Rock Fragmentation by Blasting – a review

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The rock fragmentation process in mining currently being practiced in India needs re-examination to improve the productivity of the mine. This is of immense importance that we should develop a better understanding of the explosive used and the rock mass to be blasted. The improved productivity cannot achieved by following the traditional practice of following rules of thumb such as Powder Factor (cubic meter of rock broken with a kg of explosive) or describing the target rock as weak, medium or strong, or specifying a delay interval in multi-hole blasting. In order to overcome this problem, a long-term R&D projects for understanding and quantifying the real detonation behavior of the variety of commercial explosives currently in use, under actual field conditions is the need of the hour. The current use of explosive energy figures supplied by manufacturers is woefully inadequate, as these are based on the maximum chemical energy available in a given explosive composition, which has only a very qualitative correlation with the effective energy available to fragment rock efficiently. The same would apply for selection of appropriate delay systems (shock tube or electronic), more specifically the delay interval and its correlation with fragment size distribution and digging and hauling efficiency. These studies are in their infancy, and there is little attempt in linking blast design, fragment size and loading efficiency. This paper comprises some recent R&D developments on rock fragmentation analysis and its application. The experiments were performed at Noamundi, Joda East, Katamati and Khondbond Iron mines of Tata Steel Limited.

1.0 Introduction

It is well known fact that minerals are valuable finite and non-renewable natural resources. They form the valuable inputs for diverse industrial activities. Minerals constitute the back-bone of economic growth of any country and so is the case with India as it has been generously endowed with minerals In Indian context, mining and quarrying sector accounts for about 2.5% of country's Gross Domestic Product (GDP). According to the Ministry of Mines, Government of India, India produces as many as 87 minerals, which include 4 fuel, 10 metallic, 47 non-metallic, 3 atomic and 23 minor minerals including building materials. As per the report of economic survey of India, 2015, 80% of mining activities are find in coal and the balance 20% in metallic and other raw materials such as gold, copper, iron, lead, bauxite, zinc and uranium.The gap between demand and supply of mineral is increasing day by day. By 2031, India will need a whopping 2 billion tonne of coal to take care of the energy security of the country. This will leads to an import dependence of coal in the range of 36-55 %.

The ever-increasing demand for mineral in India has necessitated construction and commissioning of large size opencast mines which force us to conduct big size blasts in the mine with improved production, productivity and safety. Blasting as stated is the first stage in comminution, the reduction of solid materials to smaller particle sizes, and it requires energy and money. Blasting is an efficient way to reduce the particle size of ore material and, if done well, mines will save significant amounts of money on crushing and grinding costs. Poor fragmentation of coal/ore and overburden/waste material can wipe millions of rupees from the value of a mine. The requirement of major rock/mineral production in India is presented in Table 1. The comparative energy costs of mining operation are given in Table 2.

Table 1. Requirement of major rock/mineral production in India

Mineral	Production
Coal	600 Mt/year
Iron Ore	137 Mt/year
Zinc	5.5 Mt/year
Bauxite	15 Mt /year
Limestone	300 Mt/year

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Table 2. Comparative Energy requirements of mining operation (Blasting to Fine Grinding):

Mineral	Production
Blasting	0.4-0.5 kWh/tonne of feed
Primary crushing	0.2-0.5 kWh/tonne of feed
Secondary/Tertiary Crushing	3.0 kWh/tonne of feed
Coarse Grinding	7.0 kWh/tonne of feed
Fine grinding	17 kWh/tone of feed

Clearly, blasting is along the lower end in terms of energy consumption. However, numerous studies have shown that fine grinding is the most expensive process in terms of energy requirement. Therefore, it makes sense to examine the blasting process (i.e. explosive selection and blast design), which is the first step in the size reduction process, to investigate its effect on the overall cost of reducing large blocks of in situ rock to fine particles. This has indeed been done, albeit at only a few selected sites, to show that the overall economic benefits of spending more on this first step (i.e. blasting) does reduce the overall cost of a mining operation. This is now described as the Mine-to-Mill concept, aimed at increasing the overall productivity of a mining operation, and thereby reduces cost.

The increasing environment constraints on vibration, overpressure and fume generation could be overcome by the use of advanced computer modelling techniques could provide productivity gains whilst simultaneously providing more control over the environmental effects and the impact on nearby infrastructure (Goswami et al., 2015). Marin et al. (2015) performed an analysis of cycle times considering different scenarios that contemplate different qualities of blasting performance. They observed that the quality of the performance is associated with the adherence to good drilling practices and blasting execution.

An equally important objective in our quest for better fragmentation is a more realistic characterization of the strength properties of the target rock. The latter has been shown to be a definite function of the rate of pressure rise in a borehole due to explosive action. These strengths under ‘dynamic’ loading conditions have been shown to be many times higher than usual ‘static’ strength employed in matching explosive to the rock. An equally important parameter has to do with fracture characteristics of the target rock under dynamic loading by explosive in the borehole.

In order to achieve this overall objective, one should have to invest substantial R&D effort in quantifying the size reduction process in rock, in order to improve overall productivity in mining operations. Below are listed some of the topics that need urgent attention:

- Explosives quality control
- Explosives density control in borehole
- Routine in-hole VOD measurement as standard quality control tool
- Near-field vibration monitoring to detect and investigate blast malfunctions
- Accurate measure of actual charge-weight per delay for protection of structures
- Systematic case studies at selected sites
- Comparison of fragment size analysis software tools to determine their relative merits in quantifying fragment size distribution
- Accurate monitoring of loading and hauling efficiencies and its correlation with blast design
- Numerical modeling of both production blasts and wall-control blasts

The above list is not necessarily exhaustive, nor their objectives easily met within a short span of time. However, it does show the magnitude of the challenge at hand for mining professionals to achieve the end objective of improved and efficient rock fragmentation process. There is little alternative if India has to meet its goal of self-sufficiency in mineral production.

Apart from above points focus has to be made on the factors hampering modelling. A major one is fragmentation measurements. Methods based on 2D imaging are not really sufficient. Now a day 3D imaging techniques are gaining ground for measurement on belts (Noy 2007, Thurley 2009). Muck pile measurements are not as well developed but in time they will also become fast and efficient methods whose use in the future projects will cut the work needed for fragmentation measurements to a fraction of that used in the present ones (Ouchterlony et al., 2012). More accurate fragmentation measurements will also lead to better simulation models; for blasting and for crushing and grinding.

2.0 Blast design parameters and their impact on rock fragmentation

The design of the blast does make a difference. Several factors affect the quality of a blast. The geology and geotechnical characteristics of the rock are unchangeable, but the blast pattern parameters, such as hole spacing, depth, diameter and amount/type of explosive used, can be modified. The ability to change these parameters dynamically in response to as drilled information is critical to achieving good fragmentation. The assessment of fragmentation in blasting and in any of the subsequent crushing and grinding stages is an important issue in mining control and optimization. Fragmentation characteristics influence the mucking productivity, the crusher throughput and energy consumption, the plant efficiency, yield and recovery, and the price itself of the end product in the case of industrial minerals and aggregates.

Explosive is the most commonly used energy to fragment the rock mass in mining and civil engineering projects. Main objective of blasting in mining projects is to obtain the maximum yield with desired fragmentation in a safer manner with minimum side effects like ground vibrations, noise and fly rock, while in civil engineering projects it is to create space (Sastry and Chandar, 2012). Assessment of each blast is necessary keeping the objective of the blast in back ground. Blast results can be categorized into two groups of desirable fragmentation and unwanted results like ground vibrations, noise and fly rock. In addition, there are some more minor undesirable results like back break, toe formation etc. A number of factors influence the blast results, which can be grouped into controllable and uncontrollable factors.The prediction and assessment of the rock size distribution produced by blasting are important in understanding the blasting process (Spathis, 2009). The 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 et al. 1997).

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. The cost of downstream operations can be reduced by optimizing the blast design parameters to provide target fragmentation. The parameters of target fragmentation are equipment-specific and vary in category from mine to mine. Singh et al. (2015) delineated the important parameters which decide the fragmentation level of a particular blast:

- burden to blasthole diameter ratio,
- spacing to burden ratio,
- stemming column length,
- charge factor,
- stiffness ratio,
- explosives amount, distribution and its type,
- delay timing

Parameters like explosive type, burden, spacing, sub drilling, stemming, delay timing, charge weight per delay, initiation system, initiation pattern etc., may be grouped under controllable parameters. Geological parameters like mineralogy, lithology, structural discontinuities and physico-mechanical properties of rock mass come under uncontrollable factors, as they are given by nature. Initiation system is one of the major parameters that influence the blast results considerably. Bench height should also be adequate to achieve optimal burden, spacing and charge factor (Singh and Abdul, 2012). Assessment of blast results in terms of fragmentation forms a major basis while evaluating the influence of various parameters.

3.0 Role of scattering in pyrotechnic delays on rock fragmentation

The effect of delay time on fragmentation has been discussed for a long period and despite the efforts of many researchers, delay selection for fragmentation improvement or optimisation remains a controversial issue. Katsabanis and Omidi (2015) based on small-scale tests suggest that there is influence of delay time on the larger sizes of blast induced fragmentation as well as on the uniformity of the fragmentation. Ouchterlony et al. (2015) experimented and compared the results for the electronic delay detonator rounds, which had nearly the same drilling and charging pattern as the Nonel rounds with normal specific charge show that the initiation scatter and possibly the delay malfunctioning may have a considerable effect on the blast fragmentation. The role of scattering in Nonel delay detonators (pyrotechnic delay) is very significant particularly in present scenario in India. The result of these delay detonators on fragmentation can better be understand by recording the actual detonation timing of these delay detonators.

The qualities of Nonel delay detonators of different companies have been tested by CSIR-CIMFR at all the four mines of Tata Steel Limited and one of the the procedure of test is shown in Fig. 1. The graphical presentation of the recorded scattering in firing time of Nonel delay detonators is depicted in Fig. 2.

Fig. 1. View of NONEL delay detonators connection arrangements for delay scattering test with the help of High Speed camera.

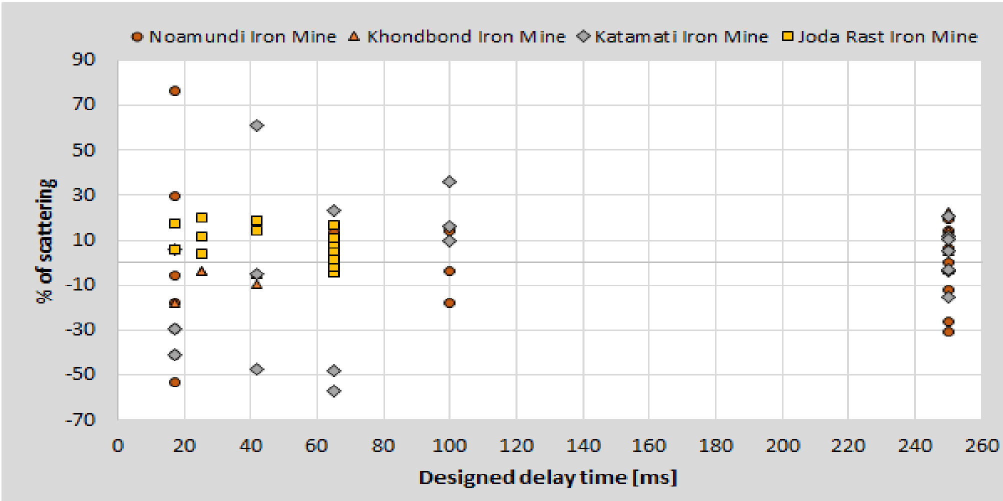

Fig. 2. Plot of recorded percentage (%) of scattering in Nonel Delay Detonators.

Besides explosives amount and quality its geometric distribution also affects fragmentation. Small charges with a distributed geometry transmit more uniformly the explosive energy to the rock, leading to better fragmentation and higher induction of micro-fractures. This reduces the total comminution energy necessary to grind the blasted material to the desired particle size (Seccatore et al., 2015).

Uniform VOD of explosives is essentially required throughout the blast holes in harder formations in order to produce sufficient detonation pressure to the borehole walls. Booster is provided in the explosive column at bottom to sustain and maintain the VOD for the uniform breakage of rock. Measurement of VOD is regularly required to maintain the quality of explosives because it is the key parameters which will decide the fragmentation level. Fig. 3 represents the typical VOD graph recorded at Noamundi Iron Mine having in-the-hole VOD of emulsion explosive of 4823.8 m/s. Fig. 4 represents the variations of in-the-hole VOD of explosives at the same mine by the same supplier over a period of time.

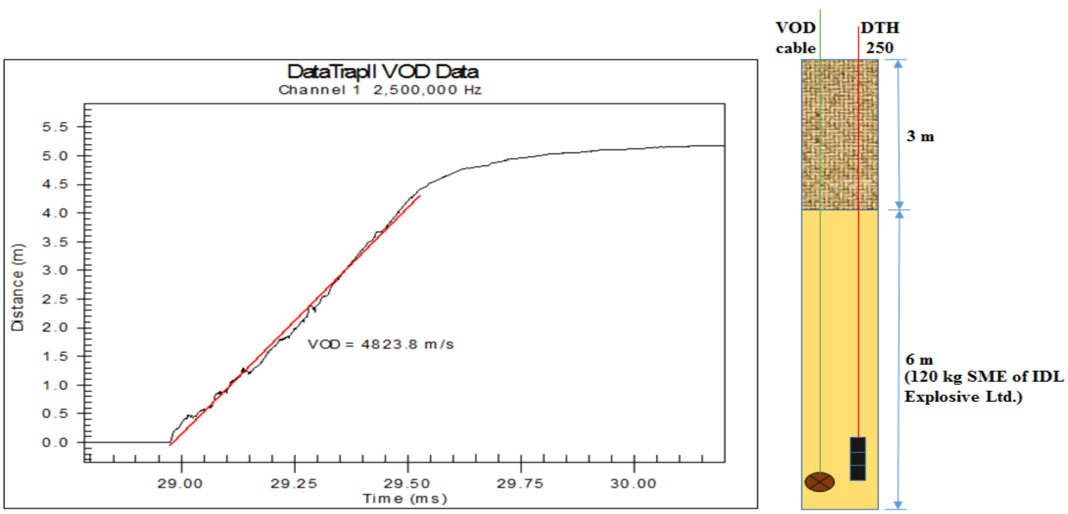

Fig. 3. Recorded signature of in-the-hole VOD of SME explosives at recorded at Hill No.5, Noamundi Iron mine.

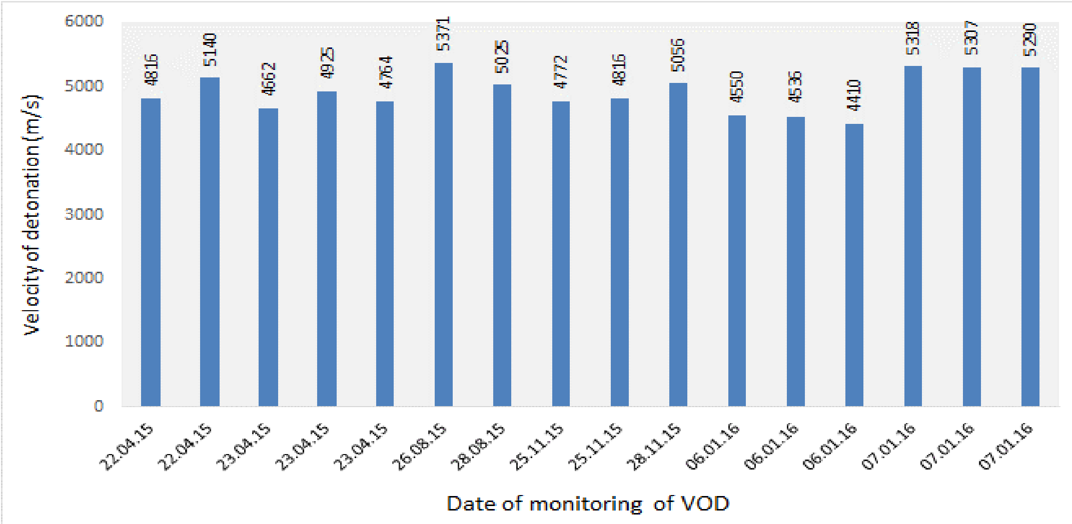

Fig. 4. Plot of variations recorded in in-the-hole VOD of explosives on different days at Noamundi Iron mine.

4.0 Rock fragmentation measuring tools

The fragmentation resulting from any blast will be heavily dependent on the properties of the rock mass being blasted; however, most empirical models rely on rock factors generated from simple rock mass properties to describe the influence of the rock on the blasting outcome. Blast-by-blast analytics, allow comparison of blasts across the mine to correlate design, execution and results. For example improvements in fragmentation can be targeted and tracked using the blast modelling tools. Fragmentation model produce two formats for analysis – a distribution curve of fragment size and a colored grid for easy identification of variation across blasts. Together with the vibration and airblast/overpressure models helps mines determine if the design will produce the desired outcome. Sharing and analyzing data instantly at critical stages helps clarify priorities. This performance can be analyzed to ensure that every aspect of the drill and blast process is fine tuned to reduce costs in downstream processing and continuously improve overall mine productivity.

Scott and Onederra (2015) characterized the rock mass properties for fragmentation modeling. They suggested that a suitable fragmentation model for any given situation is one that has been formulated to address the situation being studied and utilizes the rock mass, explosive and blast design properties that have most influence on the blasting outcome. Geotechnical engineers will tend to describe rock substance strength in terms of unconfined compressive strength (UCS) in MPa. Most blasting models use UCS as the principle parameter representing rock strength, although the failure of a cylinder of rock under compressive load with no lateral confinement does not really represent the conditions under which the rocks is expected to break under the action of an explosive. There are a wide range of fragmentation models available to the blasting industry. Some models (e.g. the Kuz-Ram model and its derivatives) utilize blasting indices compiled from relationships between basic properties describing strength, density and structure. These indices can be an effective way of identifying how blasting properties vary throughout a deposit and can be used to assist in the definition of individual blasting domains.

Empirical fragmentation models based on the application of the Rosin-Rammler distribution function have been widely and successfully applied in surface blasting by several investigators for over 30 years (Onederra and Riihioja, 2006). Its main practical application has been associated with the estimation of changes in coarse fragmentation outcomes given by estimates of the post blast mean fragmented size (X_{50}) and a descriptor of fragmentation uniformity defined as the uniformity index (n). Both of these parameters or indices have been linked to empirical relations that consider the main design variables impacting on fragmentation outcomes. A fragmentation model can be described through the mathematical relations obtained from scientific rationale or through experimental monitoring analysis (Silva, 2006).Given the complexity of the variables intervening in the fragmentation results of blasted material, as well as detailed knowledge of geo-structural conditions, it is more advisable to use empirical models that use the history available and reflect particular mine conditions.

A critical element in fragmentation system optimization is the development of practical methods of determining the degree of fragmentation. By degree of fragmentation one generally means specifying the average particle size and the distribution of the particles around that mean. Both direct and indirect methods are available for determining the fragmentation. The direct methods include screen analyses, counting boulders and measuring the pieces directly. The most accurate method of determining fragmentation is obviously to sieve the whole pile. Although this is possible to do for small amounts of fragmented materials and for very special purpose. It is very tedious, time consuming and very costly. This is even truer when measuring the pieces directly. Counting and measuring the boulders (oversize) is a common practice and easily done. It provides information about the extreme tail of the distribution but nothing more.

There are two categories of indirect techniques:

(i) Photographic methods

(ii) Measurement of parameters, which can be correlated to the degree of fragmentation.

In applying the photographic technique, the following steps are followed (Rholl et al., 1993):

The photographs should be taken with a 35-mm camera, a medium format camera or a video camera. They are then digitized. In the evaluation of the photographs, one can do the digitization by hand or with an automatic image processing program. The hand method is very tedious and time consuming. The scanner screens the image and converts it into an output consisting of x and y coordinates (the intersections of each row and column) and assigns a value corresponding to its shading on grey scale. This information triple is stored in memory and hence easily accessible for performing further digital evaluations. In the computer technique, special software is used to enhance the rock fragments and to detect the edges. The digitized points are connected to form closed shapes. Once the outlines of the individual rock fragments are defined, the sizes of the individual fragments may be determined. The sizes of the fragments are related to the minimum screen size through which they would pass. In the final step the fragmentation distribution is calculated.

Achieving better fragmentation can create huge cost savings; automated particle size analysis systems provide a continuous stream of data to allow operators to make informed process decisions based on quantifiable fragmentation results. Different fragmentation analyses system viz. Wipfrag, Split desktop and Fragylyst are available in the market which may be used for analysis. A view of the blasted muck pile of Noamundi Iron mine are presented in Fig. 5. An example of detailed fragment size analysis for the blast conducted at Noamundi Iron ore mine of Tata Steel with the help of WipFrag software is depicted in Fig. 6.

5.0 Case study at iron ore mines of India

Blasting is one of the important operations at Iron Ore mining as there is requirement for desired fragmentation. If there are many large blocks after blasting, that cannot meet the mine demand, they must be broken up by other means. This not only increases the cost, but also affects progress of the mine. In order to reduce costs and improve economic benefits, it is a challenging and hard problem to reduce boulder yield and raise utilization ratio of explosive. Currently, researchers have studied the influence of explosive type, charge structure, initiation method, delay time, burden and number of free surfaces on the blasting fragmentation effect (Ye, 1996; Yang and Jin 1999; Sun and Xu 2004). However, there are no research results about the influence of the initiation point position on blasting fragmentation. (Long et al, 2012). Total cost of aggregate production in a quarry has a minimum value at an optimum fragmentation size (Mackenzie, 1967; Morin and Ficarazzo, 2005). 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 particular blast and rock mass conditions, the contractor can adapt the blasting if possible (Engin, 2009).

The blast design parameters data collected from 36 blasts conducted at Noamundi, Joda East, Katamati and Khondbond to investigate its impact on rock fragmentation levels were analysed. The important parameters which decide the fragmentation level of particular blasts are burden to hole diameter ratio, spacing to burden ratio, stemming column length, stiffness ratio, explosives amount and its type, initiation mode and charge/powder factor. The bench heights of the mines varied between 6 m and 12 m. The burden and spacing were in the range of 2.5 to 4 m and 3 to 5 m respectively. The blasthole diameter were of 100, 150, 160 and 165 mm. The air deck techniques by using plastic air bags were used when decking is required as well as in soft strata of lower benches too. The explosives in a hole generally varied from 35 to 180 kg depending on the hole depth and type of strata. All the blast were initiated with NONEL initiation system keeping the down the hole timing of 250 ms. The delay between the holes in a row were17 or 25 ms whereas the delay between the rows varied between 42 ms to 130 ms depending on the strata and number of rows of the blasts. The near field blast vibration signatures were also recorded to diagnose the impact of delay timing on rock fragmentation. Impact of blast design parameters on fragmentation was analysed and are presented in figures 7-10.

Fig. 5. View of blasted muck pile due to blast conducted at 576 RL bench of Hill No.5.

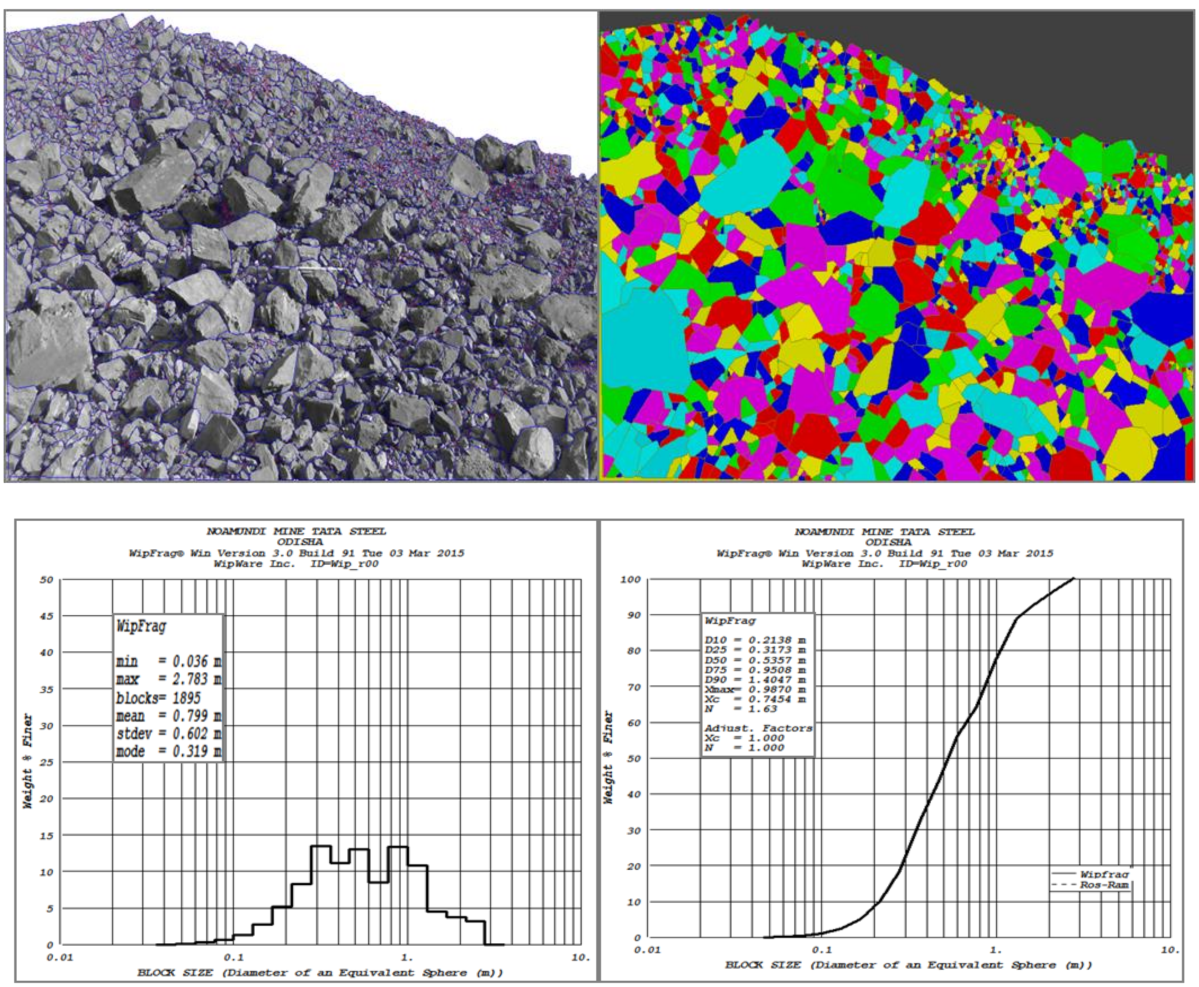

Fig. 6. Fragment size analysis at Noamundi Iron mine with the help of WipFrag software.

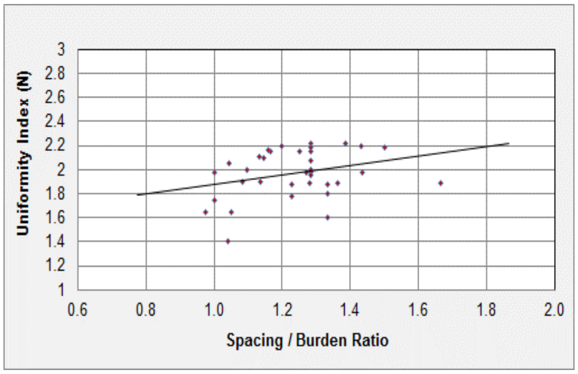

Fig. 7. Spacing to burden ratio vs. Uniformity index (N).

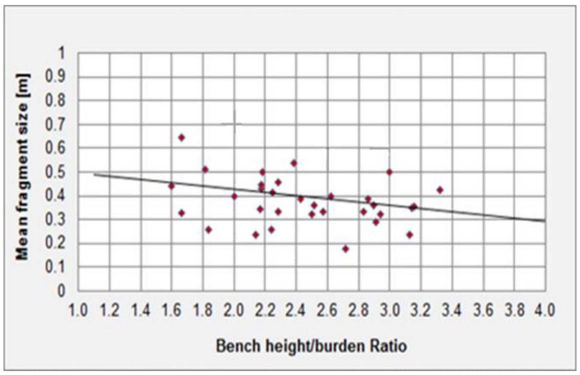

Fig. 8. Bench height to burden ratio vs. mean particle size.

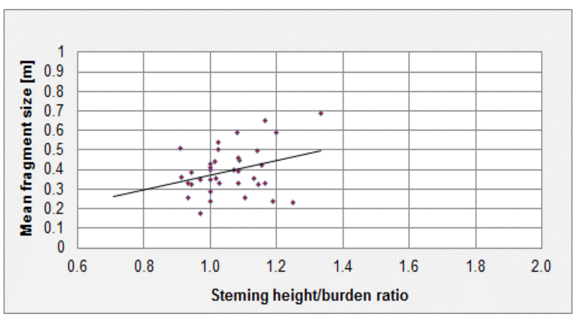

Fig. 9. Stemming length to burden ratio vs. mean fragment size.

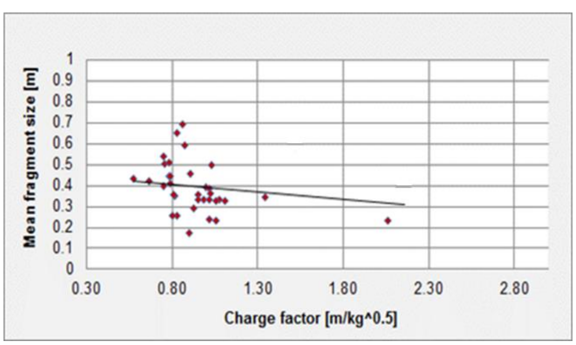

Figure 10. Charge factor vs. mean fragment size.

6.0 Conclusions

The technology available needs attention of the mine operators to collect huge amount of information that can be used to create detailed database. It is now possible to undertake a complete follow up of each loaded dumper truck and the load carried by conveyer belt by automated system. Monitoring of fragmentation level, evaluation of source rock type and its properties, and design parameters of the blast leading to fragmentation, carried out completely on line and virtually in real time is viable.

The scattering recorded in Nonel delay detonators is a matter of concern in getting desired blast results. In general the scattering percentage varied between 2 % to 37 % which has resulted into poor blast output.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 blasthole diameter was kept constant. Mean fragment size of the blasted muck decreases with the increase in the spacing to burden ratio. The optimum value of spacing to burden ratio ranged from 1.1 to 1.3 and resulted in excellent rock fragmentation. Uncontrollable parameters such as joints and fractures have significant influence on uniformity index (n). 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 resulted in increase of rock fragmentation level, i.e. decrease in the mean fragment size of the rock. The stiffness (bench height to burden ratio) vs. mean fragment size plot indicates decrease in mean fragment size with increasing stiffness.

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