Quantifying the difficulty of tunnelling by drilling and blasting

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Abstract

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We show how pull efficiency cannot be correlated to a single parameter, and how tunnelling by D&B needs to be treated as a complex system. Finally, we propose a method for quantifying and classifying the difficulty of tunnelling. The deviation of specific drilling (SD) from industrial average trend is used as an indicator of difficulty: easier when SD is lower than average, and more difficult when SD is higher than average. We show how such deviation can be preliminarily associated with lithotypes. This provides to designers and cost estimators a tool of a first approximation for D&B cost prediction at the pre-feasability and feasibility stages of a tunnelling project.

Keywords	D&B, rounds, PF, SD, Pull, Efficiency

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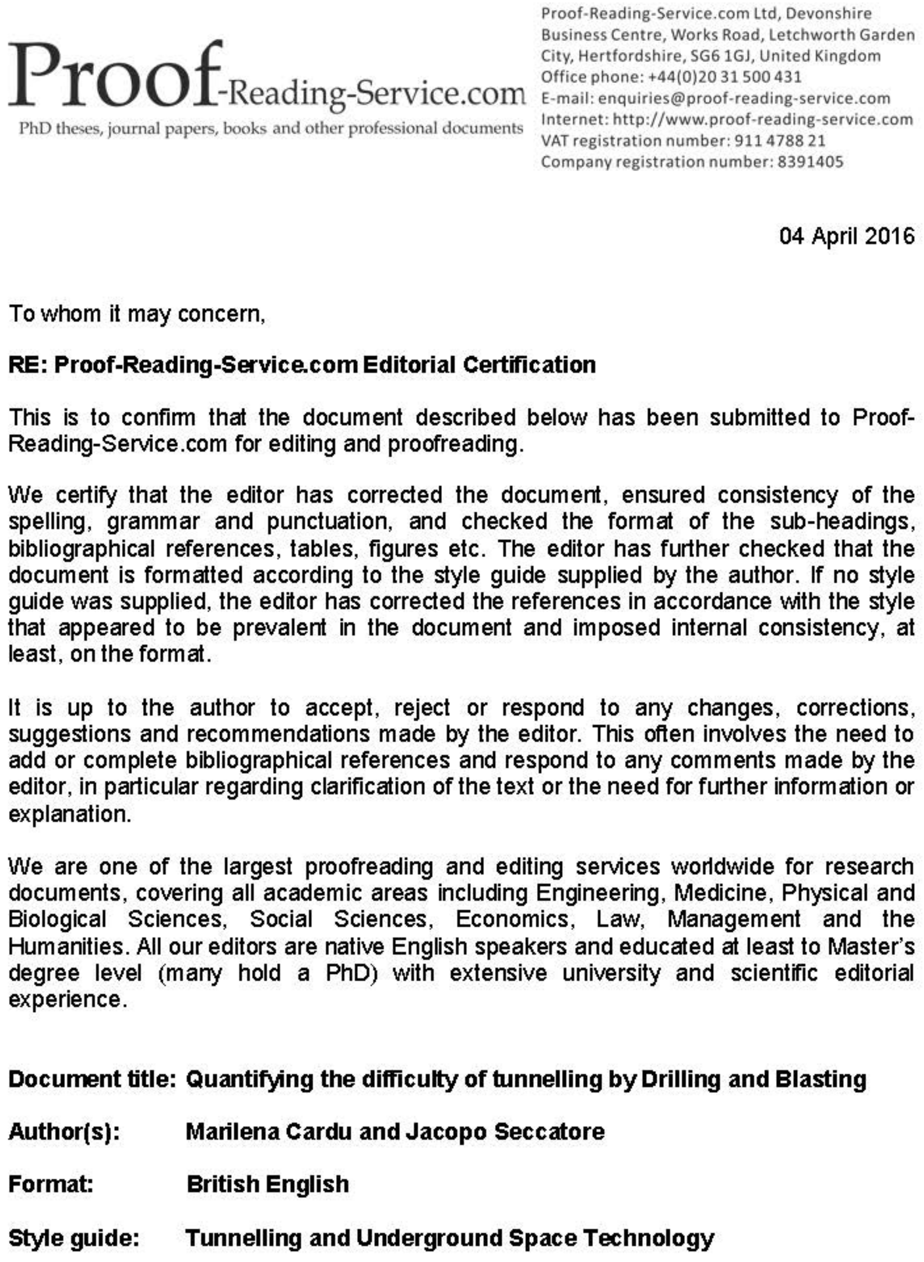

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Quantifying the difficulty of tunnelling by Drilling and Blasting

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ABSTRACT

This study deals with industrial trends in tunnelling by drill and blast (D&B). We perform a statistical analysis of accumulated experience from the 1950s to the modern day to provide advice for proper project management in tunnel driving. The basis of the study is a wide database of tunnel blast schemes. This database is made of excavation parameters, and considers two main families of blasts: with parallel hole cuts and with inclined hole cuts. Such parameters are analysed by means of statistical regression. Correlations are shown. We present a general curve of correlation between tunnel sections and specific drilling and specific explosive charges. We show how pull efficiency cannot be correlated to a single parameter, and how tunnelling by D&B needs to be treated as a complex system. Finally, we propose a method for quantifying and classifying the difficulty of tunnelling. The deviation of specific drilling (SD) from industrial average trend is used as an indicator of difficulty: easier when SD is lower than average, and more difficult when SD is higher than average. We show how such deviation can be preliminarily associated with lithotypes. This provides to designers and cost estimators a tool of a first approximation for D&B cost prediction at the pre-feasability and feasibility stages of a tunnelling project.

Keywords: D&B, rounds, PF, SD, Pull, Efficiency

1. Introduction

In rock blasting, the behaviour of the rock-explosive couple at the interface still lacks sufficient detail to develop reliable mathematical models. This makes blast design and analysis a radically empirical process; blasting for tunnel driving is no exception. Empirical design is based on correlations derived from scientific and industrial experience. In tunnel blasting, an enormous body of experience has been accumulated since the time that the first tunnels were excavated with explosives in the 1860s. One might argue the principle that successful practices thrive and spread, while unsuccessful ones fall into oblivion. Nevertheless, a statistical analysis of accumulated experience can show industrial trends and be turned into a useful source of suggestions and advice. Experience shows how the industry is in need of advice for proper project management. Efron and Read (2012) published an extensive report on tunnel costs. They interviewed tunnel engineers and cost estimators worldwide trying to understand the trends of tunnelling. Their results show important contradictions in the tunnelling industry. According to their results, geology and excavation type are the most impactful cost factors. They obtained the unanimous reaction that preliminary site investigation is a fundamental cost-saving opportunity. On the other hand, their data show that customers are unwilling to invest in site investigation, in spite of being aware of its importance. Scarce site investigations at the beginning turns into higher uncertainties during construction, therefore higher excavation difficulty and higher costs.

In this work, an attempt to understand industrial trends in tunnelling by drill and blast (D&B) was made. The work is based on a large database and its preliminary analysis provided by Mancini et al. (1998). Data have been collected from 163 cases in both mining and civil works from the 1950s. We only use cases for which a sufficiently complete description has been retained for statistical analysis out of a broader database of around 250 tunnels. The examined cases cover a wide range of rock types, explosives, and ignition systems usually encountered in tunnelling. For analysis, the description of the blasting schemes was reduced to a small number of dimensionless ratios. Analysis and discussion are then developed from their work.

2. Types of Rounds

The conventional terminology of tunnel rounds is variable and complex, including terms such as “cut holes”, which create the starting cavity in the rock face, “easers”, which widen the starting cavity, “production holes”, which remove the bulk of the rock, “contour holes”, which shape the sides and the crown of the excavation cross-section, and “lifters”, which shape the floor of the tunnel (Langefors & Kihlström, 1967). For simplicity’s sake, only two functional groups are distinguished through this statistical analysis:

- *Cut holes*: blast holes whose functions are mainly to crush the rock finely and to eject broken rock in the direction of the tunnel axis;

- *Production holes*: blast holes whose function is mainly to break the rock down to an easily removable size, and to move it mainly at right-angles with respect to the tunnel axis (easers, proper production, contours, and lifters are included).

An enormous variety of schemes is currently employed, and a comparable variety of names is found in the literature (e.g. Holmberg and Persson, 1978; 1980; Hagan, 1980; 1992; Holmberg, 1982; Ghose, 1988; Innaurato et al., 1998; Chakraborty et al., 1998). For simplicity's sake, two types are distinguished:

- *Parallel hole cuts*: the initial cavity (cut volume) is prismatic; hole density and powder factor are practically constant along the cut length; dummy holes are usually needed;
- *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.

Designers have different opinions on the mechanism underlying the development of the cut. For parallel hole cuts, the supposed functions of dummy holes are:

- to weaken the rock locally; that is, to reduce the rock quality locally before the blast;
- to dictate the position of preferred fractures;
- to provide a suitable breakage angle for charged holes;
- to provide an expansion volume for rock bulking.

For inclined cut holes, the supposed functions of inclined holes are:

- to provide an axial component to the force exerted by the explosive;
- to provide a charge concentration in the terminal part of the pull.

The analysis presented here aims to describe patterns and indicate characteristic ratios that have been proven to work satisfactorily.

3. Statistical Analysis

The statistical analysis of the data is intended to provide suitable criteria for the evaluation of the influence of rock excavation techniques adopted on the results obtained. Error: Reference source not found and Error: Reference source not found show the inverse tendencies of specific drilling (SD, density of holes per square metre of tunnel cross section) and Powder Factor (PF, kg of explosive per cubic metre of blasted rock) plotted against the cross section of the tunnel, respectively. This is a general design trend: the higher hole density of the section stays in the opening cut, and in small tunnels the cut occupies a larger part of the tunnel face, while the larger the section, the lower the geometrical proportion of the cut on the whole cross-sectional area. The data in Error: Reference source not found are more dispersed due to the variations in the density of explosives (Mancini et al., 1994). Error: Reference source not found shows the inverse tendency of SD against the pull of the blast rounds. This is again explained by the geometrical proportion of the cut on the whole tunnel section and by considerations on the tendency of Error: Reference source not found: designers tend to blast longer pulls in larger sections (Error: Reference source not found), and larger tunnels have a smaller proportion of the cut, as mentioned earlier. It must be highlighted that the tendency of Figure 4 is not a physical restriction: there is no restraint from the point of view of rock blasting theory to long pulls in small sections; it reflects nevertheless a tendency in the industry. What appears evident is that parallel hole cuts tend to disappear at larger sections and longer pulls, where inclined hole cuts allow lower SDs. Error: Reference source not found and Error: Reference source not found show the frequency distribution of the blast pull and the pull efficiency, respectively. Pull efficiency is defined as the ratio between the design and the actual obtained pull:

$$\eta = \frac{P_{real}}{P_{design}} \tag{1}$$

Error: Reference source not found shows that parallel hole cuts tend to be used in a narrower range of blast pulls. Contrary to what a designer might expect, V-cuts appear to be used in a more versatile fashion, being adopted in a wider variety of applications. As remarked above, longer pulls are dominated by the adoption of inclined hole cuts. The pull efficiency (Figure 5) appears to be higher in parallel hole cuts (average $\eta=0.93$ for parallel holes against average $\eta=0.91$ for inclined holes). Nonetheless, a correlation has been sought for efficiency with any of the other variables of the database, but none has been found. Error: Reference source not found shows the correlation matrix of the variables of the database, indicating the value of the Pearson coefficient for every couple of variables. Blast pull efficiency is not linearly related to any variable in a univocal way. Tunnel driving is evidently a complex system. The complexity of blasting operations has already been analysed both for open-pits (Seccatore et al., 2011, Dompieri, 2015) and for underground (Cardu et al., 2011). General conclusions suggest that treating rock blasting with non-linear, holistic analysis can detect hidden patterns not detectable by traditional statistics. Research of pull efficiency would benefit by being oriented accordingly.

It must be highlighted that the database does not report detailed information regarding timing and initiation sequences, which evidently play a key role in any blast performance (Seccatore et al., 2015a). Future research will deal with this aspect.

4. Difficulty of excavation

Based on the plot of Error: Reference source not found, the parameter SD appears to be the one presenting a lower dispersion, and has therefore been chosen as the most suitable indicator of the excavation difficulty. The hyperbola that best interpolates the actual values is as follows:

$$\acute{SD} = 1.25 + \frac{9.24}{S} \tag{2}$$

Where SD is expressed in m/m^3 and S in m^2. This hyperbola makes it possible to normalise the values of specific drilling compared to the parameter that has the greatest influence on it, namely the excavation cross section. The percentage deviations of the actual values compared to the average values expected from Equation (2) are calculated according to Equation (3):

$$\Delta = \frac{SD - S\acute{D}}{S\acute{D}} \cdot 100 \tag{3}$$

Such a deviation can be defined as the difficulty level of tunnel driving, since it expresses how far the case studied is from the industrial average. Six classes of excavation difficulties have been defined according to the criteria reported in Error: Reference source not found.

For more than a century, the so-called “rock coefficients” have been in use for the calculation of the charges to be used in drilling and blasting; these coefficients are related to different groups of lithological types that, in fact, are organised in classes of increasing excavation difficulty. Among them, it is worth mentioning the classification proposed by Rzhevsky and Novik (1971) as conceptually closer to the approach followed here: it is independent of a particular formula for charge calculation, defines classes of increasing difficulty (from III to XVI; the lower classes up to III do not require the use of explosives) on the basis of an objective criterion, that is, the specific consumption of an explosive in standard normalised conditions, and then assigns to each class a lithotype group. The parameter proposed here for discriminating greater or lesser ease of excavation is the specific consumption of drilling.

5. Difficulty classes and rock types

Error: Reference source not found–13 show the rock types for each difficulty class. Extreme ease of excavation (class 1), expresses the possibility of advancing with SD (and therefore a PF) of less than 35% of the average value of the corresponding cross section, as well as extreme difficulty of excavation (class 6), expressing the need to increase the powder factor by over 25% compared to the average. In general, it is evident that this categorisation works: harder rocks such as granites and gneisses appear to fall into the higher difficulty classes, while softer rocks such as sandstone are in the lower classes. Limestone appears to be omnipresent, but this is a bias due to the nature of the database adopted: it classifies only the lithology and does not possess parameters regarding the rock mass characterisation. Of course lithology is not enough and a rock mass characterisation is of the utmost importance for the correct design of tunnel rounds. Seccatore et al. (2015b) show that in a strong rock such as granite, but highly altered (RMR Class IV) and fractured, there is no way of obtaining good blast results, and excavation by D&B should not have been chosen in the first place. Nevertheless, the method described here can allow for a preliminary cost prediction for a pre-feasibility study based on the lithology to be excavated, and some considerations of its mass structure (highly fractured masses are more difficult to excavate, and, based on this parameter, one can increase the difficulty level). An average value for SD can be predicted to a first approximation on the basis of Equation (2), knowing the cross section of the tunnel; and then SD can be corrected using the deviations of Table 2 according to the lithotype. This can be a handful tool in preliminary project phases such as Front-End Loading (FEL) FEL-0 or FEL-1.

6. Conclusions

The purpose of this work was to offer statistics of industrial trends and to understand the behaviour of some variables of tunnel driving by drill and blast. To do so, a statistical analysis based on a large available database was performed. The results can be summarised as follows:

- The size of the tunnel cross section and the specific drilling and charge are inversely proportional in a very clear way;
- In general, designers tend to adopt longer pulls in larger sections, albeit this not being a physical constraint;
- Tunnel rounds with parallel hole cuts tend to have a higher pull efficiency than rounds with inclined hole cuts;
- The pull efficiency of the rounds is not linearly correlated to any other variable; a non-linear type of analysis appears to be necessary to understand how pull efficiency works thoroughly.

Based on the clear linearity of cross section and specific drilling, an average tendency of the industry was created, and the deviation from this average was defined as “difficulty of excavation”: easy to excavate when lower than average, and hard to excavate when higher than average. This difficulty is associated with the types of rocks to be excavated. This can be a tool for preliminary design in pre-feasibility and feasibility studies.

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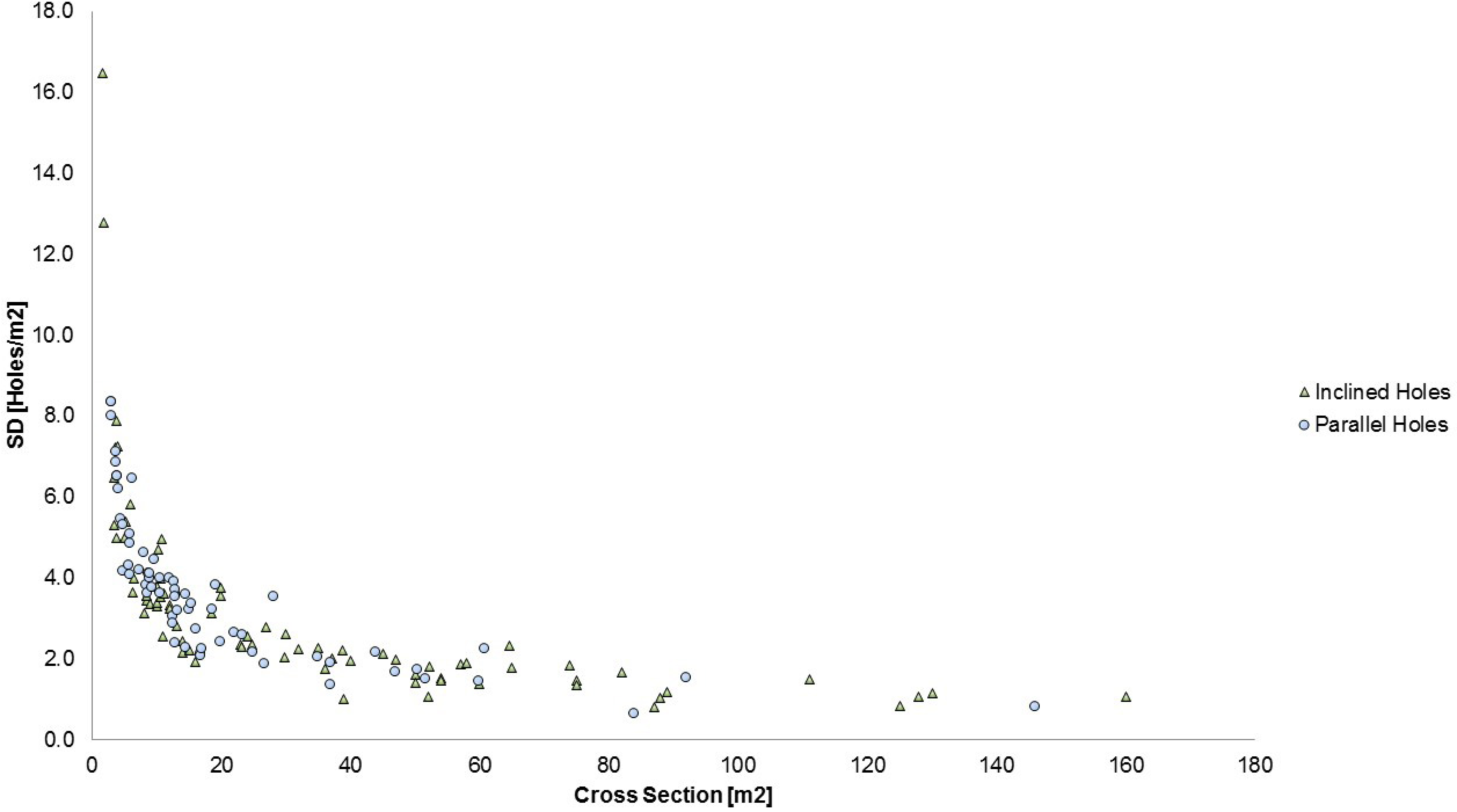

18.0
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SD [Holes/m2]
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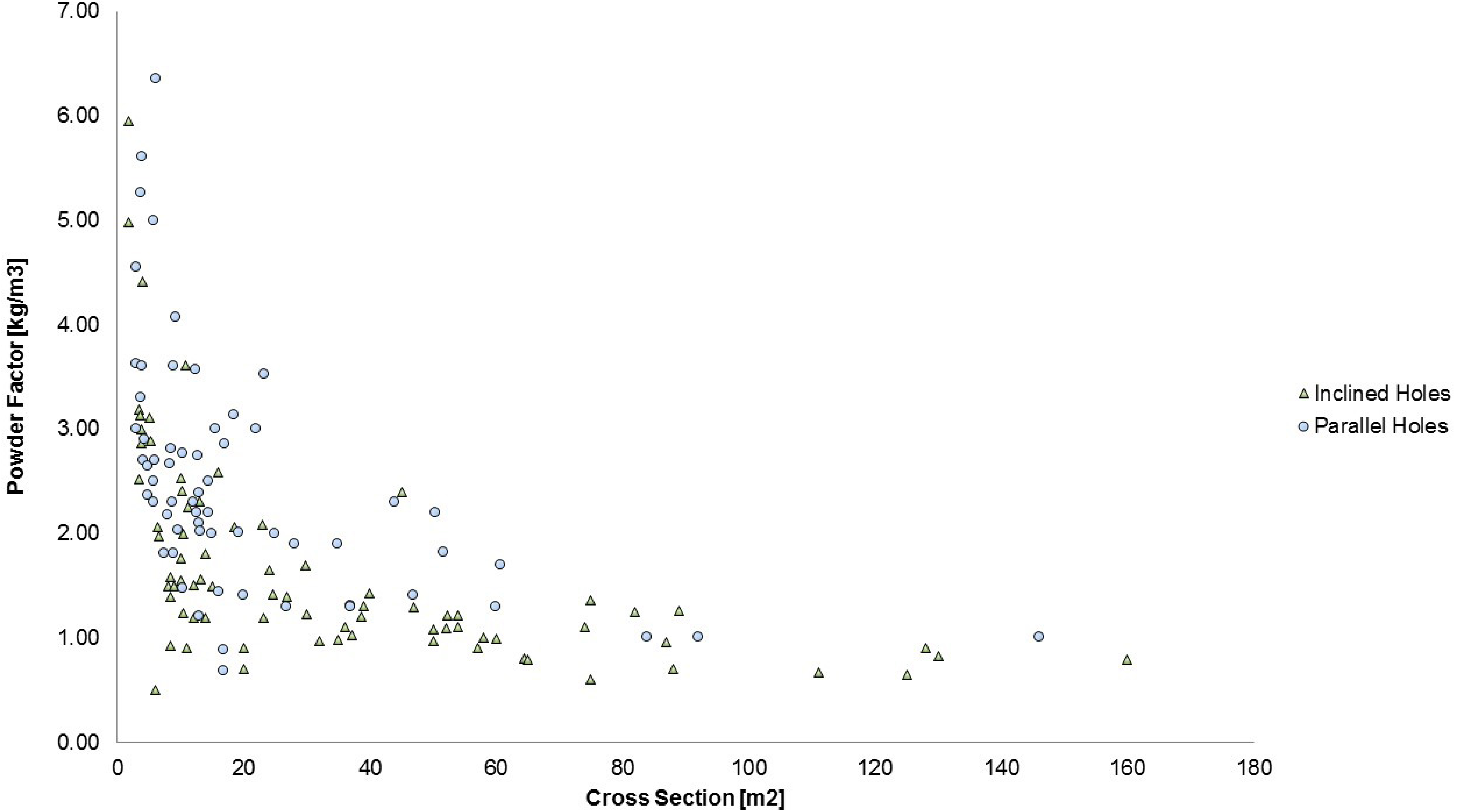
Cross Section [m2]
Inclined Holes
Parallel Holes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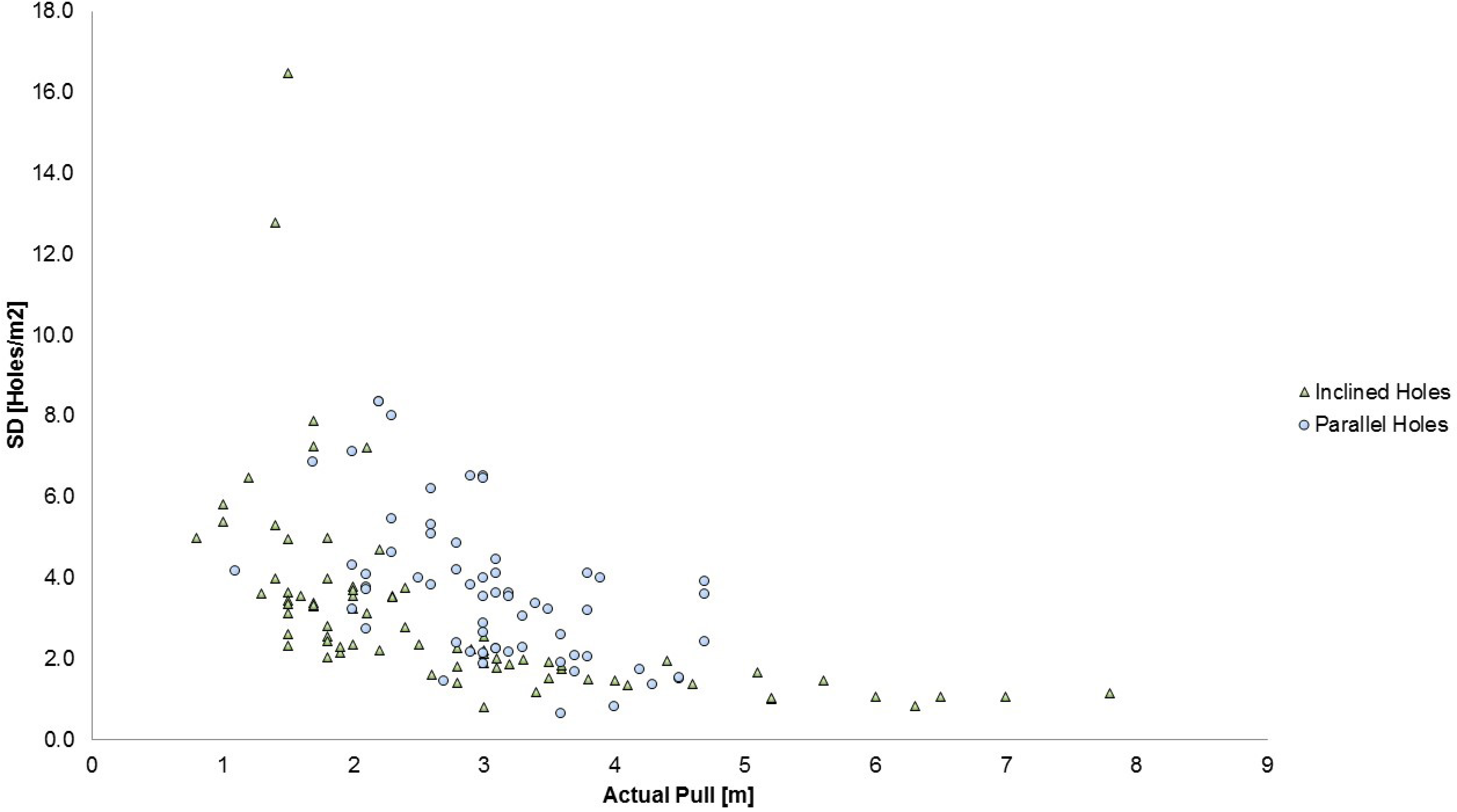
Inclined Holes
Parallel Holes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SD [Holes/m2]
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Actual Pull [m]
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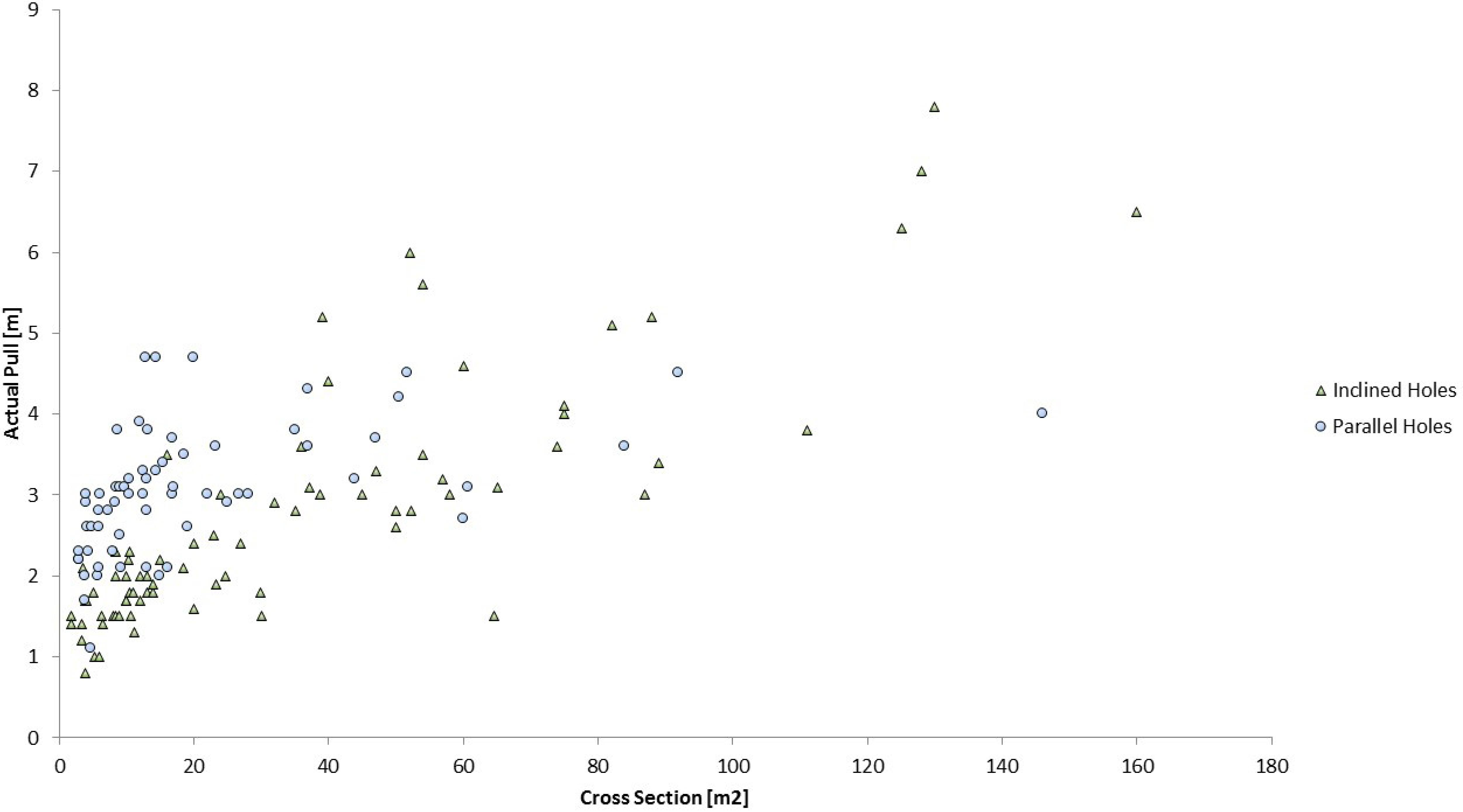
○ Parallel Holes



Actual Pull [m]
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Cross Section [m2]
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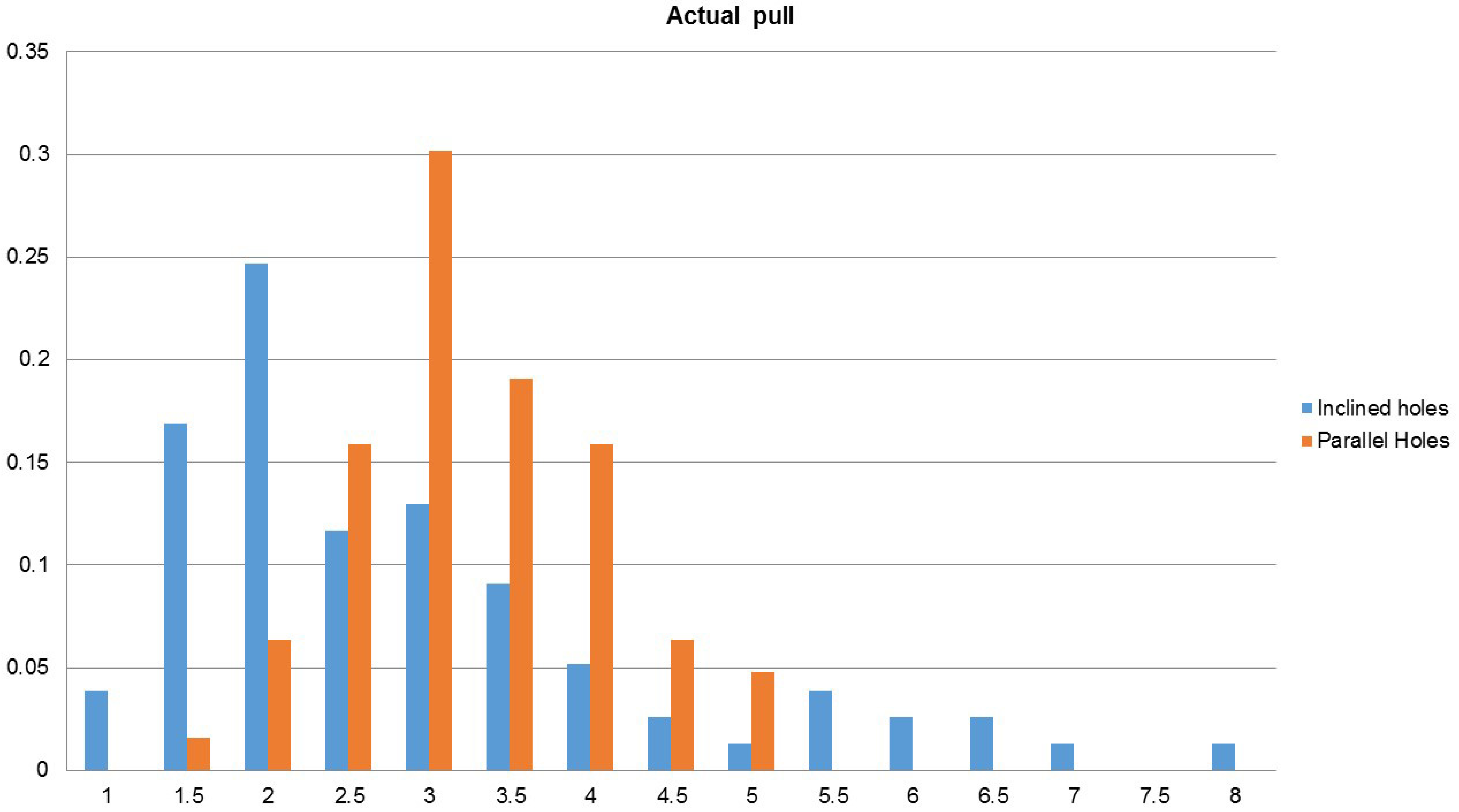
Inclined Holes
Parallel Holes


Actual pull
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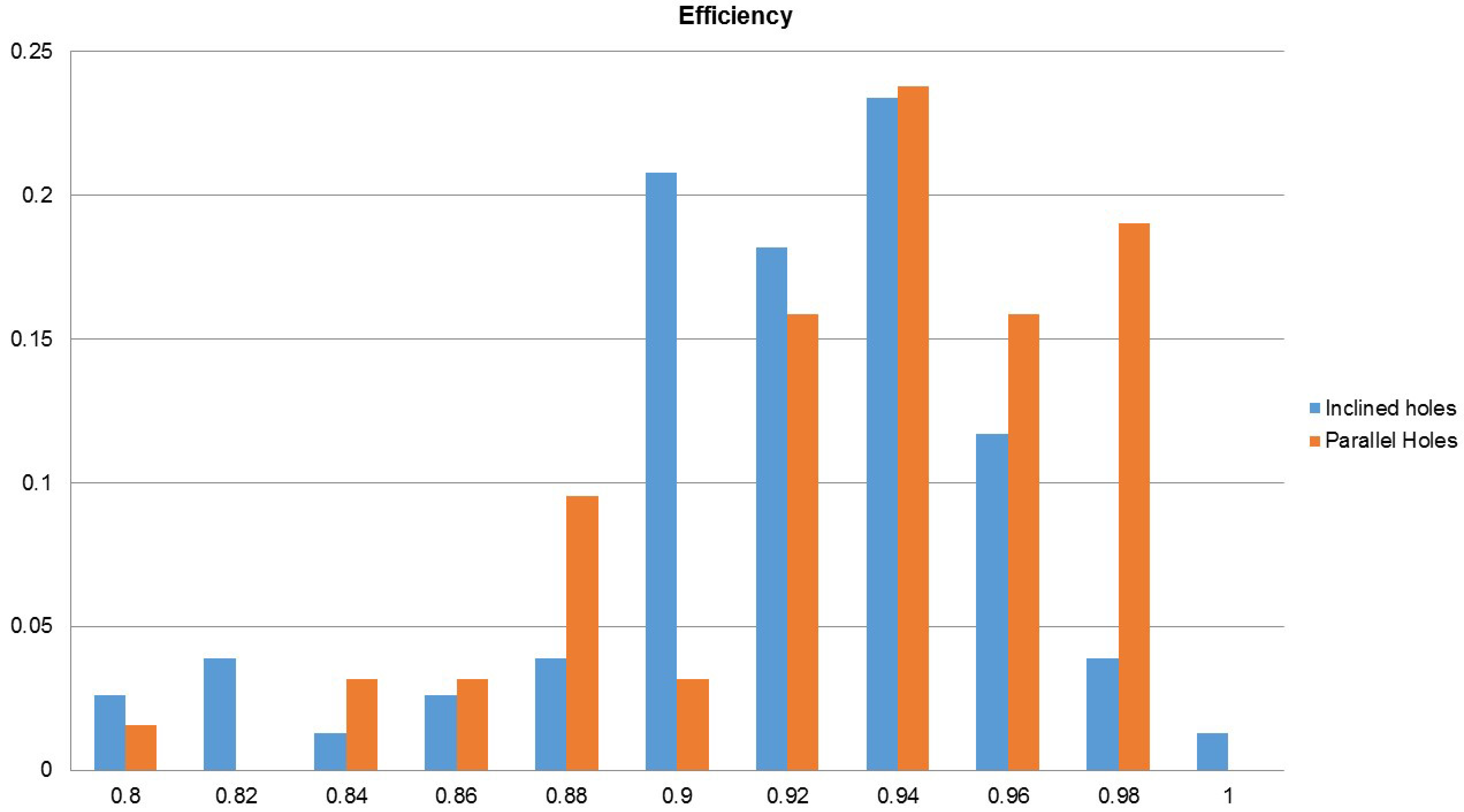
Inclined holes
Parallel Holes


Efficiency
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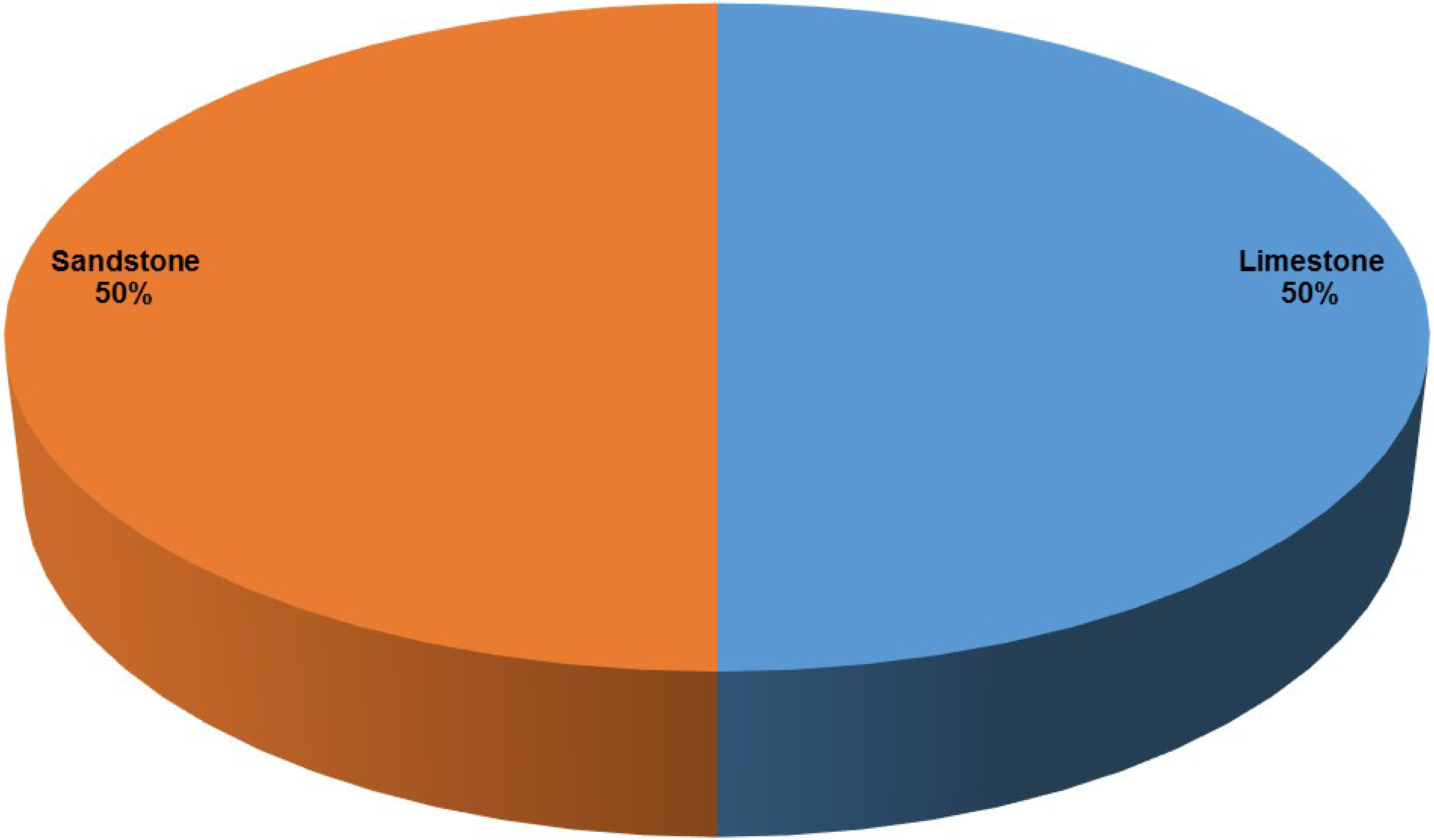
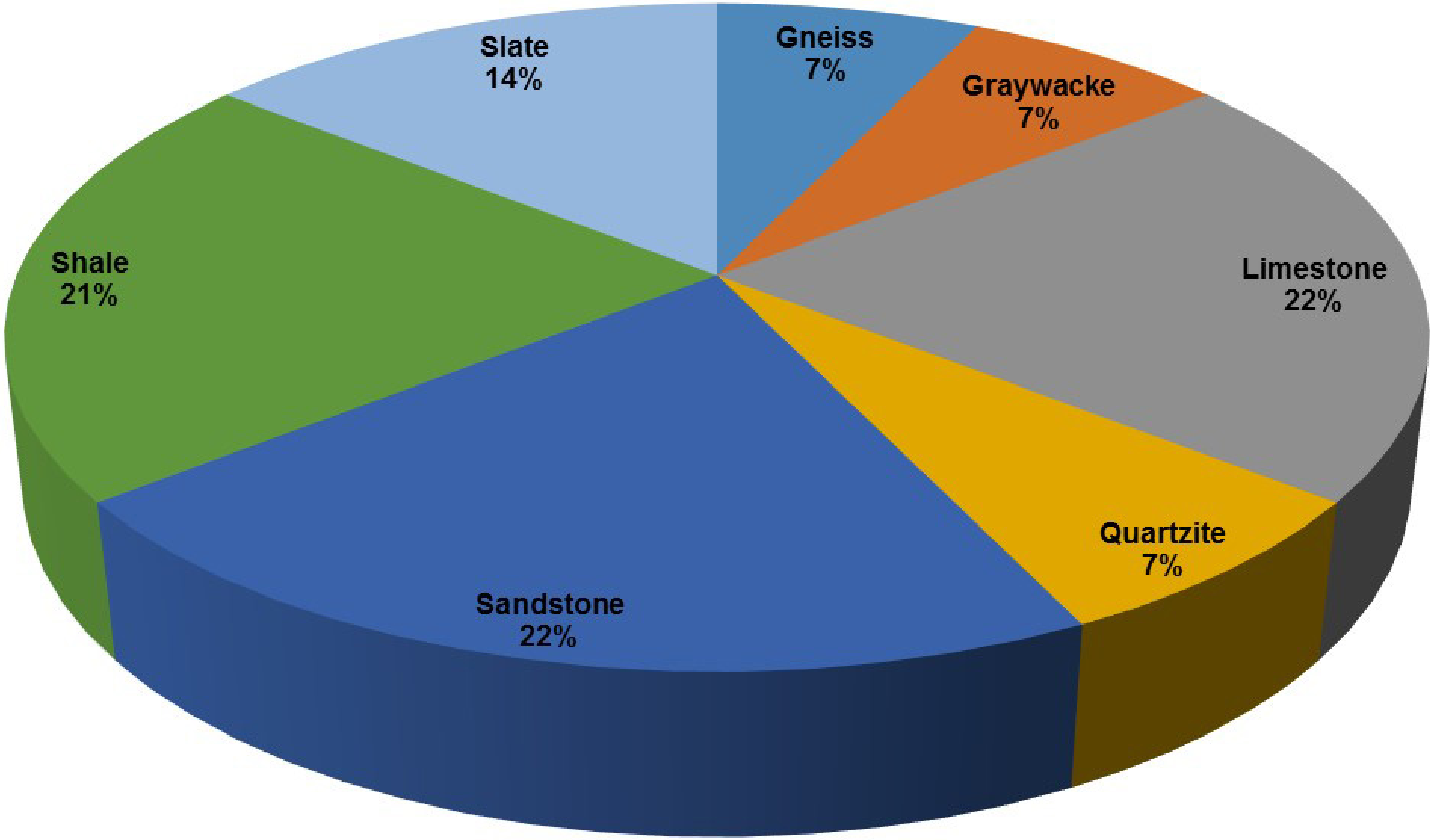
0.2
0.15
0.1
0.05
0
0.8
0.82
0.84
0.86
0.88
0.9
0.92
0.94
0.96
0.98
1
Inclined holes
Parallel Holes

	Cross Section	Design Pull	Actual Pull	efficiency	Blasted Volume	Charge	Powder Factor	Linear charge	Blastholes Diameter	Dummy Holes Diameter	Dummy Holes Number	Blastholes number	Total number of holes	Cut blastholes number	Blastholes Density	Cut holes density	Cut Cross Section	Cross section of dummy holes	Section of zero-delay holes	Angle of cut holes	Cut Volume	Cut Powder Factor	Rock Expansion Freedom - REF	Cut REF	Sc/SS	Round slenderness	Cut Slenderness	D2/D1	Qc/Q	Vc/V
Cross Section	1.00																													
Design Pull	0.71	1.00																												
Actual Pull	0.70	0.99	1.00																											
Efficiency	0.09	0.25	0.35	1.00																										
Blasted Volume	0.93	0.80	0.79	0.14	1.00																									
Charge	0.89	0.85	0.84	0.16	0.93	1.00																								
Powder Factor	-0.53	-0.32	-0.31	0.07	-0.42	-0.33	1.00																							
Linear charge	0.87	0.70	0.69	0.15	0.78	0.92	-0.31	1.00																						
Blastholes Diameter	0.25	0.28	0.28	0.18	0.17	0.36	-0.04	0.49	1.00																					
Dummy Holes Diameter	0.32	0.61	0.63	0.30	0.36	0.50	-0.19	0.47	0.43	1.00																				
Dummy Holes Number	-0.15	-0.27	-0.32	-0.32	-0.16	-0.26	0.12	-0.27	-0.15	-0.52	1.00																			
Blastholes number	0.88	0.60	0.59	0.08	0.77	0.78	-0.51	0.82	0.21	0.43	-0.20	1.00																		
Total number of holes	0.88	0.61	0.59	0.08	0.77	0.78	-0.50	0.83	0.22	0.41	-0.15	1.00	1.00																	
Cut blastholes number	0.58	0.55	0.53	0.01	0.64	0.53	-0.38	0.38	-0.19	-0.39	0.50	0.60	0.59	1.00																
Blastholes Density	-0.59	-0.52	-0.50	0.01	-0.47	-0.52	0.75	-0.58	-0.32	-0.48	0.35	-0.55	-0.55	-0.29	1.00															
Cut holes density	-0.15	-0.22	-0.21	0.02	-0.14	-0.22	0.19	-0.24	-0.28	-0.34	0.17	-0.20	-0.19	0.11	0.51	1.00														
Cut Cross Section	0.51	0.49	0.49	0.13	0.57	0.49	-0.24	0.39	-0.06	0.17	-0.03	0.45	0.45	0.59	-0.31	-0.16	1.00													
Cross section of dummy holes	0.33	0.44	0.42	0.09	0.36	0.44	-0.14	0.42	0.44	0.77	-0.03	0.47	0.47	-0.13	-0.37	-0.36	0.24	1.00												
Section of zero-delay holes	0.13	0.10	0.09	0.00	0.13	0.10	-0.11	0.11	0.37	0.13	0.35	0.14	0.17	0.05	-0.25	-0.30	0.12	0.45	1.00											
Angle of cut holes	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00										
Cut Volume	0.50	0.52	0.52	0.15	0.60	0.53	-0.19	0.38	-0.06	0.17	-0.03	0.41	0.40	0.54	-0.27	-0.16	0.98	0.24	0.12	-	1.00									
Cut Powder Factor	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00								
Rock Expansion Freedom - REF	-0.10	-0.09	-0.08	0.03	-0.10	-0.11	0.15	-0.12	-0.11	-0.10	-0.02	-0.13	-0.13	-0.07	0.20	0.46	-0.03	-0.12	-0.22	-	-0.03	-	1.00							
Cut REF	-0.04	0.09	0.08	0.06	-0.04	0.02	0.15	0.05	0.25	-0.05	0.33	-0.08	-0.06	-0.27	0.01	0.01	-0.24	0.10	0.76	-	-0.19	-	-0.20	1.00						
Sc/SS	-0.01	0.03	0.04	0.08	0.01	0.02	0.08	0.02	-0.09	0.16	-0.02	-0.01	-0.01	0.09	0.00	-0.16	0.76	0.23	0.12	-	0.75	-	-0.03	-0.14	1.00					
Round slenderness	-0.49	0.05	0.07	0.18	-0.30	-0.27	0.65	-0.43	-0.15	-0.26	0.30	-0.55	-0.53	-0.23	0.60	0.37	-0.18	-0.26	-0.19	-	-0.11	-	0.17	0.24	0.01	1.00				
Cut Slenderness	-0.14	0.18	0.19	0.18	-0.11	0.03	0.28	0.03	0.19	0.14	-0.17	-0.18	-0.16	-0.44	0.12	0.57	-0.40	-0.12	-0.27	-	-0.31	-	0.24	0.56	-0.23	0.53	1.00			
D2/D1	0.14	0.17	0.16	0.01	0.08	0.17	0.06	0.23	0.15	-0.02	-0.03	0.00	0.02	-0.30	-0.06	0.40	-0.27	-0.09	-0.09	-	-0.21	-	0.11	0.57	-0.15	0.17	0.81	1.00		
Qc/Q	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	
Vc/V	-0.04	0.00	0.01	0.08	-0.02	0.00	0.09	0.00	-0.08	0.16	-0.02	-0.04	-0.04	0.03	0.01	-0.16	0.72	0.23	0.12	-	0.72	-	-0.03	-0.10	0.99	0.03	-0.18	-0.12	-	1.00

Class I

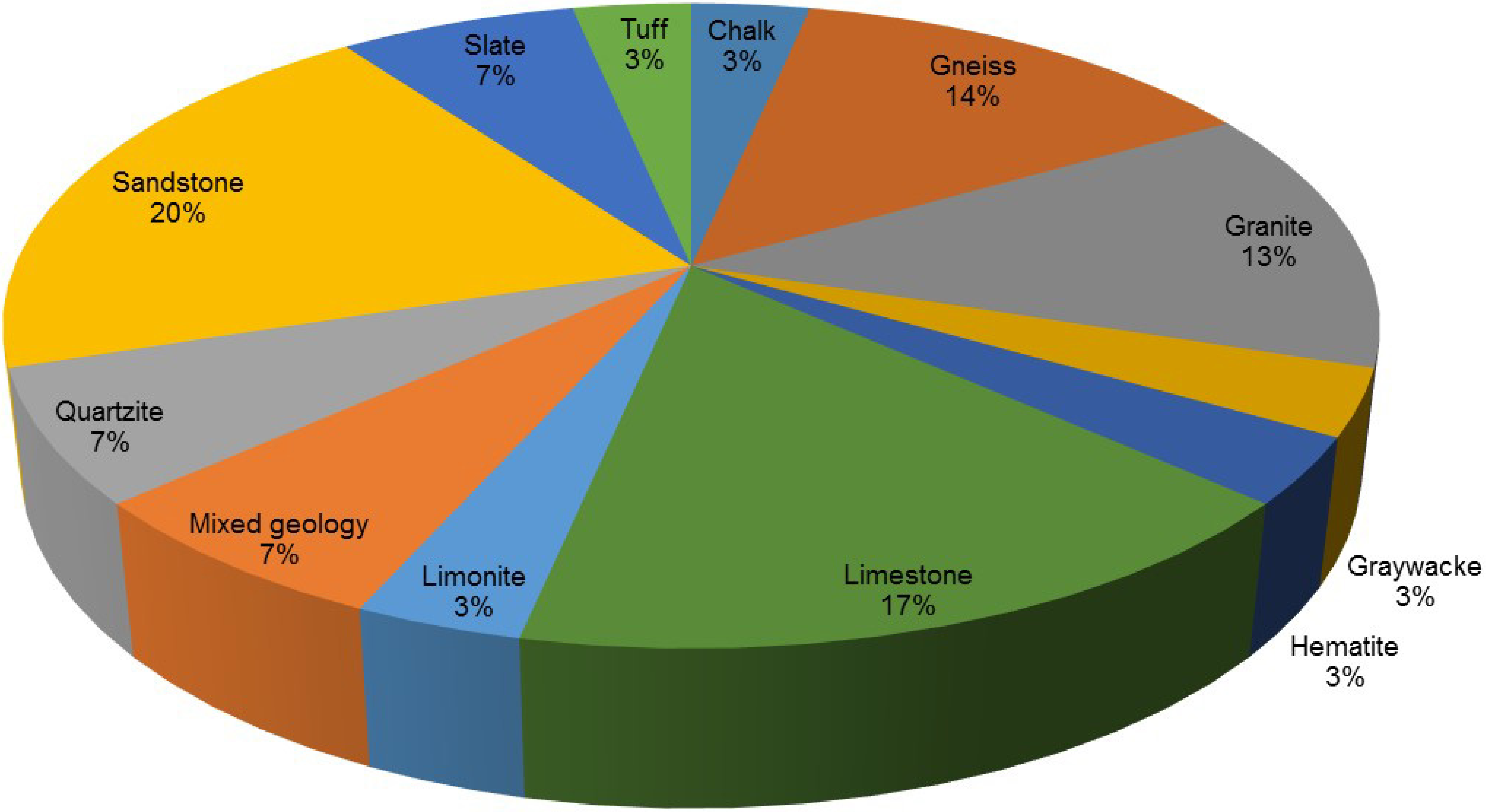


Class II

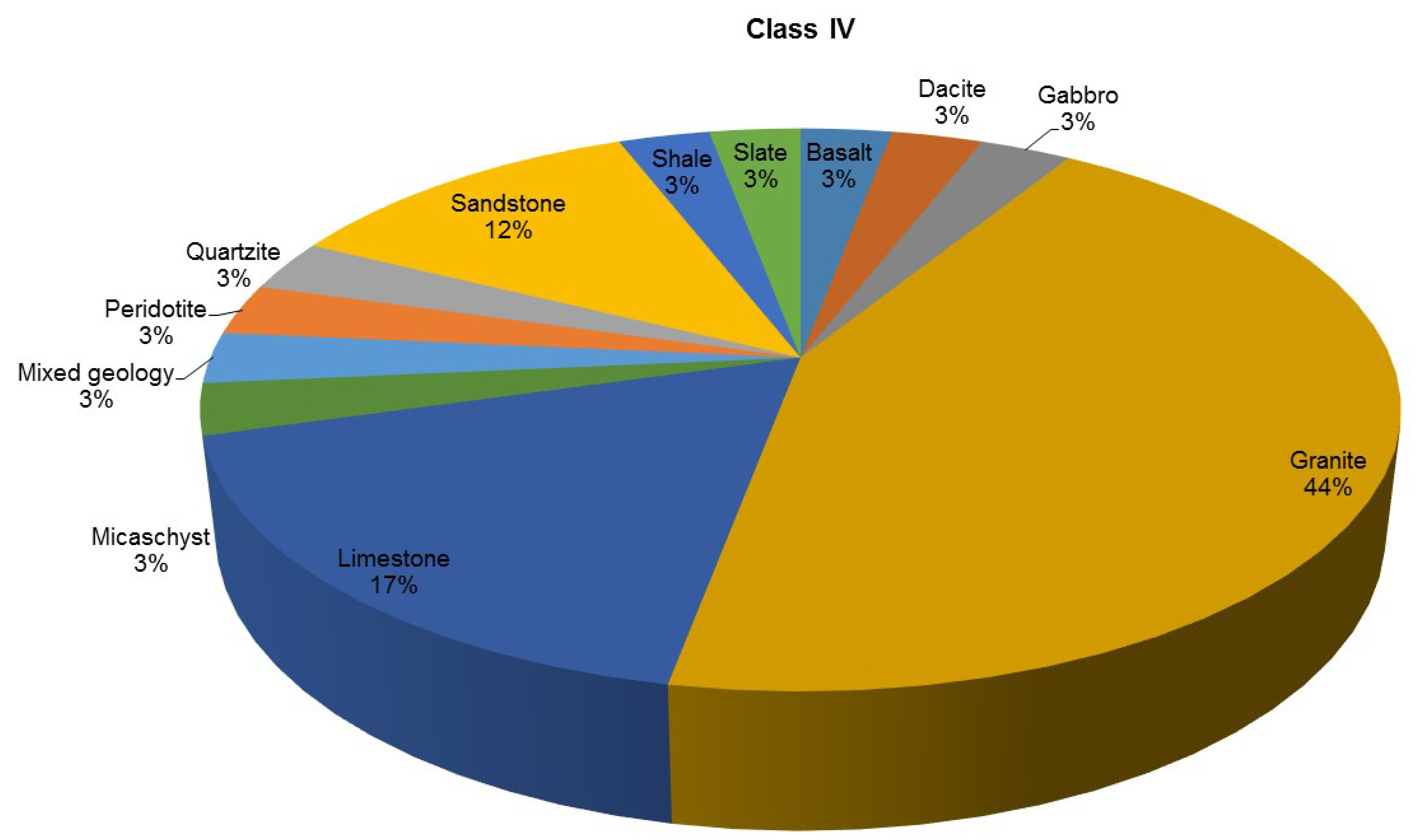


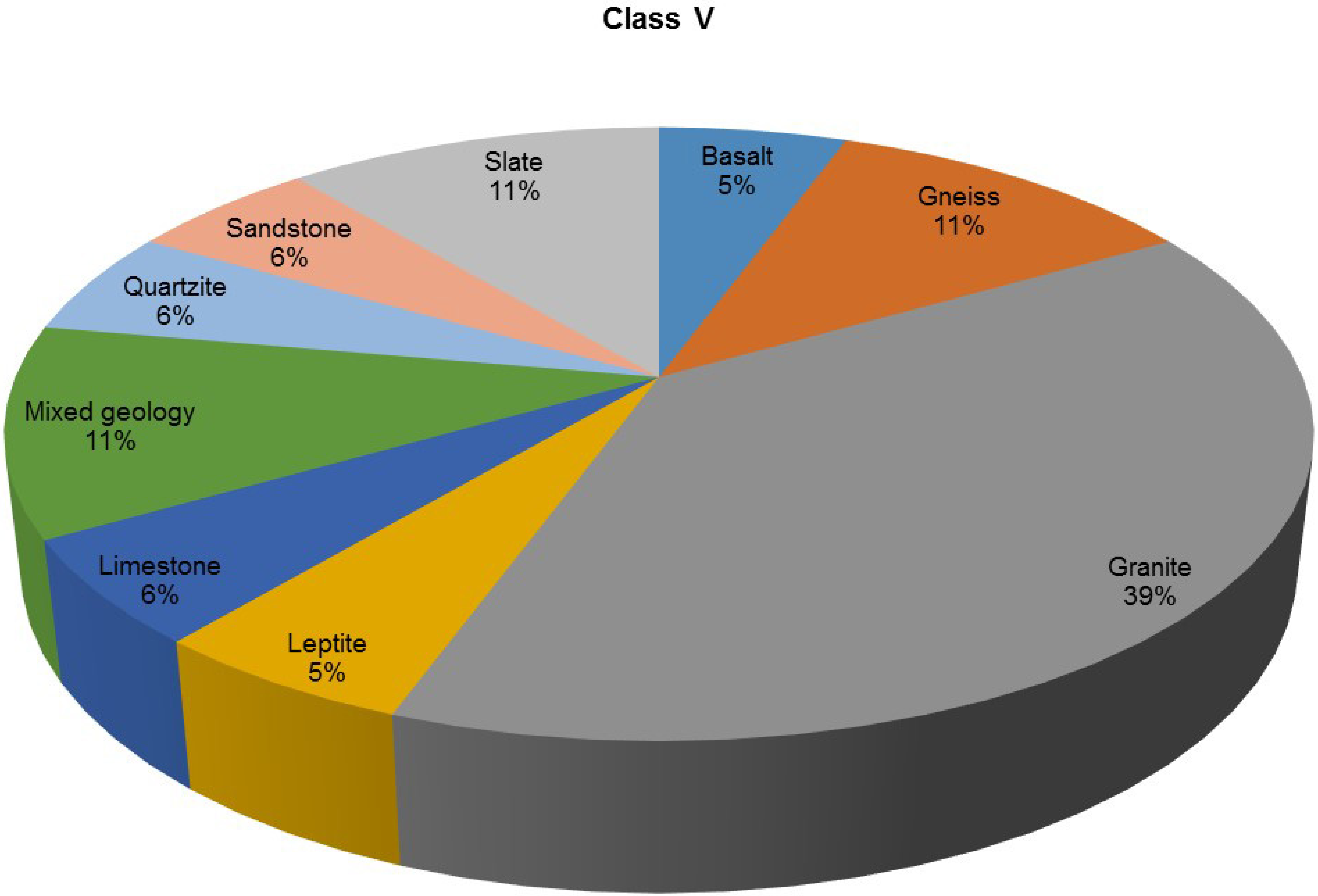
Gneiss 7%
Graywacke 7%
Limestone 22%
Quartzite 7%
Sandstone 22%
Shale 21%
Slate 14%

Class III



Chalk 3%
Gneiss 14%
Granite 13%
Graywacke 3%
Hematite 3%
Limestone 17%
Limonite 3%
Mixed geology 7%
Quartzite 7%
Sandstone 20%
Slate 7%
Tuff 3%


Class IV
Dacite
3%
Gabbro
3%
Shale
3%
Slate
3%
Basalt
3%
Sandstone
12%
Quartzite
3%
Peridotite
3%
Mixed geology
3%
Granite
44%
Micaschyst
3%
Limestone
17%


Class V
Basalt 5%
Gneiss 11%
Granite 39%
Leptite 5%
Limestone 6%
Mixed geology 11%
Quartzite 6%
Sandstone 6%
Slate 11%

Class VI

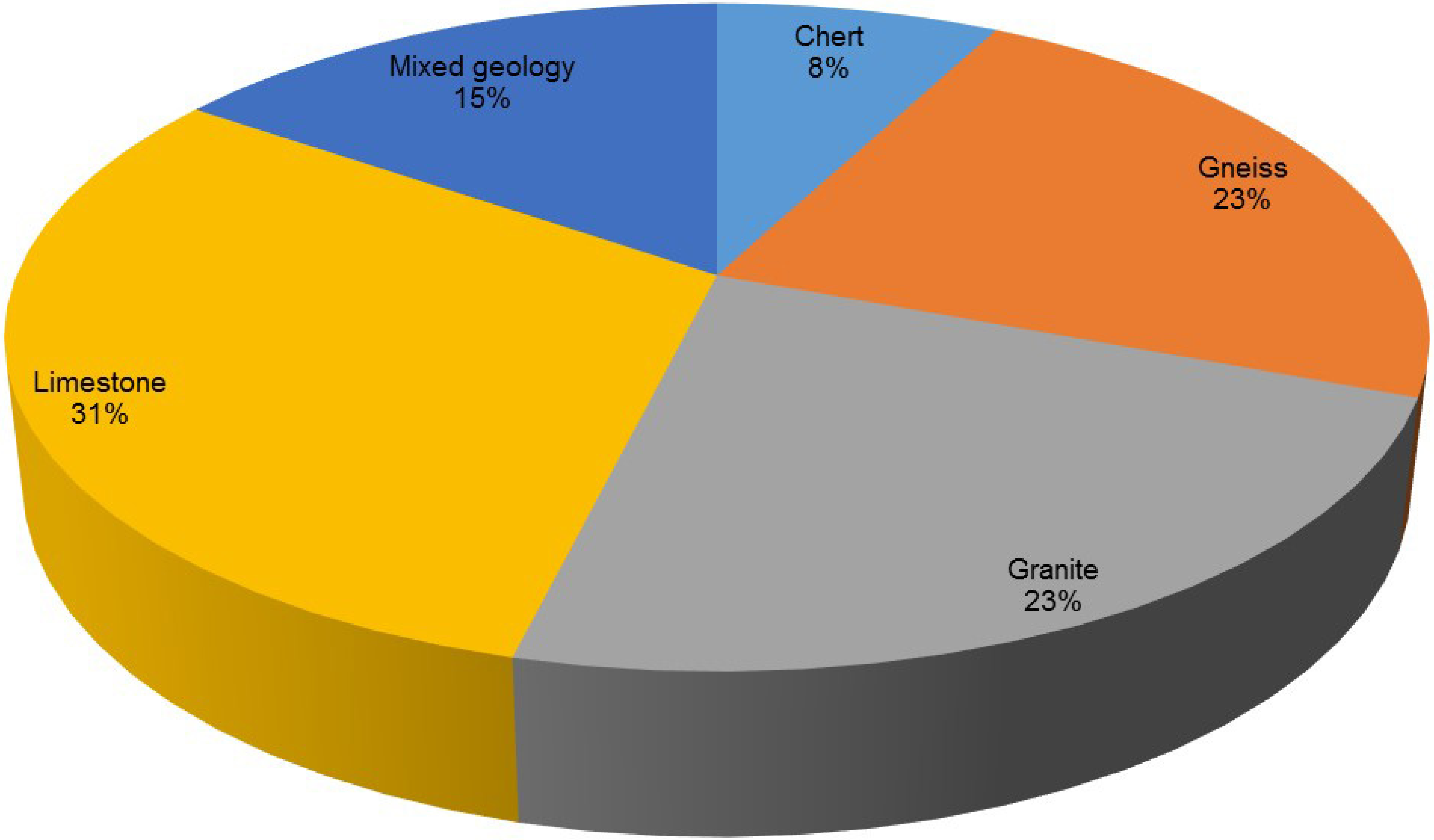


Figure 1. Specific drilling versus excavation cross-section in the examined population. The correlation is hyperbolic and quite sharp.

Figure 2. Powder factor versus excavation cross-section in the examined population. The correlation is still a hyperbola, but is much less sharp than for specific drilling.

Figure 3. Specific drilling vs. the pull of the blast rounds.

Figure 4. Actual pull vs. cross section in the examined population.

Figure 5. Frequency distribution of the actual pulls obtained from the population examined.

Figure 6. Efficiency obtained from the population examined: it appears higher in parallel hole cuts.

Figure 7 – Correlation matrix. Values are the Pearson's correlation coefficient amongst the two variables in rows and columns. Highlighted are the correlation coefficients for the pull efficiency. A detailed description of each parameter is given in Mancini et al. (1998).

Figure 8. Representation of the distribution of rock types according to Class I

Figure 9. Representation of the distribution of rock types according to Class II

Figure 10. Representation of the distribution of rock types according to Class III

Figure 11. Representation of the distribution of rock types according to Class IV

Figure 12. Representation of the distribution of rock types according to Class V

Figure 13. Representation of the distribution of rock types according to Class VI

Table 1. Classes of excavation difficulty

Class	Percentage deviations
1	$\Delta \leq -35\%$
2	$-35\% < \Delta \leq -20\%$
3	$-20\% < \Delta \leq -5\%$
4	$-5\% < \Delta \leq 10\%$
5	$10\% < \Delta \leq 25\%$
6	$\Delta > 25\%$