Vol. 11, No. 2, 2026, pp. 1-10
DOI: https://doi.org/ 10.29210/30036986000

Contents lists available at Journal ELORA

JRTI (Jurnal Riset Tindakan Indonesia)
ISSN: 2502-079X (Print) ISSN: 2503-1619 (Electronic)

Journal homepage: https://jrti.eloracenter.org/jrti

Rock mass-based blasting geometry evaluation using Kuz-Ram and split desktop for limestone fragmentation

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Article Info

Article history:

Received Aug 10th, 2026
Revised Sep 10th, 2026
Accepted Sep 17th, 2026

Keyword:

Blasting geometry,
Limestone fragmentation,
Kuz-ram,
Split desktop,
Rock mass characteristics

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ABSTRACT

This study aims evaluated limestone blasting geometry under massive and blocky rock-mass conditions and developed geometry adjustments to improve fragmentation control. Thirteen production blasts conducted at PT Semen Padang during April–May 2025 were analyzed quantitatively. Fragmentation was predicted using Kuz-Ram and verified against field fragmentation measured using Split Desktop 2.0.1, with X50 and boulders ≥50 cm as evaluation criteria. Actual boulder percentages for massive rock were 67.47% and 69.00% using Kuz-Ram and Split Desktop, respectively, whereas blocky rock yielded 44.89% and 56.00%. Kuz-Ram evaluation of the proposed geometry reduced X50 from 78.05 to 31.29 cm in massive rock and from 46.41 to 26.56 cm in blocky rock. These findings indicate that rock-mass-specific geometry adjustments can improve predicted fragmentation; however, field validation is required before operational implementation.

Introduction

Blasting is a critical stage in limestone mining because the resulting fragmentation directly affects excavation, loading, hauling, and downstream processing efficiency. Poor fragmentation, particularly the formation of oversized fragments, can increase material-handling requirements and reduce overall operational efficiency. Demonstrated that blast fragmentation has important consequences for productivity and costs in subsequent mining operations. Fragmentation performance is determined not only by explosive energy but also by the interaction between blast-design parameters and geological conditions. Sanchidrián and Ouchterlony (2023) emphasized that blast fragmentation is influenced by blast-design variables and rock-mass characteristics, particularly discontinuity spacing and orientation. Consequently, effective fragmentation control requires blasting geometry to be aligned with the mechanical and structural characteristics of the rock mass rather than applied uniformly across heterogeneous mining areas (Yilmaz, 2023).

This issue is particularly relevant to limestone mining at PT Semen Padang, where production blasting encounters different rock-mass conditions and produces variable fragmentation outcomes. The company specifies a maximum allowable boulder proportion of 20% for fragments ≥50 cm; however, field observations indicate that the existing blasting geometry does not consistently satisfy this operational criterion. Such variability is important because massive and blocky rock masses may respond differently to the same blasting configuration. Salmi et al. (2021) emphasized that geological and geotechnical characteristics should be incorporated into blastability assessment because variations in rock-mass conditions can substantially affect fragmentation performance. In the Kuz-Ram framework, these characteristics are represented through the rock factor, which influences predicted fragmentation and blast-design requirements (Yilmaz, 2023). Omotehinse et al. (2023) similarly demonstrated that fragmentation prediction depends on interactions between blast-design parameters and the characteristics of the fragmented rock. These findings suggest that a uniform blasting geometry may not provide consistent fragmentation across contrasting rock-mass conditions.

Blasting geometry further involves interdependent parameters, including burden, spacing, stemming, hole depth, subdrilling, and explosive column height. Gao et al. (2023) showed that fragmentation-size distribution reflects the combined influence of geological conditions, burden, spacing, explosive quantity, and stemming length. Burden and spacing determine the rock volume influenced by each blasthole and therefore require adjustment when rock-mass conditions change. Perincek et al. (2025) demonstrated that variations in rock conditions require corresponding adjustments in drilling patterns to improve fragmentation and digging efficiency. Stemming is equally important because it controls explosive-gas confinement and influences the transfer of explosive energy into the surrounding rock mass (Moomivand et al., 2024). Accordingly, blasting geometry should be evaluated as an integrated design system rather than through isolated modification of individual parameters (Gao et al., 2023). This interaction becomes particularly important when contrasting massive rock, with limited structural discontinuities, and blocky rock, where discontinuity patterns may facilitate or modify fragmentation (Khoddami & Mohammadi, 2025; Latyshev & Prischepa, 2018).

Previous studies provide substantial evidence for evaluating blast geometry and fragmentation, but several methodological issues remain. Murad et al. (2023) demonstrated that appropriate blasting geometry can produce limestone fragmentation distributions that more closely satisfy operational requirements, while Sanchidrián and Ouchterlony (2023) incorporated blast-design variables and rock-mass characteristics, including discontinuity spacing and orientation, into fragmentation prediction. Kuz-Ram is widely used to estimate fragmentation distributions from rock and blasting parameters, with the reliability of its predictions strongly influenced by appropriate rock-factor determination (Yilmaz, 2023). However, empirical predictions may differ from actual field fragmentation because they cannot fully represent local geological variability and operational deviations. Digital image analysis therefore provides an important complementary approach for quantifying post-blast fragmentation under field conditions. Comparisons between Kuz-Ram predictions and image-based measurements have been reported using Split Desktop (Idowu et al., 2021; Sujatono, 2024), demonstrating the value of combining predictive and field-based fragmentation assessment. Nevertheless, integrating these approaches specifically to evaluate contrasting rock-mass conditions and subsequently redesign blasting geometry remains insufficiently addressed.

This gap is important because agreement between predicted and measured fragmentation alone does not determine whether an existing blast design is appropriate for different rock-mass conditions. A more relevant evaluation must establish whether fragmentation satisfies operational targets and whether geometry should be differentiated according to rock characteristics. Therefore, this study evaluates limestone blasting geometry under massive and blocky rock-mass conditions by comparing Kuz-Ram predictions with fragmentation measured using Split Desktop and assessing both against the company criterion for fragments ≥50 cm. Specifically, the study addresses three questions: (1) how does predicted fragmentation based on Kuz-Ram differ between massive and blocky rock conditions; (2) how do these predictions compare with field fragmentation obtained through Split Desktop analysis; and (3) how should blasting geometry be adjusted for each rock-mass condition to improve predicted fragmentation performance? The working hypothesis is that rock-mass-specific geometry adjustment can reduce X50 and the proportion of boulders compared with the existing blasting configuration.

The novelty of this study lies in integrating rock-mass characterization, blast-geometry evaluation, Kuz-Ram prediction, and Split Desktop field measurement within a rock-specific framework for limestone blasting. Rather than treating blasting geometry as a fixed configuration, the study distinguishes massive and blocky rock conditions as the basis for evaluating fragmentation response and developing geometry adjustments. This approach extends previous studies that have examined blast geometry, empirical fragmentation prediction, or digital image analysis separately by connecting these components within a single field-based evaluation framework. The study is expected to provide a more technically grounded basis for selecting blasting geometry according to local rock-mass conditions while identifying discrepancies between predicted and measured fragmentation. Because the proposed geometry remains prediction-based, its operational effectiveness requires subsequent validation through repeated production blasts under controlled field conditions.

Method

This study employed an applied quantitative approach with an observational-evaluative design to assess limestone blasting performance and develop rock-mass-specific geometry adjustments. The population comprised production blasting activities within the mining concession of PT Semen Padang, while 13 production blasts conducted by PT Dahana between April 25 and May 30, 2025, at PLB, PLT, PNBP 4, PNBP 5, and PNBP 6 were purposively selected. Blast events were included when complete records of blasting geometry, rock-mass characteristics, explosive use, and post-blast fragmentation images were available and excluded when these data were incomplete or imagery was unsuitable for fragmentation analysis. Field observations were conducted from April 8 to May 30, 2025, in the Batu Gadang mining area, Padang, West Sumatra. Primary data included burden, spacing, stemming, hole depth, powder column, subdrilling, blasthole diameter, explosive consumption, rock-mass characteristics, and post-blast fragmentation images; secondary data included geological maps, blasting plans, and supporting mine documents. Recorded field geometry was cross-checked against blasting-plan documents before analysis. These blast-specific observations enabled fragmentation performance to be evaluated under actual operating conditions

Rock-mass characterization was based on Rock Mass Description (RMD), Joint Plane Spacing (JPS), Joint Plane Orientation (JPO), Specific Gravity Influence (SGI), and hardness, which were used to determine the rock factor required for Kuz-Ram prediction (Kuswanto et al., 2022; Yilmaz, 2023). Based on these characteristics, PLB was categorized as massive rock, whereas PLT and PNBP were categorized as blocky rock; specific gravities of 2.65 and 2.70 g/cm³ were applied to the respective rock conditions. Fragmentation was predicted using the Kuz-Ram model from the measured blast geometry, rock factor, explosive parameters, and powder factor, producing mean fragment size, X50, uniformity index, and the proportion of boulders ≥50 cm. Actual post-blast fragmentation was independently evaluated using Split Desktop 2.0.1 from field photographs of observable muckpiles, while Microsoft Excel was used for Kuz-Ram calculations and data tabulation. Images were analyzed using a consistent processing procedure and reference scaling to minimize differences caused by image acquisition and fragment delineation.

The analysis was conducted separately for massive and blocky rock conditions. Kuz-Ram predictions and Split Desktop measurements were compared descriptively using X50 and the percentage of boulders ≥50 cm, and their absolute differences were examined to indicate the magnitude of disagreement between predicted and image-based fragmentation. Performance was assessed against the company criteria of X50 ≤50 cm and boulders ≥50 cm not exceeding 20%. Blast events failing these criteria were evaluated through coordinated adjustments of burden, spacing, stemming, subdrilling, hole depth, and powder-column dimensions, considering their interaction with the respective rock-mass characteristics (Perincek et al., 2025; Moomivand et al., 2024). The proposed configurations were subsequently recalculated using Kuz-Ram and compared with the existing geometry in terms of mean fragment size, X50, uniformity index, boulder percentage, and powder factor. Because the proposed geometry was not implemented in production blasts, its performance was interpreted as predicted improvement rather than field-validated optimization. Accordingly, the analysis was descriptive and evaluative, without inferential statistical testing, and the proposed configurations require subsequent field validation before operational implementation.

Results and Discussions

Research findings indicate that the success of limestone blasting operations at PT Semen Padang is determined not only by the magnitude of explosive energy but also by the alignment of blasting geometry with rock mass characteristics. An analysis of 13 production blasts revealed distinct differences between massive and blocky rock formations regarding both fragmentation size and the percentage of boulders produced. A comparison between Kuz-Ram predictions and actual measurements obtained via Split Desktop further demonstrated that theoretical results do not always match actual field fragmentation conditions. Consequently, evaluating blasting geometry based on rock characteristics is crucial for meeting the company's fragmentation targets: a maximum fragmentation size of 50 cm and a boulder percentage (≥50 cm) of no more than 20%.

Actual Fragmentation Conditions Based on Rock Characteristics

Data analysis indicates that the actual blasting geometry for massive rock at the PLB site involved an average burden of 3.98 m, spacing of 4.84 m, hole depth of 9.00 m, and powder column of 5.56 m. These parameters resulted in a boulder percentage (≥50 cm) of 67.47% according to Kuz-Ram and 69% according to Split Desktop figures far exceeding the company standard of ≤20%. The X50 values reached 78.05 cm (Kuz-Ram) and 68.85 cm (Split Desktop), indicating that fragmentation of the massive rock failed to meet the target size of ≤50 cm. In contrast, blocky rock at Front B/C and PNBP was blasted with an actual geometry averaging 2.93 m burden, 3.29 m spacing, 8.80 m depth, and 5.30 m powder column. The boulder percentage reached 44.89% (Kuz-Ram) and 56% (Split Desktop). Although the Kuz-Ram X50 value of 46.41 cm remained below the 50 cm limit, the Split Desktop result showed an X50 of 55.96 cm, meaning the actual fragmentation based on image analysis did not meet the company's target.

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Table 1. Comparison of actual fragmentation based on rock mass characteristics

Rock characteristics	Method	Boulder ≥50 cm (%)	X50 (cm)	Company standards	Status
Massive (PLB)	Kuz-Ram	67,47	78,05	≤20% / ≤50 cm	Not optimal
Massive (PLB)	Split Desktop	69,00	68,85	≤20% / ≤50 cm	Not optimal
Blocky (Front B/C, PNBP)	Kuz-Ram	44,89	46,41	≤20% / ≤50 cm	Suboptimal
Blocky (Front B/C, PNBP)	Split Desktop	56,00	55,96	≤20% / ≤50 cm	Suboptimal

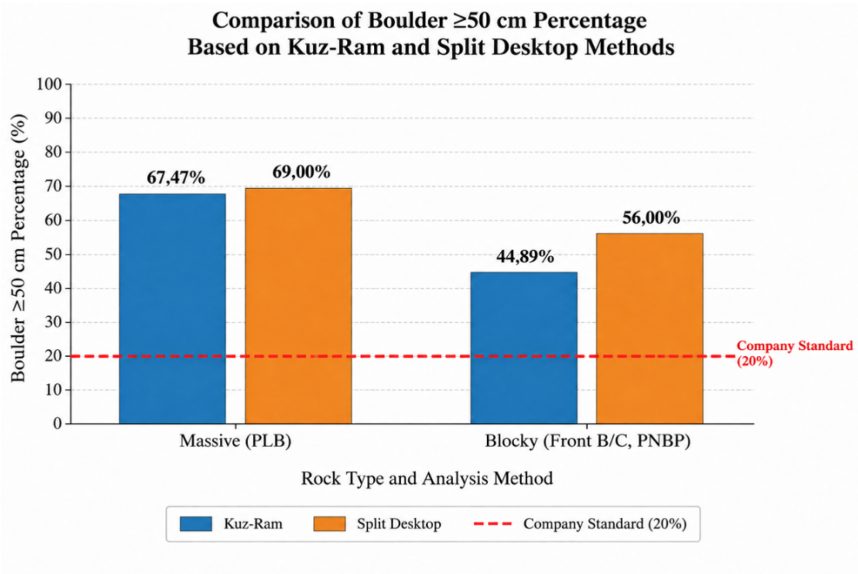

Figure 1. Comparison of the percentage of boulders ≥50 cm in massive and blocky rock masses based on the Kuz-Ram and Split Desktop methods

The results shown in Figure 1 reveal significant information regarding the two methods. For massive rock, the Kuz-Ram result of 67.47% is relatively close to the Split Desktop result of 69%, with a difference of approximately 1.53 percentage points. This proximity indicates that Kuz-Ram predictions provide a relatively consistent picture of actual conditions for massive rock formations. Conversely, for blocky rock, there is a larger discrepancy between the Kuz-Ram result (44.89%) and the Split Desktop result (56%). This difference suggests that actual rock mass conditions and blasting outcomes can produce a more complex fragmentation distribution than what is represented in theoretical calculations. These findings underscore the importance of using both prediction methods and actual measurement techniques in tandem. Kuz-Ram serves as an initial approach to estimate fragmentation distribution based on blasting parameters, while Split Desktop provides verification based on actual fragmentation results. Thus, the two approaches should not be viewed as mutually exclusive alternatives, but rather as complementary methods within the fragmentation evaluation process.

The Influence of Actual Geometry on the Fragmentation of Massive Rock

Fragmentation issues are most prevalent in massive rock formations. Research findings indicate that the current blasting geometry characterized by a burden of approximately 3.98 m, spacing of 4.84 m, hole depth of 9.00 m, and a powder column of 5.56 m results in an excessively high percentage of boulders. This suggests that blasting energy is not being effectively distributed to achieve the target fragmentation. Stemming is a key parameter requiring attention; while the current geometry for massive rock utilizes a stemming length of approximately 3.44 m, the proposed evaluation geometry suggests reducing it to 2.67 m. Furthermore, the current geometry lacks subdrilling, whereas the evaluation design incorporates 1.14 m of subdrilling. These adjustments aim to enhance blasting energy effectiveness and minimize the formation of oversized material at the base of the bench.

The high incidence of boulders in massive rock can also be attributed to the rock mass characteristics. Massive rock possesses a relatively compact structure, necessitating more effective energy distribution to induce fracturing and fragmentation. With the current geometry, increased burden and spacing unaccompanied by appropriate energy distribution can result in energy that is insufficiently effective at breaking up the rock mass. Consequently, geometric design must account for the interplay between burden, spacing, stemming, hole depth, and powder column, rather than simply modifying a single parameter in isolation.

Effect of Actual Geometry on the Fragmentation of Blocky Rock

In blocky rock, actual fragmentation conditions are superior to those in massive rock based on the Kuz-Ram X50 value; however, they still fail to meet standards regarding boulder percentage and Split Desktop results. Boulder rates of 44.89% (Kuz-Ram) and 56% (Split Desktop) indicate that the actual geometry still yields a significant amount of material exceeding 50 cm in size. Blocky rock differs from massive rock in that discontinuity planes within the rock mass can facilitate the fragmentation process; however, a non-uniform distribution of these planes can lead to uneven fragmentation results. The study indicates that the actual blocky rock geometry involved a burden of 2.93 m and a spacing of 3.29 m; this was subsequently evaluated through geometric adjustments to better align energy distribution with the rock mass conditions.

These findings demonstrate that employing smaller geometry dimensions does not automatically result in improved fragmentation. The effectiveness of a specific geometry depends heavily on the characteristics of the rock mass being blasted. Consequently, blast designs must account for local geological conditions—specifically rock mass classification and discontinuity patterns to ensure that blasting parameters are appropriately tailored to field conditions.

Evaluation of Proposed Geometry Regarding Fragmentation

Based on an evaluation using the Kuz-Ram method, geometric adjustments improved the fragmentation size distribution for both rock types. For massive rock, the mean fragmentation size decreased from 71.58 cm to 29.13 cm, while the X50 value dropped from 78.05 cm to 31.29 cm. The percentage of boulders also fell from 67.47% to 20.09%, bringing it within the company's standard threshold. The uniformity index rose from 1.37 to 1.554, indicating a more uniform fragmentation distribution. For blocky rock, the mean fragmentation size decreased from 43.36 cm to 21.85 cm, while the X50 value dropped from 46.41 cm to 26.56 cm. The boulder percentage (based on Kuz-Ram) declined from 44.89% to 5.87%, and the uniformity index increased from 1.411 to 1.702. These results demonstrate that geometric adjustments tend to improve both fragmentation size and uniformity.

Table 2. Comparison of Kuz-Ram results before and after geometry adjustment

Parameter	Actual Massive	Massive Proposal	Actual Blocky	Blocky Proposal
Average fragmentation (cm)	71,58	29,13	43,36	21,85
Uniformity index (n)	1,370	1,554	1,411	1,702
Xc (cm)	99,06	36,88	59,61	27,10
Boulder ≥50 cm (%)	67,47	20,09	44,89	5,87
X50 (cm)	78,05	31,29	46,41	26,56
PF (kg/ton)	0,179	0,233	0,179	0,289

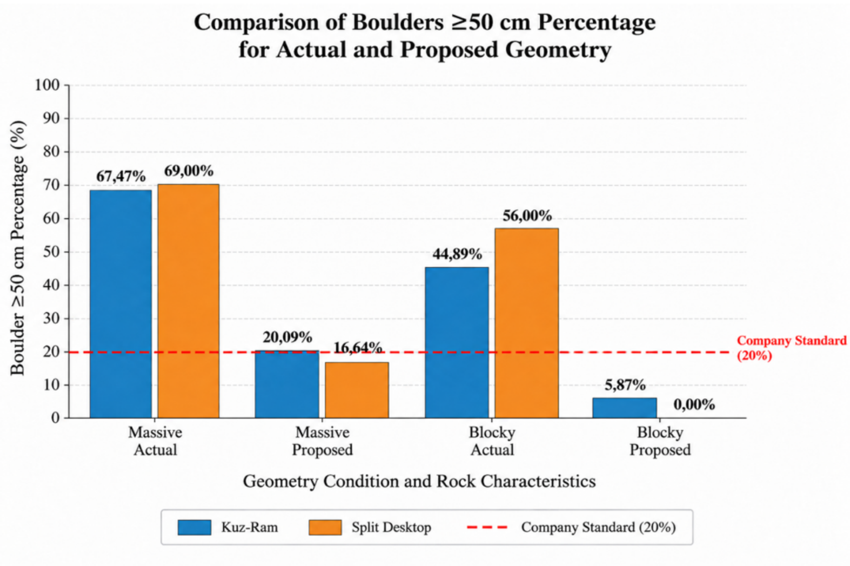

Figure 2. Comparison of actual boulder percentages and proposed geometry based on the Kuz-Ram method

The results indicate that geometric adjustments have a greater impact on massive rock, as the initial conditions were far less optimal. The reduction in boulder content from 67.47% to 20.09% represents a decrease of approximately 47.38 percentage points. For blocky rock, the reduction from 44.89% to 5.87% amounts to 39.02 percentage points. Thus, designing geometry based on specific rock characteristics is more rational than applying a single geometric pattern across all rock conditions.

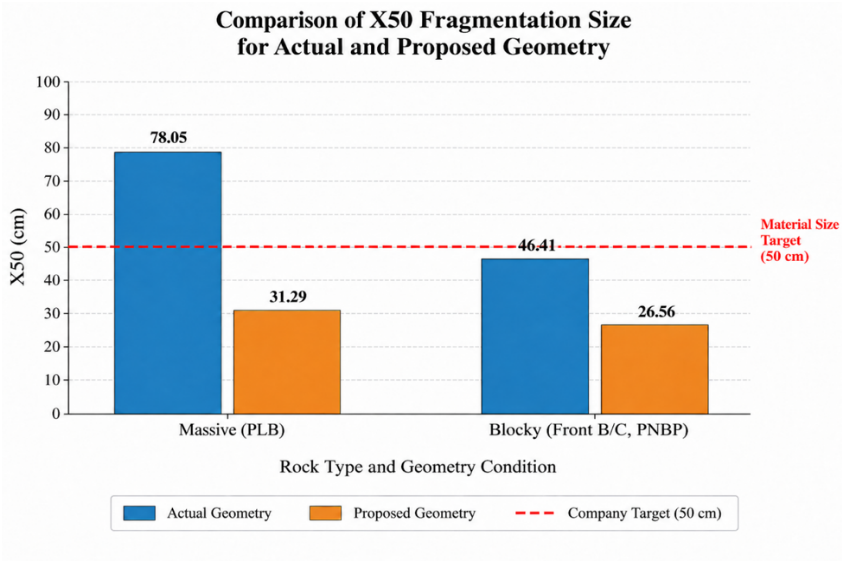

Figure 3. Comparison of actual X50 and proposed geometry for massive and blocky rock

Comparison of Kuz-Ram and Split Desktop results

A comparison of the two methods reveals that Kuz-Ram and Split Desktop do not always yield identical results. Under "massive" rock conditions, the Kuz-Ram boulder value was 67.47%, whereas Split Desktop yielded 69%; these figures are relatively close and both indicate suboptimal conditions. For "blocky" rock, the discrepancy was greater: 44.89% according to Kuz-Ram versus 56% according to Split Desktop. Such differences may stem from actual conditions not fully captured by Kuz-Ram calculations—such as variations in rock mass characteristics, non-uniform borehole distribution, drilling deviation, discontinuity plane conditions, and explosive loading practices. Conversely, Split Desktop results are influenced by factors such as image quality, camera angle, reference scaling, and the software's ability to detect fragment boundaries. Therefore, the discrepancy between the two methods' results cannot simply be attributed to an error in either method.

Table 3. Comparison of actual Kuz-Ram and Split Desktop results

Rock types	Boulder Kuz-Ram (%)	Boulder Split Desktop (%)	Difference (% points)	X50 Kuz-Ram (cm)	X50 Split Desktop (cm)
Massive	67,47	69,00	1,53	78,05	68,85
Blocky	44,89	56,00	11,11	46,41	55,96

The table shows that the greatest difference between methods occurs with blocky rock. This suggests that the variation in conditions of blocky rock masses warrants greater attention when interpreting fragmentation results. Therefore, using Split Desktop as a method for actual verification can provide additional information that is not obtained through Kuz-Ram calculations alone.

Operational Implications and Alignment with Prior Research

The results of this study reinforce earlier findings indicating a direct relationship between blasting geometry and rock fragmentation quality. Research by Murad et al. demonstrated that selecting geometry based on specific methods can lead to variations in fragmentation size, with the Konya design yielding results that better align with fragmentation targets compared to other alternatives. Meanwhile, Fitri showed that adjusting burden and spacing can significantly reduce the percentage of boulders. This study advances previous research by evaluating not only fragmentation size but also comparing theoretical Kuz-Ram predictions with actual fragmentation measured via Split Desktop and correlating these with the characteristics of massive and blocky rock masses. Through this approach, blasting geometry is treated not as a fixed parameter, but as one that requires adjustment based on specific rock conditions.

From an operational standpoint, reducing the percentage of boulders is crucial; material sized ≥50 cm increases the need for handling oversized rock and can impair the efficiency of subsequent processes. With a design that achieves an X50 of less than 50 cm and a boulder percentage approaching or falling below 20%, the proposed geometry theoretically creates conditions that better meet the company's targets.

Research Limitations and Directions for Future Research

The interpretation of the research results must take several limitations into account. First, the analysis was restricted to the Kuz-Ram and Split Desktop methods; consequently, factors such as blasting operating costs, ground vibration, noise, and environmental impacts were not quantitatively analyzed. Second, Split Desktop results depend on the quality of fragmentation documentation; therefore, camera positioning, area coverage, and the use of reference scales can influence image analysis outcomes. Future research should employ more standardized documentation procedures to ensure more consistent fragmentation representation. The study also recommends capturing photos in landscape orientation to expand documentation coverage and enhance the representativeness of the image analysis.

Subsequent research could develop an optimization model that simultaneously incorporates variables such as geometry, rock mass characteristics, powder factor, drilling deviation, and fragmentation quality. Field validation of the proposed geometry is also necessary so that the reduction in boulders predicted via the Kuz-Ram method can be compared against actual blasting results obtained through Split Desktop. In this way, the geometric design would not remain merely at the prediction stage but could be validated as a practical blasting design for field application.

The findings demonstrate that fragmentation performance was strongly associated with the interaction between blasting geometry and rock-mass characteristics. Under the existing geometry, massive rock produced substantially coarser fragmentation than blocky rock, with Kuz-Ram yielding an X50 of 78.05 cm and 67.47% boulders ≥50 cm, compared with 46.41 cm and 44.89%, respectively, for blocky rock. Split Desktop similarly identified excessive boulder proportions of 69% in massive rock and 56% in blocky rock, confirming that neither condition consistently satisfied the company limit of 20%. The poorer fragmentation observed in massive rock can be attributed to its relatively intact structure, which provides fewer natural discontinuities for crack initiation and propagation, whereas discontinuities in blocky rock can facilitate fragmentation by providing pre-existing planes of weakness. This result reinforces the principle that blastability and fragmentation cannot be interpreted solely from explosive input or geometric dimensions because structural characteristics of the rock mass substantially influence its response to blasting (Harsiga & Tono, 2024; Mat, Asmuin, Basir, et al., 2020; Nainggolan et al., 2018; Ramos et al., 2021).

The existing blast geometry also appears to be insufficiently adapted to the contrasting rock conditions. In massive rock, the average burden of 3.98 m, spacing of 4.84 m, stemming of approximately 3.44 m, and absence of subdrilling were associated with excessive coarse fragmentation, indicating that the configuration did not provide an appropriate distribution and confinement of explosive energy for the prevailing rock condition. The proposed configuration reduced stemming and incorporated subdrilling while simultaneously modifying the interconnected geometric parameters. For blocky rock, despite the smaller actual burden of 2.93 m and spacing of 3.29 m, the boulder percentage remained above the operational threshold, demonstrating that simply reducing geometric dimensions does not necessarily ensure satisfactory fragmentation. Instead, burden, spacing, stemming, subdrilling, and explosive-column dimensions must be considered as an integrated system and adjusted according to the structural characteristics of the blasted rock. This interpretation is consistent with evidence that burden and spacing influence fragmentation and digging performance, while stemming affects explosive-gas confinement and the effective transfer of blasting energy into the surrounding rock mass (Germain & Hadjigeorgiou, 1997a; Hadi et al., 2024; Hao et al., 2025; Volchenko, 1977).

The Kuz-Ram evaluation of the proposed geometry indicated substantial predicted improvements for both rock-mass conditions. In massive rock, X50 decreased from 78.05 to 31.29 cm and the boulder proportion from 67.47% to 20.09%, while the uniformity index increased from 1.370 to 1.554. In blocky rock, X50 decreased from 46.41 to 26.56 cm, the boulder proportion declined from 44.89% to 5.87%, and the uniformity index increased from 1.411 to 1.702. These changes indicate that differentiating blast geometry according to rock-mass characteristics can potentially produce finer and more uniform fragmentation than maintaining the existing configurations. Nevertheless, the predicted boulder proportion of 20.09% for massive rock remains marginally above the company limit of 20%; therefore, this configuration should not yet be interpreted as fully satisfying the operational criterion. Furthermore, the increase in powder factor from 0.179 to 0.233 kg/ton for massive rock and to 0.289 kg/ton for blocky rock indicates that improved predicted fragmentation is accompanied by greater explosive intensity, creating an operational trade-off that requires economic and field evaluation. These findings support previous evidence that effective fragmentation depends on coordinated blast-design adjustment rather than modification of a single geometric variable (Bouzakis et al., 2009; Mat, Asmuin, Md. Basir, et al., 2020; Mat & Asmuin, 2018; Mikołajczak et al., 2019).

Comparison between Kuz-Ram and Split Desktop further demonstrates the importance of combining empirical prediction with field-based fragmentation assessment. For massive rock, the boulder estimates were relatively close, at 67.47% for Kuz-Ram and 69% for Split Desktop, whereas a larger discrepancy occurred in blocky rock, with corresponding values of 44.89% and 56%. A similar pattern was observed for X50: Kuz-Ram and Split Desktop produced 78.05 and 68.85 cm in massive rock and 46.41 and 55.96 cm in blocky rock, respectively. The greater disagreement under blocky conditions may reflect geological heterogeneity that is incompletely represented by empirical rock-factor parameters, although operational factors such as drilling deviation and explosive loading may also contribute. Conversely, image-based measurements are sensitive to image coverage, scaling, camera position, overlapping fragments, and boundary delineation. Therefore, neither approach should be treated as an absolute reference; Kuz-Ram is useful for design-stage prediction, whereas Split Desktop provides complementary evidence of post-blast field conditions. Previous studies have similarly reported discrepancies between empirical fragmentation models and digital image analysis, emphasizing the value of integrating predictive and image-based approaches when evaluating blast performance (Ilham et al., 2025; Önen et al., 2017; Wang et al., 2027; Zhu et al., 2018).

From an operational perspective, the findings support a rock-mass-specific approach to blasting-geometry evaluation rather than applying a uniform configuration across heterogeneous limestone formations. Reducing X50 and oversized fragments could potentially decrease secondary handling requirements and improve downstream excavation, loading, hauling, and processing; however, these benefits were not directly quantified in the present study. More importantly, the proposed geometry represents a Kuz-Ram-based design scenario rather than a field-validated optimum, and its apparent improvement should therefore be interpreted cautiously. Repeated production-blast trials are required to determine whether the predicted reductions in X50 and boulder proportion are reproduced by Split Desktop measurements under actual operating conditions. Future optimization should also incorporate powder factor, drilling deviation, explosive consumption and cost, vibration, environmental effects, and variability in discontinuity characteristics to determine whether improved fragmentation is achieved without creating unacceptable economic or operational trade-offs. Such validation would extend the present evaluation from predicted fragmentation improvement toward a comprehensive and operationally verified blasting-optimization framework (Germain & Hadjigeorgiou, 1997b; Müller et al., 2010; Wu & Yang, 2003; Zhang et al., 2026).

Conclusions

This study concludes that blasting geometry should be designed adaptively according to rock-mass characteristics to obtain controlled limestone fragmentation. The actual blasting results indicate that the existing geometry was not consistently able to satisfy the company's fragmentation requirements, particularly for boulder control. The comparison of Kuz-Ram predictions with Split Desktop measurements confirms the importance of combining predictive and image-based analyses in evaluating blasting performance. Geometry adjustment based on the distinction between massive and blocky rock conditions improved the predicted fragmentation size, uniformity, and boulder control, demonstrating that a single blasting configuration is less appropriate for heterogeneous rock-mass conditions. The study therefore contributes a practical framework for integrating rock-mass characterization, fragmentation prediction, and field verification into blasting-geometry evaluation. Its application can support more effective fragmentation control and improve the efficiency of subsequent material handling processes. Further research should validate the proposed geometry through repeated field implementation and incorporate drilling deviation, blasting cost, vibration, and environmental parameters into a comprehensive optimization model.

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