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Damage to surface structures due to blasting – a new criteria

This paper describes effect of blast produced ground vibration on damage potential to residential structures to determine safe levels of ground vibration for the residential structures and other buildings in mining areas. Impacts of 341 blasts detonated at two mines were monitored at the test structures and 1871 blast vibrations signatures were recorded on or near the test structures. Cosmetic cracks in a native brick-mud-cement house were detected at peak particle velocities (PPV) between 51.6 and 56.3 mm/s. The reinforced concrete and cement mortar (RCC) structure experienced cosmetic cracks at PPV's of 68.6 to 71.3 mm/s at the first floor, whereas at second floor it was detected at PPV levels of 71.2 to 72.2 mm/s. Minor damage in brick-mud-cement house was recorded at PPV levels of 81.0 to 89.7 mm/s. The RCC structure at first and second floors experienced minor damage at PPV levels of 104 mm/s and 98.3-118 mm/s respectively. The brick-mud-cement house experienced major damage at PPV level of 99.6 to 113.0 mm/s, while major damage was recorded in RCC structure on first floor at PPV of 122 mm/s, the second floor at PPV levels of 128.9-161 mm/s. Recommended threshold limits of vibrations for the different type of structures is based on these measurements and observations.

1.0 Introduction

Ground vibrations from blasting have been a continual problem for the mining and construction industries, the public living near the mining activities and regulatory agencies responsible for setting safety and environmental standards. Questions frequently arise about blast vibration effects and specifically about whether vibrations can or could have caused cracking and other damage in homes and other structures. The answer depends primarily on vibration levels, excitation frequencies and to a lesser degree on specific site and structure specific factors.

The real cause of complaints by people about blasting is related to how much complainant's houses shake, not how much the ground shakes (Pedgen et al., 2005). The three factors of ground vibrations that determine the degree of house shaking are ground vibration amplitude (peak particle velocity), its duration and its dominant frequency and the response frequencies of the structure (Singh et al., 1996). Human beings notice and react to vibration at levels much lower than the levels established as structural damage thresholds (Dowding et al., 1980; Siskind et al., 1980). Previous studies on human response to transient vibrations have established that human tolerance to vibration decreases the longer the vibration continues (Siskind et al., 1980; Siskind, 1991).

The mining industry needs realistic design levels and also practical techniques to safeguard the structures on their periphery. At the same time, mine safety control agencies responsible for blasting and explosives need reasonable, appropriate and technologically established and supportable blast vibration damage criteria on which to base their regulations (Crum & Pierce, 1995; Singh & Vogt, 1998; Rudenko, 2002). Finally, neighbours around the mining operations require protection of their property and health. Last but not the least the mining operations should not be inhibited by the apprehension rather than the reality of damage to the structures/buildings (Singh et al., 2005; Medearis, 1978; Just & Chitombo, 1987; Dowding, 1966; Singh et al., 2008).

2.0 Existing blast vibration standards

Different countries have set their own standards on the basis of their extensive field investigations carried out in their mines for several years. There is a plethora of standards available world-over based on various aspects of ground vibrations e.g. amplitude, peak particle velocity, frequency, acceleration, etc. These parameters are used either as a single criterion or in combination; sometimes frequency is combined with amplitude and velocity. Peak particle velocity has been traditionally used in practice for the measurement of blast damage to structures. In this criterion the shape of the waveform and duration of dynamic loading are not taken into account.

United States Bureau of Mines (USBM) published RI 8507 (Siskind et al., 1980) and recommended blasting level criteria which set a peak particle limit based upon predominant

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frequency of the seismic wave. Review of other control limits raise a question about how relatively small limits, such as 5 mm/s can be technically justified (Singh et al., 2008). Several researchers stated that no engineering study or research justified such limits. When such restrictive levels are imposed, they seem to be intended limits reduce public annoyance and the corresponding complaints. Furthermore limits to eliminate public annoyance seem to be set arbitrarily by the regulatory authority. Adherence to such arbitrary limits to reduce complaints is obligatory, and the economic impact of compliance can be substantial. Criteria applied, as law should be based upon solid research conducted by a well-recognized and accepted authority/ institution.

Legislation should set limits that balance the costs and benefits to all stakeholders which are based upon standards grounded in good science

TABLE 1: USA STANDARD AFTER SISKIND ET AL. (1980)

Type of structures	Peak particle velocity (mm/s)	
	Frequency (<40 Hz)	Frequency (>40 Hz)
Modern homes, dry wall interior	18.75	50
Older homes, plaster on wood lath construction	12.5	50

TABLE 2: GERMAN STANDARD AFTER GERMAN DIN4150 (1986)

Type of structures	Peak particle velocity (mm/s) at foundation		
	<10 Hz	10-50 Hz	50-100 Hz
Offices and industrial premises	20	20-40	40-50
Domestic houses and similar constructions	5	5-15	15-20
Buildings that do not come under the above because of their sensitivity to vibration	3	3-8	8-10

TABLE 3: USSR STANDARD

Type of structures	Allowable PPV (mm/s)	
	Repeated	One fold
Hospitals	8	30
Large panel residential buildings and children's institutions	15	30
Residential and public buildings of all types except large panels, office and industrial buildings having deformations, boiler rooms and high brick chimneys	30	60
Office and industrial buildings, high reinforced concrete pipes, railway and water tunnels, traffic flyovers	60	120
Single storey skeleton type industrial buildings, metal and block reinforced concrete structures, soil slopes which are part of primary structures, primary mine openings (service life upto 10 years) pit bottoms, main entries, drifts	120	240

TABLE 4: AUSTRALIAN STANDARD 2006 (AS 2187.2)

Type of structures	Maximum values
Historical building and monuments and building of special value	0.2 mm displacement for frequencies less than 15 Hz
Houses and low rise residential buildings, commercial buildings not included below	19 mm/s resultant ppv for frequency greater than 15 Hz
Commercial buildings and industrial buildings or structures of reinforced concrete or steel construction	0.2 mm maximum displacement corresponds to 12.5 mm/s ppv at 10 Hz and 6.25 mm/s at 5 Hz

TABLE 5. PERMISSIBLE PEAK PARTICLE VELOCITY (PPV) IN MM/S AT THE FOUNDATION LEVEL OF STRUCTURES IN MINING AREA (DGMS CIRCULAR 7 OF 1997)

	Dominant excitation frequency, Hz		
	< 8 Hz	8-25 Hz	> 25 Hz
(A) Buildings/structures not belong to the owner			
1. Domestic houses/structures (kuchcha, brick and cement)	5	10	15
2. Industrial buildings	10	20	25
3. Objects of historical importance and sensitive structures	2	5	10
(B) Buildings belonging to owner with limited span of life			
1. Domestic houses/structures	10	15	25
2. Industrial buildings	15	25	50

and justice. An overview of the vibration standards implemented by a few countries is given in following Tables 1-5 (Siskind et al., 1980; DIN, 1986; DGMS, 1997).

TABLE 6: PHYSICO-MECHANICAL PROPERTIES OF CONSTRUCTION MATERIALS FOR RCC STRUCTURES.

Name of the project	Sample	Compressive strength (MPa)	Tensile strength (MPa)
Sonepur Bazari mine	RCC concrete block	23.85	4.37
Kusmunda mine	RCC concrete block	24.67	4.52

3.0 Location and geology of the experimental sites

Experimental test houses in this study were located at Sonepur Bazari and Kusmunda opencast mines. Sonepur Bazari mine is located in the Eastern part of Raniganj Coalfields. Four coal seams viz. R-IV, R-V, R-VI and R-VII are mainly exposed in the mine. Presently, seams R-V and R-VI are being extracted by opencast methods of mining. The mine produces about 3.5 Mt of coal which requires removal of about 12 million m^3 of overburden. The stripping ratio of the mine is 4.72 m^3 per tonne coal produced. The total reserve of the mine is 188.26 Mt.

Kusmunda mine is located on the western bank of Hasdeo River in the central part of Korba coalfields. The Kusmunda project is flat terrain with minor undulations. The upper Kusmunda seam out-crops below a cover of 6-31 m in an elliptical fashion and overlies lower Kusmunda seam after sandstone parting of 65 to 75 m. The area constitutes a doubly planging anticlinal trend. The lower Kusmunda seam is composite in western part of the property but the same splits into two section viz. lower Kusmunda (top split) and lower Kusmunda (bottom split) eastwards. One oblique set of faults strike across the anticlinal axis, while the other set of faults appear to strike parallel to the anticlinal axis. The seam generally has a dip ranging from 50° to 100° (1 in 5.6 to 1 in 11.5) and the overall grade of coal is Grade 'F'. The mine produces 8 Mt of coal per annum which requires removal of some 9 million m^3 of overburden.

4.0 Test structures details and instrumentations

Test house locations were chosen in consultation with the mine officials by estimating the advance of working benches in the following 15-20 months. A minimum stand-off distance of about 1800 m was planned at both sites from the nearest working bench at the time of completion of the construction of test structures. Three types of test structures viz. (a) Mud house with Raniganj tiles, (b) Brick-mud-cement plaster house with Raniganj tiles and (c) Double storey three rooms RCC structure were constructed at both the sites. The view of the newly construed test structures at Kusmunda mine is shown in Fig.1. The physico-mechanical properties of the construction material of RCC structure is presented in Table 6.

Fig.1 Newly constructed test structures for study purpose at Kusmunda mine

Ground vibrations from blasting were typically measured with velocity-sensing geophone transducers attached to digital recorders. The peak particle velocity was recorded simultaneously by deploying 6-12 seismographs in all the structures at various locations. Sensors were mounted on prefixed brass rod (non-ferrous) base plates placed in the structure at the time of casting of the roof and plastering of the wall. Vibrations were recorded at different points of the structures viz. floor, mid wall, windows, ventilator, roof centre, roof corner and at ground surface near the foundation of the structures. The locations of vibration monitoring transducers are shown as M-1, M-2 in mud house, T-1……T-8 in the brick-mud-cement house and R-1…..R-9 in RCC structure (Fig. 2).

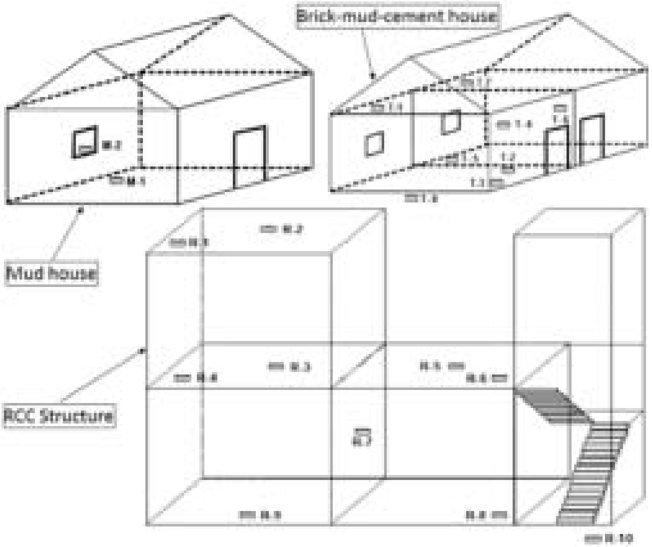

Fig.2 Vibrations monitoring locations in different structures built at Sonepur Bazari mine

5.0 Experimental details

Field trials were conducted with blasts initiated at the coal, shovel and dragline benches at Sonepur Bazari mine. Drill diameters were 160 and 270 mm. Hole depths varied from 4 to 33 m. Burden varied from 3 to 8.5 m. Similarly, spacing varied between 4 and 9.5 m. The number of holes detonated in a blast round varied from single hole to 60 holes. The total explosive detonated in a blast round varied from 100 to 44,800 kg. The explosive detonated per delay varied from 50 to 1650 kg. Blasts were initiated with detonating cord as well as Nonel initiating system. Distance of the test structures from the blasting face varied from 20 to 1800 m. Structure response was measured and cracking was observed for some 182 blasts, which involved some 1073 vibration records at various locations and on the test structures.

At Kusmunda mine field trials were conducted with blast initiated at shovel and coal benches. Drill diameters were of 160 and 270 mm. Hole depths varied from 4-20 m. Burden varied from 3-8 m. Similarly, spacing varied between 3.8 and 9 m. The numbers of holes detonated varied from single hole to 157 holes. The total explosive detonated in a blast round varied widely from 50 to 13,905 kg. The explosive detonated per delay varied from 50 to 4,450 kg. Distance of the test structures from the blasting face varied from 10 to 750 m. Structure response was measured and cracking was observed for some 159 blasts, which involved some 798 vibration records at various locations and on the test structures. The recorded range of vibration and dominant excitation frequencies along with the amount of explosives detonated to achieve the objectives of the study is presented in Table 7.

6.0 Vibration monitoring on the structures

Out of 1871 vibration data recorded at six structures at two experimental sites, 398 were recorded near the foundation of the structures and 1473 were recorded at various locations within the test structures. An attempt was made to record the vibration simultaneously within structures and near the foundation to document the response spectra of the structure to blast vibration. Scaled distance-PPV plots of the vibration data recorded near the foundation of the structures and at different locations in the structures are presented in Fig.3. Similarly, the plots of peak particle velocities (PPVg) recorded on the ground near foundation of the structures and corresponding peak particle velocities (PPVs) recorded on the structures at different locations are presented in Fig.4.

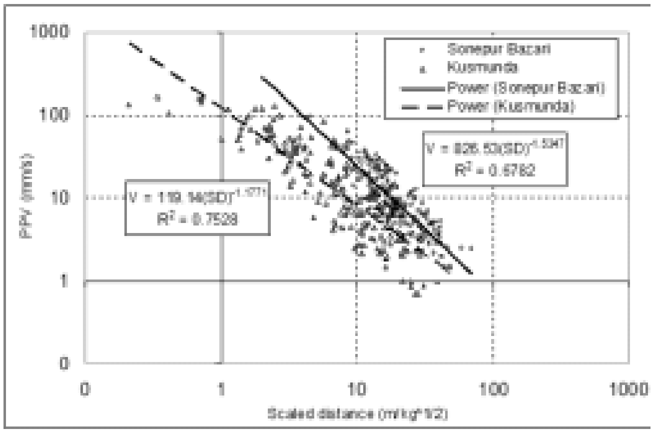

Fig.3 Propagation plots of recorded PPV at ground surface near the foundation of structures at respective scaled distances

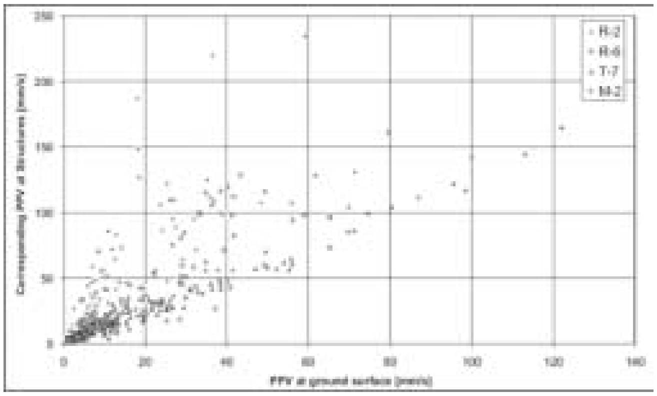

Fig 4 Plot of recorded PPVs on the ground and corresponding recorded PPVs on the structures at different locations and in different structures

7.0 Determination of natural frequency of the test structures

The natural frequency of the structures is determined with the help of a transfer function analysis. To determine the natural or fundamental frequency of the structure, the amplitudes of vibration on the structure at various points viz. at corner and centre of the roof level, mid-wall, corner wall etc. and on the ground surface near the foundation of the structure were simultaneously recorded. For this purpose transducers of 8-channel seismographs were used. The ground motions and the response motions in each structure were recorded. The amplification range recorded at different locations in the structures such as mid-walls, corners etc. are presented in Table 8.

8.0 Test structures response and dynamic amplification

Vibrations in structures can be amplified relative to the forcing vibration in the ground. Amplification of ground vibration

TABLE 7: SUMMARISED BLAST DETAILS OF THE EXPERIMENTAL SITES.

	No. of blasts	No. of PPV data recorded	Range of total explosive weight (kg)	Range of explosives weight per delay (kg)	Range of distances (m)	Range of recorded PPV (mm/s)	Range of dominant peak frequency (Hz)
Sonepur Bazari	182	1073	100-44800	50-1650	20-1800	0.31->254	2.38-38.5
Kusmunda	159	798	50-3905	50 -4450	10-750	0.38->254	2.13-39.8
Total	341	1871	50-44800	50 - 4450	10-1800	0.31-261	2-39.8

TABLE 8: RANGE OF AMPLIFICATION OF VIBRATION RECORDED IN THE TEST STRUCTURES AND THEIR FREQUENCY RANGE

Locations and type of structures	Range of amplification		Range of frequency contributing maximum amplification	Natural frequency of the structures [Hz]
	Minimum amplification	Maximum amplification		
		Sonepur Bazari mine		
1. RCC structure – second floor	1.26	5.21	4.5 -11	6.38 - 9.88
2. RCC structure – first floor	1.05	3.08	2.8 - 11.6	6.13 - 8.25
3. Brick-mud structure	1.12	2.75	4.3 - 14.0	9.2 - 11.3
4. Mud structure	1.00	1.74	3.2 - 6.5	6.25-10.3
		Kusmunda mine		
5. RCC structure – second floor	1.14	5.03	4.5-21.3	6.63-8.13
6. RCC structure – first floor	1.12	4.82	2.5-24.3	6.25-7.88
7. Brick-mud structure	1.11	2.63	5-20.3	6.0-14.8
8. Mud structure	1.08	1.95	4.8-21.5	9.13-12.8

depends on the amount of energy in the ground vibration spectrum at frequencies near the natural frequencies of the structures as well as the structures damping coefficient. The peak structure response and the incoming ground vibrations waveforms were superimposed for absolute and differential response analyses. The maximum amplifications occurred when excitation frequency was close to the response frequency as shown in Fig.5 because of low differential responses. Ground motions frequencies below the structure natural frequency did not show amplifications, and showed no relative displacement and hence, no strain.

The highest response is expected from the excitation at the structure's natural frequency. The amplification of motions in all the test structures was determined and is presented along with the corresponding ground vibration frequencies in Fig.6. The maximum level of amplification recorded at Sonepur Bazari mine was 5.21 whereas at Kusmunda mine it was 5.03. This high amplification factor was found at second storey of the RCC structures at both the mines. Maximum amplifications were found to be associated with ground motions between 3 to 16.1 Hz. Siskind et al. (1980) did similar study and reported that maximum amplifications were found to be associated with ground motions between 5 to 12 Hz, as expected from the natural resonance frequencies of the residences.

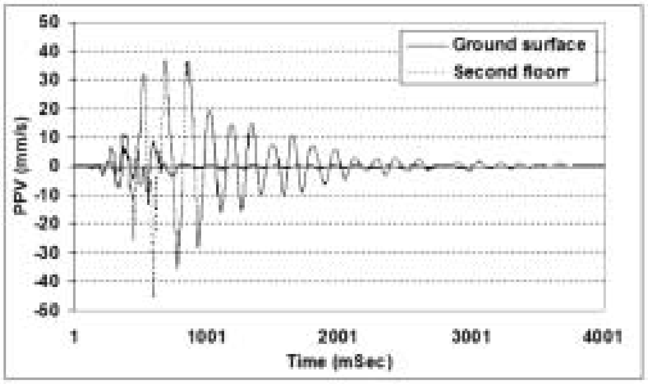

Fig.5 Peak structural response and forcing ground vibration (L-direction) for the second floor of the RCC test structure due to blasting at Sonepur Bazari mine

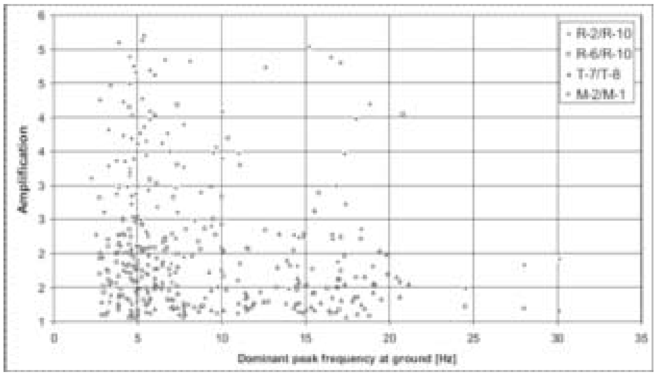

Fig.6 Plot of amplification of vibration in the test structures at their respective ground motion frequency

9.0 Damping of the test structures

Damping is a function of building construction and to some extent the intensity of vibration. Thus, it cannot be simplified as easily as the natural frequency. Measurement reveals a wide range of damping for residential structures with an average of 5% (Dowding et al., 1980). The damping (ß) of the structures is proportional to the rate at which the vibration decays with time and it can be calculated from the free response of the structure, ideally being the rate of decay of the response vibration after the ground vibration or driving function ceases.

$$\beta = \left(\frac{1}{2\pi m}\right) \times 100\ L_n\left(\frac{A_n}{A_{n+m}}\right) \qquad \ldots \quad (1)$$

where, L_n is the log, A_n is the response amplitude and A_m is the amplitude m cycles later.

The damping of vibration at different parts of the constructed test structures was determined. These parts

Table 9: Ratio of vibration levels at various locations in the structures at Sonepur Bazari mine

	Ratio of vibration levels at different monitoring locations		Range of amplifications
1.	Ratio of PPV at the corner of second floor to that of ground surface	R-2/R-10	1.26 - 5.21
2.	Ratio of PPV at corner of the first floor to that of ground surface	R-6/R-10	1.05 - 3.08
3.	Ratio of PPV at the ground floor to that of ground surface near foundation	R-8/R-10	1.07 - 1.44
4.	Ratio of PPV at the wall to that of ground surface of brick-mud structure	T-7/T-8	1.12-2.75
5.	Ratio of PPV at the wall to the floor or ground surface of Mud structure	M-2/M-1	1.0-1.74

Table 10: Ratio of vibration levels at various locations in the structures at Kusmunda mine

	Ratio of vibration levels at different monitoring locations		Range of amplification
1.	Ratio of PPV at the corner of the second floor to that ground surface near foundation	R-1/R-10	1.14 - 5.03
2.	Ratio of PPV at the centre of the first floor to roof of ground floor to that of ground surface near foundation	R-4/R-10	1.12 - 4.82
3.	Ratio of PPV at the wall of ground floor to that of ground surface near foundation	R-6/R-10	1.10 - 2.34
.	Ratio of PPV at the ground floor to that of ground surface near foundation	R-8/R-10	1.09-1.61
5.	Ratio of PPV at the wall to that of ground surface of brick-mud structure	T-7/T-8	1.11-2.63
6.	Ratio of PPV at the wall to the floor or ground surface of Mud structure	M-2/M-1	1.08-1.95

included the ground floor and first floor of RCC structures, window of brick-mud-cement house as well as window of the mud house. The damping at the corner was in the range of 2.1 to 10.9% and in the mid-wall it was in the range of 1 to 7.4% with the overall damping range of 0.6-10.9% in the test structures of Sonepur Bazari mine. The damping at the corner was in the range of 1.1 to 9.5% and in the mid-wall it was in the range of 1.7 to 4.9% with the overall damping range of 0.5 to 9.5% in the test structures of Kusmunda mine. The ratio of vibration level at various points of the structures at both the experimental sites is given in Tables 9 and 10.

10.0 Damage observed in test structures and classification thereof

The brick-mud wall with cement plaster and RCC test structures were whitewashed so that the cosmetic cracks can be visually observed. The test structures were closely inspected visually. Crack monitor gauges were used to document the width of the cracks. Photographs were also taken of the existing cracks and newly formed cracks in the structures after each of the blasts. In all the test structures cracking/damage was observed. The levels of damage in the test structures were influenced by peak particle velocity and its associated frequency.

Based on the observed damages an attempt has been made to classify them based on the peak particle velocity with associated dominant peak frequency. The damages were classified in four categories (Table 11). These are no damage, cosmetic damage, minor damage and major damage. No damage was below the cosmetic damage level and reported as threshold limit of vibrations for the safety of residential buildings/structures in mining areas (Singh & Roy, 2006).

10.1 Damage in the test structures at Sonepur Bazari mine

Monitoring of the test structures continued for 16 months without any cracking. The condition of the structures was documented after each blast. Although there were 86 blasts with a maximum PPV of 42.3 mm/s, no cracking was observed.

Finally, blast conducted at 3rd overburden bench with charge weight per delay of 800 kg and total charge of 9750 kg caused cosmetic cracks in few portion of the structures. The blast face was 245 m away from the test structures. The recorded vibration in the notch near the window of brick-mud-cement house was 56.3 mm/s with dominant peak frequency of 6 Hz. The vibration recorded on the first floor and second floor of the RCC structure was 47.8 mm/s and 71.2 mm/s respectively. The dominant peak frequency in the latter was 6.2 Hz. The cosmetic cracks were recorded in the wall of second floor of the RCC structure and near the window of brick-mud-cement house (Fig.7). Fig.8 depicts the blast vibration signature that caused cosmetic cracking in the first floor of RCC structure. There was no damage or cracking in the first floor of the RCC structure. It was difficult to document the cosmetics cracks in the mud house. Although,

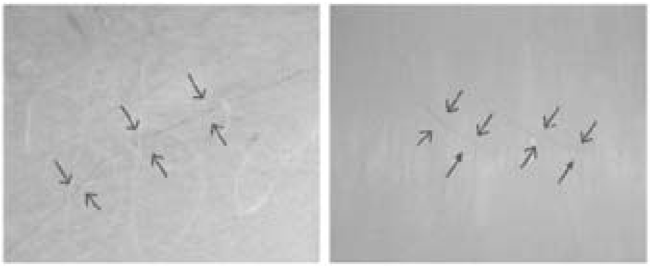

Fig.7 View of the cosmetic damage at first floor of the RCC structure at Sonepur Bazari mine

TABLE 11: DAMAGE CLASSIFICATION

Classification	Description of damage
Threshold limit	Visually no crack/deformation in the wall of the structure due to blasting.
Cosmetic damage	Loosening of paint; small plaster cracks at joints between construction elements; initiation of hairline cracks, lengthening of old cracks.
Minor damage	Loosening and falling of plaster; cracks in masonry around openings near partitions; hairline to 3- mm cracks, falls of loose mortar/plaster.
Major damage	Cracks of several mm in walls; rupture of opening vaults; structural weakening; fall of masonry; detachment of bricks from the walls etc.

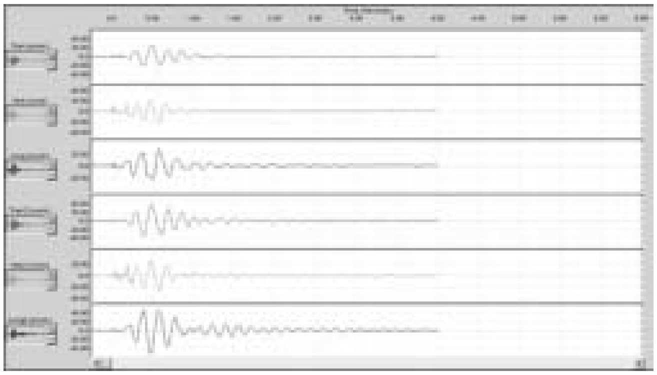

Fig.8 Blast wave signature recorded at first floor (Trans2, Vert2, Long 2) of the RCC structure and near the foundation (Trans, Vert, Long) which caused cosmetic cracks in the RCC structure at Sonepur Bazari mine

the recorded vibration in the mud house was 45.9 mm/s with dominant peak frequency of 6.3 Hz.

A blast conducted at 1st overburden bench with explosives weight per delay of 800 kg caused minor damage in almost all the structures. The blast face was 175 m away from the structures. In total explosives detonated in the blast round was 5970 kg. The recorded vibrations in the test structures were: mud house, 55 mm/s with associated dominant peak frequency of 4.38 Hz; wall of brick-mud-cement house, 81 mm/s with dominant peak frequency, 5 Hz; RCC structure, second floor, 98.3 mm/s with dominant peak frequency, 5.6 Hz. The minor damages were observed within the structures for the corresponding vibration and frequencies mentioned above are shown in Fig.9. The same blast produced only cosmetic cracks in the first floor of RCC structure at vibration level of 71.3 mm/s with dominant peak frequency of 5 Hz. Cracks were located near the windows in the first floor. Fig.10 depicts the blast vibration signature that caused minor damage in brick-mud-cement house.

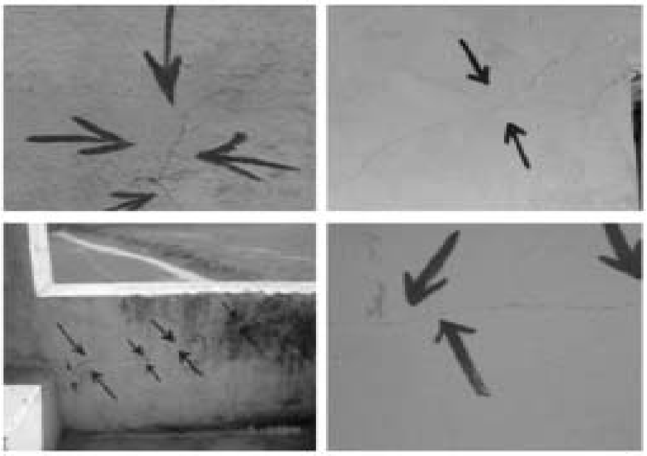

Fig.9 View of the minor damage at second floor of the RCC structure at Sonepur Bazari mine

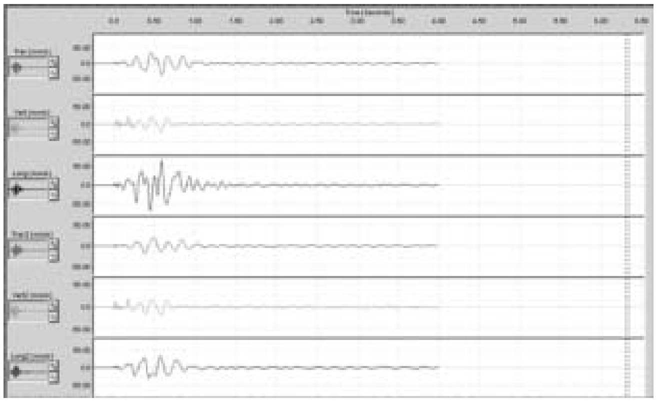

Fig.10 Blast wave signature recorded in brick-mud-cement house near the window (Trans, Vert, Long) and near the foundation (Trans2, Vert2, Long2) which caused minor damage in brick-mud-cement house at Sonepur Bazari mine

The cracks in the structures and their extensions were marked and documented after each and every blast. The widening of cracks was recorded with crack monitor gauges. The existing cracks extended and became wider due to the repeated blasting with closer blasting sites and higher PPV. Some of the blasts generated more than 254 mm/s of PPV (the recording limit of seismograph).

The study was carried out to document the effect of repeated blasting on the collapse of test structures. It was recorded that when blast face was only 20 m from the structures (Fig.11) the mud house collapsed but the brick-mud-cement and RCC structures were standing with major damage in the plaster. At the end the measurements of cracks with crack monitor gauge showed width of cracks up to 35 mm, while the width of detached parts of the plaster ranged between 1 cm and 40 cm. Details of excitation motion and corresponding response motion which caused different levels of damage to the test structures at Sonepur Bazari mine is presented in Table 12.

TABLE 12: STRUCTURE MOTION (PPVS) AND DOMINANT FREQUENCIES (FS) AND GROUND MOTION (PPVG), FREQUENCIES (FG) AND ASSOCIATED CRACKING/DAMAGE STATES DUE TO THE BLAST CONDUCTED AT SONEPUR BAZARI PROJECT (SBP) AND KUSMUNDA PROJECT (KP)

House	Site	Observed cracking/damage					
		Cosmetic PPVs/PPVg [mm/s]	fs/fg [Hz]	Minor PPVs/PPVg [mm/s]	fs/fg [Hz]	Major PPVs/PPVg [mm/s]	fs/fg [Hz]
Mud	SBP	No damage detected		55/35	4/5	87/58	6/9
	KP	No damage detected		56/29	21/14	104/53	19/10
Brick-mud-cement	SBP	56/22	6/6	81/39	8/5	100/39	7/4
	KP	52/30	20/20	52/30	20/20	90/56	20/18
First floor RCC	SBP	71/39	5/5	No damage detected		No damage detected	
	KP	69/46	18/21	104/50	6/10	122/25	13/10
Second floor RCC	SBP	71/30	6/8	98/36	6/5	129/43	14/4
	KP	72/14	17/11	118/46	20/21	161/50	14/11

Fig.11 The view of the location of the test structure indicating working benches at 20 m from structures at Sonepur Bazari mine

Fig.12 The view of cosmetic cracks developed in the brick-mud-cement house at Kusmunda mine

10.2 DAMAGE IN THE TEST STRUCTURES AT KUSMUNDA MINE

Monitoring of the test structures continued for 4 months without any cracking in the structure. Although, 42 blasts were conducted and the blast face advanced from 435 to only 256 m from the test structures. The maximum PPV recorded was 42.3 mm/s. The first cosmetic cracks were observed at vibration level of 51.6 mm/s with dominant peak frequency of 19.8 Hz monitored at wall of brick-mud-cement house. The blast was conducted at top shovel bench, 180 m away from the structures. Blastholes in each row were fired instantaneously to increase charge per delay. The maximum explosive weight per delay and total explosive detonated in the blast were 2600 kg and 5100 kg respectively. View of the cosmetic cracks developed in brick-mud-cement structure is shown in Fig. 12. Cosmetic cracks at the second floor of RCC structure were developed at a vibration level of 72.2 mm/s with dominant peak frequency of 17.3 Hz. The corresponding blast was performed at 2nd bench, 135 m away from the RCC structure. Explosive detonated in the blast round was 2330 kg and charge per delay was also 2330 kg because all the holes were fired instantaneously to generate higher level of vibration.

All the test structures develop cosmetic cracks and/or minor damage from a blast with 15 holes drilled 78 m from the test structures loaded with a total charge of 4500 kg of explosives and detonated with charge weight per delay of 1800 kg. The mud house experienced vibration of 56.1 mm/s with peak dominant frequency of 21.1 Hz and suffered minor damage. The walls of first floor of RCC structure at corners near the roof developed cosmetic cracks and the walls of second floor of RCC structure developed minor damage. The corresponding vibration levels recorded was 68.6 mm/s with peak dominant frequency of 18.1 Hz on first floor and 118 mm/s with peak dominant frequency of 5.16 Hz on second floor. The brick-mud-cement house also suffered minor damage in its walls at corner. The vibration recorded was 89.7 mm/s with peak dominant frequency of 19.5 Hz.

As the blast face approached closer and closer to the structures the vibration levels increased in the test structures. As a result, extension of minor damage was also observed in almost all the test structures. Major damage by a blast 55 m away from the test structures as shown in Fig.13. Some 53 holes were drilled and loaded with 11907 kg of explosives. The blast was initiated with detonating cord with a maximum charge weight per delay of 3890 kg. The vibrations generated from the aforesaid blast on the second floor of the RCC test structure was 161 mm/s with dominant peak frequency of 14 Hz. The major damage was detected in the brick-mud-cement

Fig.13 View of blast face at 55 m from the nearest test structure at Kusmunda mine

house at the vibration level of 113 mm/s with dominant peak frequency of 7.5 Hz. The mud house also developed major damage at PPV of 104 mm/s with dominant peak frequency of 18.9 Hz.

Although, major damage was recorded in all the structures, the study was continued to document the level of vibration necessary to collapse the structures. Destruction was attempted when the face was only 35 m away from the structure. Some 22 holes were drilled in two rows and were loaded with a total of 5223 kg of explosives. Each row was fired instantaneously. The maximum explosives weight per delay was 2750 kg. None of the structures collapsed from the aforesaid blast. However, major damage was recorded in the first floor of RCC structure. The recorded PPV was 122 mm/s with dominant peak frequency of 13.4 Hz. The vibration at the second floor of RCC structure was more than the recording limit of the seismograph (i.e. 254 mm/s). The second floor was damaged at many locations and x-pattern cracks were documented (Fig.14).

Another blast was detonated 10 m from the test structures to try again to collapse the test structures. All the structures were standing having major damage in their walls but did not collapse. Although the vibrations experienced by them were in excess of 254 mm/s.

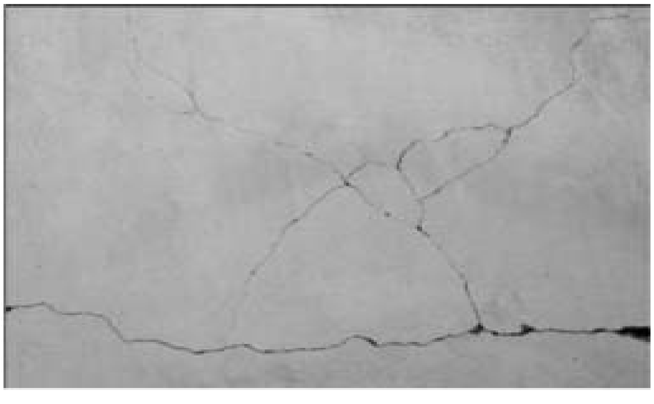

Fig.14 Typical blasting X-cracks developed at the RCC structure at Kusmunda mine

Details of excitation motion and corresponding response motion along with their frequencies which caused different levels of damage to the test structures at Sonepur Bazari mine and Kusmunda mine are presented in Table 12.

11.0 Discussions and conclusions

These tests and observations are important. They present response of a wide range of structures from inexpensive to moderately expensive masonry structures. As such these observations are unique while there are a large number of publications available on ground vibrations and blasting; however, a few contain actual observations of damage and corresponding measurements of ground motions. These tests not only involve observations of the onset of cracking, but also incorporate recording of excitation response motions. Frequencies were determined directly from the vibration time histories and by real time spectral analysis. In some cases, the records showed two dominant frequencies; high frequency for first few hundred milliseconds, and then a significantly longer low frequency to the later part of the vibration record that perhaps produced the larger structural response. The upper parts of structures tend to amplify horizontal ground motion with the amount of response dependent on the ground vibration frequency, the natural frequency and damping of the structure.

The amplification of vibration recorded in the mud house at both the sites was in the range of 1.0 to 1.95. The corresponding excitation frequency was in the range of 3.2 to 21.5 Hz. The natural frequency of the mud houses was between 6.25 and 12.8 Hz. Similarly, the amplification of vibration recorded in the brick-mud-cement house at both the sites was in the range of 1.11 to 2.75. The corresponding excitation frequency was in the range of 4.3 to 20.3 Hz. The natural frequency of the brick-mud-cement houses at different locations was between 6 and 14.8 Hz.

The amplification of vibration recorded in the first floor of RCC structures at both the sites was in the range of 1.05 to 3.08. The corresponding excitation frequency was in the range of 2.5 to 24.3 Hz. The natural frequency of the first floor of the RCC structure at mid walls, corner etc. was between 6.13 and 8.25 Hz. The amplification of vibration recorded in the second floor of the RCC structures was in the range of 1.14 to 5.21. The corresponding excitation frequency was in the range of 4.5 to 21.3 Hz. The natural frequency of the second floor of RCC structure at mid walls, corner etc. was between 6.38 and 9.88 Hz.

The field investigation conducted elsewhere under different Indian geo-mining conditions reveals that the amplification of vibrations in different types of structures ranges between 1.13 and 5.62. The corresponding excitation frequency was in the range of 2.4 to 16 Hz. The natural frequencies of the structures were between 3.13 and 20 Hz. Normally, most of the structures have natural frequency less than 15 Hz. However, a few structures do have natural frequency up to 20 Hz.

The blast vibrations close to the structure's resonant frequency and their resulting responses at each experimental site were determined. The maximum amplifications of response occurred at excitation frequencies near the structures natural frequency. Motions with dominant frequencies below the structure natural frequency did not show amplifications. Dominant excitation frequencies of blast vibration were less than 15 Hz for 94% of the recorded data. These low frequencies may be a result of the low-velocity surface layer (top soil) and the far-field monitoring locations.

For near field monitoring (less than 150 m) involved the higher blast motion frequencies, whereas at greater distances (more than 150 m) the excited frequencies were much lower. FFT analyses of ground motions revealed that the maximum concentration of vibration energy was in the range of 3.3-9.2 Hz. The structures studied had fundamental frequencies between 6 and 14.8 Hz. The incoming vibrations thus excited the structure in those range of natural frequencies. Even so amplification of ground motion remained below 5.5. Taller structure amplifies the motion more than short structures.

The recorded frequency of ground vibration are categorised in three groups based on the response characteristics of the structures. Low frequency (< 15 Hz): The natural frequencies of structures studied were between 6 and 14.8 Hz. The maximum amplification of vibration was recorded for ground motion with dominant frequencies of 2.8 to 14 Hz. Medium frequencies (15-30 Hz): The frequency above the natural frequencies of the structures. Moderate amplification of vibration was recorded in the structures. High frequency (>30 Hz): The frequency much higher than the natural frequencies of the structures. No amplification of vibration was recorded in the structures.

The maximum vibration recorded was at the corner of second floor. As the height of the structure increases the amplification of vibration in the structures increases. The ratio of vibration produced in the corner of the second floor to that produced on ground surface was between 1.26 and 5.21. The ratio of vibration at corners of second and first floors varied from 1.03 to 3.09. The ratio of vibration at corner of second floor and mid-wall of first floor was between 1.13 and 2.21. The amplification of vibration in the mid-wall to that of first floor was in the range of 1.02-1.80. The ratio of vibration in the window to that of first floor of brick-mud-cement house was in the range of 1.11 to 2.63. The wall near the window of mud house experienced vibration of 1-1.95 times higher than those experienced by the ground floor of the mud house.

12.0 Recommendation of threshold level of ground vibration

The cracking threshold criteria are low probability values for cosmetic crack damage. Exceeding them by a small amount will not cause either extensive damage or a crack in every structure. The cosmetic cracks were produced in brick-mud-cement houses at PPV of 56.3 mm/s at Sonepur Bazari mine and at 51.6 mm/s at Kusmunda mine. The corresponding PPV recorded on the ground surface near the foundation were 21.8 and 29.9 mm/s respectively. The amplification of vibration recorded in the wall near window of the brick-mud-cement house was 1.73 to 2.58 times to that of ground motion. Thus, the PPV near the foundation of the brick-mud-cement structures of 21.8 mm/s caused cosmetic cracks in one of the brick-mud-cement houses.

Similarly, cosmetic cracks detected in the first floor of RCC structures occurred at PPV of 71.3 mm/s at Sonepur Bazari mine and at 68.6 mm/s at Kusmunda mine. The corresponding PPV recorded on the ground surface near the foundation were 39.3 and 46.1 mm/s respectively. The cosmetic cracks detected in second floor of RCC structures occurred at PPV of 71.2 mm/s at Sonepur Bazari mine and at 72.2 mm/s at Kusmunda mine. The corresponding PPV recorded on the ground surface near the foundation were 29.9 and 14.35 mm/s respectively. The highest amplification of vibration of 5.03 was recorded in the RCC structures at second floor. The PPV of 14.35 mm/s caused cosmetic cracks in the second floor of the RCC structure. It was difficult to record the cosmetic cracks in the mud house.

Minor and major damage recorded in the mud house was for a PPV of range of 55-56.1 mm/s and 87.1-104 mm/s respectively. The recorded PPV near the foundation of mud house which caused minor and major damage were 34.8 and 29.3 mm/s and 57.7 and 53.3 mm/s respectively. The PPV level of 29.3 mm/s near the foundation of mud house caused minor damage and the PPV level of 34.8 mm/s caused major damage in the mud houses.

Minor and major damage recorded in the brick-mud-cement house was produced by PPV of 81 and 99.6 mm/s respectively at Sonepur Bazari mine. The corresponding PPV recorded on the ground surface near the foundation were 38.6 and 39.4 mm/s respectively. Similarly, the minor and major damage recorded in the brick-mud-cement house was produced by PPV of 89.7 and 113 mm/s respectively at Kusmunda mine. The corresponding PPV recorded on the ground surface near the foundation were 55.9 and 56.1 mm/s respectively. Thus, the PPV near the foundation of the brick-mud-cement structures of 38.6 mm/s caused minor damage and 39.4 mm/s caused major damage in one of the brick-mud-cement houses.

The minor and major damage recorded in the RCC structures at second floor were for PPV of 98.3 and 128.9 mm/s respectively at Sonepur Bazari mine. The corresponding PPV recorded on the ground surface near the foundation were 35.9 and 42.7 mm/s respectively. Similarly, the minor and major damage recorded in the RCC structures at first were for PPV of 104 and 122 mm/s respectively at Kusmunda mine. The corresponding PPV recorded on the ground surface near the

TABLE 13: RECOMMENDED THRESHOLD LIMIT OF PEAK PARTICLE VELOCITY (PPV) IN MM/S AT THE FOUNDATION LEVEL OF BUILDINGS/STRUCTURES IN MINING AREAS

	Dominant excitation frequency, Hz		
	< 15 Hz	15-30 Hz	> 30 Hz
(A) Buildings/structures not belong to the owner			
1. Domestic houses/structures (kuchcha, brick and cement)	12	20	25
2. Industrial buildings	18	30	40
3. Objects of historical importance and sensitive structures	5	7	10
(B) Buildings belonging to owner with limited span of life			
1. Domestic houses/structures	18	30	40
2. Industrial buildings	30	40	50

foundation were 49.9 and 45.3 mm/s respectively. The minor and major damage at second floor of RCC structures were for PPV of 118 and 161 mm/s respectively. The corresponding PPV recorded on the ground surface near the foundation were 46.1 and 49.9 mm/s respectively. Thus, the PPV near the foundation of the RCC structure of 35.9 mm/s caused minor damage and 42.7 mm/s caused major damage in one of the RCC structures.

The cosmetic cracks found in the test structures due to blasting were from PPV of more than 50 mm/s. The PPV measured outside and close to the structures of concern on ground surface were 21.8 mm/s for low rise houses and 14.35 mm/s for high rise structures which caused cosmetic cracks in the test structures. The minor damage levels recorded in mud house was at PPV of 55 mm/s. The mud house response characteristic to blast vibration was of meagre in nature. However, the recorded minor damage in the other brick-mud-cement houses were more than 81 mm/s for low rise house and 98.3 mm/s for RCC structures.

Despite these high-observed values, the threshold limit of vibrations for different types of structures has been recommended at a significantly lower level. This is based not only on the structural response and actual observations of cracking/damage in test structures from the blasts conducted at the mines but also on the basis that these structures were newly constructed for the purpose of the study and therefore may have superior vibration resistance than similar but much older structures. The vibration levels below that which caused development of cosmetic cracks levels are being recommended as threshold level of vibration for the safety of buildings/structures in mining areas for different categories of frequencies. The recommended vibration levels for safety of residential structures/building in mining areas in terms of peak particle velocity in mm/s with corresponding frequencies are given in Table 13.

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