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Assessment of contour profile quality in D&B tunnelling

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ABSTRACT

Contour profile quality affects tunnel excavation costs, in terms of operational safety, support materials and construction time. In drill and blast tunnelling, under/over-excavation and rock mass damage arising from excavation phase can be evaluated by means of the elaboration of survey data and geophysical testing or coring, before and after the blast. As far as the quality of the profile is concerned, some indices can be used to define the contour and for the rock mass in the boundary as well.

This paper proposes a methodology well applicable to rock tunnelling, and a case study based analysis to correlate the over-excavation and the rock mass conditions is discussed to validate the procedure. Profiles and geological parameters have been processed with automatic code specifically developed for the study. Over-excavation distance and Tunnel Contour Quality Index are evaluated and compared with Q-system values. The results have been discussed, compared with other literature cases and validated for engineering applications.

1. Introduction

The quality of the excavated contour in underground tunnel directly affects final costs of the infrastructural facilities (Scoble et al., 1997; Hu et al., 2014). Poor contouring can produce under or over-excavation and artificial fractures into the rock mass. These factors produce many unfavourable consequences: scaling or specific supports are required, advancing rate decreases, convergences may increase, time schedule increases and safety is compromised. Directly related to the convergences and safety, also static approval tests are facilitated by a good contour profiling: in fact, both first phase lining and final lining are affected in terms of thickness, strength and durability (Pelizza et al., 2000a, 2000b).

Rock mass conditions are an essential factor in choosing the adequate excavation method (Mahdevari et al., 2013); drill and blast (D&B) technique is the most appropriate in rock masses that present high compressive strength and that are abrasive (Cardu et al., 2004). Contour quality in D&B tunnelling depends on many factors: geological properties and conditions (e.g. rock mass quality and stress), blast design and drilling pattern execution (Oggeri and Ova, 2004; Singh and Xavier, 2005; Singh et al., 2003). Initial rock mass conditions depend on the site geology, but drilling operations and blasting round affect the rock mass structure because of vibrations, shock wave propagation, gas pressure and stress redistribution (Singh et al., 2003; Hu et al., 2014). These factors act on the rock mass depending on the microstructural fabric orientation (Nasseri et al., 2011) and pre-existing fractures. Charge per delay and total charge per round must be adequately set to preserve rock mass integrity or avoid previous fractures worsening. Charge limit criteria cannot be based on the peak particle velocity (PPV) values as it happens for the man-made structures, because the limit charge is usually determined to control excessive vibration consequences at distance (Cardu et al., 2004). However, even if approximated from elastic media and pure compression waves, PPV relates the acoustic impedance with the stress level that the blast produces because of rock type, stress conditions, rock properties (i.e. density, porosity, anisotropy), water content and temperature (Singh et al., 2003). Blast sequence directly affects the extension of induced fractures; all blasting (contour, production, smooth) in each round produce a cumulative damage effect, both with smooth blasting or pre-splitting method. However, the two methods present some differences in the orientation and intensity of the damage that they generate. The smooth blasting produces both columnar shaped elements finely spaced and also widespread micro cracks; while in the pre-splitting the formation of columnar steep elements is more extended (Hu et al., 2014).

Taking into account the importance of the determination of rock damage and contour conditions after a D&B tunnelling, related to rock mass geology, geostructural features, drilling pattern and blasting sequence, this paper focuses on the assessment on the quality of the tunnel profile by means of some indices. This can be done using quick, easy to find and reliable profile survey techniques, properly adjusted and whose data can be processed to let a practical tool available for technical control and also to limit contractual disputes.

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2. Damage indices

Damage in rock mass means a drop of strength, caused by the opening or shearing of new or extended cracks and joints (Scoble et al., 1997). It can affect both underground and open pit excavations and it is related to the previous discontinuities conditions. The blast produces a direct damage around the blastholes and also an indirect damage due to vibration and rock block dislocation. Vibrations and explosive detonation products can propagate fractures into the rock mass and open existing joint, and this can induce an excavation disturbed zone (EDZ). This zone is the resulting volume around the tunnel boundary, whose extension depends on the excavation method, also valid for the extent of non-blasting methods (Barton, 2007), affected by damages due to excavation and disturbance due to stress state modification. Considering underground tunnelling, the damage can be generally divided in three classes:

- Major damage: when there is rock falling from tunnel roof and/or pillar.
- Minor damage: when there is chips detachment from tunnel roof and/or pillar.
- No damage: when there is not visual damage.

Various techniques can be used for the rock damage evaluation, some were developed for particular studies, and others are used during excavation routine (Scoble et al., 1997; Singh and Xavier, 2005):

- Assessing pre-blast: the inherent damage is evaluated, constructing a geomechanical classification (i.e. Bieniawski's classification) in order to build a base reference for post blast.
- Visual inspection and survey: provide qualitative information on pre/post blast damage and a rock mass classification. Also a borehole camera can be used for core assessment.
- Traditional observation methods: give an indirect measurement of damage. Usually the Half-Cast Factor (HCF) or scaling time is used.
- Rock mass classification methods: empirical rock mass quality rating systems (e.g. Q-system), inherent-damage index and blast-induced damage (e.g. Blast Damage Factor, Blasting Damage Index).
- Geophysical methods: such as seismic tomography, loose rock detection sensors and ground-penetrating radar, high-frequency cross-hole seismic, seismic-refraction tomography.
- Vibration analysis: the damage in the near-field is evaluated from peak particle velocity (PPV) values and rock mass strength.

Four main indices are available for this evaluation: Blast Damage Factor, Blast Damage Index, Failure Approach Index and Tunnel Quality Index, that are briefly illustrated in the following sections. They 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. During an underground excavation, each blast round is individually mapped, in order to evaluate or update the required support (Barton et al., 1995) and to modify, if necessary, drilling pattern and blast design.

The Q index has been the one used in this study because of the available data. Anyway, the others are presented here in order to provide a more complete overview on the available indices. These could be used in further work if the data collection will take their parameters into account.

2.1. Blast damage factor

The Blast Damage Factor D (Hoek et al., 2002; Hoek, 2012) is a parameter introduced in 2002 into the Hoek-Brown failure criterion. It estimates the global rock mass strength and the rock mass modulus. Its range falls between 0 (undisturbed rock mass) and 1 (highly disturbed rock mass). This parameter must be set only for the actual zone of damage, not for the entire rock mass surrounding the excavation and the definition of this extension represents a meaningful assessment. Ideally, the volume between front and undisturbed rock mass can be divided into a number of layer with different values of D using numerical modelling, but usually a single D-value is set for practical reasons. The production blasting data help to determine the actual damaged volume; some outlines (Hoek et al., 2002) suggest the right D-value by giving a description of the rock mass and its appearance. Figs. 1–4 show some examples for D&B tunnelling (and also one example of mechanized underground excavation).

Fig. 1. Primolano tunnel (Italy). High quality of the tunnel contour, half blasthole clearly evident at ribs and crown. Suggested $D = 0$. (Courtesy Italesplosivi).

2.2. Blast damage index

Blast Damage Index (BDI – Eq. (1) was developed by Yu and Vongpaisal (1996) for mining works. This relation takes into account the mechanics and the effects of wave propagation into the rock mass: the compression wave arrives at the free surface and is reflected as a tensile stress wave that causes the damage (Barton, 2007). They analysed how much mining work affects slope walls and roof stability. Cardu et al. (2004) used this index to assess rock slope induced damage along mountainsides, when the advancing face of a tunnel approaches the external slope.

$$BDI = \frac{IS}{DR} = \frac{VdC}{KT} \tag{1}$$

where

Fig. 2. Irregular tunnel contour after D&B; shotcrete for the first phase support is smoothing asperities and over excavation, but nominal profile is not obtained yet. Suggested $D = 0.7$. (Anonymous).