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Geological challenges in limestone quarrying and strategies to improve fragmentation in blasting

Globally, the surface mining is considered to be primay mining operation for achieving sustained mineral production, which has shown augmented production with significant deployment of large capacity. These equipment require higher investment, and thus, mining engineers should plan to attain the best performance from these equipment. The capability of the loading and hauling equipment largely entrusted on the outome of the blast, particularly, the fragmentation and spreading of rockpile. Generally, the mine owners ignore geological descriptions and features apart from the nature of rock and began quickly quantifying the rockmass properties only whether it is hard or soft based on its geomechanical properties. From the geological studies, it is understood that the response of deep weathering of any deep-seated massive rock resulting in producing thick boulders. These embedded boulders possess the characteristics completely different that of surrounding rockmass and any other soil present in the vicinity. The blast fragment size generally dictates the output of equipment working in such formation and affects the productivity of the mine. Thus, an effective blasting is need of the hour in such formations that affects the cost of entire mining activities. Therefore, it is important to study the effect of blasting parameters on fragmentation of such embedded boulders through existing field practices and also using the advanced blasting technologies. This paper concerned with the fragmentation of embedded boulders/floaters under difficult geological conditions. Geology plays a critical role in every aspects of a blast's performance and it is the chief uncontrollable factor to be considered for any blast design. The authors discuss the difficulties in identifying the embedded boulders by understanding the geological features properly and discussed the possible solutions to enhance its breakage during the blasting through conducting few experimental blasts in a limestone quarry.

Keywords: Geology, mining, embedded boulder; blast design and fragmentation.

1.0 Introduction

Mining was an important activity in the ancient times and it is valuable operation today and also for the future survival of mankind. In any country, the economics shall be sustained only when adequate natural resources are available as it will provide platform for industrial development, employment generation and community development. India possess 87 minerals comprising 4 fuel-related minerals, 10 metallic minerals, 47 non-metallic minerals, 3 atomic minerals and 23 minor minerals (Roy and Singh, 2016). Besides power and cement industries, increased infrasturucture development and automative production are responsible for rapid growth of the mining sector currently in India.The domestic mining sector currently contributes about 10% -11% to the industrial sector and about 2.2% - 2.5% to the economy's GDP (Anon, 2018). Here, it has been observed that every 1% upsurge in growth of mining sector yields 1.2% to 1.4% improvement in the industrial sector growth which concurrently enhance the country's GDP to 0.3%. Apart from providing direct contribution to the government earnings and significant addition to export revenues, it also provides direct employment to over 2.5 million people. India is enriched with sizable reserves of vital metallic and non-metallic minerals including iron ore, bauxite, coal, limestone and manganese. India is among the top 10 producers for these ores globally. It has been observed that the mining industry has contributed substantially as the backbone for infrastructure development of nation and also for the economic development of inaccessible regions in the country (Chakraborty et al., 2004).

It has brought the advancement of civilization which means significant requirement of different minerals to meet the economic demands. Hence, it has paved a way for opening up and expansion of open pit mines setting with higher production targets. Even though the basic objective is to raise the fiscal benefit produced by the mine but a rapid growth in mechanization can be made by efficient and effective mining operations (Sastry and Chandar, 2012). To ensure the

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augmented production in the mines, the deployment of higher capacity and modern equipment, adoption of advanced rock blasting technology, innovative processing, and increased application of information and computational technologies are becoming inevitable. However, the outcome of blast performance such as fragment size, its spreading and muck profile characteristics measures the success of these equipment, particularly the loading and hauling equipment (Yan et al., 2015; Alok Vardhan et al, 2017).

In the weathered formations of limestone quarries, the disposition of deep-seated boulders in the surface benches is common in nature. This deep-seated boulder is commonly known as 'embedded boulders', which are basically a ball-shaped product on a fractured rock that normally cores rounded form, separated by regions of highly weathered rock (Bhatawdekar et al, 2019). The formation of such boulder is also normally related to the exfoliation process in which the rock separates from the unrefined earth. Here, the rupturing activities on the substratum gradually divide the bedrock into smaller blocks and hence resulting in the spheroidal weathering to become finally into the rounded ones. Such embedded boulders are generally thrown out in the muckpile without any breakage in the course of blasting action (Zheng et al., 2018; Bhandari, 1997). It creates an environment of accomplishing secondary breakage of such boulders by blasting or using rock breakers (Jimeno et al, 1997). But, the identification of such in-situ boulders in the geological set up is quite challenging one and the reliability of such identification techniques is considerably low. Therefore, such ample size fragments require secondary breakage as the production of overfines can result from improper blast design and inadverse geological conditions (Hustrulid, 1999; Singh et al, 2019). Unfortunately, the knowledge of acquiring relevant geological principles to apply it during the blast design process is not a regular feature. Hence, the authors felt that a case study of limestone mine where the embedded boulders covered with soft soil require the modifications in existing blast design, such as usage of proper explosive energy and placement of explosive column to produce an effective breakage at the time of blasting.

2.0 Embedded boulders

2.1. Mode of Occurrence

Boulder may be described as a capstone that formed through the reaction of spheroidal weathering on disintegrated bedrock which are surrounded by concentric rindlet layers and saprolite (Rishikesh et al, 2019; Fletcher et al., 2006). It is also termed as spherical or rounded shape, possessing different size and formed anywhere in the geologic medium (Veneziano and Van Dyck, 2006). Boulder is also defined as a large rounded mass of rock possessing a size of greater than 0.3 m which generally lies on the surface of the ground or embedded in the sediment and soil (Felletti and Beretta, 2009). The shape of the boulder varies from spherical to ellipsoidal and some of them can be found nearly perfect spheres while others are almost cubic with rounded edges (Twidale, 1982). The various shapes of boulder are formed due to the spheroidal weathering reaction on fractured rock. This spheroidal process gradually minimizes the volume of the boulder and when it becomes rounded, the rate of weathering will be slower (Jamtveit and Hammer, 2011). These boulders are commonly surrounded by three to six concentric sheets or layers. There are various names for the concentric layers of such boulders, termed as onion-skin layers, shells or spherical shell, or rindlets. Some geological and petrographical parameters can be assessed qualitatively, like the degree of interlocking in the rock microfabric or the quality of binder minerals (eg. in sandstone), but only very rarely in categories like the weathering or alteration stages in rock mass (IAEG, 1981; ISRM, 1978).

In this case study, nature of the rock formations undergo typical weathering process whereby it changes the fresh rock to be completely. This weathering can even occur at a depth of up to 50 m and however it is limited to 10 to 20 m only in case of metamorphic rocks. Besides, the high intensity of rainfall in this tropical region will rapidly increase weathering action on the certain rockmass as the infiltration of rainfall deep into bedrock under soil stratum gradually transform intact bedrock to be chemically weathered rock. This concept of deep weathering on fractured rock formation creates some concentric fractures on the bedrock and then progressively altering the rock turn to become oblong in shape or rounded known as boulder.

2.2. Identification of Embedded Boulders in the Quarries

In general, the following practices are adopted in any mines or quarries to recognize the locality and features of such embedded boulders in the in situ conditions. However, every method possesses its own merits and demerits. Based on the site conditions and requirements of the study, suitable methodology can be implemented to find out the position of such boulders.

- The normal method of identification of such buried boulders is through the preparation of structural mapping (Fig.1) and however it has been found unrealsitic in practical situations as it depends heavily on the expertise of the geologists who prepares the mapping. In this regard, Ground penetrating radar (GPR) has been established as a valuable tool to accurately spot out the underground storage tank (UST) or any other utilities such as buried drums etc (Richard and Lynn, 2016). It may be also used to expose any objects below reinforced concrete floors and even it was used as an archaeological tool to search any buried historical objects. During the process of detection, these boulders and debris produce reflections which are similar to pipes and tanks. Any remarkable changes in the electrical properties along the traverse is indicated by changes in the charactersitics of

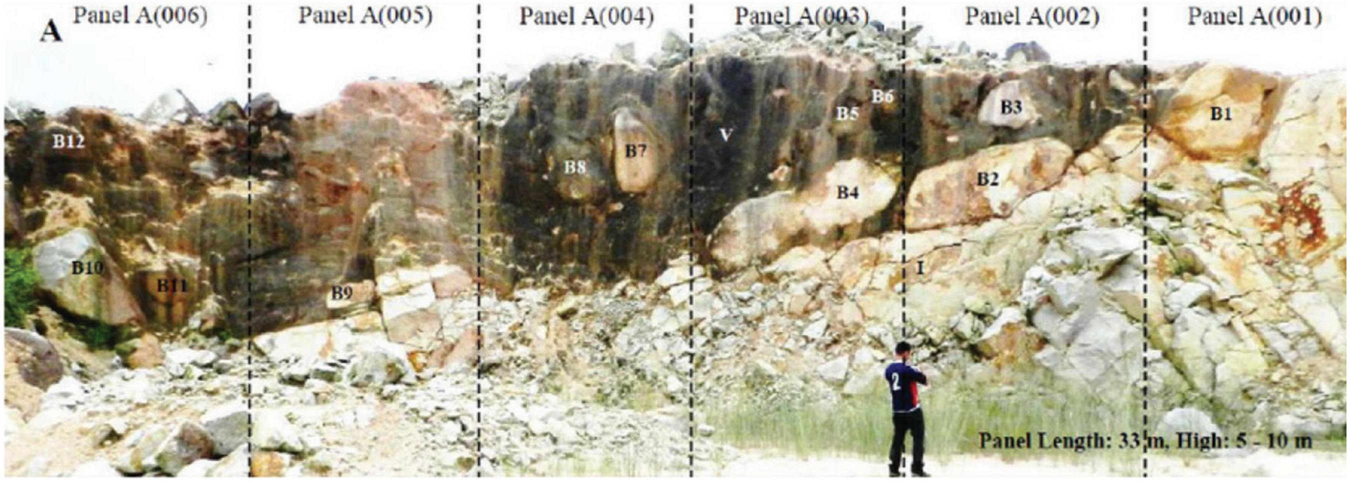

Fig.1: Geological mapping for 'floaters' in limestone benches

soil as it produced "noise" which can make interpretation difficult.

- DC resistivity and electrical resistivity tomography (ERT) are basically the surface geophysical methods through which an electrical current is passed into the ground and there will be two electrodes on the surface are used to measure and reveal the direction and amount of current flow in the subsurface (Richard and Lynn, 2016). Based on the resistivity we identify the material in the subsurface by comparing with the standard chart given by the geologist and we can able to map the subsurface and identify the deposit of the subsurface.

Besides the above, the detection of embedded boulders can be achieved through the drillhole logging during the exploratory drilling operations. Because the drillhole logs give the variety of minerals present in the ground and also we can able to learn the subsurface for various depths (Karthikeyan et al., 2014). Further, the spotting of boulder is identified from the analysis of drill chips produced during production drilling operations. However it requires experience and skill from the drilling equipment operator and sample crew.

2.3. Impact of Embedded Boulders in Blasting Operation

The production of embedded boulders from the blasting always causes difficulty in operating the loading equipment efficiently and also causes the blockage of the crusher if it is valuable mineral. During the normal course of a blast, the boulders are generally produced due to presence of hard and massive rock in the uncharged part of the blasthole (stemming area), bedding plane slabs from within the blast, hard rock at or near intrusive dykes and rock isolated from influence of explosive energy causing excessive back break (Jemino et al., 1995). However, if the embedded unfissured boulders or floaters are detected, then the strain waves produced from the explosion propagate with little attenuation in the floaters, but their energy is rapidly dissipated in the matrix (Balamadeswaran et al, 2018). Because, the embedded boulders which do not contain even part of explosive charge receive very little strain wave energy and hence it is usually heaved out as 'intact' into the blasted muckpile (Fig.2).

These embedded boulders known as 'floaters' which is basically unfissured oversize rubbles of strong rock enclosed with much softer or weaker matrix (Hembram et al, 2017; Hagan and Reid, 1983). The characteristics of the embedded boulders are different from the normal boulders and also with the surrounding rock mass. Generally, these boulders are not fragmented during the blasting and popped out of the soil or any other matrix causing the boulders to occur (Fig.3).

On the other hand, the normal boulders are emanated from the blasting operation due to presence of joints or discontinuities, improper blast design, ineffective explosive energy and poor blasting practices.

3. Case study

3.1. Site Description

The study area is having a limestone quarry with the mining lease area of 65.15 ha, situated in the state of Tamil Nadu in India (Fig. 4). The total strike length of 2.35 km is divided into cluster of small pits for operational flexibility starting from ML-C, ML-B, ML-A, and ML-0 to ML-42. The length and depth of each pit varies from 45-50m and 25m to 40m respectively from the surrounding ground level.

The metamorphic rock is hosting limestone which possesses the density of 2.56 g/cc. The mine is worked in benches as the top soil cover comprising black cotton soil alone is excavated (without blasting) by the diesel operated hydraulic excavators of 3.6 cum utilizing the haul trucks of 38t capacity. However, the subsequent benches comprising limestone strata has been excavated by adopting the conventional mode of breakage, i.e, the blasting operations.

3.2. Geology of the study area

The massive calcarious continuous bands granulites form

Fig.2: Presence of 'floaters' in the soft rock matrix

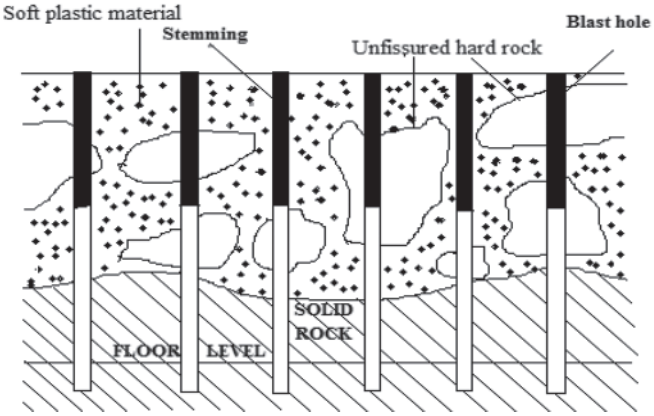

Fig.3: Presence of embedded boulders in the soft rock matrix

thick and laterally interbanded with crystalline limestones and garnet-biotite-sillimanite graphite gneisses. The noteworthy features include an intense fracturing (Fig.5) and fine-grained nature. In some parts of the mine it was also observed that the calc granulites veined by pegmatites both across and along the foliation.

The earlier studies (Nageswara Rao and Srinivasan, 1980) also shows that the geology of the Palaghat area belongs chiefly to the formations of Precambrian metamorphic complex with the sedimentaries forming a narrow belt along the coastal plains. The existing gap in the formation composed mainly of migmatitic gneisses and associated granites which is attached to the northern side by khondalite, calc granulites and crystalline limestones. From the borehole logging carried out after exploratory drilling, the variety of minerals/composition of different minerals found and corresponding bench face are shown in Fig.6(a) and 6(b). Each rock requires a unique blast design based on the rock characteristics in order to maximise the fragmentation and reduce the environmental impacts of blasting such as ground vibration, flyrock, etc (Sasaoka et al, 2011; Balamadeswaran and Mishra, 2020).

3.3. QUARRYING OPERATIONS

The quarrying operations in the studied mines is accomplished by conventional means of open pit mining involving blasting operations. The drilling operation is achieved through hydraulic DTH rotary-percussive machinery for producing 115 mm diameter blastholes. Both the detonating fuse and non-electric shock tube (nonel) system are used for the initiation purposes during the blasting operation. The blasted muck is excavated by 3.6 cum diesel operated hydraulic excavator loaded into dump trucks of 38 tonne capacity and is transported to the crusher or waste dump located at the surface of the quarry leasehold area. In

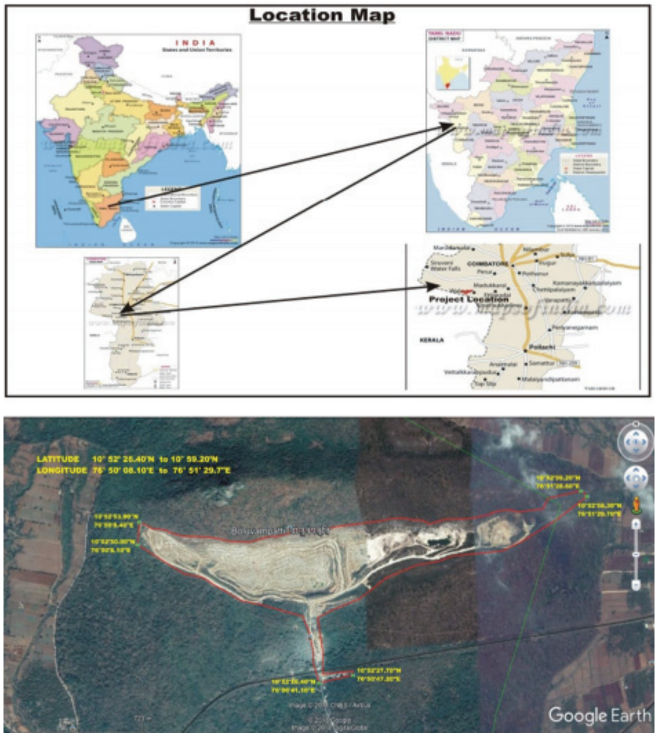

Fig.4: Location of mine area (Source: Google Earth)

case of coarser material produced from the blasting, the rock breaker is used for secondary breakage.

Fig.5: Intense fracturing in calc granulites

3.4. FRAGMENTATION ASSESSMENT

In order to determine the effect of fragmentation of embedded boulders, total number of eleven trial blasts are executed incorporating different design parameters in the identical formation adopting the similar initiation patterns, namely, echelon pattern and open chevron. During the blasting, NONEL shock tube initiating system was used in all the blasts for ensuring effective initiation and achieving better breakage. To quantify the fragmentation characeristics of the blasted muckpile, an image analysis software - 'Fragalyst 4.0' was used for all the blasts carried out in the different rock types and characterizing the rocks and optimizing blast (Balamadeswaran et al., 2017). To avoid or to minimize the effect of the issues while taking photographs, certain basic precautions to be taken into consideration while photography to get reliable results in image analysis are followed (Franklin et al., 1996; Raina et al., 2012; Keneti and Sainsbury, 2018).

Fig.6: (a) Bench face

(b) Drillhole logging

3.5. EXPERIMENTAL BLASTS

In the study area, a series of eleven number of experimental blasts were carried out in the aforesaid

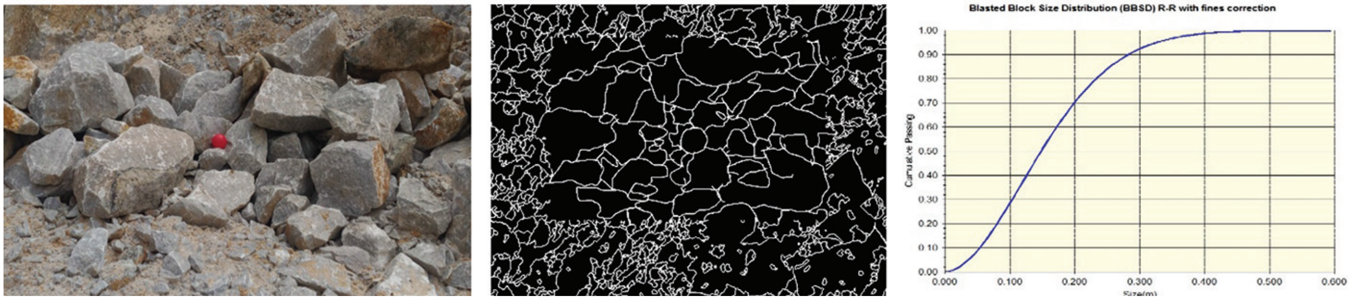

Fig.7: Improved fragmentation of muckpile using V initiation system blast design

Fig.8: (a) Presence of embedded boulders in the face

(b) Ineffective fragmentation of boulders in the face quarry to assess the fragmentation size distribution in the top benches where the occurrence of embedded boulder formation is very common. No decking has been included in the blast design adopted in the blasting. About 40-50 images of broken muckpile per blast were photographed in proper light and after 30-45 min to include the swelling factor as well. Using the Fragalyst software, the fragementation characersitics of the muckpiles is then obtained. The blast design parameters of the trial blast are given in Table 1. The digital image analysis software provides the graphical output both in Rosin-Rammler curve and the normal distributions (Fig.7). The photographs of the blasted muck pile are taken with a referencing scaling object, such as a ball of known diameter, and are compared with the standard photo to deduce the fragmentation in the blast (Raina et al., 2002).

4.0 Results and discussions

i. Due to existence of difficulties for identifying embedded boulders and also to perform drilling in such areas, it was observed that better fragmentation was obtained using V-initiation pattern of firing as compared to diagonal line of firing or row-by-row line of firing in the same rock environment.

ii. It was found that the fragmentation level has not improved by just raising the explosive quantity alone. The existence of embedded boulders in the soft rock matrix (Fig.8) will always provide path through soil for allowing the explosive energy to escape and hence it results in poor usage of explosive energy for fragmenting the rock.

iii. It was noted that the fragmentation level is having a linear increase with the stiffness ratio and nevertheless the fragmentation was found to be optimum in the last three number of blasts conducted in the quarry. The theory suggests that the stiffness ratio of 3 to 4 always produces the excellent fragmentation (Scott and Onederra, 2015). Even after maintaining the stiffness ratio of 3.66 in the aforesaid blasts, the oversize fragments were produced {Fig.8(a) and (b)} due to nonavailaility of explosive energy in the boulders nested in the soft matrix.

iv. The stemming length was not maintained as per the required design and less stemming length will always increase the probability of the existence of explosive energy without proper utilisation. Besides, the type of stemming material will also assist the fragmentation level as an effective stemming will confine the explosive energy properly. But the fine powdered drill cuttings used for stemming which possess the capability of ejecting explosive energy through stemming column results in very poor fragmentation and also produces flyrock considerably (Mishra et al., 2003).

v. During the blasting, it was seen that the row-by-row or diagonal line of firing produced the fly rock to a distance of more than 200 m due to presence of clay cover over the embedded boulders. However, it was seen that the fly

TABLE 1: BLAST DESIGN AND PERFORMANCE PARAMETERS OF THE TRIAL BLASTS

Parameters	Blast 1	Blast 2	Blast 3	Blast 4	Blast 5	Blast 6	Blast 7	Blast 8	Blast 9	Blast 10	Blast 11
No. of holes	13	9	19	13	11	11	21	21	15	15	12
Depth of the hole (m)	3.5	4.5	9	9	9	9	11	11	11	12	12
Spacing and burden (m)	3 & 2.5	3 & 2.5	3 & 2.5	3 & 2.5	3 & 2.5	3 & 2.5	3 & 2.5	3 & 2.5	3 & 2.5	3.2 & 2.7	3.2 & 2.7
Drilling pattern	Staggered		Square	Staggered							
Stemming length (m)	0.8	1.0	2.0	2.0	2.0	2.2	2.8	2.8	2.5	3	3
Column charge	ANFO	Slurry	ANFO	ANFO	ANFO	ANFO	ANFO	ANFO	ANFO	ANFO	ANFO
Primer charge	Slurry	Slurry	Slurry	Slurry	Slurry	Slurry	Slurry	Slurry	Slurry	Slurry	Slurry
% of primer	22.30	16.60	41.70	41.70	41.70	38.15	11	25	32	25	22.50
Max. charge/delay (kg)	25.76	16.86	60	60	60	58	58	58	60	73	76
Initiation system	NONEL	NONEL	NONEL	NONEL	NONEL	NONEL	NONEL	NONEL	NONEL	NONEL	NONEL
Volume of material (m^3)	341.25	303.75	1282.50	877.50	742.50	742.50	1732.50	1732.50	1237.50	1555.20	1244.16
Charge factor (kg/m^3)	0.98	0.50	0.89	0.89	0.89	0.90	0.74	0.74	0.73	0.63	0.78
Spacing/burden ratio	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.18	1.18
Blast hole dia/BH ratio	32.85	25.55	12.77	12.77	12.77	12.77	10.45	10.45	10.45	9.58	9.58
Stiffness ratio	1.4	1.8	3.6	3.6	3.6	3.6	4.4	4.4	4.4	4.4	4.4
Initiation pattern	V-Pattern	Diagonal	Row-by-row	Row-by-row	Row-by-row	Row-by-row	Row-by-row	Row-by-row	Row-by-row	V-pattern	Row-by-row
Mean fragment size (m)	0.27	0.59	0.46	0.90	0.90	0.78	0.89	0.75	0.84	0.36	0.61

rock distance has been reduced to less than 200 m in case of 'V' line of firing.

5. Conclusions

Presently, the blast monitoring process is begun with initial site supervision by the mine geology team with inputs received from the drilling and blasting crew and later it has been incorporated in the MOS prepared exclusively for the mine site. The management operating system (MOS) is a system of controls, communication, and activities that have been implemented to accomplish the managerial objectives quickly and efficiently. For ensuring an optimum rock fragmentation, it is imperative that exhaustive geological studies are carried out systematically to identify the existence of weakness planes, discontinuities, voids and fractures, etc before designing the blast. An optimum fragmentation achieves maximum efficiency with reducing the cost of production. Therefore, an optimum fragmentation means that the blasted muckpile does not require further treatment. Considerable amount of research has already been carried out on the many aspects of the fragmentation with the sole objective of improving the same (Monjezi et al., 2014). However, the blasting operation in the benches comprising embedded boulders covered with soft soil is a different cup of tea and the following points shall be considered for improving the fragmentation when accomplishing the blasting operations in such formations:

i. The bench face shall be geologically evaluated by using appropriate technique considering site-specific conditions to reveal the position and qualities of embedded boulders for deciding the effective drill patterns, explosive characteristics and its quantity, initiation pattern and sequence. A clear knowledge on geology and its consequence on blast performance will always help to improve the quality of blasting operation.

ii. Before commencement of the drilling operations and subsequently while charging with explosives for any given conditions, an effective communication with the mine geologist shall be established.

iii. The description of boulders encapsulated with a soft rock matrix is always challenging and the reliability of any techniques used for the identifying the boulders is also low. Hence, it is recommended that the blastholes can be drilled in a staggered pattern which can be charged with the explosives possessing higher shock energy and finally initiated with 'V' patterns keeping adequate delay interval.

iv. In the case of non-availability of any tools for identifying the embedded boulders, the 'stab' holes can be drilled with shorter length using smaller diameter in between the regular designed holes. Further, the stemming length may be appropriately reduced as well as keeping low energy explosive column charge in the top portion of the hole such that it will not produce any fly rock through stemming ejection.

v. Finally, with an objective of enhancing the breakage, drillers are properly educated to preserve the records which indicate at what depth the drill bit enters and leaves each boulder encountered. Such practices will always provide an opportunity to optimize the locations of charges, placement of decking and stemming materials.

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