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Original Article

Analysis of Overbreak in Development Headings of An Underground Metal Mine

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ABSTRACT

Overbreak—the removal of rock beyond the intended excavation profile—represents one of the most persistent challenges in underground mining. While frequently overlooked as a secondary effect of blasting, overbreak significantly influences ground stability, development efficiency, and project economics. This study presents a comprehensive, field-based analysis of overbreak in development headings at a large underground metal mine in Rajasthan, India. Data were collected over five months using total-station surveys, blast performance records, and ground support documentation. Excavation profiles were analyzed with AutoCAD and Geovia SURPAC to quantify deviations from design, while statistical methods were employed to establish relationships between blasting parameters and overbreak. Results revealed an average overbreak of 7.68% across all monitored rounds. Correlation analysis identified three key parameter driving overbreak: final cup density in perimeter holes. To address these issues, a modified perimeter-control blasting strategy was developed, featuring decoupled charges. The findings highlight that overbreak should not be accepted as inevitable but recognized as a controllable engineering parameter. With targeted adjustments in blasting design and execution, significant improvements can be achieved in safety, efficiency, and cost optimization. This research thus contributes both practical strategies for industry and empirical insights for advancing controlled blasting practices in underground metal mining.

Keywords: Overbreak; Underground Excavation; Controlled Blasting; Burn-Cut Method; Perimeter Control; Blasting Optimization; Development Headings

INTRODUCTION

1.1 General Background

Mining has historically sustained industrial growth by supplying essential raw materials (Hartman & Mutmansky, 2002). While open-pit methods dominate shallow deposits, underground mining becomes indispensable at depths beyond 300 m or where surface disturbance must be minimized (Brady & Brown, 2006). Globally, underground methods enable access to deeper, often higher-grade ores while reducing land-use conflict compared to surface operations (Hustrulid & Bullock, 2001). In India, depletion of near-surface deposits has increased reliance on underground mining (DGMS, 2020). Among available excavation methods, drill-and-blast remains the most widely applied for hard rock, owing to its flexibility, relatively low capital demand compared with tunnel boring machines, and adaptability to varied geometries (Singh, 2018). However, blast energy is difficult to control. Detonations generate stress waves and gas pressures that propagate beyond intended contours, creating three distinct zones: overbreak, or excavation outside design boundaries; damaged rock, with reduced strength; and disturbed zones, characterized by minor stress adjustments (Ibarra et al., 1996; Saiang & Nordlund, 2007). Overbreak is the most visible and operationally disruptive of these.

Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

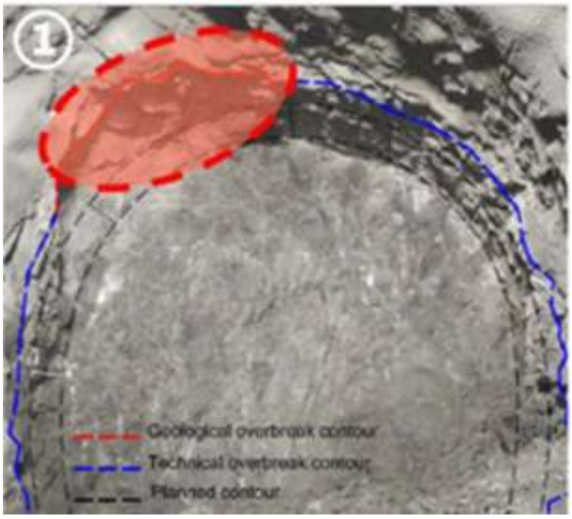

Figure 1 Overbreak (Front view)

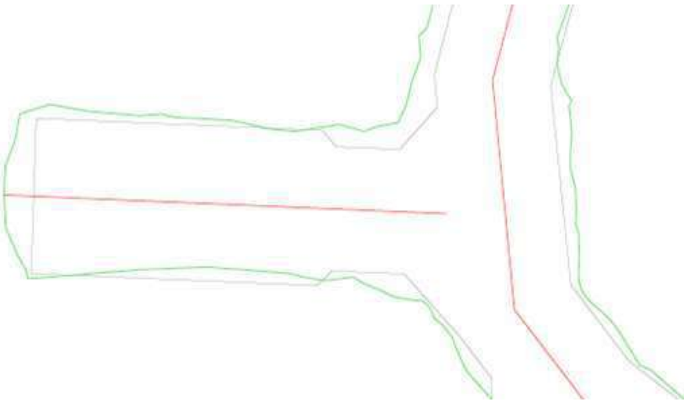

Figure 2 Overbreak in development heading (Plan view)

1.2 Importance of Overbreak Control

Overbreak is often treated as a minor irregularity, but its implications are significant.

- Economic impacts: Excess excavation increases mucking, hauling, and disposal costs, while inflating consumption of shotcrete, bolts, mesh, and backfill. Stabilization costs may reach INR 2000/m³, with project-wide development costs rising 15–18% (Verma et al., 2018; Foderà et al., 2020).
- Safety impacts: Overbreak destabilizes profiles, leaving wedges and blocks susceptible to collapse. This exposes miners during scaling and complicates effective installation of supports (Sellers, 2011).
- Operational impacts: Irregular profiles obstruct ventilation, delay drilling sequences, and hinder installation of utilities. These small inefficiencies, when accumulated, reduce advance rates (Orica, 2014).

1.4 Knowledge Gaps and Research Need

Although overbreak is well documented in tunneling and some international mines (Ibarra et al., 1996; Saiang & Nordlund, 2007), there is lack of Indian field based overbreak studies in underground mines. Most published research emphasizes laboratory tests or predictive modeling, often in the context of civil tunnels whose design and performance criteria differ from metalliferous mining (Foderà et al., 2020; Hong et al., 2023). Given India's lithological complexity, stress variability, and operational difficulties, there is a need for empirical, field-based studies that document overbreak patterns and evaluate mitigation strategies specific to mining. This research work takes 5-month fields data, analyses quantified overbreak and suggests modified blasting strategies.

1.5 Objectives and Methodological Overview

This study was designed to:

- To study various blasting techniques used in development headings of underground metal mines.
- To monitor the overbreak in different kinds of development headings.
- To analyse the relation between different blasting parameters and overbreak in development headings.
- To assess the time delay in completion of development headings caused due to overbreak.
- To propose modified blasting technique for different development headings.

The methodology comprised: total-station surveys for post-blast profiles; volumetric comparisons using AutoCAD and Geovia SURPAC; statistical evaluation of relationships between overbreak and blasting parameters; validation with case studies; and modified trials featuring decoupled charges, optimized stemming, refined delays, and improved drilling accuracy. This ensured empirical rigor and operational relevance.

1.6 Structure of the Paper

The paper is structured as follows: Section 2 reviews literature on blasting and overbreak control; Section 3 presents the study site and methodology; Section 4 reports field results and analysis; Section 5 proposes and evaluates a modified blasting strategy; and Section 6 concludes with findings and recommendations.

2. Literature Review

2.1 Blasting Techniques for Development Headings

The drill-and-blast method remains the dominant excavation technique in underground hard-rock mining due to its adaptability across diverse geological conditions (Hustrulid & Bullock, 2001). Unlike surface mining, however, underground blasting faces the limitation of a single free face, necessitating specialized cut designs such as *wedge-cut* and *burn-cut*.

Wedge-Cut Blasting:

The wedge-cut, an early innovation, employs angled blastholes forming a V-shaped cavity to generate relief. Though effective in small drivages, its sensitivity to drilling accuracy makes it unsuitable in jointed or weak rock, where cavity formation often fails and results in unbroken holes or poor fragmentation (Hartman & Mutmansky, 2002). Consequently, wedge-cuts are rarely applied in large-scale mechanized operations.

Burn-Cut Blasting:

Burn-cut designs employ uncharged reamer holes surrounded by charged blastholes, facilitating expansion of the cavity. Typical burn-cuts for a 4.8 m × 4.8 m heading involve 50–60 holes, making the method compatible with mechanized drilling jumbos and parallel-hole layouts. Though cut rounds consume more explosives, their reliability and adaptability in competent formations ensure widespread use, particularly in Indian base metal mines (Singh, 2018). While wedge-cuts retain niche utility in smaller headings, the burn-cut has become the standard practice due to its consistency and compatibility with mechanized rigs.

2.2 Perimeter Controlled Blasting

Cut design establishes an initial cavity, but perimeter control determines wall stability. Unlike production blasting—focused on fragmentation—controlled blasting emphasizes limiting damage (Orica, 2014). Several methods are documented:

- **Decoupled Charges:** Reduced-diameter cartridges within larger boreholes lower borehole pressure and confine radial cracks. Trials in Indian mines showed up to 25% reductions in overbreak at decoupling ratios of 0.5–0.7 (Singh, 2018; Orica, 2014).

- **Line Drilling:** Rows of uncharged boundary holes act as stress-relief planes and reduce crack propagation. Effective in competent rock, the method is less reliable in weak formations (Brady & Brown, 2006).

- **Firing Sequence Optimization:** Extended delays for perimeter holes (50–100 ms) allow central muck displacement before boundary detonation. Millisecond-precision electronic detonators have enhanced effectiveness (Iverson et al., 2013).

- **Explosive Selection and Charging:** Low-velocity explosives, such as ANFO blends and low-density emulsions, reduce shock energy transfer. Stemming methods like air decking minimize outward shattering (Sellers, 2011).

- **Advanced Tools:** Sophisticated modeling (e.g., FLAC3D, LS-DYNA, ANSYS) and vibration monitoring have enabled predictive adjustment of blast patterns. Indian field studies show that simulation-based designs substantially improve perimeter quality (Foderà et al., 2020).

Together, these techniques illustrate that wall integrity depends not only on explosive energy but also on precision in design and execution.

2.3 Review of Related Research Work

2.3.1 Mechanisms of Overbreak:

Ibarra et al. (1996) demonstrated that geological discontinuities and blast design parameters jointly control overbreak. They introduced the Perimeter Powder Factor as an important index of damage. Saiang and Nordlund (2007) extended this by modeling blast damage zones, showing that overbreak is part of a broader degradation process influenced by tensile strain.

2.3.2 Advances in Controlled Blasting:

Sellers (2011) emphasized controlled blasting's role in reducing both overbreak and safety hazards. Iverson et al. (2013) highlighted buffer holes as an effective energy barrier between production blasts and excavation boundaries. Industrial trials reported by Orica (2014) demonstrated reductions of overbreak from 30% to <5% through modified explosives and refined delay sequencing.

2.3.3 Empirical Models and Drilling Accuracy:

Verma et al. (2018) derived correlations linking damage distance to rock quality (Q-value), charge weight per delay, and confinement. Singh (2018) stressed drilling accuracy as the most decisive operational factor, since computer-aided jumbos outperform manual drilling in precision. Ganesan and Mishra (2020) distinguished constructional overbreak (drilling and execution errors) from geological overbreak (lithological weaknesses), establishing that rock quality governs which factor dominates.

2.3.4 Recent Developments:

Foderà et al. (2020) introduced laser scanning technologies for distinguishing technical versus geological overbreak sources. Vishwakarma et al. (2020) analyzed Indian base metal mines, linking high-VOD explosives and poor delay sequencing to heightened overbreak. More recently, AI-based models such as XGBoost have been applied to integrate nonlinear influences of geology, drilling, and blast design, with promising results for parameter optimization (Hong et al., 2023; Liu et al., 2023).

2.4 Causes of Overbreak

From the literature, four consistent causes of overbreak emerge (Fig. 3)

1. Geological and stress-related conditions – weak or jointed rock masses, shear zones, weathered material, or adverse stresses (Ibarra et al., 1996; Ganesan & Mishra, 2020).
2. Blast design parameters – inappropriate burden or spacing, excessive charge density, coupled charges, and poor sequencing (Verma et al., 2018; Iverson et al., 2013).
3. Operational and human factors – drilling deviations, stemming errors, or inconsistent execution (Singh, 2018).
4. Explosive energy characteristics – high-VOD or unsuitable formulations based on local lithology (Vishwakarma et al., 2020).

These categories directly frame the present study, which evaluates geological variations, drilling and design parameters, and perimeter charging practices under Indian mining conditions.

2.5 Impacts of Overbreak

The literature consistently identifies negative consequences:

- Reduced stability due to damaged excavation walls and wedge failures (Saiang & Nordlund, 2007).

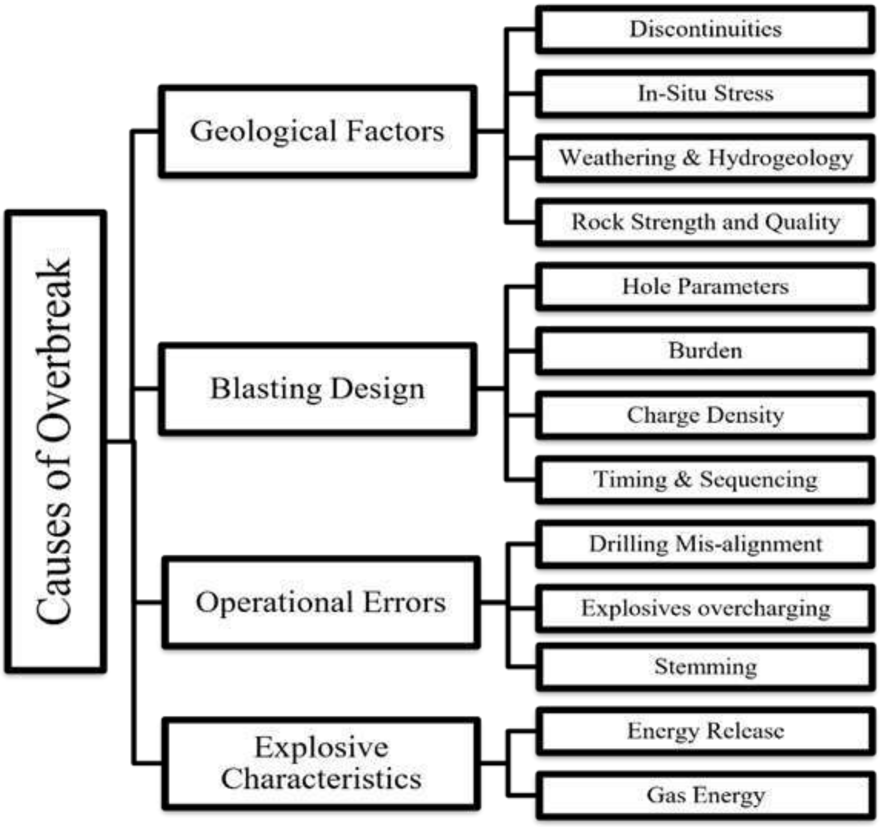

Figure 3 Causes of overbreak

- Increased costs of 15–18% from elevated support demand and corrective profiling (Foderà et al., 2020).
- Productivity losses from additional scaling, muck handling, and slower cycle times (Orica, 2014).
- Additional environmental burdens from increased waste rock volume for disposal (Brady & Brown, 2006).

METHODOLOGY

A systematic methodology (Fig. 4) is crucial to investigating overbreak, since the phenomenon arises from the interaction of geological, design, and operational parameters. This study adopted a field-based, empirical approach in which overbreak was quantified through precise survey measurements, correlated with blasting variables, and validated through both statistical analysis and comparison with published literature. The methodology comprised four key stages:

(i) characterization of the study site,

(ii) structured data collection,

(iii) data processing and statistical analysis, and

(iv) validation and verification.

3.1 Study Site

The investigation was carried out in a large underground metal mine located in **Rajasthan, India**, one of the country's most mineral-rich states. The mine extracts base metals using underground development methods, with ore bodies hosted primarily within **graphite mica schist**. The geological environment is further complicated by intersecting **shear zones**, zones of **waste rock**, and regions filled with **pastefill** from earlier stoping operations. The mine follows standard development practices, advancing arched headings with dimensions of **4.8 m** × **4.8 m**. The drivages are advanced primarily using the **drill-and-blast method**, executed with **mechanized twin-boom jumbos**. Ground support consists of **resin-grouted rock bolts**, installed in a systematic pattern but often requiring additional support in weak or overbroken ground. This setting provided an ideal field laboratory to study overbreak, given its geological variability and reliance on conventional burn-cut blasting techniques.

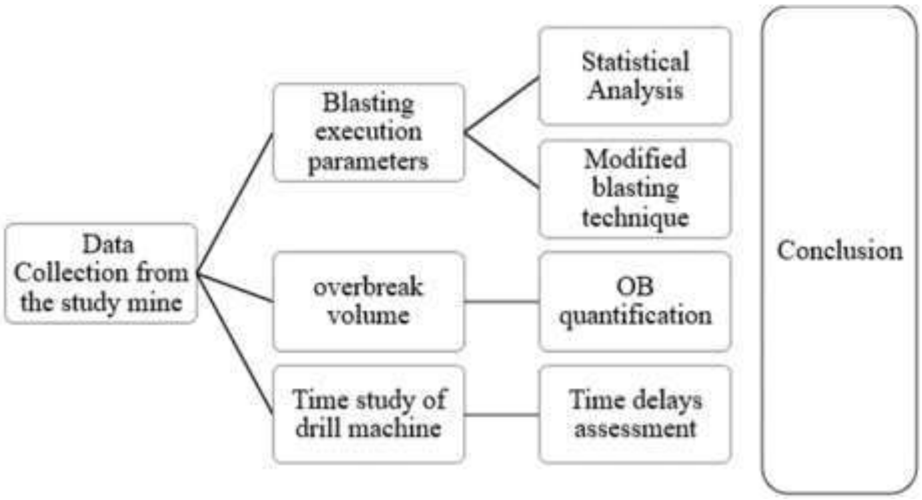

Figure 4 Methodology of research work

3.2 Data Collection

Field data were collected systematically over a **five-month monitoring period**, ensuring sufficient sample size and temporal coverage. The rage of collected data is shown in table 1.

3.2.1 Geometrical Measurements

- **Overbreak Percentage (%OB):** Defined as the volumetric deviation between the designed excavation profile and the actual post-blast profile.
- **Pull:** The actual length of heading advance achieved.

Profiles of development headings were captured using a **total station survey instrument**, providing high-accuracy three-dimensional point data. Survey stations were established at regular intervals, and post-blast profiles were measured immediately after mucking to avoid distortions caused by subsequent scaling or support installation.

3.2.2 Drilling and Blasting Parameters

Operational records were collected for each blast round, including:

- Number, length, and diameter of blastholes.
- Reamer hole dimensions.
- Explosive type, density, and total charge weight.
- Initiation sequence and delay timing.

3.2.3 Operational and Support Data

To assess the downstream impacts of overbreak, additional operational indicators were monitored:

- **Support consumption:** Number of resin-grouted bolts installed in each round.
- **Cycle delays:** Additional hours spent on scaling and stabilization due to overbreak.

During the monitoring period, all deviations from the planned support pattern were recorded and linked to measured overbreak events.

Table 1 Range of collected data: -

Data	Range
Overbreak (%)	1.7,20.3
Depth of cut holes(m)	2,5
Final Cup Density (t/cum)	0.6,0.96
No.of blast holes (No.s)	27,96
Total explosive consumed (Kg)	43.9,625.7
Powder Factor (t/Kg)	0.6,4.67
Pull (m)	1.5,4.8
Drill Yield(m^3/m)	0.23,2.55

3.3 Data Processing and Analysis

The collected datasets were processed through a multi-stage workflow:

3.3.1 Profile Analysis

Survey data were imported into **AutoCAD** and **Geovia SURPAC**, both widely used in mining for geometric and volumetric analysis. Designed excavation profiles were overlaid with actual survey profiles to calculate deviations. Overbreak was quantified as:

$$\%OB=(V_{actual}-V_{design})/V_{design}\times 100$$

where V_{actual} is the measured excavation volume and V_{design} is the planned excavation volume.

The software platforms also enabled visualization of overbreak distribution along heading walls, crown, and floor, facilitating identification of localized trends.

3.3.2 Statistical Analysis

Data were subjected to descriptive and inferential statistical analysis. The following metrics were computed:

- **Central tendency:** Mean, median, mode of overbreak values.
- **Dispersion:** Standard deviation, variance, and coefficient of variation.
- **Distribution characteristics:** Skewness and kurtosis, to detect the presence of high-magnitude outliers.

To explore relationships between overbreak and blasting parameters, **correlation analysis** was performed. Pearson's correlation coefficients were calculated between overbreak percentage and selected variables, namely final cup density, burden-to-spacing ratio, and charge concentration.

3.3.3 Operational Impact Assessment

The operational consequences of overbreak were quantified in terms of:

- **Ground support over-consumption:** Measured as the difference between actual and planned resin bolt usage.
- **Additional labor hours:** Estimated by tracking man-hours spent on scaling and extra support beyond standard cycles.

3.4 Validation and Reliability

To ensure the robustness of results, multiple validation steps were incorporated:

1. **Cross-checking with Literature:** Observed ranges of overbreak and its causes were compared with published case studies from both mining and tunneling projects (e.g., Orica, 2014; Singh, 2018; Foderà et al., 2020). Consistency with established benchmarks confirmed the reliability of site-specific findings.
2. **Triangulation of Data:** By combining survey profiles, operational logs, and support consumption records, the study minimized reliance on any single dataset, thus enhancing credibility.

3.5 Ethical and Practical Considerations

The study was conducted within the operational framework of the host mine, with due regard for worker safety and production schedules. All data collection activities were coordinated with mine management to avoid disruption of operations. No confidential production data beyond blasting and support information were disclosed, maintaining compliance with industry protocols.

RESULTS AND DISCUSSION

This section presents results from field investigations and their interpretation. Findings are grouped into four themes: current blasting practices, quantification of overbreak, operational impacts, and statistical relationships. Each is critically discussed in the context of geological variability, blast design, operational practices, and existing literature.

4.1 Current Blasting Practices

The study mine predominantly employs the burn-cut method for development headings. Each round involves 50–60 parallel blastholes drilled using mechanized jumbos, with four large-diameter reamers forming the central void. Bulk emulsion explosives are used, with detonation sequenced as cut → easers → lifters → perimeter holes via non-electric detonators. Although perimeter holes are lightly charged to minimize wall damage, outcomes were inconsistent. Some rounds produced smooth excavation surfaces, while others demonstrated significant overbreak. Variations were attributed to (i) minor deviations in drilling alignment, (ii) variability in explosive column distribution, and (iii) local geology, particularly shear zones. These findings echo Singh (2018), who emphasized drilling accuracy in burn-cut performance, and Orica (2014), which documented variability in perimeter charging effectiveness in heterogeneous ground.

4.2 Quantification of Overbreak

Survey-based volumetric comparisons revealed an average overbreak of 7.68% relative to designed excavation. Most rounds fell between 4–10%, though extreme cases occasionally exceeded 20%, largely in weak geological zones.

Figure 5: Average OB in different rock type

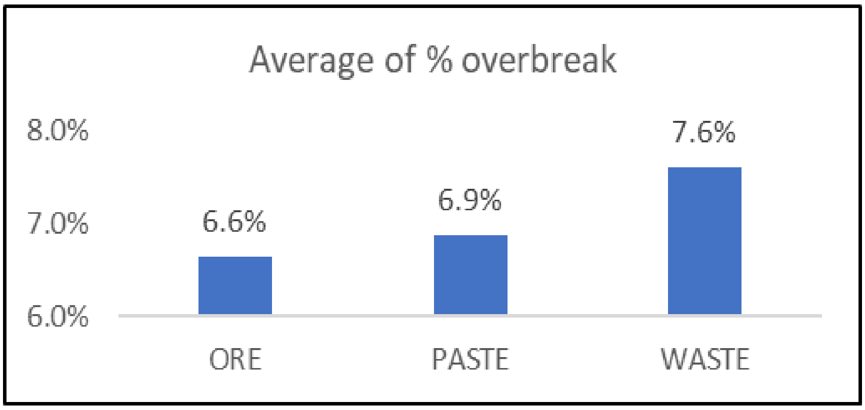

Figure 6 Box and whisker plot for OB data

The data exhibited positive skewness, driven by infrequent but severe outliers. Such events significantly raise averages and underscore the need for designs that accommodate variability rather than targeting mean conditions only.

4.3 Operational Impacts

Overbreak had direct consequences on mine efficiency.

Ground Support: During the study, 3,081 more resin-grouted bolts were installed than planned, representing a 23.5% increase. This reflects the extra support required to stabilize irregular boundaries.

Labor Requirements: Scaling and installing supplementary support consumed an additional 285 man-hours, elongating cycle times and reducing development advance rates.

Broader Impacts: Beyond immediate stability, irregular profiles hampered drilling alignment in subsequent rounds, obstructed ventilation circuits, and complicated utility installation. The cumulative effect suggests that overbreak imposes both short- and long-term operational inefficiencies.

4.4 Statistical Relationships-

Table 2 Correlation of blasting parameters with OB

Parameter	Correlation with OB	Remarks
Avg. depth of holes	0.18	Weak positive correlation
Explosive Density	0.45	Strong positive correlation
No. of blast holes	0.15	Very weak positive correlation
Total explosive consumed (Kg)	0.11	Very weak positive correlation
Powder Factor (t/Kg)	0.19	Weak positive correlation
Pull (m)	-0.13	Weak negative correlation

Final Cup Density: Higher charge density in cut holes correlated positively with overbreak (can be observed in Fig. 7) as high-energy zones induced excess cracking. Iverson et al. (2013) observed similar uncontrolled fracturing from dense central charges.

Overall, these findings suggest overbreak correlates more strongly with energy distribution than with total explosive quantity.

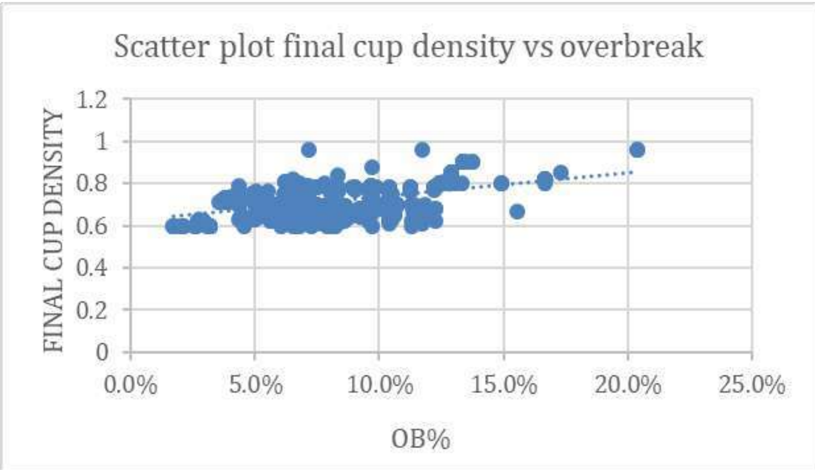

Figure 7 Scatter plot final cup density vs overbreak

4.5 Comparative Discussion with Literature

The measured average overbreak of 7.68% aligns with reported international benchmarks (5–12%) (Foderà et al., 2020; Singh, 2018). Sporadic cases >20% reinforce the nonlinear nature of overbreak in heterogeneous ground. Observed key parameter—final cup density, is consistent with earlier studies (Ibarra et al., 1996; Iverson et al., 2013). This validates the universality of certain design principles across diverse geological contexts.

4.6 Key Insights

The study generated several insights:

- Overbreak is causally linked to identifiable geological and blasting parameters rather than being random.
- Its operational impact is substantial, raising support demand, labor inputs.
- Outliers must be addressed, as extreme cases disproportionately influence averages and stability risk.
- Optimizing perimeter charging and improving drilling precision remain the most practical levers for control.

5. Proposed Blasting Strategy

Field investigations revealed that final cup density was the most influential contributor to overbreak.

These effects were amplified by geological variability, such as in weak pastefill and shear zones. To mitigate these issues, a modified perimeter-control blasting strategy was designed. This section outlines the rationale, specific modifications.

Although burn-cut blasting is effective in creating voids and advancing headings, its limitations in perimeter control were evident in the study mine. Excessive energy transmission into excavation boundaries produced irregular profiles, unstable rock, and elevated support demand. Key shortcomings included:

- Fully coupled perimeter holes transmitting excessive radial energy.
- Drilling deviations altering planned drill design.

The primary objective was therefore to redistribute energy within desired profiles while lowering boundary damage, without compromising fragmentation and advance rates.

5.1 Key Modifications Introduced

5.1.1 Decoupled Charges

Perimeter holes loaded with smaller-diameter cartridges, leaving an annular air gap (as shown in Fig. 8) to reduce borehole pressure and restrict crack propagation. Decoupling ratios of 0.6–0.7 were tested, consistent with recommendations by Singh (2018) and Orica (2014).

5.1.2 Drilling Accuracy Improvements

Enhanced supervision of jumbo operations ensured hole alignment matched design plans. Operator refresher training was conducted, reducing deviations that previously led to localized overbreak.

Together, these modifications balanced fragmentation efficiency with smoother, stable excavation profiles.

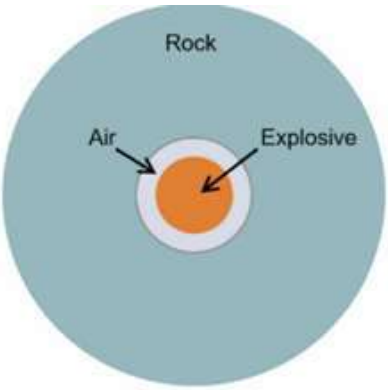

Figure 8 Decoupled charge illustration

5.2 Practical Significance

The proposed strategy carries broader implications for underground mining operations:

1. Cost Optimization: Less ground support and reduced cycle delays deliver direct cost savings. Even small reductions in overbreak compound into significant financial benefits across large-scale operations.
2. Safety Enhancement: Smoother excavation walls reduce rockfall risk, while easier support installation improves workplace safety.
3. Improved Stability: Limiting blast-induced damage improves long-term drivage stability, especially critical in weak or stressed ground.
4. Operational Flexibility: The strategy is customizable across lithologies, with decoupling, stemming, and timing adjusted to ore, waste, or pastefill zones.

5.3 Limitations and Future Scope

Despite improvements, certain limitations remain:

- Effectiveness in deeper, higher-stress zones remains untested.

- Decoupled charges require more careful handling, which increased charging time during trials.
- The trial spanned five months; long-term stability benefits warrant ongoing monitoring.

Future research directions include:

- Incorporating AI-driven predictive models to optimize blast designs dynamically.
- Utilizing laser scanning for high-resolution monitoring of profiles and overbreak.
- Conducting comparative trials with electronic detonators for greater timing precision.

6. Conclusions and Recommendations

This research provided a detailed, field-based investigation into the phenomenon of overbreak in underground development headings of a metal mine in Rajasthan, India. By integrating precise survey data, statistical analysis the study generated both empirical evidence and practical strategies for controlling overbreak.

The key conclusions are summarized below:

1. **Magnitude of Overbreak-** The average overbreak across all monitored rounds was **7.68%**, However, occasional high-magnitude events exceeded **20%**, especially in weak pastefill zones and shear zones.

2. **Causal Parameters-** Statistical correlations identified a parameter with the strongest influence on overbreak: final cup density in perimeter holes.

3. **Operational Impacts-** Overbreak resulted in a **23.5% increase** in resin-grouted bolt consumption and **285 additional man-hours** of scaling and support. These impacts translated into substantial cost penalties and productivity losses, reinforcing the economic significance of overbreak.

4. **Modified Blasting Strategy-** A suggested strategy incorporating **decoupled charges can** produce smoother profiles, reduced ground support demand, and improved cycle efficiency.

5. **Broader Implications-** The study highlights the need for lithology-specific blasting practices rather than uniform designs.

6.1 Recommendations

Based on the findings, the following recommendations are made for both industry practice and future research:

6.1.1 Industry Practice

1. **Adopt Perimeter-Control Techniques as Standard-** Mines should systematically employ decoupled charges, optimized stemming, and refined delay timing for perimeter holes. These practices should become standard operating procedures rather than ad hoc measures.

2. **Designs Tailored to Geology-** Blasting parameters should be adjusted for varying lithologies. In weak pastefill and shear zones, stricter perimeter control and reduced energy input are essential.

3. **Invest in Drilling Accuracy-** Mechanized drilling jumbos should be complemented with rigorous monitoring systems to minimize hole deviation. Periodic operator training and quality checks should be institutionalized.

4. **Systematic Overbreak Monitoring-** Regular survey-based measurement of overbreak should be integrated into the development cycle. Monitoring not only quantifies performance but also provides feedback for continuous improvement in design.

5. **Economic Evaluation-** Mines should quantify the costs of overbreak in terms of additional support, labor, and delays. By linking technical performance with financial outcomes, management can justify investments in improved blasting technology.

6.1.2 Future Research

1. **Advanced Predictive Models-** Artificial intelligence (AI) and machine learning models, such as **XGBoost** or **neural networks**, should be

explored to predict overbreak based on geological and blasting parameters.

2. **Numerical Simulation-** Finite element and discrete element methods (e.g., FLAC3D, LS-DYNA) can provide predictive insights into stress wave propagation and optimize designs before field trials.

3. **High-Resolution Monitoring-** Laser scanning and photogrammetry can offer superior accuracy in capturing excavation profiles, enabling more precise measurement of overbreak.

4. **Comparative Trials with Electronic Detonators-** The use of programmable electronic detonators should be tested against non-electric systems, particularly to evaluate the benefits of millisecond precision in initiation timing.

5. **Long-Term Stability Studies-** The long-term impacts of reduced overbreak on drivage stability should be evaluated through monitoring of convergence, bolt performance, and support longevity.

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