Support Decision Criteria for Tunnels in Fault Zones

Andreas Goricki, Nikos Rachaniotis, Evert Hoek, Paul Marinos,
Stefanos Tsotsos and Wulf Schubert

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Abstract

A procedure for the application of designed support measures for tunnelling in fault zones with squeezing potential is presented in this paper. Criteria for the support decision based on quantitative parameters are defined. These criteria provide an objective basis for the assignment of the designed support categories to the actual ground conditions. Besides the explanation of the criteria and the implementation into the general geomechanical design process an example from the Egnatia Odos project in Greece is given. The Metsovo tunnel is located in a geomechanical difficult area including fault zones and a major thrust zone with high overburden. Focusing on squeezing sections of this tunnel project the application of the support decision criteria is shown.

Introduction

Tunnelling in fault zones in general is associated with frequently changing ground and ground water conditions together with large and occasionally long lasting displacements. Besides the difficulty to predict the geological setup and structure of the ground correctly, the acquisition of physical parameters, as well as the prediction of the ground and system behaviour is extremely challenging. In the design stage the recently used methods of analysis allow the relatively precise design of the excavation and support for a wide range of ground and boundary conditions. The uncertainties inherent in the ground model however make it difficult to assign appropriate excavation and support measures to each location along the alignment prior to construction. To successfully tunnel through fault zones, the final decisions on excavation and support methods have to be made on site. Without of objective criteria, the assignment of appropriate construction methods on site is also extremely difficult. A large number of reports on lining failures, extensive repairs or reshaping due to an overestimation of the ground quality or underestimation of the deformation magnitude shows this.

During the design stage the rock mass is characterized, the behaviour of the unsupported rock mass is evaluated, excavation and support are designed, and the system behaviour of the rock mass and the support measures are analysed and predicted for the various combinations of possible geomechanical ground conditions. This procedure allows the combination of rock mass characterization and the behaviour oriented rock mass classification. Based on this process criteria for the application of the designed support categories can be defined using the quantitative characterization parameters and the observed system behaviour of the already constructed tunnel (displacement monitoring, utilization of the support measures, depth of plastic zone from extensometers).

The decisions on site have to be based on:

- A realistic prediction of the geological and geomechanical conditions and a continuous updating of the model during construction
- A reasonable tunnel design

- An appropriate monitoring program to capture the actual ground and system ehaviour
- A contract which allows a flexible application of the designed excavation and upport ategories to the actual ground conditions, and adjustments if required
- Objective decision criteria for the assignment of the designed excavation and support categories

This paper focuses on one specific issue of the process – the definition of relevant and objective decision criteria for the application of the previously designed support measures on site. In the first part the general process of the application of the excavation and support on site applying the Geological Strength Index GSI concept is outlined briefly. Then the support decision criteria are discussed and finally the application of the support decision criteria is demonstrated.

Geomechanical Design Procedure

Having defined the geological model the procedure of the geomechanical design (1, 2) is based on the following steps:

- characterization of the rock mass and classification into ground types
- determination of the potential failure mechanisms due to an unsupported excavation and classification into behaviour types
- determination of excavation and support measures, leading to an acceptable system behaviour and definition of support categories

This process is generally similar for the design and construction stages. The main difference results from the revealed information during the construction. After characterizing the actual rock mass and evaluating the ground conditions the support category designed for these conditions has to be selected. Therefore it is essential to define clearly structured criteria for the support decision based on parameters which can be observed or evaluated on site. These criteria are defined as the result of the design and have to be evaluated and updated during the construction by observing the system behaviour.

The procedure of rock mass characterization, classification and final support decision on site is illustrated in figure 1. During the construction the ground model has to be updated and improved according to the actual ground conditions. First the actual ground type is determined on basis of the selected key parameters. Then, by observing geological trends, and evaluating the monitoring data, a prediction of the ground structure and its behaviour ahead of the face is done. Shown in figure 1 are trends of displacement vector orientations along the tunnel axis and the displacement pattern in two cross sections. Both, the change of the orientation of the displacement vector trends, as well as the asymmetric displacement in the cross section indicate a fault zone in front of the excavation face, crossing the axis in an acute angle. On the basis of the predicted ground conditions excavation and support measures can be assigned to the next section. The criteria for assigning the appropriate construction practice are defined during the design stage and have to be updated during the construction.

Experience gained during the construction of the tunnel, mainly from observations of the system behaviour allows a refinement of the assignment criteria.

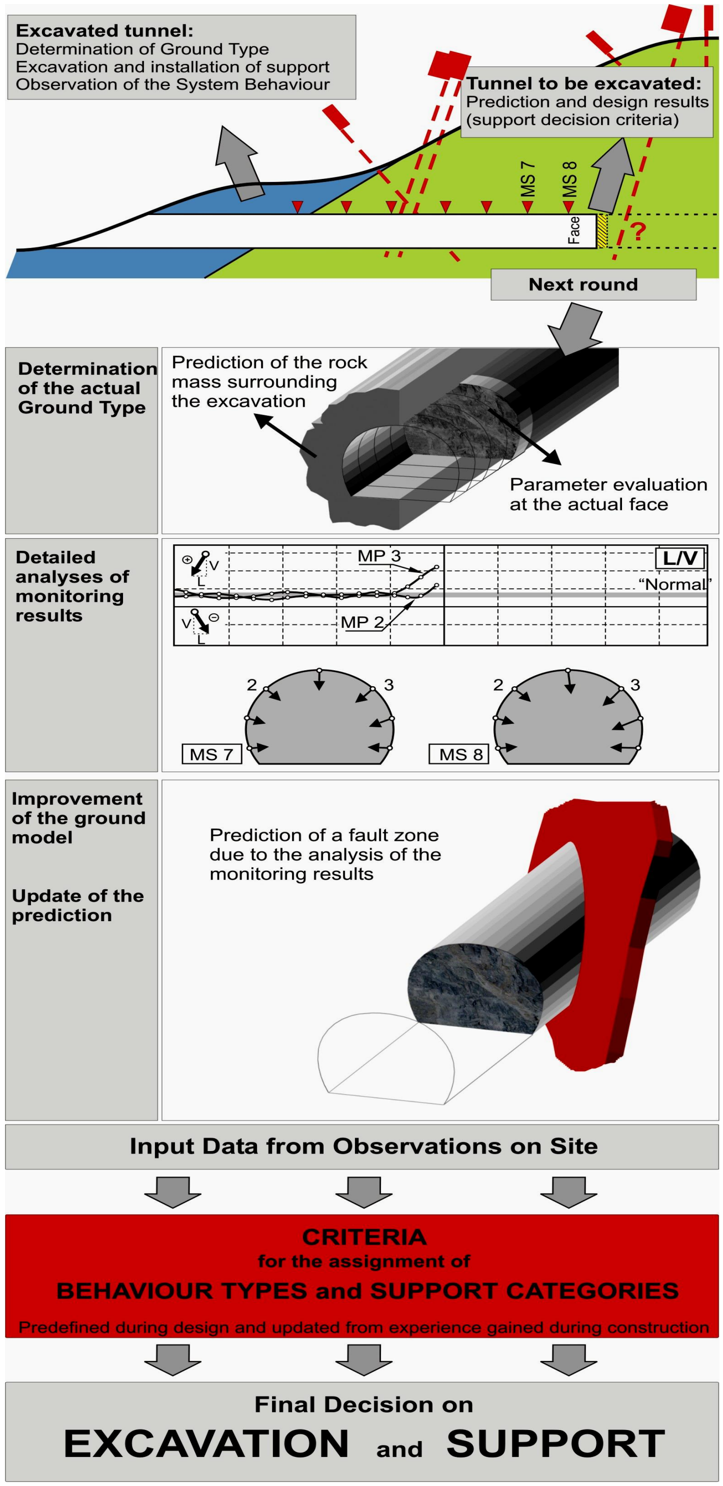

Figure 1. Procedure of rock mass characterization, classification and final support decisions during construction

Application of the GSI System

The determination of the rock mass properties is one of the most important issues in the design and the construction of tunnels in fault zones. A widely used method for the evaluation of the rock mass properties is the GSI system (3). It allows the determination of the most important rock mass parameters from the properties of the intact rock and the discontinuities of the rock mass by using the Hoek-Brown failure criterion (4,5). The system is quantitative, well described and gives reasonable results for blocky rock masses. Recently the GSI concept has been expended for sheared and weak rock masses (6,7).

The GSI does not include all influencing factors relevant for the characterization of rock mass. For example the rock mass anisotropy is not considered. The influence of water to the strength of rock masses that are prone to deterioration as a result of changes in moisture content is qualitatively assessed (8). However engineering judgement and experience have to be used to evaluate their influence on the rock mass properties. Generally the GSI system is applicable in rock masses where the intact rock properties and the joint properties can be evaluated. It is very important to evaluate the parameters for the intact rock and the joints independently. In sheared rock mass as in fault zones the intact rock strength is not necessarily low. In such cases it is the low GSI value that allows the reduction of the overall rock mass strength. On the other hand, in a soft rock mass with a minor mechanical importance of the fracturing low rock mass properties are the result of a low intact rock mass strength with a high GSI value. The GSI system reaches its limitations with the occurrence of weak sheared rock masses when intact rock and joints cannot be described separately. In such conditions the rock mass strength should be evaluated with different methods like direct testing of the rock mass in a proper scale or the evaluation or the properties using the Block-in-Matrix (BIM rock) approach (9).

A big advantage of the GSI system is the ability for its almost unlimited application during the different project stages. It can be used for the characterization of rock mass from investigation drillings, as an indirect input parameter for numerical analyses and also during the excavation. This results in a continuous use of the parameters with a gradual increase of information quality of the parameter values during the project development from the first exploration phase through the construction.

The GSI-system is used as a tool for the characterization of the rock mass. It is very important to clearly separate this step from the step of the geomechanical evaluation of the ground behaviour. The behaviour types and the system behaviour are evaluated in an independent step, but are based on the data of the rock mass characterization.

Criteria for the Support Decision

The definition of formal predefined criteria for the selection of the support categories provides guidelines for the application of the design. The criteria contain detailed information about the design assumptions and help the engineers on site to correctly assign the designed excavation and support to the actual ground conditions.

In the design stage the evaluation of the excavation and support is based on input data which are mainly predictions and assumptions about the ground conditions. The predicted system behaviour is based on these assumptions. Variations of the parameter values within reasonable ranges can help to provide a more general picture of the behaviours to be expected. The results of the design are support categories which lead to an acceptable system behaviour if combined with a certain ground condition represented by several parameters. Additionally more detailed correlations and dependencies can be described. During the construction of the tunnel parameters of the rock mass and the system behaviour are observed and evaluated. The data quality is very high and the rock mass can usually be described in more detail than during the design stage.

It is essential for the definition of the assignment criteria that the relevant parameters of the tunnel design can be observed during the construction. In fault zones with squeezing potential the most important quantitative parameters for the tunnel design are the rock mass strength, deformation characteristic and the primary stress condition. Based on these parameters criteria for the application of the support categories are defined as a matrix or a diagram. Figure 2 gives an example for the correlation of the parameters observed on site to the verification of the System Behaviour including the designed support categories.

Figure 2 shows a schematic diagram of the sequence of support decision on site. Using the GSI system, the rock mass is described primarily by the UCSi (σ_{ci} – intact rock) and the GSI. The UCSrm (σ_{cm} - rock mass) is selected as the main input parameter describing the rock mass properties. In the quadrant 1 and 2 the UCSrm is modified due to the impact of the orientation of the main discontinuities (10) and ground water. In the third quadrant the primary stress condition is introduced and quantified by the overburden. This results in a stress factor which is defined as the UCSrm divided by the primary vertical stress. In the fourth quadrant the behaviour types and the support categories are defined, based on the tunnel design. Also shown in this quadrant are the expected displacements of the supported tunnel. In this schematic example the parameters UCSrm (based on UCSi and GSI), discontinuity orientation, ground water and overburden stress and displacements are selected as the most relevant for tunnelling in fault zones. Of course other parameter can be used depending on site specific ground conditions. The important issue is to correlate the relevant parameters following the design assumptions and results and set up a consistent procedure for the support decision and verification on site. The content of the diagram represents a simplification of the results of the design process. It is rock mass and project specific. The criteria presented are applicable for the squeezing sections only where stress induced failure of the rock mass is dominating the system behaviour.

Case Study Metsovo Tunnel - Greece

Project overview

The most significant highway project in Greece is the Egnatia Odos Motorway, which is 680 km long and crosses, from west to east, the Regions of Epirus, Macedonia and Thrace; its budget is expected to reach € 6 billion. 400 km of motorway, more than the half of the project, have already been opened for traffic. Egnatia Odos SA, who is the owner of the project, has obtained a wide knowledge of mountainous tunnelling from the 43 twin tunnels already constructed, totalling more than 60 km in single bore length. The tunnels were excavated in various geological and geotechnical conditions (gneiss, limestone, flysch, peridotites, phyllites etc. of very poor to good quality rock-mass) as it can be seen in figure 3.

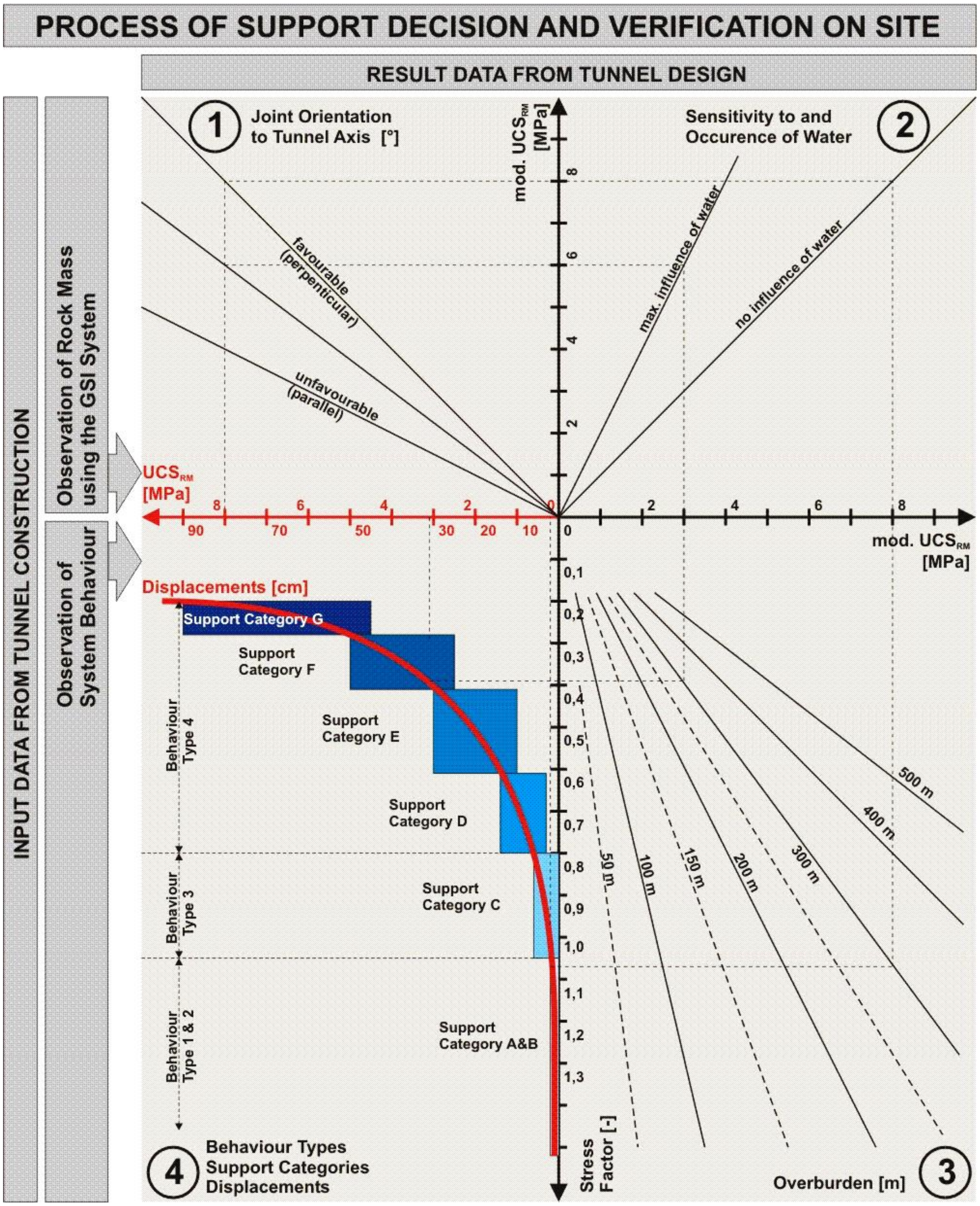

Figure 2. Process of support decision and support verification on site for rock masses with squeezing potential

A 7.6 km long critical mountainous section has been awarded this year with a budget of € 160 million. It includes, amongst other structures, the construction of the second bore of the Metsovo tunnel of 3.5 km length. The first Metsovo tunnel bore has been completed in 1992. Several problems, related to collapses of the top heading in the thrust zones and excessive displacements in the area of severe tectonic features leading to failure of the primary support shell, have occurred during the excavation of the first bore (14).

The predominant construction method to be applied on the second bore of Metsovo tunnel, is the conventional one, following the general principles of NATM. The contractual emphasis of conventional approaches is on “quality production tunnelling”, with exact contours and cost optimization. The price list and the technical specifications have been thoroughly examined and modified, following the owner’s new strategy (11). Operation analysis was used to estimate the cost per linear meter for each designed excavation and support category. Clear guidelines for the construction works were defined as well as a set of parameters, which directly affect cost; these will be monitored during construction to enable early correction measures when needed.

Geological model

The Metsovo tunnel in Pindos Mountain in NW Greece is located in the area of a huge tectonic cover where ophiolites have been thrusted over the flysch of the Pindos zone during the alpine orogenesis. The geological building is complicated and has resulted from emplacements and deformations since the early Mesozoic. Thus a series of fault zones have been produced and are crossed by the tunnel axis.

The geological evolution of the broader area has been the subject of recent research (12, 13). Neotethyan oceanic rocks including Triassic-Jurassic rift related volcanic rocks and deep sea sediments, accretionary mélange and ophiolitic complexes were tectonically emplaced onto the Apulian continent margin to the west, where the Pindos mountains are located today, and at the Pelagonian microcontinent to the east. The Pindos ophiolitic complex is underlain by a metamorphic amphibolitic sole. The mélange formation, present in the whole complex, is a Jurassic accretionary wedge, a block in matrix complex in which blocks of limestones, cherts and lavas and assorted oceanic lithosphere fragments occur within a typically mudstone matrix.

The ophiolites and their mélange base were originally emplaced by obduction to the NE. Mylonitic deformation characterizes a “trailing” end in the western part of the slab, in Pindos, where the ophiolites are far more tectonically disturbed than in other sectors of the slab. A later compressive “back-thrust” verging to the SW placed the ophiolites complex finally over the late Cretaceous-mid-Eocene Pindos flysch. The mélange exposes the most incompetent lithological nature and present continuing deformation. Flysch, with weak sequences of siltstones, exhibited a ductile deformation during the main alpine process with a series of inverse faults and thrusts where the rock mass is heavily sheared. In Figure 4 the model of the evolution of the Pindos region is given in the following steps:

First period of alpine orogenesis:

(a) Production of rift related rocks and ophiolitic complexes. The intraocean subduction of the Neotethys ocean.

(b) The subduction of the ocean drust under the Cimmerian – Eurasian plate and the tectonic placement by obduction of the ophiolites in the Cimmerian margin.

Second period of alpine orogenesis:

(c & d) The convergence on the continent plates with subduction of the Neotethys ocean with thickening of the crust and compressional tectonics with thrusts and nappes.

In Figure 5 the geological model of the Metsovo tunnel based on this tectonic evolution is sketched. In this model the limits of the various formations encountered during the construction of the existing Metsovo tunnel (14) are respected.

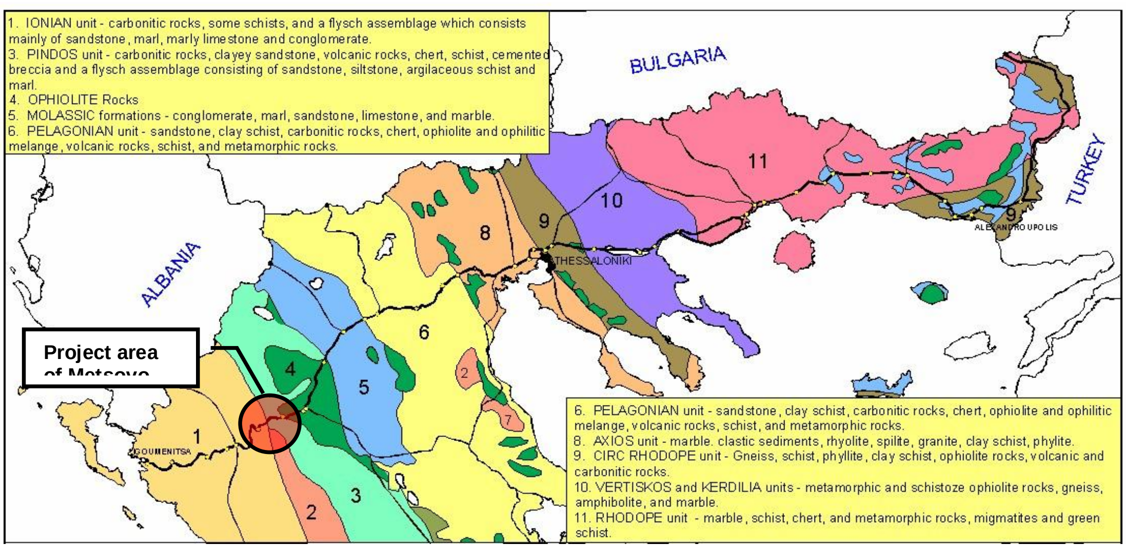

Figure 3. Geotechnical units along Egnatia Odos highway

Geomechanical model and support design

Based on the geomechanical investigation and reports from the construction of the first tunnel tube, squeezing ground conditions are predicted for the major thrust zone at the contact between flysch and ophiolites and other tectonised zones of weak rock masses under high overburden. A collapse of the top heading in the thrust zone and problems with failure of the primary lining and under-profile due to large displacements in the sections with high overburden were reported (14).

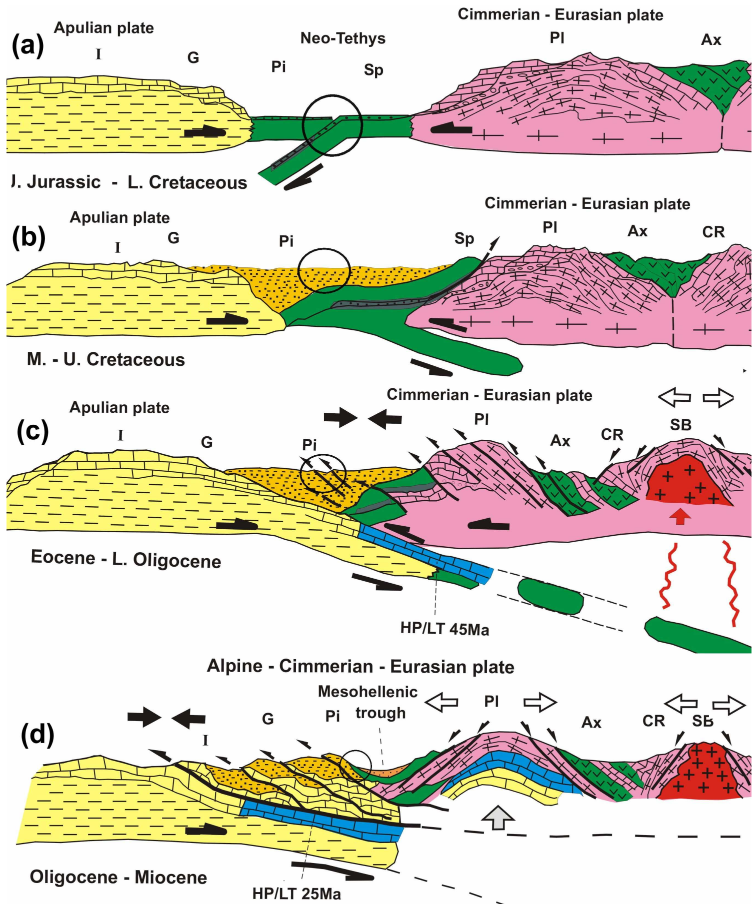

Figure 4. Schematic section of the geodymanic evolution of the Hellenides, Northern Greece (15); the location of the Metsovo tunnel is shown with a circle

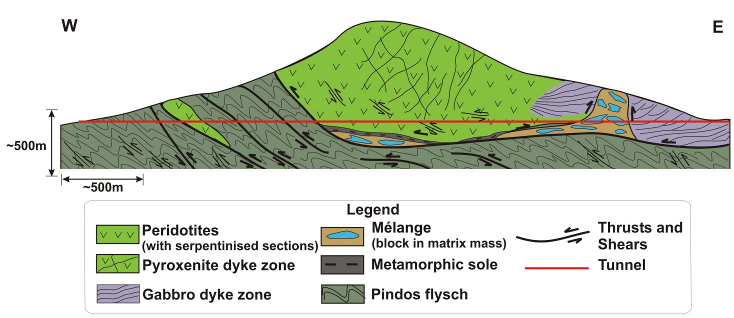

Figure 5. Sketch of the geological model of the massif of the project area of the Metsovo tunnel.

For the design of the 2nd tunnel tube the rock mass characterization was based on data from the old tunnel and the results of an investigation program consisting of horizontal drillings from the existing tunnel, additional geological field work and an intensive laboratory testing program. The UCS of the intact rock and the GSI have been used as main input parameters for the determination of the rock mass parameters UCSrm, cohesion, friction and Young modulus. These parameters are used in the numerical analyses for the verification of the tunnel support systems. Three of the nine support categories are designed for squeezing ground conditions with predicted displacements up to 100cm. Lining stress controllers are used to provide a controlled yielding of the tunnel lining in the squeezing sections.

The orientation of the main discontinuities and the water condition generally are very important parameters for the tunnel design, but according to the information gained from the first bore the potential for variations in this project is very low. Therefore these two influencing parameters are included in the rock mass properties of the different ground types.

Support decision criteria

For the support decision on site simple decision criteria are defined based on the following relevant input parameters:

- UCS of the intact rock (σ_{ci})
- GSI
- Overburden

These parameters are observable during the construction, and are considered as the keys to verify the design assumptions for the rock mass and the ground conditions. It is known that parameters, such as Young modulus, cohesion or friction can not be directly observed during the construction. Other influencing factors such as the discontinuity orientation and the water are neglected as criteria due to their minor potential for variation within the specific rock masses. The stress factor has been defined as the rock mass strength divided by the vertical primary stress component. Based on the results of the numerical analyses criteria for the assignment of the support categories are defined using this factor. Additionally in some sections the volume of potential key blocks are defined as support decision criteria. For different ground types with different stress factors the support categories are assigned. It is important to note that different ground types may need different support for the same stress factor due to different failure mechanisms, rock mass behaviour and System Behaviour. This has been investigated in detail during the design process. For the practical application on site the defined criteria are presented in tables and in diagrams. Figure 6 shows a diagram with the support decision criteria for the three ground types of the Flysch zone. For every ground type behaviour types and support categories are assigned based on the overburden within certain limits of the stress factor. The limits of displacements for all support categories, which are verified on site by absolute displacement monitoring are presented as well.

GROUND TYPES			
	GT1	**GT2**	**GT3**
Description	Flysch, Sand- /Siltstone	Flysch sheared	Flysch heavily sheared
UCSi [MPa]	25 - 100	25 - 50	10 - 20
GSI	30 - 50	20 - 30	15 - 20
UCSrm [MPa]	4 - 20	2 - 7	0,7 - 2,5

BEHAVIOUR TYPES	
BT2	Deep reaching, discontinuity controlled, gravity induced falling and sliding of blocks
BT3	Shallow stress induced shear failure in combination with gravity controlled failure
BT4/1	Deep stress induced shear failure
BT4/2	Deep stress induced shear failure, large displacements

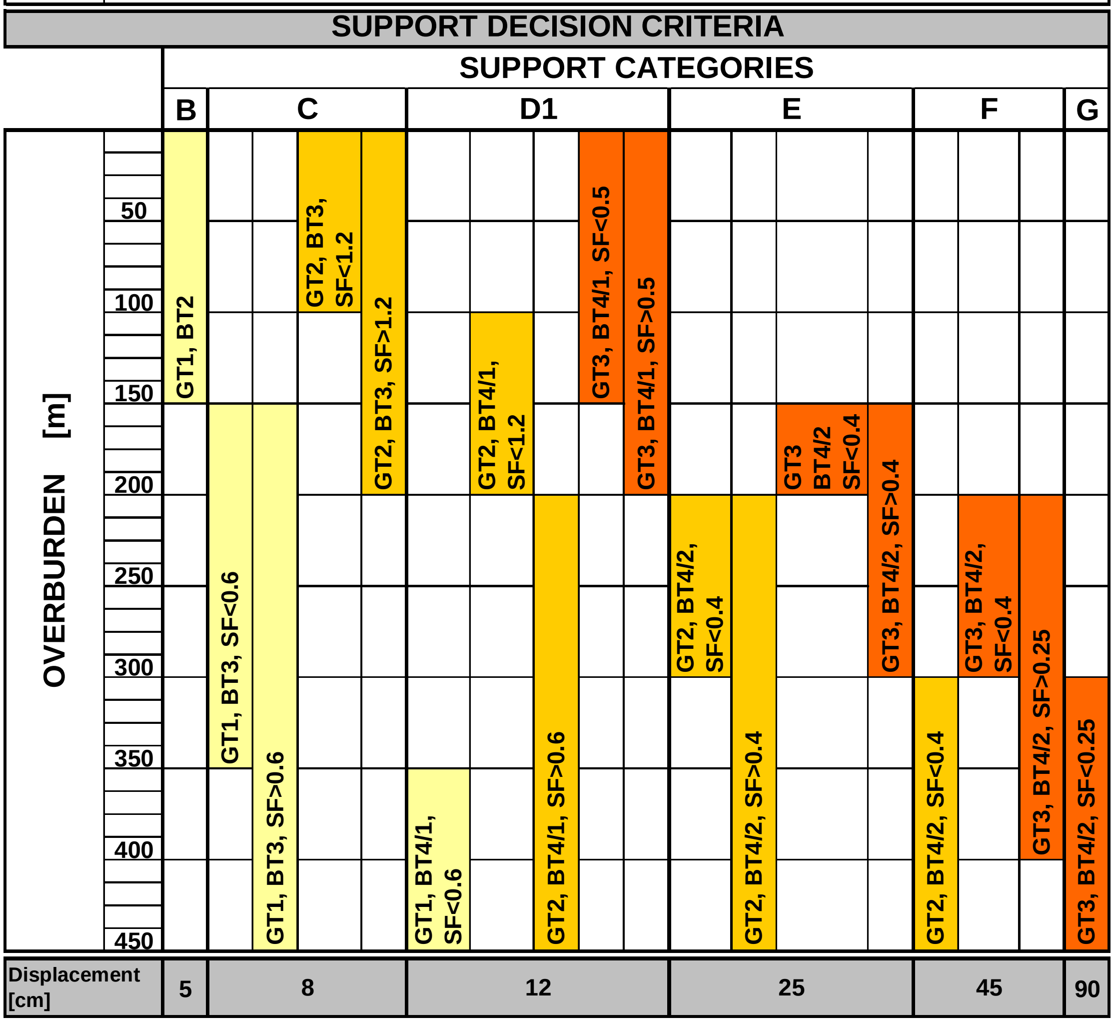

Figure 6. Support decision criteria for the Ground Types of the Pindos Flysch for the Metsovo Tunnel; Stress Factor SF=UCSrm/σ_v

Conclusion

Approximately half of the second bore of Metsovo tunnel has already been excavated. The GSI system has shown to be applicable. The index values are easy to estimate and result in a reliable determination of the rock mass properties. Several zones of difficulties reported from the fist tube have already been constructed successfully. In the squeezing zones the ductile support behaves well. The Support Categories are applied following the predefined support decision criteria with minor modifications due to the observed System Behaviour. The detailed and formal pre-definition of criteria for the support decision on site provided a sound basis for the design.

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For further information, contact:

Dipl.-Ing. Dr. Andreas Goricki, 3G Gruppe Geotechnik Graz ZT GmbH, Elisabethstraße 22, A-8010 Graz, Austria, E-mail: goricki@3-g.at