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ON THE CLASSIFICATION OF THE ROCK MASS EXCAVATION BEHAVIOUR IN TUNNELING

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ABSTRACT: This paper deals with the forecasting of excavation behaviour in tunneling and presents a new scheme for a rational classification. In particular, a scheme is proposed essentially based on the combination of two classification systems: the first is basically centred on the results of stress analysis, while the second, which is made up of the RMR system, is specifically directed towards the representation of the geostructural characteristics of the rock mass and to the relative self-supporting capacity. The matrix that results from this double-classification approach allows for first an optimal focalisation of the design problem and then a rational choice of the stabilisation measures in function of the most probable potential deformation phenomenon. A practical application is presented with probabilistic implementation of the method.

1 INTRODUCTION

Almost ten years have passed since a joint initiative of the main Italian associations working in the sector of tunneling, developed the “Guidelines for the Design, Tendering and Construction of Underground Works” ("LGP", NPSUW,1997). As can be deduced from the title itself, this document did not intend to be a design manual, but rather a recommended procedure for the organic and complete development of a project. Although this methodological approach is relatively limited at a national level, the Italian LGP has surely spurred analogous reflections in other countries and one of the ITA Working Groups is specifically dedicated to the setting up of an international reference for tunnel design.

As remarked in the LGP, as well as in a previous paper (Russo et al., 1998), one of the elements of greatest importance in design development is a clear distinction between the concepts of geomechanical classes (or groups), behaviour categories and technical classes of excavation.

In the following, some new considerations on the general classification of the excavation behaviour are presented.

2 GENERAL CLASSIFICATION OF THE EXCAVATION BEHAVIOUR

According to LGP, for the correct typological choice and dimensioning of stabilisation measures, it is first of all important to analyse the excavation behaviour of rock masses, classified in homogeneous geomechanical groups, under the existing stress conditions at tunnel level, in the theoretical hypotheses of absence of any design interventions.

Moreover, in general terms, a sufficiently complete classification of the response of excavation requires the joint development of stress and geostructural analyses.

In practice, it is generally useful to make use of a reasonably simplified approach which can offer a first general picture of the expected behaviour, after which it is necessary to carry out detailed verifications with more rigorous and precise methods. From this point of view, stress analyses are often performed to quantify some classification indexes that are able to express the potential intensity of the expected deformation phenomena.

Reference to an “equivalent-continuous” geotechnical model is in such case generally implicit, whether making use of empirical or more analytical methods. In the former case, a typical example is that of the “Competence Indexes”, which express the relationship between a representative term of the stress conditions at tunnel level (stresses at the excavation boundary or the lithostatic pressure itself), and a term relative to the strength (of the rock matrix or of the rock mass) that can be mobilised.

Such an approach is commonly used for the prevision of both “squeezing” behaviour (see for example, as reported also by Barla, 1998, the “Competence Indexes” proposed by Jethwa et al., 1984; Aydan et al., 1991; Singh et al., 1992; Hoek and Marinos, 2000) and of rockburst phenomena (“Damage Indexes”: Russenes, 1974; Hoek and Brown, 1980; Grimstad and Barton, 1993; etc.).

Fig.2.1: Example of rockburst (left: Loetschberg Tunnel, Diederichs, 2005) and squeezing behaviour (right: deformation in the pilot tunnel of the Fleres railway tunnel excavated by TBM

A design alternative, which is relatively more accurate than the index method, uses an analytical approach, for example the "convergence-confinement" method, to directly quantify the response of the excavation in deformational terms. For example, in the previously mentioned article by the authors, a classification of the behaviour was presented in which 6 categories (a→f) were identified in function of both the radial deformations at the excavation face and the development of the plastic zone around the cavity (for relative details, see the left part of Fig. 2.3).

In addition, by means of geostructural type analysis, it is possible to focus better on the gravitational instabilities connected to the real discontinuous character of the rock masses.

On the other hand, the stress analyses on their own cannot supply univocal indications of the expected deformation phenomenon: for example, it is quite intuitive that a high stress to strength ratio can differently determine “squeezing” behaviour or "rockburst" according to real geostructural conditions (Fig.2.1). For these reasons, as previously mentioned, similar indexes (either of competence or damage) are used for the empirical forecasting of both phenomena.

Consequently, as a first classification, it is useful to refer jointly to adequate geostructural indexes, especially when they can be related to the consequent self-supporting capacity of the rock masses (for example, the well-known systems RMR of Bieniawski and the Q of Barton).

Accordingly, Fig.2.2 shows the basic scheme for a general picture of the possible behaviour during excavation in terms of typical deformation phenomenon.

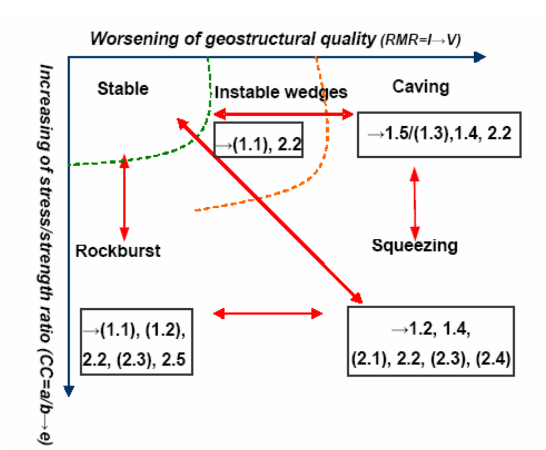

Fig.2.2: Conceptual scheme for a general setting of the ground behaviour upon excavation. The numbers in the box refer to the attempt of association of stabilisation measures later described in section 2.2. (..),/=eventual, alternative measure

2.1 *Proposed classification system*

Following the conceptual scheme of Fig.2.2, the classification system currently adopted by the authors combines the above mentioned behaviour categories with the Bieniawski RMR classes (Fig.2.3, Russo et Grasso, 2006). As can be seen, the matrix that results from such a double classification approach allows an optimal focalisation of the specific design problem. Furthermore, a rational choice of the type of stabilisation measures may be derived as a function of the most probable potential deformation phenomenon that is associated to the different stress and geostructural combination.

It is, however, necessary to add that the proposed classification matrix is not able, as it is logical, to cover all the possible design criticalities and some particular geological conditions have to be analysed separately (for example, the presence of swelling material, complex geostructural situations, etc.).

It is important to note that the proposed scheme may supply also a further indication of the most suitable design analysis, with assimilation either to a continuous or discontinuous model as a function of the geostructural characteristics of the rock masses.

The analysis for the forecasting of the excavation behaviour may be developed in probabilistic terms, incorporating the variability and uncertainty of the geomechanical and boundary conditions. A practical example is presented below.

The case refers to a stretch of a circular tunnel with a 5m radius and 300m of overburden, realised in calcareous-dolomitic formations. The input geomechanical data, mainly based on the results of some boreholes, are summarised in Table 2.1. The probabilistic distribution of the GSI (Geological Strength Index, Hoek et al., 1995) represents the *best-fitting* of the results of MonteCarlo simulation graphically reported in Fig. 2.4. In particular, the "quantitative" approach proposed by Cai et al. (2004), based on the estimation of the block volume (Vb) and the Joint Condition Factor (Jc) has been in this case applied. It should be noted that these last input parameters have been measured and statistically treated excluding fault zones, in order to represent the "ordinary" rock mass condition.

Input			
	Distribution	min	max
GSI	LGN(50,7)	35	67
σ_c (MPa)	TRG(30,50,70)	30	70
m_i	UNF(8,12)	8	12
RMR	BETA(12,12,84)	22	65
Output			
RMR→ CC↓	II	III	IV
c	0.8%	58%	40%
d		0.4%	0.8%

Table 2.1 Main input parameters and output of the probabilistic analysis of the excavation behaviour. Notes: LGN=lognormal; TRG=triangular; UNF=uniform; σc=uniaxial compression strength of the intact rock; m_i=Hoek-Brown constant of the intact rock (1980); CC=behavioural category (stress analysis).

The behavioural analyses were performed with the “Convergence-Confinement” method (Carranza T. solutions, 2004). The GSI is used to derive the rock mass parameters from those of the intact rock by using for shear strength and deformability, respectively the Hoek et al. (2002) and the Hoek and Diederichs (2006) equations. From the results of the probabilistic analysis, reported in Fig. 2.5 and Table 2.1, the following comments may be added:

- according to the stress analysis, the response to the excavation is always elasto-plastic and in 99% of the cases the intensity of the deformation phenomena is relatively contained (“c” behaviour category); the excavation face is consequently stable and the total radial displacements, in the absence of stabilisation measures, are limited to few centimetres;
- in almost all cases, the RMR class falls between the III (58%) and the IV (41%): the geomechanical quality of the rock mass is consequently fair to poor; taking into account the diameter of the excavation, the relative self-supporting rock mass properties are such as to require increasingly more important measure of confinement and/or reinforcement;
- the most important deformation phenomenon for dimensioning the stabilisation measures is therefore that

of a gravitational type, passing from the potential detachment of rock wedges to purely caving behaviour in the most unfavourable contexts. It is important to note that, in function of the orientation of the discontinuities, the gravitational collapses could also involve the excavation face.

The detailed design, as a result, should include the use of the most suitable methods for the analyses of a discontinuous medium, applying, for example, solutions based on the limit equilibrium theory and/or, preferably numerical methods like distinct element (D.E.M.).

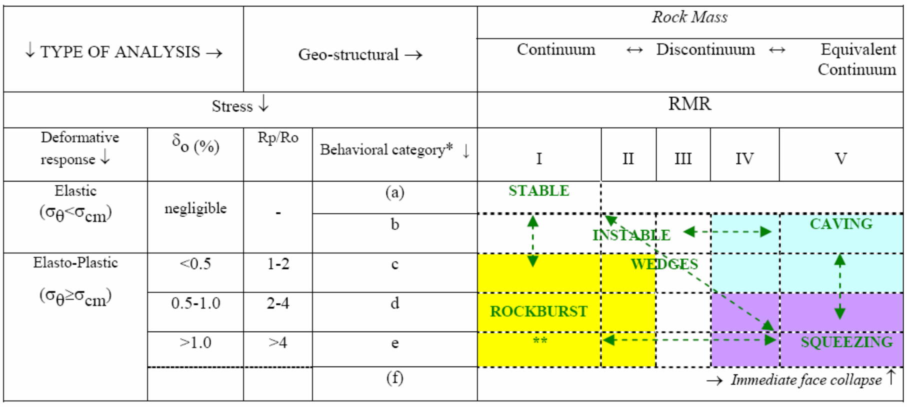

Fig.2.3: General classification scheme of the excavation behaviour Notes: δo=radial deform. at the face; Rp/Ro=plastic radius/radius of cavity; σθ=max tang. stress; σcm=rock mass strength. (i) The limits of shadow zones are just indicative; (ii) in the brittle failure domain (→rockburst) the deformation index of the stress analysis can be intended just as indicators of the increasing potentiality of the deformational phenomenon; (iii) according to Diederichs (2005) the potentiality of the rockburst becomes relevant for rock masses with Brittle Index IF=(σc/σt)>8 e σc>80MPa. In other cases, the shear failure appears to be more probable and squeezing is still the most typical deformation phenomenon.

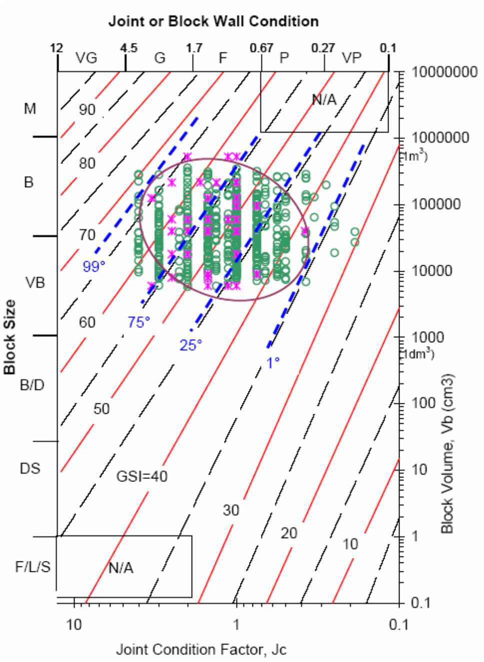

Figure 2.4: Example of probabilistic estimate (n.500 simulations) of the GSI derived from the quantitative approach proposed by Cai et al. (2004). Notes: M=Massive; (V)B=(Very) Blocky; D=Disturbed; DS=Disintegrated; F/L/S=Foliated/ Laminated/ Sheared. (V)G=(Very)Good; F=Fair; (V)P=(Very)Poor.

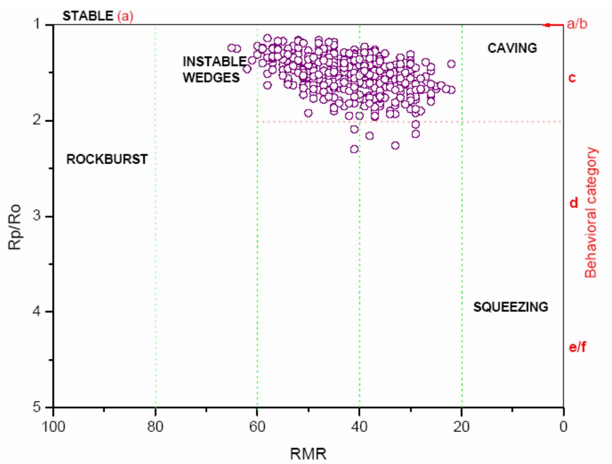

Figure 2.5: Example of behaviour classification obtained through probabilistic analysis.

2.2 *Definition of the types of stabilisation measures*

The design choice of the stabilisation measures (confinement, reinforcement, etc.) and therefore the composition of the Section Type is a consequence of the behavioural classification.

An example, in this sense, basically connected to excavation by traditional techniques, is presented below.

In Table 2.3, the main design actions that can be applied in the underground excavation have been schematically summarised with some examples of the consequent stabilisation measures. Furthermore, as above anticipated, an attempt of association of these main design actions to the different deformation phenomena is schematised in Fig. 2.2.

#	**Design action ***	**Stabilization measure (example)**

1	**In advancement to the excavation**	
1.1	Pre-confinament of instable wedges	Forepoling
1.2	Pre-reinforcement of rock mass contour	Pre-riqualification of rock mass by fully connected elements
1.3	Pre-confinement of the excavation contour	Sub-horizontal jet-grouting canopy
1.4	Tunnel face pre-reinforcement	Injected fiber-glass elements, jet-grouting, etc.
1.5	Pre-reinforcement of excavation contour	Umbrella arch
..	..	..
2	**During excavation**	
2.1	Over-excavation to allow convergences	
2.2	Radial confinement	Bolting (instable wedges confinement); shotcrete (fiber-reinforced or with wire mesh); steel ribs; etc.
2.3	Rock mass reinforcement	Riqualification by means of fully connected elements
2.4	De-confinement (to allow convergence for stress unloading)	Sliding steel-ribs; joints and/or deformable elements in the shotcrete
2.5	Protection	Anchored double-torsion steel mesh

Table 2.3 Main design actions in underground excavation and examples of the typical associated stabilisation measures.
Notes: *The drainage of water in advancement should be generally added when necessary.

As can be seen in Fig. 2.2, the design solutions are not always univocal and different stabilisation measures can theoretically be applied, measures whose application possibilities should be opportunely verified with design calculations and then compared in terms of construction time and costs.

A typical example concerns the stabilisation measures that can be chosen in the case of "squeezing" behaviour, where may be necessary to evaluate (and compare) contrasting procedures:
(i) to allow a certain decompression of the rock mass;
(ii) on the contrary, to prevent it with pre-reinforcement for increasing the geomechanical properties of the rock mass at the excavation face and/or at the boundary, or
(iii) to apply some "hybrid" stabilisation solutions.

The design calculations will allow to differentiate the intensity of the interventions, as a function of the detailed analysis relative to the different geomechanical conditions classified in Fig. 2.3.

As an example, the results of the probabilistic analysis presented in Table 2.1 would lead to the typological indications shown in Table 2.4.

Classification →	c/III (≈ 60%)	c/IV (≈40%)
Section Type	C1	C2
Stabilization measures in advancement	-Eventual* bolting of tunnel face	-Eventual** pre-reinforcement of tunnel face and crown
Radial stabilisation measures	-Sistematic bolting; -Shotcrete (fbr)	-Steel ribs; -Shotcrete (fbr)

Table 2.4: Practical example of the typological choice of the stabilisation measures with reference to the case presented in Table 2.1. Notes: fbr = fiber-reinforced; *in function of the possible kinematic instability of rock wedges; **in function of the possible kinematic instability and/or when the intervention allows an optimisation of the construction times and costs.

3 CONCLUSION

A framework for comprehending the expected excavation behaviour is proposed, based on the combination of two classification systems, in order to take into account both the results of stress analysis, as well as the geostructural characteristics of the rock mass and then its self-supporting capacity. The matrix that results from the double classification approach allows for first an optimal focalisation of the design problem and then a rational choice of the stabilisation measures in function of the most probable potential deformation phenomenon.

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