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GEOLOGICAL BEHAVIOUR OF ROCK MASSES IN UNDERGROUND EXCAVATIONS

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Abstract

The paper deals with the engineering geological behaviour of rock masses in underground excavations. In general, the application of the well-known classification systems has the drawback of not displaying necessary information concerning the behaviour of rock masses, especially the weak ones, in tunnelling. Consequently, there are many cases in which the geological "identity" of the geomaterial is lost since it is not involved in the analysis. In that way it is possible that its special characteristics are mislaid. Within this framework, a system for assessing the failure type mechanisms of the rockmass (i.e. deformation due to overstressing, overbrakes or wedge failure, "chimney" type failure, ravelling ground) for unsupported tunnel-section is presented. These parameters, used for this system, are the structure of the rockmass, the intact rock strength and the overburden thickness. The experience gained by the recent tunnelling construction in the Greek territory, under particularly difficult geological conditions, provided excellent and numerous data for this study.

Key words: *rock mass classification, tunnelling, weak rock mass, failure type*

1. Introduction

A sound and economical design of an underground excavation is based on the compilation of a realistic geological model, the engineering geological characterization of the rock mass and the appraisal of the in situ stresses and the hydrogeological conditions. Tunnelling in rock masses requires instinct knowledge of the geomaterial since the features of mineralogical composition, lithology, structure, fracturing, tectonic disturbance, weathering, and groundwater presence, vary and change frequently with tunnel depth and makes the design a procedure with great particularities.

Tunnel design is a complex procedure and is composed of several stages. In the last decades, there has been a rapid growth on the computational analysis of tunnels. Regardless to these present calculative tools and friendly software the results must be carefully reviewed due to possible lack of precision and parameter uncertainties. Hence, a clear understanding of the rock mass tunnel behaviour followed by the proper parameter specification should be a basic concern before final tunnel design analysis.

There are no clear solutions on this approach. Nowadays, the role of the geological material in the design is improved with the progress of the investigation methods, the advancement of the geotechnical classification systems and the consequent quantification of the rock masses. All these are crucial to the tunnel design. On the other hand, the wide use of the well known classifications (GSI, RMR, Q or others) may guide to reverse or misleading results, namely the by-pass of basic geological and mechanical principles, which consist the fundamental background for the geotechnical design. The use of the geotechnical classification systems, as proper as it may be done, is confined to the quantification of the rock mass without any consideration on the behaviour that the geomaterial "prefers" when excavated. The behaviour in tunnelling may differ from rock mass to rock mass, even if they have the same characterization value, under the same stress field and hydrogeological conditions. An example of two equally classificated rock masses with the GSI and RMR systems but with completely different behaviour after their excavation, is shown in figure 1.

What is highlighted in this paper is that the classification "numbers" must be also supported, in an engineering friendly way, by the engineering geological behaviour, namely the type and the mechanism of failure that "fits" best to the rock mass under consideration. Otherwise, the geological identity of the geomaterial is lost, while any in situ particularities which can be crucial to the tunnel instability may be disregarded.

Rock mass behaviour appraisal in tunnelling and its connection to the design has been the subject of significant research interest. Goricki et al. (2004), Schubert (2004), Poschl and Kleberger (2004) and Potsch et al. (2004) study the rock mass behaviour from the design and construction experience of the Alpine tunnels and Palmstrom and Stille (2007) of other tunnels.

In this context, a database named "Tunnel Information and Analysis System" (TIAS), was designed and created (Marinos et al., 2006) for Greek tunnels. A huge number of geological, engineering geological and geotechnical data from the site investigation, design and the construction of 62 tunnels of Egnatia Highway in Northern Greece were considered. The data from this information, together with relevant field work, were processed and evaluated by numerous correlations. This work resulted to a classification and a tunnel behaviour system is proposed. The results of this research intend to assist to the selection of the appropriate design parameters and the conceptual choice of the support measures.

2. Engineering Geological Behaviour in Tunnelling

2.1 General

Failures or instabilities are certainly an undesirable phenomenon to tunnel construction. Nevertheless, they express the most accurate "method" to confirm or re-evaluate the geotechnical model and thus use the appropriate design tools. The term instability mechanism-behaviour as referred here involves all the mechanisms that endanger the tunnel section either when the rock mass has not been yet supported after its excavation or temporarily supported behaving together with the support shell. In this paper, the reaction of the rock mass immediately after its underground excavation and before the support implementation is examined. Thus, the engineering geological characteristics – keys to the tunnel stability are of great importance.

2.2 Design methodology

A design methodology for this approach is proposed by Goricki et al. (2004) and Schubert (2004), a section of which is studied here. The first step of this methodology involves the definition of rock mass types, the second the evaluation of rock mass tunnel behaviour, the third step suggests the setting of the tunnel excavation-support system based on the previous behaviour with the inclusion of the geotechnical parameters, the fourth the detection of unified characteristics-sections of equal support requirements along the tunnel and final the fifth step the determination of the excavation and support categories qualified to cost and time terms (organization of the tender documents). This paper focuses on the second and third step.

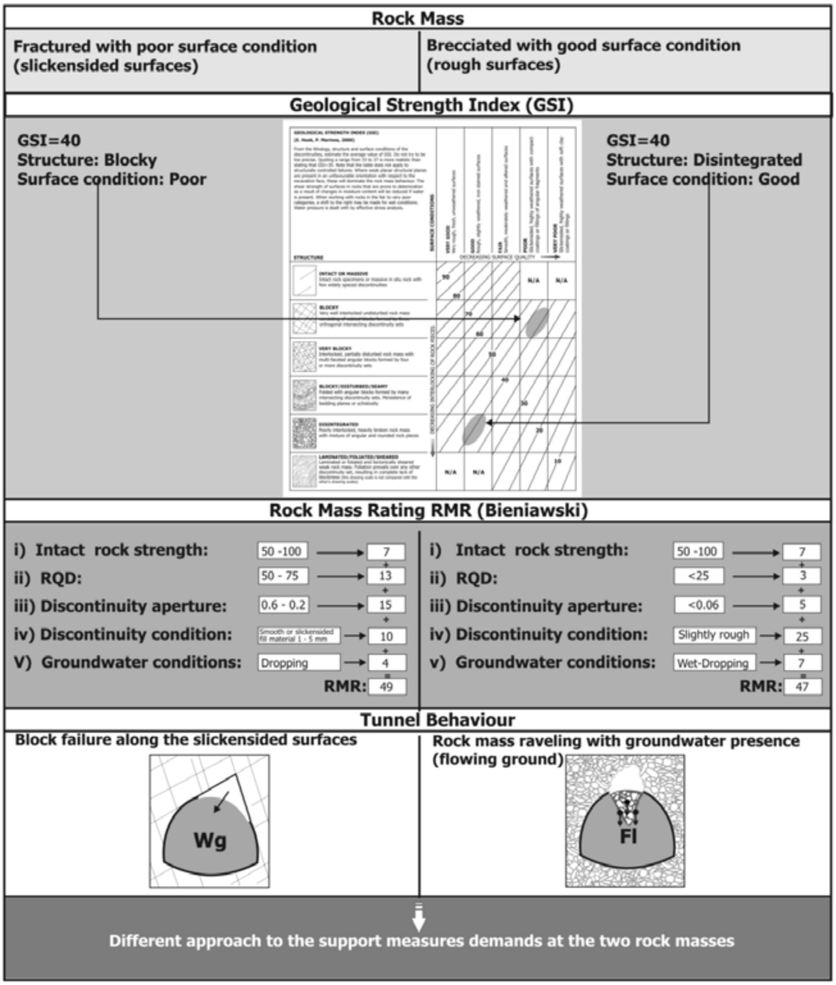

Fig. 1: Example of two equally rated rock masses with the GSI and RMR system but with completely different behaviour in tunnelling and supporting measures.

The rock mass behaviour, in a non urban environment, from the excavation of 62 tunnels in northern Greece, was examined for the purpose of this research.

2.3 Tunnel Behaviour Types

A tunnel behaviour assessment in order to assist to the design parameter selection and the support elements selection is presented hereafter. The behaviour type must be precise and solid. This can be achieved initially by the recognition of the general failure category, referred mainly as gravity and stress controlled and then by a more specific inspection in each category. Normally, there are cases when both general categories may be applied. Tunnel behaviour types are presented and briefly described in figure 2. It should be noted that deformation problems are estimated by the ratio of the uniaxial rock mass strength to insitu stresses, σ_{cm}/p_o (Hoek and Marinos, 2000).

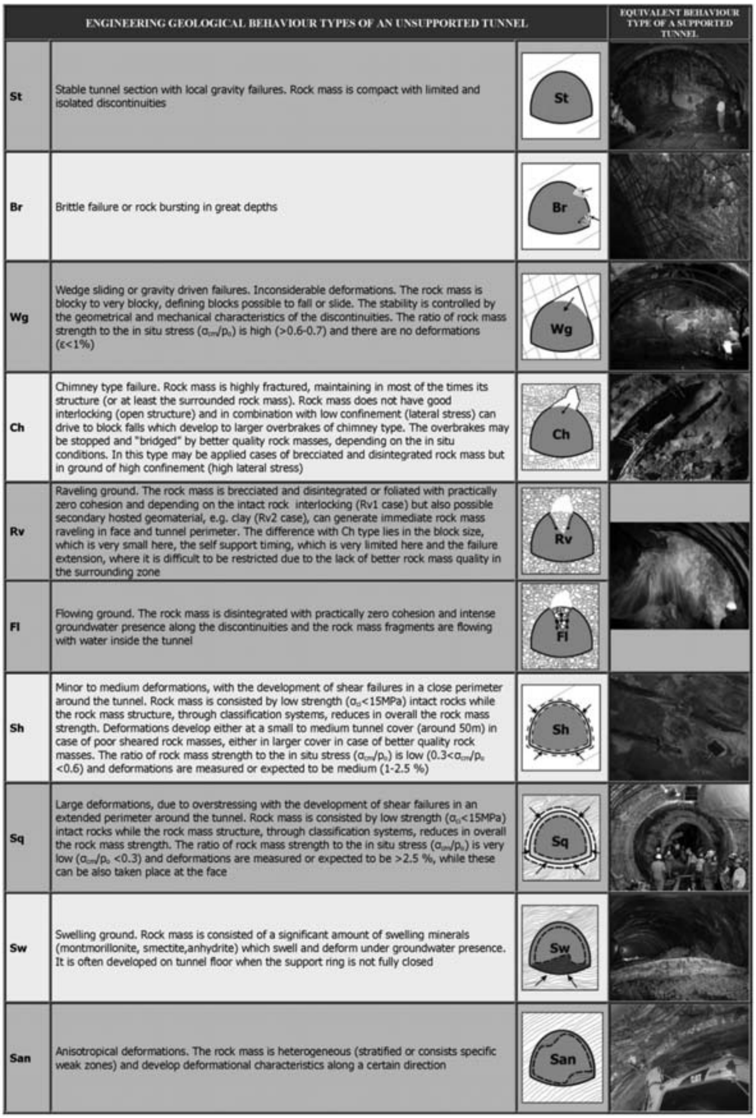

Fig. 2: Brief description and schematic presentation of the tunnel behaviour types (based on data from Potsch et. al., 2004 and from the author)

3. Tunnel Behaviour System

3.1 Methodology

The assessment of the engineering geological behaviour of the rock mass was done with a certain method-philosophy. The first step involves the understanding of the possible tunnel failures-behaviour, as far the mechanism is concerned. The next step was to define all the possible rock mass types for several formations which were identified by specific engineering geological characteristics affecting their behaviour. These types where recognized along the 62 tunnels which were investigated, together with their design parameters. The following stage involved the grouping of the support categories for a number of rock mass models and a variety of insitu conditions. At the same time, a comparison of the rock mass behaviour after its excavation was done, in order to compare it with the design. In the next step, the effort was focused on handling the construction records. The data were justified by field work and in situ inspections and the behaviour was classificated for every rock mass type. Finally, the temporary support measures philosophy and principles for a certain behaviour type was assessed.

3.2 Rock mass behaviour assessment

The demand for classificated geological information, directly linked to the design and tunnel support measures to be applied, guided to a system for the assessment of the failure type mechanisms and behaviour of the rock mass for unsupported tunnel-section, based on the structure of the rock mass, the intact rock strength and the thickness of the overburden.

The suggested system, called Tunnel Behaviour Chart (TBC), is shown in figure 3. The scope of this diagram is to provide the logic and failure mechanism of several rock mass types often met in nature. It is noted that in the chart there are no quantified limits-ranges of the uniaxial compressive strength of the intact rock (σ_{ci}) and the overburden thickness (H), but only qualitative of high and low values. However, some general quantified limits for σ_{ci} and H for each GSI structure column are presented in table 1. These values although, based on reasonable trends, should only be considered as purely indicative.

The data of this assessment were based on the excavation of tunnels with the conventional method with top heading and bench in a non-urban environment with an overburden, less than 600m. The philosophy of the Tunnel Behaviour chart becomes more comprehensible if we acknowledge the following:

- The rock mass structure is a basic parameter to estimate its immediate response in underground excavation. The pattern of structures of the GSI system was selected.
- Overburden thickness H is an other principle parameter to access the behaviour type, since it is in conjunction to the insitu stresses and the general confinement conditions. The behaviour types that were examined are referred to tunnel construction under a cover of 30m to 300m (a case around 600m was also included). For the gravity driven failures, tunnel depth can determine the extent or restrain of a failure, since the degree of interlocking between the rock blocks changes and the confinement pressure is different. For example, a ground may ravel (Rv) close to the ground surface but under higher cover a chimney type (Ch) failure may be observed. As far as the stress controlled behaviour is concerned, overburden thickness H defines when shear failures and deformations are generated.
- Intact rock strength σ_{ci} values that were involved in the design of those tunnels, ranged between 5 to 40 Mpa. The selected extreme values that nominate the rock mass behaviour are based in two criteria: i) the value when shear failures and deformations initiate and ii) the value which accords best with the present deformational characteristics of the rock mass structure (e.g. fractured, brecciated, sheared).

The surface condition of the discontinuities, the second composite of GSI system, mainly affects the intensity of the failure phenomenon and is not accounted to the behaviour type definition. Only few are the cases where surface quality can accommodate a behaviour type. For example, high clay presence along the discontinuities or as a zone in the rock mass may shift the gravity driven behaviour types to the vertical axis of the chart (e.g. from Wg [9] to Ch [13]). Groundwater presence does not affect the behaviour type but affects the factor of safety. However, in some cases, like in “Disintegrated” rock mass, the groundwater presence may “shift” from a Chimney (Ch) or Raveling (Rv) behaviour type to Flowing ground (Fl) type.

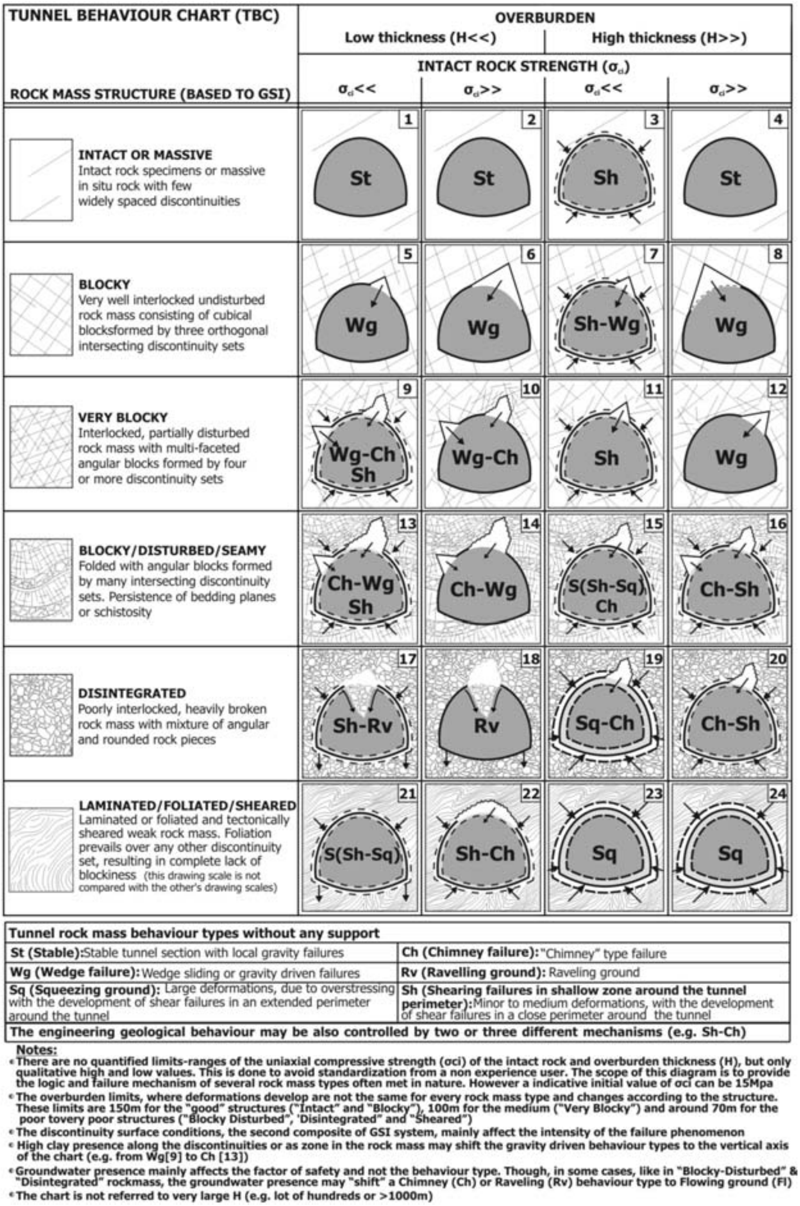

Fig. 3: Tunnel Behaviour Chart (TBC): A system for rock mass behaviour assessment.

Stress controlled failures: The development of remarkable deformations around a non-urban tunnel is characterized by a ratio of σ_{cm}/p_o <0.6-0.7 (Hoek and Marinos, 2001). In particular, when σ_{cm}/p_o is among 0.3 and 0.7, shear failures can propagate in a shallow zone around the tunnel perimeter (Sh behaviour). Such cases concern rock masses with poor to very poor structures and low intact rock strength (<10-15Mpa) under medium overburden or with good structures and low intact rock strength under high cover. Squeezing conditions (behaviour Sq) with severe tunnel deformations may develop when σ_{cm}/p_o <0.3.

Table 1. General indicative quantified ranges for σci and overburden thickness (H) and GSI values for every tunnel behaviour type (1-24) from the Tunnel Behaviour Chart of figure 3.

TBC Case	*GSI value range*	*GSI Structure*	*σci (MPa)*	*Overburden thickness H (m) limit*
1, 3	70–80	Intact	<15	150
2, 4	70–90		>15	
5	50–60	Blocky	10–15	20–150
6	50–80		>15	<150
7	50–60		<15	>150
8	50–80		>15	>150
9, 11	35–55	Very Blocky	10–15	100
10 – 12	40–60		>15	
13, 15	25–45	Blocky – Disturbed/Seamy	<15	70
14, 16	30–50		>15	
17 – 19	15–35	Disintegrated	<15	70
18 – 20	35–45		>15	
21, 23	15–25	Disintegrated	<10	70
22, 24	15–35	Laminated/Foliated/Sheared	>10	

Gravity controlled failures: Gravity driven failures can take place when a rock mass is fractured in planes and is formed by blocks. When these blocks are revealed after the excavation they may fall or slide, according to the tunnel geometry and the shear strength characteristics of the discontinuity planes. Chimney (Ch) and raveling (Rv) types can take place in rock masses with low interlocking of blocks. The rock mass cannot "bridge" immediately after the fall and the overbreak may be irregular and significant. Volume and frequency of these behaviour types depend on the structure of the rock mass ("Blocky-Disturbed" and "Disintegrated"), its relaxation ("open structure") and the tunnel depth, since it will improve the rock mass quality and the confinement pressure which may tighten the structure of the rock blocks.

4. Tunnel support measures – Design philosophy

The design of the temporary support categories consists of two stages: the selection of the proper support elements and their analysis. The general concept and the selection of the elements lie on the uncertainty of the engineering geological behaviour of the rock mass. This procedure is very important, since there are cases where a specific behaviour cannot still be accurately. That is why the decision is frequently based on the experience and the geotechnical appreciation and less on analytical solutions.

Thus, in conjunction with the tunnel behaviour system, presented in the previous paragraph, this study concluded also to a step-by step procedure towards the design. This approach initiates after the definition of the rock mass types along the tunnel and the evaluation of the geological and insitu conditions. The rock characteristic – "keys", which dictates the stability or instability of the tunnel, are then assessed. The behaviour of the rock mass after its excavation in an unsupported section is then investigated and the design philosophy is defined. After the identification of the failure mechanism, the suitable design parameters can be selected. Finally, the tunnel support philosophy and the re-

ENGINEERING GEOLOGICAL CHARACTERIZATION FOR TUNNELING (1/2)

Classification phase (primary, evaluation, construction):	
Location:	
Date:	

I. GEOLOGICAL CONDITIONS	
a) Lithology	
Geotectonic unit:	
General formation it may belongs (e.g. Flysch):	Pindos ophiolitic complex
Rock mass name:	Serpentinised Peridotite with foliated-clayey serpentinite zones Note: information concerning significant alteration of the rock mass, intact rock or surface weathering, presence of hosted - clayey geomaterial and bedding thickness if it is stratified
b) Tectonism	
Tectonic zones:	The big thrust of Pindos ophiolites over the geotectonic unit of flysch is extended in the wide tunnel area but does not crossed
– Major thrust zones which affect the project in great scale:	–
– Localized fault or disturbed zones:	– Several foliated zones across the peridotite blocks
Fracturing or Shearing:	
– Fracturing degree:	– Slightly fractured [ ] Fractured [ ] Very fractured [√] Brecciated [ ]
– Continuation- persistence of fracturing with depth:	– Preserves the same structure characteristics to tunnel depth (~90m)
– Shearing or foliation across the rock mass or along the discontinuities:	– Foliation met mainly along the joints, only sometimes has "intruded" to the rock mass
Folding:	
– Type:	–
– Geometry:	–
c) Weathering	
Discontinuities:	Serpentinised discontinuities (slickensided)
Intact rock:	Only locally affected
Persistence with depth:	It does not follow any pattern. Irregular geometry and extent also in depth
d) Permeability	
Qualitative appraisal:	High ($k>10^{-3}$m/sec) [ ] Low ($k:10^{-7}$-10^{-9}m/sec) [√] Practically impermeable ($k<10^{-9}$m/sec) [ ] Medium($k:10^{-3}$-10^{-7}m/sec) [ ] Very low ($k:10^{-5}$-10^{-7}m/sec) [ ] Localized groundwater presence in the peridotite rock trapped behind clayey zones
Quantitative appraisal:	k: [ ] m/sec

II. INSITU CONDITIONS	
a) Overburden	
Overburden range with similar behaviour:	H: 30 - 100 m / H: [ ] m / H: [ ] m
Insitu stresses ($P_o=\gamma H_{min}$-γH_{max}):	P_o: 0.75 - 2.5 MPa / P_o: [ ] MPa / P_o: [ ] MPa
b) Surrounded zone close to tunnel perimeter	Competent zone [ ] Incompetent zone [√]
Competent zone around one tunnel diameter distance:	Dip: [ ] / [ ] Dip Direction Thickness: [ ] m
Low strength zone around one tunnel diameter distance:	Geological characteristics: Possible foliated-clayey serpentinite in 2m zones
c) Hydrogeological conditions	Unknown
Aquifer according to the tunnel axis:	
d) Stress field	Foliated-clayey zones may specify irregular blocks
Particular presence or absence of lateral pressures:	
e) Other boundaries	

III. CHARACTERISTIC "KEYS" FOR TUNNEL STABILITY OR INSTABILITY	
Intact rock strength:	>30MPa
Rock mass strength to insitu stress ratio(σ_{cm}/P_o):	$\sigma_{cm}/P_o>1$ [√] $0.3<\sigma_{cm}/P_o<1$ [ ] $\sigma_{cm}/P_o<0.3$ [ ]
Structure "interlocking":	Due to the serpentinisation it does not have good interlocking
Presence of low strength minerals:	Serpentinite at discontinuities. Clay topically at discontinuities
Intact rock weathering, clay filling:	Foliated-clayey zones may specify irregular blocks
Groundwater presence:	Possibility of trapped permeable small aquifers behind impermeable clayey zones which may be unfavorably to the tunnel stability due to excessive pressures. May act as a "lubricant" to the serpentinised discontinuities decreasing its strength characteristics.
Block geometry - bed thickness:	0,2-0,5m x 0,2-0,5m
Rock mass structure (based to GSI):	Blocky [ ] Very blocky [√] Blocky/Disturbed/Seamy [ ] Disintegrated [ ] Laminated/Sheared [ ]
Discontinuity geometry:	It poses significant role in wedge failures
Discontinuity persistence:	They present persistence but is reduced due to the serpentinised zones
Discontinuity quality (based to GSI):	Very good [ ] Good [ ] Fair [ ] Poor [√] Very poor [√]
Rock Quality Index (RQD):	RQD: [ ]
Other characteristic:	
Basic-"Keys" characteristics:	
The behaviour is controlled by the rock mass: Yes [ ] No [ ] Fill the relevant rock mass parameters in field "Va"	The behaviour is controlled by the discontinuities: Yes [√] No [ ] Fill the relevant parameters of the discontinuities shear strength in field "Vb"

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Fig. 4: Rock mass characterization method in tunnelling towards the design (Sheet 1/2).

ENGINEERING GEOLOGICAL CHARACTERIZATION FOR TUNNELING (2/2)

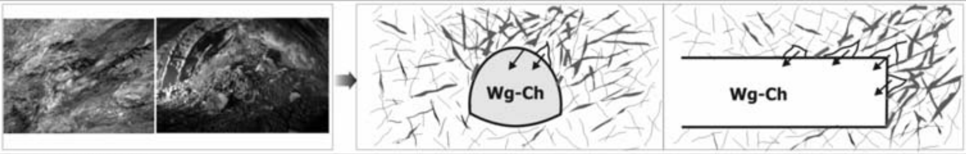
IV. ROCK MASS BEHAVIOUR IN TUNNEL EXCAVATION

a) Isotropy:

Isotropical:	Yes ☐ No ☐	
Anisotropical:	Yes ✓ No ☐	Gravity driven failures

b) Behaviour type of unsupported tunnel section:

- **Qualitative:** Wedge slidings (Wg) or gravity driven failures. Possibility for greater-more extended chimney type failures (Ch) containing blocks which are surrounded by clayey foliated zones. Face stability problems may also occur from the same mechanism. Special attention should be given in possible "lubrication" of the serpentinised zones if water is present. If these zones appear in critical tunnel section areas, as the foundation area, vertical displacements (settlements) of the whole section may be developed



c) Design philosophy:

Wedge analysis (e.g. Unwedge Analysis)	✓	The use of the classifications are recommended only for the design parameters selection and not for categorization and selection of the support section
Wedge and shear failure deformation analysis (Wedge and Numerical Analysis)	☐	
Shear failure -Deformation analysis (Numerical Analysis)	☐	Stress problems should also be analyzed but will not govern the support selection
Empirical design	☐	

V. DETAIL CHARACTERISTICS AND DESIGN PARAMETERS

a) Rock mass parameters (Hoek & Brown):

- **GSI value:** 30 - 35

GSI chart (2000)

- **·Intact rock strength:** σ_{ci}: 30 MPa
- **Constant m_i:** 22
- **γ:** 0.026 MN/m^3
- **Modulus Ratio (MR) or (Ei):** MR=550
- **Disturbance factor (D):** 0
- **Classification RMR, Q:** -

b) Discontinuity parameters:

- **Number of discontinuities:** 4

	J_1	J_2	J_3
Geometry (Dip/dip direction)	/	/	/
Persistence	1 - 3 m	m	m
Distance	0.2 - 0.5 m	m	m
Aperture	1 - 3 mm	mm	mm
Filling material: Hard<5mm	☐	☐	☐
Hard>5mm	☐	☐	☐
Soft<5mm	☐	✓	✓
Soft>5mm	✓	☐	☐
None	☐	☐	☐
Weathering: Unweathered	☐	☐	☐
Slightly	☐	☐	☐
Moderately	☐	✓	✓
Highly	✓	☐	☐
Decomposed	☐	☐	☐
Ground water conditions: Dry	☐	☐	☐
Sub-wet	☐	☐	☐
Wet	✓	✓	✓
In drops	☐	☐	☐
Flow	☐	☐	☐
Joint Roughness Condition (JRC):	4 - 6		
Joint Compression Strength (JCS):	25 MPa	MPa	MPa

Discontinuities:

	J_1	J_2	J_3
Friction angle (φ):	25- 30 °	°	°
Cohesion (c):	0 KPa	KPa	KPa

VI. TUNNEL SUPPORT PHILOSOPHY

Qualitative:

Excavation phases:	Two phases (Top Heading and Bench)
Excavation step:	Small tunnel advance (~1.5m) in order to confine the rock mass and avoid the revealing of the foliated zones
Shotcrete bolts:	Shotcrete should be applied to control the gravity controlled failures and not the deformations (depends with depth). Bolts should have a significant length to contain greater overbrake
Steel sets:	Should be closely implemented (1-1.5m) to confine some blocks often marked by the weak clayey zones
Not heavy face support (e.g. spiles):	It may be required to apply spiles and face buttress in case of continuous appearance of the clayey zones
Face support (e.g. fibreglass, forepolling, invert):	In higher overburden (>200m) heavier support measures may be applied
Water drainage:	Long drainage holes to avoid water pressure behind the support shell and the face. Protected drainage canals on the tunnel floor to avoid the "lubrication" of serpentinised zones
Other (e.g. grouting):	

VII. REMAINING RISK

- Possible rock strength reduction due to "lubrication" by water circulation when the trenches along the tunnel are poorly constructed. In this case significant vertical convergence due to the settlement of the support shell may developed

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Fig. 5. Rock mass characterization method in tunnelling towards the design (Sheet 2/2)

maining risk are reported. This method of rock mass characterization in tunnelling is presented in two sheets with a given example in figure 4 and 5.

5. Conclusions

The use of rock mass classification systems and the resulting quantitative characterization of rock masses cannot directly correspond to their behaviour in underground excavations. Great care should be given to the assessment and sound understanding of the engineering geological behaviour types, prior to tunnel design and analysis. That is to identify the possible failure modes and nature of problems which is expected for the particular rock mass type. In that order, the selection of the tunnel support elements and characteristics together with the evaluation of the geotechnical properties can be soundly assessed from the beginning. Hence a more realistic design along the tunnel can be performed.

A methodology where the rock mass behaviour integrates to the tunnel design procedure is suggested. For this methodology, the basic step is to identify the "key" engineering geological characteristics, which control instability potential of the rock mass. Towards this direction a system for the tunnel behaviour assessment is presented based on the rock mass structure, the intact rock strength and the overburden thickness.

6. Acknowledgments

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