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Analysis of Blasting Geometry on Limestone Fragmentation Distribution in Mining Activities at PT Solusi Bangun Indonesia Tbk Narogong Plant

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Abstract:
PT Solusi Bangun Indonesia Tbk Narogong Plant is a company engaged in limestone mining using a quarry system employing the drilling and blasting method. The primary issue in blasting activities is the control of blasting geometry to produce rock fragmentation that is compatible with the capacity of loading and hauling equipment and the crusher. The method employed is a quantitative method involving the collection of primary data in the form of blasting geometry parameters and fragmentation documentation, as well as secondary data obtained from the company. The data were processed empirically and theoretically using the Kuz-Ram method and analyzed using WipFrag software as a comparative tool. Furthermore, a proposed blasting geometry design was developed using the C.J. Konya and ICI Explosive methods. The results indicate that the actual conditions produced an average fragmentation of 17.16 cm with a passing percentage of <50 cm at 95.61% and a powder factor of 0.43 kg/BCM. The C.J. Konya method yielded finer fragmentation of 15.55 cm with a passing rate of 96.63% and a powder factor of 0.53 kg/BCM, whereas the ICI Explosive method produced coarser fragmentation of 22.45 cm with a passing rate of 88.35% and a powder factor of 0.33 kg/BCM. Overall, blasting geometry significantly influences the distribution of rock fragmentation and the efficiency of explosive usage.

Keywords: C.J. Konya; Fragmentation; Blasting Geometry; ICI Explosive; Kuz-Ram.
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1. Introduction (Heading 1)

PT Solusi Bangun Indonesia Tbk Narogong Plant is one of the companies engaged in limestone mining as the primary raw material for the cement industry. The company is located in Bogor, West Java, with the mining system implemented being the quarry method. In this mining activity, rock breakage is carried out using drilling and blasting because the rock is compact and massive and cannot be excavated directly with mechanical equipment.

Blasting activity constitutes one of the important stages in the mining process, aimed at producing rock fragmentation that meets operational requirements. One of the factors influencing the success of blasting is blasting geometry. Blasting geometry, which includes burden, spacing, stemming, and blast hole depth, plays a role in regulating the distribution of explosive energy within the rock mass, thereby affecting the resulting fragmentation size [1].

In limestone mining activities, the rock fragmentation size must be adjusted to the capacity of the loading and hauling equipment as well as the material processing unit. The company's primary crusher has a maximum allowable feed size of <100 cm. However, this value represents only the absolute crusher feed limit. For operational control, the company applies a stricter internal fragmentation KPI, namely at least 95% of the blasted material passing <50 cm and no more than 5% retained >50 cm. Therefore, the <50 cm passing percentage is used in this study as the operational acceptance criterion, while the <100 cm limit remains the absolute crusher feed constraint. Fragmentation exceeding this size may produce boulders that have the potential to obstruct the loading and hauling process of materials. Conversely, excessively fine fragmentation may result in the utilization of blasting energy becoming less effective [2].

The distribution of rock fragmentation size resulting from blasting is influenced by various factors, including rock characteristics, the type of explosive, and the blasting geometry design applied. Therefore, the relationship between blasting geometry parameters and fragmentation distribution constitutes an important aspect that needs to be analyzed in order to determine the performance of blasting activities in the field [3], [4]. Various previous studies on blasting fragmentation have generally focused on conditions in which the fragmentation results have not yet met the target, so that the research was directed toward efforts to evaluate and improve blasting geometry [3], [2].

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The purpose of this study is to analyze blasting geometry with respect to the distribution of limestone fragmentation in mining activities at PT Solusi Bangun Indonesia Tbk Narogong Plant by employing a theoretical approach to predict fragmentation distribution through the Kuz-Ram method and comparing it with the actual conditions in the field. In addition, a proposed blasting geometry design was developed based on the C.J. Konya and ICI Explosive approaches in order to determine the characteristics of the resulting fragmentation. This study is expected to provide information regarding the relationship between blasting geometry and rock fragmentation distribution and to serve as a basis for the evaluation of blasting activities in the field.

2. Methodology

This study was conducted at PT Solusi Bangun Indonesia Tbk Narogong Plant, located in Bogor, West Java. The method employed in this study is a quantitative method, which combines direct observation in the field with theoretical calculation analysis to examine the relationship between blasting geometry and rock fragmentation distribution.

The data used in this study consist of primary data and secondary data. Primary data were obtained through direct measurement in the field, which included blasting geometry parameters as well as documentation of rock fragmentation results. Meanwhile, secondary data were obtained from the company in the form of blasting design data, blasting activity reports, and other supporting data relevant to the study.

Data processing in this study was carried out through the following stages:

- Calculation of actual blasting geometry parameters based on data obtained from field observations.
- Calculation of the distribution of rock fragmentation resulting from actual blasting using the Kuz-Ram method, while image analysis using WipFrag software was performed on available fragmentation samples as comparative data.
- Design of proposed blasting geometry based on the C.J. Konya and ICI Explosive approaches.
- Calculation of predicted rock fragmentation distribution from the proposed blasting geometry using the Kuz-Ram method.
- Comparative analysis between the actual fragmentation results and the theoretical calculation results as well as the results of the proposed blasting geometry.

Data processing in this study was carried out to determine the relationship between blasting geometry and rock fragmentation distribution.

2.1 Blasting Geometry

The calculation of blasting geometry was performed based on actual data in the field, which included the parameters of burden, spacing, stemming, subdrilling, and blast hole depth. In addition, a proposed blasting geometry design was developed using the theoretical approaches of C.J. Konya [5] and ICI Explosives to be compared with the actual conditions [24].

The design of blasting geometry using the C.J. Konya method was carried out by taking into consideration the main parameters such as burden (B), spacing (S), stemming (T), subdrilling (J), blast hole depth (H), and the length of the explosive charge column (PC) [6]. The relationships between these parameters were used to design a blasting configuration suitable for the field conditions. The formula can be seen in equation 1 – 5.

$$B = 3.15 \times D_e \times \left(\frac{SG_r}{SG_e}\right)^{0,3} \quad (1)$$

$$S = \frac{H+7B}{8} \quad (2)$$

$$T = 0.7 \times B \quad (3)$$

$$J = 0.3 \times B \quad (4)$$

$$PC = H - T \quad (5)$$

Where:
B= Burden (m)
S = Spacing (m)
T = Stemming (m)
J = Subdrilling (m)
H = Blast Hole Depth (m)
PC = Charge Column Length (m)
De = Blast Hole Diameter (m)
SGe = Specific Gravity of Explosive
SGr = Specific Gravity of Rock

2.2 ICI Explosive Blasting Geometry

The ICI Explosive method was employed as an empirical approach (trial and error) in designing blasting geometry [7]. The main parameters were determined based on the blast hole diameter (D) and field conditions. The formula can be seen in equations 6 – 10.

H = 60D − 140D (6)
B = 25D − 40D (7)
S = 1B − 1.1B (8)
T = 20D − 30D (9)
J = 8D − 12D (10)

2.3 Geological setting and rock mass uniformity

The quarry is developed in a massive to thick-bedded limestone unit. Geological mapping and scanline surveys were conducted across the active mining area. The rock mass is characterized by two dominant joint sets with consistent orientation and spacing. The weathering grade is uniformly fresh to slightly weathered. Based on these observations, the rock mass was considered homogeneous for the purpose of the Kuz-Ram analysis, and a single Rock Factor (A = 3.94) was applied to all blasting events.

The Rock Factor used in this study was derived from a single Blastability Index evaluation. Although the geological conditions were considered uniform, spatial variability in joint condition, weathering, and strength may exist at a finer scale. This introduces uncertainty into the Kuz-Ram predictions. Future studies should perform systematic rock mass characterization for each blast block to enable spatially variable Rock Factors.

2.4 Powder Factor (PF)

Powder factor (PF), also referred to as specific charge, is defined as the quantity of explosives in kilograms required to break a unit volume or tonnage of rock, thereby serving as a fundamental indicator of blasting efficiency and explosive consumption in mining operations [8], [20]. It is commonly expressed in units such as kg/m³ or kg/t, with the selection of an appropriate powder factor directly influencing fragmentation size, as excessively high values may cause overbreak, fly rock, and finer fragmentation, while insufficient values result in boulders and underbreak that necessitate secondary blasting [8], [20]. Furthermore, the optimal powder factor is governed by intact rock properties, including uniaxial compressive strength, density, and seismic wave velocity, as well as blasting geometry and explosive characteristics [21][22]. The PF formula can be seen in equation 11.

PF = "weight of explosive" / "volume of rock" (11)

2.5 Kuz-Ram Fragmentation Distribution Calculation

The size of rock fragmentation produced by the blasting process has an influence on the performance of loading and hauling equipment. If the resulting fragmentation size is relatively large, the time required for the excavation process will be longer. Conversely, smaller fragmentation will facilitate the loading process, thereby shortening the excavation time. Therefore, rock fragmentation size constitutes an important parameter in evaluating the success of blasting activities. The theoretical fragmentation calculation method using the Kuz-Ram equation employed in this study refers to [23], which has become a standard reference in blasting analysis within the Indonesian mining community. The fragmentation resulting from blasting can theoretically be calculated using the Kuznetsov equation 12 – 15 [8].

$$\bar{X} = A\left(\frac{V}{Q}\right)^{0.8} \times Q^{0.17} \times \left(\frac{E}{115}\right)^{-0.63} \quad (12)$$

$$n = \left(2.2 - 14\frac{B}{D_e}\right) \times \left(\frac{1+\frac{S}{B}}{2}\right)^{0.5} \times \left(1 - \frac{W}{B}\right) \times \left(\frac{PC}{H}\right) \quad (13)$$

$$X_c = \frac{\bar{X}}{(0.693)^{1/n}} \quad (14)$$

$$R = e^{-\left(\frac{x}{x_c}\right)^n} \times 100\% \quad (15)$$

Where:
$\bar{X}$ = Average Rock Fragmentation Size (cm)
A = Rock Factor Index
V = Rock Volume per Hole (m³)
Q = Amount of Explosive per Hole (kg)
E = Relative Weight Strength of ANFO Explosive (ANFO = 100)
n = Uniformity Index
W = Drilling Standard Deviation
Xc = Characteristic Size (cm)
R = Percentage of Retained Material (%)
X = Specified Fragmentation Size (cm)
e = Epsilon 2.71

Table 1. Actual blasting geometry

No	Blasting date	D	LL	Actual Blasting Geometry B		S		H	T	J	L	PC	PF
				A	P	A	P						
		mm	hole	m	m	m	m	m	m	m	m	m	kg/BCM
1	08/01/2026	127	35	3.8	4.0	4.8	5.0	11	3.5	1	12	8.5	0.42
2	13/01/2026	127	33	3.8	4.0	4.8	5.0	11	3.5	1	12	8.5	0.42
3	14/01/2026	127	41	3.7	4.0	4.8	5.0	11	3.5	1	12	8.5	0.42
4	17/01/2026	127	60	3.8	4.0	4.8	5.0	11	3.5	1	12	8.5	0.42
5	19/01/2026	127	34	3.8	4.0	4.8	5.0	11	3.5	1	12	8.5	0.42
6	22/01/2026	127	71	3.7	4.0	4.7	5.0	11	3.5	1	12	8.5	0.42
7	24/01/2026	127	47	3.7	4.0	4.7	5.0	11	3.5	1	12	8.5	0.42
8	26/01/2026	127	17	3.7	4.0	4.8	5.0	11	3.5	1	12	8.5	0.42
9	27/01/2026	127	47	3.8	4.0	4.8	5.0	12	3.5	1	13	9.5	0.43
10	29/01/2026	127	35	3.8	4.0	4.7	5.0	12	3.5	1	13	9.5	0.43
11	30/01/2026	127	31	3.8	4.0	4.8	5.0	12	3.5	1	13	9.5	0.43
12	04/02/2026	127	27	3.7	4.0	4.7	5.0	13	3.5	1	14	10.5	0.43
13	09/02/2026	127	27	3.7	4.0	4.7	5.0	13	3.5	1	14	10.5	0.43
14	12/02/2026	127	30	3.7	4.0	4.7	5.0	13	3.5	1	14	10.5	0.43
15	14/02/2026	127	29	3.8	4.0	4.7	5.0	13	3.5	1	14	10.5	0.43
16	18/02/2026	127	33	3.8	4.0	4.8	5.0	13	3.5	1	14	10.5	0.43
17	20/02/2026	127	43	3.7	4.0	4.8	5.0	10	3.5	1	11	7.5	0.40
18	25/02/2026	127	44	3.8	4.0	4.8	5.0	12	3.5	1	13	9.5	0.43
19	26/02/2026	127	38	3.8	4.0	4.8	5.0	10	3.5	1	11	7.5	0.40
20	27/02/2026	127	42	3.8	4.0	4.8	5.0	12	3.5	1	13	9.5	0.43
21	02/03/2026	127	36	3.3	3.5	4.2	4.5	10	3.5	1	11	7.5	0.51
Total		**2,667**	**800.00**	**78.50**	**83.50**	**99.50**	**104.50**	**243.00**	**73.50**	**21.00**	**264.00**	**190.50**	**8.97**
Average		**127**	**38.10**	**3.74**	**3.98**	**4.74**	**4.98**	**11.57**	**3.50**	**1.00**	**12.57**	**9.07**	**0.43**

Note :
A = Actual, P = Plan, D = Blast hole diameter, LL = Blast hole, B = Burden, S = Spacing, H = Bench height, T = Stemming, J = Subdrill, L = Total hole depth, PC = P*owder column*, PF = *Powder factor* (kg/BCM).

3. Results and Discussion

3.1 Actual blasting geometry

This study was conducted at PT Solusi Bangun Indonesia Tbk Narogong Plant using 21 blasting data sets to analyze the actual blasting geometry as well as the resulting rock fragmentation distribution (see Table 1). The geometry parameters examined include burden, spacing, stemming, subdrilling, bench height, charge column length, and blast hole depth, with a blast hole diameter of 5 inches. These data were used as the basis for analyzing the relationship between blasting geometry and fragmentation distribution, as well as for designing the proposed blasting geometry.

3.2 Rock fragmentation distribution resulting from blasting at the research location

The analysis of fragmentation distribution was carried out using the empirical Kuz-Ram method and analysis software to predict the size of rock resulting from blasting based on blasting geometry parameters and rock mass characteristics. This method was employed to evaluate the suitability of the blasting results with respect to the desired fragmentation target [9].

The theoretical fragmentation analysis was performed using the Kuz-Ram method. The determination of the rock factor value was calculated through the Blastability Index (BI) approach using a weighting method. Based on the test results at the research location, the rock has a specific gravity of 2.13, corresponding to a solid density of 2.13 ton/m³ and an average uniaxial compressive strength (UCS) of 11.60 MPa. The rock factor value (A) was then determined using the [10] method based on the rock characteristic parameters.

Table 2. Blastability index weighting value

No	Parameter	Decryption	Weighting
1	Rock Mass Description (RMD)	Blocky	20.00
2	Joint Spacing (JPS)	Intermediate	20.00
3	Joint Plane Orientation (JPO)	Dip Out of Face	20.00
4	Specific Gravity Influence (SGI)	SGI = 25 x SG -50	3.25
5	Hardness (H)	Y = 1.36 ln x – 0.84	2.49
6	Blastability Index (BI)	BI = 0.5 (RMD + JPS + JPO + SGI + H)	32.87
7	Rock Factor (A)	A = BI X 0.12	3.94

Table 3. Kuz-Ram predicted fragmentation based on actual blasting geometry

Actual Kuz-Ram Fragmentation						
No	Blasting date	Uniformity Index	Average Rock Fragmentation	Size Characteristics	% Passing rate <50 cm	% Retained > 50 cm
1	08/01/2026	1.39	17.40	22.67	95.31%	4.69%
2	13/01/2026	1.39	17.40	22.67	95.31%	4.69%
3	14/01/2026	1.37	17.03	22.24	95.45%	4.55%
4	17/01/2026	1.39	17.40	22.67	95.31%	4.69%
5	19/01/2026	1.39	17.40	22.67	95.31%	4.69%
6	22/01/2026	1.36	16.75	21.95	95.44%	4.56%
7	24/01/2026	1.36	16.75	21.95	95.44%	4.56%
8	26/01/2026	1.36	17.03	22.29	95.31%	4.69%
9	27/01/2026	1.42	17.39	22.51	95.74%	4.26%
10	29/01/2026	1.37	17.10	22.34	95.38%	4.62%
11	30/01/2026	1.42	17.39	22.51	95.74%	4.26%
12	04/02/2026	1.42	16.76	21.71	96.18%	3.82%
13	09/02/2026	1.42	16.76	21.71	96.18%	3.82%
14	12/02/2026	1.42	16.76	21.71	96.18%	3.82%
15	14/02/2026	1.40	17.12	22.24	95.72%	4.28%
16	18/02/2026	1.45	17.41	22.42	96.06%	3.94%
17	20/02/2026	1.32	17.08	22.53	95.44%	4.56%
18	25/02/2026	1.42	17.39	22.51	95.74%	4.26%
19	26/02/2026	1.35	17.44	22.91	95.31%	4.69%
20	27/02/2026	1.42	17.39	22.51	95.74%	4.26%
21	02/03/2026	1.33	14.00	18.43	95.74%	4.26%
Total		**29.16**	**357.15**	**465.12**	**20.08**	**0.92**
Average		**1.39**	**17.16**	**22.33**	**95.61%**	**4.39%**

Based on the data in Table 2, which include blasting geometry parameters, physical and mechanical properties of the rock, and the type of explosive, a theoretical fragmentation calculation was performed using the Kuz-Ram method to estimate the size distribution of rock resulting from blasting. In this study, fragmentation performance is evaluated using the <50 cm passing percentage as the internal operational KPI. The <100 cm crusher feed limit is not used as the main performance indicator because it represents only the absolute maximum feed size. All evaluated blasting designs met the <100 cm crusher feed limit; however, their performance is compared based on the stricter <50 cm criterion. The results of the fragmentation calculation are presented in Table 3.

Based on Table 3, the actual fragmentation results for the high bench at the research location show an average uniformity index of 1.39, with an average rock fragmentation of 17.16 cm and a characteristic fragmentation size of 22.33 cm. The percentage of material passing the <50 cm size has an average of 95.61%, while the material retained at the >50 cm size accounts for 4.39%. These actual fragmentation data were obtained from 21 blasting activities on the high bench.

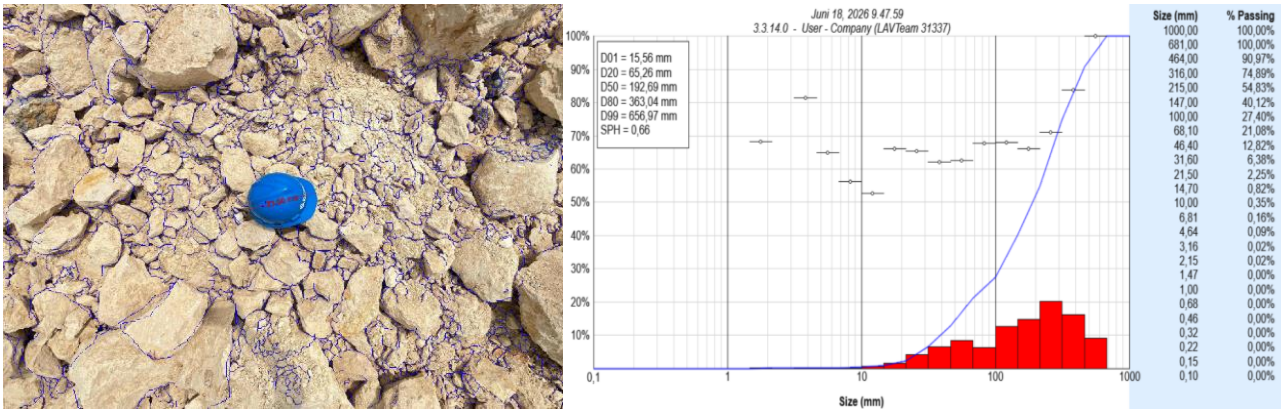

Figure 1. WipFrag image analysis (left) showing the median particle size (D_{50}) of the actual blast fragmentation using the Kuz-Ram method (right).

Based on Figure 1, the analysis of rock fragmentation resulting from blasting was carried out using WipFrag software based on the documentation of the blasting results. WipFrag is a photo analysis software that enables real-time fragmentation assessment and is widely used for blasting quality control in mining operations [17]. The analysis results show a D50 value of 19.27 cm, which represents the median particle size, the size at which 50% of the blasted material passes. This value indicates that the fragmentation is dominated by medium to coarse sizes. An SPH (Sphericity) value of 0.66 indicates that the average particle is moderately elongated (length-to-width ratio of approximately 1.5:1). According to WipFrag documentation, sphericity below 70% suggests elongated or irregularly shaped particles, which may affect flowability and crusher efficiency. It should be noted that SPH describes particle shape, not the uniformity of the size distribution [15]. In general, the blasting results produce good fragmentation and still meet the crusher feed size, thereby supporting the loading and crushing processes effectively.

3.3 Proposed blasting geometry design

Based on the results of the geometry analysis that has been carried out, modifications to the blasting geometry parameters are required to improve fragmentation and achieve the production target of 24,000 tons/day. The subsequent fragmentation analysis was performed using the Kuz-Ram method based on the geometry that has been designed in accordance with the company's production target.

Based on Table 4, the comparison of the C.J. Konya method employs a burden of 3.56 m and a spacing of 4.49 m with a powder factor value of 0.53 kg/BCM, whereas the ICI Explosive method employs a burden of 4.57 m and a spacing of 5.49 m with a powder factor value of 0.33 kg/BCM. Compared with the actual condition of 0.43 kg/BCM, the powder factor value in the C.J. Konya method increased by 23.15%, while the ICI Explosive method decreased by 22.38%. This difference indicates that geometry with a smaller burden and spacing tends to increase explosive consumption, whereas larger geometry results in a lower powder factor. These results are consistent with studies stating that changes in blasting geometry parameters directly affect fragmentation distribution and the efficiency of explosive usage [11].

Table 4. Proposed blasting geometry by C.J. Konya and ICI Explosive

Parameter	Actual	C.J Konya	ICI Explosive
Hole diameter (inch)	5.00	5.00	5.00
Burden (B), m	3.98	3.56	4.57
Spacing (S), m	4.98	4.49	5.50
Stemming (T), m	3.50	3.50	3.50
Bench high (m)	11.57	11.00	11.00
Subdrilling (m)	1.00	1.10	1.00
Hole depth (m)	12.57	12.10	12.00
Powder column (m)	9.07	8.60	8.50
Rock density, ρ (ton/BCM)	2.13	2.13	2.13
Rock volume per hole (BCM)	229.40	175.94	276.49
Rock volume (BCM)	8,664.00	13,333.00	13,333.00
Tonage	15,596	24,000.00	24,000.00
Loading Density (de), kg/m	10.76	10.76	10.76
Explosive weight per hole (E), kg/hole	97.63	92.55	91.48
Powder Factor (PF), kg/BCM	0.43	0.53	0.33
Number of holes	38.00	76.00	48.00
AN weight (kg)	3,467.00	6,614.00	4,168.00
FO weight (kg)	210.00	400.00	252.00
ANFO weight (kg)	3,677.00	7,014.00	4,420.00
Dynamite	38.00	76.00	48.00
PF difference	-	23.15%	-22.38%

Note: Tonnage is calculated using an in-situ bulk density of 1.8 ton/m³. The solid density (specific gravity) of 2.13 ton/m³ is used only for the Blastability Index calculation in Table 2. Loading density is expressed in kg/m of explosive column

Table 5. Kuz-Ram predicted fragmentation for the proposed by C.J. Konya and ICI Explosive geometries

Proposed *KUZ-RAM* fragmentation			
Parameter	**Actual**	***C.J Konya***	***ICI Explosive***
Uniformity index (n)	1.39	1.38	1.28
Fragmentation average	17.16	15.55	22.45
Characteristic Size (Xc)	22.33	20.30	29.87
% Passing rate <50 cm	95.61%	96.63%	88.35%
% Retained > 50 cm	4.39%	3.37%	11.65%

3.4 Comparison of actual and proposed Kuz-Ram fragmentation

The comparison of rock fragmentation was carried out to determine the differences in fragmentation results between the actual blasting geometry and the proposed blasting geometry based on the C.J. Konya and ICI Explosive theories for each bench category. The results of the comparison between the actual and proposed Kuz-Ram fragmentation can be seen in Table 5.

Based on Table 5, regarding the comparison of Kuz-Ram fragmentation, the C.J. Konya method produces an average fragmentation size of 15.55 cm with a passing percentage of <50 cm of 96.63%, whereas the ICI Explosive method produces an average fragmentation size of 22.45 cm with a passing percentage of <50 cm of 88.35%. Compared with the actual condition of 17.16 cm and 95.61%, it can be observed that the C.J. Konya method produces finer fragmentation, while the ICI Explosive method produces coarser fragmentation. This difference indicates that the use of a smaller burden and spacing in the C.J. Konya method enhances the distribution of blasting energy, thereby producing a smaller and more uniform fragmentation size, which is consistent with studies stating that blasting geometry parameters directly affect the distribution of rock fragmentation [12]. Changes in blasting geometry parameters such as burden and spacing directly affect the average fragmentation size, uniformity index, and rock size distribution, where the smaller the burden and spacing values, the finer and more uniform the resulting fragmentation size tends to be, thereby improving the efficiency of the material loading and hauling process in mining activities.

3.5 Calculation of fragmentation for the proposed C.J. Konya geometry of blasting results using WipFrag Software

Based on Figure 2, the analysis of rock fragmentation resulting from blasting was carried out using WipFrag software based on the documentation of the blasting results. The analysis results show a D50 value of 14.87 cm, which represents the median particle size, the size at which 50% of the blasted material passes [18]. This value indicates that the resulting fragmentation is dominated by medium to coarse sizes. An SPH value of 0.66 indicates a relatively uniform fragment size distribution. In general, the blasting results using the C.J. Konya method produce good fragmentation and still meet the crusher feed size, thereby supporting the loading and crushing processes effectively. The C.J. Konya Method has been shown to produce fine fragmentation compared with actual blasting geometry in several mining operations [19].

3.6 Comparison between Kuz-Ram and WipFrag Results

To quantify the agreement between the empirical Kuz-Ram predictions and the WipFrag image analysis, a simple percentage error metric was calculated. The use of percentage error as a validation metric for comparing predicted and measured fragmentation sizes has been widely adopted in blasting studies, including comparisons between Kuz-Ram predictions and image-based measurements.

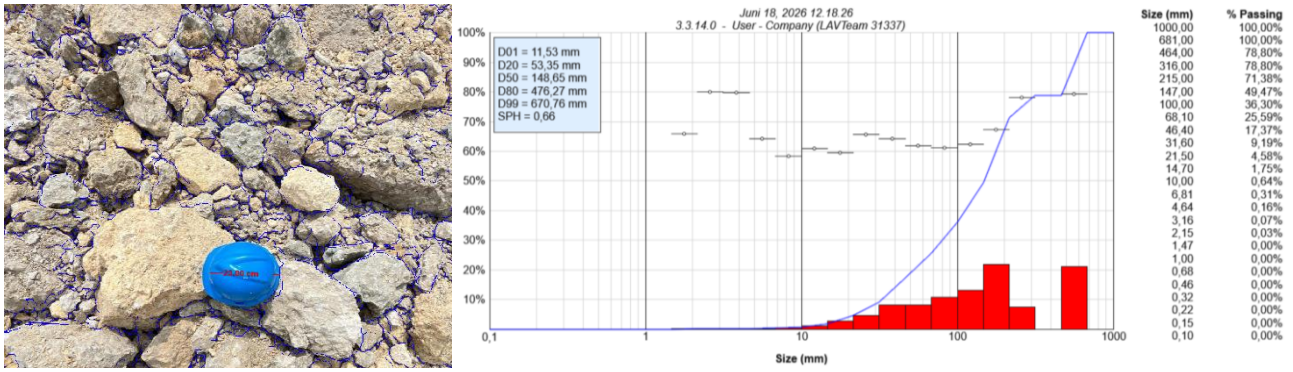

Figure 2. WipFrag image analysis showing the median particle size (D_{50}) of the actual blast fragmentation using the C.J. Konya method

Table 6. Comparison of Kuz-Ram and WipFrag fragmentation results

Condition	Kuz-Ram X_{50} (cm) (Average)	WipFrag D_{50} (cm) (Median)	Percentage Error (%)
Actual	17.16	19.27	12.3
C.J. Konya	15.55	14.87	4.4
ICI Explosive	22.45	20.36	9.3

Note: X_{50} *is the average fragmentation size predicted by Kuz-Ram.* D_{50} *is the median particle size (50% passing size) obtained from WipFrag.*

The percentage error is defined as:

$$Error(\%) = \frac{|X_{50,Kuz-Ram} - D_{50,wipfrag}|}{X_{50,Kuz-Ram}} x100\% \quad (16)$$

Where $X_{50,Kuz-Ram}$ is the average fragmentation size predicted by the Kuz-Ram method and $D_{50,WipFrag}$ is the median fragment size obtained from WipFrag analysis. This formulation is consistent with the general percentage error definition used in model validation, in which the absolute difference between predicted and observed values is divided by the reference value and multiplied by 100. A similar approach has been applied [13] and [14], which used percentage error to assess the discrepancy between the Kuz-Ram model and image analysis results, reporting an overall error of approximately 3.5% for the modified model compared with above 60% for the original Kuz-Ram. The comparison was performed for three conditions: the actual blasting geometry, the proposed C.J. Konya geometry, and the proposed ICI Explosive geometry. The results are presented in Table 6.

As shown in Table 6, the percentage errors range from 4.4% to 12.3%, indicating that the two methods are in reasonable agreement. The actual condition shows an error of 12.3%, the ICI Explosive design shows an error of 9.3%, and the C.J. Konya design shows the closest agreement with an error of only 4.4%. These results suggest that the Kuz-Ram model provides predictions that are consistent with the WipFrag image analysis, particularly for the C.J. Konya design.

However, it should be noted that the WipFrag analysis was performed on selected representative samples from the actual blast and from the proposed C.J. Konya and ICI Explosive designs, rather than on all 21 blasting events. The Kuz-Ram method, on the other hand, was applied to all 21 data sets. This limitation arises from practical constraints in image acquisition and processing, such as the availability of suitable fragmentation images for every blast. Therefore, the WipFrag results serve as an indicative validation of the Kuz-Ram predictions rather than a comprehensive independent verification. Future studies should include WipFrag analysis for all blasts to enable a more robust statistical validation.

3.7 Design-controlled versus Geology-controlled variables

Figure 1 shows the WipFrag analysis of a single representative blast from the actual geometry, with a D_{50} of 19.27 cm. Figure 2 shows the WipFrag analysis of a single representative blast from the proposed C.J. Konya geometry, with a D_{50} of 14.87 cm. These figures are intended to illustrate typical fragmentation conditions and are not combined results from multiple blasts. Because WipFrag was applied only to selected blasts, the comparison with Kuz-Ram predictions is indicative rather than comprehensive [14][16].

The fragmentation results in this study are influenced by two groups of variables that must be clearly distinguished. Design-controlled variables are parameters that can be adjusted by the blasting engineer. In this study, these include burden, spacing, stemming, subdrilling, blast hole depth, charge column length, powder factor, and explosive type. The comparison between the actual geometry, the C.J. Konya design, and the ICI Explosive design is based on differences in these parameters. Geology-controlled variables are inherent to the rock mass and cannot be modified by design. These include lithology, bedding orientation, joint orientation, joint spacing, joint persistence, weathering grade, uniaxial compressive strength, and rock mass blastability. In this study, the rock mass is a massive to thick-bedded limestone with a UCS of 11.60 MPa, a specific gravity of 2.13, a Blastability Index of 32.87, and a Rock Factor of 3.94.

The comparison of fragmentation between the three designs assumes that the geology-controlled variables remained constant across the 21 blasting blocks. This assumption is based on the uniformity of the limestone unit, the consistent weathering grade, and the similar joint characteristics observed across the mining area. However, because systematic rock mass characterization was not performed for each individual blast block, the possible influence of local geological variability on fragmentation cannot be entirely excluded.

Therefore, the differences in fragmentation between the actual geometry, the C.J. Konya design, and the ICI Explosive design are primarily attributed to differences in design-controlled variables, particularly burden, spacing, and powder factor. The smaller burden and spacing in the C.J. Konya design distribute blasting energy more effectively within the rock mass, producing finer and more uniform fragmentation. The larger burden and spacing in the ICI Explosive design result in coarser fragmentation but lower explosive consumption. These conclusions are consistent with previous studies, but they should be interpreted with the caveat that geological variability may also contribute to the observed differences.

Conclusion

This study compared rock fragmentation resulting from actual blasting geometry with the C.J. Konya and ICI Explosive designs using the Kuz-Ram approach and WipFrag software. Based on the parameters evaluated, the actual condition produced an average fragmentation of 17.16 cm (Kuz-Ram, X_{50}) and a median particle size of 19.27 cm (WipFrag, D_{50}), with 95.61% passing <50 cm and a powder factor of 0.43 kg/BCM. The C.J. Konya design produced finer fragmentation, namely 15.55 cm (Kuz-Ram, X_{50}) and a median particle size of 14.87 cm (WipFrag, D_{50}), with 96.63% passing <50 cm and a powder factor of 0.53 kg/BCM. The ICI Explosive design produced coarser fragmentation, namely 22.45 cm (Kuz-Ram, X_{50}) and a median particle size of 20.36 cm (WipFrag, D_{50}), with 88.35% passing <50 cm and a powder factor of 0.33 kg/BCM. All three conditions met the crusher feed limit of <100 cm. Under the stricter internal operational KPI of ≥95% passing <50 cm, the actual condition and the C.J. Konya design met the target, whereas the ICI Explosive design did not. Within the scope of this study, the C.J. Konya design is preferable when finer fragmentation is required, while the ICI Explosive design is preferable when lower explosive consumption is prioritized. However, these conclusions are limited to fragmentation and powder factor. Other aspects of blasting performance, such as drilling requirements, loading and hauling productivity, crusher performance, secondary breakage, vibration, flyrock, and overbreak, were not evaluated and should be assessed in future studies before an overall blasting performance recommendation is made.

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Author Contributions

Author 1: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Author 2**: Conceptualization, Methodology, Investigation, Writing – original draft, Software, Writing – review & editing. **Author 3:** Methodology, Validation, Formal analysis, Data curation, Visualization. **Author 4:** Resources, Supervision, Project administration, Funding acquisition, Writing – review & editing. **Author 5:** Investigation, Resources, Data curation, Writing – review & editing.

Data Availability

Not Applicable / The data are attached in the article already.

Conflict of Interest

The authors declare that there is no conflict of interest.

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