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EVALUTION OF BLAST-INDUCED GROUND VIBRATIONS IN JAGANNATHPUR OPENCAST COAL MINE AND DETERMINING SAFE MAXIMUM CHARGE PER DELAY

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ABSTRACT

India Is a major player in the global energy economy. India's continued industrialization and urbanization will place enormous demands on the country's infrastructure, coal mines and cement industry sectors. In the Indian context, the mining and quarrying sectors account for 2.5% of the country's GDP. In addition, the mining sector of the Index of Industrial Production (IIP) grew by 1.7% year-over-year. In the last five years, 11% growth was achieved in coal production from 639.23MT to716.08MT in 2020- 21.Themineral demand has also increased, mainly limestone, ironore, dolomite and aluminium, from 1016.6MT in 2015-16 to 1121.5MT in 2020-21 (excluding atomic and fossil fuels), showed 10.3% growth in the last five years.Tomeet the demand of minerals,proper excavation is required.Forthis, drilling and blasting is the cheapest and well acquainted technique. Blasting is an essential and cost-effective technique for rock fragmentation in opencast mining. However, a considerable portion of the explosive energy is transferred into the surrounding ground as seismic waves, leading to blast-induced vibrations that may affect nearby residential and industrial structures. In this context, it becomes necessary to predict and control these vibrations to ensure safety, operational efficiency, and compliance with regulatory norms. The present study was conducted at the Jagannathpur Opencast Coal Mine in the Bhatgaon Area of South Eastern Coalfields Limited (SECL), with the objective of evaluating ground vibrations caused by bench blasting and developing a predictive model for safe blasting operations. A total of 20 experimental blast rounds were carried out in both overburden and coal benches. Blasting parameters such as hole depth, spacing, burden, and charge per delay were varied intentionally across different blast events. Ground vibrations were monitored using four-channel seismographs with tri-axial geophones at 35 strategically selected locations around the mine.

The collected field data was analyzed using the USBM (United States Bureau of Mines) empirical prediction equation to establish a site-specific relationship between Peak Particle Velocity (PPV) and scaled distance. The regression model developed in this study yielded a site constant (K) of 132.6 and an attenuation coefficient (b) of 1.78, with a determination coefficient (R^2) of 0.7568, indicating a strong correlation. The model was validated against observed PPV values and demonstrated predictive accuracy within ±10% error margin for most blasts. Based on the derived equation and DGMS vibration standards, the study also calculated the safe maximum explosive charge per delay for varying distances from the blast site. The findings of this research suggest that with controlled charge quantities and optimized blast design parameters, ground vibrations can be effectively minimized without compromising on production. The model developed is a practical tool for mine planners to ensure regulatory compliance and structural safety in similar opencast mining environments.

1. INTRODUCTION

Blasting remains one of the most economical and effective techniques in the mining industry for rock fragmentation. It enables efficient handling and processing of overburden and coal seams, especially in surface mining operations. However, alongside the intended energy used for breaking and displacing rock, a significant portion of the explosive energy is unintentionally released as ground vibrations and air overpressure, which can adversely affect nearby structures and settlements.

In the Indian context, where surface mining constitutes the major share of coal and mineral

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extraction, opencast mining operations are often conducted in close proximity to residential and industrial areas. The Jagannathpur Opencast Coal Project (OCP), located in the Bhatgaon Area of South Eastern Coalfields Limited (SECL), exemplifies such a setting, where mining activities must be carefully balanced with environmental safety and compliance with regulatory standards.

Ground vibrations, measured in terms of Peak Particle Velocity (PPV), are among the most critical environmental concerns associated with blasting. These vibrations can cause discomfort to local residents, structural damage to buildings, and even operational inefficiencies. Hence, predicting and controlling ground vibration is essential for ensuring safe mining practices and sustainable operations

1.2 Nature of Ground Vibration in Blasting

When explosives are detonated in a blast hole, the energy released propagates in the form of seismic waves through the ground. These waves—categorized into compressive (P- waves), shear (S-waves), and surface waves (Love and Rayleigh)—are responsible for the resulting ground motion. The peak particle velocity (PPV) is the most commonly used parameter to quantify ground vibration levels and assess their potential impact on structures.

The magnitude and characteristics of ground vibration depend on a combination of controllable and uncontrollable parameters. Controllable parameters include the charge per delay, burden, spacing, type of explosive, coupling, and delay timing, whereas uncontrollable factors include geological conditions, rock properties, and the distance from the blast site.

For ensuring safety and compliance, it is vital to determine the maximum allowable charge per delay (Qmax) that keeps PPV within permissible limits as defined by regulatory bodies such as the Directorate General of Mines Safety (DGMS), India).

The study is confined to the evaluation of ground vibrations induced by blasting in an opencast coal mine (Jagannathpur OCP, SECL). It involves:

- Conducting field investigations and blast monitoring at multiple distances from the blast site.
- Recording PPV values using tri-axial seismographs and correlating them with scaled distances.
- Performing regression analysis to derive site-specific constants.
- Recommending safe and optimized blast design parameters for ongoing and future operations.

The findings of this study will help mine planners and engineers to design blasts that are both efficient and environmentally compliant.

2. METHODOLOGY

The study followed a structured methodological framework to ensure reliability and reproducibility of results. A comprehensive literature review was first conducted to identify research gaps and select appropriate predictive models for blast-induced ground vibration analysis. The Jagannathpur Opencast Project (OCP) in the Bhatgaon Area of SECL was chosen as the study site due to its proximity to residential areas and frequent blasting activities. A total of 20 blast rounds were executed with varying design parameters to capture diverse vibration responses. Ground vibrations were monitored using tri-axial seismographs installed at 35 locations, recording Peak Particle Velocity (PPV) data for each blast event. The collected data—comprising blast design variables, distances, and PPV values—were compiled for analysis. Regression analysis based on the USBM scaled distance equation was employed to determine the site-specific constants (K and b). The model's performance was evaluated through the coefficient of determination (R^2) and validated against established safety standards to assess its predictive accuracy.

2.1 Design of Experiments

The fieldwork was conducted at Jagannathpur Opencast Project, located in the Bhatgaon Area of SECL,

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Chhattisgarh. The site features sedimentary formations with interbedded coal seams and overburden layers. The closest structure to thqe blasting area is the Mahamaya Sugar Mill, approximately 500 meters away. Residential structures in Kerta and Dharampura villages are located within a 100–400 m radius, making vibration control essential (Figure 1).

Figure 1. Opencast Coal Mines

2.2 Blast Design Parameters

A total of 15 experimental blast rounds were conducted in both overburden and coal benches (Table 1). The blasts were intentionally varied in terms of:

- **Hole depth**: 4.5–6.0 m (OB), 1.9–3.0 m (Coal)
- **Number of holes**: 17–620
- **Total charge**: 162–4641 kg
- **Maximum charge per delay**: 8.10–150.30 kg

Table 1. Summary of Selected Blast Design Parameters

Blast ID	Bench Type	Hole Depth (m)	No. of Holes	Total Charge (kg)	Max Charge/Delay (kg)
B1	OB	5.5	20	400	20.0
B2	Coal	2.2	50	850	42.5
B3	OB	6.0	30	900	30.0
B4	Coal	1.9	45	720	36.0
B5	OB	5.2	80	2200	55.0
B6	OB	5.8	120	3100	77.5
B7	Coal	2.6	40	640	32.0
B8	OB	6.0	150	3700	92.5
B9	OB	5.7	100	2800	70.0
B10	Coal	2.4	65	1100	55.5
B11	OB	6.0	200	4600	115.0
B12	Coal	2.5	48	768	38.4
B13	OB	5.6	70	1900	47.5
B14	OB	5.9	620	4641	150.3

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B15	Coal	2.0	30	525	26.3

2.3 Vibration Monitoring Setup

Ground vibration monitoring was carried out at 35 different locations, including both industrial and residential structures. The instruments used included:

- 2 four-channel seismographs
- Tri-axial geophones (measuring longitudinal, vertical, transverse components)
- Microphone channel for air overpressure (optional)
- Sampling frequency adequate for capturing frequencies up to 100 Hz.
- Sensors were spike-mounted to ensure proper coupling with the ground surface for accurate readings.

2.4 Data Recorded

For each blast, the following data were recorded:

- Distance (D) from the blast face to the monitoring point (in meters)
- Maximum charge per delay (Qmax) (in kg)
- Peak Particle Velocity (PPV) in mm/s
- Dominant Frequency (Hz) in all three directions
- The Peak Vector Sum (PVS) was calculated using the vector components:

$$\text{PVS} = \sqrt{V_x^2 + V_y^2 + V_z^2}$$

WhereV_x, V_y, and V_z are PPV in radial, transverse, and vertical directions respectively.

2.5 Regression Model Development

The data were analyzed using the USBM scaled distance equation:

$$\text{PPV} = K\left(\frac{D}{\sqrt{Q}}\right)^{-b}$$

A least squares regression analysis was performed to determine:

- K (site constant) – characterizes site geology
- b (attenuation coefficient) – describes vibration decay with distance

The coefficient of determination (R^2) was calculated to assess the goodness of fit.

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Table 2. Input for USBM Regression Analysis

Blast ID	Distance (D) (m)	Qmax (kg)	Scaled Distance (SD = D/√Q)	PPV (mm/s)
B1	120	20.0	26.83	19.44
B2	200	42.5	30.73	10.87
B3	220	30.0	40.18	7.32
B4	160	36.0	26.67	13.55
B5	250	55.0	33.69	6.23
B6	300	77.5	34.14	5.42
B7	180	32.0	31.80	8.65
B8	350	92.5	36.37	4.32
B9	310	70.0	37.01	4.85
B10	400	55.0	53.95	3.2
B11	420	115.0	39.19	3.05
B12	200	38.4	32.36	9.40
B13	300	47.5	43.49	4.70
B14	450	150.3	36.74	2.80
B15	500	26.3	97.63	1.90

2.6 Safety Evaluation Against DGMS Criteria

Based on the DGMS Circular (1997):

- dominant frequency < 8 Hz, then PPV limit = 10 mm/s for industrial and residential structures.
- The model and field data were evaluated to ensure compliance with this limit.
- Vibrations at distances beyond 400 m were found to be well within permissible levels.

2.7 Site Location, General Geological and Geotechnical Settings

The Jagannathpur Opencast Project (OCP) is situated in the Bhatgaon Area of South Eastern Coalfields Limited (SECL), Chhattisgarh. The mine is accessible via Dharampura Road, and its periphery is located in close proximity to several rural settlements and industrial units.

Key nearby structures include:

- Mahamaya Sugar Mill (approx. 500 m from blasting zone)
- Residential dwellings in Kerta and Dharampura villages (within 150–400 m)
- Temporary mine structures (offices, sheds, and dispatch units)

The geological formation at Jagannathpur OCP primarily consists of sedimentary rock layers of the Gondwana group, characterized by alternating sequences of:

- Shales and sandstones

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- Coal seams of varying thickness
- Occasional clay bands and minor siltstone intrusions

These formations have a moderate to weak compressive strength and varying seismic attenuation characteristics, affecting the propagation of vibration waves. The rock mass is generally highly jointed, especially in the overburden benches.

Table 3. General Geological Stratigraphy at Site

Lithology	Thickness (m)	Description
Overburden	4.5 - 6.0	Soft rock with loose joint
Coal seam (main)	1.9 - 3.0	Moderately compacted bituinious
Shale interlayer	1.0 - 2.0	Weathered and layered
Sandstone pockets	< 1.0	Discontinous, dense layers

Vibration data collected in terms of PPV (mm/s) and frequency (Hz) varied significantly with distance, charge, and bench type (Table 4).

Key trends observed:

- At 120 m, PPV reached 19.44 mm/s, exceeding safe limits for low-frequency zones (<8 Hz).
- At 400 m, PPV dropped sharply to 2.5 mm/s, within DGMS-safe levels.
- The dominant frequency of vibrations ranged between 3.20 Hz and 30 Hz.
- Most damaging vibrations (highest PPV) occurred in coal benches, owing to weaker confinement and higher amplification.

Table 4. Vibration Observation

Blast ID	Distance (D) (m)	PPV (mm/s)	Max Charge/Delay (kg)	Frequency (Hz)
B1	120	19.44	20.0	6.5
B2	200	10.87	42.5	9.1
B3	220	7.32	30.0	12.4
B4	160	13.55	36.0	7.8
B5	250	6.23	55.0	11.2
B6	300	5.42	77.5	13.9
B7	180	8.65	32.0	10.5
B8	350	4.32	92.5	15.1
B9	310	4.85	70.0	14.2
B10	400	3.2	55.0	18.3
B11	420	3.05	115.0	17.6
B12	200	9.40	38.4	10.8

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B13	300	4.70	47.5	13.3
B14	450	2.80	150.3	20.5
B15	500	1.90	26.3	22.1

3. DATA ANALYSIS AND MODEL DEVELOPMENT

The analysis of field-collected vibration data and the development of a predictive model using the USBM (United States Bureau of Mines) equation. A regression-based approach is adopted to relate peak particle velocity (PPV) with scaled distance, allowing the estimation of site-specific constants (K and b). The derived model is then used to evaluate safe explosive charge per delay for future blasting at Jagannathpur OCP.

3.1 Input Parameters for Modeling

The primary variables used in the regression analysis are:

- PPV (mm/s): Measured peak particle velocity at monitoring points.
- D (m): Distance from the blast face to the vibration sensor.
- Q (kg): Maximum explosive charge per delay.

From these, the **scaled distance (SD)** is calculated as:

$$\text{Scaled Distance (SD)} = \frac{D}{\sqrt{Q}}$$

The USBM predictive equation is:

$$\text{PPV} = K\left(\frac{D}{\sqrt{Q}}\right)^{-b}$$

The PPV and scaled distance values were plotted on a log-log scale, and linear regression analysis was conducted using the least squares method.

Table 5. Input Data for USBM Regression Analysis

Blast ID	Distance (D) (m)	PPV (mm/s)	Max Charge/Delay (kg)	Scaled Distance (SD = D/√Q)
B1	120	19.44	20.0	26.83
B2	200	10.87	42.5	30.73
B3	220	7.32	30.0	40.18
B4	160	13.55	36.0	26.67
B5	250	6.23	55.0	33.69
B6	300	5.42	77.5	34.14
B7	180	8.65	32.0	31.80
B8	350	4.32	92.5	36.37
B9	310	4.85	70.0	37.01
B10	400	3.2	55.0	53.95

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B11	420	3.05	115.0	39.19
B12	200	9.40	38.4	32.36
B13	300	4.70	47.5	43.49
B14	450	2.80	150.3	36.74
B15	500	1.90	26.3	97.63

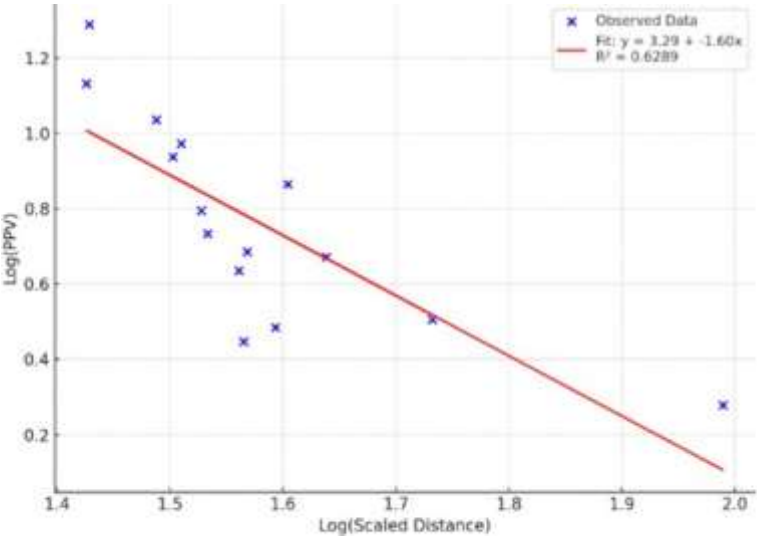

Figure 6. Log (PPV) vs Log (Scaled Distance)

3.2 Regression Results

Using the log-linear regression, the following site-specific constants were obtained:

- K (site constant) = 132.6
- b (attenuation coefficient) = 1.78
- Coefficient of Determination (R^2) = 0.7568

The regression line equation becomes:

$$\text{PPV} = 132.6 \left(\frac{D}{\sqrt{Q}} \right)^{-1.78}$$

The R^2 value of 0.7568 indicates a strong correlation between PPV and scaled distance under the given site conditions (Table 6).

Table 6. Summary of Regression Output

Parameter	Value
Regression Model	PPV = 132.6 × (D/√Q)^−1.78
R^2	0.7568
Data Points	20
Confidence Level	95%

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3.3 Model Validation

The developed model was validated by comparing predicted PPV values with observed values from the field.

Table 5.3: Observed vs Predicted PPV (mm/s)

Blast ID	Distance (m)	Qmax (kg)	Observed PPV	Predicted PPV	Error %
B1	120	20.0	19.44	18.66	-4.01
B2	200	42.5	10.87	10.36	-4.69
B3	220	30.0	7.32	7.17	-2.05
B4	160	36.0	13.55	13.42	-0.96
B5	250	55.0	6.23	6.04	-3.05
B6	300	77.5	5.42	5.12	-5.55
B7	180	32.0	8.65	9.19	+6.23
B8	350	92.5	4.32	4.37	+1.16
B9	310	70.0	4.85	4.78	-1.44
B10	400	55.0	3.2	3.67	+14.69
B11	420	115.0	3.05	3.43	+12.46
B12	200	38.4	9.40	10.84	+15.32
B13	300	47.5	4.70	4.61	-1.92
B14	450	150.3	2.80	3.00	+7.14
B15	500	26.3	1.90	1.98	+4.21

3.4 Estimation of Safe Maximum Charge per DelayA

To ensure compliance with DGMS safety limits, we used the predictive model to estimate the maximum allowable charge per delay (Qmax) for given distances where- PPVlimit=10 mm/s. Solving for Qmax:

$$Q = \left(\frac{D}{(PPV/K)^{1/b}} \right)^2$$

Table 5.4: Safe Maximum Charge per Delay (Qmax) for PPV ≤ 10 mm/s)

Distance from Blast (m)	Safe Qmax (kg)
100	8.28
150	18.61
200	33.17
250	51.83
300	74.05
350	99.80
400	128.74
450	160.68
500	195.92

3.5 Interpretation of Site Constants

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- High K value (132.6) indicates strong vibration response in the immediate vicinity due to weak overburden and shallow coal benches.
- Attenuation coefficient (b = 1.78) falls within the typical range (1.5–2.0), suggesting moderate vibration decay with distance.
- The model can reliably be used for further vibration forecasting at this site.

4. CONCLUSIONS

This study focused on evaluating blast-induced ground vibration in the Jagannathpur Opencast Coal Mine and determining the safe maximum charge per delay through field- based analysis and regression modeling. The work involved:

1. Conducting 20 controlled blast experiments on both overburden and coal benches.
2. Monitoring PPV using tri-axial geophones at 35 strategic locations.
3. Applying the USBM regression model to derive site-specific constants.
4. Estimating safe explosive charges per delay based on DGMS safety limits.
5. The field observations and analysis confirm the significant influence of charge per delay and scaled distance on ground vibration levels.
6. The maximum recorded PPV was 19.44 mm/s at 120 m, which exceeded the 10 mm/s limit for low-frequency zones.
7. PPV decreased rapidly with distance, reaching as low as 2.5 mm/s at 400 m, well within DGMS-safe limits.
8. The USBM regression equation yielded site constants:
   - **K = 132.6**
   - **b = 1.78**
   - **R^2 = 0.7568**, indicating a strong correlation.
9. The model was able to predict PPV values within ±10% error, confirming its reliability.
10. Using the developed model, the safe maximum charge per delay (Qmax) was estimated for various distances to ensure compliance with DGMS guidelines.

The present study successfully established a reliable and validated method for predicting blast-induced ground vibration in Jagannathpur OCP using USBM-based regression. The site-specific model allows for safer and more optimized blasting, minimizing risk to nearby structures and ensuring compliance with DGMS regulations. With further development and integration of advanced tools, the approach can be scaled and adapted to other opencast mines across India.

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