Damage and contour quality in rock excavations for quarrying and tunnelling: assessment for properties and solutions for stability

E Costamagna[1], C Oggeri[1] and R Vinai[2]

[1]DIATI Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[2]CEMPS, University of Exeter, Harrison Building, North Park Road, Exeter EX4 4QF, United Kingdom

claudio.oggeri@polito.it

Abstract. Excavations in rock masses determine the creation of temporary or final exposed surfaces. Features of these surfaces are depending on both geostructural pattern of the rock mass and adopted excavation method: among the others, roughness, quality of the contour and induced damage inside the rock left in place. These aspects are important as they are requirements expected during the excavation and construction procedures, such those involving dam sidewalls, quarry benches, tunnel profile, slope scaling.

This methodological paper describes a list of the possible cases, with a particular emphasis on quarrying and tunneling. By following current modes for profile surveying, the damages are reported, in order to obtain suitable indices for induced damage. Finally the proper techniques for excavation are commented on the basis of real case histories of tunnels and quarries in order to reach the primary objectives of damage reduction and stability/productivity goals.

1. Introduction

Excavations in rock masses for civil or mining purposes involve the creation and development of new exposed surfaces, either temporary or final. Rock mass properties and geostructural features are driving the adopted excavation techniques, namely blasting, mechanized (punctual or full face), scaling, profiling, sawing and cutting. The local stress state and the extension of the contour (free surfaces) are then completing the pattern that determines the final behaviour of the rock mass. The combination of such a consistent number of conditions claims for the assessment of key factors that can induce a damage in the rock mass: this is a particularly relevant aspect as it is linked with geomechanical properties, such as in situ strength and deformability, convergence and displacements, mode of detachment of rock elements, changing the local conditions for hydraulic conductivity and for support selection, if any. The paper focuses on the possible cases, referring to quarrying, tunnelling and slope stabilization. Then, description of current modes for surveying the induced damages and the corresponding suitable indices to determining the contour profile quality are reported. Damage in rock mass around the excavation is accompanied by a strength reduction, caused by the opening or shearing of new or extended cracks and joints as a consequence of lack of confinement and it can affect both underground and open pit excavations. Poor profiling or off-profile directly affect construction costs:

in tunnelling more supports are required to avoid that some rock falls and more concrete is necessary to fill up empty spaces in order to help covering layer installation; in quarrying there are consequences of poor blast control in terms of higher consumption and undesired effects (projections, inaccurate grain size distribution); in dimension stone quarrying block recovery and safety during exploitation are directly dependant on proper profiling techniques and careful local geostructural pattern assessment can lead to proper solutions.

The unwanted damage induced by excavation methods, particularly when drilling and blasting (D&B) operations are carried out, has important consequences affecting the quality of the rock mass around the excavation, and therefore the efficiency of blast pull, the need for extra supports such as shotcrete and concrete, the need for extra mucking effort and ultimately the safety, cost and timing of the excavation project. Figure 1 shows a sketch of the different zones that can be found around the excavation of a tunnel: (a) the design profile, which is the desired result, (b) the excavation profile, which is the result of the blast pull, (c) the under- or over-excavation area, this latter also known as "overbreak zone", (d) the damaged zone, the rock body beyond the overbreak zone where the effects of D&B produced irreversible and major changes in the rock mass properties (due to the opening of a crack network that deteriorates the mechanical and physical properties of the rock mass), and (e) the disturbed zone, i.e. the rock mass portion where the changes in physical and mechanical properties are negligible [1].

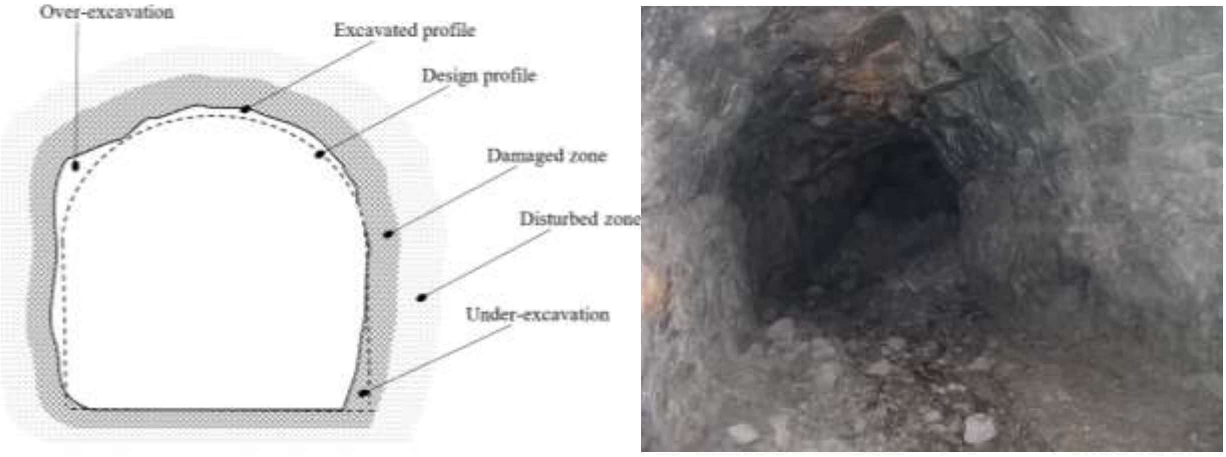

Figure 1. Sketch of a tunnel section with indication of the different zones in the rock mass affected by D&B operations (left); mine drift excavation in hard rock with contouring blastholes in methamorphic rock (gneiss): half cast holes are visible on the walls. Induced damage for detachment of small pieces due to preexisting closed joints.

2. Description of the profile quality of blast operations and damage indices

The concern related to the blasting pull quality and its repercussions on excavation time and costs fostered several studies dating back in time, both in mining as well as in civil engineering projects. The quality of the excavation depends on many factors, some of which are out of the control of the project designers (i.e. the natural conditions of the rock mass, summarized in rock mass classifications), whereas others are directly related to the execution of the excavation (drilling pattern and blasting sequence mainly in D&B [2], the geometry of the tunnel) and thus in the control of the project designers. Efforts have been carried out in order to find correlations between main blasting quality parameters and rock mass quality, although the obtained correlations have not been always clear due to the variety of factors that are involved in the blasting operations and the sometime unpredictable response of the rock mass to the excavation. Innaurato et al. investigated the parameters describing the quality of blasts in tunnel driving such as the pull efficiency, the overbreak and the Half

Cast Factor (HCF, i.e., the ratio of the observed length of half cast on the tunnel wall to the total drilled length of the contour holes) and examined the influence of the quality of the rock mass on said parameters, using the RMR (Rock Mass Rating) according to Bieniawski and the rock mass strength according to Hoek and Brown criterion as indicators for the rock mass quality. Vibrations and HCF was found to be a sensitive indicator of the quality of blasting, identifying a significant correlation between the HCF and the rock mass quality [3]. Ground vibrations measurement is a common technique for assessing the blast induced damage as its analysis makes possible prediction of damage extent. Most of these vibration-based predictors are developed from the measurement of actual damage extent using current geo-physical tools, namely, P-wave velocity, bore hole pressure monitoring, electrical resistivity, GPR (ground penetrating radar).

Many methods for the evaluation of surface roughness have been proposed which covers from the qualitative assessments based on visual and hepatic perception to quantitative instrumental measurement methods. Measurement methods are mainly divided into two groups, contact methods which include surface profilometer and atomic force microscope, while light interferometer and machine vision being considered in noncontact methods.

The digital JRC estimation works acceptably well and typically the roughness is digitally overestimated only by 1 JRC unit over the trend line. It is possible to record the rock joint in continuous circles of camera locations at three different angles. These requirements cannot be met when performing in-situ photogrammetry in open-pit or underground mines. The post-processing of the images differs very little between laboratory and in-situ photogrammetry. Further development includes a more realistic fracture network with fracture set sequencing and termination. This enables the photogrammetry to record a fracture network intersecting the open surfaces and then generating the corresponding minimum energy extension to inside the rock mass [4].

The extension of the damage area around the tunnel section is of particular importance for properly assigning reduced mechanical properties to the rock mass when modeling its behavior [2, 5]. Verma et al. proposed an empirical correlation that takes into account the blast design parameters and the rock mass quality. The raw data were obtained from five tunnel projects in the Himalaya Mountains, and the method was validated using geophysical tests on samples obtained from different locations [1].

A reliable prediction of overbreak has obvious consequences in the management of the project, and understandably this topic has been receiving high attention in the literature. Recent approaches suggest to separate the construction (or technical) and geological reasons for overbreak, where the former are due to inaccuracy in the drilling and other excavation operations, whereas the latter are due to the nature of the rock mass and its inherent damage [6,7]. The detailed description of the current trends for the overbreak prediction however falls outside the scope of this paper.

The overbreak contributes 15–18% of total tunnel construction cost. Rock mass rating (RMR) and Rock mass quality (Q-system) are extensively used classification index for rock mass, incorporating all the geological features that influence the overbreak [6].

A variety of methods can be found in the literature for the evaluation of rock damage, as discussed by Costamagna et al. [2]. In this section, the main damage indices and the proposed rock mass classifications that include the damage assessment are discussed in further detail as of primary importance in the description of the damage and its effects.

2.1. Damage indices and monitoring

As discussed in Costamagna et al. [2], the four main indices available for the evaluation of damage are: (a) Blast Damage Factor, (b) Blast Damage Index, (c) Failure Approach Index, and (d) Tunnel contour quality index [2].

- *Blast Damage Factor.* It is a parameter introduced in 2002 and revised in 2012 by Hoek [8] into the Hoek-Brown failure criterion. The parameter D ranges between 0 (undisturbed rock mass) and 1 (highly disturbed rock mass); its estimation is obtained through a description of the excavation contour conditions and *D* is involved in the assessment of both rock mass strength and deformability close to the excavation boundary.

- *Blast Damage Index*. The index was proposed by Yu and Vongpaisal [9] and was mainly intended for mining works. It consists of a ratio that takes into account the effects of wave propagation into the rock mass. It has been used in the literature for assessing the severity of the effect of blasting operations on the stability of nearby slopes.
- *Failure Approach Index.* The index was developed by Xu et al. [10] for the modelling of layered rock mass. An elastic-plastic constitutive model was proposed for layered rock systems, and the Failure Approach index was developed including a damage factor into the constitutive model. The method was validated analyzing the construction of a hydropower project, predicting position and intensity of failures and collapses during excavation.
- *Tunnel contour quality index.* The index is based on laser profiling techniques and has been developed for the effective management of tunnel contour quality [11]. The index is calculated as a fraction form consisting of three elements (overbreak depth, contour roughness, longitudinal overbreak variation) that are obtained from surveyed tunnel profiles, three weights for the elements and one constant for range adjustment.

In order to consider the rock mass conditions due to the inherent structure (i.e. geological damage), Paventi [12] proposed the use of the Inherent Rock Mass Damage Index (D_i), which is based on a rating system that involves four components (intact rock strength, meso-structure, joint conditions, macro-structure). Recently, Adoko and Zhael [13] proposed a methodology for assessing rock mass damage in underground mining by introducing the Rock Mass Damage index (RMDi), which is based on the methodology of the Rock Engineering System introduced by Hudson in 1992. The RMDi is based on the assessment of 9 parameters encompassing the quality of rock and the type of excavation technique, combined according a specific weighting that has been calibrated on a limited number of datasets. Jang et al. [14, 15] proposed an Overbreak Resistance Factor (ORF) examining the relationship between rock mass characteristics (unsupported face condition, uniaxial compressive strength, face weathering and alteration, discontinuities- frequency, condition and angle between discontinuities and tunnel contour) and the depth of overbreak through using feed-forward artificial neuron networks.

Figure 2. Left: Damaged wall at a crossing section between two temporary mine drifts in talc schist, at 450 m of depth: poor profile due to uncontrolled blasting and texture of the rock mass; half of a 2.5 m long rockbolt is in the plasticized/sheared zone of the pillar (Italy). Right: 18 m high bench in horizontally laminated limestone, careful blasting and scaling (Portugal). (credits Oggeri)

2.2. Rock mass classifications addressing the excavation damage

Rock mass classifications are fundamental tools for the assessment of the quality of the rock mass, and, following the wide adoption of some classifications such as the Bieniawski's Rock Mass Rating (RMR) system [16], empirical relationships have been developed both in mining as well as in civil engineering industries for prediction of technological features of rock structures (Figure 2). Some modifications or novel classifications including the effects of damage on the rock mass quality have been proposed in the literature:

- *Modified RMR (MRMR).* Laubscher and co-workers proposed a modification of the Bieniawsky classification since 1977 and in several editions, with the aim of using efficiently the RMR classification in mining context. The modified RMR system (MRMR) adjusts the basic RMR value by considering the in-situ and induced stresses, stress changes and the effects of blasting and weathering, and support recommendations are proposed accordingly [17].
- *Modified basic RMR (MBR).* Another modification of RMR for block cave mining was proposed by Cummings et al. [18]. The method included different ratings for the original RMR parameters as well as adjustments for blast damage, induced stresses, structural features, distance from the cave front and size of the caving block.
- *Slope Mass Rating (SMR).* Romana proposed an extension of the RMR system called slope mass rating (SMR) for use in rock slope engineering. It involved new adjustment factors for joint orientation and blasting/excavation to RMR system for slopes [19].
- *Geological Strength Index (GSI).* The index was initially proposed by Hoek assessing a simplified set of rock mass parameters (basically mass structure conditions and rock discontinuity surface conditions). The Damage factor D was introduced for the empirical determination of Hoek-Brown failure criterion parameters from GSI [8, 20].

2.3. Cutting methods and contour measuring techniques

Depending on the rock formation, the geostructural pattern, the aim of the excavation and the local topography, technicians can select the most appropriate contour blasting method among several types [21]. 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.

In addition, mechanized methods (full face or punctual) can be selected and, finally, also surface cutting methods can allow a quasi-planar face at the end of the operation (Figure 3). Contour blasting methods are affected by the amount of bench burden or wall burden to be removed and on the round parameters adopted (charge per delay, type of blasting agent). The aim of the techniques can be the controlled excavation of a defined rock volume, repeating a regular blasting scheme, in particular when it is necessary to maintain a certain block size distribution of the muck; the other feature of economic and environmental relevance is the efficient use of the blasting agent. In other cases, such as slope profiling or excavation close to sensitive targets, the aim is to achieve a good control on the residual profile at the rock face: the purposes are keeping a good stability after excavation and a relevant reduction in induced vibrations. In the case of dimension stones (that is the production of large volume blocks for dimension stones exploitation) the detached rock material is valuable and so both the elements and the face should be as regular as possible in order to achieve commercial blocks not damaged, a limited need to secondary cuts to keep waste rock amount as lower as possible and to maintain the faces regular and stable.

A specific application of contour blasting is represented by the splitting [21]: this technique is intended to create one (or even more) separation fractures, which are surrounding a given volume of rock; the isolated volume can be blasted in a second phase (pre-splitting in tunnel excavation or in bench quarrying) or can be regularly squared (dynamic splitting in dimension stone quarrying). This latter type of contouring can adopt stretches of detonating cord which can guarantee a high decoupling factor (ratio between detonating cartridge or cord diameter and blasthole diameter) when inserted in the holes; usually stemming is made with water, easy to handle and effective in the regular transmission of pressure to the rock.

It can be useful to notice that the block recovery is the result of a combination of inherent factors in the quarry context, such as: deposit type (sedimentary, metamorphic or igneous), structural geology (joint network), mineralogical composition of the rock and its inclusions, mechanical properties of the rock, location of the quarry and its topography, quarrying method used, cutting techniques applied, geotechnical evaluation. Referred to other types of mining, dimension stone quarrying does not possess an index capable of establishing the economic value of the material, which is given by its demand in the market that is linked to its external appearance: this is a reason to pay attention to induced damage reduction and to proper cutting technique and face profile control. As the determination of a stone block arrangement within a blocky rock mass may be considered as a packing problem, that is the profitable stereo-geological division in commercial elements of a given rock mass volume: this reflects the attention to contour quality in this field of mining.

Induced damage in rock mass means a drop of strength as a consequence of the opening or shearing of new or extended cracks and joints; this can affect both underground and open pit excavations and it is related to the existing discontinuity conditions. A lack in the contouring control is affecting construction costs: in tunnelling increased amount of support is requested to avoid rock falls and more sprayed concrete is necessary to fill up empty spaces; in quarrying poor blasting control determines higher agents consume and undesired effects (projections, inaccurate grain size distribution); in ornamental stone quarrying, as said, block recovery and safety during exploitation are strongly dependant on suitable profiling techniques following directions of geostructural pattern determination.

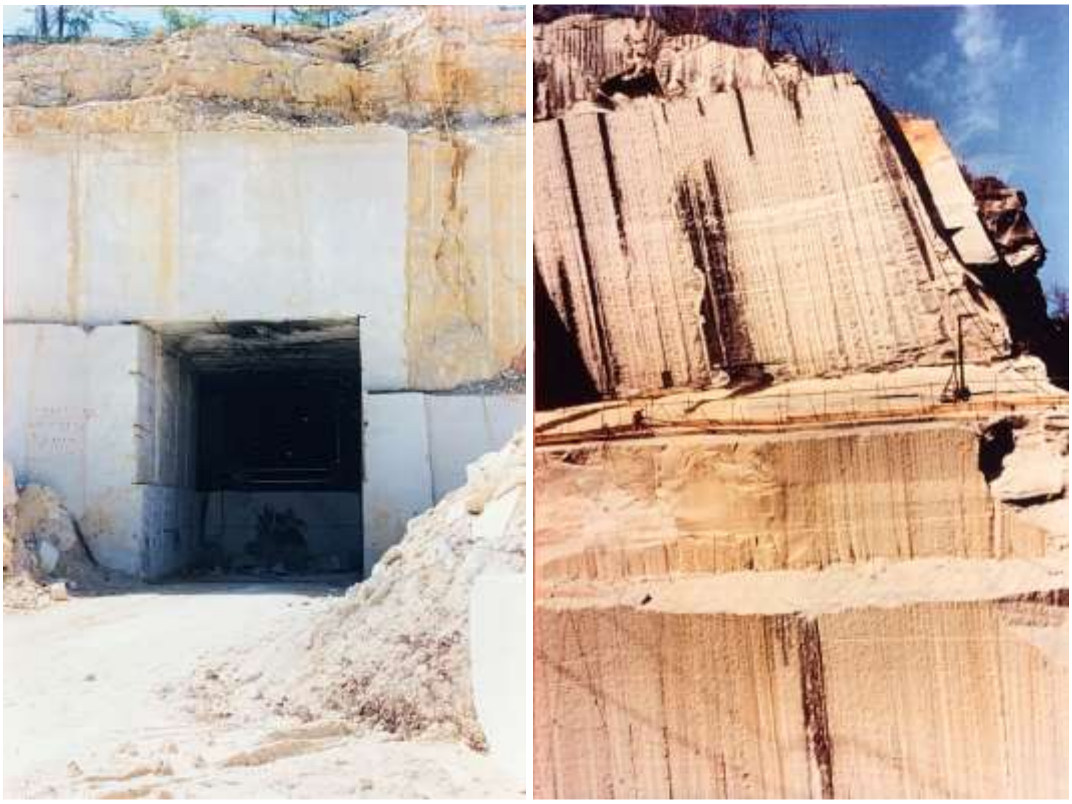

Figure 3. Left: underground voids in hard limestone obtained by cutting saw (Croatia). Right: dynamic splitting in granitic rock for dimension stone quarrying (Italy). Both cases represent good results in terms of stability and block recovery ratio. (credits Oggeri)

Measurement of profiles at sections or in a continuous mode along the tunnel axis or along benches or slopes is nowadays relevant for the mentioned aspect and also for contractual aspects between owner and contractor, in order to evaluate excavation quality, excavated volumes, supports, recovery ratio. The available techniques are contact types (finger probes, tape extensometer and section profiler) and non-contact types (theodolite, total stations, photogrammetry, optical triangulation and Terrestrial Laser Scanning – TLS). Among the others, photogrammetric techniques, Terrestrial Laser Scanner (TLS) or conventional survey with total station are the most used.

The photogrammetric techniques can provide a 3D scan of the bench extent collecting each surface point at least in two photographs. It is a quite low cost technique but is not common in underground works because the surface is irregular and there is not enough light for taking quality pictures.

The Terrestrial Laser Scanner (TLS) can rapidly locate points with high accuracy (e.g. thirty meters can be scanned in ten minutes) and it provides a point cloud; data can be reported in a virtual reality model and it is possible to render a photorealistic VR model. TLS (or ground Lidar) collects a very accurate, high resolution 3-dimensional image of its surroundings. While the use of Lidar in underground environments has been primarily limited to as-built design verification in the past, there is great value in the scan data collected as the excavation advances. The increased scanning rate of newer systems makes it possible to remotely obtain detailed rock mass and excavation information without costly delays or disruption of the construction workflow with a simple tripod setup. Tunnels are non-traditional environments for laser scanners and add limitations to the scanning process as well as the in-office interpretation process. Operational applications of the data include: calculation of shotcrete thickness, as-built bolt spacing, and regions of potential leakage. Lidar data, when correctly interpreted, can also provide detailed 3-dimensional characterization of the rock mass. Geometrical characterization of discontinuity surfaces including location, orientation, frequency and large-scale roughness can be obtained [22].

The total station needs a calibration and some starting parameters are set manually: profiles interval, measuring angle, beginning and ending chainages; then total station could reveal points automatically with iterations. The instrument should be located as near as possible to the symmetry axis, in order to equilibrate the density of the points on the contour; this surveying method took about one hour each ten meters of tunnel. This procedure is usually done after scaling and shotcreting the tunnel vault for safety reasons. TLS and the total station survey can be affected by the presence of reflective objects.

3. Conclusions

Efforts to keep low induced damage for underground and open pit excavations can provide satisfactory results in terms of stability conditions, temporary and final, less consumptions of support systems (namely shotcrete in tunnelling), higher block recovery ratio in dimension stone exploitation, control in the block size distribution in quarry aggregates and minerals production, less induced vibrations.

Parameters to classify the rock mass and to assess the quality of the contour profile after excavation can help the control of the excavation process and measurement can be carried out to quantify the thickness of rock mass damaged thickness.

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