Blast Design Parameters and Their Impact on Rock Fragmentation

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ABSTRACT

Blasting operations play a pivotal role in the overall economics of opencast mines. The blasting subsystem affects all the other associated subsystems, i.e., loading, transport, crushing and milling operations. Fragmentation control through effective blast design and its effect on productivity is a challenging job for the practicing blasting engineer due to inadequate knowledge of actual explosive energy released in the borehole, effect of varying initiation practice in blast design and its effect on explosive energy release characteristic. This paper describes the result of a systematic study on the impact of blast design parameters on rock fragmentation at two mines in India. Both the mines use draglines and shovel-dumper combination for removal of overburden. Despite its pivotal role in controlling the overall economics of a mining operation, the expected blasting performance is often judged almost exclusively on the basis of poorly defined parameters such as powder factor and is often qualitative, which results in a very subjective assessment of blasting performance. Such an approach is a very poor substitute for accurate assessment of explosive and blasting performance. Forty-seven blasts were conducted with varying blast designs and charging patterns and their impact on the rock fragmentation are documented. A high-speed camera was deployed to record the detonation sequences of the blasts. The efficiency of the loading machines was also correlated with the mean fragment size obtained from the fragmentation analyses.

INTRODUCTION

Rock fragmentation distribution influences a range of mining and milling processes including load and haul rates, crushing and grinding performance and ore recovery in beneficiation processes (Michaud, Lizotte and Scoble, 1997). In open pit mining, where blasting is employed for excavation, the overall cost-effectiveness of the production operation is compatible with optimisation of drilling and blasting parameters. Rock fragmentation depends upon two groups of variables: rock mass properties, which cannot be controlled and drill and blast design parameters, which can be controlled and optimised. The cost of downstream operations can be reduced by optimising the blast design parameters to provide target fragmentation. The parameters of target fragmentation are equipment-specific and vary in category from mine to mine. The high level of mechanisation and the integrated nature of the production systems adopted in the mining industry demand that all the units must function with designed reliability and capacity to achieve the planned production targets (Singh and Narendrula, 2009).

The objective of a blasting engineer in a mine is to generate a suitable muck pile having suitable size distribution of the rock that can be efficiently loaded, transported and milled (Singh, Narendrula and Duffy, 2005). The goal of efficient blasting can be achieved by investigating the relationship between blast design parameters and fragmentation achieved. It is extremely important to make the connection between rock blasting results and their impact on the downstream operations. While it is well accepted that fragmentation has a critical effect on the loading operations, little quantitative information is available, upon which rational blasting strategies can be outlined. Spathis (2002 and 2009) discussed some aspects of size reduction and its influence on mineral liberation, which mainly described the area of prediction and assessment together with the related assumptions: fines, mean size, oversize, cumulative size distributions and measurement protocol.

The total cost of aggregate production in a quarry has a minimum value at an optimum fragmentation size (Mackenzie, 1967; Morin and Ficarrazzo, 2006). Prediction of the optimum fragmentation size will help the quarry owners in selecting blasting parameters to produce required material size at a known cost and also in selecting other crushers and conveyor systems. Optimum fragmentation size may not be the required size but knowing the size distribution for a particular blast and rock mass conditions, the contractor can adapt the blasting if possible (Engin, 2009).

Hustrulid (1999) cites from Burkle (1979) that blasting results are affected by the orientation of the rock mass structures. Three cases which have to be considered are:
1. shooting with the dip
2. shooting against the dip
3. shooting along the strike.

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While shooting with the dip, backbreak increases, toe problem decreases resulting in a smooth floor and throw of the blast increases resulting in scattered and low muck pile (Figure 1a). When shooting against the dip, less backbreak, more toe problems resulting in uneven floor and throw of the blast decreases resulting in higher muck pile profile (Figure 1b). Finally, when shooting along the strike (Figure 1c) the floor can be highly toothed due to the different rock types intersecting the floor. For the same reasons the backbreak is irregular. The effect of jointing on rock fragmentation has been documented by Hustrulid (1999) and is presented in Figure 2.

For prediction of the fragmentation size after blasting the Kuz-Ram model is generally used. The Kuz-Ram model is an empirical fragmentation model based on the Kuznetsov (1973) and Rosin and Rammler equations (Rosin and Rammler, 1933) modified by Cunningham (1983, 1987), which derives the coefficient of uniformity in the Rosin and Rammler equation from blasting parameters. Rock properties, explosive properties and design variables are combined in this modern version of the Kuz-Ram fragmentation model.

The Rosin-Rammler equation (1933) used by Cunningham (1983) for blasting analysis is:

\[ R = e^{\left(\frac{x}{x_c}\right)^n} \]  

where:
- \( R \) is the fraction of material retained on screen
- \( x \) is the screen size
- \( x_c \) is a constant called characteristic size
- \( n \) is a constant called uniformity index

The uniformity index typically has values between 0.6 and 2.2 (Cunningham, 1983). A value of 0.6 means that the muck pile is non-uniform (dust and boulders) while a value of 2.2 means a uniform muck pile with majority of fragments close to the mean size. The importance of the uniformity index is size distribution curves having the same characteristic size but different values of uniformity index.

The Kuznetsov equation relates the mean fragment size to the quantity of explosives needed to blast for a given volume of rock. The Kuznetsov equation is:

\[ k_{50} = A\left(\frac{V}{10^8}\right)^{0.8}Q^{1/6} \]  

where:
- \( k_{50} \) is the average fragment in cm
- \( A \) is a rock factor
- \( V \) is the rock volume in m³ broken per hole (burden × spacing × bench height)
- \( Q \) is the mass in kilograms of TNT equivalent explosives per hole

According to Gheibie et al (2009): \( A = 7 \) for medium rocks; \( 10 \) for hard, high fissured rocks; and \( 13 \) for hard, weakly fissured rocks. Cunningham (1983) associated \( A \) with rock mass description (friable, jointed or massive), joint spacing, rock density, rock uniaxial compressive strength and the Young's modulus.

Since TNT is no longer used as a standard explosive for comparison, an equivalent quantity for an explosive (\( Q_e \)) related to TNT is calculated as:

\[ Q = Q_e \left(\frac{E_e}{1090}\right) \]  

where:
- \( E_e \) is the absolute weight strength of the explosive (cal/g)
- \( 1090 \) is the absolute weight strength of TNT

The above two equations can further be simplified as the following expression:

\[ k_{50} = Aq^{0.8}Q_e^{1/6}\left(\frac{E_e}{1090}\right)^{-19/30} \]  

where:
- \( q \) is the inverse of \( V/Q_e \) defined as the powder factor (kg/m³)

![FIG 1](image1.png) – (A) Diagrammatic representation of shooting with dip; (B) diagrammatic representation of shooting against the dip; (C) Diagrammatic representation of shooting along strike (Burkle, 1979).

![FIG 2](image2.png) – Effect of jointing on fragmentation (after Hustrulid, 1999).
The mine is producing about 4.5 Mt of coal and removal of overburden is about 12 Mrm³. The stripping ratio of the mine is 1.472, ie 4.72 m³ of overburden is to be removed for mining of 1 t of coal. The total coal reserve of the mine is 188.26 Mt.

**METHODOLOGY**

Blast design parameters of bench blasting are the controlling parameters which regulate the desired fragmentation level of a particular blast. Rock mass properties and blasting parameters control the efficiency of a blasting operation. But all the blasting design parameters cannot be changed depending on type of strata and bench height. Hole diameters of 159 mm, 269 mm and 311 mm diameter were used depending on their bench height. Bench height is related to the working capability of loaders and varies from 5 m to 42 m. A few blasts were performed by the existing blast design practiced in the mine and after each blast, scaled digital photographs (ten to 20 numbers) of the fragmented rock pile were taken as well as loading efficiency of the shovel were also recorded. Fragmentation characteristics such as mean fragment size, uniformity index and characteristic size were calculated using image analysis system called Wipfrag software. The physico-mechanical properties of rock sample collected at Nigahi mine and Sonepur Bazari mine are presented in Table 1. Figure 4 depicts the view of the detonation sequence of shovel bench blast at Nigahi mine. Fragmentation analyses were carried out for all the blasts in different segments.

**Analysis of data**

The blast design parameters data was collected from 47 blasts at two coalmines and analysed to investigate its impact on rock fragmentation. The important parameters which decide the fragmentation level of a particular blast are burden to hole diameter ratio, spacing to burden ratio, stemming column length, stiffness ratio, explosives amount and its type and charge factor. The near field blast vibration signatures were also recorded to diagnose the impact of delay timing on blast fragmentation. The blast wave signature recorded at 100 m from one of the hard overburden (OB) dragline bench blast is depicted in Figure 5. In this blast the delay interval between the holes were 17 ms and between the rows the delay intervals were 65 ms, 84 ms, 100 ms, 125 ms and 142 ms in subsequent rows.

The fragmentation achieved from blasts gave different results. Most of the blast results had good fragmented rock profile with uniformity. Few blast results also showed scattered results in terms of big size boulders and fine and dust particles as represented in terms of uniformity index (n). The fragment size analyses were carried out using Wipfrag software. The output of the analyses are in the form of number of exposed fragmented blocks, maximum, minimum and mean size of the fragmented blocks, sieve analysis as per the requirement ie at different percentile size viz. D10, D25, D50, D75 and D90. (Percentile sizes: for example D10 is the ten-per centile, the value for which ten per cent by weight of the sample is finer and 90 per cent coarser. In terms of sieving, D10 is the size of sieve opening through which ten per cent by weight of the sample would pass.) One of the fragmented size analysis of the blast conducted at medium-hard OB bench of Nigahi mine is shown in Figure 6. The loading cycle of 10 m³ shovel was documented at hard OB shovel bench and is presented in Figure 7. The similar fragmentation analyses were carried out at hard OB bench blast at Sonepur Bazari mine and is presented in Figure 8. Figure 9 shows the loading cycle of the 10 m³ shovel operated at hard OB shovel bench at Sonepur Bazari mine.
Burden to hole diameter ratio
Hole diameter and burden are two important blast design parameters. In these trial blasts, hole diameter was of three different types ie 159 mm, 269 mm and 311 mm, but out of 47 blasts, 45 blasts were conducted with 269 mm diameter. Therefore, it can be said that the variation in burden to hole diameter ratio was in fact the variation in burden alone. Figure 10 depicts the plot between burden to hole diameter ratio versus mean fragment size. It is observed from Figure 10 that mean fragment size increases with increase in the ratio of burden to hole diameter. Some data do not show the expected trend probably because of the role of geology on blast fragmentation. In general the small diameter holes with smaller burden produces smaller fragments.

Spacing to burden ratio
Spacing and burden are important parameters and have a direct impact on rock fragmentation in blast design. Excessive burden creates resistance to penetrate the explosion gases into the fracture and displace rock and will also produce excessive vibration level. Small burden allows the gases to escape and pushing the blasted rock uncontrollably with high speed. Small spacing causes excessive crushing between the holes and superficial crater breakage. Excessive spacing results in inadequate fracturing between the blastholes which creates irregular faces with toe problem issues. The spacing to burden ratio can also be adjusted by changing the blast detonation sequence through different cut design viz diagonal firing, V-cut and elongated V-cut firing. If burden is not compatible with spacing, the blastholes will not connect resulting in inadequate use of explosive energy. Normally, the spacing to blasting ratio varies between one and two but the optimal spacing to burden ration was considered as 1.15 for staggered pattern and 1.25 for rectangular pattern of blastholes. Mean fragment size and index of uniformity (n) verses spacing to burden ratio were plotted and are presented in Figures 11 and 12 respectively. As most of the data have little variation in spacing to burden ratio, the outcomes of the graphs are not so significant. It also appears from Figure 12 that index of uniformity in few blasts is not in accordance with trend line which resulted either in poor fragmentation in terms of fine fragment or big size boulders. However, spacing to burden ratio between 1.1 and 1.3 shows excellent results except for a few blasts, which are having low index of uniformity (n) due to presence of joints and backbreak of previous blast.

<table>
<thead>
<tr>
<th>Name of the project</th>
<th>Rock type / location</th>
<th>Compressive strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Density (kg/m³)</th>
<th>Poisson's ratio</th>
<th>Young's modulus (GPa)</th>
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<tbody>
<tr>
<td>Sonepur Bazari</td>
<td>Sandstone (dragline bench)</td>
<td>37.29</td>
<td>3.46</td>
<td>2320</td>
<td>0.23</td>
<td>7.05</td>
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<tr>
<td></td>
<td>Sandstone (shovel bench)</td>
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<td>3.41</td>
<td>2300</td>
<td>0.23</td>
<td>7.02</td>
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<tr>
<td>Nigahi</td>
<td>Sandstone (dragline bench)</td>
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<td>3.53</td>
<td>2054</td>
<td>0.21</td>
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<tr>
<td></td>
<td>Sandstone (shovel bench)</td>
<td>29.56</td>
<td>3.23</td>
<td>2010</td>
<td>0.20</td>
<td>3.25</td>
</tr>
</tbody>
</table>

**TABLE 1**
Physico-mechanical properties of rock at both the mines.
FIG 5 – Blast wave signature recorded at 100 m from the dragline bench blast at Nigahi mine.

FIG 6 – Netting, contouring, histogram and cumulative size curve view of fragmented block at Nigahi mine.
Stemming length to burden ratio

Stemming length is another blast design parameter that affects rock fragmentation. This becomes even more significant when the blast faces encounter hard rock near the blasthole collar zone. If the rock has natural cracks in burden portion then long stemming may be recommended but on the other hand for massive rock, stemming column is required to be kept short. For the blasts in sandstone benches of coalmine, stemming length to burden ratio was plotted against mean fragment size. The data points are relatively scattered but the general trend shows that mean fragment size of fragmented rock decreases with the decrease in stemming length to burden ratio (Figure 13).
Blast Design Parameters and their Impact on Rock Fragmentation

Charge/powder factor

Charge factor is the ratio between the total weight of explosive and the amount of rock broken. It is an important parameter in blast design and has a vital influence on the resultant fragmentation. Lower charge factor causes oversize and higher charge factor results in crushed rock. Mean fragment size was plotted against the charge factor for 47 blasts of coal overlying overburden benches and are presented in Figure 14. The general trend shows that with increase in charge factor, the mean fragment size decreases. A few scattered data in this graph are due to the geological discontinuities of the rock mass of the blasting patch.

Stiffness (bench height to burden ratio)

Stiffness is the ratio of bench height and burden and also influences the resultant fragmentation, although bench height is usually decided on the basis of the working specifications of the loading equipment. Bench height should also be adequate to achieve optimal burden, spacing and charge factor (Singh and Abdul, 2012). The mean fragment size was plotted against stiffness, as shown in Figure 15. It is observed that a stiffness value of less than two gives coarser fragmentation and the best optimum value comes around three. Change in the burden or spacing has significant effect on rock fragmentation. In case of high stiffness value, it is easy to displace and deform rock especially at the centre of the bench (Ash, 1985), but on the other hand, there can be problems relating to blasthole deviation.

Joint plane orientation and spacing

Joint and bedding planes act as natural presplits during blasting and if possible, should be used to improve performance. For example, horizontal bedding allows pull to be maximised and the blasted rock will tend to split horizontally. Spacing of joints within a rock mass will have significant impact on the size distribution of the blasted muck. In general, the joint spacing will also improve the fragmentation level. It is suggested that in a rock mass with small joint plane spacing, explosives having lesser shock energy and high gas energy should be used while in case of rock mass having larger joint spacing, higher shock energy and less gas energy should be used for better shattering effect.
CONCLUSIONS

Optimum blasting should comprise the generation of fragment size distribution with suitable muck pile optimal for loading, which should improve the downstream operations. This study is confined to the effect of blast design parameters on the fragment size distribution of the blasted muck. The main conclusions of the study are:

- Mean fragment particle size increases with the increase in the burden to hole diameter ratio. This increase was mainly due to the increase in burden as the hole diameter was kept constant.
- Mean fragment size and index of uniformity ($n$) of the blasted muck decreases with the increase in the spacing to burden ratio. The optimum value of spacing to burden ratio in most of the blasts ranges from 1.1 to 1.3 and it resulted in excellent fragmentation.
- Stemming length to burden ratio was plotted against mean fragment size and the general trend shows that mean fragment size of fragmented rock decreases with the decrease of stemming length to burden ratio.
- As anticipated, the increase in the charge/powder factor will increase the rock fragmentation level, ie decrease the mean fragment size of the rock.
- Change in burden with respect to bench height has significant effect on rock fragmentation. Therefore, the stiffness (bench height to burden ratio) value of less than two gives coarser fragmentation and the best optimum value was around three.

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