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Technical Note

Blast design and vibration control at an underground metal mine for the safety of surface structures

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1. Introduction

Vibrations as a result of blasting practices in mining engineering are complex phenomena controlled by many variables. Ground vibrations from blasting have been a continuous problem for the mining and construction industries, the public living near the mining activities and the 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 and frequencies and to a lesser degree on site and structure specific factors. All blast vibration complaints are due to how much complainant's houses shake, not how much the ground shakes. The three factors of ground vibrations that determine the degree of shaking are ground vibration amplitude (peak particle velocity; PPV), its duration and its frequency.[1] Apart from the PPV, the frequency content and the relative amplitude of horizontal and vertical components can also play important roles with regards to the response of structures in the nearby areas. On the other hand, various variables such as the charge loading density, site geology, blast geometry, can also affect the ground shock at a given scaled distance.[2] Further, the influence of the blasting excavation disturbance on the surrounding rocks of deep-buried tunnels is mainly embodied by the damage or failure of rock masses caused by the stress redistribution of surrounding rocks, the blasting load of the excavation blasting and the transient unloading of the excavation load.[3] Li et al.[4] tried to assess the tunnel safety by analyzing the PPV and stress distribution. Xia et al.[5] observed that the rock damage extent around the tunnels linearly increases with the peak particle velocity (PPV). Human beings notice and react to vibration at levels much lower than the levels established as structural damage thresholds.[6,7] Previous studies on human response to transient vibrations have established that human tolerance to vibration decreases the longer the vibration continues.

Reidarman and Nyberg[8] made an attempt to characterize the vibrations that occur along tunnel walls during excavation blasting. The effect of underground structures on above ground buildings has been studied in the past focusing mainly on the resulting surface settlements.[9] Recently, the effect of underground structures on the seismic response of ground surface has attracted the attention of researchers, since it has been concluded that the presence of these subsurface structures has also effects on the seismic response of nearby ground.[10] Smerzini et al.[11] proposed an analytical solution to describe the effect of underground cavities on the ground motion generated by P, S or R seismic waves. However, these methods consider some simple assumptions such as elastic medium in the analyses. The other factors such as soil nonlinearity were not considered in those methods.[12] The mining industry needs realistic blast design levels and also practical techniques to safe guard the structures in their periphery. At the

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same time, mines 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.[13–15] Finally, neighbours around the mining operations require really protection of their property and health. Last but not the least; the mining operations should not be stopped only due to apprehension of the damage to the structures/buildings.

This paper investigates the issue of ground vibration complaints at Kayad village due to the blasting at Kayad underground mine and its possible solutions. The study was conducted through systematic steps by changing blast design viz. amount of explosives in a blast round or in a delay, number of holes, position and timing of deck, firing sequence, hole diameter and length and detonation of explosives by different initiating devices.

2. Geological details

The study has been carried out at a Kayad underground mine. It is a lead-zinc mine of Hindustan Zinc Limited and is located at Kayad village in Ajmer district of Rajasthan state in India. The mine is located on the Eastern fringe of Kayad village. The deposit lies between latitude N26°31′30″ and longitude E74°41′ and 74 °42′. The Kayad village is 9 km NNE of Ajmer city and is well connected by tar road.

There are three lenses – the Main lens, K1A lens and S1 lens. The earlier three lenses viz. K1, K2 and K3 have been re-correlated as one single lens on account of the positive intersections encountered in the drilling in the vacant spaces between these lenses. The main host rock is Quartz mica schist with some mineralization also occurring in calc silicate. Main lens has been dissected at many places by pegmatite. The lenses lie parallel to the axial plane foliation/cleavage/fracture of the fold system or shear fractures governed by the lithological variations. The main lens has been explored to variable depths and maximum upto 50 mRL while K1A and S1 go upto 350 mRL. The main lens ranges in average width from 5 m in steeper portions to about 40 m in the flat lying portion. Maximum strike of the main lens is 900 m at the depth of approximate 250 m from the surface. It shows a general reducing trend in depth. This lens shows swelling and pinching nature probably because of superimposition of different phases of folding. The total reserves and resources of the mine are 11.4 Million tonnes with 10.61% Zn, 1.61% Pb and 33 ppm Ag.

3. 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.

United States Bureau of Mine (USBM) published RI 8507[16] and recommended blasting damage criteria which set a peak particle limit (12.5 mm/s) based upon predominant frequency of the seismic wave. A further review of limits imposed, raise question about how relatively small limits, such as 0.25 in./s can be technically justified. Several researchers stated that no engineering study or research justified such limits. But when such restrictive levels are imposed, they are more of a political limits intended to reduce or eliminate public complaints. Australian and German standard recommended their minimum PPV level of 19 mm/s[17] and 5 mm/s[18] respectively for domestic houses. Indian standard suggested by Regulatory agency is presented in Table 1.[19]

Table 1
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 (Mud/ 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

4. Blasting details and monitoring of vibration

Blast vibration monitoring was carried out at three to four locations in Kayad village due to blasting at Kayad underground mine. Development face blasts were performed at different locations in the mine. The number of holes detonated in a blast round for development blasting, varied from 17 to 78. In case of slot raise and ring blasting, the number of holes generally varied between two and thirteen. The total explosives weight detonated in blast around varied from 70 to 310 kg. The maximum explosives weight per delay varied between 3.90 and 18.75 kg. The diameters of the blast holes were 45 mm in case of development face blasting and for slot raise and ring blasts the drill diameter was 76 mm.

The blast vibration generated due to development faces, slot raise and ring blasts have been taken for analyses. In all the cases the monitoring of blast vibration were performed for vertical depth of 30–185 m and horizontal distance up to 300 m from the vertically above point from the underground blasting face. Recorded blast vibration data were in the range of 2.34–14.6 mm/s. The structural responses of various houses of the village were determined and their natural frequencies were recorded which are in the range of 14–16 Hz. The incoming higher dominant peak frequency of vibration caused reduction of vibration in the structures at various floor levels as the natural frequencies of the houses are in the lower range. Details of few houses/structures of the village are depicted in Table 2 and blast wave signature for determination of natural frequency is presented in Fig. 1.

The recorded frequencies of vibrations were in the range of 30.1–246 Hz. The Fast Fourier Transform (FFT) analyses of vibration data obtained shows that the concentrations of vibration energy were in the range of 50–150 Hz. Thus, the safe level of vibration has been taken as 15 mm/s for the safety of houses/structures as per DGMS standard (Table 1). The plot of recorded dominant peak frequency of vibration in village at various radial distances from the blasting sites is presented in Fig. 2.

Recorded blast vibration data were analyzed at a regular interval. The vibration data recorded due to development face blasts and production blasts (slot raise and ring) have been taken for analyses and generalized prediction equation has been established and it is given as

$$v = 490.1\left(R/\sqrt{Q_{\max}}\right)^{-1.314} \quad (1)$$

where, v is the peak particle velocity (mm/s), R is the distance between vibration monitoring point and the blasting face, and