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ORIGINAL PAPER

Blast vibration dependence on total explosives weight in open-pit blasting

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Abstract

It is well established that the blast design parameters, namely explosives weight per delay, distance between the blast site and monitoring location, delay interval, total explosives detonated in a blasting round, velocity of detonation (VOD) of explosives, burden, spacing, explosive column length, top stemming length, number of decks and their length, transmitting media and its geology, and scattering in the delay time of detonators, influence blast-induced vibrations. A study was conducted to assess the effect of total weight of explosive detonated in the blasting round on the magnitude of blast vibrations at four big coal open-cast mines in India keeping all the parameters constant as stated above. Accordingly, experimental as well as production blasts were conducted at dragline and shovel benches. The results revealed that the magnitude of blast vibrations was influenced by the total amount of explosive detonated in a blasting round at shorter distances regardless of maximum explosives weight per delay. This paper describes the result of a study carried out to investigate these effects at open-cast projects in India. The study involved 60 blasts with varying blast designs and 498 vibration data were recorded.

Keywords Blast vibration · Total weight of explosives · Explosives weight per delay · Scaled distance · Zone of influence

Introduction

The ever-increasing demand for coal in India has necessitated commissioning of large open-cast mines. These big-sized mines require massive removal of overburden by big size blasts for speedy exploitation of coal to meet the energy demand of the country. The big size blasts may generate higher levels of vibration, noise, fly rock, dust, and fumes if not planned scientifically. It is also a subject of environmental concern (Singh 2004). Therefore, the techno-economic aspect of these issues needs special attention (Kahriman 2004). Many researchers have studied the generation and propagation of blasting-induced ground vibrations in open-cast mines (Davies et al. 1964, Langefors and Kihlström 1963, Ghosh and Daemen 1983, Hustrulid 1999, Kahriman 2002). Ground vibration associated with big blasts has been a major concern in populous India, which needs to be addressed promptly. The blast vibrations measured in terms of peak particle velocity are the guiding parameter for designing a safe blast for controlling damage to surface structures (Dowding and Dowding 1996, Oriard 1999, Singh and Roy 2010). It is also being used increasingly to investigate the performance of the explosives used in the blast (Mohanty and Yang 1997). The characteristics of blasting vibrations depend critically on the amount of explosives detonated at any given time, the delay intervals employed in the blast round, and the prevailing local geology (De Silva 2007). It is believed that optimum delay between the blast holes and rows of holes results in better fragmentation with lower levels of vibration (Mishra et al. 2019, Agrawal and Mishra 2018a, Singh et al. 1996).

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Table 1 Physico-mechanical properties of rock

Name of the project	Rock type /location	Compressive strength (MPa)	Tensile strength (MPa)	Density (kg/m^3)	Poisson's ratio	Young's modulus (GPa)
Kusmunda	Sandstone (shovel bench)	26.55	2.1	2027	0.24	5.57
Nigahi	Sandstone (dragline bench)	31.72	3.5	2064	0.20	3.41
	Sandstone (shovel bench)	29.65	3.2	2011	0.20	3.25
Sonepur Bazari	Sandstone (dragline bench)	37.32	3.4	2330	0.22	7.05
	Sandstone (shovel bench)	36.54	3.4	2310	0.23	7.02

In has been further reported that there is a significant effect of total weight of explosives fired in a blasting round on the magnitude of vibration at relatively closer distances from the blast (Garai et al. 2018b, Singh et al. 1994, Singh 1998). It has also been stated that vibrations resulting from a single-hole delay blast and a multi-hole delay blast, both containing the same total explosives weight, are significantly different (Agrawal and Mishra 2018b, 2019, Garai et al. 2018a). But it is also true that the adjustment of delay times will significantly reduce the vibration level without adversely affecting the blast performance (Singh et al. 2019). Most empirical equations take into account the weight of explosive detonated in particular time intervals and the distance between the monitoring location and blasting site. Holmberg and Persson developed a near-field vibration model in which the standard charge weight scaling law was used to estimate the peak vibration level due to a blast hole explosive source (Holmberg 1979). In this model, the continuous length of explosive was modelled by summing charge elements along the borehole. However, Blair and Minchinton (2006) showed that this model was unsound because it did not correctly sum (integrate) the vibration contribution from each charge element. This unfortunate situation arose because the charge weight scaling law does not contain waveform information and hence cannot provide any rational means of estimating the total peak vibration level from the sum of waveforms that would be produced by all elements of a charge.

The most widely accepted blast-induced ground vibration predictor equation is the square root scaled distance equation developed by the United States Bureau of Mines (USBM) (Duvall and Petkof 1959). The corresponding equation is of the following form:

$$\mathrm{PPV} = K \times \left(\frac{D}{\sqrt{Q_{\max}}}\right)^{n}$$

where PPV is the peak particle velocity in millimeters per second, K and n are site constants, D is the distance of the point of interest for vibration monitoring from the blast site (m), and $Q_{\max}$ is the maximum explosives weight per delay (kg)

However, in recent field studies, it has been realized that there is a significant impact of the total weight of explosives detonated in a blast round on the magnitude of blast vibrations at nearby distances which needs to be quantified as the prediction of vibration based on the maximum explosives weight per delay for various distances may not be reliable and adequate in many circumstances (Agrawal and Mishra 2018c). Apart from this, there is also a concept of cooperating charge, i.e., the total charge per interval multiplied by the reduction factor appropriate for the interval used. Therefore, in this paper, the outcome of the study, i.e., the influence of total weight of explosives detonated in a blast round in addition to the

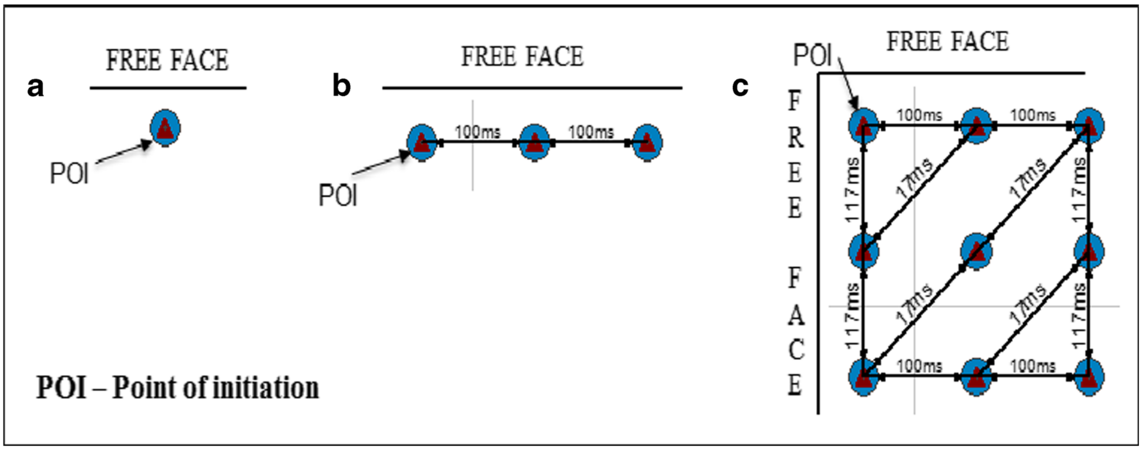


Fig. 1 **a**–**c** Blast sequence of 3 trial blasts performed at shovel bench of Jayant project

Table 2 Blast design details of 3 trial blasts conducted at the Jayant project and as presented in Fig. 1

Blast design parameters	Blast 1	Blast 2	Blast 3
No. of holes	1	3	9
Hole depth	16 m	16 m	16 m
Burden × spacing	9 m	9 m × 10 m	9 m × 10 m
Total charge (Q_t)	681 kg	2043 kg	5814 kg
Explosives weight per delay (Q_{max})	681 kg	681 kg	681 kg

effect of explosives weight per delay on blast-induced ground vibration, has been discussed in detail.

Experimental site details

Experimentations were performed at four different coal mines in India, i.e., Sonepur Bazari, Eastern Coalfields Limited (ECL); Kusmunda project, South Eastern Coalfields Limited (SECL); Jayant project and Nigahi project of Northern Coalfields Limited (NCL).

Sonepur Bazari is an open-cast coal mine of a mini ratna company ECL, and it has four coal seams, viz. R-IV, R-V, R-VI, and R-VII. At present, seams R-V and R-VI are being extracted by the open-cut mining method. The stripping ratio of the mine is 1:4.72 m^3. The mine is producing about 4.5 Mt of coal and removal of overburden is about 12 million cubic meters. The total coal reserve of the mine is 188.26 Mt.

Kusmunda project is an open-cast coal mine project of SECL, located in the western bank of the Hasdeo River in the district of Korba Chhattisgarh state, India. The seams generally have a dip ranging from 1 in 5.6 to 1 in 11.5, and the overall grade of the coal is grade “F.”

Jayant and Nigahi projects have rocks of Lower Gondwana Formation. The mines have three coal seams, namely Turra and Purewa (bottom, top, and sometimes combined) seams with thicknesses of 13–18 m, 10–12 m, and 5–9 m respectively. The average stripping ratio is 1:3.76 and 1:3.8 in Turra and Purewa seams respectively (3.76 and 3.8 m^3 of overburden are to be removed for extraction of 1 tonne of coal). Both mines are currently producing 14 million tonne of coal per annum.

The physico-mechanical properties of rock samples collected at Nigahi, Sonepur Bazari, and Kusmunda mines are presented in Table 1.

Experimental setup details

In order to investigate the impact of total weight of explosives detonated in a blasting round on ground vibration, 60 blasts were performed. The hole depths varied from 7.5 to 40 m, and the numbers of holes detonated in a blasting round varied from 1 to 97. The experimental setup was designed in such a way that two rounds of blasts having identical blast design parameters were performed with a different total weight of explosives in each round at the same bench. This made one set of trial blasts. The making of explosives and its accessories, charging pattern, initiation pattern, and explosives weight per delay were kept the same while the total amount of explosives detonated in a round was varied. In total, 28 sets of such

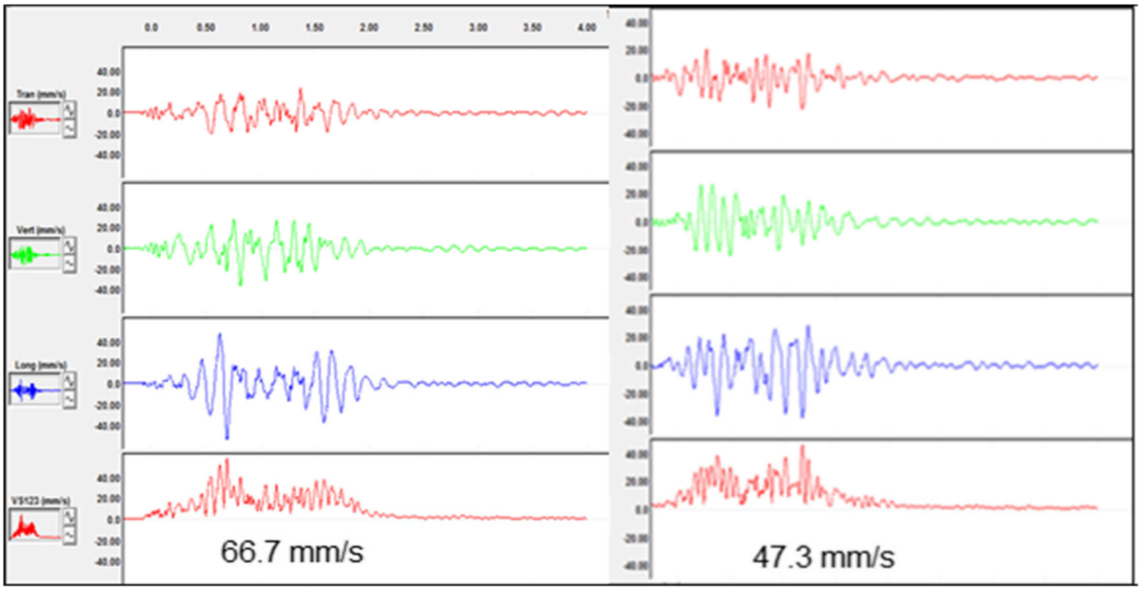


Fig. 2 Blast wave signatures recorded at 450 m from 2 different blasts due to detonation of total explosives weight of 197,407 kg and 111,000 kg at dragline bench of Jayant project, and the recorded PPV is 66.7 mm/s in the first blast and 47.3 mm/s in the second blast with only change in total weight of explosives

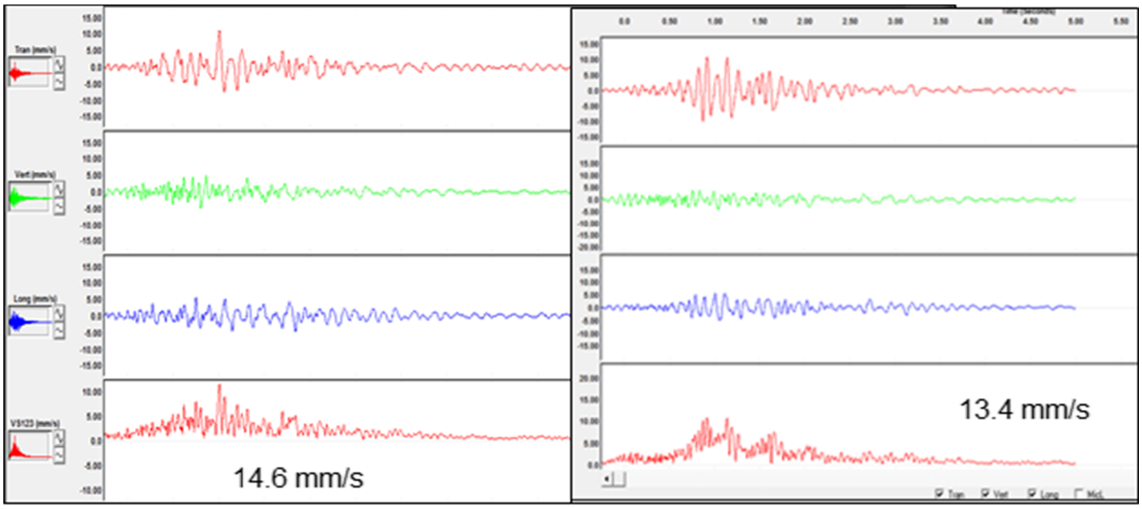


Fig. 3 Blast wave signatures recorded at 2540 m from 2 different blasts due to detonation of total explosives weight of 197,407 kg and 111,000 kg at dragline bench of Jayant project, and the recorded PPV is 14.6 mm/s in the first blast and 13.4 mm/s in the second blast with only change in total weight of explosives

blasts were performed at four mine sites. Vibrations were monitored in an array of 5 to 11 locations.

Experimental blasts were carried out at the Jayant project of Northern Coalfields Limited by detonating a single hole with 681 kg of explosives instantaneously and vibration monitors were placed at 8 locations ranging between 40 and 270 m from the blasting site at an interval of 25–50 m. At the same blast face, two sets of holes consisting of three holes and nine holes were charged with 681 kg of explosives in each hole and detonated by providing a delay interval of 100 ms between the holes in both the blasts as shown in Fig. 1. The 100-ms delay is used to ensure that there should not be any superimposition of waveforms due to delay time scattering.

Furthermore, vibrations were monitored at similar locations at 40 m to 270 m from the blasting site. Thus, the charge weight per delay in the latter two sets of blasts was 681 kg but the total explosives weights were 2043 kg and 5814 kg for sets of 3 holes and 9 holes. The recorded vibration levels up to 170 m were higher in second and third rounds of blasts as compared with the first one, which was fired with only one hole. But at locations further away from the blast site, the vibrations recorded were almost of similar magnitude in all the three blasts. Other details of trial blasts as discussed above are presented in Table 2. Similar trial blasts were also conducted to investigate the influence of total explosives weight detonated in a blast round on the magnitude of vibration at the Nigahi project, Kusmunda project, and Sonepur Bazari project.

Fig. 4 Plot of recorded PPV at various scaled distances due to detonation of varying total explosives weight in a blast round while other parameters were constant at dragline bench of Sonepur Bazari project

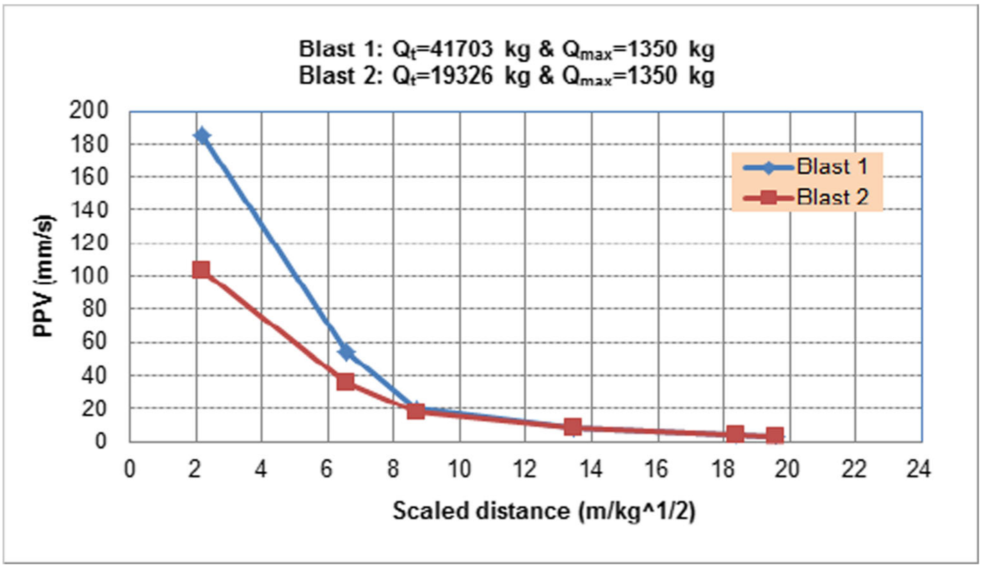


Table 3 Recorded percentage differences in PPV data due to detonation of large and small amounts of total explosives weight at dragline bench of Sonepur Bazari project

Distance (m)	Scaled distance (m/kg$^{0.5}$)	PPV recorded (mm/s)		% difference in PPV
		Large Q_t = 41,703 kg	Small Q_t = 19,326 kg	
80	2.18	185	103.4	44.11
240	6.53	54.1	35.5	34.38
320	8.71	20.3	18.3	9.85
495	13.47	8.73	8.12	6.99
675	18.37	4.57	4.12	9.85
720	19.60	3.65	3.41	6.58

Analysis of the blast wave signatures

The blast wave signatures recorded at various locations for each set of experiments indicate that the blasts, in which the total weight of explosives detonated was larger, generated higher levels of vibration in near-field in comparison with those blasts in which the total amount of explosives detonated was less than the previous blast. This observation was made in spite of the fact that the explosives weight per delay, delay intervals, blast design parameters, and explosives properties were kept identical. The persistence of vibrations was of shorter durations in those cases where the total amount of explosives detonated was in lower side.

The blast wave signatures recorded due to detonation of blast at dragline bench of Jayant project revealed that the impact of total explosives weight on generation of vibration is prominent in the near-field. The ground vibration waveforms were recorded simultaneously at 450 m and 2540 m from two blasts conducted for this purpose with total explosives weight of 197,407 kg and 111,000 kg respectively, although other blast designs and explosive parameters were kept identical. The recorded waveforms from both the blasts are presented in Figs. 2 and 3. The waves represent the clear difference between the peak generated due to change in total explosive charge in blasts. It is just to represent the clear comparison of both blasts. Similarly, blast wave signatures were also recorded at Nigahi project, Kusmunda project, and Sonepur Bazari project.

Analyses of recorded vibration data

Trial blast sets consisting of 2 or 3 blasts each were planned at the same bench of the mine with a view to avoid the influence of geology on blast vibration transmitting characteristics. In all the sets of trial blasts, the blast design parameters were kept constant while the total amount of explosives detonated in a blasting round was only varied. The recorded blast vibration data showed that there is a significant influence of total amount of explosives detonated in a blasting round on blast-induced ground vibration. Furthermore, it is found that beyond a certain distance, the percentage difference in peak particle velocity (PPV) corresponding to large

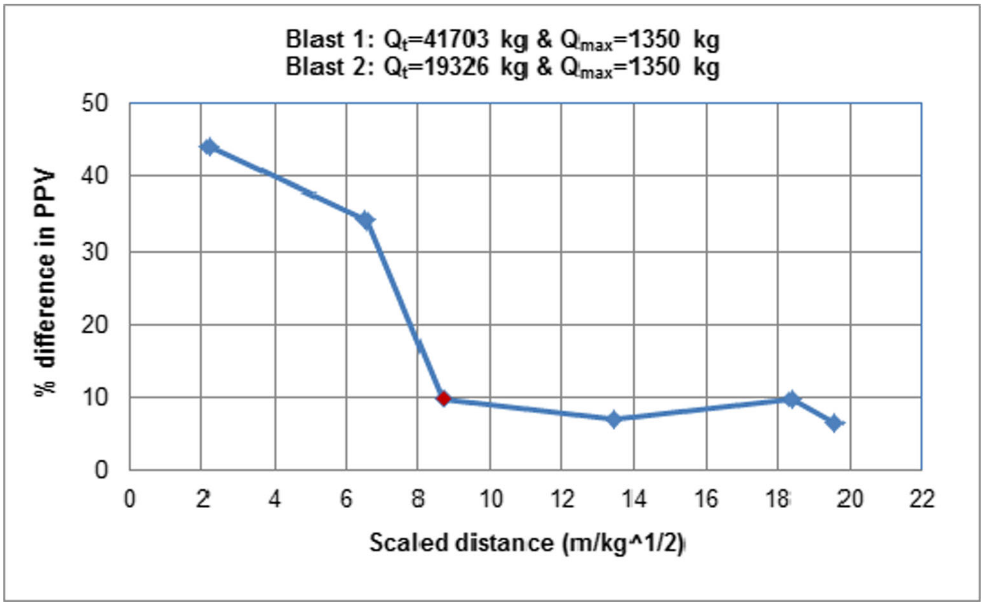


Fig. 5 Percentage difference in the recorded PPV due to detonation of large and small amounts of total explosives weight in a blasting at Sonepur Bazari project as presented in Table 3

and comparatively lower amounts of total charge has been in the range of 0 to 10.48%. Figure 4 depicts the recorded vibration data at various scaled distances when two blasts were conducted with large and comparatively lower amounts of total explosives weight at the same blasting patch at the Sonepur Bazari project. Similar trends were found at Jayant, Nigahi, and Kusmunda projects.

Determination of the zone of influence of total weight of explosives on blast vibration

The vibration data recorded from trial blasts conducted at four sites have been grouped together for determining the zone of influence of the total amount of explosives detonated in a blasting round on blast vibration.

In order to get the zone of influence of total explosives weight detonated in a blasting round, graphs of percentage difference in PPV due to detonation of large and comparatively small amounts of total explosives weight versus respective scaled distances have been plotted for each set of trial blasts. When three trial blasts have been conducted at a site with large, intermediate, and comparatively small quantities of total explosives weight, the percentage difference between PPV due to large amounts of explosives and intermediate amounts of explosives has been plotted. Another graph between percentage differences of PPV due to intermediate amounts of explosives and small amounts of explosives has been plotted for comparison and study purposes. From the plots, the

Table 4 Summarized results of the trial blasts conducted at four sites representing the impact of total explosives weight on blast vibration at various scaled distances

Set no.	Mine site	Hole depth (m)	No. of holes	Total explosives weight detonated in a blast round		Max. explosives weight/delay (kg)	Obtained scaled distance beyond which the impact of total charge diminishes (m/kg$^{0.5}$)
				Large (kg)	Relatively small (kg)		
1	Jayant project	35	72	141,705	88,820	4200	11.57
2		25	52	66,916	1285	1285	10.87
3		16	9	5814	681	681	7.47
4		28	54	84,456	62,400	4695	10.95
5		11	85	28,740	325	325	8.13
6		34.5	97	197,407	111,000	2200	18.1
7		14.5	2	1060	530	530	6.95
8		35	76	143,412	96,103	2100	13.2
1	Nigahi project	18.2	24	17,496	7290	3120	7.16
2		16	2	1270	635	635	6.15
3		18.5	3	2220	1480	740	6.43
4		18.5	3	2220	1480	740	6.06
5		18.5	3	2220	1480	740	6.06
6		40	64	198,400	124,800	3120	15.19
1	Kusmunda project	13.5	7	1963	1120	280	7.47
2		14	9	3200	2100	1125	6.71
1	Sonepur Bazari project	15.5	36	12,188	4287	350	9.35
2		29	28	35,944	24,230	1300	9.7
3		30	32	41,703	19,326	1350	8.71
4		15	26	9113	6669	350	8.01
5		14.5	15	4430	3004	360	7.11
6		15	12	4200	2180	360	8.17
7		15.5	24	8790	2450	380	7.69
8		7.5	24	2400	1800	200	6.36
9		14	2	600	300	300	5.88
10		14	6	1800	600	300	5.77
11		13	4	1200	600	300	6.35
12		13	4	1200	600	300	6.35

threshold value of scaled distance has been considered beyond which the difference in PPV of large and small total explosives weights in a blast round is below 10%.

To analyze the influence of total explosives weight detonated in a blasting round on blast-induced ground vibration, the difference in the recorded PPV level due to detonation of large and comparatively small total explosives weights detonated in a blast at Sonepur Bazari project is presented in Table 3. Figure 5 presents the plot of the recorded PPV and their percentage difference due to detonation of large and comparatively small amounts of total explosives weight. It has been found that at shorter distances, the effect of total explosive charge was found to be more in comparison with larger distances. The reason for this may be due to the damping of shock waves at longer distances.

Similar trends were observed from the recorded PPV and their percentage differences due to detonation of large and comparatively small amounts of total explosives weights for trial blasts conducted at Jayant, Nigahi, and Kusmunda projects.

The percentage difference in PPV recorded due to detonation of large and comparatively small amounts of total explosives in blasting rounds is in the range of 1.31 to 80.45%. The scaled distance values from all the plots were determined corresponding to the difference in PPV value below 10%. This limit of percentage difference in PPV has been considered to filter out error in mounting of geophones, noise, signal to noise ratio, if any, and other abnormalities in recording of vibration. It has been noticed that when there is a significant difference (say 1:50 or more) in the total amount of explosives in a set of experiments, the recorded percentage difference was up to 80.45. Only two such types of cases have been observed out of 28 sets of trial blasts. The reason may be that in these 2 sets of experiments, the first blast was a single-hole blast and the second blast was a production blast where the number of holes was more than 40, causing overlapping of waves due to delay blasting. In these two cases, the obtained scaled distance has been considered, taking the percentage difference in PPV of 74.23% and 68.26%. The summarized details of the observed scaled distance value beyond which the influence of total charge is minimal based on the records of percentage difference in PPV are presented in Table 4.

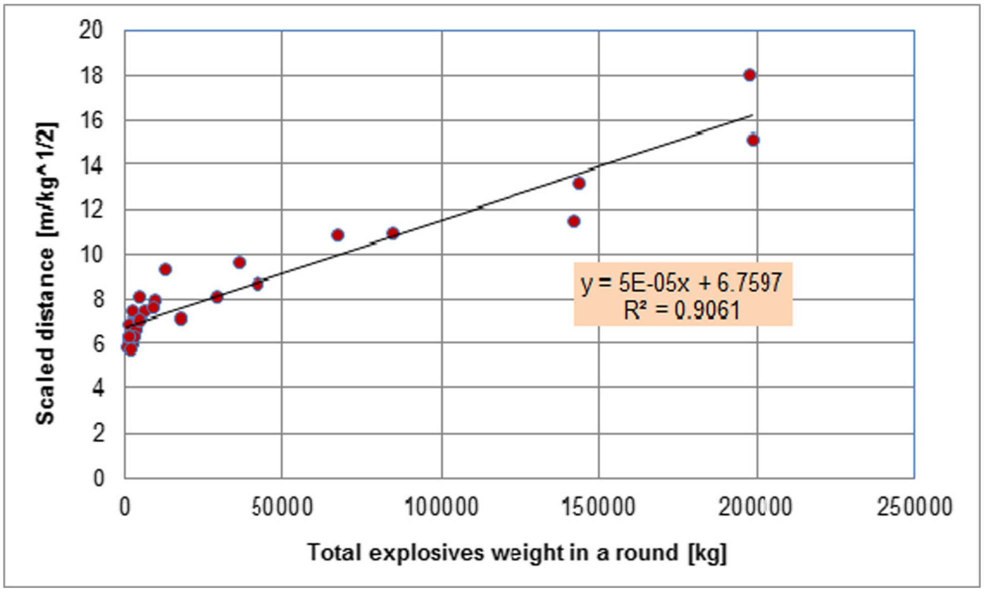
The weight of total explosives detonated in a blasting round is a function of hole depth and number of holes detonated in a blasting round. Figure 6 represents the respective scaled distance value for different large amounts of explosives detonated in a blasting round which shows that there is a significant impact of total explosives weight on blast-induced vibration.

Conclusions

The analyses of vibration data recorded from detonation of blast holes at shovel and dragline benches with varying hole depths from 7.5 to 40 m show that there is a significant influence of total weight of explosives detonated in blasting round on blast-induced vibration at near-field locations. With the study conducted, the following conclusions have been drawn:

- The impact of total weight of explosives on blast-induced ground vibration due to experimental blasts of 1 to 6 holes in a round has been found to go up to scaled distance of 6.95 m/kg$^{0.5}$ beyond which it diminished. While in the case of production blast of shovel benches having hole depths ranging from 7.5 to 18.5 m, the impact of total weight of explosives on blast-induced ground vibration has been recorded up to scaled distance of 9.35 m/kg$^{0.5}$.

Fig. 6 Plot of impact of total explosives weight in blast round on generation of vibration at various scaled distances



- At dragline benches having hole depths from 25 to 40 m, the impact of total weight of explosives detonated in a round on blast vibration has been recorded up to scaled distance of 18.1 m/kg$^{0.5}$.
- The statistical analyses of the scaled distance values obtained for all range of hole depths and total weight of explosives detonated in a blast round clearly indicate that the impact of total weight of explosives on blast-induced vibration is in the range of scaled distance of 6.75 to 16.5 m/kg$^{0.5}$ for a maximum total weight of explosives detonated in a blasting round of 200,000 kg.

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