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Dynamic simulation approach to assess influence of charging parameters on blast induced vibration

Blast induced ground vibration is one of the key concerns from safety view of nearby structures. There are many direct and indirect parameters responsible for blast induced ground vibration. Explosive parameters including its charging quantity and quality is one of them. Velocity of detonation of explosives, its interaction with rock strata and charging condition of a blasthole influences blast outputs in the form of fragmentation as well as undesirable effects like ground vibration, flyrock, air-over-pressure/noise etc. Researchers around the globe have established empirical formulations to investigate effects of explosive parameters on blast induced ground vibration. Following paper focused on investigating influence of charging parameters on blast induced ground vibration. Numerical simulation using dynamic modelling package of FLAC3D have been used for this. Signature hole geometry with rock properties and explosive properties in the form of detonation pressure has been modelled. Detonation pressure of the explosive was estimated from recorded in-the-hole velocity of detonation and density data for different explosive types. Damping parameters in the form of damping coefficient and frequency has been given to deplete blast vibration velocity for the medium. This was estimated by back calculation from recorded blast vibration data. Influence of hole diameter, distance of blast face from monitoring point, column length of explosive charge and charge distribution on blast induced vibration were assessed. Blast induced ground vibration in the form of history of velocity peaks has been plotted against dynamic time of blast wave propagation. Results of the dynamic simulation shows effects of hole diameter and charge column length on blast vibration in the same line with explosive weight per delay considered in USBM predictor equation. Investigation of effects of distance on blast induced vibration shows dependency of blast vibration on directional distance rather than radial distance. Charge distribution effects shows considerable reduction in blast vibration magnitude for distributed charge than full column charge.

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1. Introduction

Blasting is the most extensively used method for the excavation of minerals throughout the world in spite of being associated with various undesirable effects causing environmental spoliation and exasperation of neighbouring residents. In spite of large amount of energy produced during blasting only a small fraction of it (20-30%) is actually available for rock breakage purpose and rest of it contributes to vibration, air blast, flyrock, backbreak, overbreak etc. (Ghasemi et al., 2012). Blast induced ground vibration is a key concern for the blasting engineers in order to design parameters of controlled blasting, as blast vibration on the ground amplifies its magnitude on structure (Pal Roy, 1998). Although, blast induced ground vibration is influenced by many parameters, but United States Bureau of Mines (USBM) predictor equation is most acceptable worldwide. The parameters considered in USBM predictor equations are maximum charge per delay (MCPD) of a blast and distance of nearby structures from blast face (Duvall and Petkof ,1959). Researchers around globe considered various controllable and uncontrollable parameters for prediction of blast induced ground vibration. Kumar et al., 2016 considered rock parameters like unit weight of rock mass, rock quality designation (RQD), geological strength index (GSI), uni-axial compressive strength (UCS) of rock etc. as the parameters which influence blast vibration. Geological discontinuities play pivotal role in vibration wave propagation, as it influence reflection and refraction of blast wave through propagation media (Wu et al., 1998; Hao et al., 2001). Statistical regression analysis based approach is most common to predict blast induced ground vibration. Vibration data generated for this purpose from field experimentation is grouped together to develop site specific predictor equation. However, characteristics of blast wave and propagation media are not considered in this approach (Blair, 2014). Velocity of detonation and rock characteristics like rock mass parameters and p-wave velocity have more influence on blast vibration than charge weight per delay. Blair, 2014 correlated blast vibration with column length of explosive charge under three conditions with VOD greater than p-wave velocity, VOD equal to p-wave velocity and VOD less than p-wave velocity. Ainalis et al., 2016 used pressure modelling approach for numerical simulation of ground vibration. The approach in this paper has used numerical simulation for prediction of blast induced ground vibration. Detonation pressure as a function of velocity of detonation and density of explosive has been simulated for this purpose. Results were compared to field data for different diameter of blastholes and different charge length.

2. Parameters influencing blast induced ground vibration and its prediction approach

Charge weight per delay is most widely accepted parameters influencing blast induced ground vibration. A number of empirical models have been developed over the years, by Duvall and Fogleson (1962), Duvall et al. (1963), Ambraseys-Hendron (1968), Ghosh and Daemen (1983), Pal Roy (1993) and many other investigators. Peak particle velocity is the concerned parameter in these predictor equations. The scaled distance concept which is generally used for blast vibration prediction is defined as the actual distance (R) of the measuring point from blasting face divided by some power of the maximum explosives weight per delay (Q_{max}). These site-specific empirical equations cannot be generalized for use at other sites. Any available site PPV model does not accurately predict PPV for other sites.

Literatures on parameters influencing blast induced vibration suggests three types of parameters responsible for blast vibration - rock mass properties, Propagation media for blast vibration waves and blast design parameters including explosive parameters. Explosive energy required for breakage of rocks is function of rock strength. Impedance or TNT equivalent of rock mass could be an approach to assess explosive energy for different rock mass (Bollinger, 1980; Fouchier et al., 2017). Interaction of explosive energy with rock mass creates excavation damage zone. This excavation damage zone is dependent on rock mass properties (Yu et al., 2017). Propagation media of blast vibration wave influences its attenuation and amplification. Resende et al., 2104 considered propagation path or local amplification as more important parameter than explosive weight and distance for prediction of blast vibration. Joints and discontinuities affect considerably in reduction or amplification of blast vibration waves. Blast wave propagation in the free field is significantly governed by field geological conditions especially the interface between rock and soil layers (Wu et al., 1998 ; Hao et al., 2001; Gui et al., 2017). This concept is sometimes used to intentionally reduce the blast vibration magnitude. Artificially created pre-cut discontinuity, water bodies, voids etc. in the path of blast wave propagation reduce vibration magnitude (Lee et al., 2016; Singh et al., 2015). Blast design parameters including explosive properties are controllable parameters which influences blast induced vibration. Charge per delay, column length of explosive charge, hole diameter , burden and spacing etc. is optimized to keep vibration within safe limits. Elevli et al., 2010 correlated burden, spacing, hole diameter and charge per delay for blast vibration prediction using relation diagram method. Explosive quality in terms of velocity of detonation and density of explosive has role in blast induced vibration. Explosive VOD can direct the damage zone near a free surface. It has been observed from analytical modelling that increase in VOD channelled the vibration energy farther away from the near field (Blai, 2015).

3. Case study: Moher and Moher Amlori opencast project, India

3.1 Mine Description and Geology

Moher and Moher-Amlohri extension coal blocks are situated in the Singrauli coalfield which lies between latitudes 23°47'00" and 24°12'00" North and longitudes 81°40'00" and 82°52'00" East covering an area of 2202 sq km and is mainly located in the Singrauli district of Madhya Pradesh, India. Moher and Moher Amlohri extension opencast project is captive coal supplier to Sasan Power Limited. Mine is having annual coal production capacity of 16 million tonnes. It is equipped with dragline and shovel for excavation of coal and overburden. An overview of the Moher and Moher Amlori ext. OCP is presented in Fig.1.

Fig.1 An overview of Moher and Moher Amlori extension opencast project, Singarauli, India

Moher and Moher Amlori extension opencast project lies in Singrauli coalfield. The coalfield is broadly divided in two parts, the eastern most part of the coalfield is known as Moher sub basin and the western part is known as Moher main basin. The present mining block is situated in the Moher sub basin which is a broad basinal structure with uneven undulations on its limbs. The beds have an almost north-south strike in the east as well as in the west which gradually swings to east-west strike in the southern part revealing a half basin whose northern part is cut by a prominent E-W trending boundary fault. In the present mining block consisting of Moher and

Moher-Amlohri extension blocks the southern part which mainly comes under the Moher block is structurally disturbed whereas the northern part of the Moher Block and the whole of Moher-Amlohri extension block are generally free from geological disturbance.

3.2 Experimental blast details

Blasts were conducted at various shovel and dragline benches of the mine. Altogether thirty four experimental blasts were conducted consisting of 07 dragline bench blast and 27 shovel bench blast. Experimentation and field trial was conducted to optimize blast design parameters for safe and productive mining. Signature holeblasts were conducted to validate results of numerical simulation. Blastholes were charged with SME and ANFO explosives. Explosive type was decided based on strata condition to provide appropriate detonation energy for fragmentation. Charged holes were initiated with non-electric detonators (Down-the-hole delay detonator-DTH and trunk line delay detonator-TLD) and detonating fuse (DF). Blast vibration monitoring was done by placement of seismographs at different locations in and around mine premises to document blast induced ground vibration, frequency of blast vibration and air-overpressure. Blast output was recorded in terms of vibration, air-overpressure/noise, flyrock ejection, throw of blasted muckpile, fragmentation etc.

Dragline bench blast was having bigger size to optimize the dragline utility from single sitting point. The blast face for dragline bench consisted of 120-250 blastholes of hole diameter 311mm and hole depth 40m-55m. The holes were designed in the fashion of burden × spacing of 10m × 13m. Each hole was charged with average explosive weight of 4000kg-4500kg contributing to total explosive charge of 405 to 982 tonnes in a blasting round. Deck blasting pattern with decking length of 3.5-4.0m was followed.

Shovel bench blast was conducted with hole diameter of 259mm, 159mm and 150mm. Maximum 249 holes were fired in a blasting round during experimental blast. Each holes were charged according to hole depth. Decking was done to avoid generation of boulders and the better utilization of explosives. The deck length was selected as 8-10 times of the drill diameter and not exceeding 15-17 times of drill diameter. Concentrated booster was placed for explosive column not exceeding 8-10m to sustain explosive energy in the column. Booster concentration was optimized using comparison of in-the-hole velocity of detonation (VOD) for different booster concentration, and 0.2% to 0.25% of explosive column charge were found optimum to maintain optimal explosive energy discharge during the blasting.

3.3 United State Bureau of Mines (USBM) predictor equation for the site

USBM predictor equation is widely accepted for prediction of blast induced vibration. The equation is empirical relation between peak particle velocity (PPV), distance of monitoring station from blast face and maximum explosive weight per delay for blast. This equation is site specific and can be characterized by two site constants obtained from regression analysis of blasting data. Ground vibrations data recorded of the case study mine have been grouped together for statistical analysis. Regression analysis has been done to develop predictor equation for the site. Regression plot for shovel and dragline benches of the mine has been presented in Figs.2 and 3 respectively. USBM predictor equation of the site for shovel and dragline benches has been presented in equations 1 and 2 respectively (Himanshu et.al., 2018).

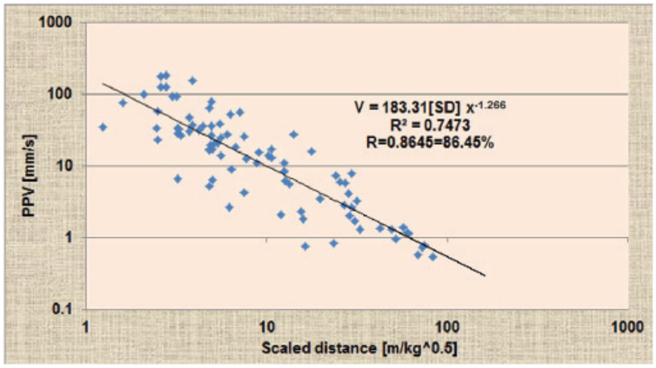


Fig.2 Regression plot of recorded PPV due to blasting at shovel bench faces at their respective scaled distances at Moher and Moher Amlori ext. OCP

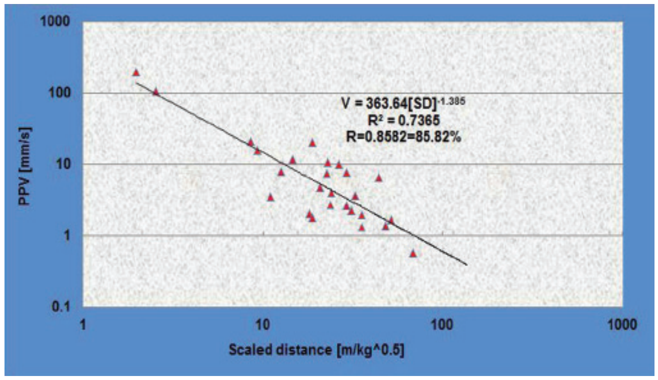


Fig.3 Regression plot of recorded PPV due to blasting at dragline bench faces at their respective scaled distances at Moher and Moher Amlori ext. OCP

$$PPV = 183.31 \times \left(\frac{D}{\sqrt{Q_{max}}} \right)^{-1.266} \quad \text{... (1)}$$

$$PPV = 383.64 \times \left(\frac{D}{\sqrt{Q_{max}}} \right)^{-1.385} \quad \text{... (2)}$$

where, PPV = Peak particle velocity (mm/s)

D = Distance between vibration monitoring point and blasting face (m)

Q_{max} = Maximum explosive weight per delay (kg)

3.4 Dynamic Simulation approach for prediction of blast induced vibration.

Dynamic simulation tool uses basic properties of elasticity to get deformation across modelled geometry. This can be achieved by tool packages of finite element, finite difference, discrete element or suspended particle hydrodynamics. Advantage of simulation approach is homogeneity of materials throughout model, and hence parametric response can be recorded, which is difficult during experimental trials. The approach used in this paper is finite difference approach using FLAC3D. Geometry has been modelled to simulate blast across single hole. Explosive energy in the form of detonation pressure has been given as input parameter. Stemming material is modelled as void considering its very low strength and instantaneous release during blast. Monitoring points have been fixed in model at desired radial distances from detonation point.

3.4.1 Material properties

Overburden material above Purewa coal seam of the mine is mainly sandstone. Experimental blasts were conducted at these sandstone benches. Numerical simulation was performed using elastic model of FLAC3D code. Rock mass properties for the sandstone available at case study mine and simulated in the model are shown in Table 1.

Table 1: Rock mass properties used in numerical simulation

Elastic modulus	5.7 GPa
Poisson’s ratio	0.25
Density	2310 kg/m^3

3.4.2 Boundary conditions

Boundary conditions have been given to modelled geometry, to fix deformation along all directions except direction of stemming ejection. “Quiet” boundary conditions have been given in all directions, which allows blast wave in the form of stress wave to be absorbed along boundaries. However, reflection and refraction of blast waves are usual in real case scenario leading to blast attenuation progressively. So, vibration predicted using this approach will be over prediction.

3.4.3 Damping and blast attenuation

All natural dynamic systems are subjected to a certain degree of damping of the vibrational energy within the system to prevent it from vibrating indefinitely when subjected to driving forces. Damping is due to the fact that there is always some amount of energy loss which is attributed to the internal friction in the material and due to the discontinuities present. The inclusion of damping in numerical simulation for dynamic analysis is to recreate the real mine conditions by generating similar types of energy losses as in natural scenario when subjected to dynamic loading. Rayeligh damping condition has been simulated for this case study. Damping co-efficient and frequency has been taken by back calculation approach to match the simulated blast vibration with recorded data. Damping co-efficient of 0.1% and frequency of 12 Hz have been taken for this problem.

3.4.4 Explosive properties and dynamic loading

The explosive energy has been modelled in the geometry in the form of detonation pressure. The detonation pressure associated with the reaction zone of a detonating explosive is a function of velocity of detonation (VOD) and density of explosive. It can be estimated by relation presented in equation 3.

$$P_d = \frac{1}{2}\rho_e (VOD)^2 10^{-6} \quad ... (3)$$

where, P_d = Detonation pressure (MPa)

ρ_e = Density of explosive (kg/m^3)

VOD = Velocity of detonation (m/s)

Explosive VOD has been measured at different benches for different hole diameter and explosive type. In-the-hole VOD measurement using Data Trap II instrument was performed for this purpose. The recorded VOD for ANFO explosive at 159mm diameter blasthole of shovel bench is 4052.8 m/s. Plot of recorded VOD for ANFO explosive in case of 159 mm diameter blasthole is presented in Fig.4. The recorded VOD for ANFO explosive in 311mm diameter blasthole at dragline bench is 4478.6 m/s. Plot of recorded VOD for ANFO explosive at dragline bench with 311 mm blasthole diameter is shown in Fig.5. Summary of recorded VOD for different hole diameter and explosive type is shown in Table 2. Dynamic loading to the model was provided in the

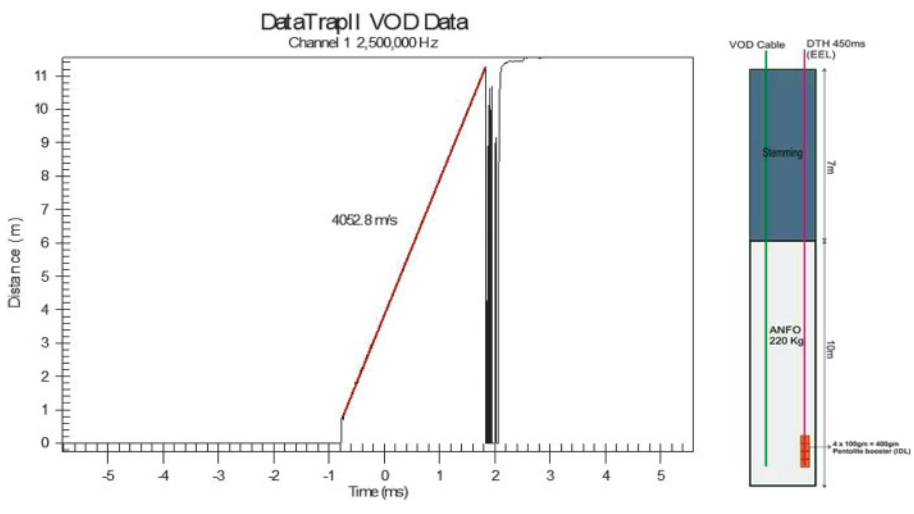
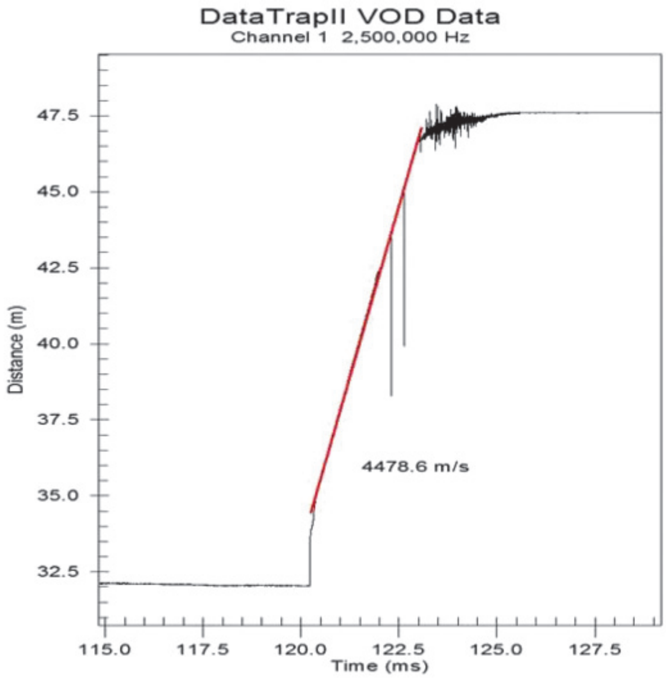


Fig.4 Plot of recorded VOD of ANFO explosive for 159mm diameter blasthole at shovel bench



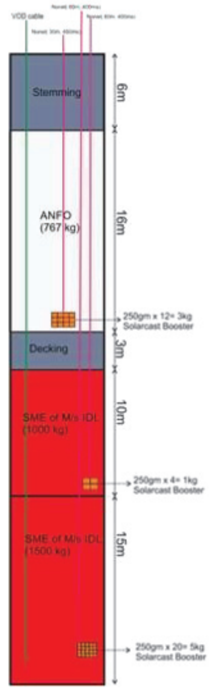


Fig.5 Plot of recorded VOD of ANFO explosive for 311mm diameter blasthole at dragline bench

TABLE 2 SUMMARY OF RECORDED VOD AT MOHER AND MOHER AMLORI EXTENSION OPENCAST PROJECT

Hole diameter [mm]	Explosive type	Recorded VOD [m/s]
159	Site mixed emulsion (SME)	4235-4852
159	Ammonium nitrate euel oil (ANFO)	4052-4091
259	Site mixed emulsion (SME)	4690-5545
259	Ammonium nitrate fuel oil	(ANFO) 4255
311	Site mixed emulsion (SME)	Not recorded
311	Ammonium nitrate fuel oil (ANFO)	4478.6

TABLE 3 EXPLOSIVE PROPERTIES SIMULATED IN THE MODEL

Velocity of detonation	5165 m/s
Density	1100 kg/m^3
Detonation pressure	14.67 GPa

form of detonation pressure. Explosive properties simulated in the model have been presented in Table 3.

4. Results and analysis

Blast vibration in the form of velocity magnitude (peak vector sum for seismograph recorded data) were assessed for signature hole blast. Effects of explosive column length, distance of blast face from monitoring point, hole depth and hole diameter were studied at fixed monitoring stations. Monitoring stations were fixed at radial distances of 50m, 100m and 150m. All the monitoring stations fixed at these radial distances considers similar directional distances. Simulated wave shows spherical behaviour of blast wave propagation. Stress wave input in blasthole causes simultaneous initiation of explosive throughout column, whereas bottom initiation is followed for real time blast using Nonel or electronic initiation system. The spherical nature of blast wave demands additional booster after certain column length in a long explosive column. Simulated results have been compared to experimental signature hole blast conducted at site.

4.1 EFFECT OF EXPLOSIVE COLUMN LENGTH ON BLAST VIBRATION

Effect of explosive column length for signature hole blast in model shows increasing trend for blast vibration with increasing charge column length. This is as per scaled distance law. Simulated blast vibration result at a radial distance of 50m for 20m deep blasthole and 14m charge column length is shown in Fig.6. Simulated results of blast vibration have been compared to estimated PPV using USBM predictor equation and have been presented in Table 4. The result shows likely trend of blast vibration for 100mm diameter blasthole, however simulated result of PPV is over prediction for 159mm diameter blastholes. This is due to consideration of homogeneity of rock mass in the modelled geometry or variation in direction of blast vibration monitoring.

4.2 EFFECT OF DISTANCE AND DIRECTION OF VIBRATION MONITORING ON BLAST VIBRATION

Effect of distance of vibration monitoring site from blast face is well understood, and has been presented as scale distance law by many researchers. However, simulated model shows that three different components of distance (longitudinal distance, vertical distance and transverse distance) have individual effect on blast vibration rather than radial distance. Model was simulated for this purpose taking equal radial distance with variation in directional distances. Result of the simulated model shows variation in vibration for equal radial distance and varying directional distances. This is due to variation in directional component of blast vibration at different monitoring locations of same radial distance. Peak vector sum of vibration resulted from simulation at radial distance of 50m and directional distances along longitudinal, transverse and vertical direction as 43m, 20m and 17m respectively is 25.85 mm/s. The plot of vibration at this monitoring station is shown in Fig.7. Vibration in longitudinal, transverse and vertical directions attain their peak at 32.5ms, 42.5ms and 50ms respectively resulting into respective magnitude of directional vibration as 20.9mm/s, 18.1mm/s and 13.0 mm/s. The plot of

Table 4 Simulated and predicted results of blast vibration for different charge length

Hole diameter (mm)	Hole depth (m)	Charge length (m)	Radial distance (m)	PPV (mm/s)	Predicted PPV using USBM predictor equation
100	20	16	50	30.84	29.3
100	20	15	50	24.42	28.14
100	20	14	50	19.84	26.9
159	20	16	50	118.8	52.73
159	20	15	50	100.4	50.62
159	20	14	50	84.96	48.46

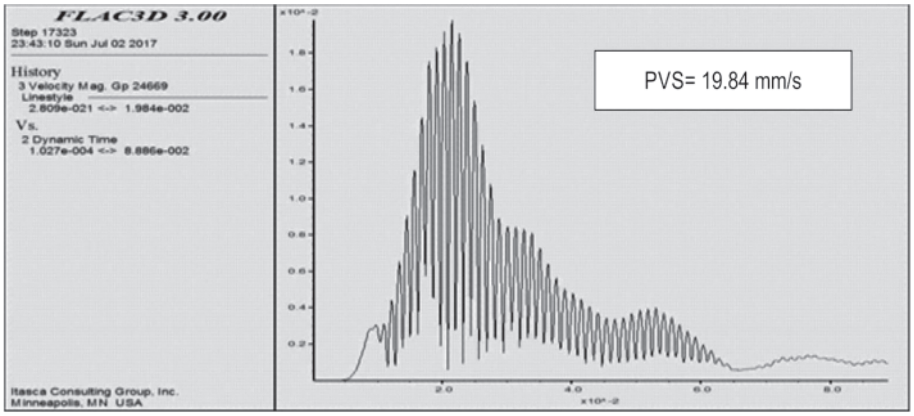


Fig.6 Simulation result of blast vibration recorded at 50m radial distance for blasthole of diameter 100mm and depth 20m with 14m charge column length

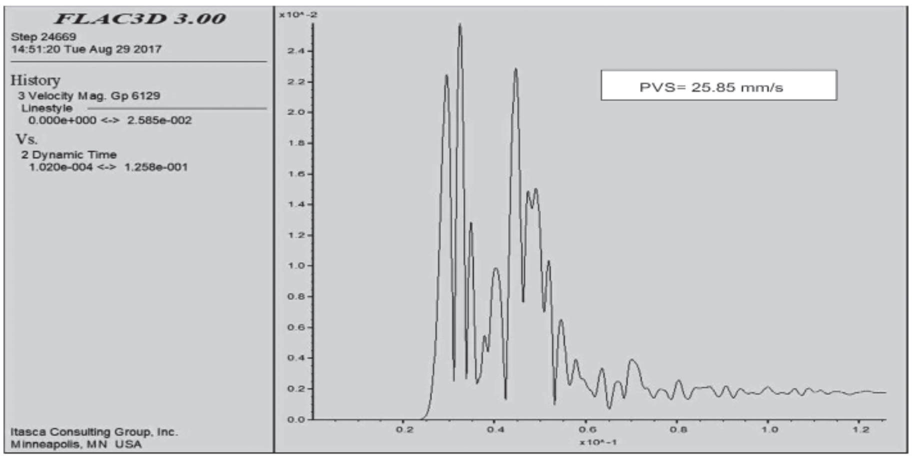


Fig.7 Vibration resulted from simulation of blasthole of depth 20m with charge length 14m at radial distance of 50m, longitudinal distance 43m, transverse distance 20m and vertical distance of 17m

directional vibration in longitudinal, transverse and vertical direction is shown in Figs.8, 9 and 10 respectively. The peaks of vibration in the plot shows that vector sum of directional vibration at 32.5ms were maximum, giving peak vibration magnitude due to longitudinal distance. The case differs in results for another set of directional distances. Direction of free face and stress relief are other parameters which gives different vibration magnitude at same radial distance. It is revealed from experimental blasts that magnitude of blast vibration is greater in back side of the free face.

4.3 Effect of hole diameter of blastholes on blast vibration

Investigation of effect of hole diameter on blast vibration shows powered increasing trend of vibration with hole diameter. The regression analysis of simulated results shows relation of PPV and hole diameter as equation 4. The simulated result of blast vibration for different hole diameter has been presented in Table 5.

$$PPV \propto \varphi^{2.7} \quad \text{... (4)}$$

where, PPV = Peak particle velocity of blast induced vibration. (mm/s)

φ = Hole diameter (mm)

4.4 Effect of deck charging on blast vibration

Modelled geometry was simulated for full column and deck charging of blastholes. Simulated results show considerable reduction in blast vibration due to deck charging. Vibration resulted from blasthole of 20m hole depth with 14m full column charge is 25.85mm/s whereas it is 17.74 mm/s for deck charging of 3m between charging length of 7m and 4m. This can be further reduced by providing different delays between decks to reduce maximum charge per delay as per scaled distance law.

Table 5 Simulated result of blast vibration for different hole diameter of blasthole

Hole diameter	Hole depth	Charge length	Distance	PPV
100	20	14	100	11.2
159	20	14	100	50.6
259	20	14	100	160.1
311	20	14	100	250.7

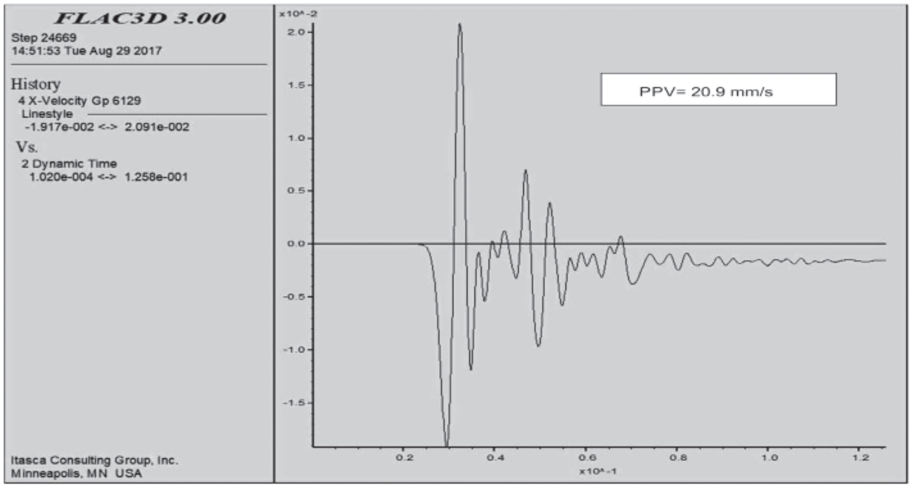


Fig.8 Longitudinal vibration resulted from simulation of blasthole of depth 20m with charge length 14m at radial distance of 50m and longitudinal distance of 43m

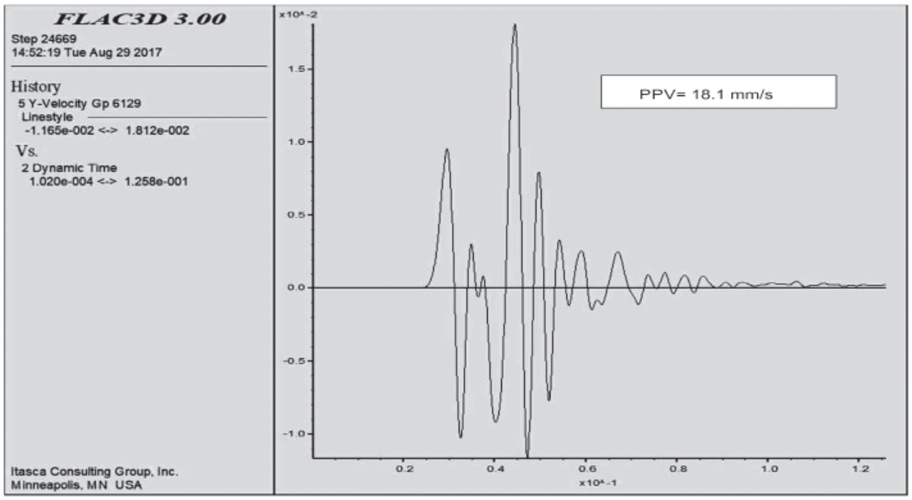


Fig.9 Transverse vibration resulted from simulation of blasthole of depth 20m with charge length 14m at radial distance of 50m and transverse distance of 20m

Contour of displacement magnitude have been analyzed to assess effect of stress wave on deformation, which shows deformation zone along vertical direction between 30 and 70 times of square of hole diameter. Deck charging length should be optimized accordingly for better fragmentation with reduced vibration. Contour of displacement along blasthole for 20m hole depth and 14m charge length is shown in Fig.11.

5. Limitations of numerical simulation approach

Numerical simulation approach is advantageous in many aspects to assess science of blast wave responses. It gives faster results with parametric influences. However, it has many limitations like crack expansion due to gaseous pressure of explosive cannot be simulated in the model. Modelled grid deformation is not possible in simulation using FLAC3D, however it is possible with finite element method, discrete element method and suspended particle hydrodynamics packages. Real mine situation represents heterogeneity in rock structure at various scale of which full replica is not possible with numerical simulation.

6. Conclusions

Blasting is the dominant method of mineral extraction around globe. Rock blasting phenomenon using explosive energy results into many undesirable phenomenon of environmental concern. Blast induced vibration is one of the key concern parameter as its greater magnitude with resonant frequency can lead to structural damage in the periphery of blasting area. Regulatory agancies of different countries have framed regulations for vibration limits as per distance of blasting face from surface structures. Hence, prediction of blast induced vibration is an important task for blast designers. USBM predictor equation

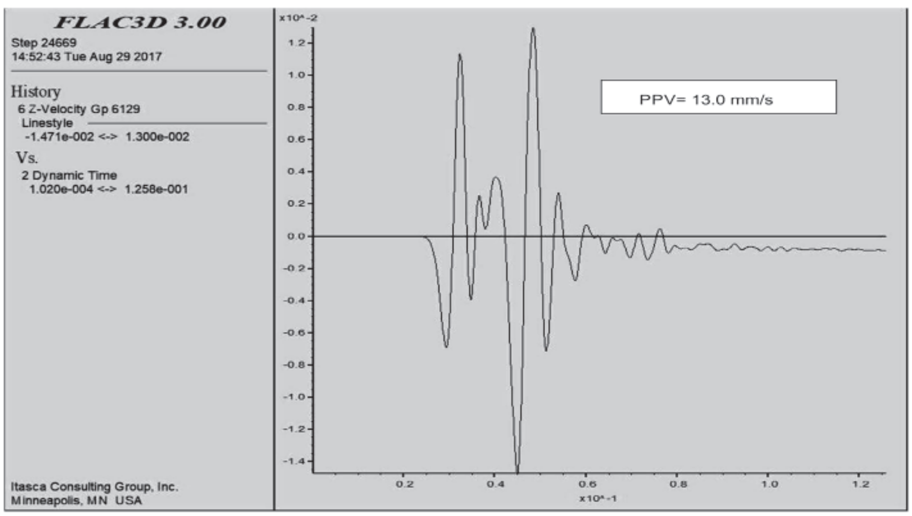


Fig.10 Vertical directional vibration resulted from simulation of blasthole of depth 20m with charge length 14m at radial distance of 50m and vertical distance of 17m

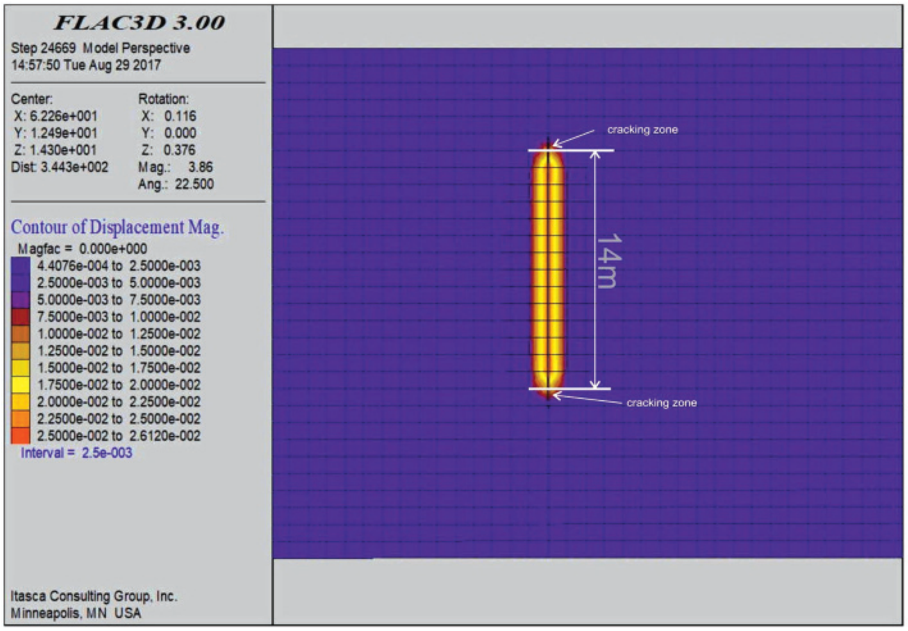


Fig.11 Contour of displacement magnitude for 20m blasthole depth with 14m charge length

approach is used globally for prediction of blast vibration, which considers charge weight per delay and distance of blast face from structure as responsible parameters for blast vibration. However, many other controllable and uncontrollable parameters have relation with blast induced vibration. This paper dealt with numerical simulation approach to assess influence of charging parameters on blast vibration. Stress wave in the form of detonation pressure has been modelled for this purpose in FLAC3D. Influence of explosive column length, hole diameter, hole depth, directional distances and charge distribution were assessed in the modelled geometry. The simulation results show effects of explosive charge column length and hole diameter equivalent to explosive weight per delay for the blast. Assessment about distance of monitoring station from blast face shows effects of directional distances on blast induced vibration. It has been observed that vibration magnitude at different directional distances varies even for same radial distance. Charge distribution effects were assessed using column and deck charging. It has been observed that distributed charge reduces blast vibration considerably even when they are fired at same delay.

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References

1. Ainalis Daniel, Kaufmann Olivier, Tshibangu Jean-Pierre, Verlinden Olivier and Kouroussis Georges (2016): Assessing blast source pressure modelling approaches for the numerical simulation of ground vibrations. 23rd International congress on sound and vibration, Athens, Greece.
2. Ambraseys NR, Hendron AJ (1968): Dynamic behaviour of rock masses: rock mechanics in engineering practices. Wiley, London.
3. Blair D.P (2014): Blast vibration dependence oncharge length,velocity of detonation and layered media. *International Journal of Rock Mechanics & Mining Sciences* 65, pp 29–39
4. Blai D.P (2015): The free surface influence on blast vibration. *International Journal of Rock Mechanics and Mining Sciences,* Volume 77, pp 182-191
5. Bollinger G A (1980): Blast vibration analysis. Lllinios university press, pp.30
6. Duvall WI, Fogelson DE (1962): Review of criteria for estimating damage to residences from blasting vibrations. US Department of the Interior, Bureau of Mines.
7. Duvall WI, Petkof B (1959): Spherical propagation of explosion generated strain pulses in rock. USBM RI 5483
8. Duvall WI, Johnson CF, Meyer AVC (1963): Vibrations from blasting at Iowa limestone quarries. USBM RI 6270.
9. Ebrahim Ghasemi, Mehmet Sari & Mohammad Atei (2012): Development of an empirical model for predicting the effects of controllable blasting parameters on flyrock distance in surface mines. *International Journal of Rock Mechanics and Mining Sciences.* Volume 52 pp 163-170.
10. Elevli1 Birol and Arpaz2 Ercan, Roník15 Acta Montanistica Slovaca (2010): Evaluation of parameters affected on the blast induced ground vibration (BIGV) by using relation diagram method (RDM), íslo 4, pp 261-268.
11. Fouchier C, Laboureur D, Youinou L, Lapebie E, Buchlin J.M (2017): Experimental investigation of blast wave propagation in an urban environment. *Journal of Loss Prevention in the Process Industries.* Volume 49, Part B, pp 248-265.
12. Ghosh A, Daemen JK (1983): A simple new blast vibration predictor. Proc. 24th US Symp. Rock Mechanics, Texas, USA, pp 151-161.
13. Gui Y.L, Zhao Z.Y, Goh A.T.C, Jayasinghe L.B (2017): Numerical Simulation of Rock Blasting Induced Free Field Vibration. Procedia Engineering, Volume 191, pp 451-457.

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