
Research article

Field-based performance evaluation of air-deck blasting in open-pit iron ore mines of Iran

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Abstract: Drilling and blasting operations directly influence fragmentation quality and downstream efficiency in open-pit mines. Air-deck blasting has been proposed as a charge-modification technique that may improve the spatial and temporal distribution of explosive energy within the blasthole. This study presents a field-scale comparative evaluation of conventional production designs and implemented bottom air-deck production designs under actual operating conditions in three Iranian open-pit iron ore mines: Gol-e-Gohar, Sadat-Siriz, and Smalon. A total of 36 production blasts were analyzed using a paired field-comparison framework. Fragmentation was quantified using image-based analysis and the D20, D50, and D80 indices, while powder factor, specific drilling, blasthole productivity, and mine-specific oversize fraction were also evaluated. Under the tested field conditions, the implemented bottom air-deck production designs were associated with finer image-based fragmentation, as indicated by leftward shifts of the cumulative particle-size distribution curves. The median fragment size, D50, decreased by approximately 19–33% across the studied mines. These changes were accompanied by approximately 20–22% reductions in powder factor, 8–10% reductions in specific drilling, and 9–11% increases in blasthole productivity. Paired statistical tests and linear mixed-effects models indicated statistically significant reductions in D20, D50, and D80 within the available paired dataset. However, because the trials were conducted under routine production conditions, some design parameters, including hole length, stemming length, explosive column length,

and subdrilling, varied between the conventional and bottom air-deck designs. Therefore, the results represent the combined field performance of the implemented bottom air-deck production designs rather than the isolated effect of the air column alone. The findings indicate favorable performance under the investigated conditions, while further controlled studies with detailed rock-mass characterization and mechanistic monitoring are required before broader generalization.

Keywords: air-deck blasting; rock fragmentation; open-pit mining; blast design optimization; image-based fragmentation analysis

1. Introduction

Drilling and blasting are fundamental operations in open-pit mining and strongly influence fragmentation quality, loading efficiency, haulage performance, and the energy demand of downstream crushing and grinding. A major challenge in production blasting is to improve the proportion of released explosive energy that contributes effectively to rock breakage while limiting undesirable effects such as ground vibration, air overpressure, flyrock, back-break, and excessive local crushing. Early production, presplit, underground, and tunneling applications of air decking reported potential improvements in fragmentation and explosive economy and, in some cases, reductions in blast-induced vibration [1–6]. Therefore, improving the distribution and utilization of explosive energy within the blasthole remains an important objective in blast design optimization.

Air-deck blasting is one of the charge-modification techniques proposed to improve explosive energy utilization. In this method, a deliberate air gap is introduced within or adjacent to the explosive column, thereby modifying the coupling condition, temporal loading history, and gas-pressure distribution along the blasthole. Mechanistic investigations have examined stress-wave interaction and borehole-pressure response in air-decked charges [7,8], while review and field-oriented studies have documented the sensitivity of performance to deck configuration and operating conditions [9,10]. Analytical and measurement-based studies further indicate that air decking can modify borehole-wall pressure and stress response [11,12]. Numerical and experimental investigations have shown that air-deck geometry and deck-charge structure can affect fragmentation [13–15], whereas other studies have reported effects on ground vibration, emulsion explosive performance, and detonation behavior [16–18]. Overall, the effectiveness of air-deck blasting is strongly design-sensitive and depends on factors such as air-deck length and position, charge distribution, stemming length, blasthole diameter, bench geometry, and rock-mass conditions.

Although air-deck blasting has been investigated through laboratory experiments, numerical simulations, analytical studies, and site-specific field trials, several practical uncertainties remain. Field applications have included integrated bottom air-deck designs aimed at reducing explosive consumption [19], top air-deck applications for collar-zone fragmentation and comparisons of alternative deck positions [20–22], and production-scale implementations addressing fragmentation, vibration, and charge configuration [23–27]. More recent field and operational studies have examined the combined influence of decking length, firing pattern, deck location, fragmentation response, and Power Deck implementation [28–31]. These studies show that blasting response is sensitive to air-deck position and length, stemming, explosive-column distribution, borehole geometry, initiation practice, and rock-mass conditions. However, many investigations remain site-specific or focus on a restricted

set of performance indicators. Multi-site production-scale comparisons that simultaneously assess fragmentation, drilling demand, explosive consumption, productivity, and oversize generation under actual operating conditions therefore remain limited.

Accordingly, the objective of this study is to conduct a multi-site field-scale comparison of paired conventional production designs and implemented bottom air-deck production designs at the Gol-e-Gohar, Sadat-Siriz, and Smalon open-pit iron ore mines. Fragmentation is evaluated using D20, D50, D80, and oversize fraction, while powder factor, specific drilling, and blasthole productivity are used as operational indicators. Because several production-design parameters were adjusted simultaneously, the results are interpreted as the combined performance of the implemented bottom air-deck production designs under the investigated conditions, rather than as the isolated effect of the air column alone.

2. Air-deck blasting technique: Mechanism and field implementation

Air-deck blasting is a charge-modification technique in which a deliberate air column is introduced within the blasthole to modify the spatial and temporal distribution of explosive energy. In conventional production blasting, the explosive column is commonly coupled with the blasthole over most of the charged length, and subdrilling may be used to improve toe breakage. In the present field trials, all implemented configurations were bottom air-decks, with the air column positioned at the bottom of the blasthole and air isolated using a deck separator or plug, while stemming was retained at the collar to provide confinement.

From a mechanistic perspective, previous studies have suggested that the impedance contrast at the explosive-air interface may influence stress-wave propagation and gas-pressure evolution. Stress waves generated by detonation propagate toward available free surfaces and may return as reflected tensile waves, which can contribute to crack initiation and propagation. In air-deck configurations, additional wave interaction may occur near the explosive-air interface, and the gas-pressure history within the blasthole may be redistributed. These mechanisms have been reported in the literature [32,33], but they were not directly measured in the present field trials.

Recent studies on blast-induced rock damage have further shown that fragmentation and crack development are controlled not only by charge configuration but also by the mechanical response of the rock. Wang et al. [34] numerically investigated tensile damage and blast-crater formation in brittle rock subjected to explosive loading and emphasized the importance of tensile failure in blast-induced fracture development. Wang et al. [35] compared the performance of different constitutive models in finite-element simulations of blast-induced rock cracks and showed that simulated crack patterns are sensitive to the adopted damage model and rock-mechanical parameters. More recently, Feng et al. [36] developed a thermo-mechanical damage constitutive model for deep rock considering brittleness-ductility transition characteristics. These studies collectively indicate that mechanistic interpretation of blasting performance requires careful consideration of rock strength, deformability, brittleness, and damage evolution.

Air-deck length and position are design-sensitive parameters. Although previous studies have often reported effective air-deck ratios of approximately 20–30% of the explosive column length or blasthole depth, the practically implemented ratios in production blasting depend on bench height, stemming requirement, blasthole diameter, explosive column length, rock-mass condition, and safety constraints. Therefore, the air-deck ratios used in the present study should be interpreted as conservative production-scale implementations rather than as a full optimization of air-deck length.

Figure 1 provides a simplified conceptual comparison between conventional and air-deck blasthole configurations. The arrows indicate possible stress-wave propagation toward the free face, reflected tensile-wave development at the free face, and possible interaction near the explosive-air interface. The schematic is intended to clarify the conceptual charge configuration and should not be interpreted as a direct measurement of pressure or wave propagation in the present field experiments.

3. Case studies: Iron ore mines of central Iran

This study was conducted at three major open-pit iron ore operations in southeastern and central Iran: Gol-e-Gohar No. 1, Sadat-Siriz, and Smalon mines. These sites were selected to represent varying geological, structural, and operational conditions while maintaining comparable large-scale production environments. The primary objective of selecting multiple sites was to evaluate the performance of air-deck blasting under diverse field conditions and to ensure the generalizability of the findings. A field-based comparative framework was implemented to assess conventional fully coupled blasting and air-deck blasting with respect to fragmentation quality, drilling and blasting efficiency, and operational productivity. The geographical locations of the studied mines are illustrated in Figure 2.

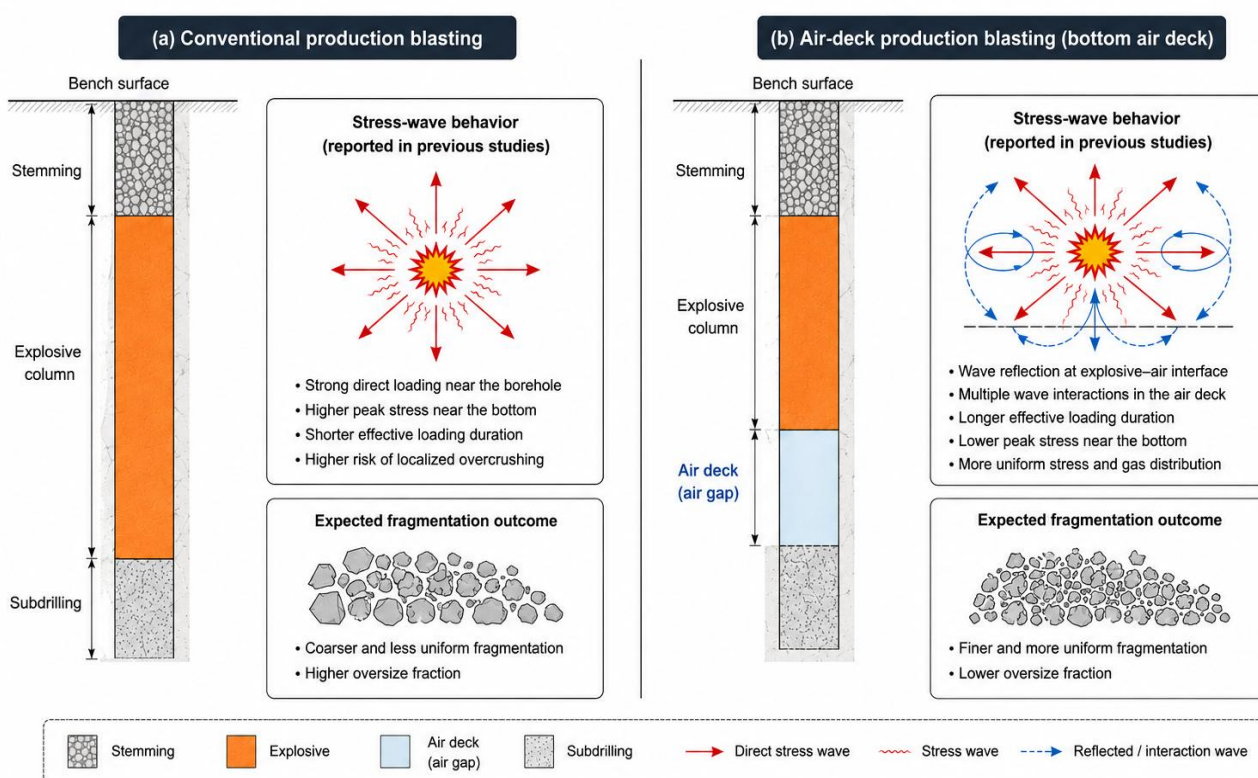


Figure 1. Conceptual comparison between conventional and air-deck production blasting designs. The schematic illustrates the main charge-configuration differences and possible stress-wave/gas-pressure redistribution mechanisms reported in previous studies. The arrows are conceptual and do not represent direct borehole pressure or stress-wave measurements from the present field trial.

3.1. *Gol-e-gohar iron ore mine No. 1*

The Gol-e-Gohar mining district is located within the Sanandaj–Sirjan metamorphic belt in southeastern Iran and is structurally influenced by major regional tectonic systems, including the Dehshir Baft fault and the Zagros thrust zone. The district contains six iron ore deposits distributed over an area approximately 10 km in length and 4 km in width, with total geological reserves exceeding 1.2 billion tons. The No. 1 deposit, selected for this study, is situated approximately 235 km southwest of Kerman. The orebody is hosted within metamorphic sequences consisting primarily of mica-schist, amphibolite, quartz schist, marble, and dolomitic units of Paleozoic age. The economically recoverable reserve is approximately 280 million tons. The final pit is approximately 4,500 m long and 1,600 m wide, comprising 41 benches with a standard bench height of 15 m. Drilling patterns vary depending on material type. For waste rock, typical burden and spacing configurations range between 8×6.5 m and 9×7 m, using 8-inch and 10-inch diameter holes. Ore benches are typically drilled using 6-inch diameter holes with a 5×4 m pattern. ANFO is used in dry holes, while water-resistant emulsions are employed in wet conditions. Initiation systems include CORTEX detonating cord and Nonel delay detonators.

3.2. *Sadat-siriz iron ore mine*

The Sadat-Siriz deposit is located northwest of Kerman within the Kashmar tectonic domain of Central Iran. The mineralization is primarily associated with Neoproterozoic to Lower Paleozoic carbonate host rocks and is characterized by hydrothermal magnetite mineralization accompanied by minor sulfide phases. The estimated reserve is approximately 32 million tons with an average iron grade of approximately 52%. The final pit dimensions are approximately 1,570 m in length and 870 m in width, with an ultimate depth of about 580 m. Bench heights are typically 10 m, and more than 40 benches are currently being developed. Drilling parameters differ for ore and waste zones. Waste benches are typically drilled using 6-inch diameter holes in a 4.5×4 m pattern, while ore benches utilize 4-inch diameter holes with a 4×3 m pattern. A row-to-row delay interval of approximately 50 ms is applied. ANFO and ammonalite are used as primary explosives, with 1–2 lb boosters for initiation. The relatively closer drilling pattern at Sadat-Siriz provides a useful comparative case for assessing air-deck performance under higher powder factor conditions.

3.3. *Smalon iron ore mine*

The Smalon deposit is located at the structural boundary between the Central Iran zone and the Sanandaj–Sirjan belt. The deposit is influenced by regional tectonic structures, including the Dehshir fault system. Host rocks consist mainly of granitoid intrusions and carbonate formations, with magnetite as the dominant iron mineral. Mining operations are conducted across three active zones: Smalon-1, Smalon-2, and Smalon-3. The eastern pit, which forms the basis of this study, measures approximately 597 m in length and 400 m in width, with bench heights ranging between 8 and 15 m. Drilling diameters range between 4.5 and 6.5 inches. Typical drilling patterns are 4.5×5.5 m for waste material and 3.5×4.5 m for ore benches. ANFO is used as the primary explosive, with initiation provided through CORTEX and Nonel systems. Compared with the other two mines, Smalon presents denser drilling patterns and relatively variable ore grades, offering an additional operational scenario for evaluating the adaptability and robustness of the air-deck blasting technique.

3.4. Representative rock-mechanical properties

Representative mechanical properties of the principal ore and waste-rock units were obtained from laboratory testing records of the respective mines and are summarized in Table 1. These values support comparison of the broad mechanical contrast among the investigated materials; however, they are mine-scale representative properties rather than measurements from every individual blast block.

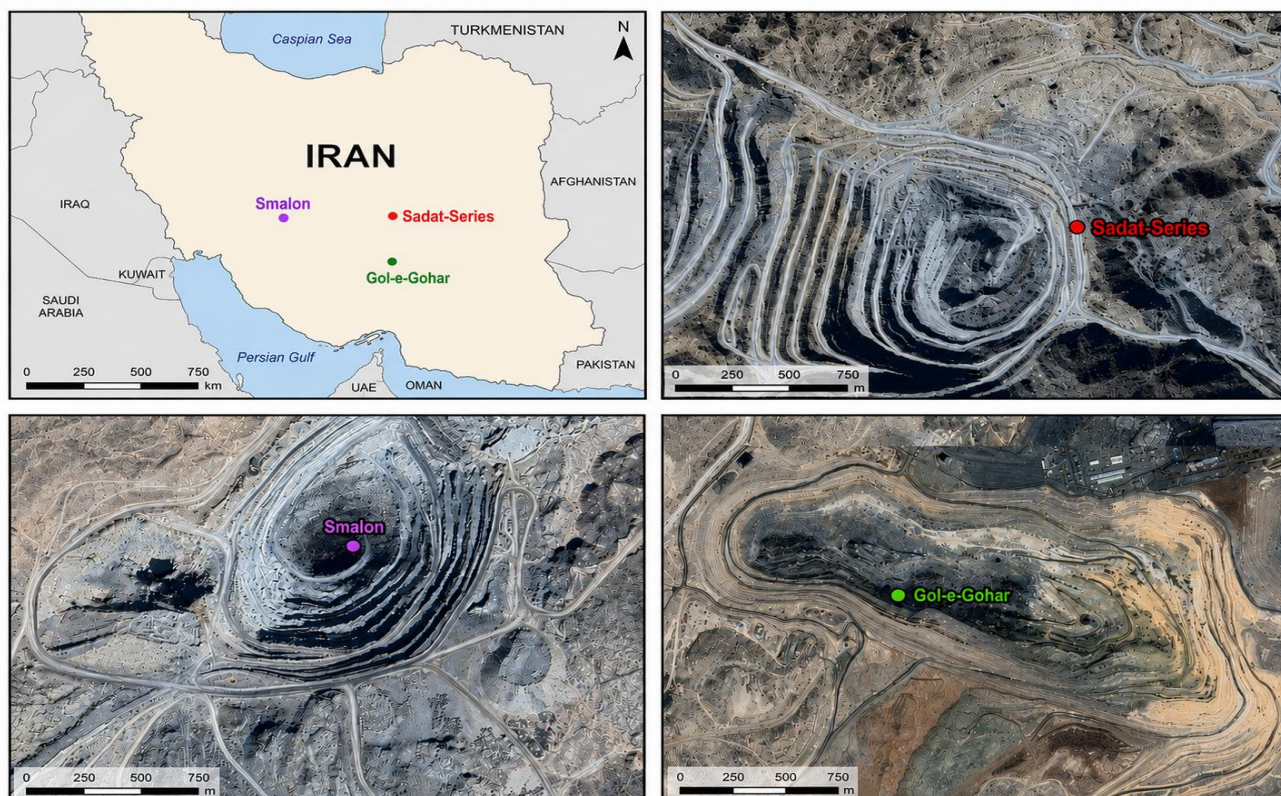


Figure 2. Geographical location and spatial distribution of the studied mines.

Table 1. Representative laboratory-measured mechanical properties of the principal rock units at the investigated mines.

Mine	Rock unit	Density (kg/m ³)	Young's modulus (GPa)	Poisson's ratio	UCS (MPa)	Tensile strength (MPa)
Gol-e-Gohar	Iron ore	4500	32.1	0.33	120.0	11.79
Gol-e-Gohar	Alluvial waste	1880	1.5	0.15	20.0	3.50
Gol-e-Gohar	Competent waste	2850	3.0	0.26	68.0	6.81
Sadat-Siriz	Iron ore	3420	15.17	0.32	120.0	12.70
Sadat-Siriz	Waste rock	2740	11.19	0.36	35.3	4.80
Smalton	Iron ore	3100	28.75	0.33	112.8	11.86
Smalton	Waste rock	2520	15.14	0.36	52.2	5.47

Values were obtained from laboratory testing records of the respective mines and represent typical properties of the principal ore and waste-rock units. They should not be interpreted as blast-block-specific measurements for every production blast. Detailed joint and discontinuity data were not consistently available for all investigated blast blocks.

4. Materials and methods

4.1. Study sites and experimental design

This investigation was conducted under full-scale production conditions at three open-pit iron ore mines in Iran: Gol-e-Gohar, Sadat-Siriz, and Smalon. The objective was to compare the field performance of conventional production blasting and air-deck production blasting in terms of fragmentation quality, explosive consumption, drilling requirements, and blast-hole productivity. A total of 36 production blasts were analyzed, including 14 blasts at Gol-e-Gohar, 12 at Sadat-Siriz, and 10 at Smalon. At each mine, each conventional blast was paired with a bottom air-deck conducted on the same bench and in an adjacent production block. The paired blasts were selected to have comparable lithology; the same material class (ore-to-ore or waste-to-waste); similar boundary conditions; close execution dates; and the same nominal borehole diameter, burden, and spacing. These criteria reduced geological and operational variability as far as practicable. Nevertheless, the trials were not fully isolated single-variable experiments. In the implemented bottom air-deck production designs, subdrilling was eliminated and hole length, stemming length, and explosive-column length were adjusted. Consequently, the comparisons represent the combined field performance of the implemented production designs rather than the isolated effect of the air column alone.

4.2. Drilling and charging parameters

Detailed drilling and blasting parameters for each mine are summarized in Tables 2–4. Both ore and waste benches were included to capture variability in field operating conditions. The recorded parameters included average hole length, hole diameter, burden, spacing, stemming length, explosive column length, subdrilling, and air-deck length. In all implemented bottom air-deck production designs, the air column was positioned at the bottom of the blasthole. Subdrilling was eliminated and replaced by a controlled bottom air column according to the operational design adopted at each mine. The ratio of air-deck length to explosive column length ranged from approximately 12% to 20%. This range represents a conservative field implementation selected in relation to bench height, stemming requirement, hole diameter, explosive-column length, safety, and production stability; it should not be interpreted as a universal optimum.

Table 2. Average drilling and blasting parameters at Gol-e-Gohar mine.

Parameter	Iron ore		Waste			
	Conventional	Air deck	Conventional	Air deck	Conventional	Air deck
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

Table 3. Average drilling and blasting parameters at Sadat-Siriz mine.

Parameter	Iron ore		Waste	
	Conventional	Air deck	Conventional	Air deck
Average hole length (m)	11.0	10.0	13.0	12.0
Hole diameter (inch)	4.0	4.0	6.0	6.0
Burden (m)	3.0	3.0	4.0	4.0
Row spacing (m)	4.0	4.0	4.5	4.5
Stemming length (m)	3.0	2.5	3.5	3.0
Explosive column length (m)	8.0	6.6	9.5	8.1
Sub-drilling (m)	1.0	0.0	1.0	0.0
Air deck length (m)	0.0	0.9	0.0	0.9
Number of blasts	3	3	3	3

Table 4. Average drilling and blasting parameters at Smalon mine.

Parameter	Iron ore		Waste	
	Conventional	Air deck	Conventional	Air deck
Average hole length (m)	11.5	10.0	14.0	12.5
Hole diameter (inch)	4.5	4.5	6.5	6.5
Burden (m)	3.5	3.5	4.5	4.5
Row spacing (m)	4.5	4.5	5.5	5.5
Stemming length (m)	3.5	3.0	4.0	3.5
Explosive column length (m)	8.0	6.0	10.0	8.0
Sub-drilling (m)	1.5	0.0	1.5	0.0
Air deck length (m)	0.0	1.0	0.0	1.0
Number of blasts	3	3	2	2

Because the field trials were conducted under routine mine-production conditions, the paired comparisons were not designed as fully isolated single-variable experiments. Several design parameters were necessarily adjusted together with the introduction of the bottom air deck to satisfy operational, safety, and productivity requirements. To improve methodological transparency and avoid over-attribution of the observed changes to the air column alone, Table 5 summarizes the control status of the main blast-design variables and clarifies their implications for interpreting the results.

Accordingly, the statistical comparisons presented in this study should be interpreted as evidence of performance differences between implementable conventional and air-deck production blasting designs under the investigated field conditions. They should not be interpreted as a complete decoupling of the isolated effect of the air column from other simultaneously adjusted production-design variables.

Table 5. Control status and interpretive implications of the principal geological and blast-design variables.

Variable group	Parameter	Status in paired comparison	Relevance to blasting response	Implication for interpretation
Site-level condition	Mine site	Controlled	Controls the broad geological, operational, and equipment-related setting.	Comparisons were primarily made within the same mine to reduce site-level variability.
Local rock-mass condition	Bench/block lithology and structure	Approximately controlled	Influences fragmentation, toe breakage, muckpile looseness, and size distribution.	Blocks were selected under broadly comparable lithological and structural conditions; however, complete rock-mass covariates were not available for all production blasts.
Blast pattern	Burden and spacing	Mostly controlled	Strongly affects energy distribution, burden movement, and fragmentation uniformity.	Nominal burden and spacing were kept similar within each mine as far as operationally feasible.
Explosive system	Explosive type	Mostly controlled	Influences detonation energy, gas volume, water resistance, and fragmentation.	ANFO or emulsion explosives were used according to mine-specific field conditions, especially water presence.
Initiation design	Initiation system and delay practice	Mostly controlled	Affects inter-hole interaction, burden movement, vibration, and muckpile formation.	Comparable mine-specific initiation systems and delay practices were used during production blasts.
Borehole geometry	Hole diameter	Controlled / mostly controlled	Affects charge diameter, coupling condition, and energy concentration.	Hole diameter was kept the same within each paired comparison or within each mine-specific design class.
Borehole geometry	Hole length	Changed	Influences charge length, drilled volume, toe condition, and specific drilling.	Hole length was generally reduced in the air-deck production designs; therefore, its contribution cannot be completely separated from the air-deck design effect.
Confinement condition	Stemming length	Changed	Controls collar confinement, gas retention, flyrock risk, and collar-zone fragmentation.	Stemming length was adjusted according to the air-deck configuration and production requirements.
Charge distribution	Explosive column length	Changed	Directly affects explosive quantity, powder factor, energy distribution, and fragmentation.	Explosive column length was reduced in the air-deck production designs; therefore, the observed response reflects a modified charge-distribution design.

Continued on next page

Variable group	Parameter	Status in paired comparison	Relevance to blasting response	Implication for interpretation
Toe-control condition	Subdrilling	Changed	Influences toe breakage, floor condition, and stress distribution near the bench bottom.	Subdrilling was eliminated in the air-deck production designs; its effect may be coupled with the air-deck configuration and cannot be fully decoupled using the available field dataset.
Treatment variable	Air-deck length and position	Introduced only in air-deck design	Modifies charge configuration and may influence stress-wave interaction and gas-pressure redistribution.	The introduced air column is the defining feature of the air-deck production design; however, the results are interpreted as the combined performance of the implemented air-deck production design, not as the isolated effect of the air column alone.

4.3. Field data collection procedure

All blasting activities were supervised by certified blasting engineers to ensure compliance with operational safety standards and consistency in data recording.

4.3.1. Selection of test blocks

At each mine, matched conventional and bottom air-deck test blocks were selected on the same bench and in adjacent production blocks. Each pair had comparable lithology, the same material class (ore-to-ore or waste-to-waste), close execution dates, and the same nominal hole diameter, burden, and spacing. These criteria were used to minimize geological and operational bias under production conditions. However, hole length, explosive-column length, stemming length, and subdrilling changed as components of the implemented bottom air-deck production designs. The comparison therefore represents the performance of the complete implemented production design relative to the conventional design rather than the isolated effect of the air column alone.

4.3.2. Recording of blast geometry and charge configuration

For each blast, detailed geometric and charging parameters were documented using standardized field sheets. These data were later used to calculate powder factor, specific drilling, and air-deck ratio.

4.3.3. Post-blast fragmentation imaging

Following each blast, 10–15 high-resolution images were captured during loading operations from multiple viewing angles. A calibrated 20 cm reference sphere was placed within the field of view to ensure accurate image scaling. This procedure reduced scaling bias and improved reliability in subsequent image-based fragmentation analysis.

4.3.4. Operational performance indicators

The following quantitative performance indicators were calculated: (i) powder factor (kg/m^3), (ii) specific drilling (m/m^3), (iii) blast-hole productivity (t/hole), and (iv) oversize fraction (%). These metrics enabled integrated technical and economic performance evaluation.

4.3.5. Fragmentation analysis

All images were processed using Split Desktop software. D20, D50, and D80 were selected to characterize the lower, central, and upper portions of the cumulative image-based particle-size distribution. D20 is the fragment size corresponding to 20% passing and represents the finer portion of the distribution; D50 is the median fragment size; and D80 is the fragment size corresponding to 80% passing and characterizes the relatively coarse portion. Oversize fraction was evaluated separately using the operational size threshold adopted at each mine. Fragments larger than 1200 mm at Gol-e-Gohar, 1000 mm at Sadat-Siriz, and 800 mm at Smalou were classified as oversize. Unlike D80, which is a percentile of the cumulative distribution, oversize fraction represents the percentage of fragments exceeding a predefined mine-specific operational limit. Cumulative particle-size distribution curves were generated for each blast, and the image-acquisition, scaling, segmentation, and uncertainty-control procedures are described in Section 4.3.6.

4.3.6. Image-analysis procedure and uncertainty control

The Split Desktop workflow was expanded and clarified to improve transparency in the image-based fragmentation analysis. For each production blast, 10–15 images were captured from different positions around the muckpile during loading. Images were selected to represent the visible size distribution as broadly as possible while avoiding strongly shadowed areas, excessive dust, blurred images, and photographs in which the scale object was not clearly visible. A calibrated 20 cm reference sphere was placed in the field of view and used for image scaling before particle-size extraction.

Representative raw muckpile images used for the fragmentation analysis are shown together with the cumulative fragmentation curves in Figures 3–5. These images document the field image-acquisition procedure, the use of calibrated reference objects for scale control, and the variability of production-scale imaging conditions during Split Desktop processing.

Image processing was carried out using a semi-automatic procedure. After scaling, particle boundaries generated by the software were visually checked, and clear segmentation errors around large fragments were manually corrected where necessary. Images with excessive overlap, insufficient contrast, or unreliable scaling were excluded from the final analysis. The D20, D50, and D80 values reported for each blast were obtained from the cumulative particle-size distribution generated from the accepted image set.

The Split Desktop results do not constitute a complete reconstruction of three-dimensional particle geometry; they are two-dimensional image-based estimates of the visible muckpile surface. Particle overlap, partial burial of fragments, lighting conditions, camera angle, image resolution, limited visibility of fine particles, and manual boundary correction may influence the estimated particle-size distribution. Fine material may be underestimated because very small particles can be hidden between larger fragments or fall below the effective image-resolution limit. Accordingly, the

reported D20, D50, D80, and oversize values should be interpreted as image-based estimates rather than direct three-dimensional measurements or mechanical sieve measurements.

Mechanical sieving was not feasible under full-scale production conditions because of the large muckpile volumes and operational constraints at the mines. To reduce uncertainty, the same imaging protocol, scaling approach, and processing procedure were applied consistently to both conventional and air-deck blasts within each paired comparison. Nevertheless, the absence of sieve validation is acknowledged as a limitation of the present field study, and future work should include calibration of image-based results against physical sieving or three-dimensional fragmentation measurement where operationally possible.

4.4. Statistical analysis and validation

To evaluate the statistical significance of observed fragmentation differences, a two-stage statistical framework was adopted. All statistical analyses were performed using R software (version 4.x.x). The significance level was set at $\alpha = 0.05$. Before hypothesis testing: (i) Normality was evaluated using the Shapiro–Wilk test, (ii) Homogeneity of variances was assessed using Levene’s test.

4.4.1. Two-sample t-test

A paired-sample t-test was used to compare the fragmentation indices between matched conventional and air-deck blasting observations under comparable field conditions. The paired design reduces the influence of local geological and operational variability by evaluating the within-pair difference for each fragmentation index. The test statistic is expressed as follows, in Eq (1):

$$t = \frac{\bar{d}}{\frac{sd}{\sqrt{n}}} \quad (1)$$

where $\bar{d}$ is the mean paired difference between conventional and air-deck blasting, sd is the standard deviation of the paired differences, and n is the number of matched blast pairs. The null hypothesis (H_0) assumed that the mean paired difference was zero. Statistical significance was accepted when $p < 0.05$.

4.4.2. Linear mixed-effects regression model

To account for the paired field design and the hierarchical structure of the dataset, linear mixed-effects regression models were fitted to the combined fragmentation dataset. Separate models were developed for D20, D50, and D80. In each model, the blasting method was considered as the fixed effect, while the matched blast pair, nested within the mine site, was treated as a random intercept. This structure allowed the effect of air-deck blasting to be estimated while accounting for the non-independence of paired conventional and air-deck blasts conducted under comparable field conditions.

The model was formulated as follows, in Eq (2):

$$Y_{ijk} = \beta_0 + \beta_1 \text{Method}_{ijk} + u_k + u_{j(k)} + \epsilon_{ijk} \quad (2)$$

Where:

fragmentation index (D20, D50, or D80): Y_{ijk}

blast observation within each paired blast set: i

paired blast set: j

mine site: k

binary variable (0 = conventional blasting, 1 = air-deck blasting): $Method_{ijk}$

intercept / baseline fragmentation for conventional blasting: β_0

fixed effect of air-deck blasting relative to conventional blasting: β_1

random effect for matched blast pair jjj nested within mine site k : $u_{j(k)}$

residual error: ϵ_{ijk}

Model performance was evaluated using:

Marginal and conditional: R^2

Akaike information criterion: AIC

95% confidence intervals for: β_1

A negative and statistically significant β_1 ($p < 0.05$) indicates lower image-based fragment sizes for the implemented bottom air-deck production-design category than for the conventional category within the paired dataset. It should not be interpreted as the isolated causal effect of the air column because other production-design variables also changed.

5. Results and discussion

5.1. Overall fragmentation and operational trends

Across all three mines, the implemented bottom air-deck production designs were associated with improved image-based fragmentation quality relative to the corresponding conventional production designs. This improvement is evident from the cumulative particle-size distribution curves in Figures 3–5, where the air-deck curves generally show a leftward shift, indicating a higher passing percentage at a given fragment size. In practical terms, the air-deck production designs produced finer and more uniform image-based size distributions under the tested field conditions.

In addition to fragmentation refinement, the air-deck production designs were associated with reduced explosive consumption, lower specific drilling, improved blasthole productivity, and reduced oversize fraction. These changes suggest improved operational performance under the investigated production-scale conditions. However, because the tests were conducted during routine mine production, the observed improvements should not be interpreted as the isolated effect of the air column alone. Some design parameters, including hole length, stemming length, explosive column length, and subdrilling, changed simultaneously with the introduction of the air deck.

Although similar trends were observed across the three studied mines, these results should be interpreted within the limits of the available production-scale dataset. The findings suggest the potential applicability of the implemented bottom air-deck production designs under the investigated field conditions; however, broader generalization requires further controlled studies with detailed rock-mass characterization and mechanistic monitoring.

5.2. Gol-e-gohar mine

At Gol-e-Gohar, the implemented bottom air-deck production design was associated with finer image-based fragmentation, as indicated by the cumulative size distribution in Figure 3. The air-deck

curve remains left-shifted compared with conventional blasting, indicating a higher proportion of fine and intermediate-size fragments and a corresponding reduction in coarse fragments. Operational indicators also showed simultaneous improvements, including reduced explosive consumption and drilling requirement, together with higher blasthole productivity, as summarized in Table 6.

These outcomes may be consistent with more efficient explosive-energy distribution in the implemented bottom air-deck production design, as suggested by previous air-deck studies. However, because borehole pressure, stress-wave propagation, and crack development were not directly measured in the present trials, this interpretation should be regarded as a plausible literature-based explanation rather than direct mechanistic evidence. From an operational standpoint, the observed fragmentation improvement may contribute to smoother loading, reduced crusher interruptions, and lower secondary breakage demand, although these downstream effects were evaluated indirectly through operational indicators rather than through a complete production-system cost analysis.

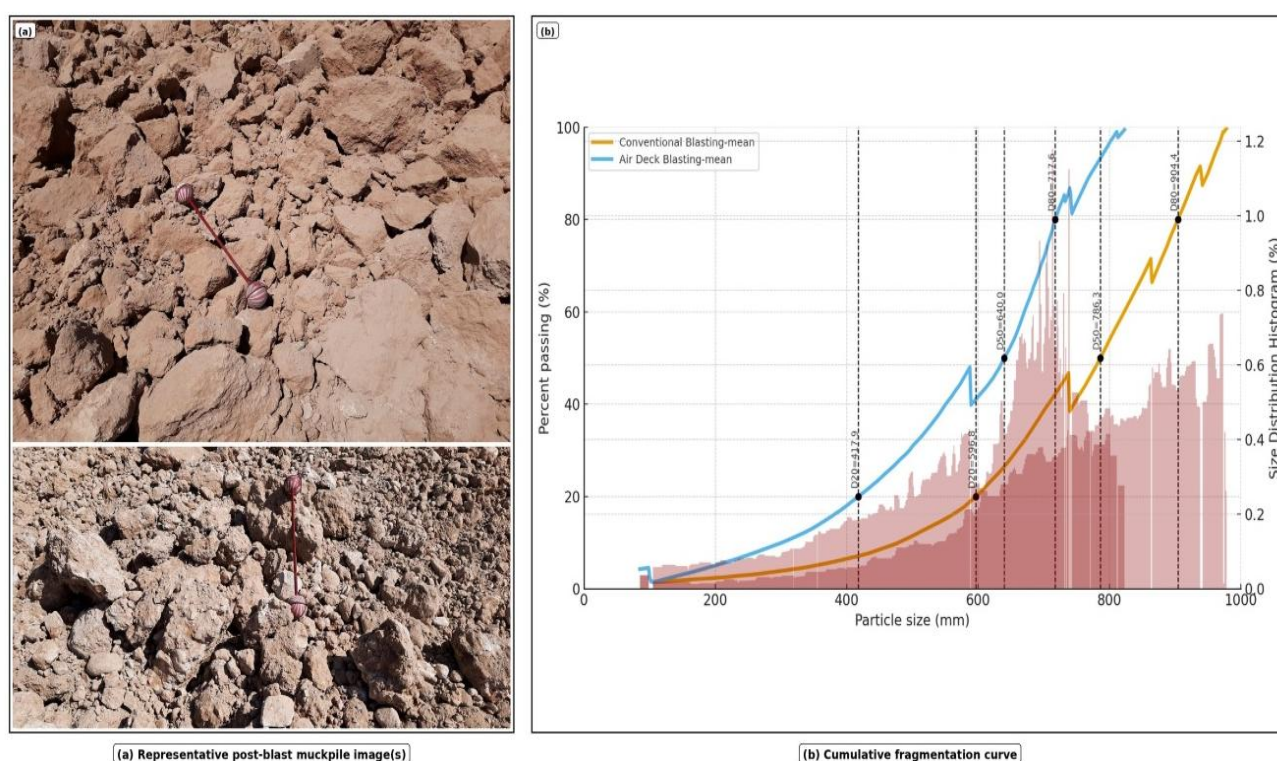


Figure 3. Representative post-blast muckpile images and cumulative particle-size distribution curves comparing air-deck and conventional production blasting at the Gol-e-Gohar mine.

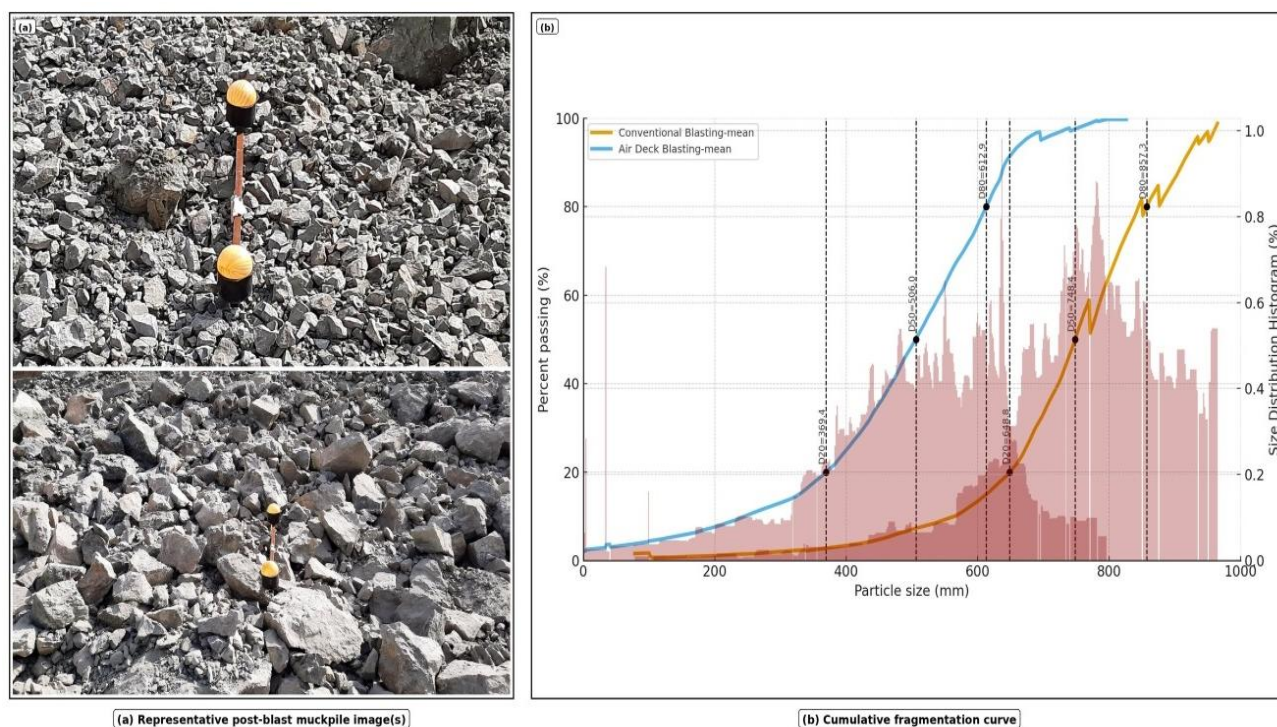


Figure 4. Representative post-blast muckpile images and cumulative particle-size distribution curves comparing air-deck and conventional production blasting at the Sadat-Siriz mine.

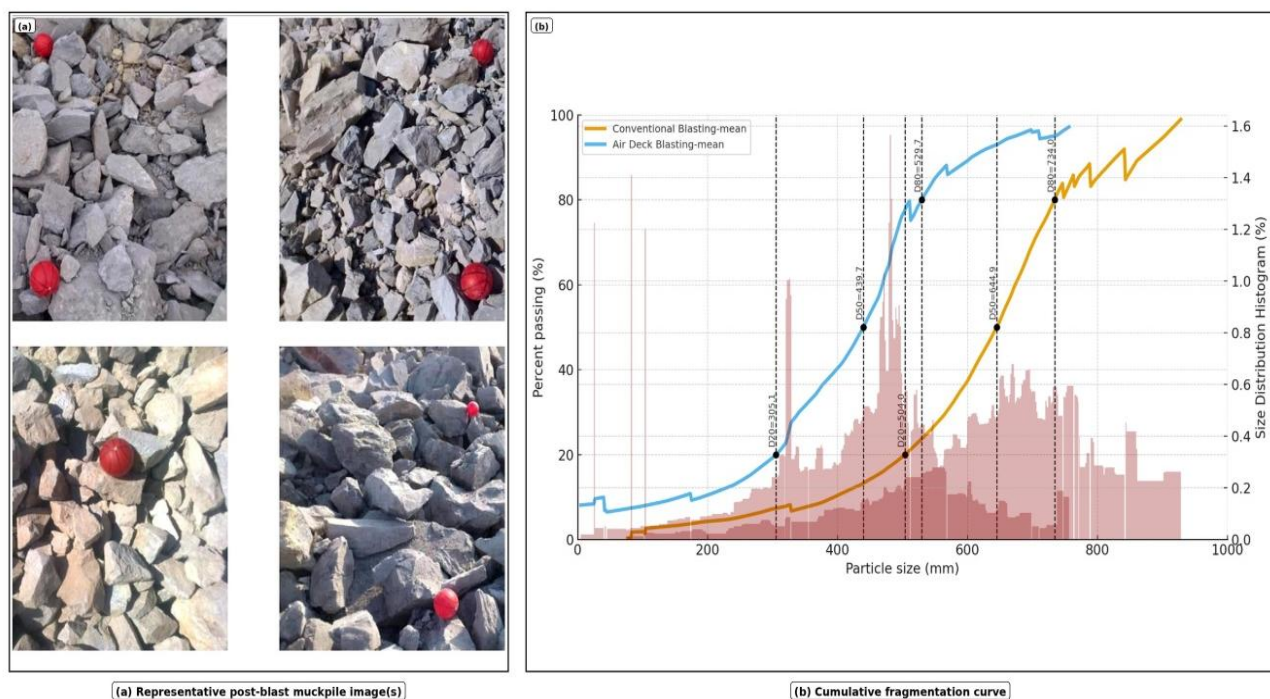


Figure 5. Representative post-blast muckpile images and cumulative particle-size distribution curves comparing air-deck and conventional production blasting at the Smalon mine.

Table 6. Comparison of blasting performance between conventional and Air-Deck techniques at the Gol-e-Gohar mine.

Parameter	Conventional	Air deck	Improvement (%)
D20 (mm)	596.8	417.9	−30.3
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

Oversize fraction refers to fragments larger than 1200 mm.

5.3. Sadat-Siriz mine

Sadat-Siriz exhibited the largest image-based fragmentation improvement among the three mines. As illustrated in Figure 4, the implemented bottom air-deck production design generated a pronounced leftward shift in the cumulative distribution curve, indicating substantial refinement of the size distribution and improved uniformity. The drilling geometry at Sadat-Siriz is relatively dense compared with the other sites, which may have contributed to improved confinement and energy distribution under the tested conditions. Improvements were also observed in key operational indicators, as summarized in Table 7, suggesting that the implemented bottom air-deck production design improved overall blasting performance without compromising production requirements.

Table 7. Comparison of blasting performance between conventional and Air-Deck techniques at the Sadat-Siriz mine.

Parameter	Conventional	Air deck	Improvement (%)
D20 (mm)	648.8	369.4	−43.1
D50 (mm)	748.4	506.0	−32.4
D80 (mm)	857.3	612.9	−28.5
Specific charge (kg/m ³)	0.85	0.66	−22.4
Specific drilling (m/m ³)	0.54	0.49	−9.3
Hole productivity (t/hole)	92	102	+10.9
Oversize fragments (%)	18.6	12.9	−30.6

Oversize fraction refers to fragments larger than 1000 mm.

The observed fragmentation improvement may be consistent with mechanisms reported in previous air-deck studies, including modified stress-wave interaction and gas-pressure redistribution. Nevertheless, these mechanisms were not directly measured in the present field trials and should therefore be interpreted cautiously. Field observations, such as muckpile looseness and improved shovel digging conditions, qualitatively support the quantitative trends, but these observations were not used as independent mechanistic measurements.

5.4. Smalon mine

At Smalon, the implemented bottom air-deck production design was also associated with finer image-based fragmentation, as shown by the left-shifted cumulative curves in Figure 5. Compared with conventional blasting, the air-deck configuration reduced characteristic fragment sizes and improved distribution uniformity, indicating more effective breakage of coarse fragments under the tested production conditions. Operational performance followed a similar pattern to the other sites, with reductions in specific charge and specific drilling and an increase in blasthole productivity, as summarized in Table 8. These combined outcomes indicate that the implemented bottom air-deck production design improved both fragmentation performance and operational efficiency within the available field dataset.

The observed results may be consistent with more efficient spatial utilization of explosive energy, as reported in previous air-deck studies. However, this interpretation should be treated cautiously because borehole pressure, vibration response, and crack propagation were not directly measured in the present study. In addition, the air-deck production designs involved simultaneous changes in explosive column length, stemming length, and subdrilling. Therefore, the results are best interpreted as the combined response of the implemented bottom air-deck production design rather than as the isolated effect of the air column alone.

Since borehole pressure, vibration response, and crack propagation were not directly measured in this study, the following discussion should be interpreted as a literature-based explanation of possible mechanisms rather than as direct mechanistic evidence obtained from the present field trials. The observed improvements in fragmentation are therefore discussed as being consistent with mechanisms reported in previous air-deck and blast-damage studies, not as proof of a uniquely measured stress-wave or gas-pressure process in the tested blasts.

Previous studies have suggested that the impedance contrast at the explosive-air interface may partially reflect stress waves and modify the loading history acting on the borehole wall. In an air-decked blasthole, this process may contribute to a staged loading-unloading response and a longer duration of tensile stress around the charge column. Such a response can promote crack initiation and propagation while reducing excessive localized crushing close to the explosive column. Under the present field conditions, the reduction in D20, D50, D80, and oversize fraction is compatible with this interpretation, but the contribution of this mechanism cannot be separated from other design changes without direct monitoring or numerical modelling.

From an operational perspective, the simultaneous reduction in powder factor and improvement in fragmentation may indicate more efficient spatial utilization of explosive energy in the implemented bottom air-deck production designs. However, this result should be interpreted cautiously because the air-deck designs also involved changes in explosive column length, stemming length, and subdrilling. In particular, the elimination of subdrilling may have influenced the stress distribution near the bench floor and may have interacted with the air-deck effect. Therefore, the present results are best interpreted as the combined response of the implemented bottom air-deck production design rather than the isolated effect of the air column alone.

The variability in the magnitude of improvement among Gol-e-Gohar, Sadat-Siriz, and Smalon further indicates that air-deck blasting is design-sensitive and strongly affected by site conditions. Rock strength, discontinuity spacing, joint orientation, confinement, drilling geometry, and charge placement can all influence the observed fragmentation response. Accordingly, the mechanisms

discussed here are plausible explanations supported by the literature, while future work should include borehole pressure monitoring, vibration measurements, crack mapping, and numerical simulations to verify the dominant mechanism under each mine condition.

Table 8. Comparison of blasting performance between conventional and Air-Deck techniques at the Smalon mine.

Parameter	Conventional	Air deck	Improvement (%)
D20 (mm)	504.0	305.1	−39.5
D50 (mm)	644.9	439.7	−31.8
D80 (mm)	734.0	529.7	−28.8
Specific charge (kg/m ³)	0.78	0.62	−20.5
Specific drilling (m/m ³)	0.51	0.46	−9.8
Hole productivity (t/hole)	94	102	+8.5
Oversize fragments (%)	15.4	10.9	−29.2

Oversize fraction refers to fragments larger than 800 mm.

The field results should be interpreted in the context of the complete implemented bottom air-deck production design. The reduction in explosive-column length directly contributed to the lower powder factor, while the reduced hole length contributed to lower specific drilling. The modification of stemming length may have affected collar confinement and gas retention, and elimination of subdrilling may have influenced toe breakage and stress development near the bench floor. These variables may have interacted with the bottom air deck and cannot be independently decoupled using the available production dataset. Similar coupled design modifications have been reported in previous bottom air-deck and power-deck field applications, although the magnitude of fragmentation and operational improvement has varied among sites. This variability supports a site- and design-dependent interpretation.

5.5. Literature-based interpretation of possible mechanisms

Since borehole pressure, vibration response, and crack propagation were not directly measured in this study, the following discussion should be interpreted as a literature-based explanation of possible mechanisms rather than as direct mechanistic evidence obtained from the present field trials. The observed improvements in fragmentation are therefore discussed as being consistent with mechanisms reported in previous air-deck and blast-damage studies, not as proof of a uniquely measured stress-wave or gas-pressure process in the tested blasts.

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The oversize fraction decreased under the implemented bottom air-deck production designs at all three mines. However, the operational oversize thresholds differed among the sites: 1200 mm at Gol-e-Gohar, 1000 mm at Sadat-Siriz, and 800 mm at Smalon. Therefore, the cross-site comparison should be interpreted in terms of the direction and relative magnitude of improvement within each mine rather than as a direct comparison based on a common absolute fragment-size threshold.

5.6. Statistical validation of performance differences

To evaluate whether the observed fragmentation differences were statistically detectable within the available paired dataset, two complementary statistical approaches were applied. First, paired t-tests were used to compare the characteristic fragmentation indices between matched conventional and air-deck blasting observations at each mine. The results presented in Table 9 indicate statistically significant differences for D20, D50, and D80, suggesting that the implemented bottom air-deck production designs were associated with finer fragmentation at the site scale.

Second, linear mixed-effects regression models were fitted to the combined paired field dataset to account for the non-independence of matched conventional and air-deck blasts. In these models, the blasting method was treated as the fixed effect, while the matched blast pair was included as a random intercept. The results are summarized in Table 10. The fixed-effect coefficients for air-deck blasting were negative for all fragmentation indices, with estimated reductions of 217.4 mm for D20, 198.3 mm for D50, and 201.9 mm for D80. All coefficients were statistically significant at $p < 0.001$, indicating that the reductions in fragment size were not attributable to random paired-blast variability. The marginal R^2 values ranged from 0.51 to 0.56, indicating that the blasting method/design category explained a substantial proportion of the observed variation in fragmentation indices within the available paired dataset. The conditional R^2 values ranged from 0.92 to 0.94, indicating that the inclusion of paired-blast random effects substantially improved model explanatory power. However, the models did not include explicit rock-mass covariates, such as UCS, P-wave velocity, RQD, GSI, joint spacing, and discontinuity orientation. Therefore, the statistical results support a consistent association between the implemented bottom air-deck production designs and finer fragmentation within the available field dataset, rather than proving complete independence from geological variability.

Table 9. Results of paired-sample t-tests for fragmentation indices based on the matched field comparisons.

Mine	D20 (t, p)	D50 (t, p)	D80 (t, p)	Confidence Level
Gol-e-Gohar	8.05 (p < 0.001)	11.99 (p < 0.001)	11.49 (p < 0.001)	99.9%
Sadat-Siriz	12.21 (p < 0.001)	15.16 (p < 0.001)	13.56 (p < 0.001)	99.9%
Smalon	10.97 (p < 0.001)	16.15 (p < 0.001)	18.17 (p < 0.001)	99.9%

To establish a higher-level engineering interpretation of the field-scale results, an integrated cross-site performance synthesis was conducted using the primary dataset obtained from the three investigated open-pit iron ore mines. This synthesis was developed to evaluate whether similar performance trends were observed across the investigated sites. Accordingly, the key fragmentation and operational indicators were consolidated into a unified comparative framework covering five principal performance domains: fragmentation quality, explosive energy efficiency, drilling efficiency, production efficiency, and downstream operational response. For each indicator, the overall mean responses of conventional and air-deck blasting were quantified, and the corresponding absolute change, relative change, normalized performance ratio, and cross-site consistency were determined. The normalized performance ratio provides a scale-independent measure of the magnitude of improvement, while the cross-site consistency criterion indicates the robustness of the response across different geological, structural, and operational settings. This integrated assessment is particularly important because improvements in blast performance should not be interpreted solely through fragment-size reduction; rather, they must be evaluated in relation to explosive consumption, drilling demand, hole productivity, and oversize generation. Therefore, the synthesis presented in Table 11 provides a comprehensive engineering basis for assessing the practical efficiency, operational reliability, and field applicability of air-deck blasting under full-scale production conditions.

The cross-site synthesis indicates that the implemented bottom air-deck production designs were associated with improvements in all evaluated engineering performance domains under the investigated field conditions. The fragmentation indices D20, D50, and D80 decreased by 37.7%, 27.2%, and 25.5%, respectively, demonstrating finer and more uniform image-based fragmentation estimates. In parallel, specific charge and specific drilling decreased by 21.0% and 9.2%, while hole productivity increased by 9.4% and the oversize fraction decreased by 30.1%. These similar trends across the three mines suggest that air-deck production designs can provide operational benefits; however, the magnitude of improvement remains site-dependent and should be interpreted in relation to local rock-mass and design conditions.

5.7. Limitations and future research needs

This study was conducted under routine full-scale mine-production conditions. Although conventional and bottom air-deck blasts were paired on the same bench and in adjacent production blocks, with comparable lithology, material class, hole diameter, burden, spacing, and execution date, complete single-variable control was not achievable. Hole length, stemming length, explosive-column length, and subdrilling changed as components of the implemented bottom air-deck production designs. Consequently, their individual effects cannot be completely separated from the contribution of the air column.

Representative laboratory-measured mechanical properties were available for the principal ore and waste-rock units. However, blast-block-specific UCS, tensile strength, P-wave velocity, RQD, GSI, joint spacing, persistence, aperture, infilling, and discontinuity orientation were not available for every production blast. Local geological and structural variability may therefore have contributed to the observed response.

Fragmentation was evaluated using two-dimensional image analysis. Camera angle, fragment overlap, partial burial, lighting, image resolution, segmentation quality, and limited visibility of fine particles may affect the estimated particle-size distribution. The reported D20, D50, D80, and oversize values should therefore be interpreted as image-based estimates rather than complete three-dimensional measurements.

The economic evaluation was limited to operational performance indicators rather than a complete cost-benefit analysis. In addition, mine-specific oversize thresholds differed among the three sites; cross-site oversize means therefore summarize the relative response under local operational criteria and are not values based on a common absolute threshold.

All tested configurations were bottom air decks with air-column lengths of approximately 0.9–1.2 m. The study did not examine top, middle, multiple, or alternative bottom air-deck arrangements and was not a factorial optimization study of air-deck position or ratio. No direct borehole-pressure, vibration, or crack-propagation measurements were obtained. The conclusions are therefore limited to the implemented production designs and investigated mine conditions. Future studies should independently vary air-deck length and position while maintaining equal charge weight or normalized energy input, include detailed block-scale rock-mass characterization, and validate image-based fragmentation using physical sieving, photogrammetry, or three-dimensional measurement where operationally feasible.

6. Conclusions

This study compared paired conventional production designs and implemented bottom air-deck production designs under actual operating conditions at three Iranian open-pit iron ore mines. Within the available field dataset, the implemented bottom air-deck production designs were associated with lower D20, D50, D80, powder factor, specific drilling, and oversize fraction, together with increased blasthole productivity.

The paired statistical tests and linear mixed-effects models indicated statistically significant differences in the image-based fragmentation indices within the matched dataset. However, these findings should not be interpreted as the isolated causal effect of the air column because hole length, stemming length, explosive-column length, and subdrilling were also modified as components of the implemented production designs.

Representative laboratory-measured mechanical properties differed among the investigated mines, while complete blast-block-specific discontinuity data were unavailable. The magnitude of improvement was also site-dependent. Accordingly, the results support the potential field applicability of implemented bottom air-deck production designs under the investigated conditions but should not be generalized to all air-deck configurations or rock-mass environments.

The observed trends are compatible with stress-wave interaction and gas-pressure redistribution mechanisms reported in previous studies; however, these mechanisms were not directly measured in the present trials and remain literature-based interpretations rather than direct mechanistic findings.

Table 10. Linear mixed-effects regression results for fragmentation indices based on the paired field dataset.

Response variable	Observations	Paired blast sets	Fixed effect	Estimate β_1 (mm)	SE (mm)	95% CI (mm)	z-value	p-value	Marginal R^2	Conditional R^2	AIC
D20	36	18	Bottom air-deck design vs. conventional	-217.4	14.3	-245.4 to -189.4	-15.22	< 0.001	0.56	0.92	420.9
D50	36	18	Bottom air-deck design vs. conventional	-198.3	12.4	-222.6 to -173.9	-15.97	< 0.001	0.53	0.93	415.4
D80	36	18	Bottom air-deck design vs. conventional	-201.9	11.4	-224.3 to -179.6	-17.70	< 0.001	0.51	0.94	414.3

The models were fitted using the blasting method as a fixed effect and matched blast pair as a random intercept. Negative β_1 values indicate lower fragment sizes for air-deck blasting compared with conventional blasting. Marginal R^2 represents the variance explained by the fixed effect, while conditional R^2 represents the variance explained by both fixed and random effects

Table 11. Cross-site engineering synthesis of air-deck blasting performance based on the primary field dataset.

Performance domain	Indicator	Desired direction	Conventional mean	Air-deck mean	Absolute change	Relative change (%)	Normalized ratio	Cross-site consistency
Fragmentation quality	D20 (mm)	Decrease	584.2	364.1	-220.1 mm	-37.7	0.62	Improved in 3/3 mines
Fragmentation quality	D50 (mm)	Decrease	726.5	528.6	-198.0 mm	-27.2	0.73	Improved in 3/3 mines
Fragmentation quality	D80 (mm)	Decrease	831.9	620.1	-211.8 mm	-25.5	0.75	Improved in 3/3 mines
Energy efficiency	Specific charge (kg/m ³)	Decrease	0.78	0.61	-0.16 kg/m ³	-21.0	0.79	Improved in 3/3 mines
Drilling efficiency	Specific drilling (m/m ³)	Decrease	0.51	0.46	-0.05 m/m ³	-9.2	0.91	Improved in 3/3 mines
Production efficiency	Hole productivity (t/hole)	Increase	95.3	104.3	+9.0 t/hole	+9.4	1.09	Improved in 3/3 mines
Downstream performance	Oversize fragments (%)	Decrease	16.1	11.2	-4.8 percentage points	-30.1	0.70	Improved in 3/3 mines

Relative change was calculated using the overall mean values of the primary field dataset. Negative values indicate reductions relative to conventional blasting, whereas positive values indicate improvement for productivity. The normalized performance ratio represents the air-deck value divided by the conventional value. Values below 1.0 indicate reduction, while values above 1.0 indicate improvement for productivity-related indicators. Oversize thresholds were mine-specific: 1200 mm at Gol-e-Gohar, 1000 mm at Sadat-Siriz, and 800 mm at Smalon. Therefore, the cross-site mean oversize fractions summarize relative operational responses under the respective mine-specific criteria and should not be interpreted as values calculated using a common absolute size threshold.

Future investigations should independently vary air-deck length and position while maintaining equal charge weight or normalized energy input, incorporate detailed block-scale rock-mass characterization, and validate image-based fragmentation using physical sieving, photogrammetry, or three-dimensional measurement methods.

Author contributions

A.K.S: conceptualization, methodology, simulation, validation, formal analysis, data curation, and writing—original draft preparation. F.S: writing—review and editing, and final approval of the manuscript. M.A: writing—review and editing, and final approval of the manuscript. M.K: writing—review and editing, and final approval of the manuscript. M.A.H: validation, formal analysis, and data curation. All authors have read and agreed to the published version of the manuscript.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

Manoj Khandelwal is an editorial board member [AIMS Geosciences] and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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