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BLASTHOLE DIAMETER AND ROCK FRAGMENTATION IN UNDERGROUND MINING: DISTINGUISHING OPERATIONAL EFFECTS FROM DIAMETER SENSITIVITY

DIÂMETRO DE FUROS DE MINA E FRAGMENTAÇÃO DE ROCHA NA MINERAÇÃO SUBTERRÂNEA: DISTINGUINDO EFEITOS OPERACIONAIS DA SENSIBILIDADE AO DIÂMETRO

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ABSTRACT

Rock fragmentation in underground mining results from the interaction among blasthole geometry, explosive energy, rock mass characteristics, and drilling accuracy. Although blasthole diameter is a fundamental design variable, its individual effect on fragmentation is difficult to distinguish under actual operating conditions because changes in diameter are commonly accompanied by variations in burden, spacing, explosive loading, hole length, and geomechanical conditions. This study evaluates the influence of blasthole diameter on predicted rock fragmentation using operational data collected over approximately six months from three underground metal mines and the empirical Kuz-Ram model combined with the Rosin-Rammler distribution. Representative operating scenarios with production blasthole diameters of 76, 89, and 95 mm were established from consolidated operational, geometric, explosive-loading, and geomechanical information. These scenarios were compared with a deterministic sensitivity analysis in which blasthole diameter was systematically varied while the remaining parameters within each mine were held constant. Under the representative operational conditions, the 89 mm scenario yielded the lowest predicted P80, whereas the 95 mm scenario yielded the highest. Conversely, under controlled sensitivity conditions, increasing blasthole diameter increased explosive mass per hole and powder factor and consequently reduced predicted P80 in all three mines. Diameter also produced a secondary change in the Rosin-Rammler uniformity index through the D/B relationship adopted in the model. These apparently contrasting results demonstrate the difference between the isolated model sensitivity to diameter and the effective influence of diameter within an actual drilling-and-blasting system. The findings indicate that blasthole diameter should be treated as a system-level design variable rather than an isolated drilling

parameter. Its selection should consider blast geometry, powder factor, rock mass response, blasthole geometric accuracy, and downstream fragmentation requirements within an integrated *Mine-to-Mill* framework.

Keywords: blasthole diameter; underground mining; rock fragmentation; Kuz-Ram; Rosin-Rammler; blasting; Mine-to-Mill.

RESUMO

A fragmentação de rocha na mineração subterrânea resulta da interação entre a geometria dos furos de perfuração, a energia do explosivo, as características do maciço rochoso e a precisão da perfuração. Embora o diâmetro do furo de perfuração seja uma variável de projeto fundamental, seu efeito individual sobre a fragmentação é difícil de distinguir em condições operacionais reais, pois alterações no diâmetro são comumente acompanhadas por variações no afastamento, no espaçamento, no carregamento de explosivo, no comprimento do furo e nas condições geomecânicas. Este estudo avalia a influência do diâmetro do furo de perfuração na fragmentação de rocha prevista, utilizando dados operacionais coletados ao longo de aproximadamente seis meses em três minas subterrâneas de metais e o modelo empírico Kuz-Ram combinado com a distribuição de Rosin-Rammler. Cenários operacionais representativos com diâmetros de furos de produção de 76, 89 e 95 mm foram estabelecidos a partir de informações operacionais, geométricas, de carregamento de explosivo e geomecânicas consolidadas. Esses cenários foram comparados com uma análise de sensibilidade determinística na qual o diâmetro do furo de perfuração foi sistematicamente variado, mantendo-se constantes os demais parâmetros de cada mina. Sob as condições operacionais representativas, o cenário de 89 mm apresentou o menor P80 previsto, enquanto o cenário de 95 mm apresentou o maior. Por

outro lado, sob condições de sensibilidade controladas, o aumento do diâmetro do furo de perfuração aumentou a massa de explosivo por furo e o fator de carga e, consequentemente, reduziu o P80 previsto nas três minas. O diâmetro também produziu uma alteração secundária no índice de uniformidade de Rosin-Rammler por meio da relação D/B adotada no modelo. Esses resultados aparentemente contrastantes demonstram a diferença entre a sensibilidade isolada do modelo ao diâmetro e a influência efetiva do diâmetro dentro de um sistema real de perfuração e desmonte. Os achados indicam que o diâmetro do furo de perfuração deve ser tratado como uma variável de projeto em nível de sistema, e não como um parâmetro isolado de perfuração. Sua seleção deve considerar a geometria do desmonte, o fator de carga, a resposta do maciço rochoso, a precisão geométrica dos furos de perfuração e os requisitos de fragmentação a jusante dentro de uma estrutura integrada *Mine-to-Mill*.

Palavras-chave: diâmetro do furo de perfuração; mineração subterrânea; fragmentação de rocha; Kuz-Ram; Rosin-Rammler; desmonte com explosivos; Mine-to-Mill.

1. INTRODUCTION

Underground mining involves geometric, geomechanical, operational, and safety constraints that require rigorous control of drilling and blasting operations. These processes are strongly interconnected and directly affect mine productivity, operating costs, excavation stability, ore recovery, dilution, and the performance of downstream operations such as loading, haulage, crushing, and comminution (Hustrulid & Bullock, 2001; Darling, 2023).

Drilling performance is governed by the interaction among drilling equipment, operating parameters, execution quality, drilling tool condition, and rock mass properties. Among the main design variables, blasthole diameter influences the volume of rock removed per unit length drilled, drilling energy requirements, tool wear, blasthole stability, explosive loading capacity, and blast geometry. Under comparable conditions, increasing blasthole diameter increases the amount of rock that must be fractured per unit advance and may consequently affect rate of penetration (ROP), depending on available drilling power, drilling method, intact rock properties, abrasivity, and rock mass structure (Curi, 2017; Dougherty & Schissler, 2020).

From a blasting perspective, blasthole diameter defines the cross-sectional area available for explosive loading and consequently influences explosive mass per hole, powder factor, and the geometric relationship among burden, spacing, and charged length. Changes in diameter can therefore modify both the magnitude and spatial distribution of explosive energy within the rock mass. Inadequate fragmentation can negatively affect downstream operations. Coarse fragmentation may increase secondary breakage requirements, loading time, and operational variability, whereas excessive energy concentration may increase fines generation, vibration, overbreak, dilution, and damage to excavation boundaries.

However, the influence of blasthole diameter cannot be interpreted independently of other design variables. In actual mining operations, changes in diameter are commonly associated with changes in blast pattern geometry, hole length, explosive loading, drilling method, and, when different operations are compared, geomechanical conditions. Consequently, an apparent relationship

between blasthole diameter and fragmentation may represent the combined influence of several variables rather than the isolated effect of diameter.

This distinction is particularly important in underground long-hole production drilling, where blasthole geometric accuracy is critical. Deviations in collar position or blasthole trajectory modify effective burden and spacing and can create localized regions of insufficient or excessive explosive energy. Small angular errors at the collar may produce substantial positional errors at the toe of long blastholes, potentially affecting fragmentation, ore recovery, dilution, and overall blast performance.

A practical engineering challenge therefore remains: distinguishing the contribution specifically associated with blasthole diameter from the combined effects of the operational system in which that diameter is applied.

Accordingly, this study evaluates predicted rock fragmentation using representative operational data from three underground metal mines operating with production blasthole diameters of 76, 89, and 95 mm. The analysis comprises two complementary approaches. First, representative operational scenarios are compared while preserving the different blast geometry, explosive energy, and geomechanical conditions associated with each operation. Second, a deterministic sensitivity analysis is performed in which blasthole diameter is systematically varied while the remaining parameters within each mine are held constant.

The contribution of this study is therefore not the identification of a universally optimum blasthole diameter. Instead, the study

distinguishes between the fragmentation response associated with representative operational conditions and the isolated sensitivity of the fragmentation model to diameter under controlled conditions. This distinction provides an engineering framework for understanding when a change in blasthole diameter may effectively modify predicted fragmentation and when its influence is secondary to blast geometry, explosive energy, and rock mass conditions.

The practical objective is to support blasthole diameter selection as an integrated engineering decision involving drilling capability, blast geometry, powder factor, rock mass response, geometric accuracy, and downstream fragmentation requirements within a Mine-to-Mill perspective.

2. THEORETICAL BACKGROUND

2.1. Drilling, Rock Mass Properties, And Blasthole Geometric Quality

In percussive and rotary-percussive drilling, mechanical energy transmitted to the drill bit produces localized stress concentrations at the rock-tool interface, followed by crack initiation, crack propagation, rock fragmentation, and removal of the resulting cuttings by the flushing medium.

In Top Hammer systems, impact energy is generated at the drilling unit and transmitted through the drill string to the bit. In Down-The-Hole (DTH) systems, the percussion mechanism operates directly behind the drill bit inside the blasthole, reducing energy losses along the drill string. Selection of the appropriate drilling method depends on blasthole diameter, hole length, available drilling power,

rock mass conditions, expected productivity, and geometric accuracy requirements (Curi, 2017).

Rock properties strongly influence drilling response. Uniaxial compressive strength (UCS) is associated with the mechanical resistance of intact rock, whereas abrasivity contributes to drilling tool degradation and affects performance over time. Competent rocks generally require higher energy input and may produce lower penetration rates while providing greater blasthole stability. Conversely, highly fractured rock masses may exhibit apparently higher penetration rates because breakage preferentially occurs along existing discontinuities, but may also increase the probability of instability, local collapse, deviation, and loss of geometric accuracy (Park & Kim, 2020; Salmi & Sellers, 2021).

High ROP should therefore not automatically be interpreted as superior overall drilling performance. Penetration rate should be considered together with blasthole stability, drilling accuracy, drilling tool performance, and the capacity to reproduce the intended blast geometry.

Blasthole geometric quality is particularly important in underground long-hole blasting. Deviations in collar position, trajectory, inclination, or final depth modify the effective burden and spacing obtained in the field. These deviations alter the spatial distribution of explosive energy and may generate regions receiving either insufficient or excessive energy relative to the actual rock volume.

Consequently, blasthole diameter selection should be considered jointly with the capacity of the drilling system to maintain the geometric tolerances required by the blast design.

2.2. Integration Of Blasthole Diameter, Blast Geometry, And Explosive Energy

Blasthole diameter provides a direct physical connection between drilling and blasting. Increasing diameter increases the available cross-sectional area for explosive loading and may reduce the number of blastholes required for a given blasted volume. At the same time, larger blastholes can concentrate greater explosive masses at individual charging locations.

Smaller diameters may allow explosive energy to be distributed through a larger number of charging locations but generally require additional drilling. Therefore, neither larger nor smaller diameters are inherently advantageous. Their performance depends on compatibility among blasthole diameter, burden, spacing, charged length, explosive properties, rock mass characteristics, and drilling accuracy (Morais, 2004).

Powder factor, defined in this study as explosive mass per unit volume of rock, provides a useful indicator of explosive loading intensity. However, increasing explosive mass alone does not guarantee improved fragmentation. If blast geometry is inappropriate, blasthole deviation is excessive, or explosive energy is preferentially dissipated through geological discontinuities, additional explosive energy may not translate into improved blast performance.

Blast optimization should consequently not aim exclusively at minimizing P80. The engineering objective is to generate a particle-size distribution compatible with secondary breakage, loading, haulage, crushing, and processing requirements while controlling

dilution, excavation damage, energy consumption, and operational cost.

2.3. Kuz-Ram Model And Rosin-Rammler Distribution

The Kuz-Ram model combines the Kuznetsov fragmentation relationship with a representative rock factor and the Rosin-Rammler particle-size distribution. The model provides a practical empirical relationship among rock mass characteristics, explosive loading, blast geometry, and predicted fragmentation (Cunningham, 1983; Cunningham, 1987).

The mean fragment size, X50, is estimated as:

$$X_{50} = A \cdot k^{-0,80} \cdot Qe^{-0,167}$$

where **A** is the rock factor, **k** is the powder factor, and **Qe** is the explosive mass per hole.

The particle-size distribution is subsequently represented by the Rosin-Rammler function:

$$P(x) = 1 - \exp\left[-\left(\frac{x}{Xc}\right)^{n}\right]$$

where **Xc** is the characteristic fragment size and **n** is the uniformity index.

Higher values of **n** indicate a narrower predicted particle-size distribution, whereas lower values represent greater dispersion between smaller and larger fragments.

The characteristic size is obtained from:

$$\frac{X_{50}}{}$$

$$X_C = (ln2)^{1/n}$$

The particle size corresponding to a specified cumulative passing fraction is calculated as:

$$x = X_C\ [-\ln\ (1-P)\ ]^{1/n}$$

For P = 0.80, the resulting value corresponds to P80.

Although the Kuz-Ram framework is useful for comparative and sensitivity analyses, it is an empirical model. Its predictions are sensitive to the quality and representativeness of the input parameters, particularly rock factor, explosive loading, and blast geometry. Absolute predictions should therefore be interpreted cautiously and, whenever possible, calibrated against site-specific field fragmentation measurements (Ouchterlony & Sanchidrián, 2019; Quaglio, 2020).

3. METHODOLOGY

3.1. Study Design And Operational Dataset

This study follows an applied, quantitative, and empirical-comparative approach. Operational information from three underground metal mines located in Latin America was analyzed. To preserve confidentiality, the operations are designated as Mine A, Mine B, and Mine C.

All three operations use Sublevel Stoping, allowing comparison within a common underground production context while maintaining differences in geological conditions, production blasthole diameter, blasthole length, blast geometry, and explosive loading.

The operational dataset covered approximately six months of study and field observation and comprised drilling plans, blast designs, drilling reports, explosive loading information, and geological and geotechnical records. The available information was processed and consolidated into representative operating scenarios for each mine using mean, median, and representative values according to the characteristics and availability of each parameter.

The consolidated scenarios were used instead of individual production blasts because the objective was to investigate representative operating conditions and the interaction among blasthole diameter, explosive energy, blast geometry, and rock mass response.

Table 1. *General characteristics of the analyzed operational scenarios*

Parameter	Mine A	Mine B	Mine C
Predominant lithology	Actinolite/breccia, IOCG deposit	Dolomite/breccia	Polymetallic massive sulfides, VMS deposit
Mining method	Sublevel Stoping	Sublevel Stoping	Sublevel Stoping
Production blasthole diameter	76 mm	89 mm	95 mm
Representative hole depth	25 m	30 m	38 m
Representative UCS	263 MPa	190 MPa	115 MPa
Rock factor, A	7.0	4.5	5.0

Source: *Prepared by the author based on consolidated operational data.*

3.2. Definition Of The Rock Factor

Rock factor **A** was assigned individually to each mine based on the available lithological, UCS, and rock mass structural information following the empirical blastability framework incorporated into the Kuz-Ram methodology.

The objective was to represent contrasting rock mass responses rather than derive the rock factor exclusively from UCS.

Mine A is characterized by highly competent rock conditions, with a representative UCS of approximately 263 MPa. Despite localized brecciation, the rock mass was considered predominantly competent for the representative modelling scenario. A rock factor of A = 7.0 was therefore adopted.

Mine B consists predominantly of dolomite and brecciated rock, with representative UCS of approximately 190 MPa. However, its rock mass exhibits greater structural control and fracturing than Mine A. Because discontinuities can facilitate fragmentation despite relatively high intact rock strength, a lower rock factor of A = 4.5 was adopted.

Mine C represents a heterogeneous VMS environment with polymetallic massive sulfides, moderate fracturing, and representative UCS of approximately 115 MPa. A rock factor of A = 5.0 was adopted to represent its intermediate geomechanical response.

These values should be interpreted as representative empirical parameters for comparative modelling rather than direct measurements of rock mass blastability.

3.3. Data Processing And Fragmentation Modelling

The operational variables were organized into five groups:

1. geomechanical conditions;
2. blast pattern geometry;
3. explosive and charging parameters;
4. drilling-related parameters; and
5. predicted fragmentation parameters.

Data processing included unit standardization, geometric consistency checks involving blasthole diameter, burden, spacing, and rock volume, identification and exclusion of inconsistent records, and consolidation by operation.

Blasthole cross-sectional area was calculated as:

$$Af = \frac{\pi D^2}{4}$$

where Af is the blasthole cross-sectional area, and D is the blasthole diameter.

Explosive mass per blasthole was calculated as:

$$Qe = L \cdot Af \cdot \rho$$

where ***L*** is the charged length and ***ρ*** is the explosive density.

The rock volume associated with each hole was calculated as:

$$V = B \cdot S \cdot H$$

where B is the burden, ***S*** is the spacing and ***H*** is the representative blasthole advance or length associated with the blasted volume.

Powder factor was calculated as:

$$k = \frac{Qe}{V}$$

The uniformity index was estimated using the empirical relationship adopted in the Kuz-Ram framework:

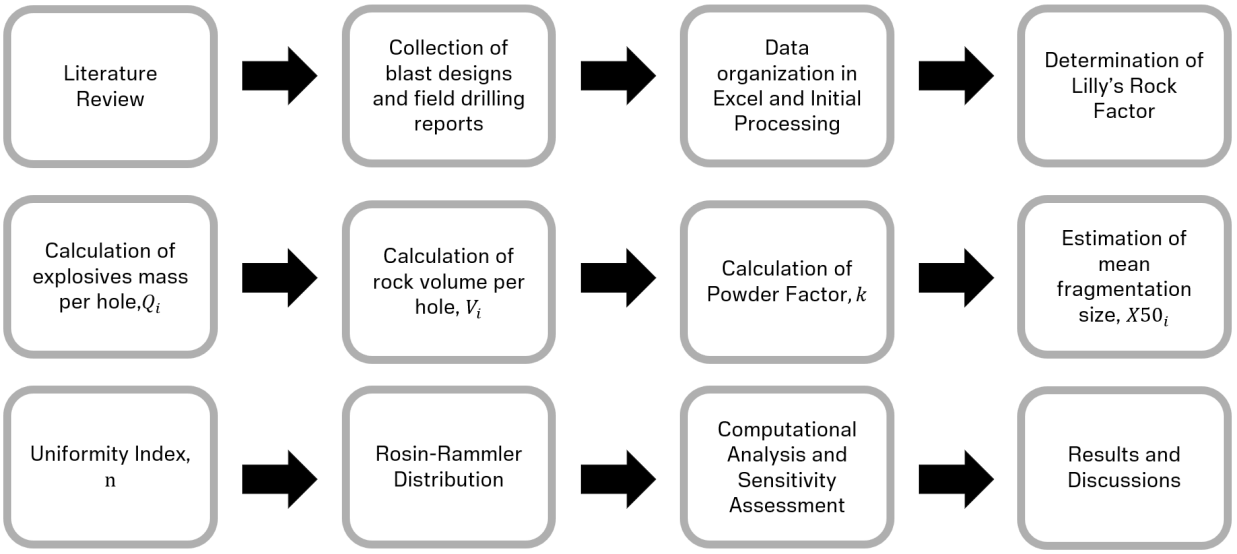
$$n = 2{,}2 - 14 \cdot \frac{d}{B}$$

where ***d*** is the blasthole diameter (m) and B is the burden (m).

The resulting values of Qe, k, and A were used to estimate X50. The calculated uniformity index was subsequently combined with X50 within the Rosin-Rammler distribution to determine Xc and P80.

The complete methodological procedure is summarized in Figure 1.

Figure 1. *Methodological workflow adopted in the study.*



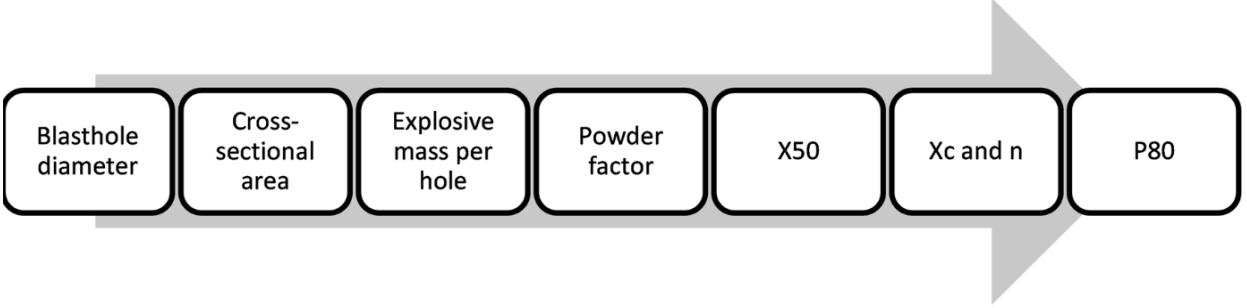
Source: *Prepared by the author.*

3.4. Controlled Blasthole Diameter Sensitivity Analysis

A deterministic sensitivity analysis was conducted to distinguish the model response specifically associated with blasthole diameter from the combined influence of variables that differ among actual mining operations.

For each mine, a representative baseline scenario was established. Burden, spacing, charged length, advance, explosive density, and geomechanical conditions were held constant while blasthole diameter varied between 76, 89, and 95 mm.

For each simulated diameter, the calculations were performed sequentially as follows:



Because the uniformity relationship contains the D/B ratio, changing blasthole diameter also produced a secondary change in **n** while

burden remained constant.

The purpose of this analysis was not to reproduce a complete blast redesign. In practice, a change in blasthole diameter would normally require reassessment of burden, spacing, charging conditions, drilling capability, and other design parameters. Instead, the sensitivity analysis represents a controlled numerical experiment designed to identify how the empirical fragmentation model responds when diameter changes independently of the other major operating parameters.

Therefore, the results should not be interpreted as recommendations to replace one blasthole diameter with another without redesigning the blast pattern.

This distinction between operational comparison and controlled sensitivity analysis is fundamental to interpretation of the results.

4. RESULTS AND DISCUSSION

4.1. Fragmentation Under Representative Operational Conditions

Application of the Kuz-Ram model to the representative operating scenarios produced substantial differences in predicted fragmentation among the three mines.

Mine B presented the lowest predicted X50 and P80 values, whereas Mine C presented the highest. The uniformity index varied over a relatively narrow interval, indicating predicted particle-size distributions with broadly similar shapes but different characteristic fragment sizes.

Table 2. *Predicted fragmentation parameters for the representative operational scenarios*

Scenario	Diameter	Qe (kg/hole)	V (m³)	k (kg/m³)	X50 (m
Mine A	76 mm	119.86	68.40	1.752	2.00
Mine B	89 mm	201.53	141.68	1.422	1.40
Mine C	95 mm	180.79	182.00	0.993	2.10

⚠ Esta tabela possui muitas colunas e foi cortada para impressão. Para visualizá-la completa, acesse o artigo original em: https://revistatopicos.com.br/artigos/blasthole-diameter-and-rock-fragmentation-in-underground-mining-distinguishing-operational-effects-from-diameter-sensitivity?noblockage

Source: *Prepared by the author.*

The intermediate 89 mm diameter used at Mine B produced the finest predicted fragmentation among the representative scenarios, with a P80 of 2.35 m. In contrast, Mine C, despite operating with the largest diameter of 95 mm, presented the coarsest predicted fragmentation, with a P80 of 3.43 m.

This result demonstrates that blasthole diameter does not independently govern fragmentation under operational conditions.

Mine B combines a relatively high explosive mass per blasthole with a powder factor compatible with its associated rock volume and a lower rock factor representing stronger structural control of the rock mass. Together, these conditions result in lower predicted X50 and P80.

Mine C presents a contrasting condition. Although its production blastholes have the largest nominal diameter, the associated rock volume is also relatively large and the calculated powder factor, 0.993 kg/m³, is the lowest of the three scenarios. Consequently, the available explosive mass relative to the associated rock volume is lower and the model predicts coarser fragmentation.

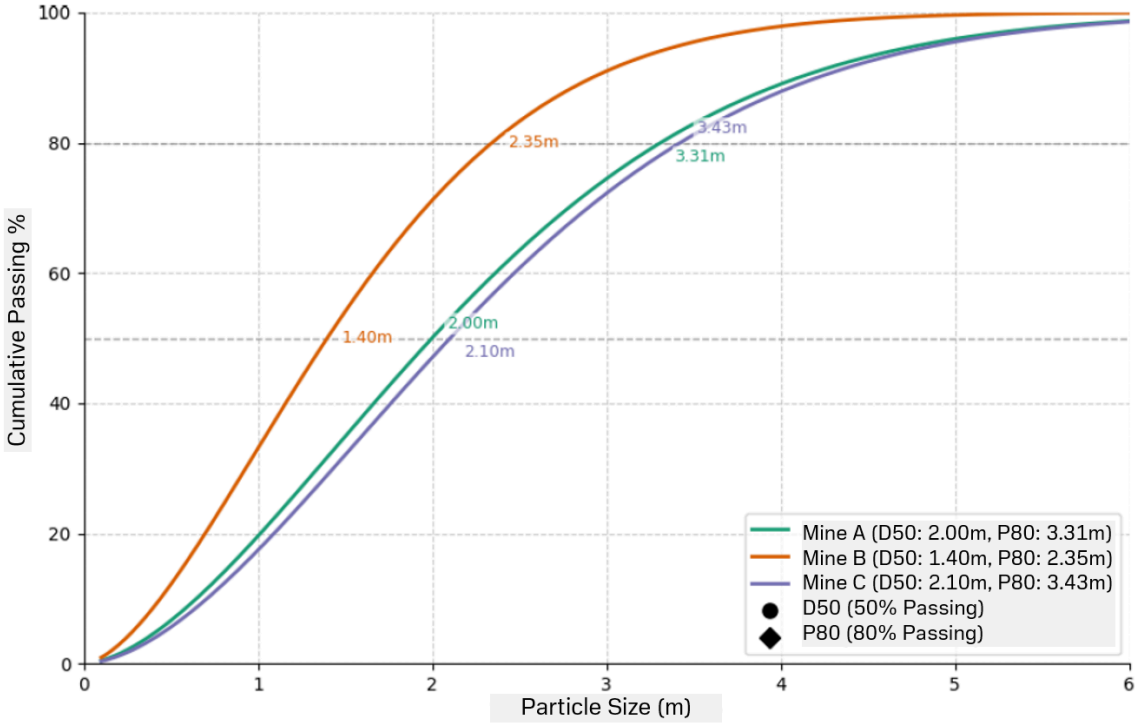
Mine A exhibits intermediate fragmentation behavior. Its relatively high powder factor is counterbalanced by the higher rock factor representing a more competent rock mass.

These results demonstrate why comparison based solely on nominal blasthole diameter could be misleading. The predicted fragmentation response reflects the combined relationship among diameter, explosive loading, associated rock volume, blast geometry, and rock mass response.

4.2. Predicted Particle-Size Distributions

The Rosin-Rammler distributions provide a more complete representation of the predicted fragmentation than individual X50 or P80 values.

Figure 2. *Particle-size distributions predicted by the Rosin-Rammler model for Mines A, B, and C, including D50 and P80.*



Source: *Prepared by the author.*

Mine B exhibits a clear shift toward smaller fragment sizes compared with Mines A and C. At a particle size of 2.0 m, the predicted cumulative passing fractions are approximately 63.2% for Mine B, 43.1% for Mine A, and 38.5% for Mine C.

The relatively similar uniformity indices, ranging from approximately 1.63 to 1.73, indicate that the principal differences among the predicted distributions are associated with fragmentation scale rather than substantial differences in distribution shape.

However, this similarity should not be interpreted as evidence of equivalent fragmentation uniformity in actual production blasts. The uniformity index was derived empirically from model inputs rather than measured directly in the field. The results therefore describe the behavior of the model under the representative input conditions.

4.3. Blasthole Diameter Sensitivity Analysis

The operational comparison includes simultaneous differences in rock mass conditions, blast geometry, explosive loading, and blasthole diameter and therefore cannot independently quantify the contribution of diameter.

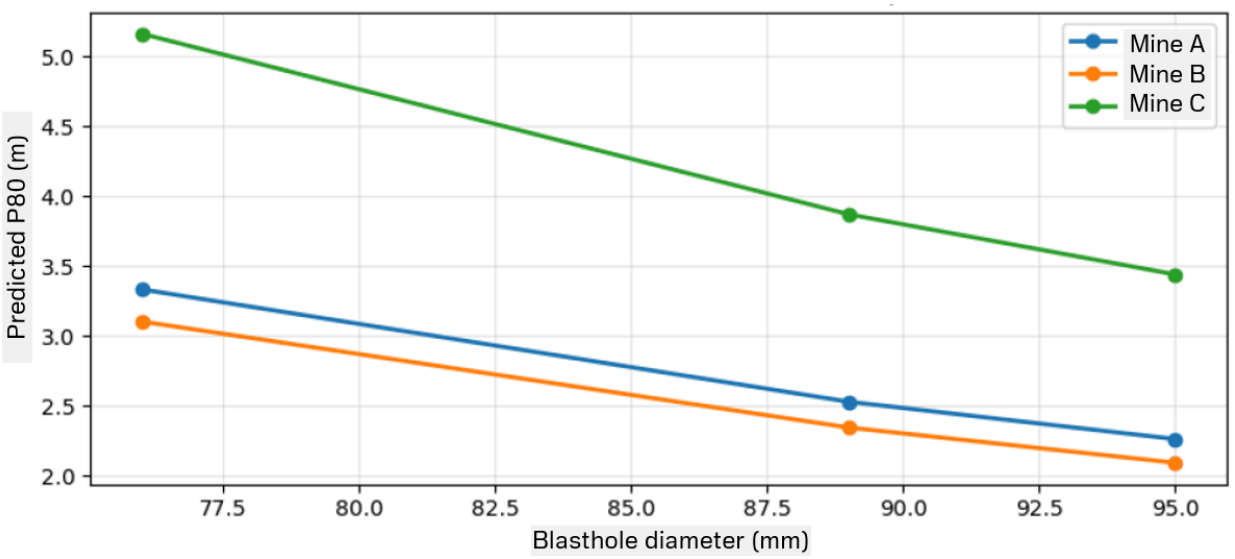
The controlled sensitivity analysis provides a complementary interpretation.

When the remaining operating parameters within each mine were held constant, increasing blasthole diameter increased the cross-sectional area available for explosive loading and consequently increased calculated explosive mass per blasthole. Because the rock volume associated with each blasthole was held constant in the analysis, powder factor also increased.

At the same time, changing diameter produced a secondary change in the calculated Rosin-Rammler uniformity index through the D/B relationship employed in the model.

The combined model response resulted in decreasing X50, Xc, and P80 as blasthole diameter increased in all three mine scenarios.

Figure 3. *Sensitivity analysis of predicted P80 as a function of blasthole diameter for Mines A, B, and C.*



Source: *Prepared by the author.*

For Mine A, increasing diameter from 76 to 89 mm reduced predicted P80 from approximately 3.33 to 2.53 m, corresponding to a reduction of approximately 24%. Increasing diameter to 95 mm reduced P80 to approximately 2.26 m, corresponding to an overall reduction of approximately 32% relative to the 76 mm baseline.

For Mine B, reducing diameter from the baseline condition of 89 to 76 mm increased predicted P80 by approximately 32%, whereas increasing diameter from 89 to 95 mm reduced P80 by approximately 11%.

For Mine C, reducing diameter from the baseline condition of 95 to 76 mm increased predicted P80 by approximately 50%, whereas reducing diameter from 95 to 89 mm increased P80 by approximately 12.5%.

Table 3. *Summary of predicted P80 sensitivity to blasthole diameter*

Mine	P80 - 76 mm (m)	P80 - 89 mm (m)	P80 - 95 mm (m)	Main variation
A	3.33	2.53	2.26	32.2% reduction from 76 to 95

				mm
B	3.10	2.34	2.09	10.8% reduction from 89 to 95 mm
C	5.16	3.87	3.43	50.1% increase when reducing from 95 to 76 mm

Source: *Prepared by the author.*

The sensitivity analysis initially appears to contrast with the operational comparison. Under the representative operating conditions, Mine C has the largest blasthole diameter but the coarsest predicted fragmentation. Under controlled sensitivity conditions, however, increasing diameter systematically reduces predicted P80.

These results are not contradictory. They represent two different analytical conditions.

The operational comparison represents the combined effect of blasthole diameter, blast pattern geometry, explosive loading, and rock mass conditions.

The controlled sensitivity analysis evaluates the model response to changes in diameter while the main operational and geomechanical parameters are constrained.

This distinction represents one of the central findings of the study.

The potential benefit associated with increasing blasthole diameter occurs when the additional loading capacity effectively increases

explosive energy per unit rock volume while blast geometry remains compatible with the larger diameter.

Therefore, increasing blasthole diameter does not inherently produce improved fragmentation.

If burden and spacing are increased simultaneously with diameter, the rock volume associated with each blasthole may increase sufficiently to offset the increase in explosive loading capacity. Similarly, blasthole deviation can modify actual burden and spacing and reduce the expected benefit of the nominal blast design.

The sensitivity analysis should therefore be interpreted as demonstrating the mechanism through which blasthole diameter can influence the empirical fragmentation response, rather than as evidence that the largest available blasthole diameter should be selected operationally.

4.4. Engineering Implications For Blasthole Diameter Selection

From an engineering perspective, blasthole diameter selection should jointly consider drilling method and available power, achievable penetration performance, blasthole length and deviation, burden and spacing, explosive properties and powder factor, rock mass characteristics, and downstream fragmentation requirements.

Larger diameters can provide greater explosive loading capacity and may reduce the number of blastholes required for a given production volume. However, these potential advantages depend on the capability of the drilling-and-blasting system to maintain compatible blast geometry and geometric accuracy.

Smaller diameters may require additional drilling but can distribute explosive energy through a larger number of charging locations. The optimal configuration therefore depends on the operational system rather than diameter alone.

This changes the engineering question from:

Which blasthole diameter produces the lowest P80?

to:

Which drilling-and-blasting configuration generates the required fragmentation while maintaining acceptable drilling productivity, geometric accuracy, explosive consumption, excavation quality, and downstream performance?

For underground long-hole applications, blasthole deviation deserves particular attention. A theoretically appropriate diameter cannot ensure expected blast performance if the final blasthole trajectory differs substantially from the design. Deviation alters effective burden and spacing and thereby modifies the actual spatial distribution of explosive energy.

Under some long-hole conditions, geometric deviations may therefore have a greater operational effect on fragmentation than relatively small differences in nominal blasthole diameter.

Diameter selection should consequently be accompanied by appropriate drilling accuracy control rather than treated solely as an equipment, drilling-consumable, or explosive-loading decision.

Ultimately, blasthole diameter should be regarded as a system-level drilling-and-blasting design variable whose engineering value depends on its compatibility with the complete operating system.

4.5. *Mine-To-Mill* Implications

The *Mine-to-Mill* concept provides an appropriate framework for interpreting these results because fragmentation establishes a direct connection between drilling and blasting decisions and downstream mining and processing performance.

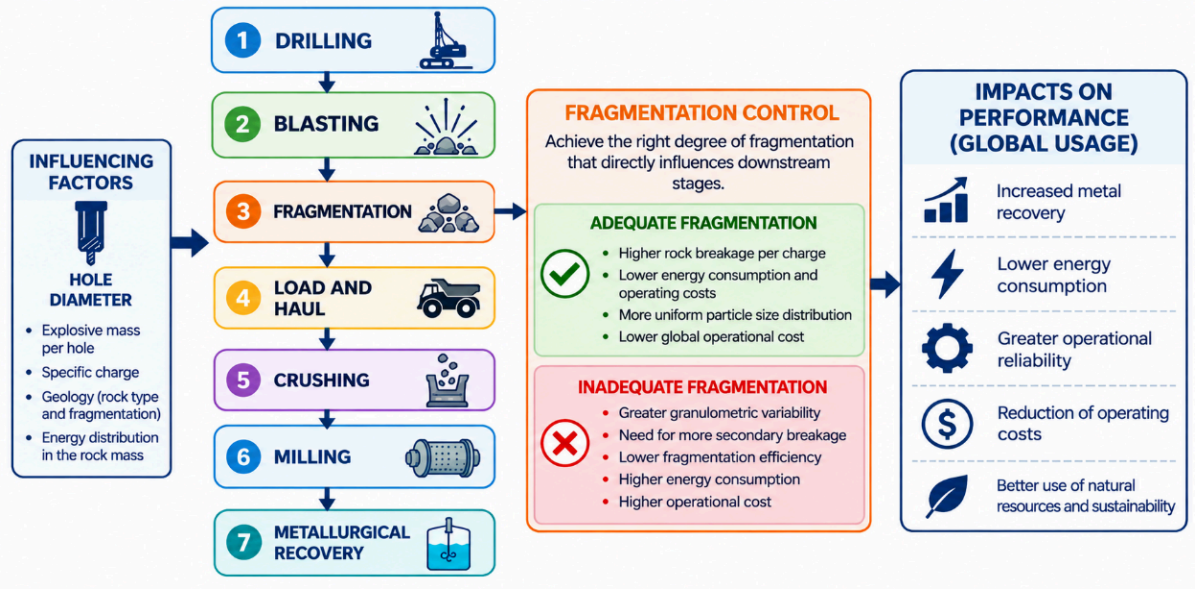
Coarse fragmentation can increase secondary breakage requirements, reduce loading efficiency, introduce handling constraints, and increase operational variability. Conversely, increasing explosive energy solely to minimize P80 is not necessarily optimal because excessive energy may increase fines generation, vibration, overbreak, dilution, and excavation damage.

Consequently, blast optimization should not target the minimum possible P80. Instead, the objective should be a particle-size distribution compatible with the operational requirements of the complete mining and processing system.

Increasing blasthole diameter may be advantageous when it reduces total drilling requirements or improves blast economics without compromising geometric accuracy or producing an unfavorable energy distribution. Conversely, a smaller diameter may remain advantageous where greater spatial control of explosive energy, drilling flexibility, or geometric precision is required.

The system-level relationships considered in this study are illustrated in Figure 4.

Figure 4. System-level influence of blasthole diameter on drilling, blast design, fragmentation, and downstream performance.



Source: Prepared by the author

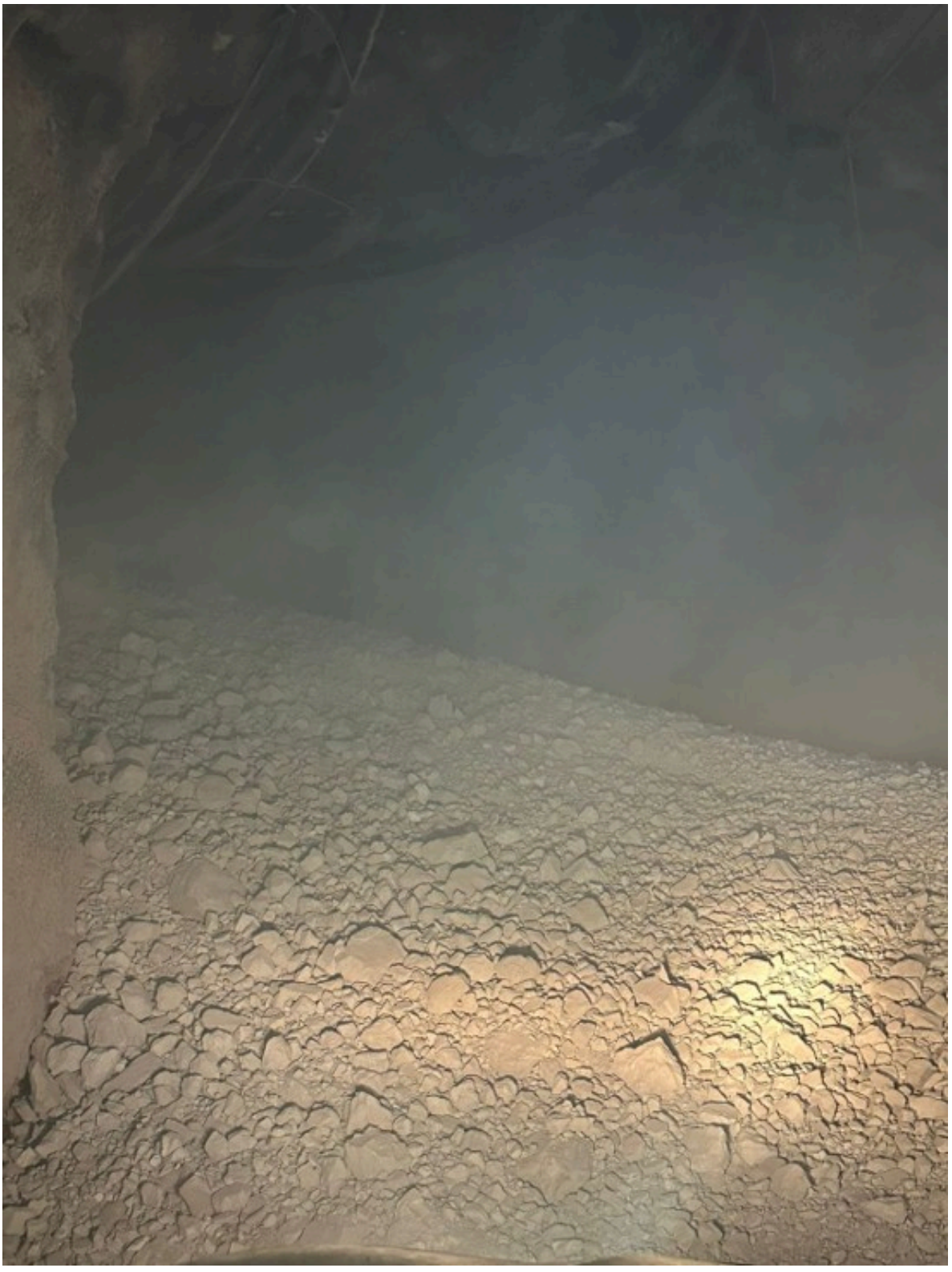
This framework reinforces the role of blasthole diameter as a connecting variable among drilling response, blast design, fragmentation, and downstream productivity.

It also supports a broader engineering philosophy: diameter selection should not be treated solely as a drilling decision. Instead, it should be considered jointly within drilling, blasting, geomechanical, and downstream process requirements.

4.6. Qualitative Comparison With Field Fragmentation

Field photographs from a blast performed using 89 mm production blastholes were examined as complementary evidence.

Figure 5. *Fragmentation observed after blasting with 89 mm production blastholes.*



Source: *Author's collection.*

Visual inspection indicates a predominance of small-to-medium-sized fragments and relatively limited occurrence of visually oversized blocks. These observations are qualitatively consistent with the modelled trend for Mine B, which presented the lowest predicted P80 among the representative operational scenarios.

However, the photographs were not originally acquired for quantitative particle-size characterization and did not include controlled calibration scales. Therefore, they cannot be used to calculate reliable field values of D50 or P80 or to quantitatively calibrate the Kuz-Ram model.

Exploratory WipFrag segmentation was used only to support visual interpretation of fragment boundaries. The resulting image analysis should therefore be regarded as qualitative supporting evidence rather than quantitative model validation.

The observed qualitative agreement between the field photographs and modelled fragmentation trend consequently does not demonstrate quantitative accuracy of the predicted P80.

4.7. Study Limitations

Several limitations should be considered when interpreting the results.

First, the operational scenarios represent consolidated conditions from three underground mines rather than controlled full-scale experimental blasts. Differences among the representative operating scenarios cannot therefore be attributed exclusively to blasthole diameter.

Second, the Kuz-Ram model is empirical and was not locally calibrated against quantitative particle-size distributions measured after blasting. The absolute X50 and P80 values should therefore be interpreted as model-based estimates rather than exact representations of field fragmentation.

Third, rock factors were assigned from the available geomechanical information and empirical blastability classifications. Although this provides a consistent basis for comparative modelling, uncertainty in the adopted rock factor directly influences predicted fragmentation.

Fourth, systematic blasthole deviation measurements were not available for all three scenarios. The calculations therefore use representative blast geometry and do not explicitly reproduce differences between designed and actual burden and spacing resulting from blasthole deviation.

Finally, although drilling performance is considered in the engineering interpretation, the present study does not provide a controlled quantitative comparison of ROP, tool life, drilling energy consumption, or drilling cost as a function of diameter. Conclusions concerning drilling performance should therefore be interpreted as engineering implications rather than results from a controlled drilling-performance experiment.

These limitations restrict the generalization of the absolute fragmentation predictions but do not invalidate the principal comparative objective of the study: distinguishing the combined effect associated with representative operating conditions from the isolated sensitivity of predicted fragmentation to blasthole diameter.

5. CONCLUSIONS

This study investigated the influence of blasthole diameter on predicted rock fragmentation in underground mining by combining representative operational data from three metal mines with Kuz-Ram fragmentation modelling and deterministic sensitivity analysis.

The results demonstrate that blasthole diameter is an important design variable but does not independently control fragmentation.

Under the representative operational conditions, the intermediate blasthole diameter of 89 mm produced the lowest predicted P80, whereas the 95 mm scenario produced the highest. This difference resulted from the interaction among explosive mass per hole, associated rock volume, powder factor, blast geometry, rock factor, and rock mass response rather than nominal blasthole diameter alone.

The controlled sensitivity analysis produced a different but complementary result. When burden, spacing, charged length, explosive density, and geomechanical conditions were held constant, increasing blasthole diameter increased explosive loading capacity and powder factor and consequently reduced predicted P80 in all three mine scenarios. Diameter also produced a secondary change in the uniformity index because n was calculated from the D/B relationship adopted in the model.

These findings are not contradictory. Instead, they demonstrate the fundamental difference between the isolated sensitivity of the fragmentation model to blasthole diameter and the effective influence of diameter within an actual drilling-and-blasting system.

Increasing blasthole diameter therefore does not inherently improve fragmentation. The potential benefit of a larger diameter occurs when the additional loading capacity translates into an appropriate increase in explosive energy per unit rock volume and when burden, spacing, charged length, and blasthole geometric accuracy remain compatible with the selected diameter.

From an engineering perspective, blasthole diameter selection should consider drilling capability, expected penetration performance, blasthole length and deviation, blast pattern geometry, explosive properties, powder factor, rock mass conditions, and downstream fragmentation requirements.

Attention should be given to blasthole geometric accuracy in underground long-hole applications. Deviations from the planned trajectory modify effective burden and spacing and can significantly alter explosive energy distribution. A theoretically appropriate blasthole diameter cannot produce the expected fragmentation when the actual blasthole geometry substantially differs from the design.

Within a Mine-to-Mill framework, the objective should therefore not be to maximize blasthole diameter, minimize P80, or maximize drilling productivity independently. Optimization should seek the drilling-and-blasting configuration that produces a fragmentation distribution compatible with the requirements of the complete mining and processing system.

Overall, the results indicate that there is no intrinsically optimum blasthole diameter. The engineering value of a given diameter depends on the compatibility among drilling capability and accuracy, blast geometry, explosive energy, rock mass conditions, and downstream fragmentation requirements. Blasthole diameter should therefore be treated as a system-level design variable rather than an isolated drilling parameter.

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