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Optimization of Maximum Charge Per Delay Using Site-Specific Ground Vibration Prediction Models for Safe Blasting in an Opencast Coal Mine

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Abstract

Drilling and blasting are critical operations in opencast coal mining that directly influence rock fragmentation, excavation efficiency, and production performance. However, excessive blast-induced ground vibration and air overpressure can create safety and environmental concerns, particularly in mines located near villages and sensitive structures. The present study was conducted at Chapapur-II Colliery, Mugma Area, Eastern Coalfields Limited (ECL), with the objective of optimizing blast design through the determination of safe maximum charge-per-delay values. A field investigation involving 20 production blasts was carried out using an Instantel Micromate seismograph to monitor peak particle velocity (PPV), vibration frequency, air overpressure, explosive charge, and monitoring distance. The monitored blasts were conducted with maximum charge per delay varying between 30 and 50 kg and total explosive charge per round ranging from 1450 to 4700 kg. Blast monitoring stations were located at distances between 100 and 180 m from the blast face. The recorded PPV values varied from 0.733 to 2.382 mm/s, which were significantly lower than the Directorate General of Mines Safety (DGMS) permissible limit of 10 mm/s for nearby residential structures. Analysis of the monitored data resulted in the development of a site-specific ground vibration predictor model with a coefficient of determination (R^2) of 0.76, indicating a good correlation between blast parameters and vibration response. Based on the developed model, safe maximum charge-per-delay values and optimized blast design parameters were recommended for different distances from nearby structures. The study demonstrates that site-specific blast monitoring and vibration-based blast design optimization can improve blasting efficiency while ensuring environmental compliance and operational safety in opencast coal mines.

Keywords: Blast design optimization, ground vibration, peak particle velocity, charge per delay, blast monitoring, air overpressure, opencast coal mine, environmental safety

INTRODUCTION

Drilling and blasting are among the most important unit operations in opencast mining and play a significant role in determining the efficiency of excavation, loading, hauling, and overall mine productivity [1]. A well-designed blast improves rock fragmentation, reduces the energy consumption of downstream equipment, and enhances the operational performance. However, only a portion of the explosive energy is utilized for rock breakage, whereas the remaining energy is dissipated in the form of undesirable environmental effects, such as ground vibration, air overpressure, fly rock, dust generation, and noise [2, 3]. These impacts can affect mine infrastructure, nearby structures, and surrounding communities, particularly when mining activities are conducted close to inhabited areas [4].

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Among the various environmental effects of blasting, blast-induced ground vibration is considered one of the most critical concerns because of its potential to cause structural damage, public complaints, and operational restrictions [5]. Ground vibration generated during blasting propagates through the surrounding rock mass as seismic waves and is commonly assessed using the peak particle velocity (PPV), which is widely recognized as the most reliable parameter for evaluating the potential impact of blasting on structures [6]. The magnitude of the vibration is influenced by several factors, including the explosive charge per delay, distance from the blast source, geological conditions, rock mass characteristics, blast geometry, and initiation sequence [7, 8].

Over the past several decades, numerous researchers have developed empirical relationships for predicting blast-induced ground vibrations. The United States Bureau of Mines (USBM) introduced the scaled distance approach, which established a relationship between the PPV, maximum charge per delay, and monitoring distance [9]. Langefors and Kihlstrom further contributed to vibration prediction by incorporating explosive and rock mass characteristics into empirical models [10]. Later studies demonstrated that site-specific vibration predictor equations provide more reliable predictions than generalized models because geological and operational conditions vary significantly from one mine to another [11]. Recent investigations have employed statistical and intelligent prediction techniques to improve vibration forecasting and blast optimization [12, 13].

In India, the Directorate General of Mines Safety (DGMS) has prescribed permissible vibration limits for different categories of structures to ensure safe blasting practices [14]. Compliance with these limits is essential for minimizing environmental impact and maintaining safe mining operations. Consequently, the determination of the safe maximum charge per delay has become an important aspect of blast design optimization. Appropriate control of the charge per delay can significantly reduce the vibration levels while maintaining adequate rock fragmentation and production efficiency [15].

Despite the availability of several empirical vibration prediction models, their applicability is often limited by site-specific geological conditions, structural discontinuities, explosive characteristics, and blast design parameters. Therefore, the direct application of generalized predictor equations may not provide accurate estimates of vibration levels for a particular mining operation [16]. This highlights the need to develop site-specific vibration prediction models based on field-monitored blasting data.

The present study was conducted at an opencast coal mine in eastern India, referred to as Mine Code M-01. The mine operates in proximity to villages and other surface structures, where blast-induced vibration control is a key environmental and operational requirement. A detailed field investigation was undertaken involving the monitoring of production blasts to evaluate the ground vibration characteristics, vibration frequency, and air overpressure levels. The monitored data were subsequently analyzed to develop a site-specific ground vibration predictor model and determine the safe maximum charge-per-delay values for different distances from sensitive structures. The outcome of this study is expected to provide a scientific basis for blast design optimization, improved environmental management, and safer blasting practices in opencast coal mining operations.

STUDY AREA DESCRIPTION

Mine Location and Mining Characteristics

The present study was conducted at an opencast coal mine in eastern India, hereafter referred to as Mine Code M-01, to maintain the confidentiality of the mining operation. The mine is situated within one of the major coal-bearing regions of the Damodar Valley coalfields and is currently being operated using opencast mining methods. The mine has a strike length of approximately 500 m and a dip-rise width of approximately 650 m, covering an excavation area of nearly 15 ha. The annual coal production capacity is approximately 0.3 million tonnes, with mining operations extending to a maximum working depth of approximately 70 m. The mine operates at an average stripping ratio of 1:4 and employs a shovel-dumper combination for the excavation and transportation of the overburden and coal. Deep-hole blasting is used to fragment overburden formations before excavation.

The geographical location and position of the study area within the coalfield are illustrated in Figure 1, and the general surface layout of the mine is presented in Figure 2. The principal mining and operational characteristics of Mine Code M-01 are listed in Table 1.

Geological Setting

The study area is located within the Damodar Valley Gondwana Basin, one of the most important coal-bearing regions in India. The coal-bearing formations comprise Lower Gondwana sedimentary sequences that rest unconformably over the Archean basement complex. The regional stratigraphy is represented by the Talchir, Barakar, Barren Measures, and Raniganj formations in ascending order. Economically viable coal seams are predominantly developed within the Barakar and Raniganj formations, whereas the Barren Measures are largely devoid of coal deposits.

The regional geological formations generally exhibit varying strike directions and moderate dip angles, although localized structural disturbances have resulted in steeper dips in some areas. The geological complexity of the coalfield is further influenced by tectonic activities, resulting in the development of faults, dykes, and other structural discontinuities. These geological features significantly affect the propagation characteristics of blast-induced vibration waves; therefore, they require careful consideration during blast design and vibration assessment. The regional geological setting of the study area is illustrated in Figure 1.

Local Geology of Mine Code M-01

The geological conditions within Mine Code M-01 are characterized by the presence of several coal seams interbedded with sandstone, shales, and other sedimentary rock formations. The mine area contains structural disturbances in the form of faults and igneous dykes, which influence both mining operations and the blast wave transmission. The coal seams occur at varying depths, with the shallowest seam located at approximately 9 m below the surface and the deepest seam extending to approximately 157 m depth.

The mine consists of multiple workable coal seams that are extracted through a combination of developed, depillared, and virgin mining blocks. The sequence of coal seams, seam thicknesses, and intervening partings observed within the leasehold area are listed in Table 2. The presence of geological discontinuities and varying lithological units creates heterogeneous ground conditions that can significantly affect blast fragmentation, vibration attenuation, and air-overpressure generation. Therefore, site-specific monitoring and analysis are essential for establishing reliable vibration prediction models and determining safe blasting parameters.

Table 1. Mining and operational characteristics of Mine Code M-01.

S.N.	Parameter	Value
1	Mining method	Opencast mining
2	Blasting method	Deep-hole blasting
3	Strike length	500 m
4	Dip-rise width	650 m
5	Excavation area	15 ha
6	Annual coal production	0.3 million tonnes (Mt)
7	Maximum working depth	70 m
8	Stripping ratio	1:4
9	Overburden removal system	Shovel-dumper combination
10	Coal transportation system	Shovel-dumper combination
11	Mining stage	Active opencast operation

Table 2. Geological characteristics of mine code M-01.

Parameter	Description
Geological province	Damodar valley Gondwana basin
Coalfield type	Gondwana coalfield
Major stratigraphic formations	Talchir, Barakar, Barren Measures, and Raniganj formations
Basement rock	Archean gneisses and schists
Principal coal-bearing formation	Barakar and Raniganj formations
Dominant lithology	Sandstone, shale, carbonaceous shale, and coal seams
Structural features	Faults and igneous dykes are present within the mining block
Minimum seam depth	Approximately 9 m
Maximum seam depth	Approximately 157 m
Number of workable seams	Multiple coal seams occurring within the leasehold area
Dip characteristics	Variable dip due to local geological disturbances
Mining status of seams	Developed, depillared, and virgin blocks
Geological significance for blasting	Structural discontinuities influence vibration propagation, fragmentation behavior, and blast performance

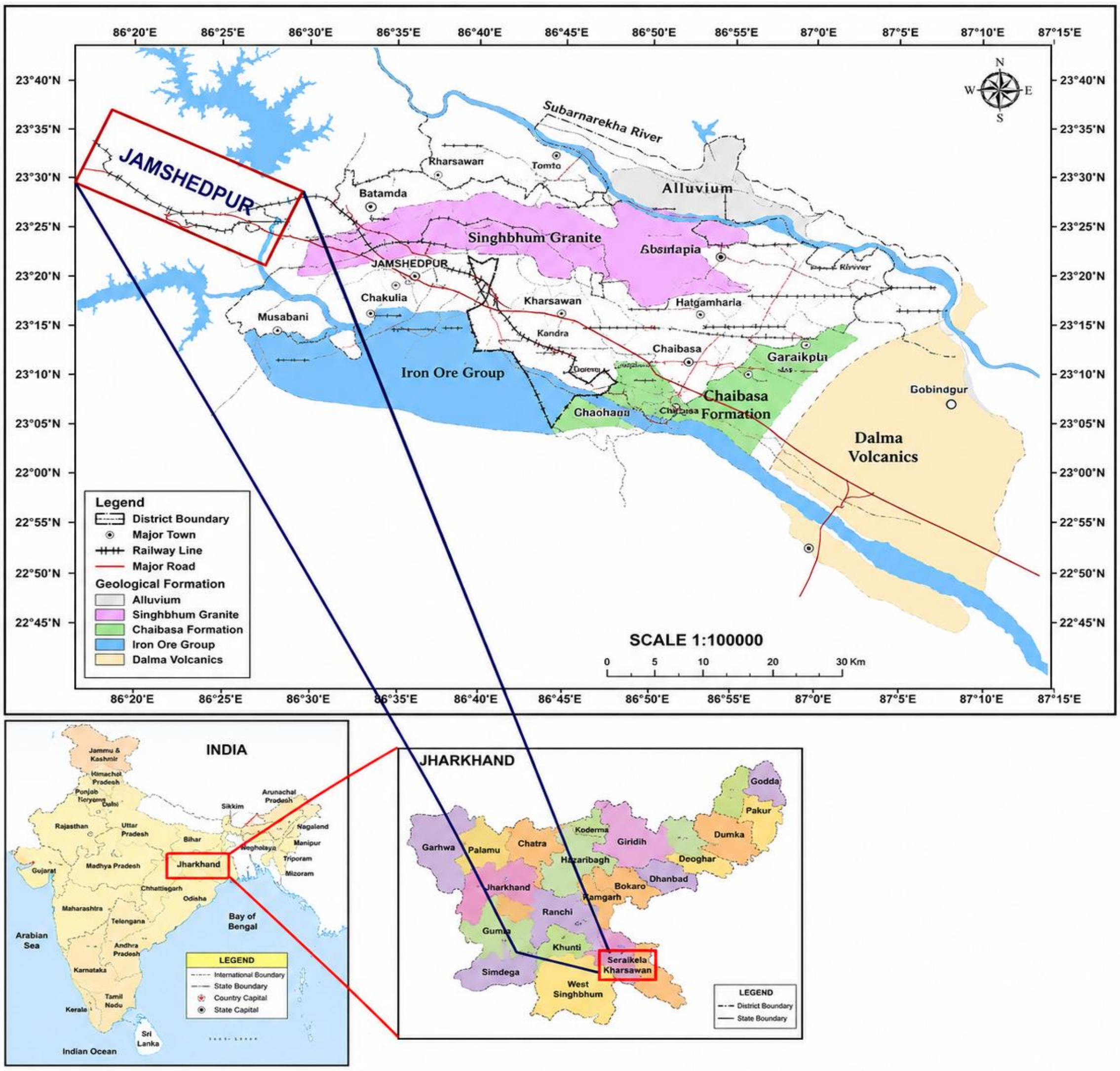

Figure 1. Geological location map.

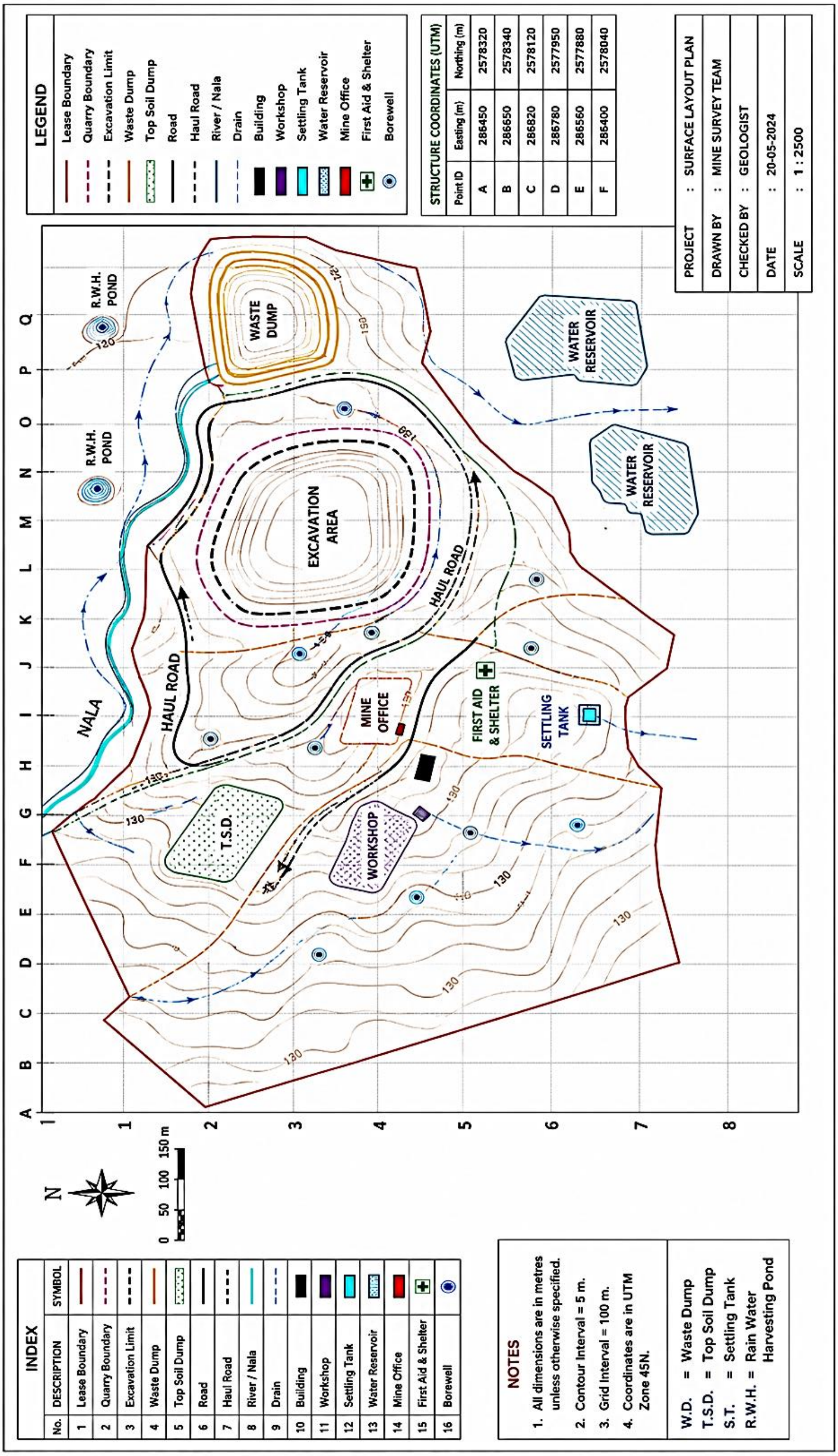

Figure 2. Surface layout plan.

The geological framework and coal seam disposition within the study area provide the basis for understanding the behavior of the blast-induced ground vibrations investigated in the present study. The geological location of the mine and its associated structural features are presented in Figure 1, and the mine layout relevant to blasting operations is shown in Figure 2.

MATERIALS AND METHODS

Existing Blast Design Parameters

Drilling and blasting operations at Mine Code M-01 are performed using a deep-hole blasting technique for the fragmentation of overburden formations. The blast design adopted at the mine was based on the local geological conditions, bench geometry, and production requirements. A staggered drilling pattern was employed to achieve uniform fragmentation and efficient explosive energy distribution. The blast holes were drilled with a burden of 3.0 m and a spacing of 3.5 m. The initiation sequence follows a diagonal firing pattern using electronic delay detonators to ensure progressive burden relief and controlled movement of the rock.

The blasting system uses SME explosive cartridges as the primary explosive charge. Blast holes are stemmed using drill cuttings and crushed stone chips to improve explosive confinement and reduce the generation of fly rock. The stemming length varied from 2.5 to 3.8 m depending on the hole depth and bench conditions. The detailed blast design parameters adopted during the monitoring program are presented in Table 3. The general firing pattern and initiation sequence used in this study are illustrated in Figure 3.

Blast Monitoring Programme

A field monitoring program was conducted to evaluate the blast-induced ground vibration and air-overpressure generated during routine production blasting operations. Twenty production blasts were monitored under different blasting conditions. The monitored blasts represented typical production practices followed at Mine Code M-01 and covered variations in the explosive charge, blast geometry, and monitoring distance.

For each blast event, operational parameters such as the maximum charge per delay, total explosive charge, burden, spacing, and distance between the blast face and monitoring location were recorded. Simultaneously, vibration and air-overpressure measurements were obtained for subsequent analysis. The monitoring locations were selected at various distances from the blast source to represent the nearby sensitive structures and operational areas. The overall methodology adopted in the monitoring program is shown in Figure 4.

Table 3. Blast design parameters adopted at mine code M-01.

Parameter	Value
Blast hole diameter	150 mm
Drilling pattern	Staggered
Burden	3.0 m
Spacing	3.5 m
Stemming length	2.5–3.8 m
Explosive type	SME
Primer	150 g Cast Booster
Detonating relay	17 ms and 450 ms
Trunk line delay	42 ms
Initiation system	Electronic detonator
Firing sequence	Diagonal firing

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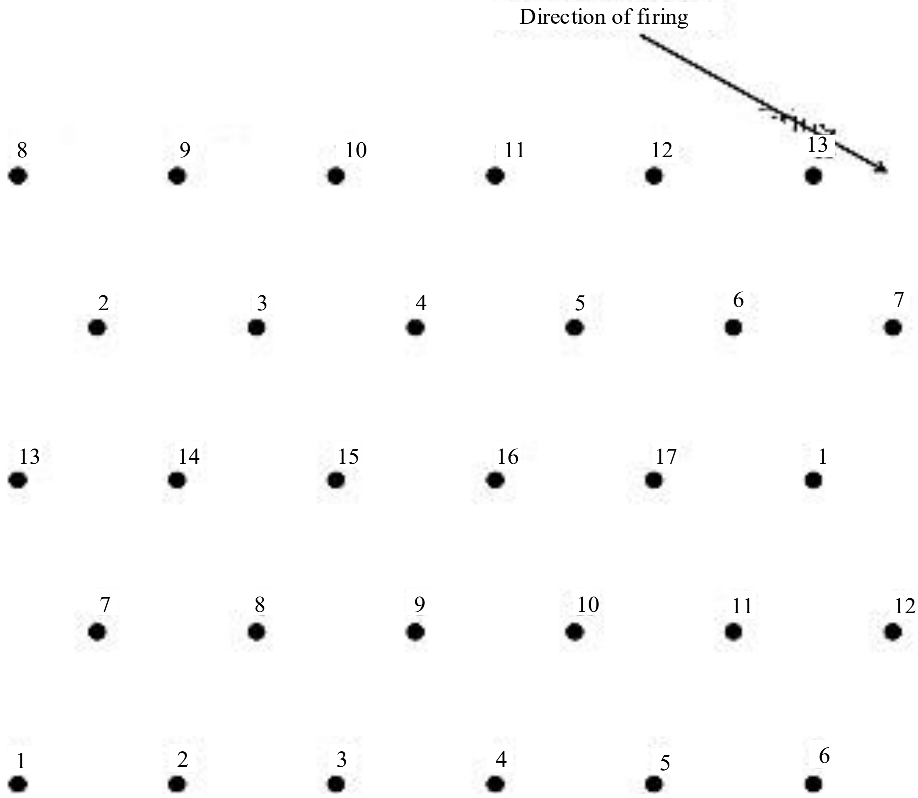

Figure 3. Typical staggered blast pattern with diagonal firing sequence.

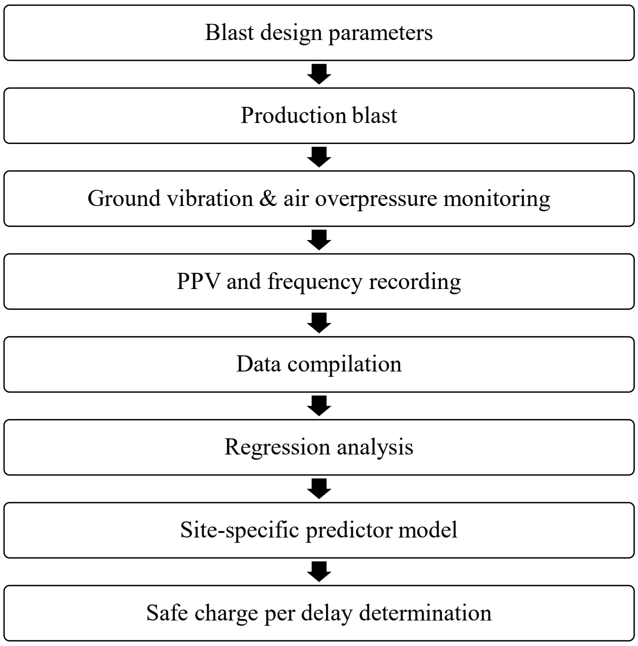

Figure 4. Blast monitoring and analysis methodology.

Ground Vibration Monitoring

Ground vibration measurements were performed using an Instantel Micromate seismograph, which is a widely accepted instrument for monitoring blast-induced vibrations in mining operations. The instrument was installed on firm ground at predetermined monitoring locations before each blast was conducted. The seismograph recorded vibration components in three mutually perpendicular directions: longitudinal, transverse, and vertical.

The recorded vibration data included the PPV and dominant vibration frequency for each blast event. PPV was used as the principal indicator for assessing the vibration intensity because it is widely recognized as the most reliable parameter for evaluating the potential response of nearby structures. The instrument setup and field monitoring arrangements are shown in Figure 5.

To ensure data reliability, all monitoring activities were conducted in accordance with standard blasting vibration monitoring procedures. The collected vibration data were subsequently used to develop a site-specific vibration prediction model.

Air Overpressure Monitoring

In addition to ground vibration measurements, the air overpressure generated during blasting operations was monitored simultaneously using an air-blast monitoring facility integrated within the Instantel Micromate system. Air overpressure represents the pressure wave transmitted through the atmosphere following explosive detonation and may contribute to community annoyance and structural issues.

The monitoring system recorded the peak air overpressure values for each blast event. The measured data were analyzed to evaluate compliance with the accepted blasting standards and to establish a site-specific relationship between air overpressure, explosive charge, and monitoring distance.

Data Analysis and Development of Ground Vibration Predictor Model

The monitored blast data were analyzed to establish the relationship between the blast-induced ground vibration, explosive charge per delay, and distance from the blast source. The analysis was based on the scaled distance approach, which has been widely adopted for vibration prediction in mining and civil-blasting operations [9, 10].

Figure 5. Ground vibration monitoring setup.

The recorded values of PPV, maximum charge per delay, and monitoring distance were compiled and subjected to a regression analysis. The predictor model parameters were determined using least-squares regression. The developed model was evaluated based on the coefficient of determination (R^2), which indicates the degree of correlation between the measured and predicted vibration values.

Determination of Safe Maximum Charge per Delay

The developed vibration predictor model was subsequently used to determine the safe maximum charge-per-delay values for various distances from sensitive structures. The calculated values were compared with the permissible vibration limits prescribed by the DGMS for residential and other surface structures.

Based on the developed site-specific model, blast design recommendations were prepared for different monitoring distances to ensure compliance with the vibration standards while maintaining the production requirements. These recommendations form the basis for blast optimization at Mine Code M-01 and provide a practical framework for controlling blast-induced environmental impact.

RESULTS AND DISCUSSION

Blast Monitoring Results

A total of 20 production blasts were monitored at Mine Code M-01 to evaluate the characteristics of the blast-induced ground vibration and air overpressure. The monitored blasts represented the typical production blasting conditions adopted at the mine. The monitoring program covered a range of explosive charge weights and monitoring distances to establish a reliable database for vibration analysis.

The monitoring distances varied from 100 to 180 m from the blast source, whereas the maximum charge per delay ranged from 30 to 50 kg. The total explosive charge per blast varied between 1450 and 4700 kg. The monitored vibration records indicated that the PPV values ranged from 0.733 to 2.382 mm/s. The summary statistics of the monitored blast data are listed in Table 4.

The observed PPV values were significantly lower than the permissible vibration limits prescribed by the DGMS for residential buildings. This indicates that the existing blasting practices at Mine Code M-01 operate within safe vibration limits. However, further optimization of the charge per delay is required to establish scientific guidelines for future blasting operations.

Analysis of Ground Vibration Frequency

The frequency content of blast-induced ground vibrations plays an important role in determining the response of nearby structures. The monitored vibration frequencies at Mine Code M-01 varied between 5 and 80 Hz.

Analysis of the monitoring records showed that approximately 17.8% of the observations exhibited frequencies below 8 Hz, whereas nearly 68.5% of the observations were within the 8–25 Hz range. The remaining observations recorded frequencies of > 25 Hz. These results indicate that most blast events generated medium-frequency vibrations, which are generally considered less damaging to residential structures than low-frequency vibrations.

Table 4. Summary of blast monitoring data used for model development.

Parameter	Minimum	Maximum	Average	Unit
Monitoring distance	100	180	140	m
Maximum charge per delay	30	50	40	kg
Total explosive charge per blast	1450	4700	3075	kg
Peak particle velocity (PPV)	0.733	2.382	1.56	mm/s
Dominant frequency	5	80	21.5	Hz
Number of blasts monitored	20	20	20	-
Air overpressure	Monitored	Monitored	Monitored	dB(L)
Coefficient of determination (R^2)	–	0.76	–	–

According to the DGMS guidelines, the vibration frequency must be considered along with the PPV when assessing structural safety. Because most of the recorded frequencies were above 8 Hz and the corresponding PPV values remained well below the permissible limits, the risk of blast-induced structural damage was found to be minimal.

Development of Site-Specific Ground Vibration Predictor Model

The monitored blast data were analyzed using regression techniques to establish the relationship between the vibration intensity, explosive charge per delay, and monitoring distance. The analysis was performed using the scaled distance approach, which is widely used in mining and civil-blasting applications.

The regression analysis resulted in the development of a site-specific ground vibration predictor model for Mine Code M-01. The predictor model exhibited a coefficient of determination (R^2) value of 0.76, indicating a reasonably strong correlation between the measured vibration levels and the blast parameters.

The regression relationship obtained from the monitored data is shown in Figure 6. The developed predictor model can be used to estimate the expected vibration levels under different blasting conditions and serves as an effective tool for blast design optimization.

The relatively high coefficient of determination demonstrates that the charge per delay and monitoring distance are the dominant parameters governing vibration propagation at the study site. Minor variations between the predicted and measured values may be attributed to local geological heterogeneity, structural discontinuities, and variations in explosive confinement.

Air Overpressure Analysis

The air overpressure generated during blasting operations was monitored to evaluate its environmental impact. Air overpressure levels are influenced by the explosive charge weight, stemming effectiveness, initiation sequence, and atmospheric conditions.

The monitored data indicated that the air overpressure values remained within acceptable limits for all blast events. The relationship between air overpressure and blasting parameters was established using regression analysis, resulting in a site-specific predictor model for Mine Code M-01. The monitored air overpressure data were compiled and analyzed to establish a site-specific relationship between air overpressure, explosive charge weight, and monitoring distance. Regression analysis was performed using the monitored blast records to develop an air overpressure predictor model for the study site. The developed model was subsequently used to evaluate the effectiveness of existing blasting practices and to assess compliance with accepted environmental standards. The methodology adopted for air overpressure model development is discussed in Section 4.4, and the resulting predictor relationship is presented in Figure 7.

The results suggest that the existing stemming practices and initiation sequence adopted at the mine are effective in controlling air-blast effects. Consequently, no significant risk to nearby structures or local communities was observed during the monitoring program.

Determination of Safe Maximum Charge Per Delay

One of the primary objectives of this study was to determine the safe maximum charge per delay that could be used under different blasting conditions without exceeding the permissible vibration limits.

Using the developed site-specific vibration predictor model, safe charge-per-delay values were estimated for various monitoring distances from sensitive structures. The analysis considered the DGMS-recommended vibration limit of 10 mm/s for residential buildings.

The calculated charge per delay values indicate that larger explosive charges may be safely used at greater distances from structures, whereas lower charge weights are necessary when blasting is conducted closer to the inhabited areas. The recommended charge per delay values for different monitoring distances are listed in Table 5.

Table 5. Recommended maximum charge per delay for different distances from sensitive structures.

Distance from blast Site (m)	Maximum allowable PPV (mm/s)	Recommended maximum charge per delay (kg)	Blasting recommendation
100	10	30	Strict control of charge per delay required
120	10	40	Suitable for controlled production blasting
140	10	50	Safe under normal blasting conditions
160	10	65	Moderate increase in charge permissible
180	10	80	Suitable for production blasting with monitoring
200	10	95	Safe for routine blasting operations
250	10	140	Increased charge can be accommodated
300	10	190	Suitable for large-scale production blasting
350	10	250	Minimal vibration risk to nearby structures
400	10	320	Safe for high-production blasting operations

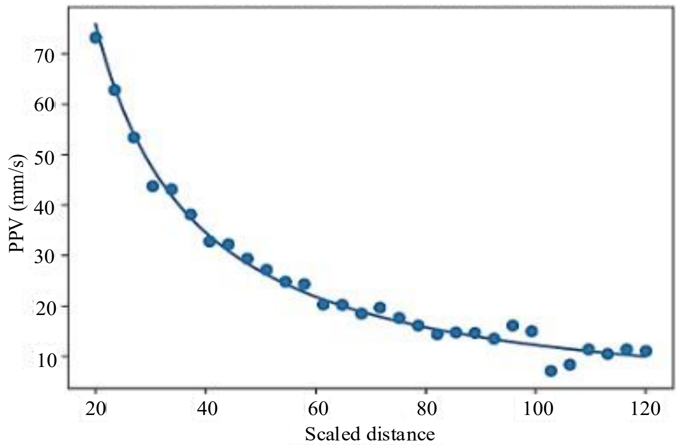

Figure 6. Site-specific ground vibration predictor model (illustrative regression plot).

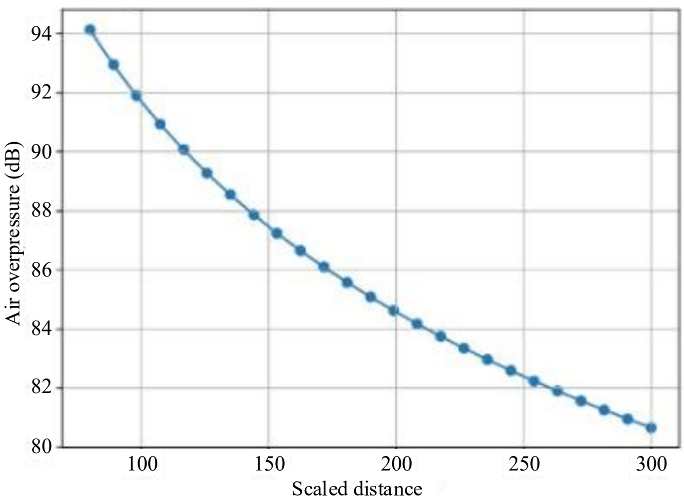

Figure 7. Site-specific air overpressure predictor model.

The results provide practical guidelines for mine planners and blasting engineers to design production blasts while maintaining compliance with environmental regulations.

Implications for Blast Design Optimization

The findings of this study demonstrate the importance of site-specific vibration monitoring for improving blast design practices. The developed predictor model enables blasting engineers to estimate the expected vibration levels before conducting a blast and thereby select an appropriate charge per delay.

The implementation of the recommended charge limits can help reduce environmental impacts while maintaining adequate rock fragmentation and production efficiency. Furthermore, the use of electronic delay detonators and diagonal firing sequences contributes to improved burden relief, controlled rock movement, and reduced vibration levels.

The methodology adopted in this study can be applied to other opencast mines after site-specific calibration of the vibration predictor equations. The integration of field monitoring, statistical analysis, and blast design optimization provides a scientific framework for achieving safe and sustainable blasting operations in the future.

CONCLUSIONS

This study investigated blast-induced ground vibration and air overpressure characteristics at an opencast coal mine in eastern India (Mine Code M-01) to optimize the blast design by determining the safe maximum charge-per-delay values. Based on field monitoring, statistical analysis, and vibration prediction modelling, the following conclusions can be drawn:

1. A comprehensive blast monitoring program involving 20 production blasts was successfully conducted to evaluate the influence of explosive charge and monitoring distance on blast-induced environmental effects.
2. The monitored PPV values ranged from 0.733 to 2.382 mm/s, which were significantly lower than the DGMS permissible limit of 10 mm/s for residential structures, indicating that the existing blasting practices are operating within safe limits.
3. The analysis of the vibration frequency data revealed that most blast events produced frequencies within the range of 8–25 Hz, suggesting a low risk of structural damage to nearby surface structures.
4. Regression analysis of the monitored vibration data resulted in the development of a site-specific ground vibration predictor model with a coefficient of determination (R^2) of 0.76, demonstrating a satisfactory correlation between the vibration intensity, charge per delay, and monitoring distance.
5. Air-overpressure monitoring indicated that the existing blast design parameters and stemming practices were effective in controlling air-blast effects within the acceptable limits.
6. Safe maximum charge-per-delay values were determined for various monitoring distances using the developed predictor model and the DGMS vibration criteria. The results provide practical guidelines for blast design optimization in the study area.
7. The adoption of controlled charge per delay, electronic delay detonators, and diagonal firing sequences can reduce environmental impact while maintaining satisfactory rock fragmentation and production efficiency.
8. The methodology developed in this study can be applied to other opencast mining operations after appropriate site-specific calibration, thereby supporting safe, efficient, and environmentally sustainable blast practices.

Overall, this study demonstrates that site-specific blast monitoring and vibration prediction modelling are effective tools for optimizing blast design and ensuring compliance with environmental and safety standards in opencast coal mining operations.

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