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Field evaluation of air-deck blasting for improving rock fragmentation at the Gol-e-Gohar no. 1 open-pit iron ore mine, Iran

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ABSTRACT

Rock fragmentation plays a critical role in the efficiency of downstream mining operations and in the overall economics of open-pit production. This study investigates the performance of air-deck blasting under full-scale production conditions at the Gol-e-Gohar No. 1 open-pit iron ore mine, Iran. . It compares its results with those of conventional fully coupled blasting. Over two months, 14 production blasts were analyzed, including 7 conventional blasts and 7 air-deck blasts selected under comparable geological and operational conditions. Fragmentation was evaluated using a consistent image-based analysis procedure, and key particle-size distribution indices, namely D20, D50, and D80, were obtained from cumulative size distribution curves. In addition to fragmentation characteristics, operational performance was assessed through specific charge, specific drilling, blast-hole productivity, oversize fraction, muckpile condition, and shovel loading behavior. The results showed that air-deck blasting generated finer and more uniform fragmentation than the conventional method, with D20, D50, and D80 reduced by approximately 30.0%, 18.6%, and 20.7%, respectively. The improved fragmentation also enhanced digging and loading conditions, leading to an approximately 10% reduction in shovel loading time and a 9% increase in blast-hole productivity. Statistical evaluation confirmed that the differences between the two blasting approaches were significant for the tested field dataset. In contrast, Split-Desktop-based statistical validation produced coefficients of determination (R^2) in the range of 0.71-0.73 and RMSE values between 8.9% and 10.1%. Although the findings are site-specific and should be verified under different rock-mass and operational conditions, they demonstrate that air-deck blasting is an effective and practical technique for improving fragmentation quality and operational efficiency in open-pit mining operations.

KEYWORDS

Air-deck blasting, rock fragmentation, open-pit mining, image-based fragmentation analysis, blast design optimization, Gol-e-Gohar Iron Ore Mine

I. INTRODUCTION

Blasting is one of the most influential operations in surface mining because it directly governs rock breakage, muckpile formation, and the efficiency of subsequent activities such as loading, hauling, crushing, and grinding (Pal Roy and Singh, 2001; Jhanwar et al., 1999; Jhanwar and Jethwa, 2000; Roy et al., 2008). The quality of fragmentation achieved during blasting has a major effect on both operational productivity and overall cost, since oversized blocks may reduce excavator performance, increase secondary breakage requirements, and decrease the efficiency of downstream size-reduction processes (Park and Jeon, 2010; Jhanwar, 2011; Lu and Hustrulid, 2003; Fourney et al., 2006). For this reason, improving blast-induced fragmentation remains a central objective in open-pit mine production.

Blast performance is controlled by a combination of geological, geometric, and explosive-related parameters. Rock mass characteristics, including structural discontinuities, joint spacing, weathering, and strength, influence the propagation of stress waves and the development of fractures around the blasthole (Rajak et al., 2018; Hayat et al., 2019; Lou et al., 2020). At the same time, design variables such as burden, spacing, stemming length, subdrilling, and charge distribution determine how effectively explosive energy is transmitted into the surrounding rock mass (Li et al., 2024; Yin et al., 2022; Rommayawes et al., 2013; Hong et al., 2025). Because these parameters interact in a complex manner, small modifications in charge configuration can lead to

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substantial changes in fragmentation pattern, throw, backbreak, and digging conditions (Balakrishnan et al., 2019; Kabwe, 2019; Sadiq, 2021).

Among the available blast design approaches, air-deck blasting has received considerable attention as a practical technique for improving explosive energy utilization and fragmentation efficiency (Kabwe, 2016; Zarei et al., 2022; Monjezi et al., 2023; Zhang et al., 2018). In this method, a deliberate air gap is introduced within the explosive column, thereby altering the internal pressure distribution, delaying gas expansion behavior, and modifying the propagation of stress waves generated by detonation (Zarei et al., 2022; Zhang et al., 2018; Baruti, 2024). The presence of the air deck can intensify local tensile failure, promote crack extension, and improve the breakage mechanism in the bench, often with a lower effective explosive charge than that required in conventional fully coupled blasting (Monjezi et al., 2023; Cheng et al., 2022; Afrasiabian et al., 2021; Fan et al., 2024). Previous studies have reported that suitably designed air decks may contribute to finer fragmentation, improved muckpile looseness, lower powder factor, and reduced drilling and blasting costs (Zhang et al., 2018; Baruti, 2024; Cheng et al., 2022; Afrasiabian et al., 2021; Fan et al., 2024).

The effectiveness of air-deck blasting, however, depends strongly on its geometric configuration and field application conditions. Parameters such as deck position, deck length, hole diameter, bench height, and explosive type must be selected in accordance with site-specific geomechanical and operational constraints (Baruti, 2024; Saharan et al., 2017; Allama, 2023; Sazid and Singh, 2013; Chandrahas et al., 2025). Experimental and numerical investigations have shown that inappropriate deck design may reduce the desired beneficial effects, whereas optimized air-deck arrangements can improve fragmentation uniformity and enhance bench excavation conditions (Cheng et al., 2022; Allama, 2023; Ricce et al., 2025). Despite these promising findings, many published studies have been carried out at laboratory scale, through numerical simulation, or under limited field conditions, and comparatively fewer investigations have evaluated air-deck blasting under full-scale production environments in active open-pit mines (Afrasiabian et al., 2021; Sazid and Singh, 2013; Saqib et al., 2024).

This issue is particularly important in large iron ore operations, where fragmentation quality has immediate consequences for shovel productivity, crusher feed consistency, and mine-to-mill performance. Under such conditions, any blasting modification must be assessed not only from the standpoint of particle size distribution, but also in terms of operational indicators that reflect the practical diggability and handling of blasted material (Jhanwar and Jethwa, 2000; Jhanwar, 2011; Li et al., 2024; Arefmand et al., 2025). Therefore, field-based evaluation of alternative charging structures is essential to determine whether theoretical or small-scale improvements can be translated into measurable production benefits.

The present study investigates the application of air-deck blasting at the Gol-e-Gohar No. 1 open-pit iron ore mine in Iran under real production conditions. The performance of this technique is compared with that of conventional fully coupled blasting using a set of full-scale production blasts. Fragmentation was characterized through image-based analysis and particle size distribution indices, while operational performance was evaluated using indicators related to charge efficiency and shovel loading behavior. The study aims to clarify whether air-deck blasting can provide a practical and statistically defensible improvement in fragmentation quality and downstream operational performance in open-pit iron ore mining.

II. AIR-DECK BLASTING TECHNIQUE: ECHANISM AND FIELD IMPLEMENTATION

Air-deck blasting is a modified charging method in which a designed air gap is introduced within the explosive column to alter the distribution of detonation energy inside the blasthole (Kabwe, 2016; Zarei et al., 2022; Monjezi et al., 2023; Zhang et al., 2018). In contrast to conventional fully coupled charges, where the explosive continuously occupies the charged section of the hole, the air-deck arrangement creates a discontinuity that changes the interaction between detonation gases, borehole pressure, and the surrounding rock mass (Zarei et al., 2022; Monjezi et al., 2023). This modification can improve the efficiency of energy transfer by promoting more favorable stress-wave reflection and crack propagation mechanisms, particularly under bench blasting conditions in surface mines (Zhang et al., 2018; Baruti, 2024; Cheng et al., 2022).

The fundamental mechanisms of air-deck blasting, including stress-wave reflection, gas-pressure redistribution, and charge configuration effects, are schematically illustrated in Fig. 1. The figure highlights key processes such as pressure amplification near the bottom of the blasthole, interaction of reflected stress waves between adjacent blast holes, and the differences in blast-wave propagation between conventional blasting and air-deck blasting configurations.

The fundamental concept behind air-deck blasting is that the air cavity acts as a compressible medium that affects the temporal and spatial evolution of explosive loading (Monjezi et al., 2023; Cheng et al., 2022; Afrasiabian et al., 2021). When detonation occurs, the presence of the air gap modifies the pressure history along the hole and may contribute to a more effective redistribution of explosive energy within the bench. Instead of concentrating the entire loading effect in a continuously coupled column, the decked structure can intensify rock breakage in selected regions and reduce unnecessary energy loss (Baruti, 2024; Afrasiabian et al., 2021; Fan et al., 2024). As a result, air-deck blasting has often been associated with improved fragmentation, reduced explosive consumption, and better muckpile formation when properly designed (Cheng et al., 2022; Fan et al., 2024; Saharan et al., 2017; Allama, 2023).

The performance of this technique depends strongly on the geometric characteristics of the air deck and on site-specific blasting conditions. The location of the air gap within the hole, its length, the proportion of explosive above and below the deck, borehole diameter, bench height, stemming length, and the mechanical properties of the rock mass all influence the final blasting outcome (Baruti, 2024; Saharan et al., 2017; Allama, 2023; Sazid and Singh, 2013; Chandrahas et al., 2025). Because of these interrelated variables, the success of an air-deck design cannot be generalized without field verification. A deck arrangement that performs effectively in one mine may not necessarily provide the same benefit under different geological or operational conditions (Allama, 2023; Chandrahas et al., 2025; Ricce et al., 2025).

From a mechanistic perspective, the use of an air deck may enhance tensile cracking and improve stress redistribution during the blasting event. Earlier investigations have suggested that this charge configuration can increase the effectiveness of breakage around critical zones of the bench, while also helping to control excessive confinement and inefficient gas energy dissipation (Monjezi et al., 2023; Cheng et al., 2022; Sazid and Singh, 2013). In practical terms, these effects may lead to finer and more uniform particle-size distribution, improved diggability, and more favorable loading conditions compared with conventional blasting patterns (Zhang et al., 2018; Fan et al., 2024; Ricce et al., 2025; Saqib et al., 2024).

For production-scale applications, however, the evaluation of air-deck blasting should not be limited to theoretical fragmentation improvement alone. Its effectiveness must also be assessed in relation to operational indicators such as powder factor, specific charge, muckpile profile, loading efficiency, and shovel digging time, since these parameters determine whether the modified charge structure offers real mine-to-mill advantages (Jhanwar and Jethwa, 2000; Jhanwar, 2011; Li et al., 2024; Arefmand et al., 2025). Therefore, field-based comparison between air-deck and conventional blasting is essential for determining the practical value of the technique in active open-pit operations.

In the present study, the air-deck technique was examined under full-scale production conditions at the Gol-e-Gohar No. 1 open-pit iron ore mine in Iran. Its performance was evaluated against conventional fully coupled blasting with emphasis on fragmentation characteristics and operational efficiency. This approach provides a practical basis for assessing whether the modified charging structure can deliver measurable improvements in bench blasting performance under actual mining conditions.

III. CASE STUDY: GOL-E-GOHAR NO.1 IRON ORE MINE

The present study was conducted at the Gol-e-Gohar No.1 open-pit iron ore mine located near Sirjan in southeastern Iran. The Gol-e-Gohar mining district represents one of the largest iron ore production centers in the country. It is situated within the Sanandaj–Sirjan structural zone, which is known for its significant iron ore deposits and complex geological structures. The region is influenced by major tectonic structures, including the Dehshir–Baft fault system and the Zagros thrust belt, which have played an important role in the formation and structural evolution of the ore bodies. These tectonic processes have contributed to the development of extensive iron ore mineralization within metamorphic host rocks. The Gol-e-Gohar mining complex consists of several iron ore deposits distributed over an area approximately 10 km in length and 4 km in width, with total geological reserves exceeding one billion tonnes. Among these deposits, the No.1 deposit represents one of the primary production pits and was selected as the case study for this investigation. Iron ore mineralization in the Gol-e-Gohar district is mainly hosted within metamorphic rock units composed of mica-schist, amphibolite, quartz-schist, marble, and dolomitic formations of Paleozoic age. These lithological units exhibit variable mechanical and structural properties that can significantly influence drilling and blasting performance, particularly in terms of rock breakage behavior and fragmentation characteristics. The economically recoverable reserve of the No.1 deposit is estimated to be approximately 280 million tonnes. The open pit currently operates with multiple working benches and large-scale mining equipment. The final pit geometry extends approximately 4,500 m in length and 1,600 m in width and includes around 41 mining benches, with a typical bench height of approximately 15 m. Drilling and blasting operations constitute the primary rock breakage method used in the mine. Blast holes are drilled using rotary drilling rigs with hole diameters ranging from 6 to 10 inches, depending on the material type and blasting conditions. Drilling patterns vary between ore and waste zones. For ore benches, a pattern of approximately 5 m × 4 m is commonly applied, while waste rock benches typically employ larger patterns ranging from 8 m × 6.5 m to 9 m × 7 m. Ammonium nitrate fuel oil (ANFO) is generally used as the primary explosive in dry blast holes, whereas water-resistant emulsion explosives are applied in wet conditions. Non-electric delay detonators and detonating cords are used for blast initiation in order to achieve controlled detonation sequencing and effective energy distribution. The geographical location of the Gol-e-Gohar mining district and the spatial distribution of the open-pit operations are illustrated in Fig. 2.

IV. MATERIALS AND METHODS

A. *Experimental Design and Field Data Collection*

This study was carried out under full-scale production conditions at the Gol-e-Gohar No. 1 open-pit iron ore mine, located near Sirjan, Iran. The primary objective was to assess the effect of air-deck blasting on rock fragmentation and overall blasting performance in comparison with conventional fully coupled blasting. A total of 14 production blasts were examined during the study period, consisting of 7 conventional blasts and 7 air-deck blasts. The experimental program followed a paired comparative design. For each air-deck blast, a conventional blast was selected from the same production campaign and from a comparable ore or waste domain, so that rock type, bench geometry, drilling pattern, explosive product, and initiation practice were as similar as operationally possible. Blasts affected by unusual local conditions, such as excessive water inflow, abnormal hole deviation, visibly different structural conditions, or changes in explosive type, were excluded from the comparison. This approach reduced the influence of uncontrolled geological and operational variability while allowing the effect of charge configuration to be evaluated under real production conditions. For each blast, the main drilling and blasting parameters, including hole diameter, hole length, burden, spacing, stemming length, explosive column length, air-deck length, and sub-drilling depth, were recorded. The average values of these parameters are listed in Table 1.

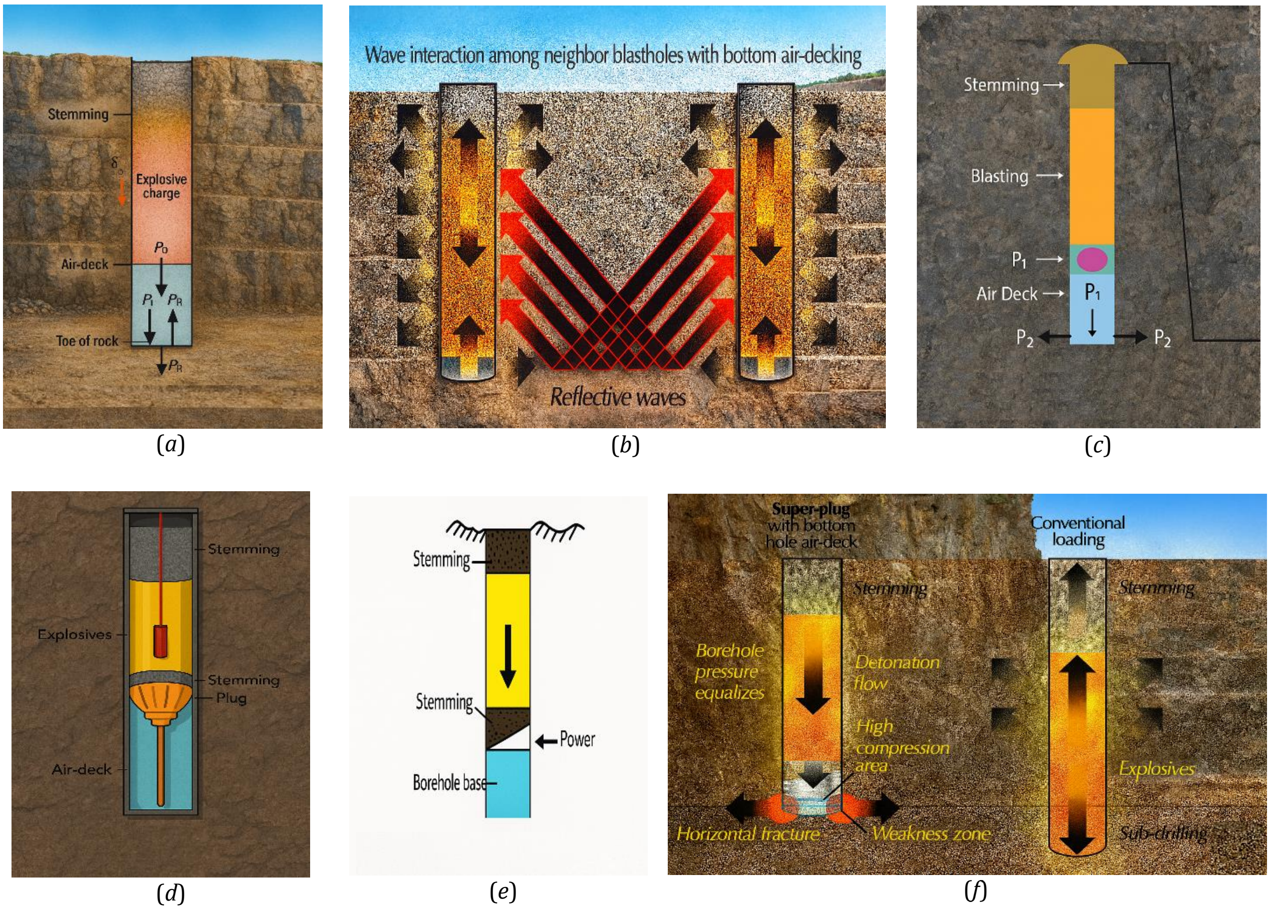

Fig.1. Schematic illustration of the air-deck blasting technique, including: (*a*) pressure development at the bottom of the blast hole; (*b*) interaction of reflected stress waves between adjacent blast holes; (*c*) pressure distribution along the air-decked explosive charge column; (*d*) a blast hole equipped with an air-deck plug; (*e*) formation of an air gap at the bottom of the blast hole; and (*f*) comparison of blast wave propagation patterns between conventional blasting and air-deck blasting.

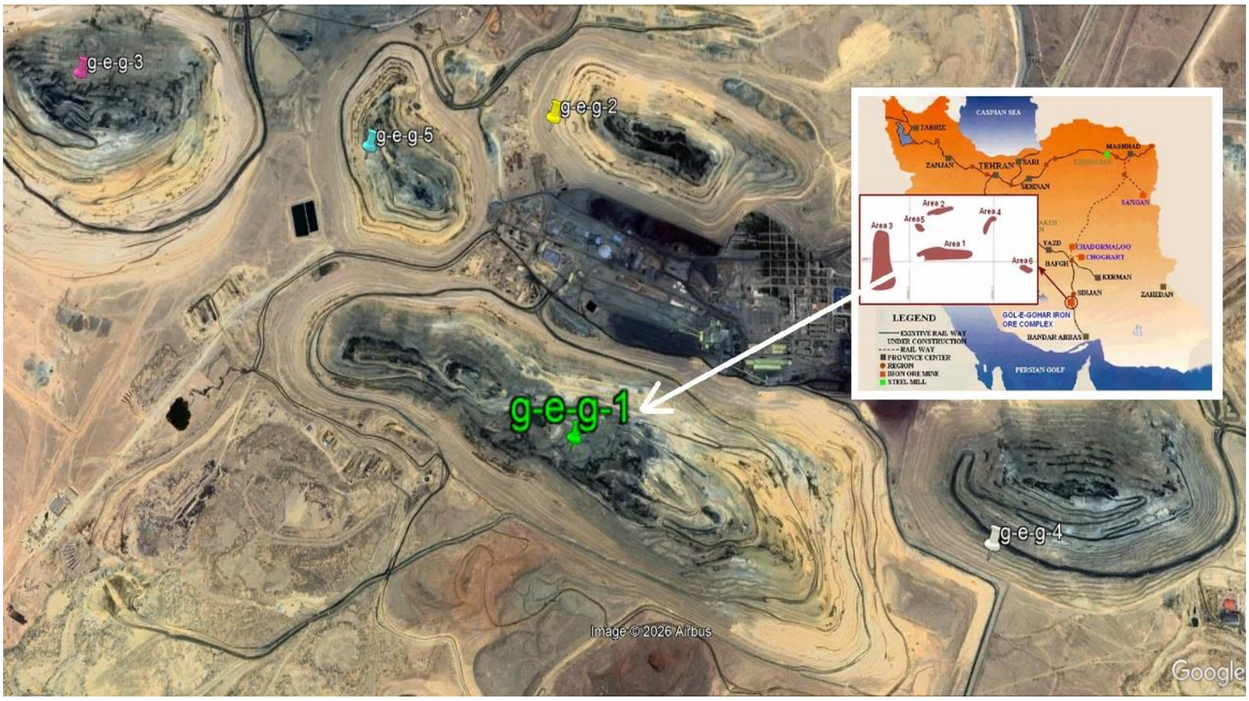

Fig. 2. Satellite view of the Gol-e-Gohar open-pit iron ore mine located near Sirjan, Iran

B. Drilling and Charging Parameters

Blast holes were drilled using rotary drilling rigs with diameters ranging from 6 to 10 in, depending on the rock type and bench conditions. The typical bench height at the study site was approximately 15 m. The conventional and air-deck blast groups were matched primarily by material domain and drilling geometry. As shown in Table 1, the compared blasts used the same nominal hole diameters, burdens, and row spacings within each ore or waste class; therefore, the main design change was the replacement of the sub-drilling section and part of the explosive column by a controlled air deck. The initiation system and delay practice were kept consistent with the mine's standard non-electric delay sequence in both blast groups so that the comparison focused on the charge configuration rather than on a change in firing design. In the conventional blasting configuration, the explosive column was fully coupled with the surrounding rock mass, and sub-drilling was applied to ensure adequate breakage at the bench floor. In contrast, in the air-deck configuration, a controlled air column was introduced within the explosive charge using a commercial deck-plug system. In this arrangement, the sub-drilling section was replaced by an air gap, thereby modifying the distribution of explosive energy along the blasthole. The air-deck length adopted in this study was 1.2 m, corresponding to approximately 12% to 20% of the explosive column length, depending on local blasting conditions and operational constraints. The corresponding average drilling and charging parameters for both blast configurations are summarized in Table 1.

In Table 1, the waste-rock columns are presented as two drilling-pattern subsets under a single waste-rock domain. This structure was used because the waste benches were drilled with two operational patterns during the study period; therefore, they are not interpreted as separate lithological waste types.

C. Fragmentation Data Acquisition

Post-blast rock fragmentation was evaluated using digital image-based analysis. Following each blast, approximately 10 to 15 high-resolution images of the muckpile were captured during loading operations, resulting in a consistent image sample for each blast. Photographs were taken from multiple viewing angles and from comparable camera-to-muckpile distances to reduce perspective bias and improve the reliability of particle-size detection. Images were captured under normal daylight or stable site-lighting conditions, and images with excessive dust, shadowing, motion blur, or a partially obscured scale object were rejected. A calibrated reference object with a known diameter of 20 cm was placed within the field of view of each image. This reference object provided the scaling factor required to convert pixel-based measurements into actual fragment sizes during image processing. The same camera procedure, scale object, image selection criteria, and processing workflow were applied to both the conventional and air-deck blast groups. Representative muckpile fragmentation images are shown in Fig. 3. As with all two-dimensional image-based fragmentation methods, the procedure may underrepresent fines hidden below coarse blocks and may be affected by particle overlap; these limitations were reduced by using multiple images from each muckpile and a consistent calibration procedure.

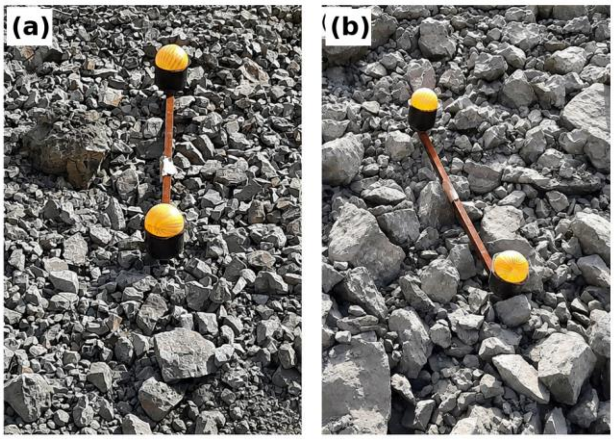

Fig. 3. Representative muckpile fragmentation images: (a) fragmentation using the air-deck technique; (b) fragmentation without using the air-deck technique.

D. Image-Based Fragmentation Analysis Using Split-Desktop

All captured images were processed using Split-Desktop software, which is widely applied in mining engineering for rock fragmentation analysis. The software uses digital image-processing algorithms to delineate fragment boundaries and estimate particle-size distributions. For each blast, cumulative particle-size distribution curves were generated from the processed images. Based on these curves, three characteristic fragmentation indices were extracted: (i) D20, the particle size at which 20% of the material passes; (ii) D50, the median fragment size; and (iii) D80, the particle size at which 80% of the material passes. These indices are commonly used in blasting studies to characterize fragmentation quality and compare blast performance. The resulting particle-size distribution curves for conventional and air-deck blasting are presented in Fig. 4.

Manual editing was limited to the correction of obvious boundary-detection errors, such as merged adjacent blocks or shadow-induced false edges, and the same editing criteria were used for all blasts. This consistency was important to ensure that differences in D20, D50, and D80 reflected blast performance rather than changes in image-processing practice.

E. Operational Performance Indicators

In addition to the fragmentation indices, several operational indicators were evaluated to assess blasting performance from both technical and economic perspectives. The selected indicators included: (*i*) specific charge (kg/m3), (*ii*) specific drilling (m/m3), (*iii*) blast-hole productivity (t/hole), and (*iv*) oversize fraction (%). The calculated values of these indicators are presented in Table 2, which provides a direct comparison between conventional and air-deck blasting.

F. Split-Desktop-Based Fragmentation Estimation and Statistical Analysis

The fragmentation estimation workflow used in this study was based on the Split-Desktop image-analysis procedure rather than on an independent empirical, regression, or machine-learning model. In this workflow, calibrated muckpile images were processed to delineate fragment boundaries, estimate particle-size distributions, and generate cumulative passing curves. The resulting Split-Desktop-derived cumulative curves were used to extract D20, D50, and D80 values and to estimate passing percentages for the conventional, air-deck, and combined datasets.

For statistical validation, the Split-Desktop-derived estimated passing percentages were compared with the corresponding observed field passing percentages obtained from the processed muckpile images. The agreement was evaluated using two performance metrics: the coefficient of determination (R^2) and the root mean square error (RMSE). In this manuscript, the terms “estimated” and “predicted” refer specifically to the Split-Desktop image-analysis estimation outputs, not to a separately calibrated predictive model. R^2 was used to quantify the proportion of variance explained by the image-analysis estimation workflow, whereas RMSE measured the average magnitude of the estimation error in percentage passing. RMSE values were expressed in percentage points of the passing fraction. The coefficient of determination was calculated using Eq. (1):

$$R^2 = \left[\frac{\sum_{i=1}^{n}(Y_{obs,i}-\overline{Y}_{obs})(Y_{pred,i}-\overline{Y}_{Pred})}{\sqrt{\sum_{i=1}^{n}(Y_{obs,i}-\overline{Y}_{obs})^2 \sum_{i=1}^{n}(Y_{pred,i}-\overline{Y}_{pred})^2}} \right]^2 \quad (1)$$

where *Pobs,i* and *PSD,i* denote the observed field passing percentage and the corresponding Split-Desktop-derived estimated passing percentage, respectively.

The RMSE was calculated according to Eq. (2):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_{obs,i}-Y_{pred,i}\right)^2}{n}} \quad (2)$$

Lower *RMSE* values indicate smaller estimation errors and therefore better agreement between Split-Desktop-derived estimates and observed field passing percentages.

In addition, the differences between conventional and air-deck blasting were evaluated using an independent two-sample t-test applied to the D20, D50, and D80 indices. Before applying the test, the data were screened for obvious outliers, and the assumptions of approximate normality and homogeneity of variance were checked using the Shapiro-Wilk and Levene tests, respectively. Because the experimental hypothesis was directional, i.e., air-deck blasting was expected to reduce characteristic fragment sizes, one-tailed p-values were reported at the 95% confidence level. The corresponding two-tailed interpretation was also considered when evaluating the strength of the evidence. The t-statistic was calculated using Eq. (3):

$$t = \frac{\overline{X_1} - \overline{X_2}}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \quad (3)$$

where the symbols represent the group means, standard deviations, and sample sizes for the conventional and air-deck blasting datasets.

V. RESULTS AND DISCUSSION

A. FRAGMENTATION CHARACTERISTICS

The effect of air-deck blasting on rock fragmentation was evaluated through image-based particle-size distribution analysis. The cumulative particle-size distribution curves for conventional and air-deck blasting are presented in Fig. 4. As shown in Fig. 4, the curve associated with air-deck blasting exhibits a clear leftward shift relative to that of conventional blasting, indicating that a greater proportion of the blasted rock mass consists of smaller fragments. The fragmentation indices derived from these curves, and summarized in Table 2, further support this observation. The median fragment size (D50) decreased from approximately 786 mm for conventional blasting to about 640 mm for air-deck blasting, corresponding to a reduction of approximately 18-19%. Likewise, the finer fraction represented by D20 decreased by about 30%, while the coarser fraction represented by D80 decreased by approximately 20.7%. These results demonstrate that air-deck blasting produced a finer and more uniform particle-size distribution than conventional fully coupled blasting. Improved fragmentation quality is expected to facilitate downstream operations, including loading, hauling, and primary crushing. The reported values should be interpreted as representative of the studied mine and production period.

B. Operational Performance Indicators

In addition to improving fragmentation, the implementation of air-deck blasting yielded favorable changes in several operational performance indicators. As summarized in Table 2, the improved fragmentation was accompanied by a reduction in specific charge, a decrease in specific drilling, and an increase in hole productivity. Moreover, the proportion of oversize fragments requiring secondary breakage decreased substantially. The reduction in specific charge from 0.70 to 0.56 kg/m^3 indicates an approximately 20% decrease in explosive consumption per unit volume of broken rock. At the same time, the increase in blast-hole productivity from 100 to 109 t/hole represents about a 9% gain in production per blasthole. The reduction in oversize fragments from 14.2% to 9.9% can also reduce secondary breakage requirements, loading delays, and crusher feed interruptions. Field observations indicated that the finer and more uniform fragmentation improved muckpile diggability and reduced shovel loading time by approximately 10%. From a productivity perspective, such cycle-time reduction can potentially increase production capacity where the shovel is a system bottleneck. However, a full mine-scale economic assessment would require additional cost and production records, including truck availability, crusher capacity, equipment dispatching, and actual costs of drilling, blasting, secondary breakage, and loading. Therefore, the present results provide practical evidence of productivity improvement, while detailed cost quantification should be addressed in future work.

C. Statistical Validation of Fragmentation Results

To further assess the reliability of the fragmentation analysis, a statistical comparison between observed field passing percentages and Split-Desktop-derived estimated passing percentages was performed. The relationship between observed and estimated passing percentages is shown in Fig. 5, while the significance of differences in fragmentation indices between the two blast configurations is summarized in Table 3, based on the independent two-sample t-test defined by Eq. (3). In addition, the mechanistic interpretation of the observed performance improvements is presented in Table 4.

The obtained R^2 values, calculated using Eq. (1), ranged from approximately 0.71 to 0.73, indicating moderate-to-good agreement between the Split-Desktop-derived estimates and the observed field passing percentages for field-scale blasting data. Most data points are located close to the 1:1 agreement line in Fig. 5, which supports the general reliability of the image-analysis estimation workflow. Nevertheless, the remaining scatter reflects the natural variability of production blasting. It indicates that the Split-Desktop-based estimates should not be interpreted as deterministic predictions for all rock-mass conditions. Furthermore, as interpreted in Table 4, the introduction of an air column improved stress-wave redistribution and crack propagation behavior, thereby contributing to the observed enhancement in fragmentation uniformity and reduction in coarse fragment generation.

D. Model Prediction Error

The estimation error of the Split-Desktop-based fragmentation workflow was further evaluated using the RMSE metric defined in Eq. (2). The RMSE values for conventional blasting, air-deck blasting, and the combined dataset are presented in Fig. 6. The RMSE values ranged from approximately 8.9% to 10.1%, indicating a moderate level of estimation error. The slightly lower RMSE obtained for the air-deck dataset suggests that the workflow reproduced the fragmentation results for this group with similar or slightly better accuracy than for the conventional blasting group. This level of error is considered acceptable for field fragmentation data, which are inherently affected by geological variability, image-analysis limitations, and operational heterogeneity.

Table 1. Average drilling and blasting parameters for conventional and air-deck blasting at the Gol-e-Gohar mine

Parameter	Iron ore		Waste rock (two drilling patterns)			
	Conventional	Air Deck	Conventional (Pattern I)	Air Deck (Pattern I)	Conventional (Pattern II)	Air Deck (Pattern II)
Average hole length (m)	16.8	15.5	14.8	14.0	17.5	16.5
Hole diameter (inch)	6.5	6.5	8.0	8.0	10.0	10.0
Burden (m)	5.0	5.0	6.5	6.5	7.5	7.5
Row spacing (m)	6.0	6.0	8.0	8.0	9.0	9.0
Stemming length (m)	6.0	5.0	5.0	4.0	6.0	5.5
Explosive column length (m)	10.8	9.3	9.8	8.8	11.5	9.8
Sub-drilling (m)	1.8	0.0	1.0	0.0	1.5	0.0
Air Deck length (m)	0.0	1.2	0.0	1.2	0.0	1.2
Number of blasts	3	3	2	2	2	2

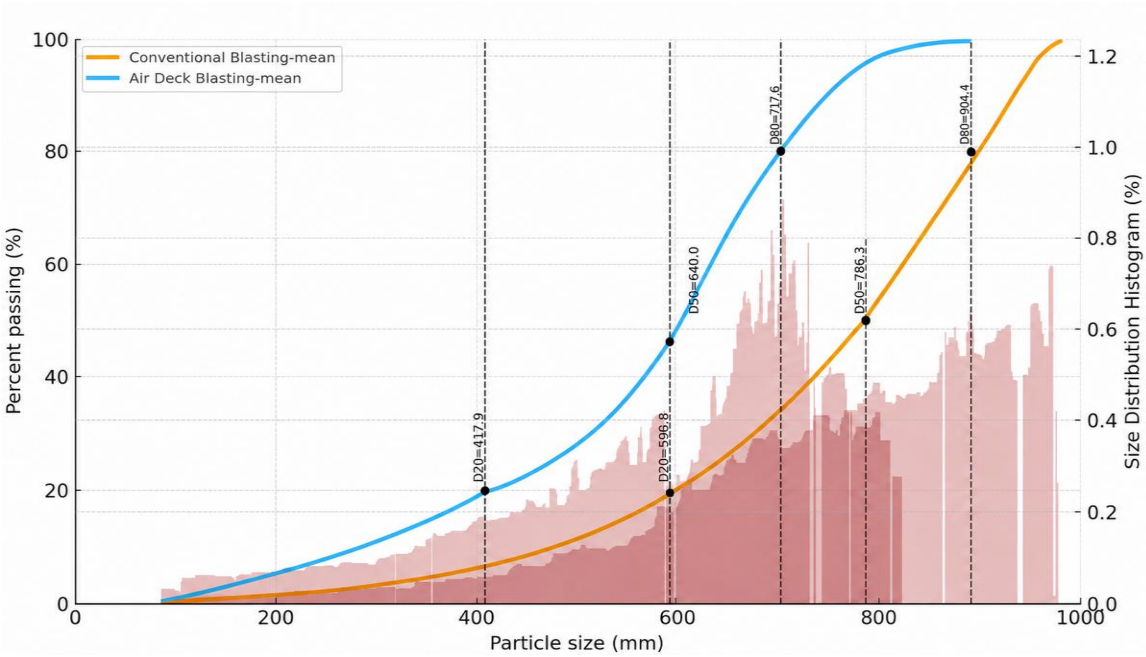

Fig. 4. Monotonic cumulative particle-size distribution curves for conventional blasting and air-deck blasting obtained from Split-Desktop image-based fragmentation analysis.

Table 2. Operational performance indicators for conventional blasting and air-deck blasting

Parameter	Conventional	Air Deck	Improvement (%)
D20 (mm)	596.8	417.9	−30.0
D50 (mm)	786.3	640.0	−18.6
D80 (mm)	904.4	717.6	−20.7
Specific charge (kg/m^3)	0.70	0.56	−20.0
Specific drilling (m/m^3)	0.48	0.44	−8.3
Hole productivity (t/hole)	100	109	+9.0
Oversize fragments (%)	14.2	9.9	−30.3

Table 3. Results of the independent two-sample t-test for fragmentation indices, calculated using Eq. (3). P-values are one-tailed, and CI values represent the 95% confidence interval for the mean difference between conventional and air-deck blasting

Mine	D20 (t, p, 95% CI)	D50 (t, p, 95% CI)	D80 (t, p, 95% CI)	Confidence Level
Gol-e-Gohar	t :2.8, p = 0.016 CI: 35-323 mm	t :2.3, p = 0.041 CI: 5-288 mm	t :2.1, p = 0.049 CI: 1-373 mm	95%

Table 4. Integrated statistical and technical interpretation of air-deck blasting performance across the studied mines

Mine	Technical Interpretation
Gol-e-Gohar	The introduction of an air column within the charge structure enhanced stress-wave reflection and energy redistribution toward the lower portion of the blasthole. This configuration reduced excessive localized crushing and promoted more effective tensile crack propagation, resulting in a measurable reduction in coarse fragment generation and improved fragmentation uniformity.

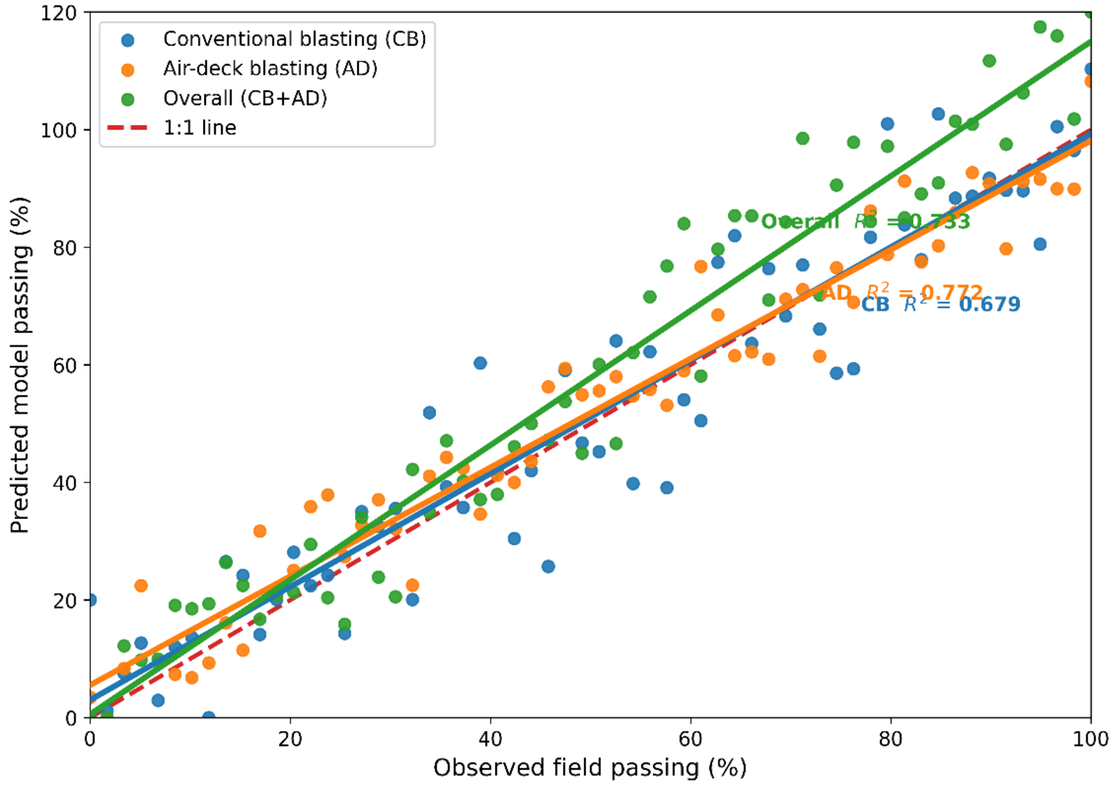

Fig. 5. Comparison between observed field passing percentages and Split-Desktop-derived estimated passing percentages for conventional blasting, air-deck blasting, and the combined dataset

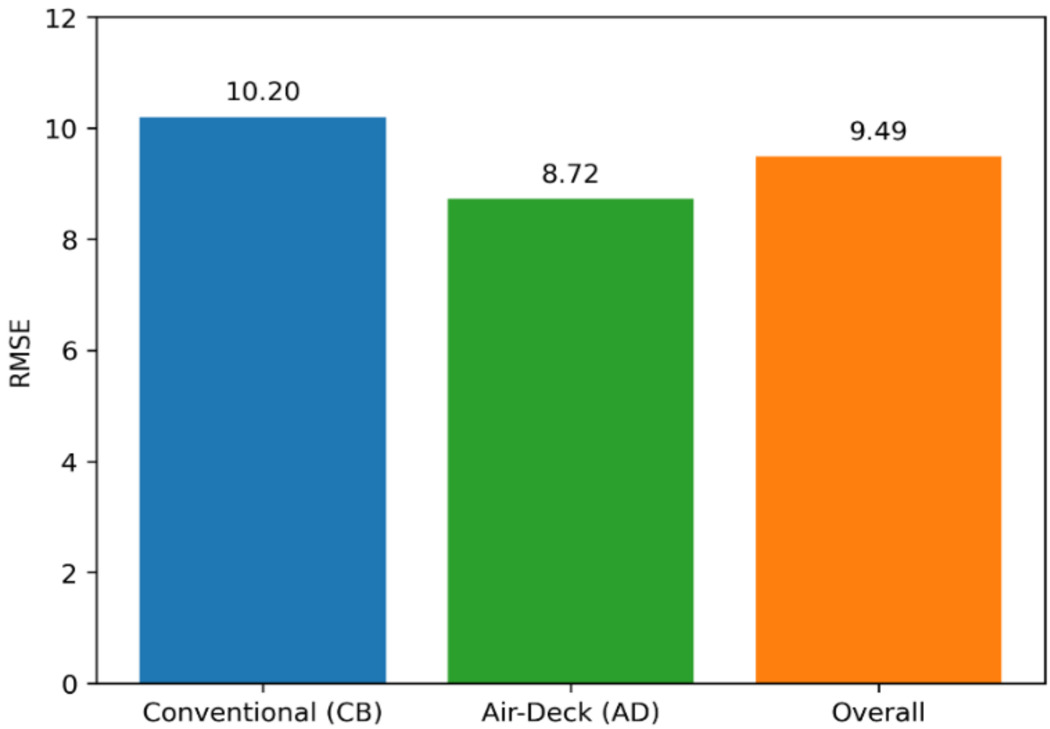

Fig. 6. RMSE values for the Split-Desktop-based fragmentation estimation workflow for conventional blasting (CB), air-deck blasting (AD), and the combined dataset

VI. CONCLUSION

This study investigated the performance of air-deck blasting under full-scale production conditions at the Gol-e-Gohar No. 1 open-pit iron ore mine in Sirjan, Iran. A total of 14 production blasts were analyzed using a paired comparative approach to compare conventional fully coupled blasting with air-deck blasting configurations. Rock fragmentation was assessed using image-based analysis, and the particle-size distribution indices D20, D50, and D80 were extracted from cumulative distribution curves. In addition, operational performance indicators and statistical validation were used to evaluate the effectiveness of the air-deck blasting technique.

The main findings can be summarized as follows:

Air-deck blasting significantly improved rock fragmentation quality compared with conventional blasting, as indicated by the leftward shift of the particle-size distribution curves.

The median fragment size (D50) decreased from approximately 786 mm to 640 mm, corresponding to a reduction of about 18.6%. Similarly, D20 decreased by approximately 30.0%, while D80 decreased by approximately 20.7%, indicating a finer and more uniform fragment-size distribution.

Operational performance indicators demonstrated improved blasting efficiency. Air-deck blasting reduced explosive consumption and the generation of oversize fragments while increasing hole productivity.

Statistical validation showed acceptable agreement between Split-Desktop-derived estimated passing percentages and observed field passing percentages. The coefficient of determination (R^2) ranged from 0.71 to 0.73, while RMSE values ranged from 8.9% to 10.1%, confirming the overall reliability of the image-based fragmentation analysis for the field dataset.

Overall, the results indicate that air-deck blasting can improve explosive energy utilization and enhance rock fragmentation under the production-scale conditions investigated in this study. The observed improvements in fragmentation quality and operational performance suggest that this technique can contribute to more efficient and economical drilling and blasting operations in large open-pit iron ore mines, provided that the air-deck geometry is verified and optimized for the specific rock mass and operational setting.

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