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Blast performance analysis using digital image processing technique – key to unlock productivity in quarries

India's emergence as a major economic hub has ensured steady growth across the nation's mining industry. As a result of strong economic growth, the Indian mining industry increased at a compound annual growth rate (CAGR) of 25.8% during the 2008-13 period to a value of more than US$20bn in 2009. With relatively stable growth rates, resilient economic structure and future growth opportunities, India has always been an attractive destination for expansion of activities such as construction, infrastructure and power generation. These activities will always continue to drive the demand for investing on mineral industries. It is well known that a typical economic pie for a mining process indicates that drill and blast accounts for 20% while rest of the operations are seriously affected by it. Rock fragmentation by blasting is of critical economic importance to the mining industries worldwide. A blast can be designed to attempt the elimination of oversized particles or to minimize the amount of fine particles in the muckpile. To optimize the entire system, it is more prudent to attempt a blast design that provides optimum platform for rest of the operations. The authors discuss a case study of limestone and an aggregate stone quarry wherein the studies have been conducted on the blast performance in terms of degree of fragmentation using digital image processing technique.

***Keywords**: Blast design, fragmentation, geology, Fragalyst, productivity and ground vibration.*

1.0 Introduction

The sustainability of civilizations and of economies rested on access to mineral resources providing the key unlocking the economies of any nation. However, the economics of mining operation primarily depends upon the efficiency of rock breakage. In majority of quarries, the blasting operation plays a significant role for the rock breaking. It facilitates not only required fragmentation but also influences subsequent mining operation such as loading, hauling, and its subsequent crushing to the proper size requirement of the processing plant which ensures sustainability development. The term 'Sustainability' may be defined as the searching of sustained or enhanced environmental quality in the mining operations to achieve high economic growth along with fulfilling the social justice [1]. Therefore, proper blast design is always required to be ensured for controlling the environmental impacts due to the blasting such as fly rock, ground vibration, noise and air blast.

The exploitation of economic minerals from earth crust is increasing day by day at a faster pace since last decade to fulfil the increasing demand of minerals. It has led to the substantial increase in the consumption of explosive. Hence, the rock fragmentation has been considered as the most significant parameter of production blasting in surface mines as it affects productivity of the quarry and the costs of subsequent quarrying and processing operations [2].The term 'rock (or blast) fragmentation' is an index that is used to estimate the effect of bench blasting in the mining industry. Knowledge of the fragmentation mechanisms in explosively loaded rock is significant for developing successful methods for excavating rock rapidly for a variety of purposes, and has advanced considerably in the last twenty years. The generation of such oversized material during the blasting operation in any quarries needs greater attention and its formation is required to be identified technically for designing the blast parameters which needs to be accepted environmentally and economically [3]. Recent studies tend to support the view that stress waves generated by the detonation of an explosive charge are responsible for the development of a damage zone in the rock mass, and for the subsequent fragment size distribution, while the explosion gases are important in separating the crack pattern that is formed after the passage of the stress wave, and in throwing the fragments. However, the blasting designs in mines are still optimized over months or years by trial and error [4].

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Hence, a series of blasts were conducted in different location of quarries in dissimilar geological conditions and analysed the fragmentation using digital image processing tool before arriving the required blast optimization. This paper describes the results of a series of blasts conducted indicating the relationship between bench conditions and the fragmentation achieved and its effect on quarry productivity.

2.0 Effect of fragmentation on blast performance

Globally, the blasting is still considered to be the cheapest and most popular method of rock breakage in the quarries. Explosive energy, which is primarily a chemical energy, is available easily and cheaply for fragmenting the rock to assist any rock excavation. A number of studies and research works carried out in the past had clearly proven that the amount of chemical energy available during the blasting process is around one fourth of the total explosive energy in a scientifically designed blasting round [5]. The utilization of available explosive energy in blasting gets further reduced when the blast is not designed properly, convenient free face is not available or the holes are over/undercharged, with poor quality of explosives and initiating system. This wastage of energy is not only an area of concern but also contribute to serious environmental impacts such as blast induced ground vibrations, airblast, flyrock, noise, and blasting fumes [6]. Besides the aforesaid environmental issues, the disparity in explosive energy liberation, propagation and utilization leads to produce oversize materials (boulders), overbreak, excessive or no throw, uneven floor conditions, etc. Even though the explosive charges detonate properly in massive rock, fragmentation is a strong function of the effective strain wave energy. In a blasthole with sub-grade drilling, if initiation occurs at the floor level rather than at the blasthole bottom, 37% higher peak strain is achieved at the floor level [7]. Therefore, it is important that each blasthole should break and displace its designated volume of burden rock providing adequate relief for the next blasthole. Generally, the blastholes in the front row possess adequate free face to displace and however, the other blastholes in second and subsequent row need internal free faces during the blasting operation. To provide required relief, adequate delay interval should be provided between rows and holes depending on the type of rock being blasted and available burden distance, yields efficient fragmentation and results in environment-friendly blasting [8]. The fragmentation refers to post-blast size distribution of the broken rock mass and optimum fragmentation should result in reduction in overall cost of mining [9]. Therefore, the optimum fragmentation can be defined as “that blasting practice which gives the degree of fragmentation necessary to obtain the lowest unit cost of the combined operations of drilling, loading, hauling and crushing.” The assessment of fragmentation by blasting and by any of the subsequent crushing and grinding stages is important in order to control and optimize the mining operation. Fragmentation characteristics influence the mucking productivity, crusher throughput and energy consumption, plant efficiency, or the price itself of the end product in the case of industrial minerals and aggregates. An optimized blast design is one that will break or move rock to the required fragment size for secondary equipment to efficiently handle it. All this must be done while minimizing secondary components such as cost and environmental effects including ground vibration and airblast.

3.0 Measurement of fragmentation performance in blasting

3.1 Conventional approach

In recent times, predictions and analyses of blasted rock mass fragmentation have increased in importance, as primary fragmentation can significantly reduce the cost of crushing and secondary breaking, on condition that the correct geometry of drilling and blasting parameters are implemented. To obtain the most beneficial costs for the whole production process, the fragmentation must be optimal [10]. This means that the influence of the plant in the later stages of processing should be considered. Fortunately, more methods allowing prediction and estimation of the fragmentation are available today. If these methods are carefully and reasonably used, they can be very helpful to engineers in their attempting to obtain an optimum fragment distribution which will lower the total cost of the whole production process along with increasing the productivity. A list of known methods includes [11, 12, 13, 14]:

1. Visual observation
2. Sieve analysis
3. Image analysis on conveyor belts
4. Image analysis of manually captured images
5. Image analysis on haul truck beds
6. Image analysis on feed dumped into the crusher.
7. Image analysis of bench face images from the shovel.
8. Image analysis of bucket images from the shovel.

Each method of assessing blast fragmentation has its own advantages and disadvantages. However, it depends on the level of detail one needs to review, each method can be considered unique based on the source of where the fragmentation is measured. Hence, there has been no accepted measure of fragmentation [15]. Sieving/screening is a direct and accurate method of evaluation of size distribution of particles or fragmentation. However, for production blasting, this method is costly, time-consuming and inconvenient. Therefore, indirect methods, such as photographic methods have been in use for the analysis of blasts. With the advances in technology, digital images processing and analysis systems are becoming increasingly popular in fragmentation measurement due to their advantages over photographic methods [16].

3.2 Digital image analysis approach

There are many methods used to predict blast fragmentation, including empirical and numerical models, field trials, and experience from ongoing blasting. All of these methods require an accurate measurement or prediction of the rock mass properties such as characteristics of the rock fractures, including fracture density, friction angle, orientation, length, roughness, fill, etc [17]. It also includes the hardness of the intact rock, water content, and other parameters.

Even today, in several cases, the effect of blasting on the fragment size of the broken material is determined by eye only during the post-blast observations in spite of more knowledge available on rock fragmentation by blasting along with great advances of computer technologies [18]. However, it may bring an error of 150-200% while estimating the effectiveness of fragmentation through naked eye observation [19]. Fragalyst is an image analysis system developed by CMRI Regional Centre, Nagpur (India) and Wavelet Group of Pune (India). This system consists of capturing video photographs of the muckpile, downloading the photographs to the computer, or capturing the photos of muckpile from field by digital camera/ordinary camera then converting the images to grey scale, image enhancement, calibration and blob (grain) analysis [20]. The steps that are involved in the Fragalyst 4.0 is illustrated in Fig.1. The system will accept a digitized image of a pile of fragments and perform a computerized analysis of the image for obtaining vital shape and size related information of the visible fragments. The system will produce graphical results in the form of various distributions like the Rosin-Rammler curve and the normal distributions.

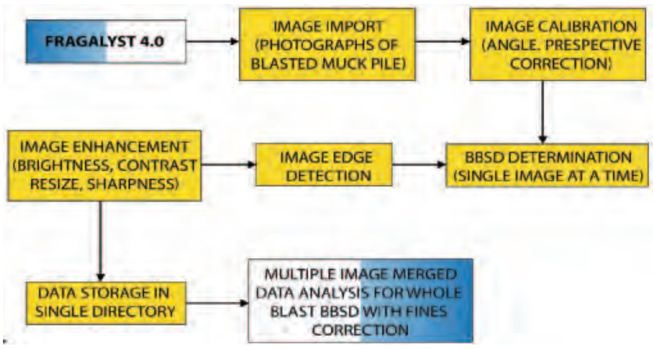


Fig.1. Different steps involved in analysing the image of a blast muckpile

With the aid of menu-driven software, it is possible to determine the area, size and shape of the fragments in a muckpile/grain aggregates on the basis of grey scale difference. The 2-D information available from software can further be processed for stereological analysis for 3-D information.

3.2.1 Digital image analysing technique – Fragalyst 4.0

In the present study, Fragalyst 4.0, a windows based digital image analysis technique software is used for blast fragmentation estimation and analysis (Fig.2). The technique includes loading of a minimum of ten digital images of blasted muckpile fragments taken after each blast will be loaded into the software system. The mean fragment size (K_{50}) and shape related information of visible fragments are obtained from the analysis. The photographs of the blasted muckpile are taken with a referencing scaling object, such as a ball of known diameter, and are compared to the standard photo to deduce the fragmentation in the blast [20].

Fig.2 Fragmentation analysis using Fragalyst image analysis software

4.0 Case studies

4.1 Case study - I: limestone quarry

A field study involving 14 experimental blasts were carried out in a limestone quarry located in the state of Andhra Pradesh using two different initiation systems comprising detonating cord and NONEL shock tube to study the fragmentation analysis in different geological settings. The extraction operation of limestone in the studied mine is carried out through different stages of extraction include drilling, blasting, loading and hauling. The blasted muck is excavated by 6.5 m^3 diesel operated hydraulic excavator loaded into trucks of 35 t capacity and is transported to the crusher unit located at the mouth of quarry. The crushed limestone ROM is transported via belt conveyor to the cement plant located at a distance of 3 km. In case of coarser material produced from the blasting, the rock breaker is used for secondary breakage.

Difficulties faced

A review of geology in the field revealed that the entire area comprises Archean formations completely covered by 3.0 to 4.0 m thick black cotton soil of recent origin. The limestone deposits are classified based on the colour of the deposit such as flaggy limestone, dark grey limestone and grey limestone. Similarly, the rock mass is generally composed of two parts of intact rock and discontinuities. The discontinuities include structures in rock mass such as joints, faults, fractures, bedding and other weakness surfaces that

Table I: Blast design parameters in the limestone quarry

Design parameters	Grey limestone bench			Flaggy limestone bench			Dark grey limestone bench
Ave. depth of the hole (m)	9	10	9	10	10	4	10
Blasthole dia				150 mm			
Burden (m)	4	4	4	4	4	4	3
Spacing (m)	8	8	8	8	8	6	4.5
S/B Ratio	2	2	2	2	2	1.5	1.5
Stemming, S_T (m)	2.5	2.5	2	2.5	2.5	2	3
Stiffness factor	2.25	2.5	2.25	2.5	2.5	1	3.3
Initiation pattern		Diagonal			Diagonal	V pattern	
Charge factor (kg/m³)	0.248	0.218	0.2321	0.243	0.238	0.226	0.232
Initiation system				NONEL			

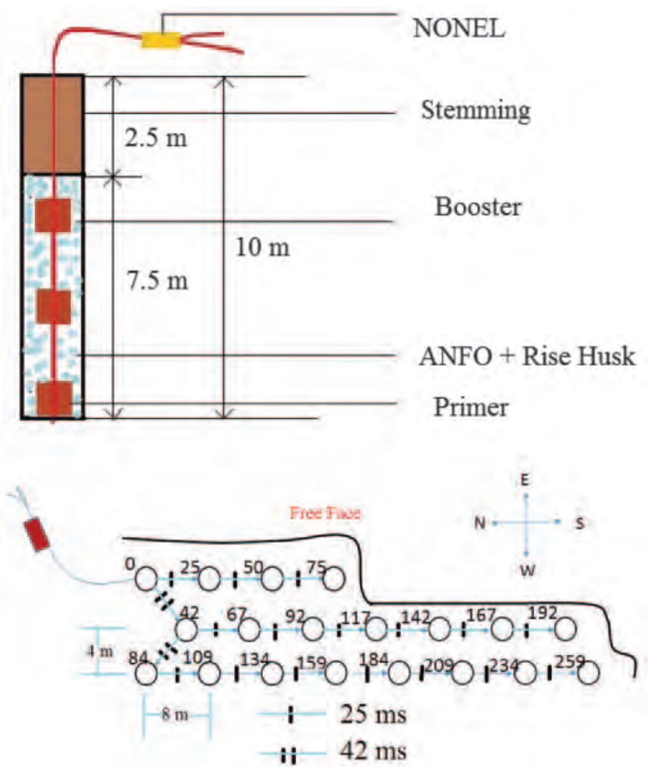


Fig.3 Charging and initiation pattern for a blast in the limestone quarry

significantly influence the engineering and mechanical properties of rock mass [21]. The above geological setting has resulted in producing coarser fragments and more fly rock which had impact on the performance of equipment and safety of men in the quarry.

Data collection and usage of digital image analysis technique

Based upon 14 blasts carried out at the limestone quarry without having any sub-drilling, a database was prepared as shown in Table I. In this database, burden (B), maximum instantaneous charge, powder factor, S/B ratio (S: spacing, B: burden), ST/B ratio (ST: stemming), stiffness factor, time delay, number of rows, blasthole inclination, blasthole deviation, blasthole diameter (D), blasting pattern and initiation sequence were measured as input parameters and muckpile fragmentation was calculated as a favourable parameter in each blasting round. The charging and initiation pattern of a blast is shown in Fig.3.

The image analysis technique was used to determine muckpile distribution and the relevant X_{80} for each blast.

In average, for each blast 20 to 30 photos were taken systematically from muckpile in different steps of loading immediately after blast and during loading, half of muckpile on the ground and at the end of muckpile loading [22]. The software was calibrated by comparing image analysis which produced the sieve results and summary details of blasts carried out in different formations in the limestone quarry are detailed in Table II. A sample work of the digital image analysis for a blast at limestone quarry and the corresponding muckpile distribution curve are shown in Fig. 4.

Results and discussion

The input parameters available in the database such as burden, maximum instantaneous charge, powder factor, spacing/burden ratio, stemming/burden ratio, stiffness factor, time delay, number of rows, blasthole inclination, blasthole deviation, blasthole diameter, burden/diameter ratio, sub-drilling/burden ratio, blasting pattern and initiation sequence were compared to muckpile fragmentation to measure the blast performance in terms of availability and utilisation of equipment, productivity, and energy utilisation in each blasting round.

Strategies

Based on the aforesaid results, the structural geology of rocks needs to be understood clearly and the rock types are required to be classified accordingly for the purpose of designing a blast with correct initiation sequence and proper delay time. It will also help in reducing the blast-induced ground vibration as the attenuation index and blasting

TABLE II: SUMMARY DETAILS OF BLAST PERFORMANCE IN THE LIMESTONE QUARRY

Design parameters	Grey limestone bench			Flaggy limestone bench			Dark grey limestone bench
Ave. depth of the hole (m)	9	10	9	10	10	4	10
Charge/delay (kg)	79.523	69.71	66.841	76.25	76.13	21.65	40.5
PPV (mm/s)	4.06	2.87	4.76	16.7	15.5	2.79	2.75
Mean fragment size (m)	0.26	0.39	0.47	0.51	0.50	0.17	0.33
Flyrock distance	<100 m	100-150 m	150-200 m	200-300 m	200-300 m	<100 m	< 70 m

Parameter	BBSD	IBSD
Slope	1.93	-
X_c	0.57	-
Energy utilized (KWh/t)	-	-
K25	0.29	-
K50	0.47	-
K60	0.54	-
K70	0.62	-
K80	0.71	-
K90	0.85	-
K95	0.94	-
K98	1.14	-

Fig.4 Digital image analysis for measuring the fragmentation in the limestone quarry

vibration constant distributes variously based on the geology.

4.2 CASE STUDY - II: AGGREGATE QUARRY

In order to study the effect of initiation system and pattern in the rock fragmentation and ground vibration, a series of experimental blasts were conducted in an aggregate quarry located in south part of Tamil Nadu.. The nearest residential area is located at a distance of about 1.7 km for the monitoring site. The geology of the study region basically comprises the charnockite and the dolerite. Charnockite is massive and forms principle rock of the region which is the older rock formation and possesses distinct joint patterns. Dolerite is basically intrusive in nature in the region as magmatic intrusions, younger to charnockite. However, the strength of dolerite is more than charnockite.

Difficulties faced

In this quarry, the term oversize boulder has been characterized as any material produced from primary blasting, which cannot be adequately handled by the hydraulic excavator of 1.1 m^3 and crushing equipment of having opening in the range of 30 to 40 cm used in this case. Hence, the material broken and produced from the primary blasting having a size of larger than 1m^3 has been called for secondary breakage with the help of rock breakers. Similarly, the excavator performance and fuel consumption are other two major issues prevailed here.

Data collection and usage of digital image analysis technique

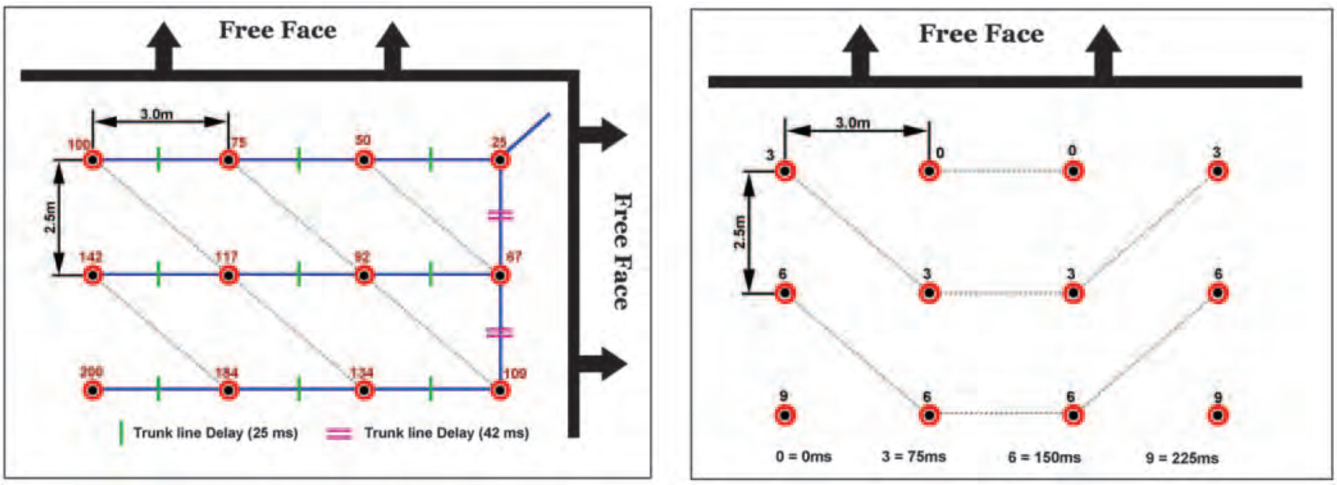
In the present study, total of eight experimental blasts were carried out. In these blasts, two were designed with echelon pattern, three were designed with open chevron and the remaining three were designed with closed chevron pattern initiation sequences as given in Fig.5. The blasts are conducted using detonating fuse and NONEL shock tube different initiation systems in the benches of 7-8 m in height. The blasted muck is excavated by 1.1 m^3 diesel operated hydraulic excavator loaded into trucks. The delay interval of 25 milliseconds to 75 ms with an increment of 25 ms is provided in the blasts using the detonating fuse initiation system. For the blasts with NONEL shock tube, the delay interval range of 25 ms to 67 ms is provided with gradual delay increment in the blasts. The summary of blasts carried out in the aggregate quarry is detailed in Table III.

Results and discussion

It was observed that the better fragmentation is achieved with increase in delay interval between the rows while using both detonating fuse and NONEL initiation system. It is mainly due to the existence of adequate relief available for the next rows of blast. The open chevron (diagonal) initiation pattern produces significantly coarser fragmentation than the both V1 (echelon) and V2 (closed chevron) initiation patterns, due to non-existence of in-flight collisions during the displacement. The detonating fuse initiation system also

TABLE III: SUMMARY OF BLAST PERFORMANCE IN THE AGGREGATE QUARRY

Blast no.	1	2	3	4	5	6	7	8
Initiation system	DF	NONEL	DF	NONEL	DF	NONEL	NONEL	NONEL
Initiation pattern	Echelon (V1)	Open Chevron	Echelon (V1)	Open Chevron		Closed Chevron (V2)		
Delay between rows (ms)	25	25 / 42*	50	25	75	25	42	67
Depth of the hole (m)	8	8	7	8	7	7	8	8
Maximum charge per delay (kg)	113.36	15.34	93.36	46.02	93.36	61.36	61.36	61.36
Boulders (oversize material) (%)	17.29	39.75	23.9	26.48	14.3	19.57	17.16	22.52
Oversize boulders (t)	343.68	677.68	52.28	440.80	210	310	315.65	407.26
Secondary breaking hours (hr)	2.8	5	4.1	6.3	3.2	6.2	3.7	7.2
Effective fuel consumption (t/lit)	7.25	6.53	7.08	6.69	6.76	7.30	7.10	6.72
Vibration (PPV) (mm/s)	21.10	19.51	19.37	33.05	19.82	11.31	15.33	21.16
Mean fragment size (m)	0.16	0.18	0.40	0.31	0.22	0.21	0.14	0.27



(a) Chevron (diagonal)

(b) Closed Chevron

Fig.5 Schematic representation of the Initiation patterns used in the blasts carried out in the aggregate stone quarry

produces considerably coarser fragmentation resulting in less effective fuel consumption of excavator (t/lit) when it was compared to NONEL initiation system. In the case of NONEL initiation system, the V2 (closed chevron) initiation pattern produces appreciably less ground vibrations than the open chevron initiation pattern. The change of initiation starting point with respect to the availability of free face possesses significant effect on rock fragmentation and blast-induced ground vibrations. Hence, the availability of free face shall be critically examined for improvising the fragmentation and also to reduce the ground vibrations.

5.0 Conclusion

Effective fragmentation of the blasted rock mass with reduced ground vibration is a desirable phenomenon both for the quarry operators and the society in the aggregate and limestone quarries as it improves the productivity and also reduces the adverse environmental effects. This could be eventually achieved by practicing optimized blast designs controlling the fragmentation and the ground vibration. Blast sequence, delay timings, blasting pattern and availability of free face were the important parameters that determine an optimum blasting in terms of effective fragmentation and reduced ground vibration. Fragmentation in consequences will reflect in the performance of excavators, in particular, the productivity which reflects the economics of small scale quarries. In the present case studies, the significance of blast design parameters such as initiation sequence, delay timings, the initiation pattern, availability of free face on the ground vibration and fragmentation with excavator performance has been exhibited. The results of the above studies have also shown that optimum fragmentation with reduced ground vibration from the blasting could be achieved with applying an appropriate knowledge of the design parameters. However, the modern techniques such as digital image analysis technique will always provide an opportunity to calibre the quality of blast performance in terms of fragmentation which plays a significant role in controlling the downstream operations of any quarry thus provides an opportunity to enhance the productivity.

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