Control Measures for Ground Vibration Induced by Blasting at Coal Mines and Assessment of Damage to Surface Structures

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ABSTRACT

This paper deals with ground vibration induced by blasting and its impact on surface structures at two coal mines. Field data from production and single hole blasts were analysed to study the influence of controllable variables on peak particle velocity and frequency of ground vibration. Besides maximum charge per delay, studies at Kamptee OCP, WCL revealed that the delay interval, the availability of free faces, the slurry explosives used had significant influence whereas the total charge had insignificant influence on peak particle velocity. Studies at OC-2, SCCL also confirmed the influence of the delay interval on peak particle velocity. Frequencies of ground vibration were confined to certain limits that could not be altered by modifying the blast design parameters.

The assessment of damage was carried out for four existing structures at Kamptee OCP and for three test structures, similar to houses/hutments found in mining areas, constructed at OC-2. Pre- and post-blast survey of these structures was systematically carried out along with vibration monitoring for a large number of blasts. No visible damage to these structures was observed even at vibration levels more than four times the permissible limits. Therefore there is a need to revise the current statutory limits, which are conservative, in the interest of the mining industry.

Keywords: Vibration control, Structure damage, Surface mines

1. INTRODUCTION

The ground vibration measured at a location is influenced by a number of parameters. Some of them like blast geometry, charging patterns, initiation sequence, explosive characteristics and delay timing are controllable while others like rock properties are uncontrollable. The degree to which each of these parameters has influence on ground vibration is to be established so that the most significant parameters can be suitably modified to control ground vibration within the permissible levels. An attempt is made in this paper to study the influence of some of the controllable variables on ground vibration.

Ground vibration can cause damage to nearby structures. Therefore there must be a proper regulation to protect them from the deleterious effect of ground vibration. Different countries adopt different standards of ground vibration depending on the type and the construction materials used. In India, permissible limits of ground vibration for different types of structures have been specified by the Director General of Mines Safety (DGMS) through its Circular No. 7 of 1997. The mining industry has been implementing the DGMS standard over the last eight years. It has been found that the vibration levels in this standard, particularly at frequencies below 8 Hz, are conservative. An overview of the observed parameters of ground vibration at different surface mines revealed that coal and lignite mines are incurring heavy penalties in complying with the vibration limits because of low frequencies that cannot be always controlled by blast design. Non-coal mines and quarries are in a better position due to relatively high frequencies (Adhikari et al, 2005). While no compromise can be made with regard to protection of surface structures from ground vibration, permissible vibration levels should not be unduly restrictive, posing constraints to mining operations.

A numbers of studies related to ground vibration and structure damage have been conducted abroad (Siskind et al, 1980) but their findings may not be directly applicable for surface structures that are normally found in mining areas in India. Some work has been conducted in India (Singh et al, 1993) but they are not conclusive enough to determine threshold values of damage vis-à-vis permissible levels of ground vibration. Therefore, an assessment of damage to surface structures is conducted at two opencast mines, namely Kamptee OCP, Nagpur area of WCL and OC-2, Godavarikhani area of SCCL. Based on the results, the possibility of revising the DGMS vibration standard has been examined.

2. BLAST DESIGN PARAMETERS

Kamptee OCP extracts coal seams that were developed earlier by Bord & Pillar method of underground mining. Blastholes of 150 mm diameter were drilled both in coal and sandstone benches up to a depth of 7.0 m. Burden and spacing were maintained at 4.0 m and 5.0 m respectively. Cartridged slurry explosives of different companies were used intentionally for the purpose of this study. The diameter and weight of the cartridge was 125 mm and 6.25 kg respectively. Normally each hole was charged with 50 kg of explosives having column to primer ratio of 6:2. Drill cuttings were used as stemming

material and stemming length varied from 2.5 to 3.0 m. Most of the blasts were fired with shock tube initiation system using in-hole delays of 200 or 250 ms, surface delays of 25 ms within the rows and 65/67 ms between the rows. A few blasts were fired with detonating cord downline with surface connectors of 65 or 67 ms between the rows.

OC-2 is well-known for in-pit crushing with conveying technology. Drilling, blasting and excavation with conventional shovel dumper combination is limited to feed the in-pit crusher. Ground vibrations due to blasting at OC-2 were monitored at different distances for several blasts. Blast design and other relevant parameters such as hole diameter, hole depth, burden, spacing, number of holes, number of free faces, initiation systems, total charge, maximum charge per delay, and distance from the blast to the transducers were recorded. The mine used either 150 mm or 250 mm hole diameter, and blasts were initiated either with shock tube initiation system or with conventional system. All blasts were conducted with site-mixed emulsions. The resulting vibration parameters such as peak particle velocity, peak vector sum and frequency were recorded.

3. GROUND VIBRATION PARAMETERS

3.1 Normal Blasts

Peak particle velocity (PPV) and frequency are the two important parameters of ground vibration that determine the damage potential to structures. Using the vibration data for all blasts, peak particle velocity was plotted against the scaled distance for Kamptee OCP (Fig. 1) and for OC-2 (Fig. 2). The best-fit equation with the correlation coefficient for each mine is shown in the respective plot. The scaled distance is defined as the distance from the blast to the monitoring location divided by the square root of the maximum charge per delay. These equations can be used for prediction of ground vibration at the mines. Alternatively, when the permissible PPV and the distance between the blast and the structure are known, maximum charge per delay can be calculated by substituting these values in the predictor equation.

The frequency of ground vibration for Kamptee OCP is shown in Fig. 3. It is mostly confined to the range of 5-20 Hz. The frequency for OC-2 is shown in Fig. 4. It is mostly confined to the range of 5 – 25 Hz. At other coal mines too (Adhikari et al., 2005), frequency was low and within the range that could cause resonance in the structures.

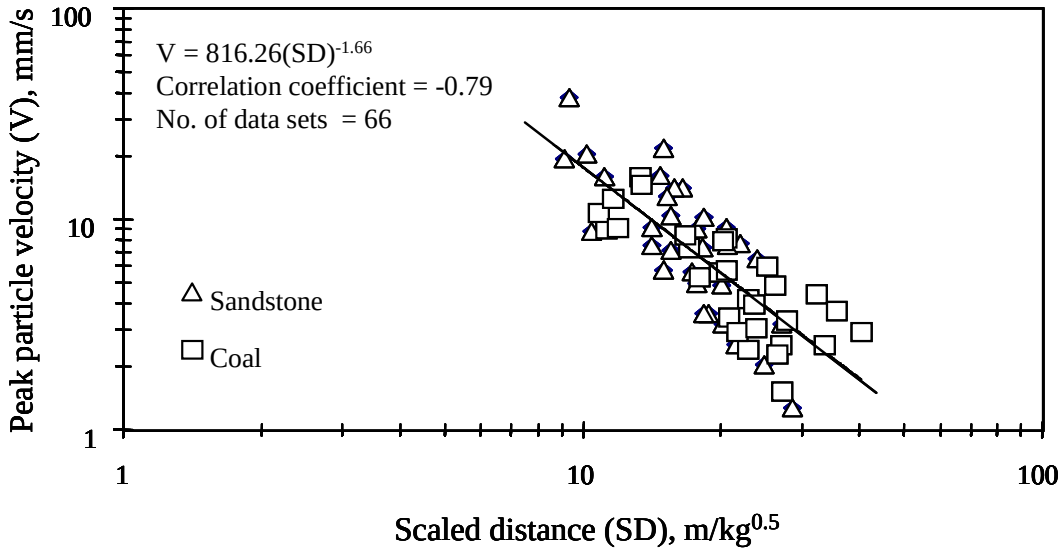


Fig. 1 - Peak particle velocity versus scaled distance for Kamptee OCP

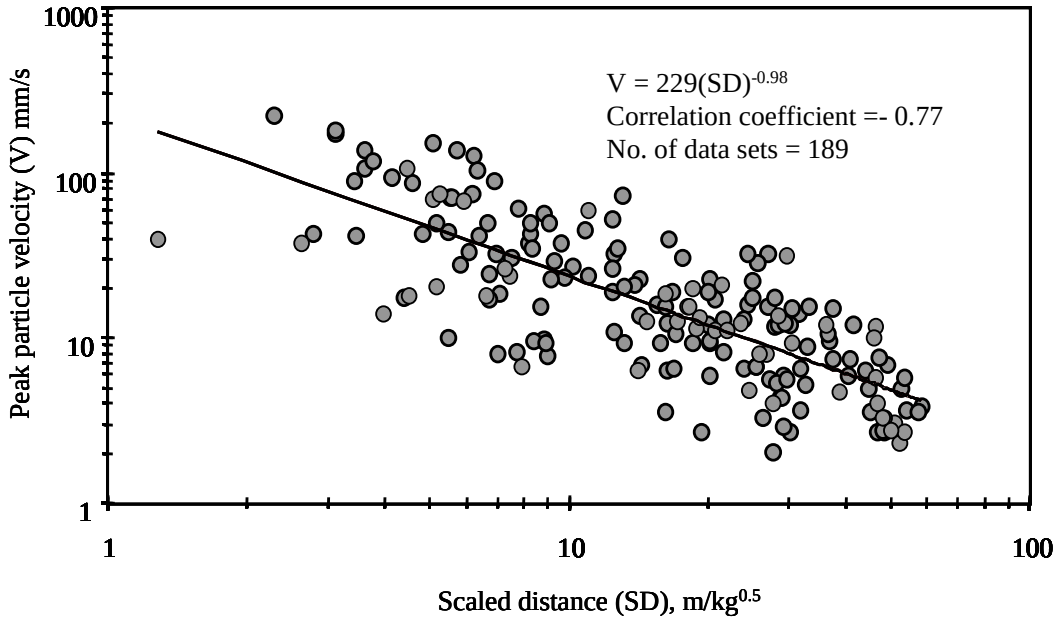


Fig. 2 - Peak particle velocity versus scaled distance for OC-2

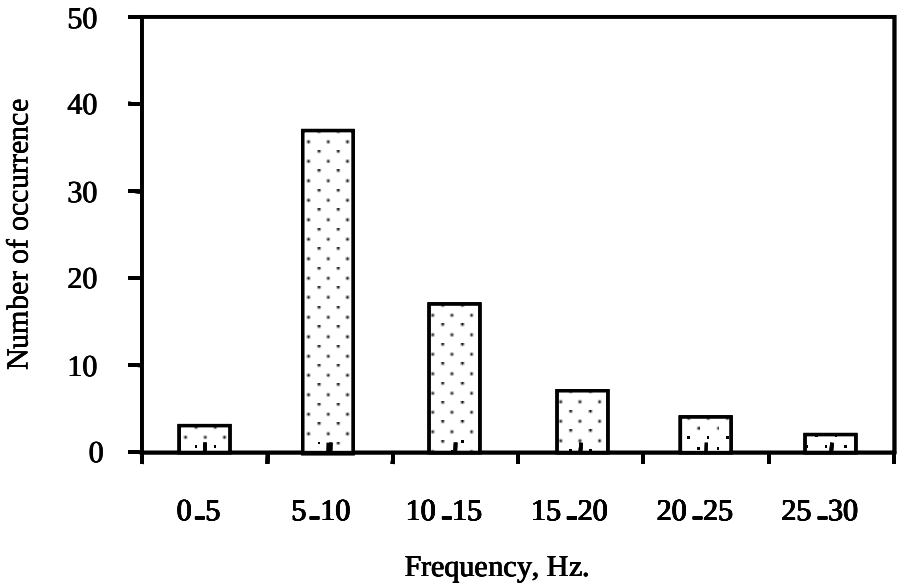


Fig. 3 - Frequency of ground vibration at Kamptee OCP

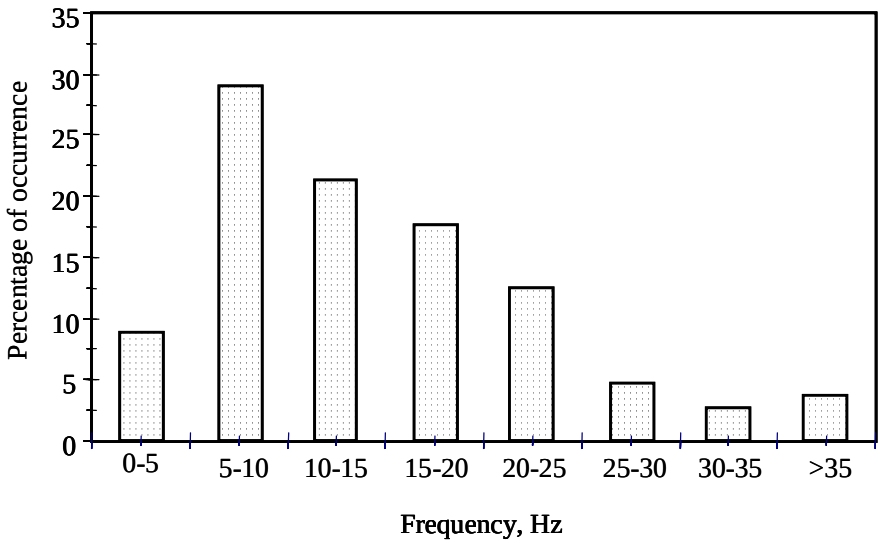


Fig. 4 - Frequency of ground vibration at OC-2

3.2 Single Hole Blasts

A single hole blast with drilling and charging parameters identical to those of overburden blasts at Kamptee OCP was conducted in the top sandstone bench. The ground vibrations were recorded at two locations. Fig. 5 shows the waveform of the peak component (longitudinal) recorded at a distance of 146 m and its frequency spectrum. Table 1 shows the peak values and the associated frequencies of ground vibration. For Kamptee OCP, the attenuation of peak values from 146 m to 188 m is normal (Fig. 1), but for OC-2, the attenuation from 69 m to 120 m is faster (Fig. 2) for some unknown reasons. The frequency of single hole blast, which varies from 5 to 18 Hz, is similar to that of the normal blasts.

Table 1- Measured ground vibration from the single hole blast at two coal mines

Mine	Distance (m)	Peak value (mm/s)			Frequency (Hz)		
		Trans	Vertical	Long.	Trans.	Vertical	Long.
KOCP	146	1.65	3.43	4.19	5-11	7-9	5-7
KOCP	188	1.27	2.29	3.68	6-11	6-18	5-11
OC-2	69	14.70	21.30	11.00	15-24	16-24	10-13
OC-2	120	4.19	5.46	3.30	15-23	10-26	13-18

Note: Trans. = Transverse and Long.= Longitudinal, KOCP= Kamptee OCP

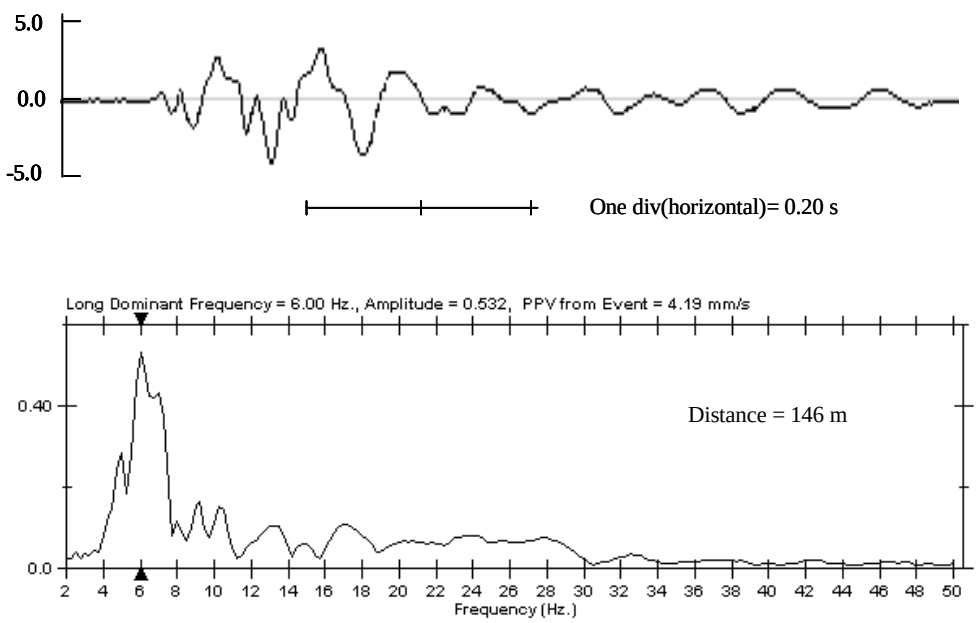


Fig. 5 - Single hole waveform and its frequency analysis

Considering the normal practices at OC-2, a single hole blast was also conducted in hard sandstone using hole diameter of 250 mm, hole depth of 9 m, burden of 6 m and charge per hole of 120 kg. The measured vibration parameters are given in Table 1. The frequency, which varies from 10 to 26 Hz, is again similar to that of the normal blasts. The ground itself in all probability acted as a big filter that attenuated higher frequencies, allowing only lower ones. Otherwise, how was it possible that there was no significant presence of higher frequencies in the single hole waveforms even at close distances? In such a situation, any attempt to control frequency by changing delay interval (Anderson et al, 1982) simply does not work.

4. INFLUENCE OF CONTROLLABLE VARIABLES ON PPV

As there was little scope to vary hole diameter, burden, spacing, etc, some other parameters like the explosives used, availability of free faces and total charge weight in a round were varied at Kamptee OCP to study the influence of these parameters on ground vibration. At OC-2, burden, spacing etc varied so widely that it was not possible to study the influence of these parameters on ground vibration by simple or multiple regression analysis.

4.1 Influence of Delay Interval

The single hole blast waveforms recorded at the mines were used to simulate the influence of delay interval between the two charges using the principle of linear superposition of waves (Hinzen, 1988). It was assumed that the waveforms from the single hole blast were reproducible and were determined primarily by the geological characteristics of the path between the blast and the monitoring location.

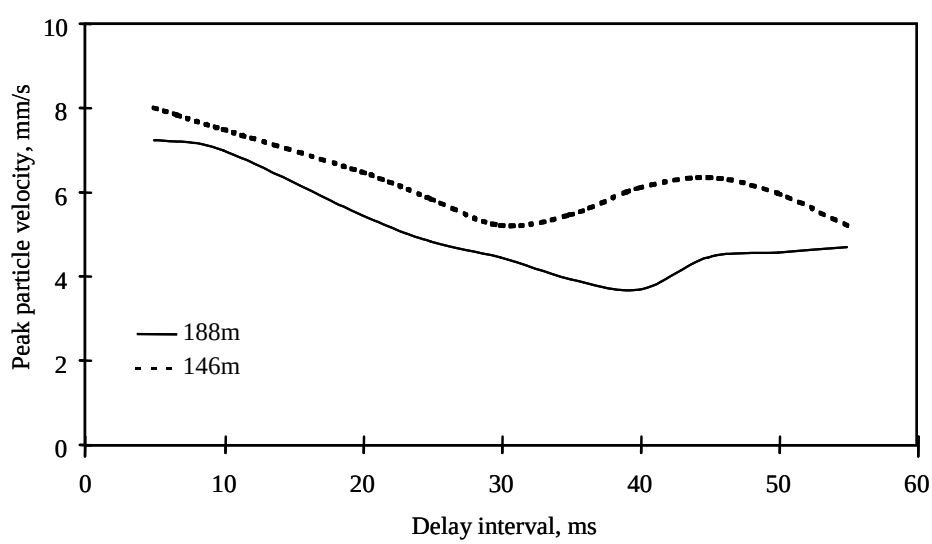


Fig. 6 - Influence of delay interval on peak particle velocity at Kamptee OCP

The single hole waveform shown in Fig. 5 was used as the seed waveform. Fig. 6 shows the effect of delay timing on PPV for the conditions of Kamptee OCP. Due to constructive and destructive interferences of waves, PPV decreases with delay interval up to a certain value and then it starts increasing. The delay interval with the lowest PPV is referred as the optimum delay that can be used for blast design. For Kamptee OCP, PPV is the lowest when the delay interval is around 30 ms at a distance of 146 m and around 40 ms at a distance of 188 m. This indicates that waveforms should be recorded at the nearest structure for effective control of PPV.

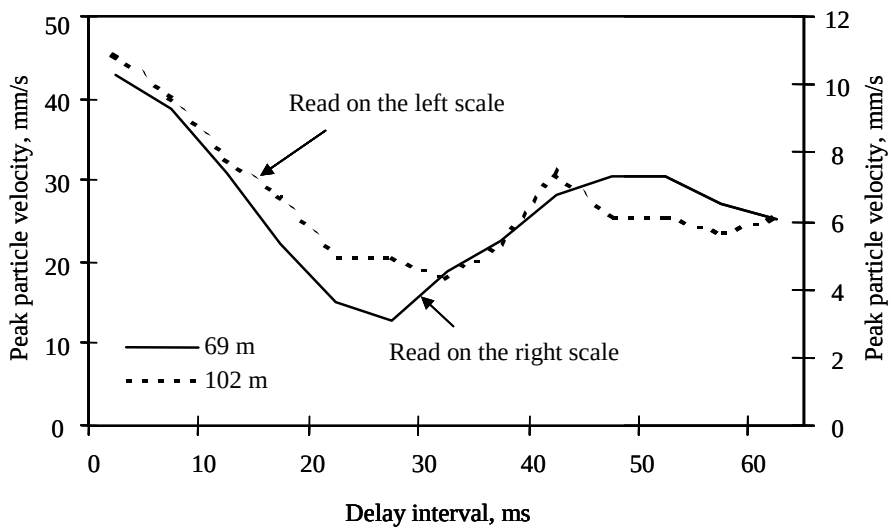


Fig. 7 - Influence of delay interval on peak particle velocity at OC-2

Using the similar approach, the influence of delay interval was investigated for the conditions of OC-2. The delay of 25 ms was found to produce the lowest vibration (Fig. 7). This agrees with the mine's practice.

4.2 Influence of Explosives

It has been found that the type of explosives has significant influence on ground vibration. Hossaini and Sen (2004) have found that ANFO generates lesser vibration than slurry explosives. Among the different blends tested, Hunter et al (1993) found that the explosive with lower density and lower detonation velocity produced lower level of ground vibration. As the shock energy component of an explosive gives rise to unwanted vibrations (Harries and Gribble, 1993), explosives having larger portion of gaseous energy should be preferred.

At Kamptee OCP, only one type of explosive was used. That was cartridged slurry explosive but there were three suppliers. The explosives supplied by different suppliers were designated as Explosive-1, Explosive-2 and Explosive-3. The vibration data with

different explosives were sorted out. Fig. 8 shows the peak particle velocity against scaled distance with different explosives.

It is observed that there is a significant difference in ground vibration produced by these explosives. Among the three, Explosive-2 has produced the lowest ground vibration. However, the results are valid within the range of range of experimental data.

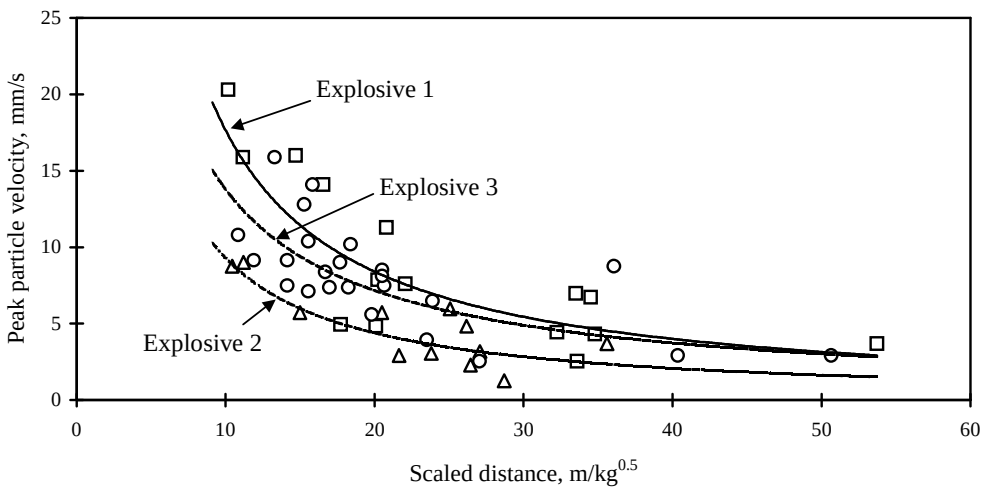


Fig. 8 - Influence of explosives on ground vibration at Kamptee OCP

4.3 Influence of Free Faces

It is known from the crater theory that, if a charge is deeply buried with no free face nearby, the rock is not adequately broken and most of the energy goes into the generation of seismic waves. When it is buried at shallow depth, the same charge may break the rock properly while producing lower ground vibration. In case of bench blasting which normally has one or more free faces, vibration should decrease as the number of free face increases. Obviously, the worst results are expected from a bench blast in the absence of free faces.

At Kamptee OCP, the number of free faces (excluding the top surface) varied from zero to two. After grouping the data, regression analysis was carried out separately for each confinement condition. Fig. 9 shows that the PPV is indeed higher when there is no free face and it decreases as the number of free faces increases. Although there is no clear segregation of the data, the trend is clear and the relation is valid within the range of the experimental data. Ground vibration can therefore be reduced by proper development of benches with free faces. In a multi-row blast, proper delay sequence and delay timing must be ensured to create successive (internal) free faces.

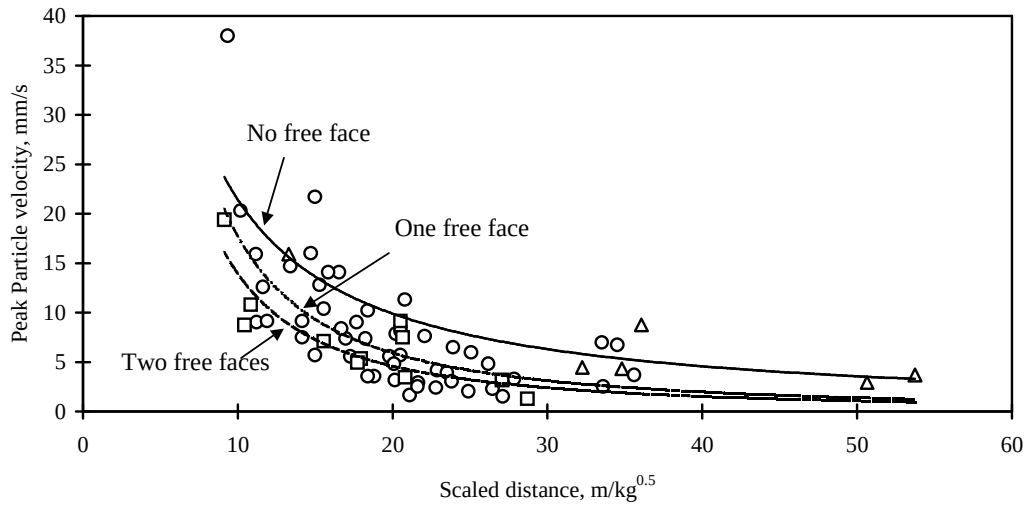
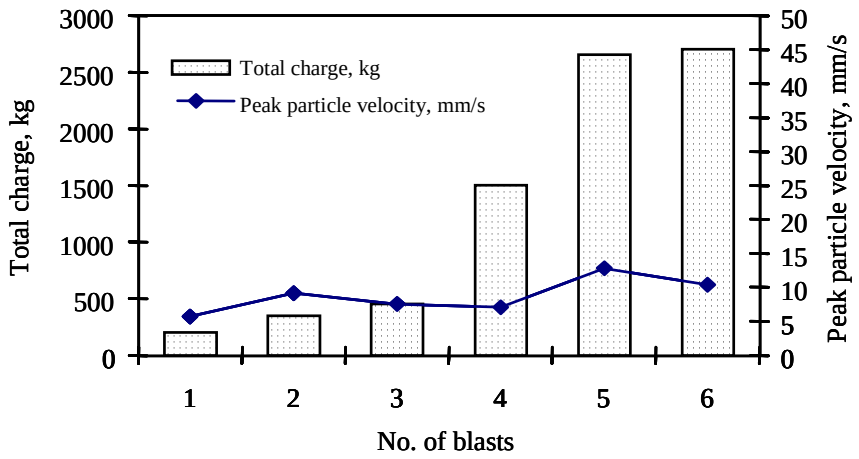


Fig. 9 - Influence of free faces on peak particle velocity at Kamptee OCP

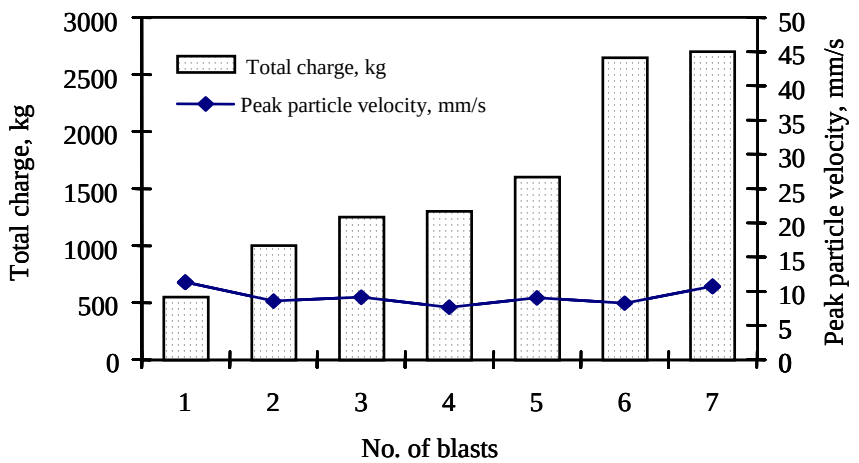
4.4 Influence of Total Charge

It is generally established that the total charge in a blast has insignificant influence on ground vibration if the delay interval is sufficient to avoid constructive interference between the waves generated by the different group of blast holes (Jimeno et al, 1995). However, Singh (1998) has reported that the total charge in a round affects the ground vibration at distances close to the blasts and its effect diminishes quickly with distance.

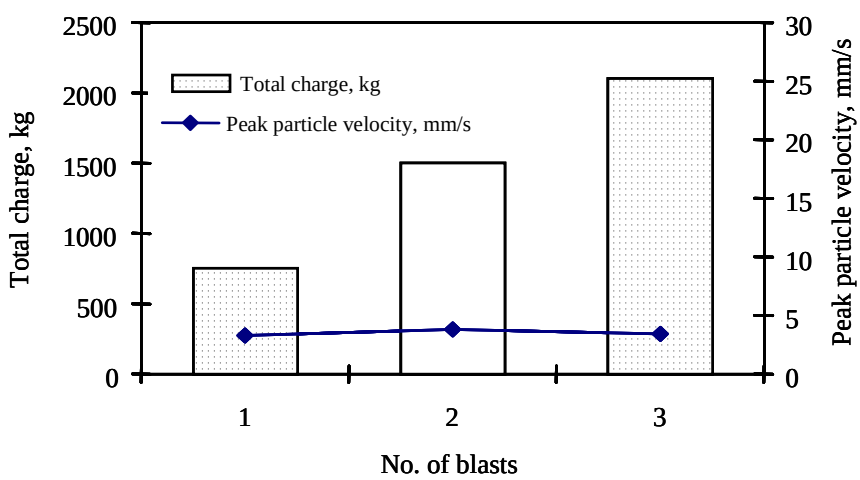
Fig. 10 shows PPV monitored at 100-110 m, 145-155 m and 250-260 m distances and the corresponding total charge for a number of blasts. All the blasts had the same maximum charge per delay of 50 kg. As there is some variation in ground vibration at closer distances and minimal at the far off distances, it may be inferred that the influence of other parameters on ground vibration also diminishes as the distance increases. Based on the analysis, there is no justification for restricting total charge in a blasting round which has been the normal practice in the mine.



(a) At a distance of 100 – 110 m



(b) At a distance of 145 – 155 m



(c) At a distance of 250 – 260 m

Fig. 10 - Influence of total charge on ground vibration at Kamptee OCP

5. ASSESSMENT OF DAMAGE TO SURFACE STRUCTURES

5.1 Selection/Construction of Test Structures

Surface structures such as evacuated/abandoned houses around the mine were surveyed so that they could be used for damage studies. At Kamptee OCP, several structures were being demolished as the mine was progressing towards the structures. Four of them were identified for damage studies. Two of them were single storied houses and third one was Colliery Manager's old office building (Fig. 11), all made of bricks with cement mortar. The last structure was over 30 years old Kali temple which was a concrete structure having a conical roof.

Fig. 11 – Existing structure selected for damage studies at Kamptee OCP

Since there were no suitable structures that could be used for damage studies around OC-2, three types of test structures representing typical residential structures in mining areas were constructed exclusively for this purpose (Fig. 12). The followings were the type of structures:

a) Mud structure
b) Single storey two room brick structure with mud mortar
c) Double storey three room brick structure with cement mortar.

Fig. 12 - Test structures constructed exclusively for damage studies at OC-2

5.2 Damage Assessment Method

Ground vibrations were monitored adjacent to the structures selected or constructed for damage studies, four at Kamptee OCP and three at OC-2. Pre- and post-blast survey of these structures was conducted for each blast. A large number of blasts were monitored over a period of six months at each mine. In collaboration with mine personnel, blasts were planned such that the structures were subjected to ground vibration from a lower to higher level. All structures had cracks from natural causes, including settlement and periodic changes in atmospheric conditions. The length and width of these cracks were marked. Pre- and post-blast observations were made for any noticeable change in the existing cracks and for the formation of new ones.

5.3 Damage Assessment at OC-2

Fig. 13 shows the plots of peak particle velocities against the corresponding frequencies for structures at OC-2. Peak particle velocity in excess of 20 mm/s was found to be lower than the threshold value of damage to these structures over a frequency range of 4 to 40 Hz. The mud structure was very much affected by the weather itself. Numerous cracks appeared on the walls after a good sunshine and disappeared after a heavy rain. Progressive cracking was observed on the walls just below the beam due to static loading. Under these circumstances, observation of damage to the mud structure did not serve the purpose.

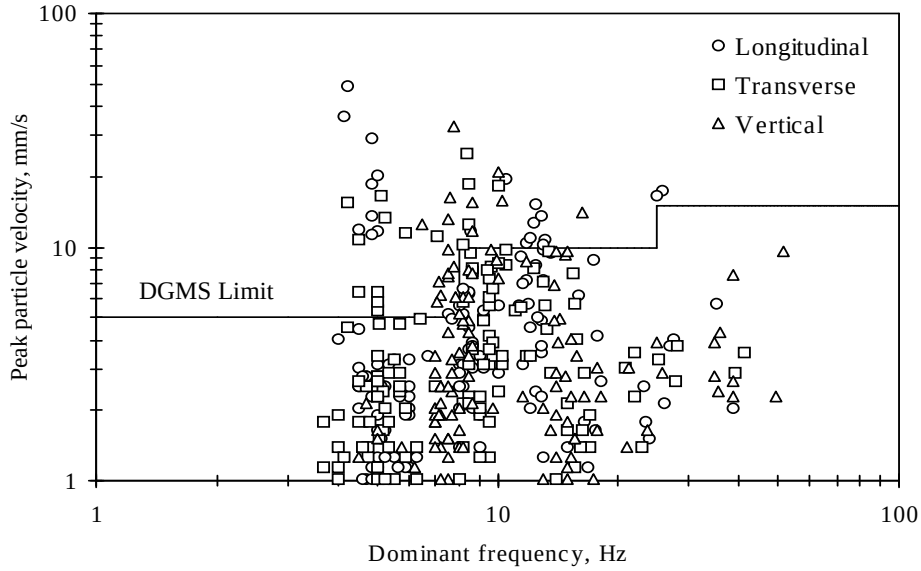


Fig. 13 - Measured ground vibrations vis-a-vis the DGMS limits for test structures at OC-2

5.4 Damage Assessment at Kamptee OCP

Similar plots of peak particle velocity against the frequency were made for the selected structures at Kamptee OCP (Fig. 14). The DGMS limits for the respective category are also drawn in these figures. No damage was observed in any of the structures when PPV exceeded 20 mm/s at frequencies varying between 5 and 27 Hz.

5.5 Possibility of Increasing Permissible Limits

The measured peak particle velocities at the test structures were lower than the threshold value of damage. Nevertheless, this study established that peak particle velocity up to 20 mm/s is absolutely safe over a frequency range of 5 to 30 Hz. Since human perception of ground vibration begins at a very low level (< 1.0 mm/s), structure damage rather than human perception should be the criteria for any ground vibration standard. On this ground, the permissible PPV of 5 mm/s at low frequency may be increased at least to 10 mm/s. This is also substantiated by the following facts:

1) Prior to the DGMS Circular, peak particle velocity of 12.5 mm/s was widely used in India and there were no cases of actual damage to surface structures even at low frequency.
2) Permissible level of ground vibration at low frequency is 12.5 mm/s as per U. S. Bureau of Mines (Siskind et al, 1980) and 10 mm/s as per Australian standard (AS2187-1993).

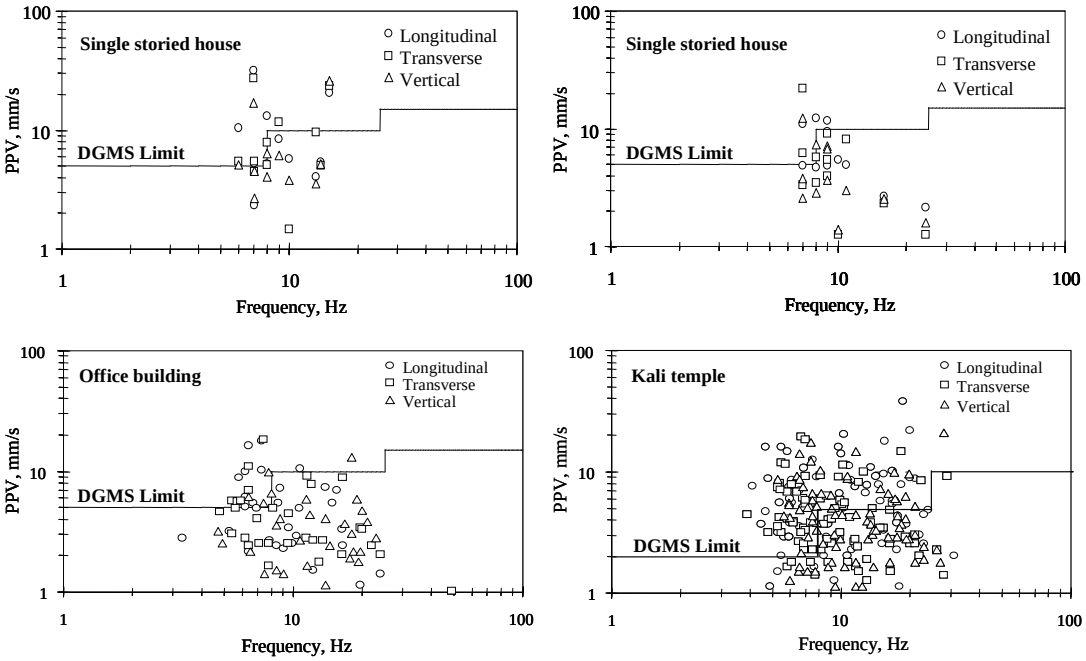


Fig. 14 - Measured ground vibrations vis-a-vis the DGMS limits for different structures at Kamptee OCP

3) Environmental changes and human activities produce strains equivalent of 12-15 mm/s and even higher in some cases. There is no logic to limit the ground vibration below the level caused by the environmental changes.
4) A research study in China (Yuan et al, 2002) recommended that the low-rise residential houses are safe for a vibration level of 20 mm/s at frequencies below 15 Hz.
5) Measurable and observable damage to internal plasterboard cladding occurred when peak particle velocity exceeded 70 mm/s at a frequency of 18 Hz (Moore et al, 2003).

The DGMS regulation was formulated at a time when the safety of surface structures due to blasting was increasingly important but limited technical information was available. Over the last eight years, the situation has changed. Two options are now available with the DGMS. They can either retain the present regulation that is absolutely safe but severely restricts the blasting operation or revise the present regulation permitting higher limits that are still safe. Whichever option is followed, it will have enormous consequences on surface mining in future. It is the second option that is the need of the mining industry.

Most vibration standards permit higher peak particle velocity at higher frequency. The DGMS standard also does the same but it has not rationally categorised the frequency bands. A proposal has been made to categorise frequencies based on structure response (Adhikari et al, 2004), which may make its way into the revised version of the DGMS standard.

6. CONCLUSIONS

Of the two parameters of ground vibration, peak particle velocity (PPV) can be controlled but the control measures may severely restrict the blasting operation. Besides maximum charge per delay, other variables such as delay interval, the explosives used and the numbers of free faces were found to have significant influence whereas total charge had insignificant influence on PPV. Frequency, on the other hand, could not be increased beyond its normal range as it was primarily controlled by the ground conditions.

The observation of structures for damage due to ground vibration at two coal mines revealed that the DGMS vibration levels are very conservative. While such conservative levels certainly enhance the factor of safety, they pose undue restriction on mining operations adjacent to surface structures. The DGMS may therefore revise the existing vibration limits without defeating its basic purpose - adequate safety of surface structures.

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References

Adhikari, G.R., Jain N.K. and Gupta, R.N. (2004) Categorisation of vibration frequency based on structure responses vis-à-vis vibration standards, *Journal of Mines, Metals & Fuels*, November 2004, pp. 275-277, 268.

Adhikari, G.R., Theresraj, A.I., Balachander, R., Venkatesh, H.S. and Gupta, R. N. (2005) Observed parameters of ground vibration at surface mines vis-à-vis the DGMS standard, *Journal of Mines, Metals and Fuels*, December 2005 (in press).

Anderson, D.A., Winzer, S.R. and Ritter, A.P. (1982) Blast design for optimising fragmentation while controlling frequency of ground vibration. *Proc. 8th Conf. Explosives and Blasting Technique*, New Orleans, pp. 69-89.

Harries, C. and Gribble, D.P. (1993) The development of low shock energy explosive ANRUB, *Proc. 4th Int. Symp. Rock Fragmentation By Blasting*, Vienna. pp. 379-386.

Hinzen, K.G. (1988) Modelling of blast vibrations, *Int. Journal Rock Mech. Min. Sci. & Geomech. Abstr*., Vol. 25, No. 6, pp. 439-445.

Hossaini, S.M.F. and Sen, G.C. (2004) Effect of explosive type on particle velocity criteria in ground vibration, *The Journal of Explosive Engineering*, July/August, pp. 34-39.

Hunter, C., Fedak, K. and Todoeschuck, J.P. (1993) Development of low density explosives with wall control applications, *Proc.19th Annual Conf. Explosives and Blasting Technique*, Jan, 31-Feb. 4, San Diego, California, USA, ISEE, pp. 549-555.

Jimeno, C.L., Jimeno, E.L. and Carcedo, F.J.A. (1995) *Drilling and Blasting of Rocks*, A. A. Balkema, Rotterdam, Netherlands.

Singh, B., Pal Roy, P., Singh, R.B., Bagchi, A., Singh, M.M. and Nabiullah, Md. (1993) *Blasting in Ground Excavations and Mines*, Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi.

Singh, P.K. (1998) *A Study on Ground Vibrations due to Rock Blasting*, Ph.D. Thesis, Technical University of Clausthal, Germany, Papierflieger, Clausthal-Zellerfeld.

Siskind, D.E., Stagg, M.S., Kopp, J.W. and Dowding, C.H. (1980). *Structure Response Produced by Ground Vibration from Surface Mine Blasting*, U.S. Bureau of Mines, RI 8507.

Yuan, L., Jianwu, L., Quanjun, X., Xizhi and Xiang, Z. (2002) Study on low-rise residential house's damage caused by blasting, *Proc. 7th Symp. Rock Fragmentation by Blasting*, China, pp. 605-609.

Moore, A.J., Richards, A.B. and Gad, E. (2003) Structural response of brick veneer houses to blast vibration, *Proc. 29th Annual Conf. Explosives and Blasting Technique*, ISEE, Nashville, Vol. 2 (Available in CD-ROM)