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Study on the impact of opencast blasting on surrounding structures in environmentally sensitive areas

Introduction

Ground vibration is an inevitable, but undesirable by-product of blasting operations. The vibration energy that travels beyond the zone of rock breakage is wasted and can cause damage to surface structures and annoyance to the residents in the vicinity of the mines (Siskind et al. 1980). The undesirable known side effects of detonation of explosives are vibration, noise/air over-pressure, flyrock, dust and fumes (Singh et al. 1996).

The real cause of why people complain about blasting is structural response. The neighbours could care less about how fast a particle on the surface of the ground in their yard is moving. All blast vibration complaints are due to how much complainant's houses shake, not how much the ground shakes. There are three factors of ground vibrations that determine how much one's houses vibrate. They are ground vibration amplitude (peak particle velocity: PPV), its duration and its spectral content.

In order to understand how these three factors control the response of a structure and how a house vibrates, one can think of a more familiar model – a swing. A swing is a single-degree-of-freedom vibration model that behaves in a manner similar to a house. The action of ground vibration amplitude on a house may be equated with a push applied to the swing. If the push it harder, the swing goes higher. The shaking of structure is also directly and linearly proportional to ground vibration amplitude. If the PPV is reduced by half, structural response will be cut in half (Rudenko 2002).

The duration of ground vibration is an equally important parameter in considering structural response. Using the swing analogy, one can easily make a swing go higher without

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pushing it harder, by simply pushing it again. The more times the swing is pushed the higher it will go. Longer ground vibrations continue to shake the house causing greater amplitude of structural response. Frequency is the most important of the three factors of ground vibration. Ground vibrations at the fundamental frequency of a house are like pushing a swing whenever it comes back to us. If we push the swing at any other time, we disrupt its rhythm. If a house is exposed to ground vibrations near its fundamental frequency, the house will amplify the vibration.

1. Objectives of the study

The surface mines which were planned earlier to be away from residential areas, are now approaching to them. The mine operators attempt to get better fragmentation of rock even if it requires high consumption of explosives per tonne of mineral produced. The vibrations generated from detonation of explosives may cause damage to structures and annoyance to their residents in the vicinity of the mines. A study was conducted at four open-pit mines in India to investigate the impact of heavy blasting on the surrounding structures in close proximity of the mines.

2. Brief geology of the experimental sites

The study was conducted at four open-pit mines in different Coalfields of India. The Sonepur Bazari project of Eastern Coalfields Limited is located in the Eastern part of Raniganj Coalfields. In the project area, four coal seams viz. R-IV, R-V, R-VI and R-VII are mainly exposed. Presently, seams R-V and R-VI are being extracted by opencast method of mining. The mine produces about 3.5 Mt of coal with a corresponding overburden removal of about 11.5 million cubic meters. The average stripping ratio is 4.72 m^3 per tonne coal produced. The total coal reserve is 188 Mt.

Jayant and Nigahi projects of Northern Coalfields Limited are located in the Singrauli Coalfields. The rocks are of Gondwana formation having coal bearings of Barakars within it. Three coal seams viz. Purewa top, Purewa bottom and Turra are being mined. The thickness of Purewa top, Purewa bottom and Turra seams are 5–9 m, 9–12 m and 13–19 m respectively. The thickness of partings between Purewa bottom and Purewa top seams is 17–32 m, whereas between Turra and Purewa bottom seams it is 52–59 m. The overburden above Purewa top seam is 12–95 m. The mineable coal reserves are 349 and 492 million tonne respectively. The average stripping ratio is 2.6 m^3 of overburden per tonne of coal. The dip of the coal seam is 1°–3° in northerly direction. Both the mines produce about 10 million tonne of coal and about 30 million cubic meters of overburden.

Kusmunda project is located on the western bank of Hasdeo River in the central part of Korba Coalfields in the district of Korba in Chhattisgarh State. The upper Kusmunda seam incrops 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 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 splits) 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). The mine produces about 8 million tonne of coal and overburden removal is of 10 million cubic meters.

3. Instrumentation and measurement techniques

The ground vibrations produced by blasting were monitored by deploying 8–10 seismographs for each blast at various locations. The seismographs deployed for monitoring purpose were namely BlastMate III and MiniMate plus, SSU 3000 LC and Mini-Seis. All the seismographs have tri-axial transducers for vibration recording and microphone for noise/air over-pressure recording. The response of structures was monitored by eight channel seismographs with geophone placed on the structures and on the ground near their foundations.

4. Experimental Details

The experimental blasts were conducted at shovel benches (SB) and dragline benches (DB) except in the Kusmunda project, where only shovel benches are operational. The

Phot. 1. Typical drill pattern at shovel bench of Jayant project

Fot. 1. Typowy schemat wierceń na wyrobisku w projekcie Jayant parameters studied were borehole diameters, hole depth, burden, spacing, number of holes detonated, variation in total quantity of explosive in a blast round and explosive detonated in a given delay (within 8 ms). The typical drill pattern at shovel bench is depicted in photograph 1. The blastholes were initiated by Nonel tubes as well as detonating cords. Extended seismic arrays were used to identify the vibration characteristics at near-field and far-field. The range of monitoring distance varied from 25 m to 6500 m. The depth of blastholes varied from 5.5 m to 42 m. The explosive charge weight per delay detonated differed widely from 33 kg to 24,800 kg. Similarly, the total explosive weight detonated in a blasting round also varied from 100 kg to 198400 kg. The details of the various parameters investigated are presented in Table 1.

TABLE 1

Summarised blast design parameters of the experimental sites

TABELA 1

Zestawienie parametrów projektowych robót strzelniczych terenów eksperymentu

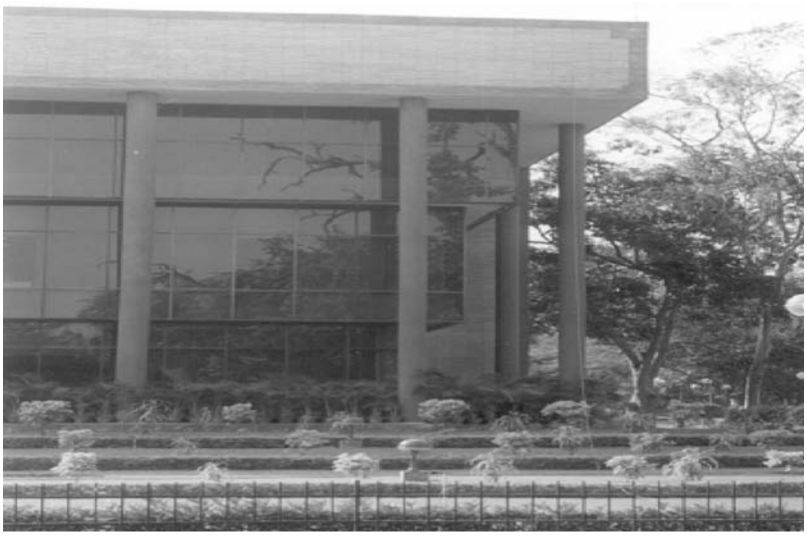
Parameters		Sonepur Bazari project	Jayant project	Nigahi project	Kusmunda project
Borehole diameter [mm]	SB	260–270	250–270	260–270	260–270
	DB	270	260–310	310	–
Hole Depth [m]	SB	7.5–18.8	11.0–28.5	9.5–19.0	6.2–17.7
	DB	22.8–34.0	28.0–40.0	38.0–42.0	–
Burden [m]	SB	5.0–7.5	5.5–9.0	6.0–10.0	5.5–7.5
	DB	8.0–9.0	9.0–10.0	10.0–10.5	–
Spacing [m]	SB	6.0–8.0	6.5–11.0	6.5–11.0	6.0–9.0
	DB	8.0–10.0	10.0–12.5	12.0–13.0	–
Number of holes detonated	SB	1–60	1–119	1–52	1–84
	DB	15–49	25–97	59–64	–
Explosives detonated in a blast [kg]	SB	300–20921	325–145137	635–36000	100–23335
	DB	19326–45808	50250–197407	153561–198400	–
Explosives detonated within 8ms delay [kg]	SB	100–550	325–12000	590–6000	33–3770
	DB	935–2400	1980–7780	17470–24800	–

SB: Shovel bench blasts, DB: Dragline bench blasts

5. Determination of natural frequency of structures

The ground motion resulting from blast induced waves is transmitted to the structure upside through the foundation, which causes the structure to vibrate. The dynamic property of structures includes its natural frequency and damping ratio. The influence of frequency on the structure's dynamic response includes two aspects. One is the frequency of blasting waves (external cause) and the other is the fundamental frequency of the structure (internal cause). The structures do not respond immediately to blast vibrations when the frequency of waves is much greater than the fundamental frequency of the structure. The attenuation of blast vibration waves with high frequency is very rapid. On the contrary, for the in-putting blast waves with low frequency, the whole structure vibrates because the half-wave length is longer than the characteristic dimension of the structure. Especially when the magnitude of primary frequency of blast waves is very close to the fundamental frequency of the structure, the structure produces the resonance and causes the whole structure to vibrate more seriously.

The study included monitoring the amplitudes of vibration simultaneously on the ground surface near the foundation of the structure and at various levels in the structures such as roof/floor levels, mid-wall, corner wall etc. For this purpose the transducers of 8-channel seismographs were used. One of the reinforced concrete structure is shown in photograph 2 whose response to blast vibration was recorded. The recorded blast wave signals on the ground and on the structure are shown in Figure 1. The Trans, vert and long in the figure are the waveforms recorded on the ground in three directions and their vector sum is shown as VS123. The Tran2, Vert2, Long2 in the same figure are the recorded response of the structure to the blast vibration in respective directions at second floor. VS456 is the vector sum of the waveforms in these three directions. The Fast Fourier Transform analyses of frequency of vibration data indicated that maximum concentration of vibration energy on the ground near structure is in the frequency spectra of 3–10 Hz whereas it is within 2.5–4 Hz in the structure.



Phot. 2. Monitoring of response of reinforced concrete structure to blast induced vibration

Fot. 2. Monitorowanie reakcji żelbetowych konstrukcji na wibracje wywołane robotami strzelniczymi

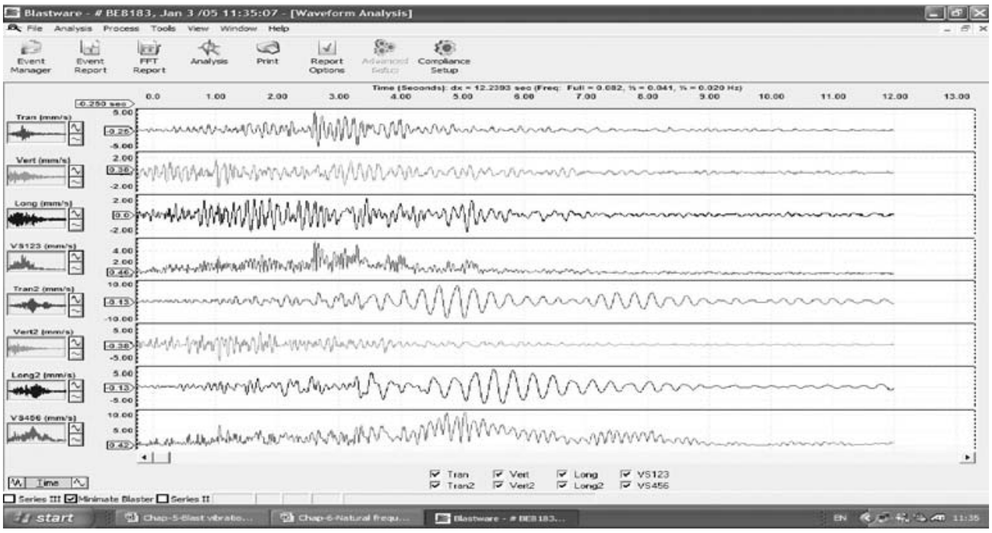


Fig. 1. Blast time history recorded at RCC structure to dragline blast at Jayant project

Rys. 1. Historia czasu trwania robót strzelniczych rejestrowana na konstrukcji RCC dla wybuchów zgarniających w projekcie Jayant

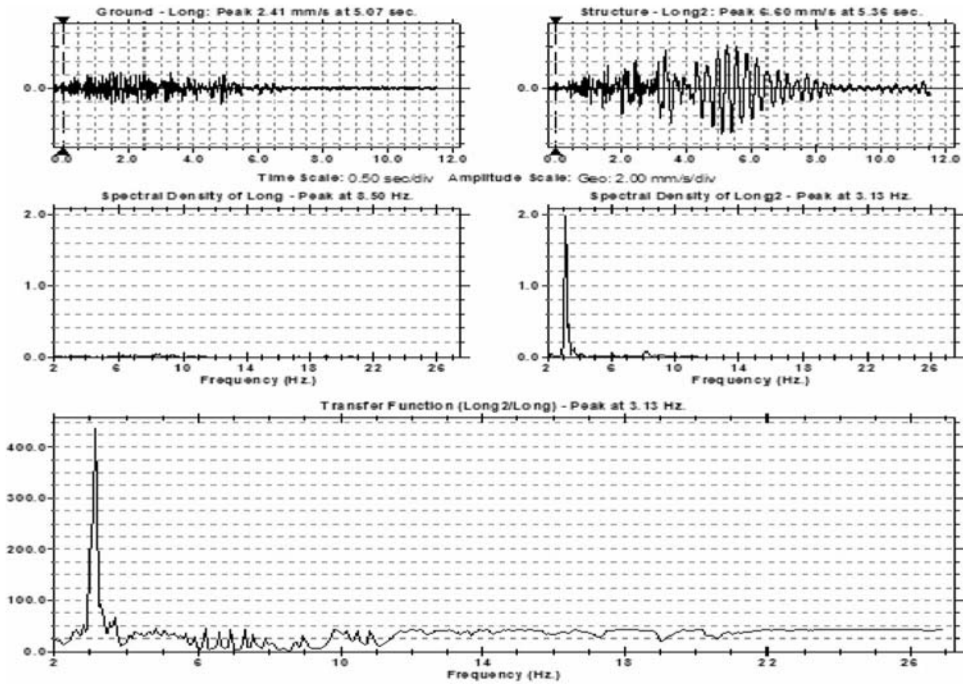


Fig. 2. Processing of blast wave signature for determination of natural frequency of reinforced concrete structure shown in Photograph 2

Rys. 2. Przetwarzania zapisu fali podmuchowej dla określenia naturalnej częstotliwości konstrukcji żelbetowych pokazanych na Fot. 2

The computational process involved in determination of natural frequency of the structure is shown in Figure 2. The recorded natural frequency of structure is between 3.13 and 4.25 Hz for roof, mid-wall and corners.

Similar exercises were carried out to monitor the response of various structures in the periphery of the mines. Amplification factor was determined directly from the vibration time histories. Maximum vibrations in the structures were documented. Ground particle vibration velocities and frequencies were then picked off the records at corresponding moments of time or immediately preceding the time of the peak structure vibrations. The maximum amplification of vibration in the structures was observed at the roof level at all the experimental sites. The natural frequencies of the structures in the periphery of the experimental sites were determined in order to design safe blasts during further investigation. The type and constructional details of some of the structures studied with their response to vibrations and their fundamental frequencies are presented in Table 2.

TABLE 2

Responses of structures to blast vibrations and their natural frequencies

TABELA 2

Reakcje konstrukcji na wibracje wywołane robotami strzelniczymi i ich naturalne częstotliwości

Sl. No.	Name and type of structure	Distance between transducer placed on the ground and in the structure [m]	PPV at ground surface [mm/s]	PPV at roof level, corner and mid-wall [mm/s]	Amplification of vibration in the structure	Natural frequency of the structure [Hz]
1.	Morwa house: (Load bearing structure)	3.5 4.2 7.2	2.34 2.37 2.83	5.07 5.45 7.51	2.17 2.30 2.65	6.94 6.69 6.81
2.	CETI Hostel: (Load bearing structure)	5.2 9.8	1.23 2.60	4.05 14.6	3.29 5.62	8.31 6.50
3.	Mart Building: (Load bearing structure)	8.1	2.97	9.73	3.28	6.25
4.	Panjare Bhawan: (Frame structure)	6.1 12.0	1.49 2.81	4.85 9.93	3.26 3.53	4.25 3.19
5.	Marhauli Sub-station: (Load bearing structure)	4.5	10.1	23.7	2.35	10.6
6.	Residential house: (Load bearing structure)	7.0	4.07	10.4	2.56	7.25
7.	Site office: (Load bearing structure)	3.3	7.52	16.5	2.19	8.75
8.	Bucyrus office: (Frame structure)	6.6	8.46	25.1	2.97	7.38

6. Discussion on structural response and dynamic amplification

The measured responses of residential and other structures are critical indicator of troublesome ground vibrations. Essentially, cracking from blast vibrations occurs when excessive stresses and strains are produced within the planes of the walls or between walls at the corners. Above-ground portions of structures tend to amplify horizontal ground motion, with the degree of response dependent on the vibration frequency, natural frequency and damping characteristic of the structure. The highest amplification factor of 5.62 was

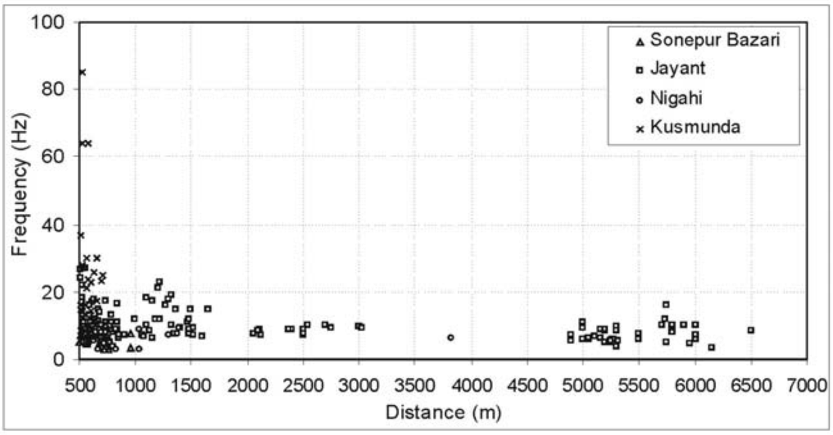


Fig. 3. Dominant frequencies of blast waves at far-field monitoring locations

Rys. 3. Dominujące częstotliwości fal podmuchowych w odległych lokalizacjach monitorowanych

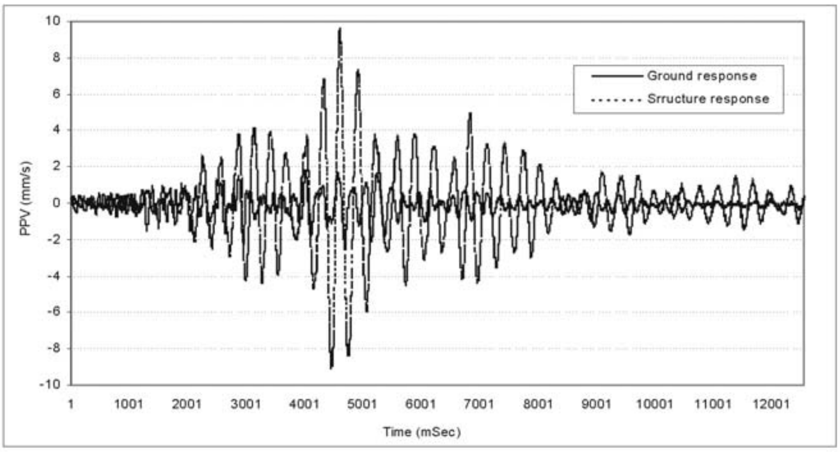


Fig. 4. Peak structure response and forcing ground vibration at RCC structure at 5.800 m from the blasting site of Jayant project

Rys. 4. Wartość szczytowa reakcji konstrukcji i wymuszanie wibracji gruntu w konstrukcji RCC w odległości 5800 m od miejsca robót strzelniczych w projekcie Jayant

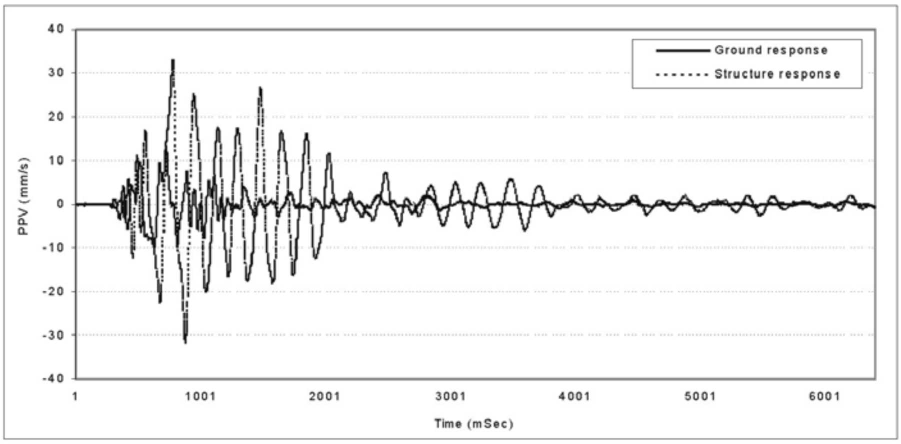


Fig. 5. Peak structure response and forcing ground vibration at double storey RCC structure at 625 m from the blasting site of Kusmunda project

Rys. 5. Wartość szczytowa reakcji konstrukcji i wymuszanie wibracji gruntu w dwupiętrowej konstrukcji RCC w odległości 625 m od miejsca robót strzelniczych w projekcie Kusmunda

monitored at CETI building at Singrauli Coalfields. The amplification factor of 1.61 to 5.62 were recorded which corresponds to excitation frequencies within 3.3–10 Hz. The natural frequencies of the structures ranged between 3.13 and 10.6 Hz. The blast wave principal frequencies recorded at 500 m to 6500 m are presented in Figure 3. The recorded principal frequencies of the blast waves were mostly in the excitation frequencies of the structures and thus, were the reasons for higher amplitude of vibration in the structures. The peak structure response and the incoming ground vibrations waveforms are superimposed for absolute and differential responses analyses. The maximum amplifications occurred at resonance frequency (Figures 4–5) because of low differential responses. The frequencies below resonance did not show amplifications because there were no relative displacement and hence, no appreciable strain.

7. Discussion on the persistence of vibration in the structures

Complete avoidance of superposition and amplification of the vibrations in a larger blast is impossible to achieve because the duration of the vibration is always considerably larger than the effective delays used between the charges in smaller blasts (Singh et al. 2003; Valdivia et al. 2003). It was observed that persistence of vibration in the structures was more than 12 seconds due to dragline blasts (Figure 1). The designed duration of blasts were upto 2184 ms. Vibrations recorded near the foundation of the structures at far-off distances (more than 5000 m) were between 1.23 and 2.97 mm/s but in the structures at various floors, it ranged between 2.56 and 14.6 mm/s. Amplifications of upto 5.6 times were recorded. Such blast events were unacceptable to the resident, although no damage was recorded in the structures. The seismologists in earthquake engineering typically used acceleration levels to quantify damage potentials. These may be of moderate and even lower levels than found in blasting. However, their low frequencies produce large particle velocities and enormous displacements. Richter (1958) stated that 0.1 g acceleration at 1 Hz is ordinarily considered damaging in earthquake seismology. The corresponding particle velocity and displacement are 156.21 mm/s and 24.89 mm respectively, assuming simple harmonic motion. The same acceleration at 20 Hz will only produce 7.82 mm/s of particle velocity and 0.06 mm of displacement. Richter also observed that the damage potential of a given vibration is dependent on its duration, with 0.1 g at 1 Hz likely not to produce damage for events for a few seconds, but very serious of earthquake-type events of 25 to 30 sec.

The long persistence of vibration (upto 15 seconds) in the structures at far-off distances was of great concern. A signature blast (single hole) was performed at Jayant project to find out the characteristics of blast vibration waves. The time history of the signature blast is shown in Figure 6. Based on the signature waveform obtained at 500 m, it would appear that a maximum delay interval of 150 ms would be required to prevent superposition of events. At representative distances for the location of structures, it could be even more than this figure. However, any delay interval of this magnitude is considered impractical in most blast situations. A practical option then would be to shift the arrival times of succeeding blastholes so that the differing arrival times destructively superpose. On the basis of the signature waveform shown in Figure 6, the effective delay interval would be nearer to 25 ms. In the row-by-row design shown, a compromise was arrived at by designing intra-row delay of

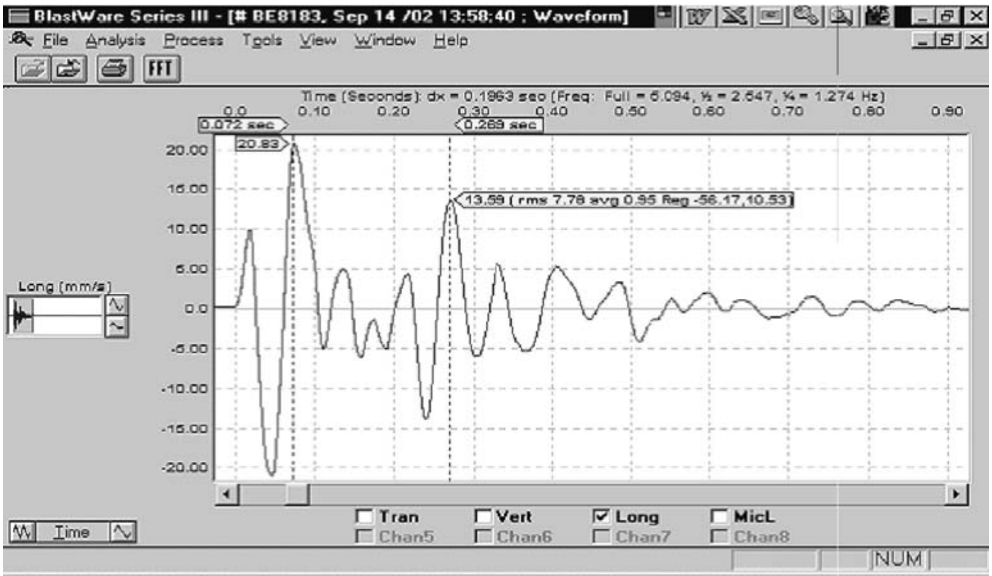


Fig. 6. Time history of the signature blast in longitudinal direction recorded at Jayant project

Rys. 6. Historia czasu w zapisie robót strzelniczych w kierunku podłużnym zarejestrowana w projekcie Jayant

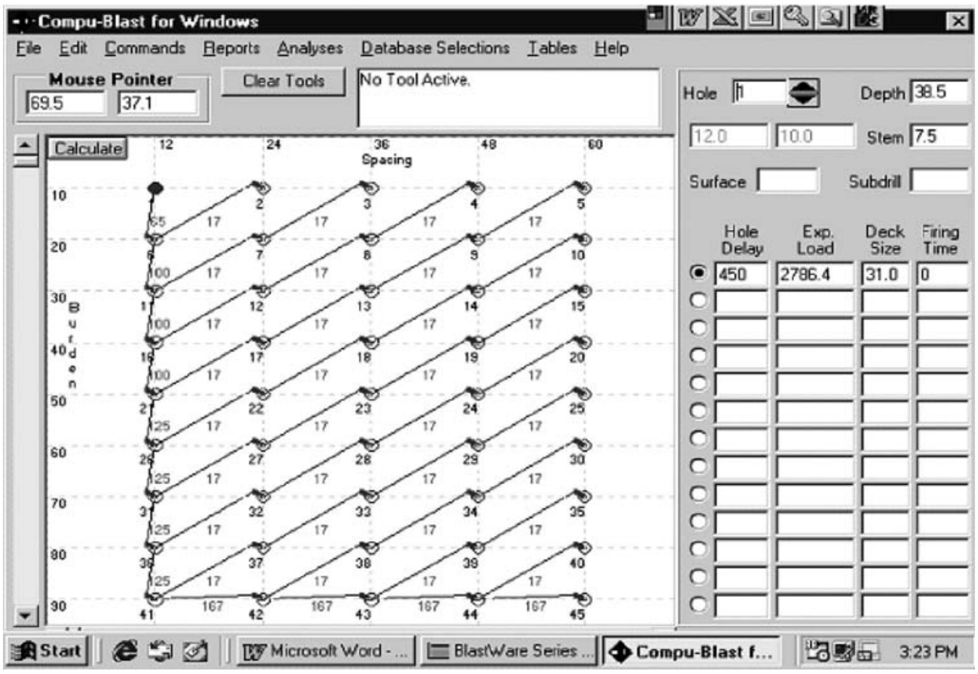


Fig. 7. Layout of modified blast design experimented at Jayant Project

Rys. 7. Rozplanowanie modyfikowanych projektów robót strzelniczych w projekcie Jayant

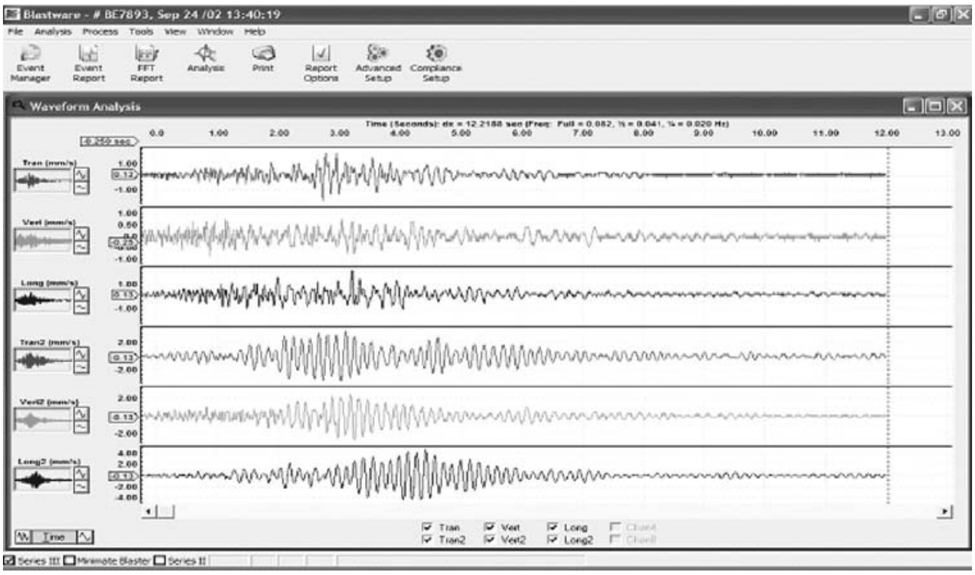


Fig. 8. Blast time history recorded at reinforced concrete structure due to dragline bench blasting of Jayant Project with the blast design depicted in figure 10

Rys. 8. Historia czasu w zapisie robót strzelniczych w konstrukcji żelbetowej w efekcie robót strzelniczych w wyrobisku w projekcie Jayant dla projektu robót strzelniczych pokazanego na rys. 10

17 ms but an average inter-row delay of 100 ms. The duration of the blast was reduced up to 1527 ms (Figure 7). The modified blast designs resulted with lower magnitude of vibration at all the monitoring locations compared to the blasts conducted with the prevailing practice. The persistence of vibration in the same structure was upto 8 seconds (Figure 8) and the amplification of vibration in the structure was 2.18 times only. The residents were comfortable with such vibration levels. In fact the higher magnitude of vibration with short duration were acceptable by the villagers whereas the vibration levels of lower magnitude with longer duration were not acceptable by the villagers.

Conclusions

In most of the blasts the frequency of blast vibration recorded is less than 7 Hz. These low frequencies are due to the low-velocity surface layer (top soil) and long vibration monitoring locations. The Fast Fourier Transform (FFT) analyses of recorded data revealed that the maximum concentration of vibration energy was in the range of 3.3–7 Hz. The structures studies were having fundamental frequencies in between 3.13–10.6 Hz. The incoming vibration has frequency in the range of fundamental frequency of the structures, resonance occurred and the resultant amplitude of vibration on the structure got amplified. This is the reason why the structures at higher floors vibrated with higher amplitude of vibration than that of ground.

It is concluded that if a structure is exposed to ground vibrations near its fundamental frequency, the structure will amplify the vibration. Ground vibrations below the fundamental frequency of the structure will cause the structure to vibrate at least as much as the ground. However, if the frequency of the ground vibration is 40% higher than the fundamental frequency of the structure, the structure will vibrate less than the ground.

The amplifications of vibration in the structures were more than five folds depending upon the height of the structures, its fundamental frequencies and also the frequencies of in-coming vibration. The persistence of vibrations were upto 15 seconds in the structures at far-off distances when the duration of blast was 2184 ms. Signature blast helped in optimising the delay intervals between the holes in a row and within the rows. The blast duration of 1527 ms resulted into reduced vibration level and less persistence of vibration in the structures. The long persistence of vibration in the structures at far-off distances was of great concern. It is recommended that the blast should be designed in such a way that its total duration should not be more than 1500 ms in environmentally sensitive areas. It has been also observed that the timing of delay intervals between two detonations had no influence on the frequency content of the vibrations. Geology was the controlling factor for predominate frequencies of vibration in this study.

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BADANIE WPŁYWU ODKRYWKOWYCH ROBÓT STRZELNICZYCH NA POBLISKIE KONSTRUKCJE W REJONACH WRAŻLIWYCH ŚRODOWISKOWO

Słowa kluczowe

Roboty strzelnicze w skałach, wibracje gruntu, kopalnia odkrywkowa, środowisko naturalne

Streszczenie

Zmierzona reakcja konstrukcji mieszkalnych jest krytycznym wskaźnikiem kłopotliwego lub potencjalnie szkodliwego wpływu wibracji gruntu. Przeprowadzono badanie mające ocenić reakcję konstrukcji w środowiskowo wrażliwych rejonach w pobliżu czterech odkrywkowych kopalni węgla w Indiach. Badanie objęło 215 wybuchów, w których zastosowano analizy jedno-, dwu- i trójotworowej kalibracji, jak również wybuchy produkcyjne. Wysokość wyrobiska wahała się od 7, 5 m do 42 m, a otwory wiertnicze wypełnione materiałami wybuchowymi emulsyjnymi i szlamowymi miały średnice 250, 260, 270 i 310 mm. Materiał wybuchowy zdetonowany w wybuchu ważył od 300 do 198.400 kg, a opóźniony – 33 do 24.800 kg. Osiem do dziesięciu trójosiowych czujników wibracji ustawiono w układzie liniowym na odległości od 25 m do 6,5 km w celu zbadania zmian amplitudy, częstotliwości i czasu trwania w funkcji odległości. Łącznie zarejestrowano 1.512 zapisów wibracji strzelniczych.

Podstawowa częstotliwość konstrukcji zawierała się pomiędzy 3,13 do 10,6 Hz. Częstotliwości fali podmuchowej na dalszych odległościach również mieściły się w zakresie podstawowych częstotliwości konstrukcji. Zarejestrowano wzmocnienie wibracji w konstrukcjach ze współczynnikiem 1,6 do 5,62. Wibracje utrzymywały się w konstrukcjach przez czas do 15 sekund. Potwierdzono, że jeżeli konstrukcja zostanie wystawiona na wibracje gruntu bliskie częstotliwości podstawowej, wzmacnia poziom wibracji. Wibracje gruntu niższe od częstotliwości podstawowej konstrukcji powodują jej wibracje przynajmniej takie same jak wibracje gruntu. Wydaje się, że to raczej warunki geologiczne są czynnikiem decydującym o amplitudzie i częstotliwości wibracji niż przedziały opóźnienia pomiędzy kolejnymi detonacjami.

STUDY ON THE IMPACT OF OPENCAST BLASTING ON SURROUNDING STRUCTURES IN ENVIRONMENTALLY SENSITIVE AREAS

Key words

Rock blasting, ground vibration, open pit mining, natural environment

Abstract

The measured response of residential structures is a critical indicator of troublesome or potentially damaging ground vibrations. A study was conducted to evaluate the response of structures in environmentally sensitive areas in the proximity of four open-pit coal mines in India. The study involved 215 blasts, employing one-, two- and three-hole calibration study, and production blasts. The bench height varied from 7.5 m to 42 m, and boreholes loaded with emulsion and slurry explosives were 250, 260, 270 and 310 mm in diameter. The explosive detonated in a blast were between 300–198400 kg whereas in a delay it was 33–24800 kg. Eight to ten tri-axial vibration sensors were deployed along a linear array from 25 m to 6.5 km, to investigate the changes in amplitude, frequency, and duration with distance. Altogether, 1512 blast vibration signatures were recorded.

The fundamental frequency of the structures ranged between 3.13 to 10.6 Hz. The blast wave frequencies at far-off distances were also in the range of the fundamental frequency of the structures. The amplification of vibration in the structures of the factor of 1.6 to 5.62 was recorded. The persistence of vibrations in the structures were upto 15 seconds. It is confirmed that if a structure is exposed to ground vibrations near its fundamental frequency, the structure will amplify the vibration level. Ground vibrations below the fundamental frequency of the structure will cause the structure to vibrate at least as much as that of the ground. It also appears that the underlying geological conditions are the controlling factor in terms of amplitude and frequency of vibration rather than the delay interval assigned between successive detonations.