Characterisation of blast vibration generated from open-pit blasting at surface and in belowground openings

P. K. Singh* **and M. P. Roy**

The safety and stability of underground coal mine workings may be affected by opencast mines operating in close proximity. A study was conducted to investigate the level of vibration generated from opencast blasting in the nearby underground coal mine openings and at a similar distance at the surface. Eight production blasts were performed and nineteen blast vibration data sets were recorded on the surface behind the opencast blasting face and also in underground openings at similar distances. It was observed that the magnitude of vibration recorded on the surface was higher than those recorded in underground openings. The findings of the study are of importance for the assessment of safety and stability of unapproachable belowground installations affected by the vibration produced due to opencast blasting.

Keywords: Blast vibration, Frequency, Underground working, Blasting, Open-pit blasting

Introduction

The ever increasing demand for coal in India has necessitated large opencast operations and extensive deposits of coal being extracted by open-pit mining. The contribution of coal is ~61% in the total energy generation of the country and opencast mines are contributing ~84% of total coal production. The mines which were planned earlier away from dwellings and other structures are now approaching them. There are a number of situations in India where underground and opencast mines are operating side by side.

The opencast blasts generate seismic disturbances, which in turn may damage the support system, ventilation/isolation stoppings and water dams in underground workings. They may induce opening of cracks in the underground strata, rendering them unstable, as well as damage in the surface structures/buildings. There is also a possibility that spalling of coal may occur in some adjoining underground workings which may lead to spontaneous heating over a period of time. The seismic disturbance induced by blasting will depend on the total explosive energy released during blasting and their nearness of the underground working to the operating opencast mines. The quality of rock in which an opening has been created may have a significant influence on the amount of damage done to it by opencast blasting. Considerable research has been conducted on blast induced vibrations and various damage criteria have been established for surface structures (DIN 4150, 1986; Siskind *et al.*, 1989; Dowding, 1996; Singh *et al.*, 1997; Kahriman, 2001; 2002; 2004; Singh, 2002; Dowding and McKenna, 2005; Gad *et al.*, 2005; Singh *et al.*, 2005). The present paper reports a stability analysis of underground workings by monitoring of blast vibration impact on the underground workings of Chora 10 pit colliery due to blasts being conducted at Sonepur Bazari project. Vibrations at similar distances on the surface were also monitored to document their likely impact on surface structures and for subsequent analyses to establish the relationship between the level of vibration on surface and belowground workings.

Previous studies on underground damage due to vibrations from opencast blasting

Considerable uncertainty exists as to what characteristics of seismic waves provide the best measure of their potential to damage underground openings. Only a limited number of case studies has been published in this regard. The use of a single index of blast vibration, such as peak particle velocity (PPV) or peak particle acceleration, is common in blasting operations. The mining industry's familiarity with PPV and its relative ease of measurement have generally formed the basis of blast damage criteria for underground opening.

In fact, the response of rock material to dynamic loading is strongly affected by strain rate. In dynamic loading, the stress can exceed the material strength, but it may not damage the material if the duration is short. Blast damage is accumulated as a function of time and the applied stress. A single field variable, (e.g. stress, strain and particle velocity), at any location and time can not be expected to characterise the dynamic fracture

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Blasting Research Group, Central Institute of Mining and Fuel Research, Dhanbad 826 001, India

*Corresponding author, email pradeep1_2@yahoo.com

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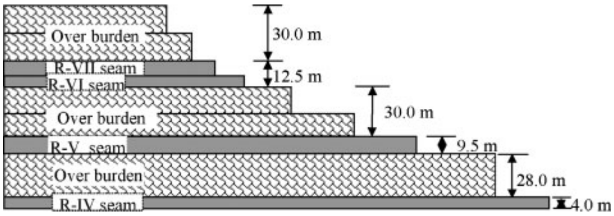
process. Damage criteria for surface structures have been reported by many researchers but for the underground roof rock or pillars, particularly for underground coal mines, published data are very scarce.

Rupert and Clark (1977) concluded that only minor damage in the form of localised thin spalls and collapse of previously fractured coal ribs resulted from blasts having an associated PPV in excess of 50 mm s^{-1}. They noted no other major damage or changes in the mine condition (roof bolts and convergence). Jensen *et al.* (1979) reported no roof failures even at roof vibrations of 445 mm s^{-1}, and only a few loose stones at 127 mm s^{-1}. Kidybinski (1986) reported that damage to underground coal mine openings in the form of small roof falls or floor heave may occur when the PPV lies in the range of 50–100 mm s^{-1}, and large roof falls at 100–200 mm s^{-1}.

Fadeev *et al.* (1987) have reported the allowable limits of vibration for various types of surface and underground structures. In the case of primary mine openings (service life up to 10 years), pit bottom, main cross entries and drifts, the allowable values reported were 120 mm s^{-1} for one time blasting and 60 mm s^{-1} for repeated blasting. For secondary mine openings (service life up to three years), haulage break-through and drifts, the allowable values suggested were 240 mm s^{-1} for repeated blasting and 480 mm s^{-1} for one time blasting. Stacey *et al.* (1990) have reported that no collapse was observed in water filled workings at 670 mm s^{-1}. Fourie and Green (1993) came to the conclusion that allowable PPV (typically 50 mm s^{-1}) to avert damage to surface structures is much lower than that at which damage begins to become a concern in underground mines. They reported that a PPV of as much as 110 mm s^{-1} produced only minor damage and serious extensive damage resulted when PPV reached 390 mm s^{-1}. Masui and Sen (1994) reported that no damage was observed in underground coal mine workings at 58 mm s^{-1}.

Andrieux *et al.* (1994) studied over-break and crack extensions from blasting which have the potential to influence long term stability of excavations. They found that most distant effect on the extension of existing cracks extended to 4·5 m. The PPV at this distance ranged between 300 and 398 mm s^{-1}. Singh *et al.* (1995) found that 48 mm s^{-1} of peak particle velocity did not cause any damage to the underground workings. Tunstall (1997) suggested that PPV of 175 mm s^{-1} did not cause any damage to underground opening when very good quality rock (Rock Mass Rating (RMR)=85) was encountered. On the other hand, with poor quality rock (RMR=49), which had been loosened by previous open-pit blast vibrations, minor visible damage at a PPV of 46 mm s^{-1} and major damage at a PPV of 379 mm s^{-1} were observed. Singh *et al.* (1999) have observed development of cracks in the coal roof at peak particle velocity of 297 mm s^{-1} but spalling of coal chips from pillars and roof started at a level of 125 mm s^{-1}. Lewandowski *et al.* (1999) set a conservative criterion of targeted maximum PPV of 50 mm s^{-1} for the safety of coal underground heading. They further stated that this conservative value of PPV was decided after investigations indicated a possible limit of 250 mm s^{-1}. Singh (2002) correlated the damage with the RMR of underground roof rock and suggested that a PPV of 100 mm s^{-1} will not cause damage to the underground workings with a RMR of 50.



1 Position of operating benches of Sonepur Bazari project

Description of experimental sites

Sonepur Bazari project of Eastern Coalfields Limited is located in the Eastern part of Raniganj Coalfields in India. The average stripping ratio of the mine is 4·72 m^3 per tonne. The total reserve of the mine is 188·26 Mt. In this area, four coal seams, namely R-IV, R-V, R-VI and R-VII, are mainly exposed. Presently, seams R-V and R-VI are being extracted by opencast mining. The overburden is medium sandstone. The physicomechanical properties of the rock samples collected from the Sonepur Bazari project were determined and are presented in Table 1.

R-VI seam is also being extracted by bord and pillar (also known as room and pillar) underground mining in Chora 10 pit colliery due to the presence of a downthrow fault. The thickness of the seam is 7·85 m. The true dip direction is S48°E and gradient is 1 in 12. The width and height of galleries are 4·8 and 3·0 m respectively. The size of pillars is 20×20 m centre to centre. The barrier between Sonepur Bazari opencast project and Chora 10 pit colliery is ∼60 m. A downthrow fault of 21 m passes through the eastern boundary of Chora 10 pit colliery at 100 m from S-1 top panel. The opencast working benches are shown in Fig. 1.

Experimental blasts

Eight blasts with varying designs and charging patterns were conducted at dragline bench and shovel benches of Sonepur Bazari project. Nineteen blast vibration data sets were recorded underground and similar data were recorded on the surface behind the blasting face at similar distances. The number of holes detonated in a blast round was 8–98. The blast holes diameter was 270 mm. Depth of holes varied between 14·7 and 22·8 m. Burden and spacing were 7–8 m and 7·5–10 m respectively. Explosives detonated in a blast ranged between 3004 and 45808 kg, whereas in a delay it varied between 300 and 935 kg. The explosives used were Bulk Emulsion. A non-electric initiation system was used at all the operating benches. The overburden removal was mainly done by electrical shovels in combination with

Table 1 Physicomechanical properties of rock at Sonepur Bazari project

Rock type	Compressive strength, MPa	Tensile strength, MPa	Density,kg m^{-3}	Poisson's ratio	Young's modulus, GPa
Sandstone	37·29	3·46	2320	0·23	7·05

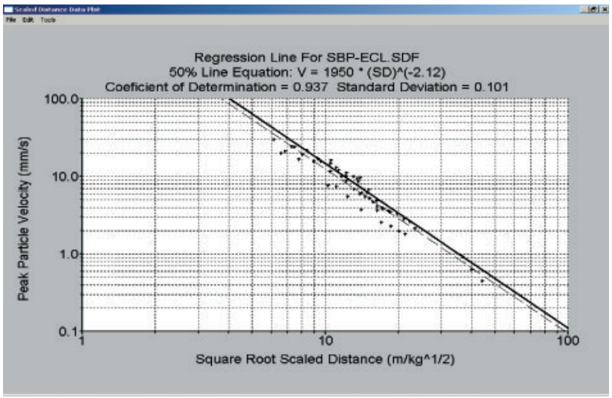
2 View of blasting face at dragline bench of Sonepur Bazari project

dumpers. A dragline is deployed for handling the overburden. The depth of cover in the underground working was 29–57 m. The horizontal distances from underground vibration monitoring locations to the blast faces ranged between 110 and 510 m. The blasting face of a dragline bench near the underground mine is depicted in Fig. 2.

Vibration monitoring

Triaxial transducers of seismographs were used to monitor the vibrations in the underground opening and on the surface. Vibrations in three directions, i.e. longitudinal, transverse and vertical, were recorded and the resultant of the three velocity components was documented. The transducers were mounted in the pillar sides along and across the bord in the underground workings. The points in the pillars were 1·0–1·2 m below the roof and 0·5–0·6 m into the pillars (Fig. 3). The recorded peak particle velocities varied widely depending upon the distance of monitoring locations from the blast face and the amount of explosives detonated in the blast round. The recorded vibration data were in the range of 2·23–43·1 mm s^{-1} in underground pillars whereas it was between 7·07 and 59 mm s^{-1} on the surface. The dominant frequency of vibration varied between 11 and 37 Hz in the underground opening and between 3·2 and 13 Hz on the surface. Fast Fourier transform analyses were carried out to identify the dominant peak frequency.

3 Monitoring of vibration in pillar of Chora 10 pit colliery



4 Regression plot of recorded PPV data at their respective scaled distances

Propagation equation for prediction of vibration

Ground vibration data recorded on the surface at various locations due to blasting at Sonepur Bazari project were grouped together for statistical analyses. The recorded 59 vibration data sets were subjected to regression analyses. Empirical relationships were established correlating the maximum explosive weight per delay ($Q_{\max}$ in kg), distance of vibration measuring transducers from the blasting face (R in m) and recorded peak particle velocity (v in mm s^{-1}). The established equation is given as equation (1)

$$v = 1950 \times \left[\frac{R}{(Q_{\max})^{1/2}}\right]^{-2\cdot12} \tag{1}$$

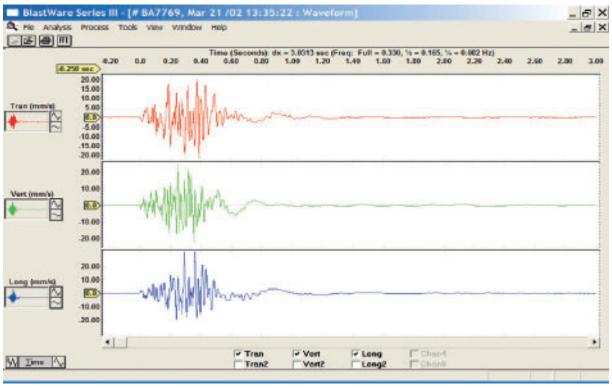
correlation coefficient = 93·7%

where v is peak particle velocity (mm s^{-1}), R is distance between vibration monitoring point and blasting face (m) and $Q_{\max}$ is maximum explosive weight per delay (kg).

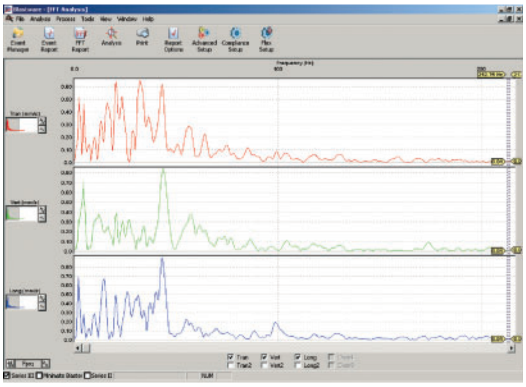
The above equation was used in computing the level of vibration at particular locations on the surface. The recorded vibration levels were in agreement with the predicted vibration levels from the above equation. The regression plot of vibration data recorded at their respective scaled distances is given in Fig. 4.

Discussions on recorded data

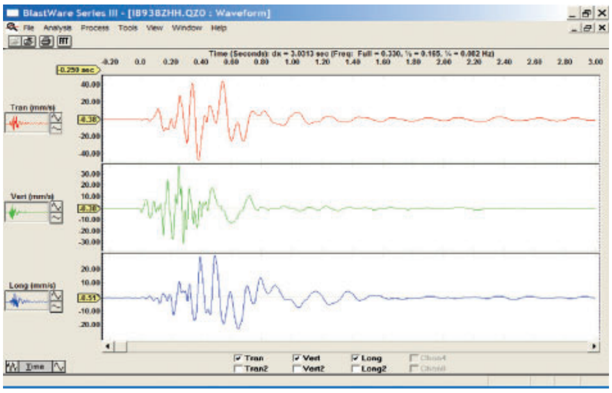
The maximum vibration recorded in the underground mine pillars was 43·1 mm s^{-1} with associated peak dominant frequency 37 Hz. The explosive detonated in each blast round was 20 921 kg and charge weight per delay was 500 kg. The blasting face was 110 m away (radial distance) from the vibration monitoring site. The vibration recorded at similar distance (110 m) behind the blast face on the surface was 51 mm s^{-1} with associated dominant peak frequency of 9·3 Hz. The nearest operating blasting face was 110 m from the nearest underground workings, so the rest of the blasts were conducted at >110 m from the underground monitoring locations.



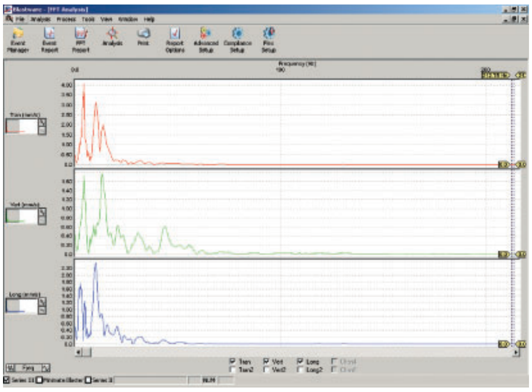
5 Blast waveform recorded in pillar of underground working at 110 m from blast face



7 Fast Fourier transform analyses of frequency of vibration of blast waveform shown in Fig. 5



6 Blast waveform recorded behind blast face at 110 m



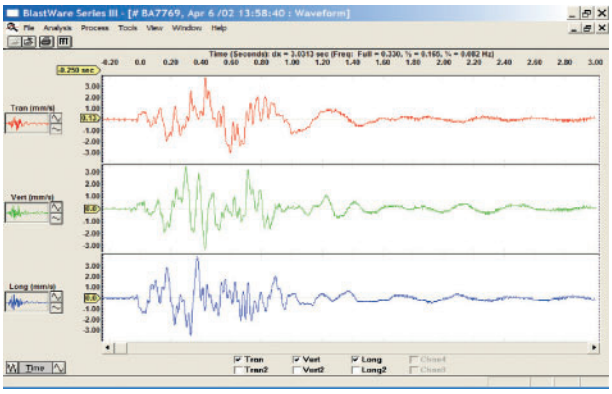
8 Fast Fourier transform analyses of frequency of vibration of blast waveform shown in Fig. 6

A dragline blast was conducted at 510 m from the underground monitoring location which generated PPV of 5·12 mm s^{-1} and the recorded PPV on the surface at 510 m was 15·3 mm s^{-1}. The explosive detonated in the blast round was 45 808 kg and charge per delay was 935 kg.

It was observed that in all the blasts the recorded PPV in underground workings was lower than that recorded on the surface at similar distances. The recorded PPV on the surface was 1·26–2·99 times higher than those recorded in underground openings. It was also observed that when vibration monitoring distances increased the ratio of vibration on the surface to that underground also enhanced. The details of recorded

Table 2 Comparison of PPV monitored on surface and in underground openings at equal radial distances

Blast no.	Total explosives detonated, kg	Maximum explosives weight per delay, kg	Vibration monitoring distance, m	Recorded peak particle velocity: On surface PPV, mm s^{-1}	On surface Dominant frequency, Hz	Underground PPV, mm s^{-1}	Underground Dominant frequency, Hz	Ratio of vibration in underground to that on surface
1.	20 921	500	110	51·0	9·3	36·1	37	1 : 1·41
2.	5267	300	110	19·2	7·5	13·5	28	1 : 1·42
			175	16·4	3·7	9·24	26	1 : 1·77
			205	10·5	4·6	5·46	27·8	1 : 1·92
3.	9113	350	250	15·7	3·7	6·12	22	1 : 2·57
			290	13·7	4·5	5·23	20	1 : 2·62
			335	11·7	5·2	4·15	20	1 : 2·82
4.	3004	380	255	7·37	3·3	3·36	16	1 : 2·19
			265	7·07	3·2	2·99	12	1 : 2·36
5.	19 570	525	115	59·0	11	43·1	19	1 : 1·37
			150	54·4	6·8	34·1	21	1 : 1·60
6.	28 085	410	270	13·8	4	6·02	24	1 : 2·29
			292	10·4	5·6	4·62	18	1 : 2·25
			315	8·45	7·8	4·16	18	1 : 2·03
			345	7·65	3·5	3·24	19·2	1 : 2·36
7.	6669	350	235	16·1	7·3	7·34	26	1 : 2·19
			280	13·7	13	5·50	26	1 : 2·49
			335	9·55	7·2	3·56	21·7	1 : 2·68
8.	45 808	935	510	15·3	3·8	5·12	11	1 : 2·99



9 Blast waveform recorded in pillar of underground working at 510 m from blast face

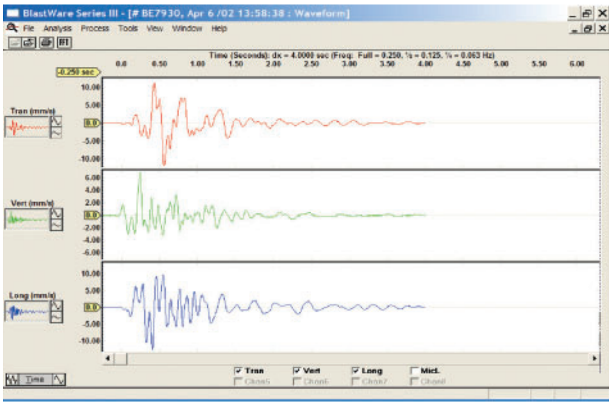
vibration underground and on the surface are presented in Table 2.

Vibration characteristics

Vibration magnitudes and frequencies recorded in underground openings and on the surface behaved differently. The blast waveforms recorded at 110 m in the underground opening and on the surface behind the blast face are presented in Figs. 5 and 6. Fast Fourier transform analyses of the frequencies of vibration of the waveforms presented in Figs. 5 and 6 are shown in Figs. 7 and 8 respectively. It is evident from the figures that in underground workings, vibration of high frequency but short duration (0·8 s) was recorded whereas the vibration recorded on the surface was of long durations (1·6 s), associated with low frequency vibration. The dominant frequency of vibration reported is the dominant frequency of the resultant of vibration in longitudinal, transverse and vertical directions. The recorded PPV at 510 m behind the dragline blasting face was 15. 3 mm s^{-1}, whereas in underground opening it was only 5·12 mm s^{-1} at similar distances. The persistence of vibration at both the monitoring locations was of similar durations. The recorded waveforms are presented in Figs. 9 and 10.

Vibration amplitudes and frequencies are affected by distance, depth below the surface and geologic composition of intervening media. Decrease in vibration amplitude with distance on the surface has been well documented in numerous studies (Siskind, 1989; Singh *et al*., 1997) but little information is available for underground openings. The strongest effect is from simple geometric spreading. Vibration energy fills a greater area (surface waves) and volume (body waves). Simple considerations of the conservation of energy and a finite available amount of energy dictate a decay of intensity with distance. In addition, there are other loss mechanisms such as absorption, dispersion, increasing depth below the surface and transmitting media.

From a theoretical viewpoint, it is not expected that low frequency waves would have any effect on old underground workings. For one reason, their wavelengths are so long that individual pillars and interpillar spaces would be invisible to them. In fact, the mined out layer acts as a reflecting surface for just this reason. Where a hard parting exists over the mined-out zone, two effects on vibrations will occur. If the parting has much higher acoustic impedance than the underlying layer, very little vibration energy will transmit downward into the lower coal measures; this was one of the reasons for lower vibration levels in underground monitoring locations.



10 Blast waveform recorded behind blast face at 510 m

Summary

The present study has demonstrated that vibration recorded on the surface will always be more intense than those recorded at similar distances in underground openings. The PPV recorded on surface was 1·26–2·99 times higher than those recorded in underground openings. The underground galleries and other discontinuities contribute to absorption of vibration in underground monitoring locations. The thick overburden of alluvium soil on the surface caused generation of low frequency vibration whereas rock parting underground was responsible for generation of high frequency vibration. It has been concluded that vibration recording on the surface will be helpful in blast design to help to ensure the safety and long term stability of underground openings.

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