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A comparative investigation of inter-row delay timing *vis-à-vis* some rock properties on high sandstone benches

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The inter-row delay timing plays a pivotal role in any blast round as it not only influences the mechanism of fragmentation, but also offers a vast potential in improving the overall results of fragmentation. It is in this perspective that the current study presents a comparative investigation of the influence of inter-row delay timing on fragmentation in two different strength sandstone formation in large-scale, multi-row blast rounds of a two surface coal mines in India. The investigations are based on full-scale field blasts. The study highlights the role of p-wave velocity and brittleness vis-à-vis impedance to shock wave propagation during the initial as well as final stages of rock breakage. Given this, the role of shattering effect (in stronger sandstone formations) and heaving effect in weaker strength sandstone has been clearly established in the rock breakage mechanism. Furthermore, the study also suggests that for weaker sandstone, longer inter-row delay timing (15-25 ms/m of effective burden) yields the best fragment size results. Similarly, for stronger sandstone formation, shorter inter-row delay timing (10-17.85 ms/m of effective burden) yields the best fragment size results.

Keywords: Inter-row delay timing, Rock strength, P-wave velocity, Brittleness, Shattering, Progressive relief, Inter-rock collision

1 Introduction

The selection of proper delay timing is as important parameter for fragmentation as the burden, spacing, sub-drilling, stemming etc. Besides affecting the fragmentation, it also exerts an almost inexpensive control on the cost of blasting program and a myriad of related problems, such as ground vibrations, fly-rocks, air blasts, over-break etc. Proper timing exerts a control on the number of rows and thus on the number of holes to be blasted in a pattern. Furthermore, any change in spacing and/or burden must be accompanied by changes in delay timing[1].

Selection of suitable inter-row delay timing is absolutely imperative for systematic release of energy and progressive burden relief from one row to another while maintaining a continuous momentum for inter-row displacements. In the instances of shorter inter-row delay interval, the burden from front row remains in place while the charges from subsequent row are also fired resulting in improper relief and excessive confinement to the subsequent rows. This, in consequence, causes upward cratering that result in poor fragmentation with little displacement, high and tight muckpiles close to the face (Fig. 1a). Additionally, excessive confinement, especially along the back rows of large-scale blasts becomes the genesis of plethora of problems like, occurrence of oversize, over-breaks, improper wall control etc.[2].

On the other hand, in the event of excessive inter-row delay timing, the material of the previous row fails to act as a screen and confine the remainder of the blast. As such, unwarranted throw/spreading of the blasted material may be witnessed (Fig. 1b). Field trials revealed that ideally the rock should be moved by one-third dimension of burden distance before firing of the next row[3]. Hence, it is consequential to understand the vast importance of inter-row delay timing and its impact on fragmentation and muck pile displacement in any blasting operation. At this point it may be worthwhile to mention that researchers have stated that inter-row delay interval is a function of nature of rock. The inter-row delay timing may be almost doubled for weak, highly fissured rocks in comparison to stronger and massive rocks[4]. Also, Quantification of inter-row delay timing on the basis of specific nature of rock has been recommended for individual cases in the field-scale blasts [5].

2 Study Objectives

In light of the foregoing discussion on inter-row delay timing and its dependence on the nature of rock,

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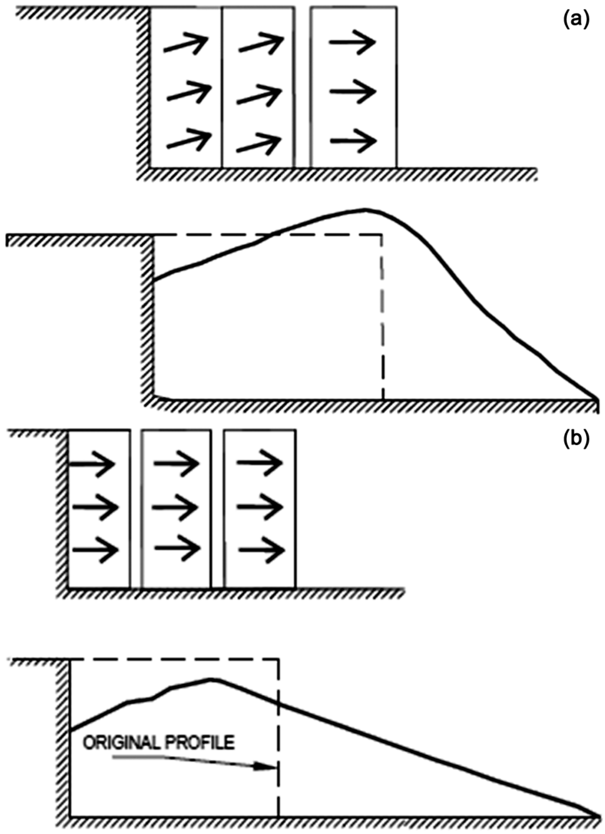

Fig. 1 — Cratering due to delays (a) Vertical cratering due to shorter delays and (b) Excessive lateral scattering due to longer delays.

the present study was conducted in two major surface mines, named henceforth as mine "A" & mines "B" of Ramagundam area, Singareni Collieries Company Ltd. (SCCL) to investigate the following:

a. Inter-row delay timing *vis-à-vis* fragment size and its distribution in the blasted muck piles in weaker sandstone bench of mine "A" for determination of suitable inter-row delay timing.

b. Inter-row delay timing vis-à-vis fragment size and its distribution, in the blasted muck piles, in stronger sandstone bench of mine "B", for determination of suitable inter-row delay timing.

c. Comparative investigation of inter-row delay timing requirements for 2-different formations in order to evaluate the delay timing requirement *vis-à-vis* nature of rock.

3 Case Description

The study mines "A" and "B" are situated in Ramagundam area (RG) of Singareni Collieries Company Ltd. (SCCL), which falls in the South Godavari basin coalfield of India. The projects came into existence in November 1974, with an estimated coal reserve of 52 million tons, at an average stripping ratio of 1:3.36.The property is bifurcated almost midway by a down throw fault in N-S direction. The seams gently slope at 6 to 16 degree on both sides of the property. The topography is almost flat and covered with a thin mantle of subsoil. The general direction of full dip of the seams is North 76 degree east. The mines cover an area of 442 hectares.

In mine "A" the fragmentation studies were conducted on the dragline bench. The thickness of this bench varied from 20-22 m and it mainly consisted of coarse to medium grained sandstone which was intercalated with shale bands and carbonaceous sandstone at some horizons. In mine "B" also the fragmentation studies were conducted on the dragline bench. However, the thickness of this bench varied from 24-27 m and it consisted of medium to fine grained sandstone. The operating dragline in both the study mines were 24/96 draglines of similar make. Furthermore, the dragline benches, in both mines, overlaid the III seam, which was almost 10-12 m thick. Average seam gradient was about 1 in 9.5 and it was worked by 4.6m^3rope shovels in conjunction with 35-tonne rear dump trucks, respectively. The overburden benches above the dragline bench in both mines were being worked by 4.6 and 10 m^3 rope shovels in conjunction with 35 and 85-tonne rear dump trucks.

The salient physico-mechanical parameters of dragline bench rocks are tabulated in Table 1.Keeping in mind these physico-mechanical parameters, the sandstone formation of dragline benches, in the study mines, could be broadly classified as weaker sandstone of mine "A" (with lower rock strengths, p-wave velocities and brittleness) and Stronger sandstone of mine "B" (with higher rock strengths, p-wave velocities and brittleness).

4 Field Study and Research Methodology

For detailed investigation and comparison, five field-scale blasts were conducted on each dragline bench of mines "A" and "B" by incrementally varying the inter-row delay timing and investigating its influence on fragmentation in the muck pile. The inter-row delay timing was varied by keeping in mind the physico-mechanical parameters of the sandstone formation (Table 1), recommendations proposed by various researchers, and also by considering the informative results provided by the operators in the same mines. Inter-row delays varying from 75-200ms and 75-175ms were implemented in mines "A" and "B" respectively. The delay sequencing for the blasts is tabulated in Tables 2 and 3 for mines "A" and "B", respectively. Inter-row delay timings of 75-200ms, in mine "A" at burden values of 8 m provided the effective delay ranging from 9.38–25 ms/m of effective burden (8 m). Similarly, 75-175 ms/m at burden values of 7 m provided the effective delay ranging from 10.7-25 ms/m of effective burden (7 m) in mine "B". Here, it may be of consequence to mention that since all the blasts were fired on row-to-row firing pattern, hence the magnitude of effective firing burden equals to the drilled burden for all the blasts in Mines A and B.

Slurry explosive (with ammonium nitrate as oxidizer and burnt furnace oil as fuel oil) was used in all the blasts. The blast design parameters, excepting the inter-row delay timing for all the blasts in each mine were almost identical. Furthermore, there were no major geological variations in the dragline benches in each mine. Other field-specific variations were minor and could be ignored. Hence, for the purpose of investigation, the rock and explosive parameters can be assumed to be reasonably constant for all the five

Table 1 — Physico-mechanical parameters of rocks studied in mines A and B.

S. No.	Mine	Nature of rock	Avge. strength ranges in MPa			Avge.	P-wave	Brittleness
			Compr. strength	Tensile strength	Shear strength	Density (g/cc)	velocity range (m/s)	
1.	Mine A	Medium to fine grained sandstone intercalated with shale bands and carbonaceous shale at some horizons	9.8-17.8	0.62-2.8	1.94-2.29	2.1	2406.66-2962.22	8.62-12.6
2.	Mine B	Medium to fine grained sandstone	27.7-44.0	1.17-2.04	5.84-6.86	2.25	3649.72-4781.66	38.86-82.1

Table 2 — Salient blasting parameters in moderately strong rocks of mine A.

Parameters	Blast Number				
	1	2	3	4	5
Hole dia (mm)	250	250	250	250	250
Bench Ht. (H) (m)	20	20	20	20	20
Subgrade (Su.gr.) (m)	1.5	1.5	1.5	1.5	1.5
SxB (m)	10x8	10x8	10x8	10x8	10x8
Stemming (T) (m)	5	5	5	5	5
No. of Holes (n)	64	72	98	84	97
Drilling pattern	Skewed	Skewed	Skewed	Skewed	Skewed
Firing pattern	Row-to-row	Row-to-row	Row-to-row	Row-to-row	Row-to-row
No. of effective firing rows (R_e)	8	9	8	8	8
Initiator	D-cord	D-cord	D-cord	D-cord	D-cord
Decking (DK) (m)	0	0	0	0	0
Total quantity of explosive (Q_t) (kg)	56387	62913	79751	78551	82638
Volume broken (V) (m^3)	110371	121105	165635	160242	170385
Delays	0/75/100	0/100/125	0/125/150	0/150/175	0/175/200
Delay per meter of 'B'	9.38	12.5	17.85	21.43	25
Column charge length (CCL) (m)	16.5	16.5	16.5	16.5	16.5
Powder Factor (PF) (m^3/kg)	1.95	1.92	2.07	2.04	2.06
K10 (m)	0.350	0.2876	0.2311	0.2253	0.2195
Mean Fragment Size (MFS) K50 (m)	0.5672	0.4145	0.3826	0.3728	0.3695
Characteristic Size, Xc (m)	0.6305	0.4531	0.4222	0.4143	0.4079
K95 (m)	0.870	0.6112	0.561	0.5572	0.549
K100 (m)	1.101	0.8162	0.710	0.695	0.687

Table 3 — Salient blasting parameters in strong rocks of mine B.

Parameters	Blast Number				
	6	7	8	9	10
Hole dia (mm)	250	250	250	250	250
Bench Ht. (H) (m)	24	25	24	24	25
Subgrade (Su.gr.) (m)	1.5	1.2	1.5	1.5	1.5
SxB (m)	9x7	9x7	9x7	9x7	9x7
Stemming (T) (m)	5	5	5	5	5
No. of Holes (n)	86	94	115	89	135
Drilling pattern	Skewed	Skewed	Skewed	Skewed	Skewed
Firing pattern	Row-to-row	Row-to-row	Row-to-row	Row-to-row	Row-to-row
No. of effective firing rows (R_e)	8	8	10	10	9
Initiator	D-cord	D-cord	D-cord	D-cord	D-cord
Decking (DK) (m)	0	0	0	0	0
Total quantity of explosive (Q_t) (kg)	92353	92212	125579	82111	141682
Volume broken (V) (m^3)	142223	160449	200927	142979	239857
Delays	0/75	0/75/100	0/100/125	0/125/150	0/150/175
Delay per meter of 'B'	10.71	14.28	17.85	21.43	25
Column charge length (CCL) (m)	20.5	21.2	20.5	20.5	21.5
Powder Factor (PF) (m^3/kg)	1.54	1.74	1.6	1.74	1.69
K10 (m)	0.2327	0.2505	0.2618	0.3862	0.4379
Mean Fragment Size (MFS), K50 (m)	0.4046	0.4241	0.4386	0.6329	0.7068
Characteristic Size, Xc (m)	0.4484	0.4734	0.4989	0.6989	0.7859
K95 (m)	0.6043	0.676	0.6963	0.9468	1.0872
K100 (m)	0.771	0.845	0.9453	1.214	1.375

blasts in each mine. Accordingly, the fragmentation evaluated in each mine could characterize the fragment size in the broken muck piles *vis-à-vis* the inter-row delay timing variation. To characterize the fragment sizes in post-blasted muck piles, the state-of-art digital image capturing, processing and analysis technique was implemented. Needless to state that with the use of computerized digital imaging, the quantification process has become largely simplified, quick and relatively inexpensive. The basis of imaging technique is to capture scaled images of the blasted muck pile using a high resolution camera in the field, and then to digitize and measure the delineated fragments to provide a measure of the particle size distribution.

In the field-scale, blasted muck piles were documented with scaled images captured from front of the blasted mucks. The scaled images were processed and analyzed by commercial state-of-art image analysis software Fragalyst[6].It is obvious that a single image or even a couple of images are incapable of evaluating huge size blasted muck piles. Hence, a series of images were captured on hourly basis to cover the entire muck pile excavation episode. Furthermore, in the event of any exceptional situation, like occurrence of large boulders/excessive fines, evidences of geological features, *etc*., a few additional images were captured. Typically, an image frame of the digital camera could capture 250-300 broken rock fragments. Analysis of almost 25-30 images for each muck pile was considered suitable for yielding a statistically representative sample for characterizing the fragmentation in one muck pile. These guidelines are as per the recommendations published by noted researchers in the area of digital imaging[7-11]**.** A square scale, painted in red color, was placed in the image frames for calibration.

5 Results and Discussion

The salient blast design parameters, of the five field-scale blasts in mine "A", along with fragment size values (K10, K50, Xc, K95, K100) are tabulated in Table 2. The complete fragment size distribution plots for these blasts have been illustrated in Fig. 2. On similar lines, salient blast design parameters and the complete fragment size distribution plots, for all five blasts in mine "B", have been presented in Table 3 and Fig. 3, respectively.

A perusal of Tables 2 and 3 reveal the blast design parameters for the five blasts in mine "A" and other set of five blasts in mine "B" reveals that these blasts were fired on row-to-row pattern with different inter-row delay timing. The hole dia., bench height, mesh area (SxB), stemming length, sub-grade drilling length and number of firing rows were almost identical for all the five-blasts set conducted on the same bench. Number of blasting rows and holes in each row were so designed that ratio of length-to-width of each blast round was maintained within a range of 1.6-2.0.

Tables 2 and 3 also reveal various inter-row delay sequences as implemented in the study blasts. It may be noted that the delay sequencing was systematically incremental and have been designated as 0/75; 0/75/100; 0/100/125; 0/125/150; 0/150/175; 0/175/200, encompassing the blast sets in mines "A" and "B". This designation of delay sequence signifies the delay interval (in ms) between the consecutive firing rows. For instance, inter-row delay sequence of 0/75/100 for blast number 1 implies that first row initiation is represented by digit 0 and after this a fixed number of successive rows (4 in this case) were fired at a delay interval of 75 ms followed by subsequent rows (3 in this case) fired at a delay interval of 100ms. Similarly, 0/100/125 delay sequence in blast no.2 implies that first row initiation is represented by digit and after this certain number of rows (four) are fired at an inter-row delay interval of 100ms following which the delay interval is slightly increased to 125 ms along the last three backrows. The delay timings of 75, 100, 125, 150, 175 and 200 ms in mine "A" correspond to timing of 9.38, 12.5, 15.63, 18.75 and 25 ms/m of effective burdens, respectively. Since the effective burden in mine "B" was 7 m the delay timings of 75, 100, 125, 150 and 175 ms in this mine correspond to timing 10.71, 14.28, 17.85, 21.43 and 25ms/m of effective burdens, respectively.

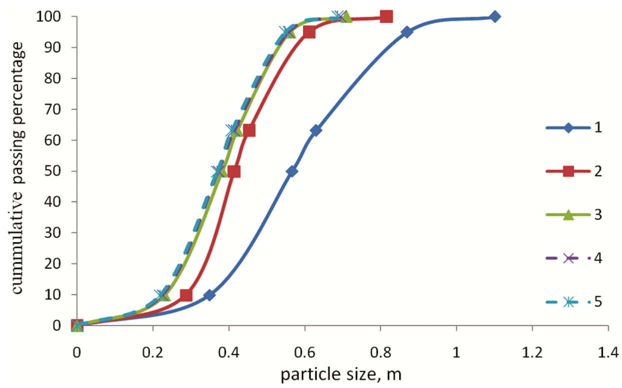

Fig. 2 — Fragment size distribution plots for blast numbers 1-5.

The fragment size results and the distribution plots (Fig. 2) of mine "A" clearly reveal the significance of delay timing on fragmentation. With shorter inter-row delay timing between 9.4-15.63 ms/m (in blast numbers B1&B2), the fragment sizes were larger in comparison to longer delay timing (15.6-25 ms/m) in this blast set. On systematically incrementing the inter-row delay timing from 15.6-25 ms/m (in blast numbers B3-B5) the fragment sizes were significantly reduced. It is worthwhile to note that even the coarse fragment size range (0.549-0.561 m) for the blast numbers B3-B5 fall within the optimum fragment size range (0.43-0.57 m) of operating 24/96 draglines. As such, the inter-row delay timing range of 15.6-25 ms/m of effective burden may be adjudged as the optimum delay interval in weaker sandstone strata. The corresponding blasts (B3-B5) fired on this optimum delay range revealed good fragmentation with fewer over size from collar and toe regions in addition to well displaced muck piles. On the other

Fig. 3 — (a) Poor fragmentation with large collar boulders and (b) Good fragmentation throughout the muck pile in mine A.

hand, large sized fragments were observed on the crust portion of freshly blasted mucks in blast numbers B1 & B2. Additionally, these blasts also manifested the occurrence of large sized boulders at the toe, collar and back row regions. Fig. 3 (a and b) reveal state of poor and good fragmentation in the blasted muck piles of mine A.

On scrutinizing the fragment size and distribution results of mine “B”, as given in Table 3 and Fig. 4**,** it is evident that the results are poor with larger inter-row delay intervals for the blasts 9 and 10. These blasts revealed very large mean, coarse (K95), characteristic (Xc) and maximum (K100) fragment sizes. On the other hand, blasts 6-8 reveal considerable improvement in fragment size results, being fired on shorter inter-row delay timings. With longer inter-row delay time ranging between 17.85-25 ms/m (blast numbers B9 and B10), the fragment sizes were very large. On the other hand, blast numbers B6-B8 with shorter inter-row delay time ranging from 10.71-17.85 ms/m provided improvement in the fragment size results. It may be noteworthy that the mean fragment sizes

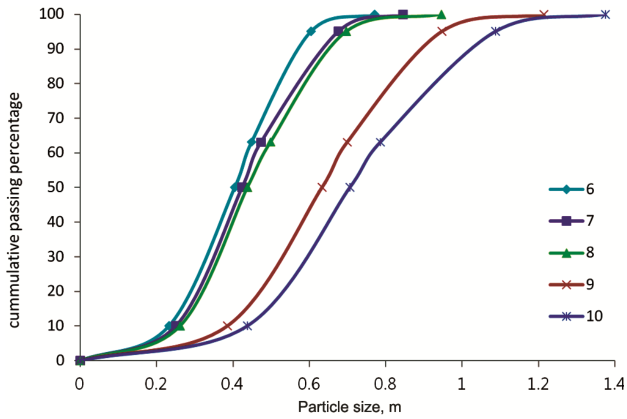

Fig. 4 — Fragment size distribution plots for blast numbers 6-10.

(0.4046-0.4386 m) and characteristic fragment sizes (0.4484-0.4989 m) in the blast numbers B6-B8 are well covered within the optimum fragment size range (0.44-0.58 m) of operating 24/96 draglines. Hence, for the given stronger sandstone formation, the results indicate that shorter inter-row delay time ranging from of 10.7-17.85 ms/m provided better results in comparison to longer delay time range (17.85-25 ms/m) in this blast set. Field observations of the blasted muck piles revealed very large sized boulders inside the dragline cut, in the collar region, especially along the back rows in the blast numbers 9&10 (fired on longer delays). However, observations on blasts 6-8 (fired on shorter delays) revealed much improved fragmentation inside the cut, along the back rows and in the collar regions.

Further examination of fragment size distribution plots of mines “A” and “B” (Figs 2 & 4) divulge that’s lopes of the fragment size distribution plots for the blasts B1 and B2 are very flat in comparison to the blasts B3-B5 in mine “A”. This indicates the presence of uniformly small sized fragments in the blasts B3-B5 in comparison to the blasts B1 & B2. Similarly, the slopes of the fragment size distribution curves are steeper for blasts B6-B8 in comparison to blasts B9 and B10 in mine “A”. This again suggests that the blasted muck piles for blasts B6-B8 had better uniformity in fragment size distribution within the muck piles in comparison to muck piles B9 and B10. Figure 5 (a & b) reveal state of poor and good fragmentation in the blasted muck piles of Mine B. This examination and interpretation cross-verifies the explanation of inter-row delay timing requirement in the preceding paragraphs of this section. From the present study, it is clearly evident that the choice of inter-row delay timing is largely governed by physico-mechanical parameters of rock formation. Stronger sandstone formation of mine “B” with higher

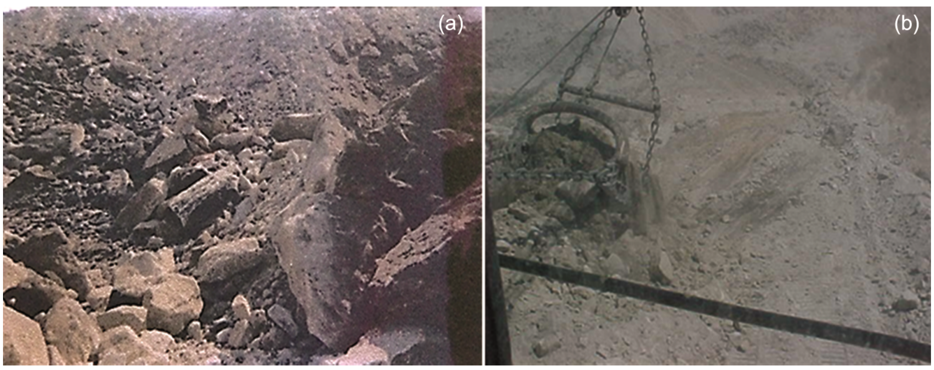

Fig. 5 — (a) Poor fragmentation in mine B within the muck pile and (b) Good fragmentation in mine B dragline bucket filled properly.

p-wave velocity and higher brittleness requires shorter inter-row delay timing for better fragmentation and vice versa for weaker sandstone formation of mine “A”. This may be attributed to the fact that greater shattering effect is required for efficient breakage in stronger formations.

The shattering effect is enhanced in stronger rocks because of higher p-wave velocities due to which the impedance to shock wave propagation in the rock mass is reduced. It is fairly established that shock wave is responsible for shattering effect by inducing network of fissures, cracks and micro-fractures in the rock mass during the initial process of breakage in stronger rocks. Higher brittleness also promotes the shattering during the initial rock breakage process in stronger rocks with higher p-wave velocity. In the subsequent stages of breakage of stronger rocks, the shattering implies that rocks between the successive rows should mutually collide vehemently before their final placement. The shorter inter-row delay timing plays its role in later stage of the fragmentation, as well, by providing good chance of vehement inter-rock collision of burden rocks before their final placement.

On the contrary, weaker formations have lower p-wave velocity range that makes them less vulnerable to breakage by shattering effect owing to higher impedance to shock wave propagation. Additionally, low brittleness of these rocks naturally dampens the possibility of breakage by shattering during the initial stages of rock breakage by blasting. Being less dependent on shattering effect the breakage of weaker rocks also does not depend much upon the vehement shattering effect provided by inter-rock collisions during the final stage of breakage. Instead, these rocks require adequate heaving and progressive relief being provided by longer inter-row delay timings. Literature also suggests that the progressive relief is important to obtain maximum utilization of explosive energy in weak or weaker rocks[12,13].

6 Conclusions

From the present case study, it is obvious that selection of delay timing *vis-à-vis* nature of rock is crucial from view point of rock fragmentation. In weaker rocks heaving effect (for progressive burden relief and placement) is important, whereas, in stronger rocks, the shattering effect is crucial during the initial as well as final stage of rock breakage mechanism. P-wave velocity and rock brittleness factors play a significant role in heaving or shattering of the burden rock mass. Furthermore, the study also suggests that proper heaving for progressive burden relief and placement entails longer inter-row delay timing. On the other hand, shattering necessitates shorter inter-row delay timing. As such, following conclusions may be drawn out from the present work:

(i) Weaker rock formations with lower p-wave velocity and brittleness offer higher impedance to shock wave propagation during the initial stage of rock breakage. Furthermore, owing to low brittleness these rocks do not bank much upon inter-rock collision during the final stages of rock breakage mechanism. On the other hand, in stronger rocks, the shattering effect is pronounced due to high p-wave velocity and rock brittleness, which, in turn, reduces the shock wave impedance during the initial stages of rock breakage. In the final breakage process such rocks derive shattering from inter-rock collisions. during the initial stages of rock breakage by blasting

(ii) In present case for weaker, coarse- to-medium grained sandstone the inter-row delay timing range of 15-25 ms/m of effective burden has yielded the best fragment size results.

(iii) Similarly, for stronger, medium to fine-grained sandstone formation, the inter-row delay timing range of 10-17.85 ms/m of effective burden has provided the best fragment size results.

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