Arch. Min. Sci. **71** (2026), 2, 219-230

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI: https://doi.org/10.24425/ams.2026.158814

JACOPO SECCATORE[1*], MARILENA CARDU[2],
TATIANE MARIN[3], FERNANDO GOLIN[4]

A NEW VARIABLE FOR TUNNEL BLAST EFFICIENCY: THE ANGLES OF BREAKAGE OF EXPLOSIVE CHARGES

Tunnel excavation by drill and blast requires creating an effective opening cut to provide a free surface for subsequent rock breakage. While numerous studies have examined blast design parameters, the exact shape and dimensions of the rock volume assigned to each blasthole have yet to be recognised as critical variables. This study introduces the angle of breakage as a measurable parameter and evaluates its influence on tunnel advance efficiency in blast rounds with parallel-hole cuts. More than 60 tunnel blast designs, as recorded in the Atlas of Blasting Rounds for Tunnel Driving, were analysed. The angles of breakage were determined from blast layouts by using CAD tools and following the delay sequence. Only holes with defined initiation timing were considered. Contour holes and simultaneous delays were excluded. For each blast, the average angle of breakage was calculated and correlated with advance efficiency, defined as the ratio between actual pull (PR) and designed pull (PD). Measured angles ranged from 35° to 140°, with typical industrial averages above 50°. The results show a clear inverse relationship between the average angle of breakage and advance efficiency. A threshold behaviour was identified at approximately 60°, above which efficiency decreases systematically. The highest efficiencies were observed for average angles near 65°. Statistical analysis indicates that the angle of breakage presents a stronger correlation with efficiency (R^2 up to 0.67 for homogeneous lithological sets) than conventional design parameters such as burden, spacing, powder factor, or hole diameter. Three lithological clusters were identified. A heterogeneous set shows scattered behaviour. A second set, representing the majority of cases across mixed lithologies, exhibits a consistent inverse trend. A third set, composed mainly of competent intrusive igneous rocks, displays a more defined correlation between increasing angle and decreasing efficiency. These results indicate that lithology modulates the sensitivity of efficiency to geometric design parameters. The findings demonstrate that the angle of breakage is a relevant design variable for tunnel blasting. Increasing the angular width of the rock prism assigned to each blasthole increases resistance to breakage and reduces advance efficiency. Blast designs, based on narrower angles

[1] UNIVERSIDAD CATÓLICA DEL NORTE, CHILE
[2] POLITECNICO DI TORINO, ITALY
[3] UNIVERSIDAD TÉCNICA FEDERICO SANTA MARÍA, CHILE
[4] PHI ENGENHARIA DE, BRAZIL

* Corresponding author: jacopo.seccatore@ucn.cl

of breakage, provide more favorable conditions for rock fragmentation and displacement. The results support the inclusion of this parameter in blast design methodologies and in the interpretation of tunnel excavation performance.

Keywords: Explosives; tunneling; angle of breakage; drill and blast; pull efficiency

1. Introduction

The drill-and-blast technique is the most typical method of tunnel excavation for medium to hard rock conditions. Key features are versatile equipment, quick startup, and low equipment costs. The drill-and-blast method, being cyclic, demands effective site organisation. Blast vibrations and noise also restrict the use of drill and blast in urban areas [1]. However, tunnel excavation by drill and blast can achieve any shape of cross-section and any angle of the tunnel axis's horizontal and vertical curves.

To enhance explosive performance, it is necessary to produce a free face against which the shockwave induced in the rock can reflect to generate a tensile stress that breaks the rock; furthermore, said free surface enables the expansion of the broken rock. To provide this free face for the blast's production holes, an opening cut must be created; in the words of [2]: "The first holes in the sequence aim at creating an opening towards which the rest of the rock is successively blasted. This opening, the cut, is the key that opens the rock."

[3] analysed a database of tunnel blasts, dividing them according to the type of opening cut: "For simplicity's sake, two types are distinguished: i. parallel hole cuts: the initial cavity (cut volume) is prismatic; holes density and powder factor are practically constant along the cut length; dummy holes are usually needed; ii. inclined cut holes: the initial cavity is pyramidal or wedge-shaped (symmetrical or asymmetrical); the hole density and powder factor increase along the cut length, from the face to the end of the pull; dummy holes are not usually needed." The literature on the subject is vast and approaches the concepts of tunnel blasting rounds from different points of view. [4] discussed the opportunity of extending the dummy hole's length beyond the production hole's drilled pull to achieve better efficiency (for the concept of pull efficiency, see Section 1.1). [5,6] elaborated on the subject of rock damage related to the perimeter holes, suggesting charge and burden limits to manage the holes' radius of damage based on the response to seismic waves. [7] provided a formal procedure to calculate the charge of tunnel blasts considering the hole diameter-burden distance relationships to achieve a cleanly blasted rock. In the following, this method will be interpreted and integrated with that of [6,8] including parameters of the rock mass to be included in blast design: density of the intact rock, rock strength in terms of the Protodyakonov Index (generally regarded as 1/10 of the uniaxial compressive strength of the intact rock expressed in MPa), rock mass joint spacing, and joint orientation. [9] indicated that the fracturing conditions and orientation of the tunnel face influence the number of blastholes required per unit area of the tunnel, a result that agrees with [3] the concept of the difficulty of tunnelling. In [10,11], the reader can find critical discussions of rock-related and dimensionless parameters related to tunnelling efficiency. [15] showed the influence of rock mass quality indexes on the performance of tunneling, especially with respect to the contour and overbreak. [16] demonstrated an effective reduction in the confinement of blasting holes along the evolution of a parallel-hole opening cut, called a "burn cut." The present study focuses on tunnel blasts with parallel-hole cuts because of the concept of the angles of breakage, which is explained in Section 1.2 of this paper.

1.1. Tunnel efficiency

When a tunnel is excavated by drill and blast, a key issue is the efficiency of advance. The issue is the efficiency of breakage at the toe (bottom of the hole). The drilled length of the blastholes (designed pull, P_D) rarely breaks in its entirety. The actual pull (real pull, P_R) obtained by the blast is frequently lower, often leaving visible "sockets" (the bottom of the holes that remain unblasted and are therefore visible on the tunnel face). The ratio between the actual and designed pulls is the efficiency of advance (Eq. 1):

$$\eta = P_R / P_D \quad (1)$$

The goal of every blast is to achieve $\eta = 1$, which minimises the time and effort required to excavate the tunnel. [3] pointed out that a mere difference in η of 0.02 can be critical: "average $\eta = 0.93$ [compared to] $\eta = 0.91$ […]. The meaning of this difference can be explained as follows: for a drilled length of 4 m, it is about 8 cm of advance gained per blast; for a tunnel of 1 km, it means 6 fewer blasts necessary for the completion of the tunnel."

Finding parameters strictly related to pull efficiency is a difficult task. In order to achieve $\eta = 1$, [17] employed a multidisciplinary approach integrating geophysical exploration, geological modelling, and advanced software simulation.

[3] analysed a vast industrial database of tunnel rounds from around the world. The atlas [18] contained key geometric and charging parameters for the blasting patterns. Vis-à-vis variable research led to the conclusion that no direct correlation can be found between efficiency and any of the other variables in the database. As [3] wrote: "Blast pull efficiency is not linearly related to any variable in a univocal way. Tunnel driving is evidently a complex system […] General conclusions suggest that treating rock blasting with non-linear, holistic analysis can detect hidden patterns not detectable by traditional statistics. Research on pull efficiency would benefit from being oriented accordingly."

The original atlas contained the graphic schemes of the blast design, and among the annotated parameters, the timing, initiation sequence, burden, and breaking angle were visible in the blast plans but not listed in the database.

The present work consists of an analysis of the variables not previously considered, focusing on the most solid variable measurable in the database: the angle of breakage of every hole in the blast. The analysis focuses solely on blast schemes that use parallel hole cuts.

1.2. Angles of breakage

The angle of breakage is defined as the amplitude of the angle of the prism of the rock that a given hole is called to break during the blast. Fig. 1a provides a conceptual illustration of the angles at which breakage occurs, analysing the first round of a parallel hole opening cut with a single dummy hole. It is evident that the angles depend not only on the drilling pattern's geometry but also on the initiation sequence.

[19] were among the first to conceptualize the idea of the blastholes' prisms of competence, as shown in Fig. 1b. However, those authors did not investigate the angle of such prisms as a variable, as is done instead in the present study.

For the design of the initial cut, Olofsson [20], with similarities to the method of Holmberg [6], considered an evolution in quadrangles around a central dummy hole. He suggested the following steps for the design of the blast, considering the parameters indicated in Fig. 2.

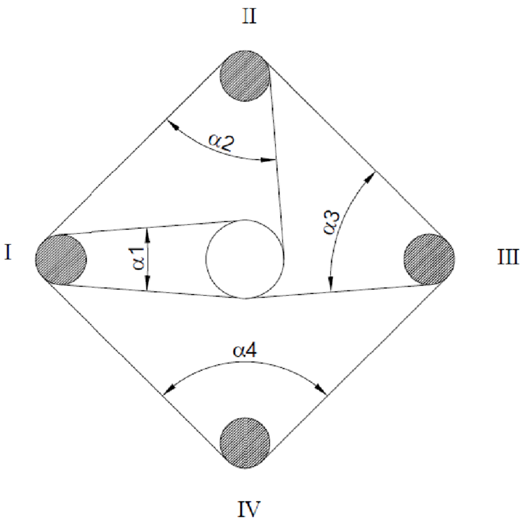

Fig. 1a. Conceptual visualisation of angles of breakage in a parallel-hole opening cut. Roman numerals (I, II, III, IV) indicate the delay sequence of initiation. Dashed: charged holes; white: dummy hole

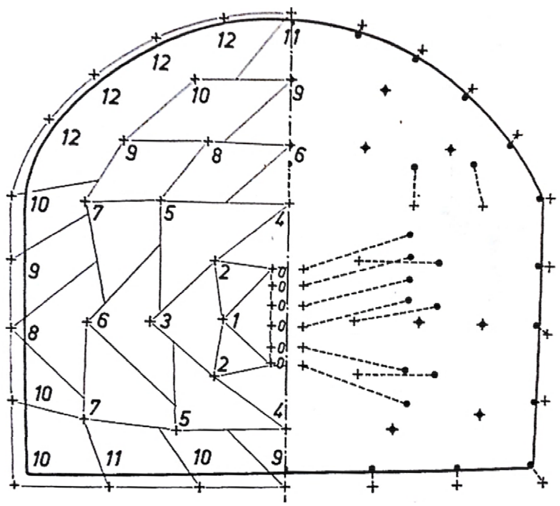

Fig. 1b. The concept of prisms of competence of every hole [19]. Graphically adapted for this publication

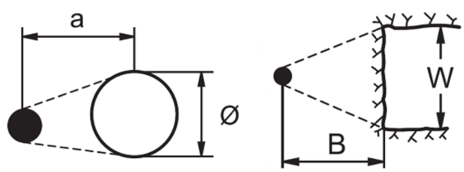

Fig. 2. Parameters for the design of the first quadrant of the cut. Adapted from [20]

For the first quadrangle (or square, or round) of the cut, the center-center distance between the dummy hole and the first charged hole is recommended according to Eq. (2).

$$a = 1 \div 2\varnothing \tag{2}$$

where ∅ is the diameter of the dummy hole, resulting in an approximate range of angles between 20° and 45°.

For the remaining quadrangles of the cut, the distance *B* between the surface of the previously created cavity and the center of the first charged hole is recommended according to Eq. (3).

$$B = 0.5 \div 1.5W \tag{3}$$

where *W* is the width of the cavity, resulting in an approximate range of angles between 40° and 90°.

The angles of breakage obviously tend to widen when developing beyond the area of the cut. This is shown in Fig. 3: a trend of evolution of the angles of breakage that increase according to the initiation sequence; the values shown in Fig. 3 are an average of the angles measured on the analysed blasts from the database. One observes that the angles of breakage increase from the opening cut to stoping holes. It is notable that the angles around the cut are well aligned along the trend while became somehow more scattered for stoping holes: this is due to the fact that the disposition of cut holes is more or less similar independent of the cut fashion, while the distribution of stoping holes is related to more aspects such as geometry, explosive used and necessity or not of smooth blasting for contour control.

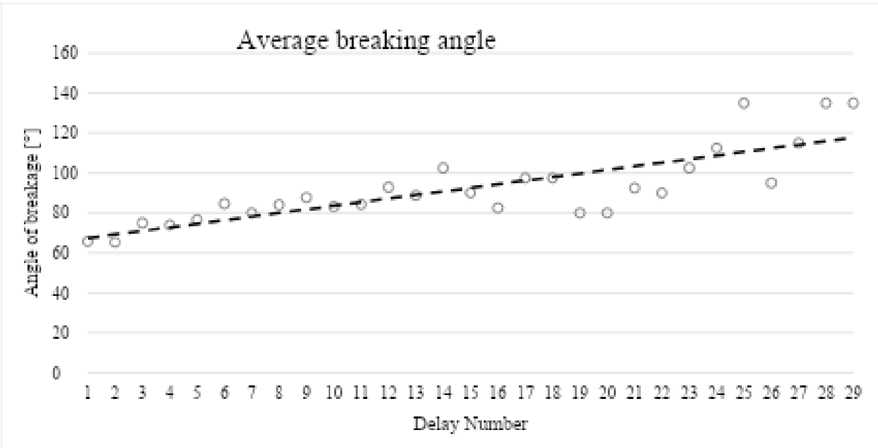

Fig. 3. Evolution of the width of the angle of breakage along the initiation sequence as an average of the analysed blast patterns

The present paper aims to answer two research questions:

1. Is the angle of breakage a significant variable in designing and evaluating tunnel blast performance?
2. How do the angles of breakage influence tunnel blast efficiency?

2. Materials and methods

To perform the present study, the following methodology was adopted to measure the breaking angles, as referred to in Fig. 4:

- The angles were measured according to their delay number, as shown in Fig. 4. After the opening cut (dashed), the first delays are 2, 3, 4, and 5. The figure shows the measurement method of the angles of breakage relative to holes with delays 4 and 5.
- When delays were not annotated on the blasting pattern, it was impossible to determine the angles of breakage, which would be the internal delays of the opening cut.
- When two adjacent holes were blasted simultaneously, the angle of breakage was not measured. i.e., the angles of breakage of the holes with delay numbers 2 and 3 were not taken.
- When simultaneous holes were distributed in the blasting pattern in such a way as to obtain different angles of breakage, the delay number was not taken into account.
- The angle of breakage of contour holes was not taken into account: this refers to delays 6, 7 and 8.

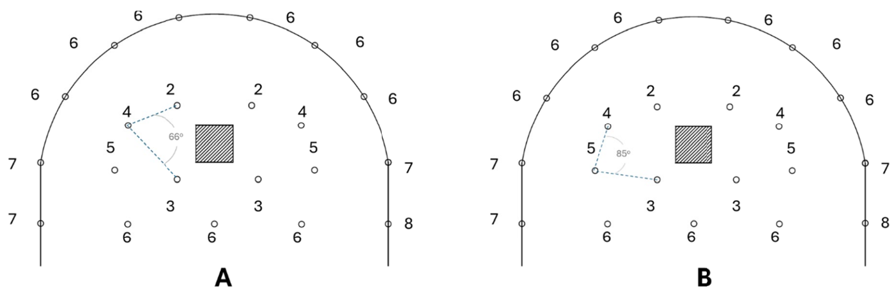

Fig. 4. Measuring the angles of breakage according to delay numbers using AutoCAD. A: Measuring the angle formed by points 2, 4, and 3 (66°) for the hole with delay number 4. B: Measuring the angle formed by points 4, 5, and 3 (85°) for the hole with delay number 5. Dashed lines: the opening cut

This was done for every blasting pattern with parallel hole cuts reported in the atlas [18]. Every blasting pattern is associated with the lithological type of rock through which the tunnel was driven. Therefore, it is possible to associate the angles of breakage with the lithotype, as shown in Fig. 5. For this, a bias must be noted: the original database created by [18] reported merely lithology and no information regarding the strength of the rock or the characteristics of the rock mass (fractures, joints, faults, and water, among others).

3. Results and discussion

Fig. 5 shows the obtained correlation between angles of breakage and pull efficiency for different sets of lithologies.

Each dot (angle of breakage) in Fig. 5 corresponds to the average of all angles measured on the blast face. This is an indicator of the general tendency of the prism shape (angle, width, burden) adopted in the blast design. The minimum value of the breaking angle measured on the

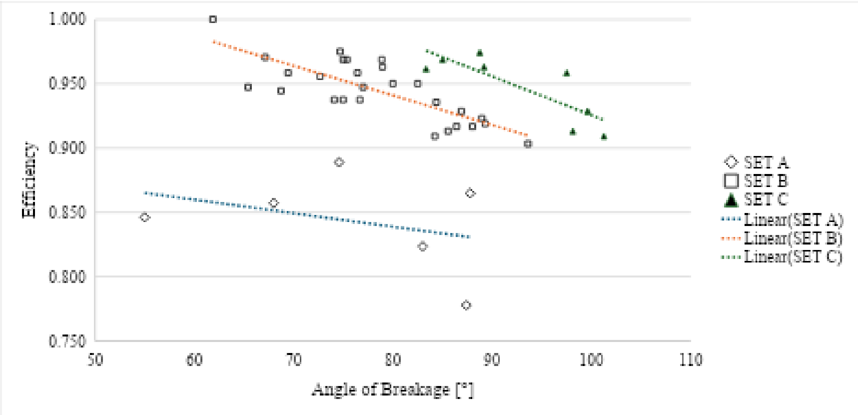

Fig. 5. Angles of breakage and efficiency of advance. The angle of breakage is the average of all the angles measured on the blast face

blast plans was 35°, and the maximum was 140°. A correlation appears above 60°: with a widened angle of breakage, the efficiency seems to decrease. Less clear correlations were encountered when plotting efficiency vs. the average angle of the cut or the angle of the first hole and are, therefore, not reported here for the sake of clarity of exposition.

Fig. 5 shows three clusters of points:

- SET A: outliers with heterogeneous lithology.
- SET B: data points grouped within a broad but consistent lithological spectrum, representing the main population of the dataset and capturing the general trend of blast performance across typical rock types.
- SET C: data points associated with high-strength, competent lithologies, predominantly intrusive igneous rocks, characterised by a distinct and more coherent response, with the exception of a fine-grained, high-resistance sedimentary rock (leptite).

TABLE 1 details the lithology of the points of the three clusters.

All sets show the same trend: lower efficiency for wider angles of breakage. Lithology also seems to play a crucial role. Whereas the outlier set comprises transversal types of lithology, a specific cluster can be isolated for highly competent intrusive rocks, such as granites and gneisses. This aspect needs further investigation.

As can be seen in TABLE 2, the only variables that show an individual (moderate) correlation with pull efficiency are the break angles of sets B and C. The low correlation in set A can be explained by the heterogeneity of the rock types. For example, the lithologies ‘Igneous mix’ and ‘Hematite’ have nearly the same average break angle, but their efficiency differs by 10 percentage points. Nevertheless, even in set A, a visual analysis suggests that pull efficiency and break angle are inversely proportional.

As commented above, the atlas did not give information regarding the characteristics of the rock mass [18]. For example, consider a system of joints in the rock that intersects the tunnel face at a determined angle; in such a case, the preferential planes of breakage are along the surfaces of these joints. The positioning of holes can favour or disfavour this preferential breakage (Figs. 6 and 7 from [21]).

TABLE 1

Lithology type associated with the angle of breakage, divided into the three data clusters

SET A		SET B		SET C	
Rock	**Average Angle of breakage**	**Rock**	**Average Angle of breakage**	**Rock**	**Average Angle of breakage**
Gneiss-granite	75	Mixed geology	62	Greywacke	101
Igneous mix	88	Granite	75	Leptite-pegmatite	100
Limestone	68	Mixed geology	67	Granite-gneiss	98
Gneiss	55	Slate	79	Igneous mix	98
Dacite	83	Leptite	75	Igneous mix	89
Hematite	87	Mixed geology	75	Granite	89
		Limestone jointed	79	Gneiss-granite	83
		Mixed geology	76	Granite	85
		Calcareous Schist	69		
		Mixed geology	73		
		Igneous mix	83		
		Gneiss-granite	80		
		Igneous mix	77		
		Granite	65		
		Granite	77		
		Granite	75		
		Shale	74		
		Mixed geology	84		
		Limestone	87		
		Granite	89		
		Sandstone	89		
		Granite-gneiss	88		
		Granite	86		
		Limestone	86		
		Greywacke	84		
		Mixed geology	94		

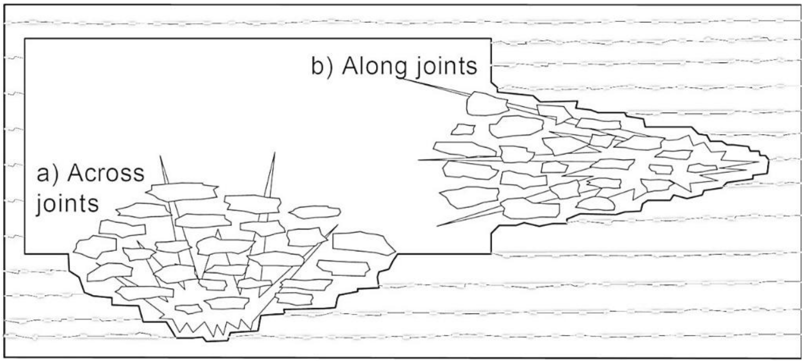

Fig. 6. Effects of joint orientation on the performance of holes. Adapted from [21]

TABLE 2

Coefficient of determination of the efficiency of the pull

Parameter	R^2	Parameter	R^2
Cross Section	0.09	Cut holes density	0.02
Design Pull	0.25	Cut Cross Section	0.13
Actual Pull	0.35	Cross section of dummy holes	0.09
Blasted Volume	0.14	Cut Volume	0.15
Charge	0.16	Rock Expansion Freedom – REF	0.03
Powder Factor	0.07	Cut REF	0.06
Linear charge	0.15	Sc/SS	0.08
Blastholes Diameter	0.18	Round slenderness	0.18
Dummy Holes Diameter	0.3	Cut Slenderness	0.18
Dummy Holes Number	–0.3	D2/D1	0.01
Blastholes number	0.08	Vc/V	0.08
Total number of holes	0.08	Angle of breakage – Set A	0.12
Cut blastholes number	0.01	Angle of breakage – Set B	0.61
Blastholes Density	0.01	Angle of breakage – Set C	0.67

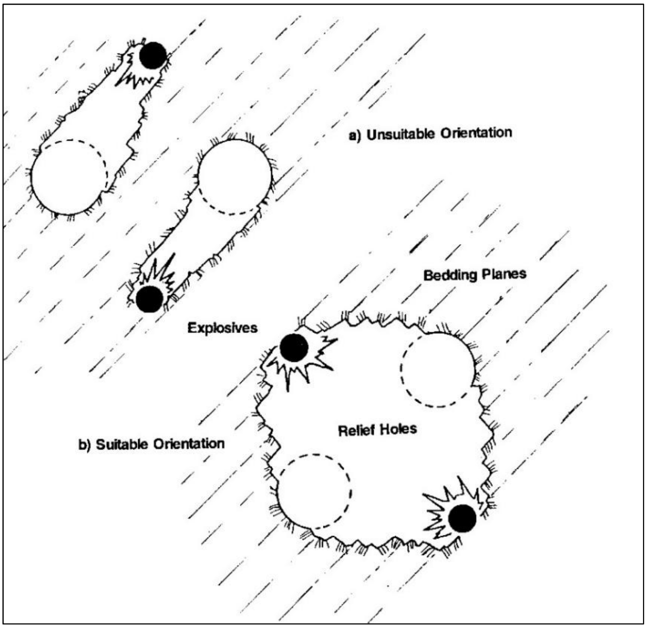

Fig. 7. Breakout angles in jointed rock. Adapted from [21]

Other authors have recently studied the versatility of drill and blast for tunnel excavation [22]. In agreement with our study, parameters considered critical to the successful excavation of rock masses include the amount and type of explosives, the drilling patterns, and the sequence of initiation [23-29]. [27] discussed the susceptibility to errors, inefficiency, and excessive demand for personnel deployment in tunnelling by drill and blast: this demonstrates the importance of a study like ours working on real field data that includes all field constraints encountered in the real cases. [28] considered the importance of real-time data acquisition of the tunnel face conditions while drilling. [29] clearly stated the importance of working on a multi-variable dataset such as the one we considered: “While there have been many individual studies on tunnel blasting, few studies have provided an overall pattern of tunnel blasting. Individual research efforts, while valuable, often lack a holistic view that synthesises these disparate findings into a coherent framework.”

[30] discussed the function of the cut holes, comparing a design method proposed by the Norwegian University of Science and Technology (NTNU) and another proposed by the Swedish school by the same authors [6,7,31]

[32] suggested, for a given blasthole diameter, arranging the burden and spacing to keep a constant charge concentration that has been calculated according to the most common literature sources. [31,33] also noted the influence of the rock’s structure and the distance between the charge hole and the dummy hole, as mentioned in the previous paragraph.

The firing pattern must be designed so that each hole has a free surface for breakage. The timing and sequence are also critical, and we recognise that our study does not take these aspects into account due to the unavailability of this parameter in the database we used. In the cut area, delays must be long enough to allow time for breakage and for rock to be thrown through the narrow dummy hole. Rock has been shown to move at a speed of 40-70 m/s [20]. A cut drilled to a depth of 4-5 m would therefore require a delay time of 60-100 ms to be cleaned. Normally, delay times of 75-100 ms for the cut and 100-500 ms for the stopping holes are of general use.

4. Conclusions

This study introduces the **angle of breakage** as a geometric parameter for the analysis and design of tunnel blast rounds with parallel-hole cuts. The parameter defines the angular width of the rock prism assigned to each blasthole and represents a direct measure of the resistance that the explosive charge must overcome during breakage and displacement.

The analysis of an industrial dataset of tunnel blasts shows that the angle of breakage is systematically related to advance efficiency. Measured angles range between 35° and 140°, with typical average values above 50°. The results indicate the existence of a threshold behaviour: for average angles above approximately 60°, a progressive reduction in efficiency is observed. The highest efficiencies are associated with average angles close to 65°.

The correlation between angle of breakage and efficiency is stronger than that observed for conventional design variables. Coefficients of determination up to 0.67 were obtained for lithologically consistent datasets. This indicates that the geometric configuration of the breakage prism is a controlling factor in blast performance.

The influence of lithology is evident. Three data clusters were identified. Heterogeneous lithologies show dispersed behaviour. Mixed lithologies define a consistent inverse trend between angle and efficiency. Competent intrusive rocks show a more pronounced response, indicating higher sensitivity to geometric constraints. This suggests that the angle of breakage interacts with rock strength and structure, affecting the mechanism of failure.

From a mechanistic standpoint, the angle of breakage governs the balance between two resisting components: (i) the burden, defined as the distance to the free surface, and (ii) the lateral resistance associated with the width of the rock prism. Increasing the angle increases the volume and confinement of the prism, requiring higher energy for breakage and reducing the effectiveness of stress wave reflection and gas expansion. Narrower angles reduce lateral resistance and promote more efficient fragmentation and displacement.

The results support the following implications for design and analysis:

- The angle of breakage constitutes an independent design variable and should be explicitly considered in blast geometry definition.
- Blast designs that impose wide prisms of competence, particularly with obtuse angles, tend to reduce advance efficiency.
- Optimal performance is associated with controlled angular configurations rather than maximisation of burden or charge concentration alone.
- The parameter provides a framework to reinterpret existing blast designs and to compare performance across different geological conditions.

The study is subject to limitations related to the available dataset. The absence of detailed rock mass characterisation (jointing, fracturing, in situ conditions) and precise timing information limits the resolution of the analysis. These factors are expected to interact with the angle of breakage and should be incorporated in future work.

Further research should focus on integrating the angle of breakage with rock mass properties and initiation timing, as well as on validating the observed trends through controlled field experiments and numerical modelling. The inclusion of this parameter in design methodologies has the potential to improve the prediction of blast performance and reduce variability in tunnel advance.

References

[1] Ö. Satici, A. Hindistan, Drilling and blasting as a tunnel excavation method. Middle East Tech. Univ., Dept. Geol. Eng., Ankara, Turkey, **24** (2006).

[2] U. Langefors, B. Kihlstrom, The modern technique of rock blasting. 2nd ed., Almqvist & Wiksells, Stockholm, Sweden (1964).

[3] M. Cardu, J. Seccatore, Quantifying the difficulty of tunnelling by drilling and blasting. Tunn. Undergr. Space Technol. **60**, 178-182 (2016). DOI: https://doi.org/10.1016/j.tust.2016.08.010

[4] T.N. Hagan, Understanding the burn cut – A key to greater advance rates. Trans. Inst. Min. Metall. Sect. A – Min. Ind. **89**, A30-A36 (1980).

[5] R. Holmberg, P.A. Persson, The Swedish approach to contour blasting. Proc. 4th Annu. Conf. Explos. Blast. Res., Int. Soc. Explos. Eng., Warrensville Heights, OH, USA, 113-127 (1978).

[6] R. Holmberg, P.A. Persson, Design of tunnel perimeter blasting patterns to prevent rock damage. Trans. Inst. Min. Metall. Sect. A – Min. Ind. **89**, A37-A40 (1980).

[7] R. Holmberg, Charge calculations for tunnelling. In: Underground mining methods handbook. Soc. Min. Eng. Am. Inst. Min. Metall. Pet. Eng., New York, NY, USA, 1580-1589 (1982).

[8] A.K. Ghose, Design of drilling and blasting sub systems – A rock classification approach. Proc. Symp. Mine Plann. Equip. Sel., Balkema, Rotterdam, 335-340 (1988).

[9] T.N. Hagan, Safe and cost-efficient drilling and blasting for tunnels, caverns, shafts and raises in India. Golder Associates Pty Ltd., Adelaide, Australia (1992).

[10] R. Mancini, P. Moser, M. Cardu, F. Gaj, An analysis of parallel holes cuts performances, based on dimensionless ratios. Proc. Int. Congr. Explos., EFEE, Leeds, UK, 75-91 (1994).

[11] A.K. Chakraborty, P. Pal Roy, J.L. Jethwa, R.N. Gupta, Blast performance in small tunnels – A critical evaluation in underground metal mines. Tunn. Undergr. Space Technol. **13**, 331-339 (1998).
DOI: https://doi.org/10.1016/S0886-7798(98)00059-5

[15] N. Innaurato, R. Mancini, M. Cardu, On the influence of the rock mass quality on the quality of the blasting work in tunnel driving. Tunn. Undergr. Space Technol. **13**, 81-89 (1998). DOI: https://doi.org/10.1016/S0886-7798(98)00027-3

[16] A. Godio, J. Seccatore, Measuring the reduction of the confinement along the evolution of a burn cut. Appl. Sci. **9**, 5013 (2019). DOI: https://doi.org/10.3390/app9235013

[17] T. Bernard, A.D. Butron, How to achieve 100% advance in tunnel. Proc. 43rd Annu. Conf. Explos. Blast. Tech., Orlando, FL, USA, 319-329 (2017).

[18] R. Mancini, F. Gaj, M. Cardu, Atlas of blasting rounds for tunnel driving. Politeko, Torino, Italy (1998).

[19] U. Langefors, B. Kihlstrom, The modern technique of rock blasting, 2nd ed., Almqvist & Wiksells, Stockholm, Sweden (1964).

[20] S.O. Olofsson, Applied explosives technology for construction and mining. APPLEX, Arla, Sweden (1988).

[21] Orica, Safe and efficient blasting in underground metal mines. Tech. Serv., Orica Australia Pty Ltd., Stockrington, NSW, Australia (1999).

[22] H. Wang, Z. Qi, Y. Zhao, Numerical analysis and application of large-diameter cavity parallel cut blasting stress field in vertical shaft. Chin. J. Rock Mech. Eng. **34**, 3223-3229 (2015).

[23] Z.Y. Zhao, Y. Zhang, H.R. Bao, Tunnel blasting simulations by the discontinuous deformation analysis. Int. J. Comput. Methods **8**, 277-292 (2011). DOI: https://doi.org/10.1142/S0219876211002599

[24] G.M. Foderà, A. Voza, G. Barovero, F. Tinti, D. Boldini, Factors influencing overbreak volumes in drill-and-blast tunnel excavation. A statistical analysis applied to the case study of the Brenner Base Tunnel – BBT. Tunn. Undergr. Space Technol. **105**, 103475 (2020). DOI: https://doi.org/10.1016/j.tust.2020.103475

[25] G.H. Zhang, W. Chen, Y.Y. Jiao, H. Wang, C.T. Wang, A failure probability evaluation method for collapse of drill-and-blast tunnels based on multistate fuzzy Bayesian network. Eng. Geol. **276**, 105752 (2020). DOI: https://doi.org/10.1016/j.enggeo.2020.105752

[26] A. Alipour, M. Mokhtarian, RSM-based model to estimate the V-cut drill and blast pattern specific charge in rock tunneling. Int. J. Geomech. **21** (11), 06021030 (2021). DOI: https://doi.org/10.1061/(asce)gm.1943-5622.0002180

[27] H. Huang, P. Li, C. Wang, B. Yuan, M. Chen, W. Feng, Research and analysis on the influence of small clear distance drilling and blasting method on the existing tunnel structure. Adv. Civ. Eng. (2021). DOI: https://doi.org/10.1155/2021/4730936

[25] Z. Sun, D. Zhang, Q. Fang, Technologies for large cross-section subsea tunnel construction using drilling and blasting method. Tunn. Undergr. Space Technol. **141**, 105161 (2023). DOI: https://doi.org/10.1016/j.tust.2023.105161

[26] W. Niu, X.T. Feng, Z. Yao, X. Bi, C. Yang, L. Hu, W. Zhang, Types and occurrence time of rockbursts in tunnel affected by geological conditions and drilling & blasting procedures. Eng. Geol. **303**, 106671 (2022). DOI: https://doi.org/10.1016/j.enggeo.2022.106671

[27] T. Kuzu, D. Leitner, Z. Zhao, The drilling and blasting tunnelling documentation process – Best practice and an integrated digital management approach. In: S. Brell-Cokcan, T. Adams (Eds.), Constr. Robot.: Res. Driven Proj., RWTH Aachen Univ., Aachen, Germany, 122-135 (2023). DOI: https://doi.org/10.18154/rwth-2023-04081

[28] M. Wang, S. Zhao, J. Tong, Z. Wang, M. Yao, J. Li, W. Yi, Intelligent classification model of surrounding rock of tunnel using drilling and blasting method. Undergr. Space **6** (5), 539-550 (2021). DOI: https://doi.org/10.1016/j.undsp.2020.10.001

[29] B. He, D.J. Armaghani, S.H. Lai, X. He, P.G. Asteris, D. Sheng, A deep dive into tunnel blasting studies between 2000 and 2023 – a systematic review. Tunn. Undergr. Space Technol. **147**, 105727 (2024). DOI: https://doi.org/10.1016/j.tust.2024.105727

[30] S. Zare, A. Bruland, Comparison of tunnel blast design models. Tunn. Undergr. Space Technol. **21**, 533-541 (2006). DOI: https://doi.org/10.1016/j.tust.2005.09.001

[31] P.A. Persson, R. Holmberg, J. Lee, Rock blasting and explosives engineering, 6th printing, CRC Press, Boca Raton, FL (2001).

[32] O. Yilmaz, Drilling and blasting designs for parallel hole cut and V-cut method in excavation of underground coal mine galleries. Sci. Rep. **13**, 2449 (2023). DOI: https://doi.org/10.1038/s41598-023-29803-6

[33] A. Teller, Uniform rock classification system for blasting. Proc. III Geo-Eng. Congr. Rock Excav., GEAM, Torino, Italy, 43-50 (1992).