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Performance analysis of parallel hole-cuts based on dimensionless ratios

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ABSTRACT: For over 150 years, a wide array of parallel hole-cut patterns for tunnel driving has been designed, tested, and (successfully) used. The geometrical aspect of the parallel cut problem is crucial, and the paper, in its first part, meticulously analyses the correlations linking dimensionless ratios (characterising the patterns) to performance indicators. This rigorous and comprehensive procedure is the most logical way to derive practical general-purpose design rules from the vast array of successfully used patterns. The statistical basis for this analysis is derived from literature and directly observed cases, further enhancing the reliability of the proposed rules. The second part of the paper delves into the sensitivity of pattern performance to drilling precision, a critical factor in pattern selection. Drawing from literature and observed cases, the paper proposes tolerance standards for drilling machinery related to drilling pattern features and highlights their immediate practical relevance. These standards, when implemented, can significantly improve the efficiency and effectiveness of tunnel excavation, demonstrating the practical relevance of this research. The paper succinctly summarizes the investigation's key findings in the concluding remarks. It highlights the general guidelines and correlations that have emerged from the analysis. These insights guide future tunnel excavation projects, providing a direction for further research and practical application.

1 FOREWORD

Parallel hole rounds represent a heterogeneous family of drilling and blasting patterns, employed mostly for small - medium cross-section tunnel excavation, having as common features the more or less perfect parallelism of the holes to the tunnel axis and the presence of dummy (uncharged) holes. Examples are known since 1865 (the pilot drift of the Frejus railway tunnel) and, therefore, this blasting method can be considered a mature technology; the variety of schemes devised and applied comes mainly from two reasons: first, the variety of theories of the dummy holes role (Olofsson, 1990; Cardu and Seccatore, 2016; Ramulu, 2012) on which the designs rest: to allow for rock bulking, to weaken the rock locally, to locate breakage surface, to determine breakage angle; second, the fact that, for practical reasons, the so-called blast design is taken as a "suggestion" rather than as a "design" by the operators, and is unavoidably subjected, besides of inaccuracies, to adaptations and trial and error adjustments (briefly to "mutations" and to "selective evolution").

Anyhow, when the result is judged in the light of a simple success indicator as the efficiency "η" (computed as the ratio of the actual pull to the drilled length), good results are usually obtained, and often excellent results, independent of the principles on which the design rests.

Mature technology is intended to allow revolutionary changes to be no longer expected but to progress through refinements of the single steps of the production process and the materials and machinery employed. Indeed, the 1865 Frejus pattern, in the gunpowder/reciprocating drill era, designed for 1 m pull, already encompasses the principles of subsequently proposed and employed working schemes. If technology is seen in an "evolutionary" rather than in

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a “revolutionary” framework, a statistical analysis of the schemes adopted and of the results obtained can provide some useful suggestions and hints, both in the design and in the evaluation of the results.

A mature technology has two interesting features: a large statistical basis (population of cases) is available for the investigation, and the best-fit practices have had ample time to develop and be selected by operators. Hence, the most frequently observed technical solutions have a good chance to be the best-fit solutions. It was then decided to develop a statistical analysis of the main features of rounds in tunnel driving since 1960, almost one century later than the first known use of the technique, which warrants only mature cases to be considered. The main features of the population investigated are shown in Figure 1, which deserves some comments, as the population examined is a biased sample of the overall population:

(a) Published data, the bulk of the data used in the analysis, preferentially refers to successes. That is shown by the η frequency histogram, where cases with efficiency lower than 0.85 are practically absent.
(b) The cross-section to which parallel hole rounds usually apply is small, less than 20 m^2, which means, in most cases, parallel holes are used in mine operations, to a lesser extent in civil works operations. The histogram reflects this general commonplace knowledge, but the quantitative conclusion that could be drawn from the histogram (70% of cases of parallel hole rounds are mining works, 30% civil works) is unsupported.
(c) Any conclusion drawn from the statistical analysis resents the above-explained bias.

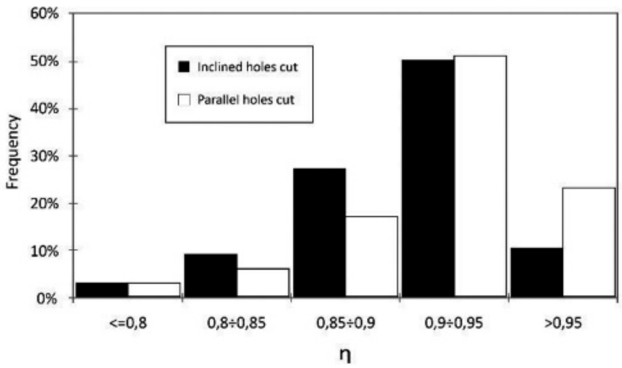

Figure 1. Frequency distribution of the round efficiency in the population examined.

Anyhow, statistics describes or, at best, suggests explanations but does not provide explanations. Rock types cover the whole range of geologic materials suitable for tunnel driving by drilling and blasting.

2 GENERAL CRITERIA OF THE STATISTICAL ANALYSIS

Referring to the geometrical features, a simplified description of the parallel hole rounds had to be adopted due to the huge variety of structures and details of the blasting patterns examined. The first simplification considers only two functional groups of blast holes: cut and production. Usually, the holes composing the pattern are classed by function as cut, easers, production, crown contour, side contour, and lifters. The function of the cut holes is to crush finely and eject the rock in the direction of the tunnel axis, while the production holes break to a coarser size and move the rock sideways.

The cut/production and the production/contour borderlines are not sharp: “production holes” are also intended, to some extent, to eject axially (easers) and a part just to split along the contour holes surface and move sideways the rock (contour holes); anyhow, the main roles can be distinguished in the above quoted simplified way. By cut holes, the minimum number of charged holes needed to surround the initial opening provided by the dummy holes is intended; among the cut holes, the z holes (the first simultaneously firing holes, having only the dummy hole/holes as a relief) and the other cut holes, in principle profiting of the relief provided by the z holes (Figure 2, left) are intended.

In the excavation cross-section (Figure 2, right), the distinction is made between Ss, i.e., the overall excavation cross-section, and Sc, the cross-section belonging to the cut.

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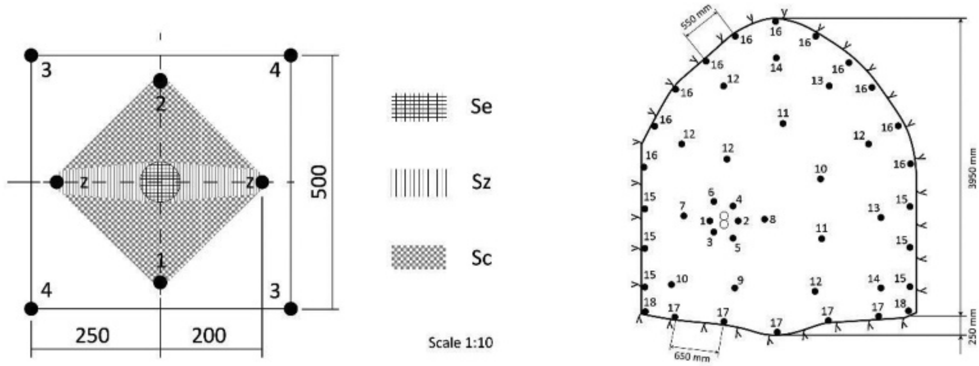

Figure 2. Left: explanation of the criterion adopted to define the cut cross-section (Mancini and Cardu, 2001). Within Sc, the dummy hole cross-section Se and the cross-section Sz of z holes are further distinguished. The measures are in mm. Right: an example of the overall cross-section Ss (Berta, 1990).

The analysis has not been carried out on the values of the above-defined cross-sections but on the dimensionless ratios, as explained in Table 1. Specific drilling (m/m^3, which coincides for parallel hole rounds with hole densities, n holes/m^2) and powder factor (g/m^3) have been separately considered for the whole round and the cut. As an indicator of the success of the blasts, the actual pull/drilled length ratio (efficiency η) has been used, as already explained. The symbols employed are explained in Table 1.

3 THE INFLUENCE OF THE CROSS-SECTION ON SPECIFIC CONSUMPTIONS

The cross-section area, as generally known, is the most important parameter in determining the specific consumptions both in terms of specific drilling and powder factor (Mei et al., 2021; Cardu et al., 2024); the correlation, more or less hyperbolic, of specific consumptions to cross-section is noticeably sharper for the specific drilling than for the powder factor, which is not surprising, being the desired rock fragmentation more strictly controlled by the distribution of the explosive in the rock, hence by holes density than by the powder factor. The same trend holds for the whole round (Figure 3) and the cut, separately considered (Figure 4).

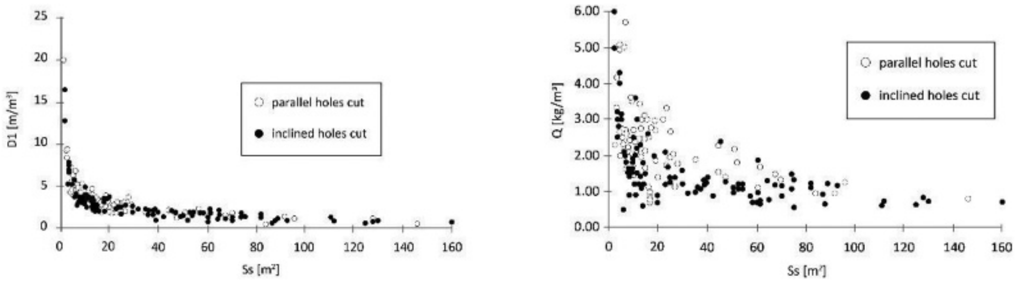

Figure 3. Left: Specific drilling for different tunnel areas in the population examined; right: Powder factor Vs. tunnel areas in the population examined.

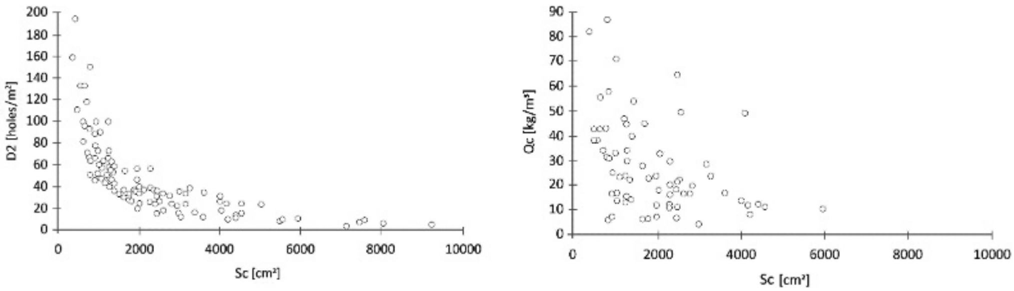

Figure 4. Left: Specific drilling Vs the cross-section of the cut in parallel hole cuts; right: Powder Factor Vs the cross-section of the cut in parallel hole cuts.

Table 1. The number of officially reported plague cases in the world.

Symbol	Units	Explanation
Q	kg/m^3	Overall design powder factor
Qc	kg/m^3	Design powder factor of the cut section
Ss	m^2	Excavation cross-section
Sc	m^2	Cut cross section (see Figure 2)
Sz	m^2	Cross section assigned to z holes (see Figure 2)
Se	m^2	Cumulated cross-section of the dummy holes
La	m	Actual pull
Ld	m	Drilled length
N1	m^{-2}	Number of holes in the round
N2	m^{-2}	Number of holes in the cut
D1	-	N1/Ns, hole density of the round
D2	$holes/m^2$	N2/Sc, hole density of the cut
η	-	La/Ld, efficiency of the blast
R1	-	Se/Sz
R2	-	Sz/Sc
R3	-	Sc/Ss
R4	$m/(m^2)^{1/2}$	$Ld/Ss^{1/2}$, the slenderness of the round
R5	$m/(m^2)^{1/2}$	$Ld/Sc^{1/2}$, the slenderness of the cut
R6	-	D2/D1, holes density ratio
R7	-	Qc/Qs, powder factor ratio

4 FREQUENCY DISTRIBUTION OF THE RATIOS R1 TO R7

The histograms essentially reflect the popularity of the round design styles.

It seems reasonable to postulate that in a successful cut, the empty space provided by the dummy holes to help the z holes open the first breach should be in a slightly constant ratio to the volume assigned to the z holes; what is observed does not confirm this expectancy.

R1 varies in a wide range (see Figure 5); a secondary frequency peak at 0.4 - 0.5 represents the influence on designers of the Langefors - Kihlström (1967) treatise, where ratios in this range are indirectly advocated; another peak at 0.6 - 0.7 probably represents the popular Coromant cut family, but the majority of the population is in the 0.1 - 0.3 range, which means that most designers consider dummy holes merely as a device to weaken the rock in the middle of the cut.

Apart from cases where R2~1 (conventional burn cut blasts, still in use but uncommon), the frequency of R2 peaks rather sharply in the 0.1 - 0.2 range, the same as where R1 peaks (see Figure 5).

In principle, no reasons exist to prefer a particular R3 value (1 m^2 cut can be as good for a 5 m^2 drift as for a 50 m^2 tunnel); however, the distribution peaks around 0.01 (Figure 6, left). The main reason is that small cross-section works, up to 20 m^2, are disproportionately represented in the population. Indeed, the R3/Ss plot (Figure 6, right) shows that two styles of cut design exist.

At low values of Ss (up to 20 m^2, which typically means in mine works), the general trend is a steep growth of Sc as Ss grows, which means operators tend to widen the cut as the cross-section of the tunnel increases. In contrast, for large cross sections (typically in civil works), scattered values of Sc suggest a mild growing trend. The reason for the two styles should reside in differences between the available machinery and preferred cyclograms in the two kinds of operations.

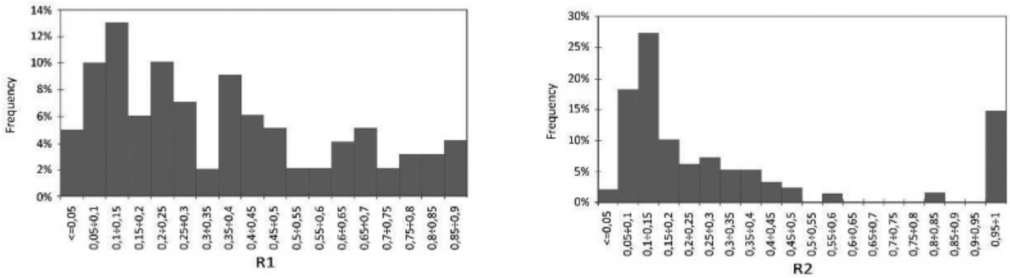

Figure 5. Left: Parallel hole cut rounds. Frequency distribution of R1 values; right: Parallel hole cut rounds. Frequency distribution of R2 values.

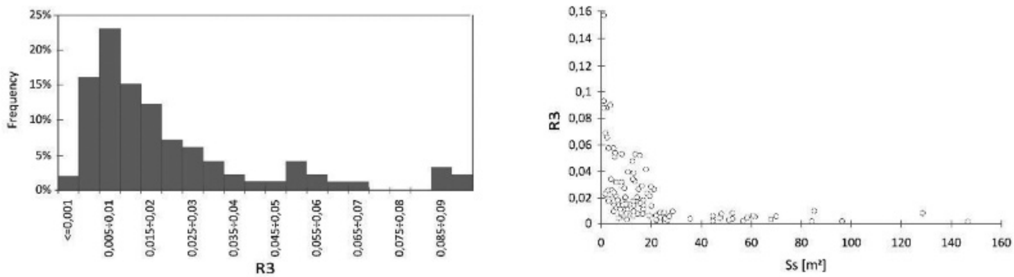

Figure 6. Left: parallel hole cuts. Frequency distribution of R3 values; right: R3 Vs. Ss plot, which shows the correlation linking the two parameters.

A similar consideration holds for the frequency peak of R6 in the 5 ÷ 15 range (Figure 7). For R3 and R6, the above characteristics range defines the customary design style of the mine works (Hu et al., 2021). The intended pull dictates the slenderness of the solid volume intended to be blasted, only loosely related to the tunnel cross-section; hence, no suggestion comes from the histogram, apart from a vaguely defined preferred range (0.5 - 1).

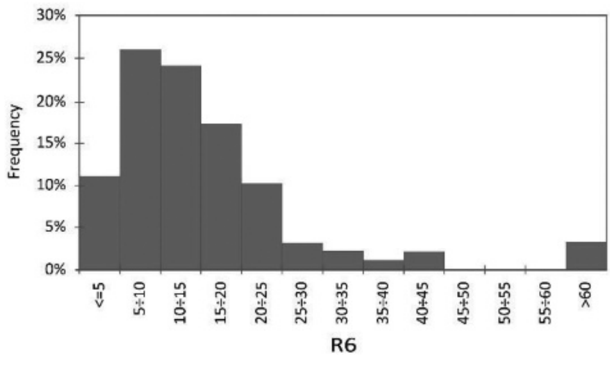

Figure 7. Parallel hole cuts rounds: frequency distribution of R6 values.

The slenderness of the solid volume intended to be removed by the cut has an upper limit dictated by the accuracy of the drilling system (see Figure 8, left); the maximum observed value for R5 is 20, but most operators keep R5 below the safer limit of 12 (see Figure 8, right). Two vaguely defined frequency peaks around 6 and 10 indicate two styles, mine and civil works, as explained when dealing with R3.

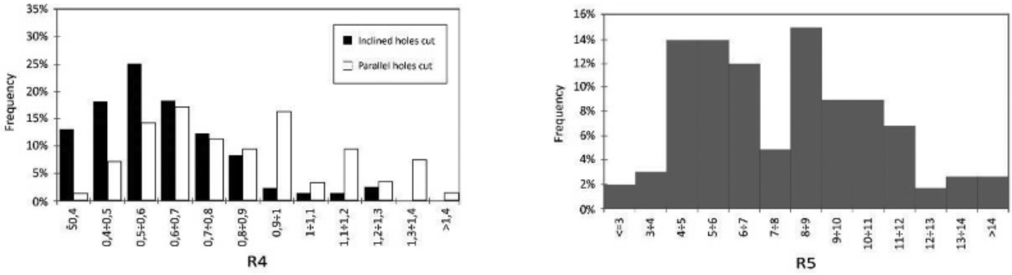

Figure 8. Left: frequency distribution of the round slenderness R4 values; right: parallel hole cut rounds: frequency distribution of cut slenderness R5 values.

The powder factor of the cut section (Figure 4, right) is higher than the overall powder factor by up to 30 times. The frequency of R7 values peaks in the 6 - 9 range, which can be assumed to be typical for mine works (Figure 9). It has been seen that the frequency of the R6 value peaks at slightly higher values, around 10. Considering that some cut holes are uncharged, it can be concluded that cut holes are usually not more heavily charged than average; the explosive, however, is often stronger.

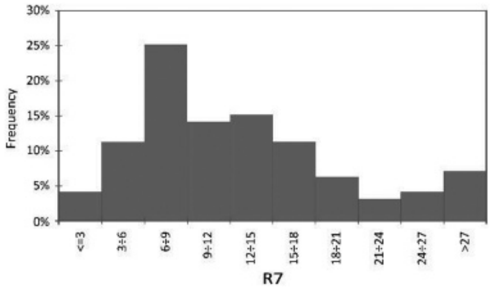

Figure 9. Frequency distribution of R7 values for parallel hole cut rounds.

5 INFLUENCE OF THE GEOMETRICAL RATIOS ON EFFICIENCY

As already observed, the population analysed is not very representative of the general population of blasted rounds in terms of efficiency. However, some observed trends can be considered meaningful.

As common sense suggests, efficiency is favourably affected by an increase in the ratio of the dummy holes' volume to the volume assigned to z holes. However, the data are widely scattered, and very good efficiency values are recorded even at low R1 values. Moreover, obtaining high efficiency as cut slenderness grows is expected to be more difficult (Lu et al., 2014).

Top efficiency is attained with slenderness in the 6 to 10 range.

6 TIMING

The statistical analysis concerning the timing of the cut holes indicates no preference nor correlation to the features of the pattern. Apart from simultaneous firing, uncommon, but still used apparently with satisfactory results, 25 ms, 30 ms, 60-100 ms (obtained by excluding some number from conventional ms series), ¼ s, ½ s are currently employed with comparable frequency, though being 60-100 ms recommended by many authors based on theoretical considerations. The main problem is probably ensuring correct succession rather than exact time intervals.

Anyhow, disturbance due to flashover, which surely occurs often, is seldom complained. That can be due to the comparative latitude of the acceptable R1 range shown by the statistical analysis: an extra hole firing with a z hole due to flashover halves R1, which in most cases still remains in the acceptable range. A slight, forcibly accepted hole deviation can produce the same effect.

7 THE DRILLING ACCURACY

Direct observation of blast results has shown that the coplanarity of the bottom holes in the design plane has a stronger influence on blast efficiency than the directional accuracy of the holes; directional accuracy, however, is important, and the same applies to collaring accuracy (an often-disregarded parameter).

Let's suppose collaring accuracy is not a problem, and only directional accuracy $\varepsilon=\Delta/Ld$ (Δ being the bottom hole deviation from the intended point) deserves control, which means the drilling system somehow warrants it. Let us suppose, further, that the rounds have been designed assuming R2=0.15±33%, which means to keep R2 in the 0.1÷0.2 range, and the statistical analysis has shown to be acceptable.

In the case all cut holes diverge from the cut center by ε, it can be easily seen that the condition posed to R2 is fulfilled provided that $1.33 \leq 1+4\ R5\ \varepsilon + 4\ R52\ \varepsilon^2$, which means, for R5=6, a moderate cut slenderness value, $\varepsilon \leq 1.28\%$ easily obtained by any drilling system; at R5=10 the required ε value drops to 0.76%, still feasible but demanding. The example shows how slenderness dictates the sensitivity of the pattern to drilling precision. 1% directional accuracy, as warranted by most jumbos, may fall short for slender rounds.

8 CONCLUSIONS

The statistical analysis does not aim to provide design criteria; in many cases, however, blast design is carried out by averaging and extrapolating data from a small number of dissimilar cases, representing a statistical procedure.

The attempt to simplify the description of the rounds to make a simple and all-encompassing statistical analysis possible is necessarily a rough, first-approximation approach. However,

Table 2. Features of a typical parallel hole round, as suggested by the statistical analysis.

Feature	Formula	Adopted Ratios	Example
Ss, m^2	//	//	15 m^2
D1, m^{-2}	D1~1+30/Ss	//	D1=3 holes/m^2
N1	N1=D1 x Ss	//	45 holes
Sc, m^2	Sc=Ss x R3	R3=0.01	Sc=0.15 m2
Ld, m	Ld=(Sc)½ x R5	R5=8	Ld=3.1 m
accuracy ε	$R5\varepsilon + R5^2\varepsilon^2=0.085$ (see text)	//	$\varepsilon \approx \pm 0.01$ (1%)
D2, m^{-2}	D2≈10+4/Sc	//	D2=36 holes/m^2
N2	N2=D2 x Sc	//	5.4 holes (round to 5 or 6)
Sz, m^2	Sz=Sc x R2	R2=0.15	Sz=0.023 m^2
Se, m^2	Se=Sz x R1	R1=0.15	Se=3.4 x 10-3 m^2 (34 cm^2)
Dummy hole diameter	//	//	one 66 mm or two 46 mm

some suggestions from the analysis regarding small-medium cross-section tunnels (5 to 20 m^2) are proposed synthetically in Table 2.

Data are not intended to represent a round design rule, but rather to define a typical round.

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