in ore passes (Brady 1971). Photographic methods of evaluating fragmentations are apparently successful but are always checked by physical measurements of a section through the muck pile (Noren & Porter). These measurements are expensive and time consuming and only a limited number of parameters can be varied. In special purpose blasting this method must obviously be ruled out. There is no second chance. Scale models suffer from unavoidable assumptions such as:

a) cracking in Perspex is similar to cracking in rock;

b) several parameters such as rock crystal size and gravity cannot be scaled.

Many industrial explosives will not detonate reliably in small diameters so that PETN based explosives have to be used (Just & Henderson 1971, Rhandari 1975, Bergmann Riggle & Wu 1973). This applies particularly to the evaluation of aluminiun explosives where the aluminium requires a finite time to react (Porter 1974). Scale models have been used by many workers with varying degrees of success.

DIGITAL SIMULATION

Digital simulation does not have the disadvantages of the above two methods. Within the limitations of the digital computer, the engineer can model any real situation, to any degree of detail required.

It is this approach which was taken here. Various assumptions were made for the propagation of cracks and these were programmed into a simulation model of the blasting area.

THE MECHANISM OF BLASTING

For the purposes of the theory the blast-hole is considered as a thick walled cylinder of rock suddenly filled by a gas at very high pressure by the detonation of the explosive. This pressure is known as the explosion pressure and is generated by the explosive when it reacts in its own volume. It is assumed that the rock is elastic. The expansion of the borehole is then calculated taking into account that, as the borehole expands, the pressure decreases until equilibrium is reached. This suddenly applied pressure creates a strain wave which propagates through the rock leaving the rock behind it in a strained condition. The intensity of this strain wave was measured with radial strain gauges in U.S.B.M. experiments! The theoretical calculations are in excellent agreement with experimental results, especially when account is taken of the varying length of the cartridge in these experiments. From an analysis of these experiments it was concluded that the strain from the side of a long cylindrical charge did not increase when the charge was longer than 32 x radius of the hole (Harries 1973). At this stage in blasting we have generated a strain wave in the rock and strained the rock by the application of the equilibrium pressure. The energy to do this has come from the explosive gas which has expanded and done work. Half this work goes into forming the dynamic strain wave and the other half into generating the static strain field. This is also in good agreement with strain energy measurements by the U.S.B.M. (Harries 1973). The rock has now been strained, but not yet cracked. The strain at any point around the blasthole can be calculated and if the tensile
breaking strain of the rock is known the number of cracks which will extend to a given distance can be determined.

This cracking will extend uniformly around the hole. During the formation of the cracks the strain wave is reflected from the free surface and can interact with the growing cracks. It will have the greatest effect on those cracks to which it is tangential. Taking the theoretical crack velocity of 0.38 V (Roberts & Wells 1954) it can be shown that the cracks at an angle of \( \tan^{-1} \) 0.38 to a line through the charge centre parallel to the free face will be opened preferentially. This angle is, in fact, the average angle of craters. The gas in the blasthole is still at a very high pressure and streams into the cracks further straining the rock and extending those cracks pointing towards the free face. It has been shown that by analogy with cratering that the gas pressure doubles the length of the strain induced cracks (Harries 1977). The assumption that the longest length of a fragment is the distance between adjacent radial cracks has been found to give fragmentation curves in good agreement with cratering experiments (Harries 1977).

**PROGRAMME DESCRIPTION**

The main programme is controlled by a descriptor file (DESCRIPT). The descriptor file sets up the conditions for the simulated blasts. The programme simulates each explosion by “drawing” the crack pattern from a given charge on a 2D array. The particular pattern chosen can be any one of three crack patterns appearing in files DPAT1, DPAT2, DPAT3 or a random pattern. Each charge has its crack pattern drawn in turn, determined by the firing order. If a particular crack meets a previous crack, the former is terminated. In simultaneous blasting a number of crack patterns are drawn "at the same time" by propagating each pattern by increments until completion.

When all charges have been "fired" the programme may print or plot a picture of the result (if instructed by the descriptor file). In working out the size distribution, points are chosen at random in a designated area of the matrix. Through each point two lines, one horizontal and one vertical, are drawn to meet the nearest crack at their end points. The size of the fragment is assumed to be the length of the shortest of the two lines. A tally of sizes is kept, and the final distribution printed or plotted, on request, at the end of the programme.

**THE VARIABLES INCORPORATED IN THE SIMULATION**

Recent experiments (Finger) show that the energy released by cylindrical charges of ammonium nitrate/fuel oil are independent of the detonation velocity and therefore the detonation pressure in diameters greater than the unconfined critical diameter. The experimental energy released is within ± 2% of the calculated value assuming the initial state is the explosion state. The energy released by an explosion is determined by the explosive pressure and the adiabatic exponent which defines the path along which the explosive gases expand.
THE ROCK

The effect of the explosive on the initial strain $k$ of the blasthole wall is given by (Harries & Mercer 1975).

The explosion pressure $p_e$ and the adiabatic exponent $\gamma$ have to be known. The $\rho$, $V$ and $\sigma$ - the density, longitudinal sound velocity and Poisson's ratio respectively - of the rock also need to be known. These properties give the dynamic elastic properties of the rock. The Hugoniot Elastic Limit for many rocks is in the range of 3.0 - 10.0 GPa (Butcher) which is the range of the expected explosion pressures. The assumption that the rock will act elastically is therefore reasonable.

If the dynamic tensile breaking strain $\tau$ is known the number of cracks $N$ around the circumference of the blasthole wall is given by (Harries & Mercer 1975).

This is the value put into the Descript file. The value of $\tau$ can be found from cratering experiments or from known blasting results. When $\tau$ is known the effects of varying the explosive can be found by calculating the new $k$ and $k/\tau$.

THE CRACK PATTERN

The number of cracks $N$ at a distance $R$ from a blasthole radius $b$ can be found from

$$ N = \frac{k}{\tau \left( \frac{R}{b} \right)} $$

It has been shown that the fragmentation from a single isolated charge can be readily calculated. Production blasting is obviously not a series of independent craters. The blastholes are placed close enough together to give a smooth face between the holes after blasting and must interact. This interaction can also be influenced by the order in which the holes are fired.

In order to model this interaction the stress/strain field around each hole has not been calculated as has been done by Bhandari. Instead the crack pattern expected for a single isolated hole has been placed around each hole and the interaction of the crack pattern is described by two rules:

(a) when the holes are fired instantaneously the cracks are terminated where they collide;

(b) when the holes are fired sequentially the cracks from the hole being fired are terminated where they meet existing cracks.

These rules were established after an examination of the firing of small charges in perspex blocks. These experiments show that the cracks from sequentially fired charges can be assumed to be straight. Those from instantaneously fired charges are slightly curved, but it is still reasonable to assume that they are straight. The fragmentation from craters can be found by calculation which assumes the cracks are disposed symmetrically around the blasthole (Harries 1977). The radial crack pattern has been laid out by assuming that the crack distribution through a section of a cylindrical blasthole perpendicular to the axis is the same as a vertical section through the centre of a crater. The cratering experiments show that the limit of practical blasting is the distance to which 7 cracks extend. The seven cracks are drawn symmetrically around the blasthole and the other cracks then added at angles of $69^\circ$ and then diagonally opposite. This process is repeated until 40 cracks have been inserted. These crack patterns can be put into DPATI, 2 and 3. A facility exists to put in a random crack pattern. The crack lengths are as calculated but the orientation of the cracks is random. This option is available in the Descript file. By analogy with cratering the strain induced cracks are found all around the blasthole. Those cracks facing the free face are extended by gas pressure. The ratio of these lengths can be specified in the

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Descriptive file. The value normally adopted is 0.5. That is the strain induced cracks are 0.5 of the length of gas extended cracks (Harries 1977). The crack pattern can be orientated in any direction specified in the Descriptive file. This direction will orient the crack pattern to the free face expected at the moment of firing. This is 90° for a row of holes fired simultaneously and 45° for holes fired singly. For instantaneously fired holes the crack patterns are drawn "at the same time" by propagating each pattern by increments until completion. In practice instantaneous firing usually means firing with a line of detonating cord and the increment is usually the delay caused by the finite velocity of the detonating fuse. This is analogous to the incremental drawing mentioned above. As the crack lengths are given in reduced lengths using the blasthole radius as a unit all burdens and spacing must be expressed similarly. Any firing order can be specified.

Having drawn the crack pattern the fragmentation in any specified area of the blast can be found by a Monte Carlo routine which generates a specified number of random points and then measures the distance to the two nearest cracks in two mutually perpendicular diameters and takes the shorter length. It is expected that long thin pieces will be broken up and the shorter length will be the most realistic. The lengths are sorted into size ranges thus allowing a size distribution curve to be generated. The crack pattern can be plotted or printed and the size distribution curve plotted or printed if desired.

The power and usefulness of the method are obvious.

COMPARISON WITH EXPERIMENT

Ash (1973) and Dick (1973) have performed a series of experiments at a dolomite quarry. This was a scaled down version of a normal blast. The scale was 1/20 of normal. The spacing/burden ratio was varied from 1:1, 1.27:1, 1.5:1 and 2:1. For each spacing/burden ratio instantaneous and delay firing was used. The fragmentation was determined by sieve analyses. The effect of the geology was also studied by firing at different sites and in different directions.

In order to compare the model simulation and experiment, the $K/T$ was varied until agreement was found between the calculated and experimental size distribution curves. For one extreme case the delay firing with a spacing/burden ratio of 2:1, $K/T$ was found to be 650. The comparison of theory and experiment is shown in Fig 2. Fig 3 shows the agreement with experiment for delay firing with a spacing/burden ratio of 1.27 and the same value of $K/T$.

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Fig. 2. Comparison of Experimental Results of Ash for Spacing/Burden Ratio of 2.0 with Calculated Result assuming $K/T = 650$.

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These figures show that:

(a) The experimental results can be represented by straight lines on Rosin-Rammler paper. This also has been found by Kuznetsov (1973).

(b) The simulation results are within the probable experimental error.

(c) The digital simulation indicates a difference between simultaneous and delay blasting. This was not found in practice. For the 38 cm burden used in these experiments the usual rule for determining delay times of 1 milli sec/30 cms of burden would give a delay time of 1½ milli secs. The simultaneous blasts could only be considered to be simultaneous.

If all the detonators used fired within 0.5 milli sec of each other. When using commercial detonators this can only be achieved by using high firing currents. Unless this is done there will be an appreciable scatter in the firing of the detonators. On the scale of this experiment such scatter will result in blasts which are effectively delayed.

(d) The model shows that in these blasts each hole can cause much more cracking than it causes in actual blasts. Much of this cracking is terminated by the cracks from previously fired holes. The energy that causes this increased cracking seems to be dissipated as increased vibration (Gribanov 1975).

It should be noted that the model and experiments both show that the most significant variable in blasting is the spacing/burden ratio. Timing seems to be less important but is still significant.

Noticeable effects are seen in practice from delay blasting. This is however not due to the effect of timing but to creation of effective free faces which alter the burden to spacing ratio. It can be seen from (Hagan 1975) that a pattern drilled square to the nominal free face can be fired so that the burden to spacing ratio at the moment of firing can be varied from 1:1 to 2:1 and almost 4:1.

THE EFFECT OF EXPLOSIVES

The model shows quite clearly that there is, for each blasting situation, an optimum explosive. If the burden and spacing, and the method of firing is kept constant and only the energy of the explosive is varied the fragmentation improves as the explosive energy is increased until an optimum is reached. Increasing the power further then causes the fragmentation to deteriorate. This is shown in Fig. 4 where the model shows that there is an optimum explosive which contains
7% of aluminium. This is in striking agreement with the results of Noren and Porter who found experimentally that if only the explosive was varied that there was an optimum explosive containing from 5 - 10% of aluminium.

![Diagram](image)

Fig. 4. The Effect of Explosive Energy on Fragmentation.

**SLOPE STABILITY**

It has been pointed out above that cracks are generated all around a blasthole. The simulation can generate not only the cracks responsible for the fragmentation but also the cracks induced in the apparently undisturbed ground. It is frequently necessary that the walls of an excavation remain stable. The simulation can show the extent and frequency of the cracking induced in the rock behind a blast and can thus be a valuable tool for assessing the effects of various blasting patterns not only on fragmentation but on slope stability.

**ROCK FAULTS**

Faults in rocks can be described as existing cracks. The effect of the geological structure of the rock on blasting can be incorporated into the simulation by inserting cracks to represent the faults. The cracks representing the faults will then terminate the cracks produced by blasting where they intersect.

**FUTURE WORK**

The present simulation is restricted to two dimensions. In modern blasting practice which uses large diameter holes the volume of rock around the collar becomes a significant proportion of the blast - often as large as 40%. Sub-grade drilling from a bench above the bench being blasted helps to crack the rock in this area, but it cannot be assumed that the rock is subjected or has been subjected to the action of an effectively continuous column of explosive. Ideally a three-dimensional simulation of at least the collar region is required. This appears to be expensive. Other methods of simulating the cross sections through the collar region are being examined.

The dynamic tensile breaking strain is very difficult to measure and has to be found from either fragmentation results or by measuring the extent of the fractured region either behind or below a blast by a seismic survey. The use of the surface energy necessary to create a new surface is being explored as an alternative rock fracture criterion. Results from perspex are encouraging but have not yet been applied to rock.

**CONCLUSIONS**

The results of the digital simulation have been shown to be in encouraging agreement with experiment over a range of spacings, blast timings and explosives. As a result the major variables of interest in blasting can be simulated. The simulation may also show the effect of blasting on the walls of an excavation.

Further work is necessary to extend the simulation to the region around the collar and provide easier methods of determining the rock failure properties.

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