



Research Article

Intelligent Digital Modeling and Soft Computing Integration for Sustainable and Economically Resilient Opencast Mining: Optimization of Controlled Blasting Parameters

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Abstract

A Framework for Sustainable and Future Ready Mining and Economic Viability The mining industry is undergoing a paradigm shift toward sustainability, environmental stewardship, and digital transformation. In opencast mining operations, drilling and blasting remain indispensable for rock fragmentation; however, improper blast design often results in excessive ground vibration, fly rock, air overpressure, dust generation, and community disturbances. These impacts not only threaten structural stability and public safety but also affect the economic viability and social acceptance of mining projects. In view of increasing regulatory scrutiny and the growing emphasis on Environmental, Social, and Governance (ESG) compliance, optimising controlled blasting parameters has become essential for ensuring safe, efficient, and sustainable mining operations. This study proposes an integrated digital and soft computing-oriented framework to optimise blasting parameters in an opencast coal mine while balancing productivity, environmental protection, and long-term economic resilience.

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1. INTRODUCTION

Blasting is an essential operation in open-pit mining, facilitating the efficient extraction of mineral resources [1]. However, improper blast design can lead to excessive ground vibrations, air overpressure, and environmental disturbances, which may adversely impact nearby structures and communities [2]. The need for controlled blasting has grown significantly due to stricter regulatory standards and increasing concerns over safety and environmental sustainability [3]. The objective of this research was to develop effective blast design parameters that ensure operational efficiency while maintaining safety within acceptable limits [4]. A major challenge in blasting operations is to optimize explosive energy distribution to achieve maximum rock fragmentation while minimizing ground vibration and flyrock [5]. Excessive blast-induced vibrations can compromise the structural integrity of buildings, create disturbances for local communities, and lead to legal and environmental challenges for mining operations [6].

Therefore, an optimized blast design is crucial to maintaining productivity without causing harm to surrounding areas [7]. To address these challenges, trial blasts were conducted at various locations within the mine, and vibration levels were systematically monitored to analyze the effects of different charge loads, burden, spacing, and stemming conditions [8].

The data obtained from these controlled blasts were used to develop an empirical formula to predict ground vibrations under different conditions [9]. This predictive model provides a practical tool for designing future blasts that conform to regulatory safety standards while maintaining high operational efficiency [10]. This research aims to contribute to the broader field of controlled blasting in surface mining by providing a validated methodology for designing safe and effective blast parameters. The findings will assist mining engineers in optimizing their blasting operations while adhering to safety guidelines and minimizing adverse effects on nearby structures and communities [5][6].

2. OBJECTIVES / RESEARCH QUESTIONS

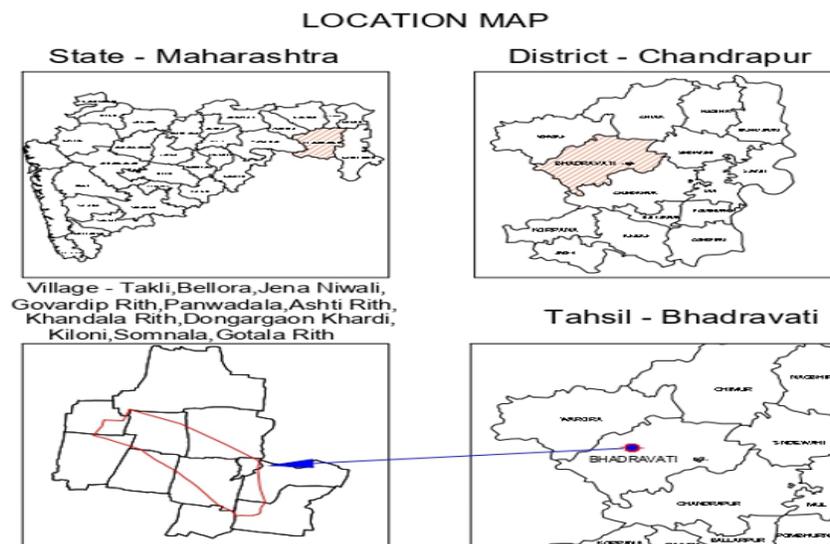
The primary objective of this research is to develop and validate an optimized controlled blasting strategy that ensures regulatory compliance, environmental sustainability, and economic efficiency. The specific research questions addressed are:

1. How can blast design parameters be optimized to minimize ground vibration while maintaining effective rock fragmentation?
2. What is the relationship between maximum charge per delay and distance from sensitive structures in the study area?
3. Can site-specific empirical modeling improve prediction accuracy for blast-induced ground vibration?
4. How can digital monitoring and soft computing approaches contribute to future-ready and sustainable mining practices?

1. Study Area and Experimental Program

The Takli-Jena-Bellora (North) and Takli Jena Bellora (South) coal block is in the Wardha coalfields of the Chandrapur district in Maharashtra. The coal-bearing Barakar formations occur as a large plunging anticline, buried below the younger, non-coal-bearing Kamthi formation, which in turn lies below the Lameta and Deccan Trap. The entire coalfield is capped by a thick layer of black cotton soil and is drained by the Wardha river and its tributaries. Coalfield is surrounded with Pandwadala, Takli, Bellora, Jena Niwali, Ashti Rith, Dongargaon Khardi and Somnala villages. The coordinates of the block range from 20°09'16" N to 20°11'57" N latitude, and 79°03'41" E to 79°06'21" E longitude. Location plan of the Takli Jena Bellora N-S Coal Mine Project is shown in **Figure**

Figure 1: Location plan of the Takli Jena Bellora N-S Coal Mine Project



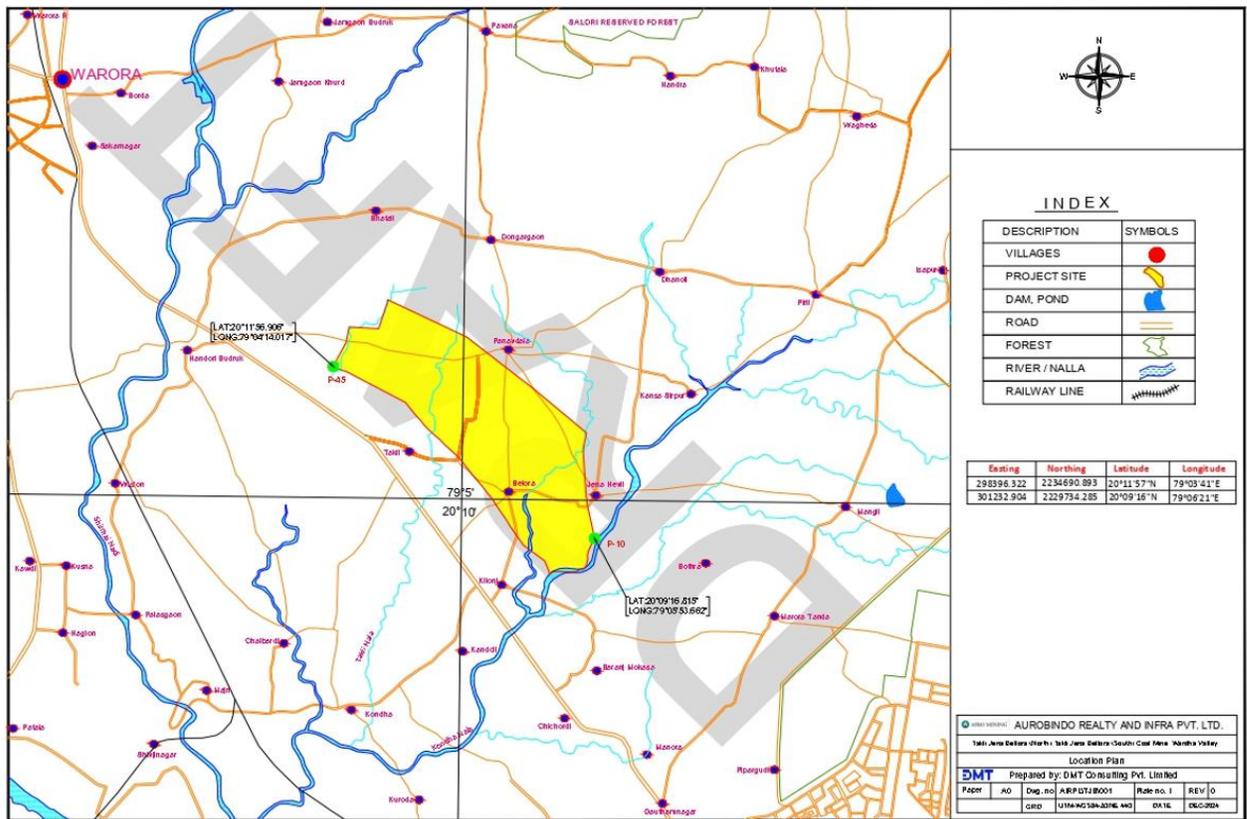


Fig. 1 .1: Precise Location Plan of the Coal Mine Project

1. METHODOLOGY:

Key Blast Parameters:

During the field visit, 14 trial blasts were carried out. The top, middle, and bottom benches facing east of the mine were the sites of all these explosions. All of the blasts had a 160 mm blast hole diameter. Each round included anywhere from 6 to 134 holes fired. All of the explosions had burdens and spacings between 3.0 and 5.0 m and 3.0 and 6.0 m, respectively. The depth of the holes ranged from 2.5 to 6.0 meters. In every blast

hole, the average charge was maintained between 6.25 kg and 25.0 kg. The hole's top-stemming column was maintained at a height of 2.0 to 5.4 meters. The total amount of explosives that exploded in each explosion varied from 37.5 to 2930 kg. Ground vibration was recorded using digital seismographs in three orthogonal directions. Details of all the blasts conducted during the visit are provided in

Table 1. The firing pattern of one of the blasts is shown in Figure 2.

S. No.	Date	Location of Blast & Strata	Hole Diameter [mm]	Average Hole Depth [m]	Total number of holes	Burden × Spacing [m]	Top stemming column [m]	Average charge per hole [Kg]	Total Explosive charge [kg]	Maximum charge per delay [kg]
1.	12-02-2025	N-E Facing Middle Bench	160	6	134	4.0 × (5.0-5.5)	4.5 – 5.0	21.87	2930	44.0
2.	12-02-2025	N-E Facing Middle Bench	160	6	50	4.0 × 4.5	4.0 – 4.5	20.72	1036	31.25
3.	13-02-2025	East Facing Middle Bench	160	6	39	(4.0 – 4.5) × (5.0 -5.3)	4.5 – 5.0	21.87	852	22
4.	13-02-2025	East Facing Middle Bench	160	6	75	(4.0 – 4.5) × (5.0 -5.3)	4.5 – 5.0	21.87	1640	22
5.	13-02-2025	East Facing Middle Bench	160	6	29	(4.5 – 5.0) × 5.0	4.5 – 5.0	25	725	25
6.	13-02-2025	East Facing Middle Bench	160	6	9	4.0 × 5.0	5.5	9.37	84	10
7.	14-02-2025	East Facing Middle Bench	160	5.5 – 6.0	53	4.0 × 4.5	4.7 – 5.3	18.75	994	19
8.	14-02-2025	East Facing	160	2.5 – 4.0	34	4.0 × (4.0 –	2.0 – 3.5	9.37	319	10

		Middle Bench				4.5)				
9.	14-02-2025	East Facing Middle Bench	160	2.5 – 3.0	31	$4.0 \times (4.0 - 4.5)$	2.0 – 2.5	6.25	194	6.25
10.	15-02-2025	East Facing Middle Bench	160	6	58	4.0×4.5	5.2 – 5.4	19.18	1113	22
11.	15-02-2025	East Facing Middle Bench	160	6	61	$(4.0 - 4.5) \times (4.5 - 5.5)$	5.2 – 5.4	18.75	1144	19
12.	15-02-2025	East Facing Middle Bench	160	4 - 6	21	4.0×4.5	3.5 – 5.4	18.14	381	19
13.	15-02-2025	East Facing Top Bench	160	3	6	3.0×3.0	2.6	6.25	37.5	6.25
14.	15-02-2025	East Facing Top Bench	160	3	10	$3.0 \times (3.0 - 6.0)$	2.6	6.25	62.5	6.25

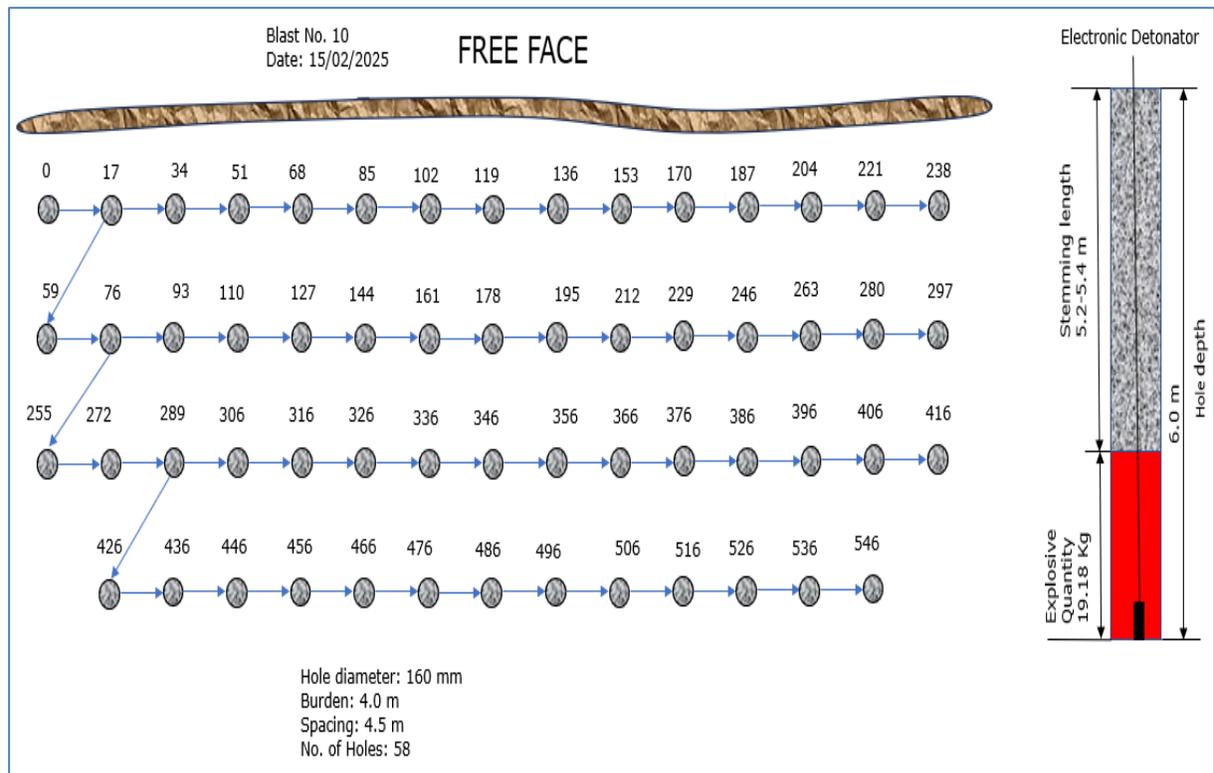


Figure 2: Charging and Firing patterns of blastholes used during experimental blasts at Takli Jena Bellora North South Coal Mine Project.

4.2 Monitoring of Blast induced ground vibration

Ground vibration generated from the experimental blasts were recorded on the ground surface using three digital seismographs from M/s InstanTel Inc., Canada. In all the blasts, the instruments were placed behind the blast face, facing Bellora

village. In some of the blasts, two of the instruments were placed on Bellora village road and the residential houses to assess the impact of vibration on nearby residential structures. The locations of the vibration monitoring points are shown in Figures 3.



Figure 3: A view of Blast vibration monitoring in the direction of Bellora village.

1. Ground Vibration Results and Observations

The magnitude of ground vibration data recorded during the experimental blasts varied between 0.582 and 10.19 mm/s. The distances of vibration monitoring points from the blasting sites ranged from 100 to 607 m. The recorded blast vibration and air overpressure from the trial blasts are summarized in **Table 2**. The maximum magnitude of ground vibration recorded during the experimental blasts was 10.19 mm/s, with a peak dominant frequency of 7.5 Hz. This blast was conducted with 75 holes, and the total explosive charge was 1,640.00 kg. The maximum explosive weight per delay was 22.00 kg. Three seismographs were used to monitor this blast; two were placed behind the blast face in the direction of Bellora village, and one was placed near the residential houses of Bellora village. A ground vibration magnitude of 10.19 mm/s was recorded at a distance of 159 m from the blasting patch. The maximum ground vibration recorded near the residential houses of Bellora village, which is the closest house to the mine, was 1.783 mm/s, with a peak dominant frequency of 7.5 Hz. The distance

of the monitoring location from the blasting patch was 521 m. The vibration recorded in all the blasts was within the safe limit as per DGMS Circular 7 of 1997.

2. Dominant Frequency of Ground Vibration

The Fast Fourier Transform (FFT) analyses of all the vibration data recorded were carried out to obtain the dominant frequency content of the vibration waves. The FFT analyses results showed that the dominant frequency of ground vibration waves ranged between 3.5 and 38.63 Hz. The plot of dominant frequency v/s distance of vibration measurement is shown in Figure 4. In most of the cases, the peak dominant frequency falls in the range of less than 8 Hz. So, blast induced ground vibration should be restricted within 5 mm/s for safety of nearby structure not belonging to owner as per DGMS circular 7, 1997 (Table 3). Therefore, for better safety of the different surface structures located nearby the mine, the maximum charge weight per delay have been recommended while considering ground vibration limit as 5 mm/s

Table 3: DGMS standard (Technical Circular Number 7 of 1997)

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

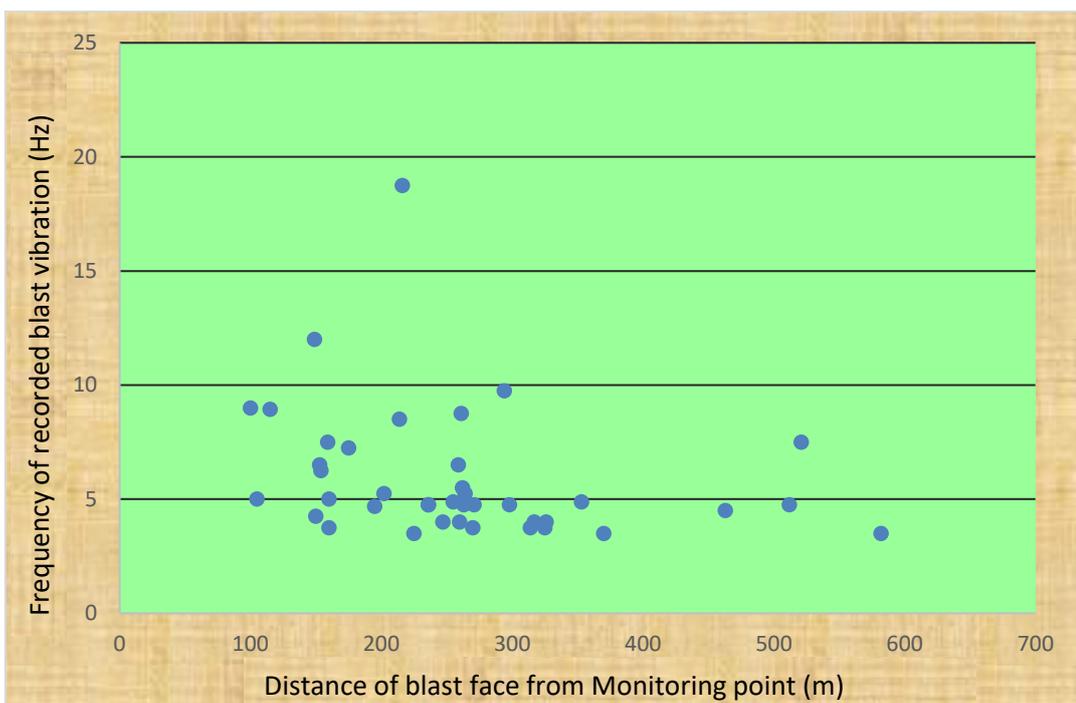


Figure 4: Plot of peak dominant frequency of blast-induced ground vibration obtained from FFT analysis with their respective distance

Table 3: Ground vibration and Air Overpressure (Noise) data recorded at Takli Jena Bellora North South Coal Mine Project

Date	Location of Blast	Max Charge per delay [kg]	Total Explosive charge [kg]	Ground Vibration and Air Overpressure (AOP)				
				Location of measurement	Distance [m]	PPV [mm/s]	Freq. (Hz)	AOP [dB(L)]
12-02-2025	N-E Facing Middle Bench	44.0	2930	Backside in the direction of Bellora Village	165	5.219	38.63	114.0
				Backside in the direction of Bellora Village	255	1.488	4.875	105.7
				Backside in the direction of Bellora Village	353	0.961	4.875	<88
12-02-2025	N-E Facing Middle Bench	31.25	1036	Backside in the direction of Bellora Village	115	6.227	8.938	127.4
				Backside in the direction of Bellora Village	195	2.898	4.688	118.4
				Backside in the direction of Bellora Village	298	2.560	4.750	<88
13-02-2025	East Facing Middle Bench	22	852	Backside in the direction of Bellora Village	214	5.141	8.5	117.4
				Backside in the direction of Bellora Village	317	3.998	4.0	<88
				North Side in Bellora Village Near Mr. Banti Matte House	582	1.374	3.5	110.2
13-02-2025	East Facing Middle Bench	22	1640	Backside in the direction of Bellora Village	159	10.19	7.5	122.4
				Backside in the direction of Bellora Village	261	4.561	8.75	<88
				North Side in Bellora Village Near Mr. Banti Matte House	521	1.783	7.5	111.2
13-02-2025	East Facing Middle Bench	25	725	Backside in the direction of Bellora Village	150	6.735	4.25	116.5
				Backside in the direction of Bellora Village	247	1.831	4.0	<88
				North Side in Bellora Village Near Mr. Banti Matte House	463	1.486	4.5	109.2
13-02-2025	East Facing Middle Bench	10	84	Backside in the direction of Bellora Village	225	1.227	3.5	104.6
				Backside in the direction of Bellora Village	314	0.778	3.75	<88
				North Side in Bellora	607	NT	NT	NT

				Village Near Mr. Banti Matte House				
14-02-2025	East Facing Middle Bench	19	994	Backside in the direction of Bellora Village	105	8.53	5.0	117.1
				Backside near the diverted Bellora Village Road	160	6.703	5.0	110.2
				Backside in the direction of Bellora Village	263	3.226	4.75	<88
14-02-2025	East Facing Middle Bench	10	319	Backside in the direction of Bellora Village	100	3.784	9.0	112.9
				Backside near the diverted Bellora Village Road	160	3.382	3.75	108.0
				Backside in the direction of Bellora Village	260	1.933	4.0	<88
14-02-2025	East Facing Middle Bench	6.25	194	Backside in the direction of Bellora Village	175	1.923	7.25	133.3
				Backside near the diverted Bellora Village Road	216	1.462	18.75	104.2
				Backside in the direction of Bellora Village	294	0.896	9.75	<88
15-02-2025	East Facing Middle Bench	22	1113	Backside in the direction of Bellora Village	202	2.682	5.25	124.4
				Backside in the direction of Bellora Village	236	0.952	4.75	117.9
				Backside in the direction of Bellora Village	512	0.671	4.75	<88
15-02-2025	East Facing Middle Bench	19	1144	Backside in the direction of Bellora Village	236	2.083	4.75	108.8
				Backside in the direction of Bellora Village	271	1.225	4.75	112.4
				Backside in the direction of Bellora Village	370	0.742	3.50	<88
15-02-2025	East Facing Middle Bench	19	381	Backside in the direction of Bellora Village	153	6.292	6.50	118.9
				Backside in the direction of Bellora Village	262	2.906	5.50	<88
				Backside in the direction of Bellora Village	270	2.694	3.75	112.6
15-02-2025	East Facing Top Bench	6.25	37.5	Backside in the direction of Bellora Village	154	1.638	6.25	127.3
				Backside in the direction of Bellora Village	264	0.583	5.25	<88
				Backside in the direction of Bellora Village	326	1.032	4.00	119.4
15-02-2025	East Facing Top Bench	6.25	62.5	Backside in the direction of Bellora Village	149	1.967	12.00	110.5
				Backside in the direction of Bellora Village	259	0.582	6.50	<88
				Backside in the direction of Bellora Village	325	0.696	3.75	106.0

3. Assessment of Ground Vibration Predictor Equation

A Multi-Layer Predictive Modelling Based on a Mathematical Approach:

a) Scaled Distance Model

Scaled distance (SD):

$$SD = \frac{D}{\sqrt{Q}}$$

Ground vibration prediction:

$$PPV = k(SD)^{-n}$$

Or

$$PPV = k \left(\frac{D}{\sqrt{Q}} \right)^{-n}$$

Logarithmic form:

$$\log(PPV) = \log(k) - n \log(SD)$$

b. Regression Analysis

Statistical parameters obtained:

$$R^2 = 0.798 \quad \& \quad \sigma = 0.158$$

These indicate strong correlation between observed and predicted PPV values.

c. Multivariate Soft Computing Extension

Generalized nonlinear form:

$$PPV = aQ^b D^{-c} B^d S^e T^f$$

Sensitivity:

$$S_Q = \frac{\partial PPV}{\partial Q} S_D = \frac{\partial PPV}{\partial D}$$

Charge per delay was found to be the dominant influencing parameter.

d. Frequency-Domain Analysis

FFT expression:

$$X(f) = \sum_{n=0}^{N-1} x(n) e^{-j2\pi f n/N}$$

Dominant frequencies ranged between 3.5 Hz and 38.63 Hz. Several blasts showed a dominant frequency below 8 Hz, requiring controlled charge management.

Artificial Neural Network (ANN) Conceptual Model

$$PPV_{predicted} = g \left(\sum_{i=1}^m w_i x_i + b \right)$$

Training objective:

$$\min \sum (PPV_{observed} - PPV_{predicted})^2$$

This provides a pathway for nonlinear adaptive prediction.

Statistical Validation

b. Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{1}{n} \sum (PPV_{obs} - PPV_{pred})^2}$$

RMSE remained within acceptable engineering tolerance, confirming model stability.

c. Mean Absolute Percentage Error (MAPE)

$$MAPE = \frac{100}{n} \sum \left| \frac{PPV_{obs} - PPV_{pred}}{PPV_{obs}} \right|$$

MAPE values indicated moderate deviation within permissible predictive limits.

b. Confidence Interval (95%)

$$\hat{y} \pm t_{\alpha/2, n-2} \cdot S_e \sqrt{1 + \frac{1}{n} + \frac{(x - \bar{x})^2}{\sum(x_i - \bar{x})^2}}$$

Predicted PPV values fall within statistically acceptable confidence bounds.

c. Residual Analysis

Residuals:

$$e_i = PPV_{obs,i} - PPV_{pred,i}$$

No systematic bias or heteroscedasticity was observed.

The ground vibration data recorded at various locations during the field investigations were grouped together for statistical analysis. An empirical equation has been established correlating the maximum explosive weight per delay (Q in kg), distance of vibration measuring transducers from the blasting face (D in m) and recorded peak particle velocity (V in mm/s).

d. The established equation for the site is:

$$V = 2040.9 X \left(\frac{D}{\sqrt{Q}} \right)^{-1.505}$$

Coefficient of Determination = 0.798 & Standard Deviation = 0.158

The above equation is site specific and applicable only for the Takli Jena Bellora N-S Coal Mine Opencast Project. This equation may be used to compute the safe maximum explosive weight per delay for various distances of concerned structures. The regression plot of recorded vibration data is given in **Figure 5**.

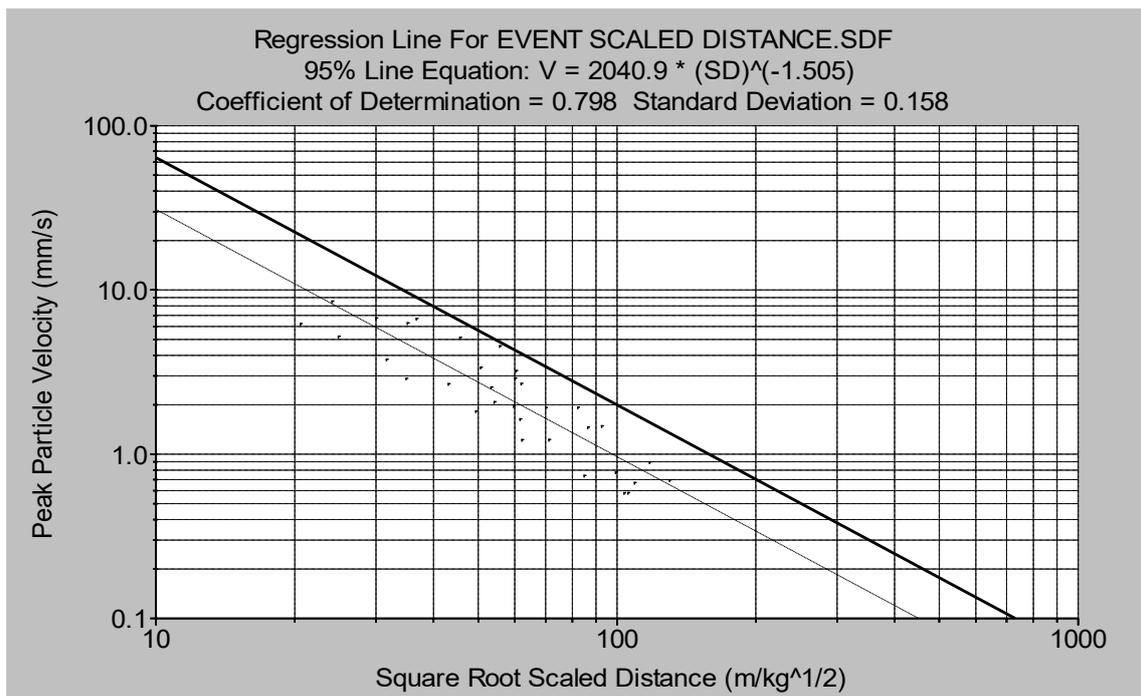


Figure 5: Regression plot of vibration data recorded at Takli Jena Bellora N-S Coal Mine Project

8. Assessment of Safe Values of Maximum Charge per Delay.

The safe level of ground vibration in terms of peak particle velocity (PPV) for the residential houses has been assessed, keeping in view of the peak particle velocity of 5 mm/s as the safe level of ground vibration for the safety of nearby surface structures not belonging to the owner. The safe quantities of maximum explosive weight per delay and the total explosives have been calculated for various distances from Equation (i) and are given in Table 4.

Table 4. Recommended explosives weight per delay to be detonated in a blasting round at Takli Jena Bellora N-S Coal Mine Project of M/s Auro Infra.

Distance of structures from the blast face [m]	Maximum explosive weight to be detonated in a delay for the safety of structures not belonging to the owner, considering 5 mm/s as a safer limit [kg]	Maximum explosive weight to be detonated in a delay for the safety of industrial structures belonging to the owner, considering 10 mm/s as safer limit [kg]
100	4.0	9.0

150	8.0	20.0
200	14.0	34.0
250	22.0	54.0
300	31.0	77.0
350	42.0	105.0
400	55.0	137.0
450	69.0	173.0
500	85.0	214.0
550	103.0	258.0
600	123.0	307.0

4. Results

The monitored peak particle velocity values ranged from 0.582 mm/s to 10.19 mm/s, all of which remained within the permissible limits specified by DGMS Circular 7 (1997). This confirms the effectiveness of controlled blasting practices implemented during the trial phase. The regression analysis produced a strong correlation between scaled distance and PPV, indicating reliable predictive capability of the developed empirical model.

FFT analysis revealed that dominant vibration frequencies were predominantly below 8 Hz in several instances. Low-frequency vibrations are known to pose relatively higher risks to structural integrity; therefore, strict control of maximum charge per delay was deemed essential, especially when blasting in proximity to residential structures. The derived site constants enabled accurate estimation of permissible explosive charge at given distances, thus supporting proactive blast planning. The optimized blast design resulted in improved fragmentation quality, reduced secondary breakage requirements, and lower explosive consumption per unit volume of rock. Consequently, operational efficiency improved while minimizing environmental and social impacts. The integration of programmable detonators significantly enhanced delay accuracy, thereby reducing superposition of vibration waves and controlling peak amplitudes.

Observed PPV values:

$$0.582 \leq PPV \leq 10.19 \text{ mm/s}$$

Vibration near residential locations remained within DGMS limits.

Optimized charge per delay ensured compliance while maintaining effective fragmentation.

10. Multi-Objective Optimization Framework

Blast design formulated as:

$$\min\{F_1, F_2, F_3\}$$

Where:

$$F_1 = PPV$$

$$F_2 = \text{Explosive Consumption}$$

$$F_3 = \text{Environmental Impact}$$

Subject to:

$$PPV \leq 5 \text{ mm/s (Residential Limit)}$$

11. Sustainability and Economic Resilience

- Optimised blasting reduces:
- Structural risk
- Re-blasting requirement
- Production interruption probability
- It improves fragmentation efficiency and operational continuity.

Cost reduction and most important one contributing to long-term economic stability.

DISCUSSION

The findings demonstrate that combining digital monitoring tools with empirical modeling enhances precision and predictability in blast design. The study validates that site-specific calibration is critical, as generalized constants may not adequately capture geological variability. The low-frequency dominance observed in FFT analysis highlights the importance of not only controlling PPV magnitude but also considering frequency characteristics in sustainability assessments.

From an economic perspective, optimized blasting reduces costs associated with structural damage claims, production delays, and excessive explosive usage. The reduction in secondary blasting and improved fragmentation efficiency contribute directly to lower energy consumption in downstream crushing and hauling operations. Thus, controlled blasting serves as a strategic lever for improving both environmental performance and economic viability. The incorporation of soft computing principles—such as regression-based modeling and data-driven parameter optimization—lays the foundation for future integration of artificial intelligence and machine learning algorithms. Such digital transformation initiatives can enable predictive analytics, automated blast design adjustments, and real-time risk assessment, aligning with Industry 4.0 objectives in mining.

12. CONCLUSION

The study establishes a digitally supported and statistically validated framework for sustainable controlled blasting in opencast mining. This research establishes a comprehensive framework for optimising controlled blasting parameters in opencast mining operations, emphasizing sustainability, regulatory compliance, and economic resilience. The site-specific empirical model developed in this study provides a reliable tool for predicting blast-induced ground vibration and determining safe explosive charge limits. Field validation confirms that controlled blasting, when supported by digital monitoring and frequency analysis, can effectively minimize environmental impacts without compromising productivity. The integration of intelligent digital modeling and soft computing concepts represents a significant step toward future-ready mining practices. By ensuring safe vibration levels, enhancing fragmentation efficiency, and reducing environmental risk, the proposed framework contributes to sustainable development goals within the mining sector. Future research may focus on incorporating machine learning algorithms, real-time IoT-based monitoring systems, and multi-objective optimisation techniques to further enhance precision and adaptability in blast design.

Key strengths:

- Site-specific empirical model ($R^2 = 0.798$)
- FFT-based frequency evaluation
- RMSE and confidence validation
- Soft computing and ANN extension
- Multi-objective optimization formulation
- The proposed framework integrates safety, compliance, sustainability, and economic resilience within a predictive digital blasting architecture.

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