Impact of Hole Depth on Vibration Magnitude *vis-à-vis* Minimization of Vibration Level for Safe Opencast Operation

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Excavation of locked up coal pillars by opencast method and presence of dwellings in close proximity to such operation needs a specialized drilling and blasting plan for its safe excavation. Introduction of private entrepreneurs sometimes urges the operating personnel and practicing engineers to introduce unsafe blast design parameters with respect to bench height for extraction of coal by opencast method. Implementation of sub-optimal blast design parameters due to mismatched drilling equipment leads to complaints from local inhabitants, damage to structures and even casualties as a result of undesired throw of blasted fragments. Comparing magnitude of vibration generated from different drill hole diameters, depth of hole and type of explosive (bulk or cartridge) this paper communicates that a maximum of 110 mm drill diameter and 83 mm cartridge diameter should be implemented for safe excavation, especially when the structures are within 100 m from the place of blasting. When the structures are between 50 m and 100 m, depth of blast hole should not be more than 5 m to contain the magnitude of vibration within safe limit. Due to high coupling factor for bulk loaded explosives, the attenuation rate of vibration for a given range of distance is slow and should not be implemented when structures are within 100 m from the place of blasting. For structures beyond 120 m from the place of blasting, bulk explosive may be implemented by limiting the bench height. Depth of holes and drill diameter for such cases may be between 8 m and 10 m and 110 mm and 160 mm, respectively. The paper also communicates that for the excavation work in close proximity to structures, burden should be less than optimum with respect to concerned bench height to contain the magnitude of vibration within the permissible limit.

Keywords : Vibration; Depth of hole; Frequency; Attenuation

INTRODUCTION

Improvement in socio-economic condition of people and sprawling of dwellings around opencast excavation work resulted in awareness to limit blast-induced vibration levels. Concern for protection of environmental degradation, avoidance of confrontation between mine management and local people, and safety of structures around mining area, safe blast-induced vibration standards have also been forced into legislation for different types of structures. Depending upon type of structures and blasting activity, various countries have also stipulated permissible vibration levels for safe excavation work. Considering the present demand for coal and the presence of underground fire in premier underground coalfields, new private entrepreneurs have been promoted for safe excavation of locked-up underground coal pillars by opencast method, presently located in close proximity to thickly populated dwellings. Since drilling and blasting are the cost-effective methods for excavation of such deposits, a need for stipulation of optimum blast parameters with respect to distance of structures from the blasting site was felt to be an essential pre-requisite. In this coal belt having almost similar geological parameters and socio-environmental condition, the authors felt that to achieve smooth running of the projects and avoid confrontation between local people and mine management, optimization of drill parameters, namely, drill diameter, depth of hole and blast geometry (burden and spacing) are essentially to be specified for safe excavation. The paper has considered magnitudes of vibration generated from different depth of blast holes for 110 mm and 160 mm drill diameter and types of explosive, namely, cartridge and bulk, for optimization of drill diameter and blast design parameters, namely, depth of blast hole, burden and spacing and type of explosive for safe excavation by opencast method. The measured magnitudes of vibration in this regard have been categorized with respect to depth of hole and types of explosive and using USBM predictor equation, best-fit predictor equation has been evaluated for each. Thereafter, considering the measured vibration data with respect to concerned distance and rate of attenuation for each, the paper recommends the most suitable drill diameter, depth of blast hole and explosive type for safe blasting operation for various distances of concern.

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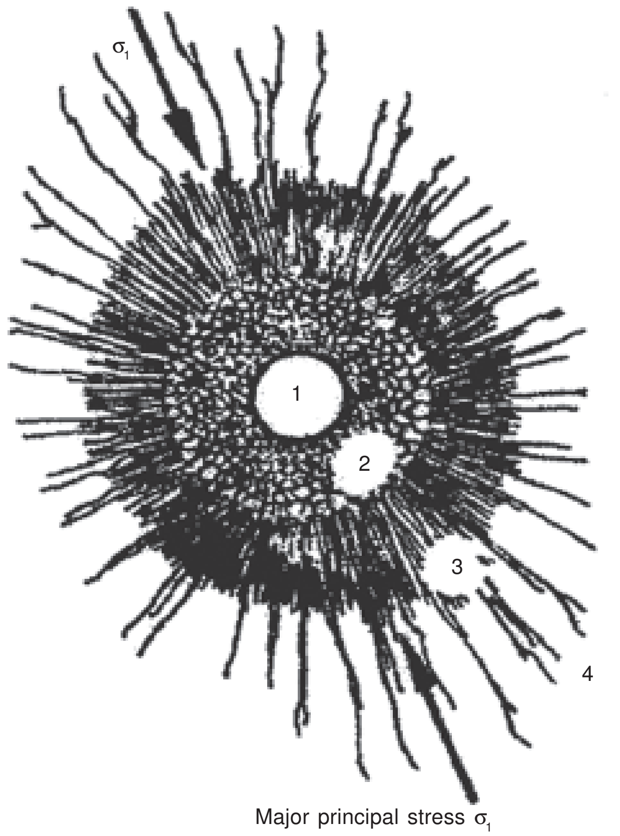
PARAMETERS AFFECTING MAGNITUDE OF VIBRATION

The magnitude of vibration, though, a prime concern for safety of structures, the general people residing around any excavation work with even low vibration magnitude poses problem for smooth excavation work. The socio-political and environmental status of local people and poor knowledge about the impacts of blasting and safe vibration standards generally correlates magnitude of air overpressure (AOP) with vibration and sometimes due to fear psychosis aggravates non-cooperative attitude towards blasting and leads to confrontation with mine management to hamper the progress. To evolve generalized blast geometry and explosive type for excavation of locked-up coal pillars and safety of structures for various distances of concern, the paper considered the blast details and vibration data generated from five sites of Bharat Coking Coal Limited (CIMFR report of investigations)[1-5].

High temperature and gaseous pressure generated during detonation of explosive melts, flows, and crushes and fractures rock mass immediately surrounding the explosive charge (Figure 1). Beyond this, extension of cracks is generally observed in the rock mass and is known as cracked zone. Monitoring of vibration is generally carried out beyond the cracked zone, commonly known as seismic disturbance zone. The paper considers propagation characteristics of blast waves in this elastic/seismic zone. Pastika, *et al* [6] analyzed different forms of cost of energy utilized in disassembling iron ore. Scott, *et al* [7] investigated overall cost for optimal, normal and poor blast fragmentation, respectively. Spathis[8] communicated that energy used for fracture, rock movement and radiated ground vibration were 0.57%, 36.6% and 7%, respectively of the available chemical energy. With an increase in excavation work, various researchers have attempted to quantify, assess and generate an empirical equation to understand the vibration propagation characteristics and limit the vibration magnitude for safety of structures[9-21]. Dowding[22] communicated that frequency of vibration and ground strained due to vibration determines the response of above ground structures. Similarly, for below ground structures, frequency in combination with propagation velocity controls the response of structures. Dick, *et al* [23] communicated that waves generated from detonation of two



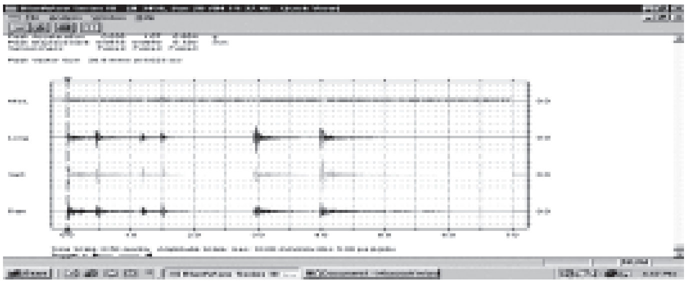
Major principal stress σ_1

Note : 1 : Borehole; 2 : Crushed zone; 3 : Crack zone; 4 : Seismic zone

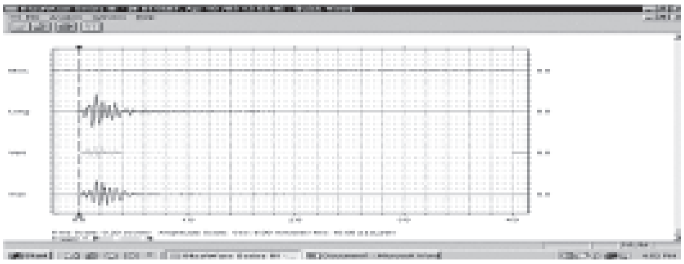
Figure 1 Effect of rock on detonation of explosive

explosive charges will act independently when their detonation is delayed by more than 8 ms. Spathis communicated that scaled charge weight superposition model can properly justify prediction at any distance of concern. In this paper, 8 ms was communicated as the suitable sliding time window over which the scaled charge weight should be summed for analysis. However, the window range may change with variation of blast geometry and charge parameters. Holmberg-Persson model communicated that for any length of blast hole, *L*, the vibration peaks due to all elemental segments may be numerically added to yield peak vibration magnitude. Blair and Jiang[24] as a function of VOD of explosive, used dynamic finite element model for single blast hole, depth up to 5 m, to evaluate the surface vibration. McKenzie, *et al* [25] used the seed waveform model to define the wave propagation characteristics.

Propagation characteristic of ground vibration is strongly influenced by lithology, strength, density and porosity of rock mass. For same blast input parameter, duration of vibration will be longer and frequency will be lower in back-filled or unconsolidated strata than those in compact strata[26]. Acceleration in terms of g for any blast also varies with distance of concern and quantum of explosive detonated in that round[27]. Propagation of vibration wave being complex phenomena and influenced by rock mass characteristics, attenuation attributed by rock mass towards propagation of ground motion is never uniform and varies with energy contained in it. In linear scale, magnitude of vibration when plotted against scaled distance ($D/\sqrt{Q}$), the regression curve always runs in asymptotic manner to the coordinate axes. Attenuation is generally observed to be faster at shorter distance and slower at longer distances of concern from any source of vibration[28]. The paper communicated that depending upon characteristics of attenuation of vibration magnitude, categorization of vibration data should be made for a range of distance having almost similar attenuation characteristics. Using USBM predictor equation with different charge parameters, namely, charge per delay, total charge and ratio between total charge and charge per delay for *Q*, propagation equation should thereafter be derived for each range of distances and the equation having least standard error of estimation for that range of distance should be considered as the best-fit propagation equation for that range of distance. However, for near-field, estimation of vibration magnitude is never correct and stress-strain analysis should be carried out to evaluate the damaging characteristics of blasting[29-30]. Mandal, *et al* [31] communicated that instead of limiting vibration magnitude for safety of structures, structural response in terms of energy transmitted to the structure namely, peak hold energy, total energy and strain energy should be evaluated. Delay detonators (long or short) used in a blasting round also influences magnitude and characteristics of vibration wave (Figure 2). Depending upon delay timings between initiation of two explosive columns in either same or different holes in a multi-row blast, wave fronts emanating from corresponding delays cooperate in either same or different phase for constructive or destructive interference of blast waves to result in either reduction or



(a) Long delay initiation



(b) Short delay initiation

Figure 2 Wave characteristics for varied delay timings

magnification of vibration magnitude at any distance of concern[32]. It has also been observed that for same blast geometry, magnitude of vibration is not proportional to the quantum of explosive detonated in a delay. Magnitude of vibration generally increases with an increase in charge per delay/hole, but with better utilization of energy, magnitude of vibration was observed to be comparatively less[33]. The excess of explosive energy is possibly utilized in adding momentum to the blasted fragments. Ratio between lengths of free face to width of blasting face also quantifies magnitude and characteristics of vibration. The blast vibration characteristics generated from shovel-dumper combination faces is somewhat different from that observed from dragline benches[34].

ANALYSIS OF VIBRATION MAGNITUDE

The paper analyzes vibration data for depth of holes varying between 3 m and 9 m and drill hole diameters between 110 mm and 160 mm. In all more than 60 vibration data from five different coal mines have been analyzed[1-5]. Excavation at all the sites was carried out over developed pillars and in close proximity to dwellings occupied by either private or company personnel. Drilling and blasting pattern, minimum and maximum vibrations monitored at corresponding distances for each site are detailed in Table 1.

At site *A*, both cartridge and bulk explosive with varied blast geometry were implemented for excavation of rock. Minimum and maximum vibration measured at different distances for both bulk and cartridge loaded blast holes are detailed in Table 1. The vibration propagation equation for each is given in Table 2. Attenuation characteristics of propagation equation for cartridge loaded explosive is observed to be slower than that observed for bulk loaded explosive (Figure 3 (a)}. In comparison to attenuation slope of 134° for bulk loaded blast holes, attenuation slope measured for cartridge loaded blast holes was 139°. In comparison to cartridge loaded blast holes, blast holes loaded with bulk explosive had good coupling with borehole wall and lesser blast geometry. Possibly the effective energy generated from bulk loaded blast holes minimized time duration for generation of cracks, burden movement, release of gas energy to general atmosphere and vibration magnitude at any distance of concern. However,

Table 1 Generalized blast design parameters followed at each site

Name of site	**Hole depth,** m	**Blasthole diameter,** mm	**Explosive type**	**Burden × spacing,** m × m	**Explosive per hole,** kg	**Total charge,** kg	**Vibration,** mm/s			
							Dist, m	**Min Vibration**	**Dist**, m	**Max Vibration**
A	8-10	110	Cartridge 83 mm	3.5 × 4.5 to 3.5 × 5.5	38 to 55.2	612.1 to 2083.8	95	3.37	30	75.8
	8-10	110	Bulk	3 × 3.5 to 3.5 × 4	33.36 to 38.92	237.5 to 739.48	110	3.99	60	21.1
B	7-8	110	Cartridge 83 mm	3 × 3.5 to 3 × 4	33.36	768.4 to 826.33	90	1.77	47	30.7
	7-8	110	Bulk	3 × 4 to 3 × 5	30.2 to 50.2	783.1 to 904	65	15.8	40	27.1
	5	110	Cartridge 83 mm	2 × 2.5 to 2.5 × 3	13.9	222.4 to 375.3	70	2.56	50	5.91
C	6	110	Cartridge 83 mm	3 × 3.5 to 2.5 × 2.75	16.1 to 19.14	205.56 to 794.44	100	4.64	40	22.4
D	3	110	Cartridge 83 mm	1.5 × 2 to 2 × 2.5	2.78	41.7 to 130.66	90	0.953	50	13.3
E	9	160	Cartridge 125 mm	3 × 3.5 to 2.5 × 4	62.5	500 to 812.5	85	7.37	45	20.8
	6	160	Cartridge 125 mm	2.5 × 3	31.25	375 to 500	100	4.07	15	71.3

for cartridge loaded blast holes, higher burden and poor coupling with borehole wall possibly enhanced borehole pressure and vibration magnitude. This possibly resulted in poor attenuation characteristics with respect to scaled distance for cartridge loaded blast holes. At this site, comparison of vibration magnitude for single and three-deck system of initiation was also carried out. It was observed that for same quantity of explosive per hole, the magnitude of vibration was higher for three-deck system. In comparison to vibration magnitude of 8.578 mm/s and 3.99 mm/s measured at 80 m and 110 m, respectively for single decked blast holes, vibration measured for three-deck system was 14.478 mm/s and 8.01 mm/s for same distances of concern, respectively. Possibly the explosive energy detonated in three independent decks was not effective for movement of front burden to release its gaseous energy and therefore, resulted in higher vibration. Constructive cooperation of charges detonated in different decks of same and/or different holes of the blasting round during the path of transmission might have possibly enhanced the vibration magnitude at the concerned distances. Number of holes for single and three-deck system of initiation was 9 and 19 with a total charge of 325 kg and 739 kg, respectively.

For site *B*, comparative analysis of vibration magnitude for 8 m depth of blast hole with respect to type of explosive, namely, cartridge and bulk, was carried out. Keeping same burden for cartridge and bulk loaded blast holes, vibration magnitude was measured at various distances of concern. At this site, for cartridge loaded blast holes vibration was also monitored for different depth of blast holes, namely, 8 m and 5 m. The best fit propagation equation and the regression line obtained for bulk and cartridge loaded blast holes are given in Table 2. The best-fit regression *vis-à-vis* attenuation characteristics for each are shown in Figure 3 (b). The slope angle of the regression line for cartridge and bulk loaded blast holes for 8 m depth of blast holes were 116° and 147°, respectively. For 8 m depth of blast holes, cartridge loaded blast holes in comparison to bulk loaded blast holes indicated faster attenuation and therefore, at scaled distances greater than nine, vibration magnitude for bulk loaded blast holes was higher than cartridge loaded blast holes. The junction of two regression lines possibly indicates that at such scaled distance vibration magnitude would be same for both, namely, bulk and cartridge loaded blast holes. For same blast geometry, possibly high coupling factor and more linear charge concentration yielded more energy to have slower attenuation rate during the path of transmission. For cartridge loaded blast holes, vibration data was also monitored for two different depths, namely, 8 m and 5 m, to make a comparative analysis between them. The slope angle of best-fit regression line for 5 m depth of hole was about 124°. In comparison to 8 m depth of blast holes, 5 m depth of holes measured less vibration magnitude for same scaled distances. However, at scaled distance greater than 11, magnitude of vibration for 8 m depth of blast holes was less than 5 m blast holes. Possibly due to greater charge length for 8 m depth of holes, interference of blast waves generated from each unit length of explosive column resulted in lesser vibration magnitude at such scaled distances. Furthermore, for 8 m depth of holes, the measured vibration at such scaled distances was possibly the result of interaction of blast waves detonated in different delays and not total charge. However, for 5 m depth of blast holes having lower magnitude of linear charge length, interference of blast holes detonated in different delays might have exhausted and at scaled distance, 11 and the vibration measured at such scaled distances was possibly the impact of total charge and not charge per delay.

Comparison of attenuation characteristics between site *C* and site *D* indicates that linear charge length and depth of blast hole influences vibration magnitude at a distance of concern {Figure 4 (a)}. For site *C*, explosive was distributed in two decks and detonated in two delays. However, for site D with depth of blast holes 3 m, explosive was detonated in single delay. For same scaled distance, vibration was less for smaller depth of blast holes. The slope angle for 6 m and 3 m depth of blast holes were 136° and 121°, respectively. The regression line for both clearly indicates that for smaller scaled distance, blasting with smaller depth of holes is most suitable for safety of structures. However, for safety of

Table 2 Vibration predictor equation and related parameters for each site

Name of site	Propagation equation	No of data analyzed	Correlation coefficient	Standard error of estimation	Slope angle, deg
A Cartridge explosive	$V = 2918\ (D/\sqrt{Q})^{-2.27}$	26	0.94	0.105	139
Bulk explosive	$V = 1437\ (D/\sqrt{Q})^{-1.89}$	24	0.94	0.0921	134
B Cartridge explosive, 8 m	$V = 7795\ (D/\sqrt{Q})^{-2.74}$	16	0.807	0.169	116
Bulk explosive	$V = 131\ (D/\sqrt{Q})^{-0.915}$	9	0.908	0.0287	147
Cartridge explosive, 5 m	$V = 977\ (D/\sqrt{Q})^{-2.05}$	12	0.876	0.621	124
C Cartridge explosive, 6m	$V = 969\ (D/\sqrt{Q})^{-1.49}$	27	0.756	0.143	136
D Cartridge explosive, 3m	$V = 1146\ (D/\sqrt{Q})^{-1.71}$	22	0.849	0.126	121
E Cartridge explosive, 9m	$V = 142\ (D/\sqrt{Q})^{-1.12}$	20	0.620	0.0746	150
Cartridge explosive, 6m	$V = 219\ (D/\sqrt{Q})^{-1.34}$	5	0.934	0.083	145

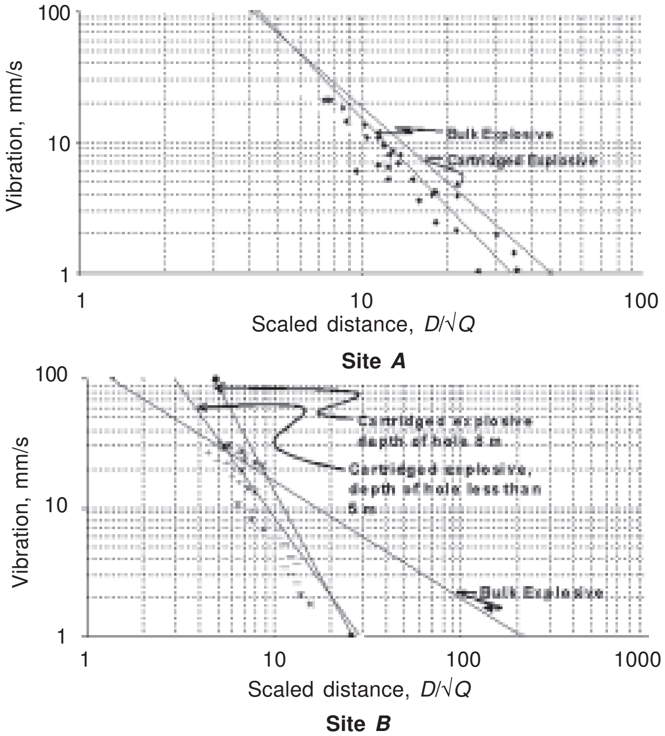


Figure 3 Log-log plot of vibration magnitude against scaled distance

inhabitants, blast pattern for smaller depth of holes should contain flying of blasted fragments well within safe limit.

For site *E*, vibration was monitored for two different depths of blast holes, namely, 9 m and 6 m. Cartridge explosive was used for both the cases. In one of the trial blast for 9 m depth of hole, vibration monitored for 2.5 m burden and 4 m spacing was 15.4 mm/s, 10.7 mm/s and 10.4 mm/s at 50 m, 60 m and 70 m distances, respectively. However, when burden was increased to 3 and spacing reduced to 3.5, vibration monitored was 18.5 mm/s, 13.3 mm/s and 7.37 mm/s at 55 m, 65 m and 85 m distances, respectively. Graphical log-log plot of vibration propagation for both 9 m and 6 m depth of holes are shown in Figure 4(b). Slope of regression line for 9 m and 6 m depth of holes were 150° and 145°, respectively. In comparison to 6 m depth of blast hole, slope for 9 m depth of hole was flatter. This possibly indicated the impact of linear charge length. Every unit of linear charge, when detonated, interacts with the transmitted vibration wave generated from detonation of earlier unit mass to cause slower attenuation rate during propagation. At this site comparison of vibration propagation for two and three-deck system of loading was also carried out. The log-log plot of PPV against scaled distance for multiple-deck loading is shown in Figure 5. Attenuation characteristics clearly indicate that two-deck system has faster attenuation than three-deck system. Interpolation of attenuation characteristics, however, indicates that multiple-deck charging is most suitable for safety of structures at lower scaled distances. However, at longer scaled distances, possibly due to cooperation of charges detonated in different delays, multiple-deck charging may not be suitable. At such distances, due to cooperation of charges and/or constructive interference of blast waves, vibration magnitude measured will be higher. Duration of vibration will also be high and therefore, structures located at such distances should be capable for sustaining longer duration of vibration.

Considering DGMS standard, Technical Circular 7 of 1997[20] and frequency of vibration at such distances to be between 8 Hz and 25 Hz, 10 mm/s has been assumed as safe vibration level for safety of structures. Using USBM predictor equation, as listed in Table 2, maximum allowable charge per delay for each category are given in Table 3. The plot of maximum allowable charge per delay for varying distances of concern and for each category is shown in Figure 6. The figure clearly indicates that for same burden and depth of blast hole, maximum allowable charge per delay for any distance of concern will be higher for cartridge loaded blast holes. Similarly, for sites *C* and *E*, each having 6 m depth of blast hole with explosive diameters of 83 mm and 125 mm in 110 mm and 160 mm blast hole diameters, respectively, maximum allowable charge per delay was more for 125 mm cartridge diameters, *ie*, site *E*. Possibly with respect to explosive loaded per hole for site *C*, the burden was high generating more borehole pressure *vis-à-vis* vibration at any distance of concern. Therefore, for constant safe limit of vibration, the maximum allowable charge per delay for site *E* was higher than that predicted for site *C*. For safety of structures at any distance of concern, bulk explosive detonated per delay should be less than cartridge loaded blast holes. For safety of structures lying within 70 m from the place of blasting, depth of hole should be restricted between 5 m and 3 m. Bulk loading, due to faster loading

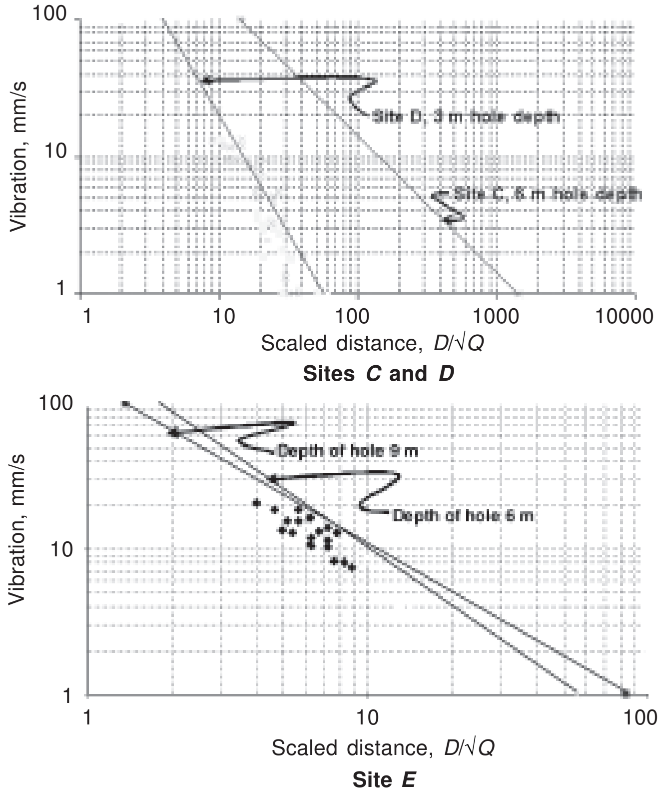


Figure 4 Log-log plot of vibration magnitude against scaled distance

Table 3 Evaluated permissible charge per delay (kg) for varying distances of concern

Distance, m	Site A		Site B		Site C	Site D		Site E	
	Cartridge	Bulk	Cartridge explosive, 8 m	Bulk explosive, 8 m	Cartridge explosive, 5 m	Cartridge explosive, 6 m	Cartridge explosive, 3 m	Cartridge explosive, 9 m	Cartridge explosive, 6 m
10	0.52	0.67	0.77	0.36	1.14	0.22	0.39	0.88	1.00
20	2.08	2.69	3.10	1.45	4.58	0.86	1.56	3.50	3.99
30	4.69	6.06	6.97	3.25	10.30	1.94	3.51	7.88	8.98
40	8.34	10.77	12.39	5.782	18.31	3.45	6.25	14.01	15.97
50	13.03	16.83	19.36	9.03	28.62	5.39	9.76	21.89	24.95
60	18.76	24.24	27.88	13.01	41.21	7.77	14.06	31.52	35.94
70	25.54	32.99	37.95	17.70	56.09	10.57	19.13	42.90	48.92
80	33.35	43.10	49.56	23.12	73.26	13.81	24.99	56.03	63.89
90	42.21	54.54	62.73	29.27	92.71	17.48	31.63	70.91	80.86
100	52.12	67.34	77.44	36.13	114.46	21.58	39.05	87.55	99.83
110	63.06	81.48	93.70	43.72	138.50	26.11	47.257	105.93	120.79
120	75.05	96.97	111.52	52.03	164.82	31.07	56.23	126.074	143.75
130	88.08	113.80	130.88	61.06	193.44	36.46	65.99	147.96	168.71
140	102.15	131.98	151.79	70.81	224.34	42.29	76.53	171.59	195.66
150	117.26	151.51	174.24	81.29	257.54	48.54	87.85	196.98	224.61

rate, should be avoided for such depth of blast holes. Care should also be taken in designing the blast pattern to contain flying of blasted fragments well within acceptable limit. For distances between 60m and 90m, depth of blast hole up to 6 m is observed to be most suitable. Similarly, for distances between 90 m and 120 m, depth of blast holes between 8 m and 9 m is observed to be suitable. In general, to contain AOP within acceptable limit and avoid fear psychosis of local inhabitants, down-the-hole NONEL system of initiation should be implemented in regular blasting.

CONCLUSION

Magnitude of vibration increases as well as attenuation rate decreases with an increase in depth of the blast hole. Magnitude of vibration is always higher for blast holes loaded with bulk type of explosive. For the same charge factor, vibration magnitude increases with an increase in burden. For the same burden, magnitude of vibration for cartridge loaded blast holes is less than for bulk loaded blast holes. Attenuation of vibration magnitude for three-deck loading is slower than two-deck loaded blast holes. Multiple-deck loading is suitable for safety of structures located close to blasting site. In comparison to multi-deck loading, direct loading is suitable for safety of structures located at higher scaled distances. Magnitude of vibration increases with diameter of explosive, linear charge concentration and linear charge length. In comparison to cartridge loaded blast holes, bulk loading system having higher coupling factor shows poor attenuation rate, which is not suitable for safety of structures located at far off distances. Small diameter explosive (83 mm) should be implemented when the structures are in close proximity to the blasting site. When structures are within 70 m, depth of hole should be restricted to 5 m. Drill and explosive diameter of 110 mm and 83 mm is most suitable when the structures are within 100 m from the blasting site. For different distances of concern, the most suitable blast hole diameter, depth of blast hole, explosive type, and blast geometry is listed in Table 4, which should

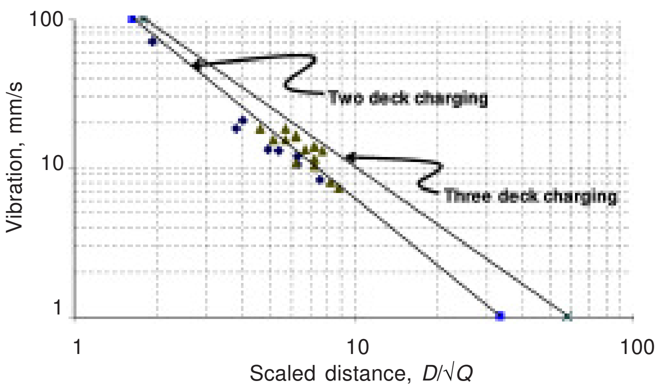


Figure 5 Log-log plot of vibration magnitude against scaled distance, Site E

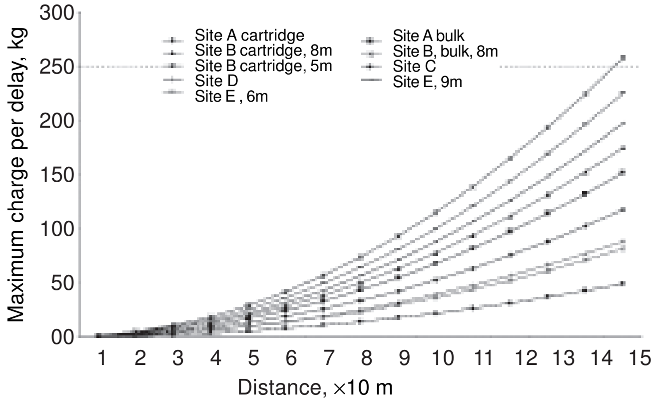


Figure 6 Plot of allowable charge per delay for varying distances of concern

Table 4 Recommended blast design pattern with respect to distances of structure

Distance of structure, m	Blast hole diameter, mm	Depth of blast hole, m	Blast geometry, Burden × Spacing, m × m
< 50	76 - 110	3 - 4	1.5 × 2
50 - 70	110	3 - 5	1.5 × 2 to 2 × 2.5
70 - 100	110	6 - 8	2 × 2.5 to 2.5 × 2.75
100 - 120	110	9 - 10	3 × 3.5 to 2.5 × 4.0
> 120	110	10	2.5 × 4.0 to 3 × 3.5
	160	10 -12	3 × 4 to 3 × 4.5

be adopted for safety of structures and contain magnitude of vibration well within the safe limit. To avoid fear psychosis and contain AOP within acceptable limit, down-the-hole NONEL system of initiation should be strictly implemented for regular blasting. The recommendations made in the paper are based on a few case studies. For standardization of the recommended blast pattern more field data should be generated.

REFERENCES

1. 'Scientific Study to Establish Safe Maximum Charge per Delay and Blast Pattern *vis-à-vis* Safety within 80 m of Occupied Buildings in Respect of 10, 11 and 12 Seam Quarry (Tetulmari Section) of Mudidih Colliery, BCCL.' *CMRI Report of Investigation, C/MT/29/2005-2006*.

2. 'Scientific Study at Tetulmari Section of Mudidih Colliery, with SMS Explosives to Contain Vibration within Safe Limit.' *CMRI Report of Investigation*, *GC/MT/146/2005-2006*.

3. 'Study of Suitable Blasting Pattern to Establish Safe and Optimum Blast Patterns.' *CMRI Report of Investigation*, *GC/MT/03/2007-2008*, Gopalichuk OCP, PB Area, BCCL.

4. 'Study of Blast Induced Ground Vibration for Safety of Structures around GOCP.' *CMRI Report of Investigation*, GC/MT/24/2007-2008, Bastacolla Area, BCCL.

5. Optimization of Blast Pattern for 5/6/7 Combined Seam at Jogidih OCP of BCCL, Dhanbad. *CMRI Report of Investigation*, GC/MT/28/2007-08.

6. P L Pastika, M Indihar and B Von Wald. 'Improved Fragmentation for Mine Cost Reduction. *68th Annual Minnesota Section*, *SME*, January 24-26, 1995, p 185.

7. A Scott, G P Chitombo and T Kleine. 'The Challenge of the Prediction and Control of Fragmentation in Mining.' *4th International Symposium on Rock Fragmentation by Blasting*, Vienna, July 5-8, 1993, p 507.

8. A T Spathis. 'On the Energy Efficiency of Blasting.' *International Symposium on Rock Fragmentation by Blasting*, *FRAGBLAST VI*, *South African Institute of Mining and Metallurgy*, 1999, p 81.

9. G Morris. 'Vibration due to Blasting and their Effects on Building Structures.' *The Engineer*, vol 190, London, 1950, p 394.

10. B M Habberjam and J T Whetton. 'On the Relation between Seismic Amplitude and Charge of Explosive Fired in Routine Blasting Operations.' *Geophysics*, vol 17, no 1, USA, 1952, p 116.

11. P A Heelan. 'Radiation from a Cylindrical Source of Finite Length.' *Geophysics*, vol 18, 1953, p 685.

12. B E Blair and W I Duvall. 'Evaluation of Gases for Measuring Displacement Velocity and Acceleration of Seismic Pulses.' *US Bureau of Mines*, RI 5073, 1983.

13. U Langefors and B Khilstorm. 'The Modern Techniques of Rock Blasting.' *John Wiley and Sons Inc*, New York, 1963.

14. N R Ambrasey and A J Hendron. 'Dynamic Behaviour of Rock Masses.' Rock Mechanics in K G Stagg and O C Zeinkiewiez (eds), *Engineering Practice*, *John Willey and Sons Inc*, London, 1968, p 203.

15. H R Nicholas, C F Johnson and W I Duvall. 'Blasting Vibrations and their Effects on Structures.' *US Department of Interior*, *Bureau of Mines Bulletin 656*, 1971.

16. A M Abo-Zena. 'Radiation from a Finite Cylindrical Explosive Source.' *Geophysics*, vol 42, 1977, p 1384.

17. D E Siskind, M S Stagg, J W Kopp and C H Dowding. 'Structural Response and Damage Produced by Ground Vibrations from Surface Blasting.' *US Bureau of Mines*, *Report of Investigation*, 8507, Washington, DC, 1980.

18. A Ghosh and J K Damen. 'A Simple New Blast Predictor (based on Wave Propagation Laws) of Ground Vibrations Induced Predictors.' 24th US Symposium of Rock Mechanics, Texas, 1983 pp 151-161.

19. P Pal Roy. 'Prediction and Control of Ground Vibration due to Blasting.' *Colliery Guardian*, vol 239, no 7, 1991, p 215.

20. 'Standards of Safe Level of Blast Induced Ground Vibration for Safety of Structures,' *DGMS Technical Circular 7*, *Ministry of Labour*, *Government of India*, 1997.

21. L L Oriad. 'Explosive Engineering, Construction Vibrations and Geo-technology.' *International Society of Explosive Engineers*, p 182.

22. C H Dowding. 'Blast Vibration Monitoring and Control.' *Prentice-Hall*, Englewood Cliffs, New Jersy, 1985, p 297.

23. R A Dick, L R Fletcher and D V D'Andrea. 'Explosives and Blasting Procedures.' *US Bureau of Mines, IC 8925*, 1983.

24. D P Blair and J J Jiang. 'Surface Vibrations due to a Vertical Column of Explosive.' *International Journal of Rock Mechanics, Mining Science and Geomechanics Abstr*, vol 32, 1995, p 149.

25. C K McKenzie, C R Scherpenisse, J Arriagada and J P Jones. 'Application of Computer Assisted Modelling to Final Wall Blast Design.' *EXPLO'95*, Brisbane, Australia, 1995, p 285.

26. P K Singh, B Mohanty and M P Roy. 'Low Frequency Vibrations Produced by Coal Mine Blasting and their Impacts on Structures.' *Journal for Blasting and Fragmentation*, vol 2, no 1, p 71.

27. S K Mandal, M M Singh, N K Bhagat and S Dasgupta. 'Charge Parameters and Its Impact on Ground Vibration.' *Proceedings of First Asian Mining Congress*, *The Mining Geology and Metallurgy Institute of India (MGMI)*, *Centenary*, January 16-18, 2006, p 405.

28. S K Mandal, M M Singh and N K Bhagat. 'Magnitude of Vibration vis-à-vis Charge per Delay and Total Charge.' *Journal of The Institution of Engineers (India)*, vol 86, pt MN/2, February 2006, p 32.

29. U Nyberg and S Fjellborg. 'Controlled Drifting and Estimation of Blast Damage. R Holmberg (ed).' Proceedings of First World Conference on Explosive and Blasting Technology, *A A Balkema*, Rotterdam, p 207.

30. U Nyberg and S Fjellborg, M Olsson and F Outcherlony. 'Judging Blast Damage in Drift Perimeters, Vibration Measurements, Damage Prediction and Fracture Mapping in Magnetite.' *Swedish Rock Engineering Research Report,* no 50, SveBeFo, Stockholm, 2000.

31. S K Mandal, M M Singh, N K Bhagat and S Dasgupta. 'Model for Energy-based Evaluation of Blast Waves to Assess Safety of Structures.' *International Journal of Mining, Reclamation and Environment*, vol 21, no 2, June 2007, p 111.

32. D P Blair. 'Charge Weight Scaling Laws and the Superposition of Blast Vibration Waves.' *Journal on Rock Fragmentation by Blasting*, FRAGBLAST, vol 8, no 4, 2004, p 221.

33. S K Mandal, M M Singh, N K Bhagat and S Dasgupta. 'Impact of Single-hole and Multi-hole Blasting on Vibration Parameters.' *Journal of Mines Metals and Fuels*, vol 56, nos 7 and 8, 2008, p 122.

34. S Guofu, L Yongmet and H Feng. 'Damage Mechanics and Assessment Methods for the Masonry Affected by Blasting.' *Seventh International Symposium on Rock Fragmentation by Blasting*, (Prof Wang Xuguang, Editor-in-Chief), Beijing, China, 2002, p 687.