The influence of rock mass fracturing on splitting and contour blasts

The Influence of Rock Mass Fracturing on Splitting and Contour Blasts

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Abstract

Splitting and contour blasting are aimed to achieve suitable profiles by cutting along a surface, while common blasting is intended to detach and to fragment relevant rock volumes by increasing the fracturing state.

These techniques are adopted in both underground works (tunnels, caverns, quarries) and also for surface excavations (quarries, mines, rock slopes engineering). Contour blasts are widely used techniques in mining and civil engineering to enhance performance while maintaining the safety of personnel and infrastructure. Splitting blasts are mainly used in dimension stone mining to obtain intact blocks of valuable ornamental stone.

The parameters of controlled blasting (geometry, charge, blast agent) require an accurate selection using optimised blasting patterns and explosive properties; most of the proposed methods are limited and unsatisfactory due to insufficient consideration of rock mass properties. A quick but effective comparison and analysis of the different characteristics of the rock mass and its heterogeneities is presented, as it indicates a better strategy to determine a tailored blasting design for a given site, thus significantly improving the contour blasting quality.

Keywords: Drill & Blast; contour blasting; Rock Quality Designation; Half Cast Factor; Over Break

1. Introduction

The disturbance induced to the rock mass due to blasting impacts or stress redistribution can significantly influence the overall performance of an excavation (*S. Kwon et al., 2007*). Direct damages to the excavation profile due to blasting are usually found by evaluating the Half-Cast Factor (HCF), the overbreak (OB) and the underbreak (UB) as control indicators: there are several tools available to minimise or eliminate these problems, i.e. by modifying the type of explosive or changing the diameter of the hole, changing the burden and spacing, decoupling or decking the explosive charge. These techniques are part of the so-called controlled blasting and are commonly employed to both quarrying and tunnelling blasts, either for civil or mining purposes (*Jhanwar, 1998; Jhanwar et al., 2000*). Contour blasting is used for removing material along the final excavation face. In some cases, it's also used before production blasting, to create an artificial fracture along the final cut surface, which will prevent the radial cracks caused by production blasting from penetrating back into the finished face (*Jimeno et al., 1995; Konya and Walter, 2006*).

It is noteworthy that recent developments by some of the authors for contour blasting in underground have been presented in *Costamagna et al. (2018);* five main indices for the evaluation of damages induced by blasting in tunnelling are considered: Blast Damage Factor "D" introduced in 2002, Blast Damage Index "BDI" introduced in 1996, Failure Approach Index "FAI" introduced in 2017 and Tunnel Quality Index "Q" developed in the Q System classification. These indices do not describe the geometrical condition of the excavated contour, which depends on the comparison with the design profile, but they focus on the rock mass damage. Referred to underground openings, tunnel excavation quality also depends on the contour geometry; this also remains a valid rule in open pit excavation, even though the access to faces is usually easier to manage. Finally, the Tunnel

Contour Quality Index "TCI" was developed by *Kim and Bruland (2015)* in order to evaluate tunnel and rounds contour quality in D&B contexts. This last index takes into account overbreak distances of each cross-section (Ov), contour roughness as ratio of contour length (RCL) and longitudinal overbreak variation (V_0). Overbreak, or bad profiling, represent the consequences of poor works; they directly affect construction costs. More support is required to avoid some rock falls, and more concrete is necessary to fill up empty spaces, in order to help covering layer installation. The parameters that describe the actual conditions are often affected by scattering due to unpredictable behaviour of the rock mass, in particular for brittle failure induced by blasting (Figure 1).

Figure 1. Contour of a tunnel wall excavated in a fractured granitic rock formation: both irregular joint surfaces and crack together with residual boreholes can be observed in close distance, proving the different results of round and damages for the same rock mass.(credits C.Oggeri, tunnel in western Alpine range, Northern Italy).

An extreme application of the concept of contour blasting is the splitting: the process consists in creating one (or more) separation fractures, which isolate a given volume of rock, to be blasted subsequently (pre-splitting) or, more frequently, to be squared to produce dimension stones (dynamic splitting). This latter type of blasting adopts decoupled strands of detonating cord inserted in the holes and usually stemmed with water, which acts both as a coupling medium and as an instrument for increasing the pressure transmitted to the rock.

There are several types of contour blasting; they vary most importantly in the amount of burden they remove and the type of charges they use. As specified, the techniques can be addressed to controlled excavation of a certain rock volume (with the purpose of maintaining a regular blasting process, thus obtaining a block size distribution of the muck and an efficient use of the blasting agent) and/or aimed to a good control on the residual profile at the rock face (with the purpose of achieving a good stability after excavation and a strong reduction in induced vibrations) and on the detached rock material, as in the case of the production of large volume blocks for dimension stones exploitation. A short list of the common methods refers to the “splitting” or “pre-cut” techniques, to “smooth”, “cushion” and “buffer” techniques, to “drilling” techniques (line drilling) and “fracture control” technique.

Contour blasting techniques that best minimise the visual impacts of the blasting process are pre-splitting and smooth blasting (*Mandal et al., 2008, Zou, 2016*). The prevailing method for underground perimeter control is smooth blasting. Increased mechanisation of the construction and mining industry demanded for faster and simpler methods for the charging of the contour holes with light and well balanced charges. The whole working underground cycle (drilling, charging the blast-holes, blasting, excavation and loading, ventilation and reinforcement) became faster, but the charging of the contour holes was still done in an old fashioned way. Trial blasts started with emulsions in the buffer holes closest to the contour and employing one string of 40 g/m detonating cord in the contour holes. The result of the trials was excellent in weathered rock (*Olofsson and Frändberg, 1993*). *Iverson et al (2013)* proposed an easy-to-use blast design method that includes improvements for determining the perimeter burden based on the effect of damage from buffer holes: this means that the distance or burden between the perimeter holes and the next line of blast-holes, defined as the buffer holes, is determined by the damage caused by the buffer holes detonation.

In such a scenario, some example of the influence of RQD on the Half-Cast Factor (HCF) as result of smooth blasting application can be found and the focus can be concentrated on examples on smooth blasting in an experimental mine, i.e. an operating limestone quarry in the metropolitan region of São Paulo (Brazil); moreover, the influence of RMR on the result of Half cast factor (HCF), and over-break (OB) in tunnel driving has been analysed. The consideration on the influence of the Barton's quality on over-break OB in underground excavations was also maintained. Finally, the evaluation of the influence of Joint Volumetric Factor (Jv) on the quality of dynamic splitting wads done, with the main aim to check the relationship between the degree of rock fracturing, the specific consumption of explosive and the displacement of the bench after the blast.

2. The influence of rock mass parameters on contour blasting quality indicators

The main controlling factors that influence the performance of contour blasting can be summarised as:

- rock mass geo-structural pattern;
- relative size and proportion between excavation and discontinuity spacing;
- relative orientation between discontinuity sets and bench/wall/face of the excavation;
- opening and weathering of joints;
- rock behaviour under blasting actions (ravelling, brittle, plastic, competent, etc).

Figures 2 to 5 show some example of rock slopes in quarries obtained with contour blasting techniques, for different rock types, to provide comparison of the above-mentioned interaction rock mass - contour blasting.

Figure 2. Blasting along the bench in a blocky quarry of peridotite (hard rock): spacing between joints: 0.5–3 m. Residual vertical blast holes are partially visible; geo-structural pattern strongly affects the result of the contour blasting (credits C .Oggeri, open pit in Western Alpine range, Italy).

Figure 3.- Quarry in a white granitic massive rock formation exploited for dimension stones: boreholes are closely spaced for the use of cutting methods (in this case, detonating cord). Credits C. Oggeri, Northern Alps, Italy.

Figure 4. Quarry face in weathered limestone with evident traces of boreholes (good HCF) along the benches during the exploitation of aggregates; three largely spaced joint systems form the rock mass. (Eastern Alpine range, Italy)

Figure 5. Quarry in limestone for aggregates, with two main joint sets; it is relevant the sub-horizontal system, with spacing of about 0.3–0.5 m. Left: blasting profile and few residual blast-holes in a vertical face 15 m high. Right: mechanical action of a hammer for detachment and scaling in a sub-vertical face 9 m high; scaling can represent an auxiliary procedure to solve mixed conditions (credits C. Oggeri and I. Cassone, quarry in South Italy).

The main definitions are summarized in table 1, where the most relevant geomechanical factors of the rock are listed.

Table 1: list of the main parameters involved in the contour blasting technique.

Parameter	*Definition*
HCF	*Half cast factor – the percentage of visible half-casts on the final wall with respect to the total drilled contour holes*
OB	*Over Break, volume excavated beyond the desired surface of breakage*
UB	*Under Break, volume remained unexcavated within the desired surface of breakage*
RQD	*Rock Quality Designation*
RMR	*Bieniawski's Rock Mass Rating*
Q	*Barton's Quality Index*
J_v	*Joint Volumetric Factor*

The correlations, linking the main rock mass parameters, are generally empirical relations. Some of those commonly used are provided in table 2, with reference to the most important classification systems developed over the years by various researchers.

The meaning of this is that all the variables discussed in this paper can be treated as a whole set of data, considering the conditions of the rock mass instead of those of the intact rock, independently of which specific rock mass parameter one considers. Such analysis will be the subject of future work.

Table 2: Empirical correlations commonly used, with reference to the most commonly used classification systems.

Correlation	*References*
$RQD = 115 - 3,3\,J_v$	*Deere, 1964; Deere, 1989; Choi and Park, 2004; Coon and Merritt, 1970; Zhang and Einstein, 2004*
$Q = RQD/Jn \times Jr/Ja \times Jw/SRF$	*Priest and Hudson, 1976; Barton et Al., 1980; Barton, 2002; Brown, 1993; Coon and Merritt, 1970; Ebisu et Al., 1992; Zhang, 2016*
$RMR = 50+15\,logQ$	*Bieniawski, 1978; Hoek and Brown,1997; Nicholson and Bieniawski, 1990; Palmström, A.,1982; Palmström, A., 2002; Coon and Merritt, 1970; Ebisu et Al., 1992; ISRM, 1978; Serafim and Pereira, 1983; Singh and Goel, 1999; Singh and Rao, 2005*
$GSI = RMR - 5$	*Coon and Merritt, 1970; Ebisu et Al., 1992; Ramamurthy et Al., 1985; Sonmez et al., 2003; Sonmez et al., 2004; Marinos and Carter, 2018; Marinos and Hoek, 2000*

2.2 Influence of RQD

Smooth blasting in an experimental mine

The authors carried out this research (details of the experimental procedure in *Seccatore et al., 2015)* in order to evaluate the minimum charge/maximum spacing ratio which guarantees a good control of the walls. Smooth blasting was employed adopting four different configurations of non-coaxial charges, following different drilling geometries (constant linear charge along the holes by varying the spacing between the contour holes; constant spacing between the contour holes by varying the linear charge along the holes). Four experimental blasts were performed. HCF was the control parameter, and it was related to RQD.

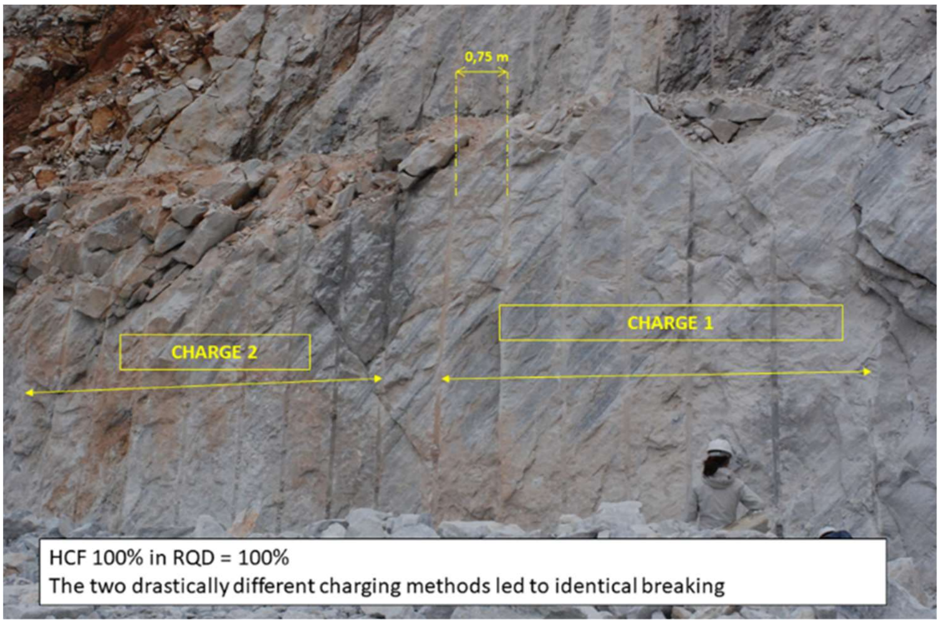
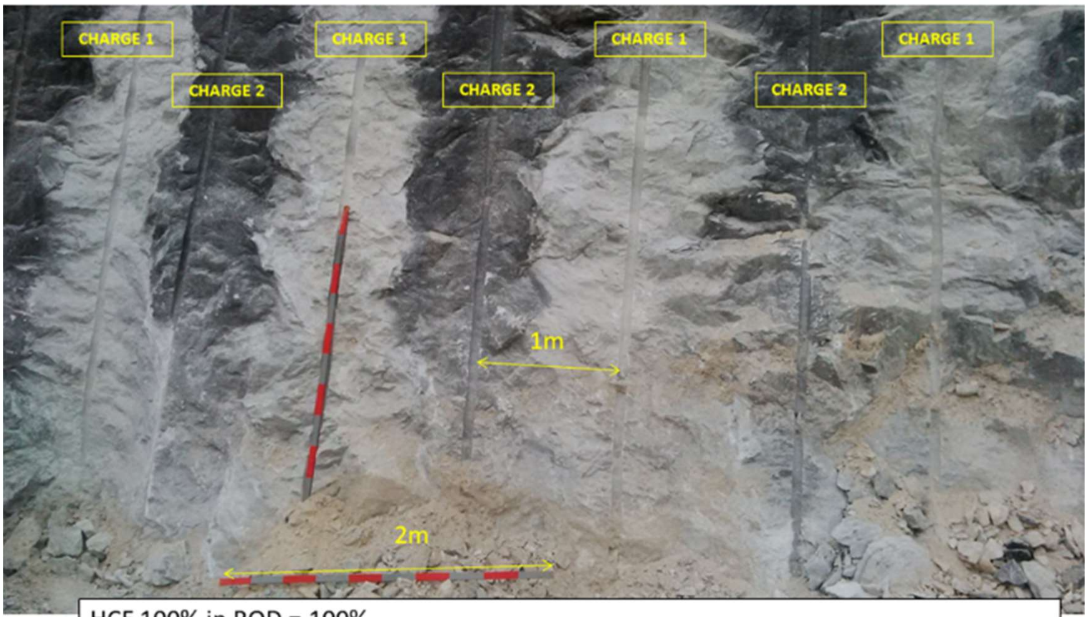


Figure 6. *Results of Blast 1. On the remaining wall, the presence of the contour holes with a HCF that approaches 100% can be observed*



HCF 100% in RQD = 100%
Alternate charging methods led to smooth, uniform breaking

Figure *7. Results of Blast 2. On the remaining wall, the presence of the contour holes with a HCF that approaches 100% can be observed. Holes charged with charge 2 (two strands of 40 g/m detonating cord along the hole) can be recognized by the black mark left by the decomposition of the cord jacket*

Results showed the operational limitations of non-coaxial charges due to the features of the rock masses encountered; in the quarry site object of this research, RQD had previously been determined by means of an on-site testing campaign, according to the standards suggested by ASTM (1996). when the rock is little fractured (RQD = 100%), open-pit smooth blasting with decoupled charges and linear charge of 40 g/m (188 grain/foot) can be extended to a spacing E = 22 Ø, being Ø the hole diameter (a proportion falling in the range of production blasting), maintaining HCF = 100% and with little or no detectable drawbacks in terms of final wall quality; when the rock is highly fractured (RQD < 40%), the quality of the final wall is heavily affected: almost no half-cast remains visible and the contour is heavily affected by over-break, despite the accuracy spent in performing the contour blasting. Figures 6 to 8 show the results obtained by experimental blasts.

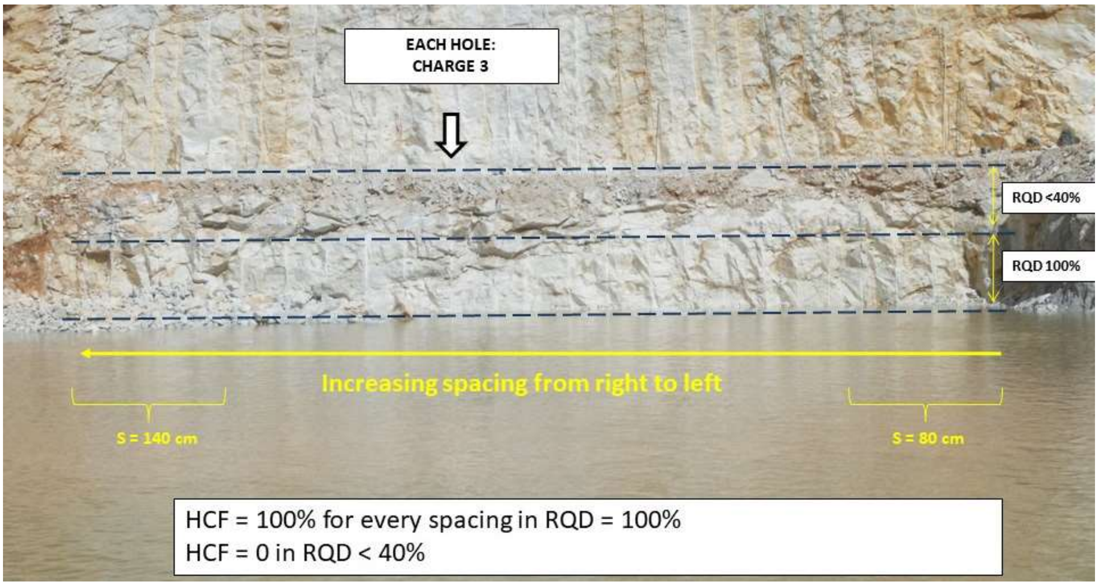


Figure 8. *Front view of the final wall obtained from Blast 3, which was performed by progressively increasing the spacing between the holes. Charge 3: single strand of high-graining (40 g/m) detonating cord along the hole.*

Blasting tests in a limestone quarry

The authors conducted experimental blasting tests (experimental details in *Barrere, 2017*) in an operating a limestone quarry in the metropolitan region of São Paulo (Brazil). The efficiency of those tests was compared to the distribution of RQD values at the surface of the slope, which was mapped thanks to a preliminary geo-mechanical study The objective of the research was to apply contour blasting techniques to solve problems related to operational safety, which are directly related to slope instability. The strong impact of rock-mass quality on the results of blasting, as well as on technical and economic sustainability of the project, was also stressed out in this study. The assessment of project sustainability was based on operational, safety and economic parameters. The results (Figure 9) showed that regions with a higher RQD presented a better blasting efficiency, which proved the importance of the rock mass quality on the blasting quality. In spite of representing an annual cost higher than that of ordinary blast techniques, contour blasting has a significant positive impact on safety and operations, by reducing the over-break, as well as the number of loose blocks at the surface of the slope, decreasing the duration of truck loading and every negative effect resulting from inaccurate control techniques. The experimental results thus showed that the application of contour blasting can be a solution in risk-exposed areas of a quarry, as it enables the increase of the operating life of the site, which turns the higher cost of contour blasting into a durable investment and improves the sustainability of the project.

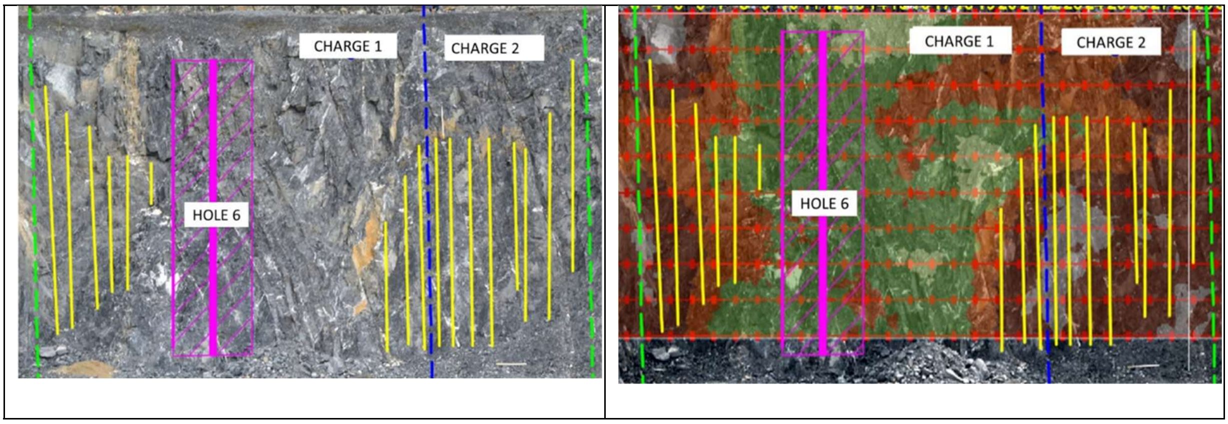


Figure 9. Left: the yellow lines show the half casts, where it was possible to visualize and measure the HCF line. Right: map overlay of RQD obtained by image analysis and the HCF. Scale of colour: light green = low RQD, dark brown = high RQD. The net of red dots was used to visually determine RQD. It is noticed that the region where there was the lowest RQD value is exactly the region between where there was the worst result in terms of HCF. Hole 6 is highlighted as, during charging, part of the hole walls collapsed and charging was made practically impossible.

2.3 Influence of RMR on Half cast factor (HCF), and over-break (OB) in tunnel driving

The quality of the excavated contour in a tunnel directly affects the final costs of the infrastructural facilities (*Scoble et al., 1997; Hu et al., 2014*). Poor contouring can produce under or over-excavation, affecting the HCF factor (*Innaurato et al., 1998*) and influencing the rock mass quality and producing unwanted artificial fractures into the rock mass. These factors produce many unfavourable consequences: scaling or specific support is required, the advancing rate decreases, convergences may increase and time schedule increases and safety is compromised. As an indicator of the quality of the rock, it was used the RMR, according to *Bieniawski* (*1973; 1984; 1989*). On the basis of observations on more than 15 stretches of tunnels in different geological conditions and excavated with different techniques, it was possible to outline the relationships between RMR and over-break and RMR and HCF (Figure 9). The analysis of the results showed that the rock-mass structure has a not negligible influence when a quality threshold (suggested by observation) has to be set for a tunnel blasting operation. Moreover, it was found that the use of sophisticated drilling systems and of expensive equipment do not provide advantages in cases of poor quality rock-masses. Finally, it was found that OB is a sensitive indicator of the quality of blasting and that the same factor evidently decreases as the rock mass strength improves (Figure 10); the better the rock, the better the quality of blasting.

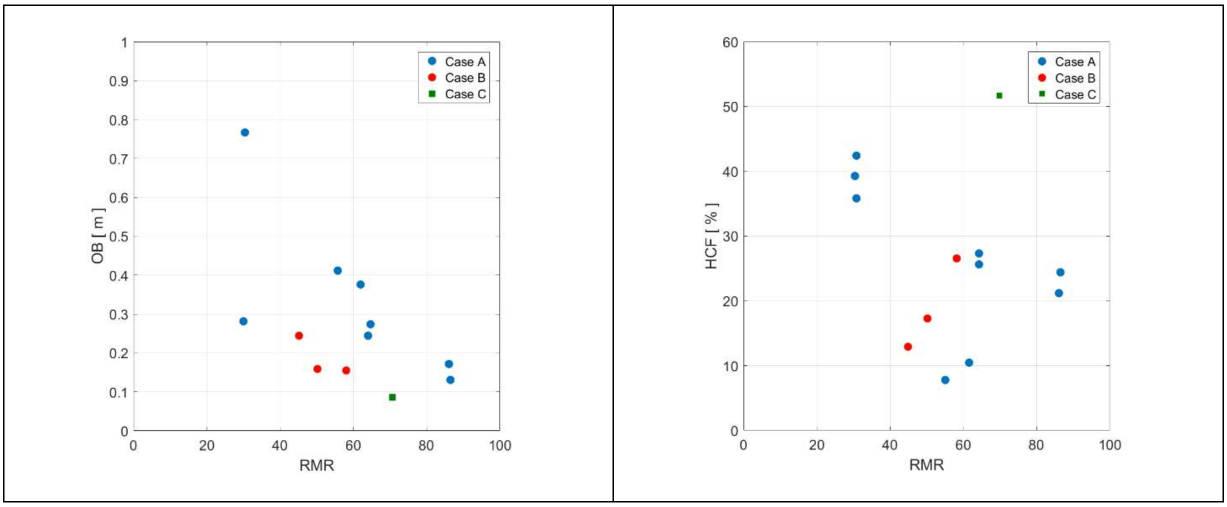


Figure 10. Left: trend of the total extra-profile OB as a function of RMR; right: trend of the HCF as a function of RMR . A: smooth blasting + manually controlled jumbo; B: computerised jumbo; C: smooth blasting + computerised jumbo. One notes that the best results are obtained when computerised jumbo is applied

2.4 Q as and its influence on Over-break OB in underground excavations

Over-break (OB) assessment in tunnels is a crucial factor for minimising cycle time operations and optimising a blast. It is influenced by geotechnical parameters, blast design, operational parameters and explosive properties. OB, moreover, has a significant impact on the project cost, construction time, safety and performance of the underground structures. In the case of civil tunnels, the zone damaged by blasting can affect the stability of the structure, requiring a support system with additional costs. The authors of the present work extrapolated upper and lower limits of the experimental data provided by *Verma et al.* (2018), who carried out field investigations at five different Himalayan tunnels to find an empirical equation for predicting blast-induced over-break for a wide range of rocks. More than 100 experimental blasts were monitored and drilling data, especially perimeter holes, were collected. Charge/hole, total charge, initiation sequence and maximum charge per delay were also recorded. The blasts were performed using emulsion explosives (40 mm, or 1.6" cartridges) and non-electric initiation system. Pull obtained from each round was accurately measured. Rock mass quality index, Q *(Barton et al. 1974),* was used for rock mass characterisation. This system is specifically recommended for civil construction, such as that involving tunnels and caverns for various purposes, like support design and engineering classification of rock mass. In Q-system, the Stress Reduction factor (SRF) is one of the parameters which accounts for active stresses during construction of an underground opening, and that is why Q-system was selected for rock mass characterisation in this study. In all the experimental sites, Q ranges from 0.03 to 17.8, showing that the suggested method can be applicable to a wide range of rock mass conditions. It was found that blast induced damage to the surrounding rock-mass depends significantly on the quality of rock mass. Figure 11 shows the trend of over-break as a function of the rock mass quality, Q; it can be noticed that the average overbreak is the highest for the lower classes of rock mass, then decreases with the increase of Q. The average OB decreases approximately by 6% when the rock-mass is good.

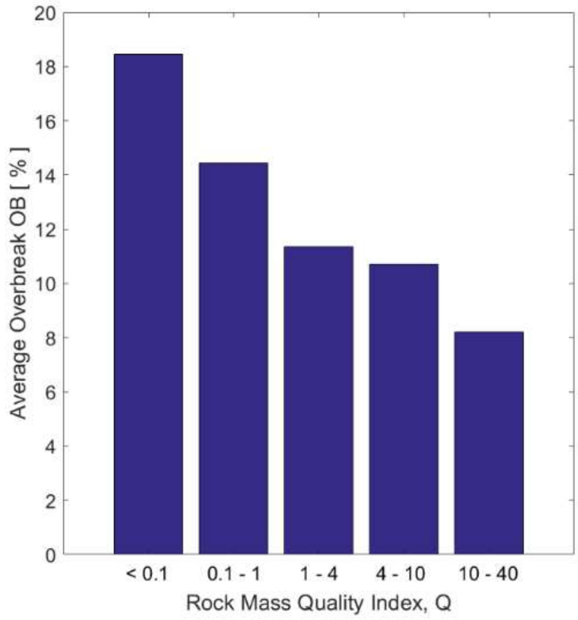


Figure 12. Trend of the average over-break as a function of the rock mass quality index Q (Modified after Verma et al., 2018).

It is, on the other hand, known that that average over-break is influenced by the contour charges distribution. A measure of the optimal working-point of the explosive energy and the progressive enlargement of the tunnel is provided by *Verma et al. (2018)* through the term q_p/A_f, i.e. the ratio of the perimeter charge factor to the advancement factor q_p (kg/m^3) is similar to the powder factor, representing the amount of explosive used in perimeter holes and the volume of rock corresponding to the burden of contour holes. A_f is the ratio of pull to the hole's depth in a round. *Ibarra et al. (1996)* observed that perimeter powder factor is directly proportional to the over-break and under-break. Analysis of observed data from the experimental blasts shows that the ratio of q_p/A_f is even better correlated with over-break in underground construction (Figure 13). A higher q_p gives rise to greater over-break. Another aspect of blast induced damage, as noticed in Figure 12, is that a better advancement in a blast round will optimally exploit the explosive energy, and hence damage to the rock mass will be reduced.

The overbreak in underground excavation is also influenced by the grain size distribution with respect to the size of opening, due to the scale effect. The index representing the ratio of tunnel cross-section to the block size was then formulated and analysed. Block size is a ratio of RQD and Joint number, Jn. A higher value of 'scale index' indicates the opening in highly fractured rock mass, whereas lower values indicate the opening in massive rock formation. Over-break will be higher for higher values of 'scale index' and vice-versa. Figure 13 shows the effect of 'scale index' on over-break.

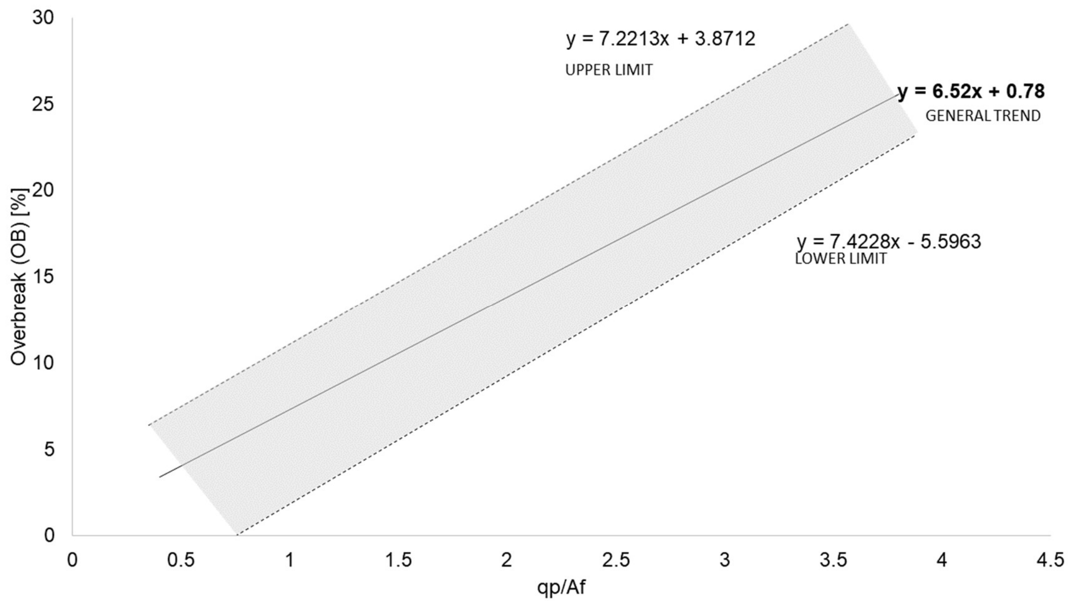


Figure 13- *Trend of the observed over-break as a function of the ratio qp/Af (from data by Verma et al., 2018).*

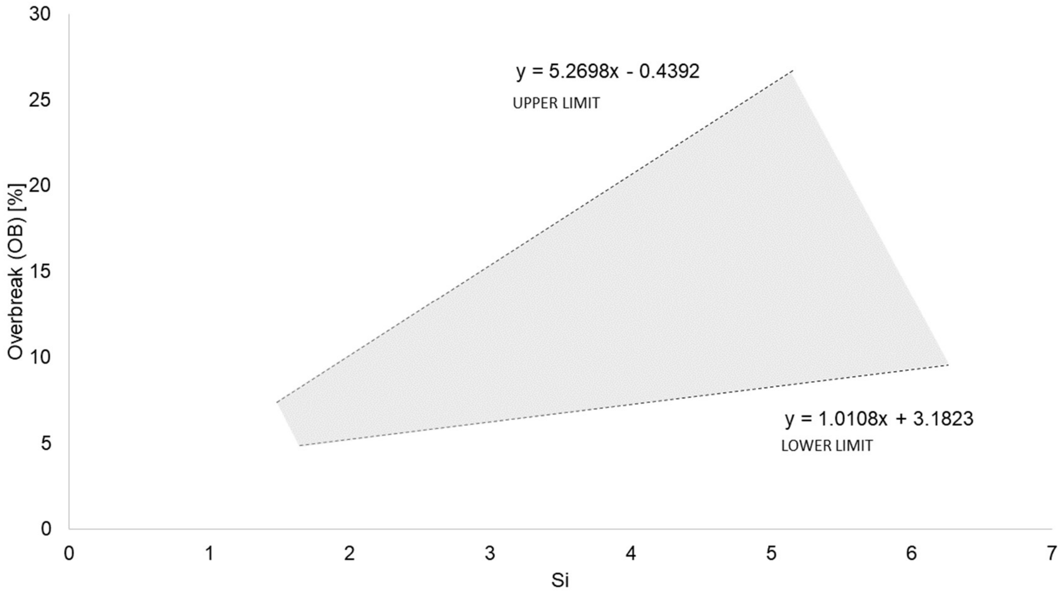


Figure 14 *- The trend of scale effect index Vs. Over-break (from data by Verma et al., 2018).*

Providing upper and lower limit to the range of overbreak can help the blast designer to control the overbreak of the excavation based on industrial experience.

2.5 Jv and its influence on the quality of dynamic splitting

The objectives were the identification of a possible correlation between the degree of rock fracturing, the specific consumption of explosive and the displacement of the bench after the blast. Evaluating the results of blasts and identifying the optimal powder factor in many quarries was the procedure followed to optimise the excavation technique currently used in a hard dimension stone basin (Luserna stone - gneiss) in Northern Italy (*Ferrato, 2010*). The experimental campaign involved: the measurement of the progressive, the position and the length of the discontinuities on the excavation face and the elaboration of the data acquired; namely, the identification of families of discontinuity; the calculation of the parameters characterising the family (spacing, length and persistence) and the calculation of the degree of fracturing (Jv).

Geometric measurements were made on the bench (height, length and width), of the blasting pattern (spacing E, burden V and diameter of holes Φ) and of the amount of explosive used (kg of black power) and length (m) of detonating cord employed; in particular, two main typical cases were taken into consideration: the volume of the bench >200 m^3 (7,062 cubic feet) and volume <200 m^3 (7,062 cubic feet). From the analysis, lower powder factors were found out in the blasts involving larger volumes of rock, and an over-use of black powder was detected with respect to detonating cord in the benches involving lower volumes, highlighting the problem of the real need of using the black powder. Therefore, the natural fractures (pre-existing discontinuities) and those induced by the blast (excess of explosive) were evaluated, and the real displacement at the base of the bench was measured; therefore, the average displacement of the bench's centre of gravity was calculated. The results showed that, for a given Powder Factor, the lower displacement is found where Jv is higher (Figure 15).

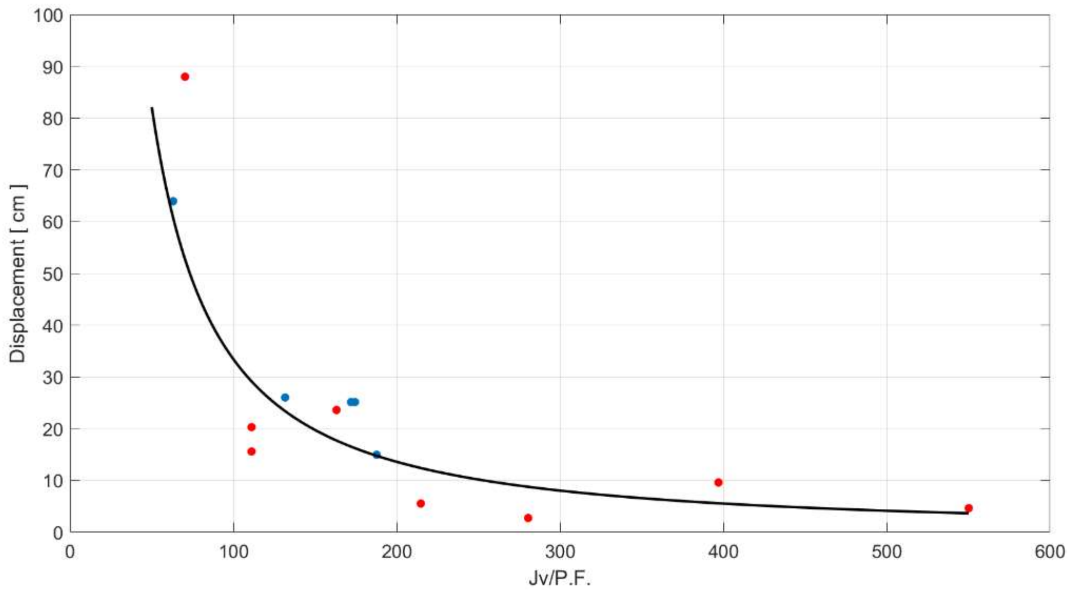


Figure 15 *- Correlations between the bench displacement and the Jv/P.F. ratio (after Ferrato, 2010). Correlation coefficient* R^2*=0,67.*

The results showed that the exploitation of the quarries in the Luserna basin takes place with an excess of charge: this involves the induction of undesired fractures in the rock; the sole use of the detonating cord is sufficient and recommended to guarantee the detachment, minimising undesired injuries, insuring the quality of rock blocks and resulting in an optimisation of explosive consumption.

4. Discussion and Conclusions

Contour blasting is also called controlled blasting as its main purpose is to minimize the damage to the rock (overbreak) beyond the boundary of the designed contour of the excavation. Some contour blasting techniques and their mechanism, contour blasting design and working methods are shown in this paper as a result of experimental tests.

Drilling and blasting techniques have been extensively applied to rock excavation both in mining and civil engineering due to their low cost, high efficiency, and easy operation. However, some negative effects are often encountered under the blasting loads, such as blast-induced damage and vibration. To minimize and reduce these problems, control techniques have been widely introduced into blasting design (quarry, rock slopes, foundations, caverns and tunnels). All of them need to drill small spacing boreholes along the designed contour line. The holes are lightly loaded and decoupled with low-powered explosives.

Those techniques are relevant for stability, production, reclamation and efficient support systems or site operation. In tunnelling, over-excavation resulting from drill and blast in a fair rock mass can affect both timing and costs (i.e., mucking and concrete/shotcrete costs), because the additional excavated volume usually needs to be replaced by additional shotcreting and other reinforcing works. In open pit exploitation, acceptable profiling drives the evolution of rock slope, for regular blasting pattern and stability features control.

Many factors are influencing the choice of the method and the results of operation as well for surface excavations, taking into account the unavoidable natural heterogeneities in rock masses.

The review of data presented in this paper shows that the characteristics of the natural fracturing of the rock mass has an undeniable influence on the performance of surface-cutting blasts, such as contour or dynamic splitting.

For practical reasons, authors choose some particular but suitable parameters to characterise the rock mass conditions during their research and projects, and similarly, some indices can be adopted to quantify the quality or damages induced in the residual rock mass. Nevertheless, the parameters used for rock mass characterisation are interchangeable among themselves, as they refer to the same characteristics (discontinuities present in the rock mass and their characteristics) merely by different systems of measurement. The authors suggest the grouping of such variables and their analysis as a whole, focusing on the specific use of blasting and on its design.

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