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# A CONSISTENT ENGINEERING APPROACH TO TUNNEL DESIGN

**SUMMARY:** Currently excavation and support determination in tunnelling is mainly based on experience, supplemented by simplified models and calculations. There are no standardized procedures, making it difficult to technically review or audit designs, collect, evaluate and compare data from different sites and designs. In this paper a step-by-step procedure is outlined, which promotes an engineering approach to the design and construction of tunnels. In the pre-construction phase support concepts are based on Rock Mass Behaviour Types developed from Rock Mass Types and influencing factors. The System Behaviour describes the rock mass-support interaction. An analytic procedure is presented, which allows the assessment of rock mass behaviour, support requirement, and costs of an entire tunnel deterministically or probabilistically. This is used for preliminary design of tunnels, comparison of routes and different construction methods, and risk analyses. During construction geological and geotechnical monitoring, and observations allow the support and excavation design to be completed. The observed and predicted behaviours are continuously compared. The procedure is illustrated by a case study from an Austrian tunnel project.
Keywords: Tunnel, design, rock mass characterisation, support, monitoring, risk analysis

# INTRODUCTION

Currently, there are no standardized procedures to determine excavation and support for underground openings. This lack of consistency makes it difficult to technically review or audit designs, collect, evaluate, and compare data from different sites and designs.

A sound and economical tunnel design depends on a realistic geological model (Riedmueller and Schubert, 2001), a quality rock mass characterization, and the assessment of influencing factors such as primary stresses, groundwater, and kinematics. Despite this requirement it is still current practice to base the tunnel design primarily on experience, basic empirical calculations, and standardized rock mass classification systems. Additionally, the on site decisions on excavation and support modifications are frequently based more on intuition than on analyses. This is especially true for tunnels with high overburden in complex geological conditions where limited information is available in the pre- construction phase.

On the other hand, the quantitative rock mass classification systems presently in use (Bieniawski, 1974, 1989, Barton et al., 1974, Barton, 1989) have severe shortcomings. One of the main deficiencies is that the classification parameters are universally applied to all Rock Mass Types. Especially in heterogeneous and poor ground conditions these classification methods may provide misleading results while other shortcomings include the lack of consideration for different rock mass failure modes and ground-support interaction (Riedmueller and Schubert, 1999). These schematic procedures have the potential to make tunnel design appear rather simple. Frequently, a few specific parameters are determined and simple classification formulas are applied to achieve a rating. Then with a design chart a support method is determined. No reference is made to project specific requirements or to boundary conditions. Especially in complex rock masses, where the varying stiffness of the ground lead to complex stress and strain distributions, a sound engineering approach is required to allow for a safe and economical construction.

For this reason, it was decided to develop a consistent method for tunnel design, from the pre-construction phase through the tunnel construction, applicable to all rock mass conditions. In general, the final design process continues into the construction phase. The procedure developed, allowing an

objective and unbiased decision making process was published in the form of a guideline (OeGG, 2001).
The concept recently was extended to risk analyses, considering the natural spread of geotechnical parameters (Goricki, 2003).

# PROCEDURE DURING DESIGN

The geotechnical design, as part of the tunnel design, serves as a basis for approval procedures, the tender documents (determination of excavation classes and their distribution), and the determination of the excavation and support methods used on site (Schubert et al., 2001).
The flow chart (Figure 1) shows the basic procedure, consisting of 5 general steps, to develop the geotechnical design, beginning with the determination of the Rock Mass Types and ending with the definition of excavation classes. During the first two steps statistical and/or probabilistic analyses should be used to account for the variability and uncertainty in the key parameter values and influencing factors, as well as their distribution along the projects route (Goricki et al. 2002). The probabilistic analyses are then continued throughout the entire process as necessary, resulting in both a risk analysis and a distribution of excavation classes on which the tender documents are based (Goricki et al., 2002).

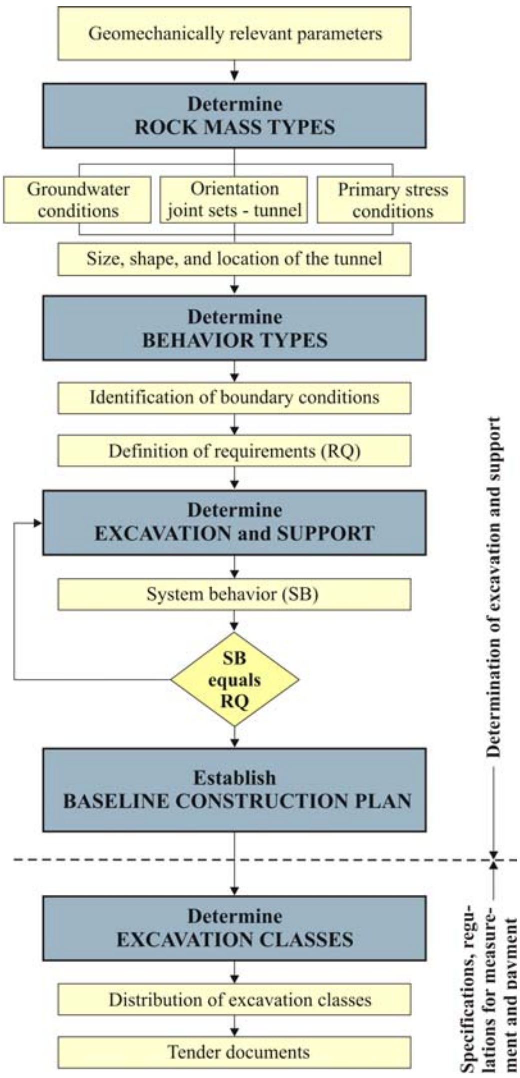


**Figure 1** Flow chart of the basic procedure of excavation and support design for underground structures

The five steps to be followed are outlined below.
**Step 1 – Determination of Rock Mass Types (RMT):** The first step starts with a description of the basic geologic architecture and proceeds by defining geotechnically relevant key parameters for each ground type. The key parameters values and distributions are determined from available information and/or estimated with engineering and geological judgment. Values are constantly updated as pertinent information is obtained. Rock Mass Types are then defined according to their key parameters. The number of Rock Mass Types elaborated depends on the project specific geological conditions and on the stage of the design process.
Physical and hydraulic parameters have to be established for each Rock Mass Type.

**Step 2 – Determination of Rock Mass Behaviour Types (BT):** The second step involves evaluating the potential rock mass behaviours considering each Rock Mass Type and local influencing factors, including the relative orientation of relevant discontinuities to the excavation, ground water conditions, stress situation, etc. (Feder, 1978, Hoek, 1999). This process results in the definition of project specific Behaviour Types.
The rock mass behaviour has to be evaluated for the full cross section without considering any modifications including the excavation method or sequence and support or other auxiliary measures.
Eleven general categories are listed in the guideline (table 1). More than one BT being identified in one of the general categories requires assigning sub types. A concise description of the applicable Rock Mass Types, the influencing factors, the specific behaviour, failure modes, as well as estimates of the displacements for each BT is required. The BTs form the basis for determining the excavation and support methods as well as assist in evaluating monitoring data during the excavation.

Table 1 General categories of Rock Mass Behaviour Types

| | **Behaviour Type (BT)** |
|---|---|
| 1 | Stable |
| 2 | Discontinuity controlled block failure |
| 3 | Shallow stress induced failure |
| 4 | Deep seated stress induced failure |
| 5 | Rock burst |
| 6 | Buckling failure |
| 7 | Shear failure under low confining stress |
| 8 | Ravelling |
| 9 | Flowing |
| 10 | Swelling |
| 11 | Frequently changing behaviour |

**Step 3 – Determination of the excavation and support:** Based on the defined project specific Behaviour Types, different excavation and support measures are evaluated and acceptable methods are determined.
The System Behaviour (SB) is a result of the interaction between the rock mass behaviour and the selected excavation and support schemes. The evaluated System Behaviour has to be compared to the defined requirements. If the System Behaviour does not comply with the requirements, the excavation and/or support scheme has to be modified until compliance is obtained. It is emphasized, that different boundary conditions or different requirements may lead to different support and excavation methods for the same Behaviour Type even within one project.
Once the acceptable excavation and support methods have been determined both risk and economic analyses should be performed to allow appropriate assessments during the tender process.

**Step 4 – Geotechnical report – baseline construction plan:** Based on steps 1 through 3 the alignment is divided into “homogeneous” regions with similar excavation and support requirements. The baseline construction plan indicates the excavation and support methods available for each region, and contains limits and criteria for possible variations or modifications on site.
The plan summarizes the geotechnical design and should contain information on the geological conditions, relevant geotechnical features, limitations (e.g. surface settlements, blasting vibrations, etc.), as well as warning criteria and remedial measures.

**Step 5 – Determination of excavation classes:** In the final step of the design process the geotechnical design must be transformed into a cost and time estimate for the tender process. Excavation Classes are defined based on the evaluation of the excavation and support measures. The excavation classes form a basis for compensation clauses in the tender documents. In Austria the evaluation of excavation classes is based on ONORM B2203-1 (2001). In other locations the local or agreed upon regulations should be used.

The distribution of the expected behaviour types and the excavation classes along the alignment of the underground structure provides the basis for establishing the bill of quantities and the bid price during tender.

# PROCEDURE DURING CONSTRUCTION

Due to the fact, that in many cases the rock mass conditions cannot be defined with the required accuracy prior to construction, a continuous updating of the geotechnical model and an adjustment of excavation and support to the actual ground conditions during construction is required.

The final determination of excavation methods, as well as support type and quantity in most cases is possible only on site. Figure 2 shows the basic procedure to be followed for each section.

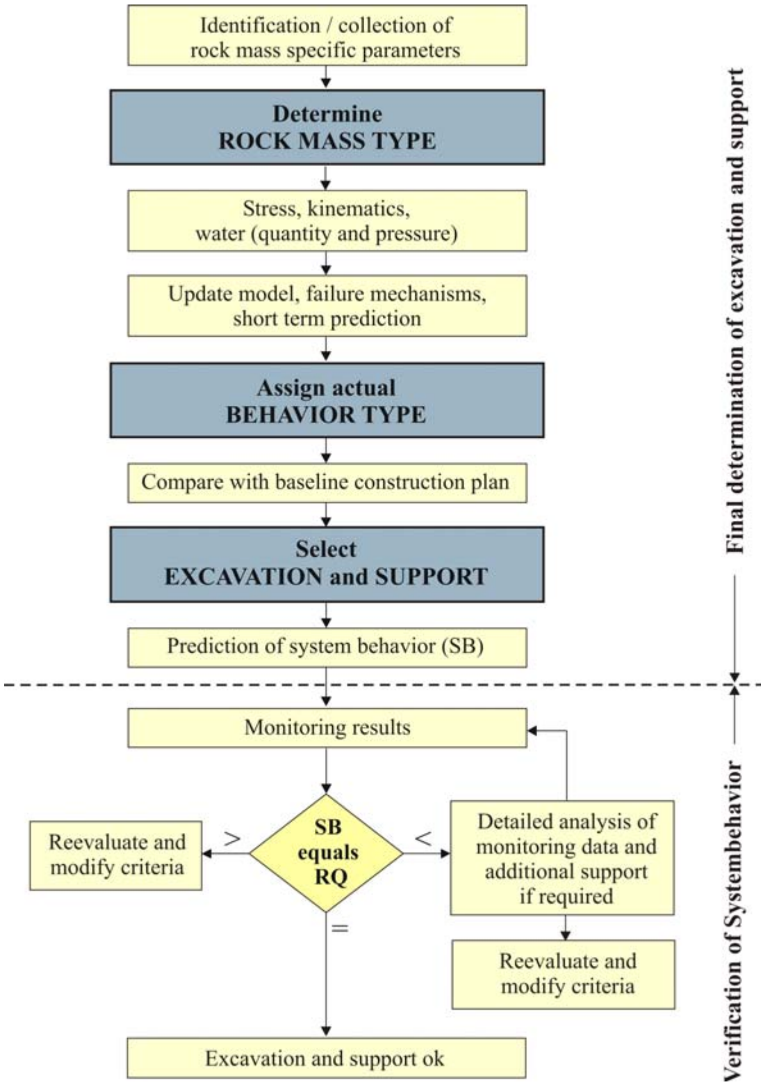


**Figure 2** Flow chart of the basic procedure during construction

**Step 1 – Determination of the encountered Rock Mass Type**

To be able to determine the encountered Rock Mass Type, the geological investigation (documentation) during construction has to be targeted to collect and record the relevant parameters that have the greatest influence on the rock mass behaviour (Liu et al., 2001).

The geological and geotechnical data collected and evaluated on site are the basis for the extrapolation and prediction of the rock mass conditions into a representative volume (rock mass volume, which determines the behaviour). The geological work thus has to exceed the mere recording of the face conditions, and include predicting the conditions in the volume of rock that controls the rock mass response. Up to date methods of data collection support the continued geological modelling (Gaich et al., 2001). Predefined criteria and weighted parameters are used to identify the appropriate Rock Mass Type.

**Step 2 – Determination of the actual Rock Mass Behaviour Type**

Observations during excavation, such as signs of excessive stress, deformation pattern and observed failure mechanisms, and results from probing ahead are used to continuously update the geotechnical model. Appropriate evaluation of monitoring results support the short term prediction, which is the basis for the determination of the actual Behaviour Type expected on the next rounds. (Steindorfer, 1998)

**Step 3 – Determination of excavation and support**

To determine the appropriate excavation and support the criteria laid out in the design have to be followed. Consequently, the actual rock mass conditions (RMT, BT) continuously have to be compared to the prediction for compliance. The additional data obtained during construction form the basis for the final determination of the excavation and support methods.

Based on the evaluated Behaviour Type, and the excavation and support layout determined according to the defined criteria, the System Behaviour for each section has to be predicted (Sellner, 2000).

Both excavation and support, to a major extent, have to be determined prior to the excavation. After the initial excavation only minor modifications are possible. This fact stresses the importance of a continuous short-term prediction.

**Step 4 – Verification of System Behaviour**

By monitoring the behaviour of the excavated and supported section the compliance with the requirements and criteria defined in the geotechnical safety management plan is checked. When differences between the observed and predicted behaviour occur, the parameters and criteria used during excavation for the determination of Rock Mass Type and the excavation and support have to be reviewed and adjusted if required. In case of less favourable System Behaviour than predicted improvement measures (like increase of support) may be necessary.

# STATISTICAL ANALYTICAL METHOD

For the quantitative realisation of the outlined procedure a Statistical Analytical Model has been developed. Based on the geological and geotechnical input data the behaviour of the rock mass surrounding the unsupported excavation is determined. Figure 3 shows the structure of the probabilistic determination of the Rock Mass Types. By using distributed input parameters and a Monte Carlo simulation the distributions of the result parameters can be obtained.

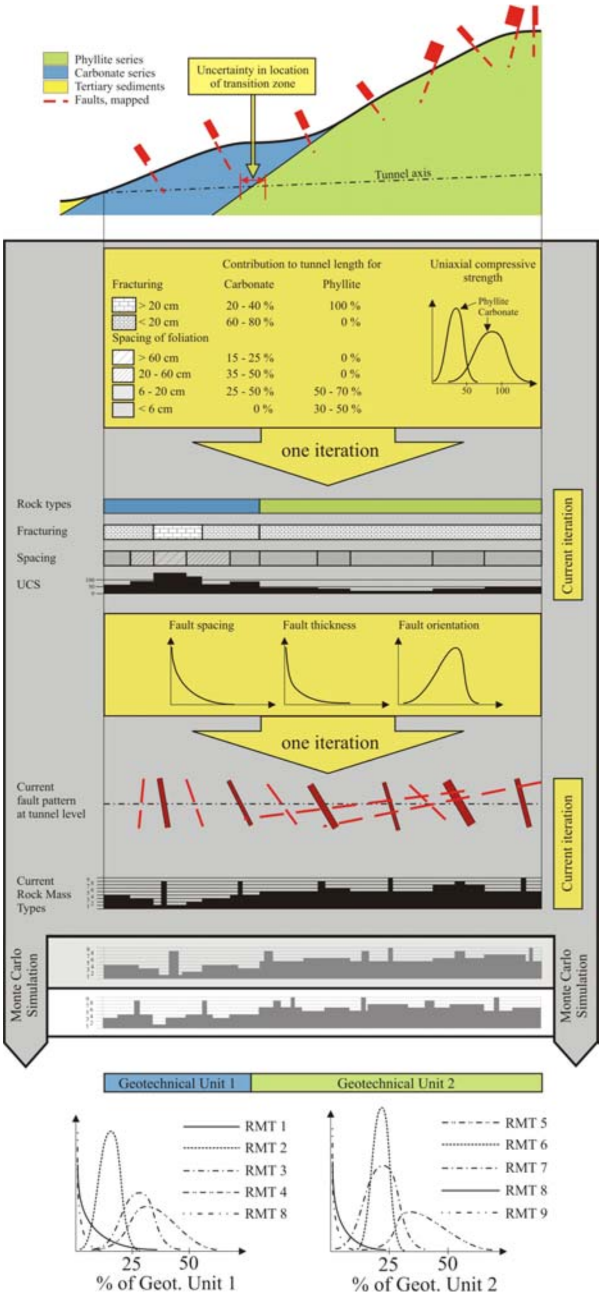


**Figure 3.** Example for the probabilistical determination of Rock Mass Types

Variations within the iteration steps include the extension of the lithological units, rock and rock mass properties, as well as spacing, thickness and orientation of fault zones. Based on a predefined matrix the Monte Carlo simulation leads to a distribution of the percentage of the Rock Mass Types within the geotechnical units or the tunnel alignment.

Especially in complex rock masses or deep tunnel excavations the variations of geomechanically relevant parameters should be described in a probabilistically way. The variations within the iteration steps are related to the extension of the lithological units, the rock and rock mass properties, or the spacing, thickness and orientation of fault zones. With a predefined matrix the simulation leads to a distribution of the percentage of the Rock Mass Types within the geotechnical units or the tunnel alignment.

Based on this information about the rock mass and the assigned influencing factors the behaviour of the rock mass can be determined. Therefore the entire alignment is divided into calculation segments with a length related to the geotechnically similarity of the properties, for example 10 meters.

With different analytical models for overbreak, stress induced failure, or heterogeneous rock mass conditions (Goricki et al. 2002) the rock mass behaviours are determined for any calculation segment within each iteration step of the Monte Carlo simulation.
By setting delimiting criteria the Behaviour Types can be determined form the quantitative behaviour of the rock mass. By summarizing the information for all calculation segments and all iteration steps the distribution of the Behaviour Types within the calculation segments, geotechnical units, or the entire tunnel alignment can be given. Based on this data obtained from the quantitative rock mass characterization the excavation and support measures can be designed and assigned to the correlating Behaviour Types in the Statistical Analytical Model. Based on local standards or contractual needs the excavation and support measures can be classified into excavation classes. Additionally, time and costs can be determined for the defined excavation and support concepts and assigned to the correlating Behaviour or Excavation Type. Finally it is possible to present percentages of Rock Mass Types, Behaviour Types, Excavation (and Support) Classes, and time and costs for the entire tunnel alignment or individually defined tunnel sections. These results are directly correlated to the input parameters of the rock mass and the influencing factors based on the analytical determination of different failure modes and rock mass behaviours and represent the geotechnical risk - as the range of possible values of tunnel costs and their likelihood of occurrence.

# APPLICATION

The outlined and discussed procedure has been applied in various projects for preliminary studies, cost estimations, and tender design. The presented example deals with the comparison of tunnel alternatives and construction methods for the Semmering base tunnel project (Grossauer et al. 2003). The base tunnel has a total length of approx. 22 km and an overburden up to 900 meters.
Two different tunnel alternatives were investigated in terms of technical feasibility and risk: a double track tube with a service tunnel and two single track tubes. For both alternatives different excavation methods (NATM, TBM) were investigated. The described method was applied for a probabilistic determination of the geotechnical risk. The process includes geological modelling as well as rock mass characterization, tunnel design and the assignment of time and costs to construction measures and singular events.

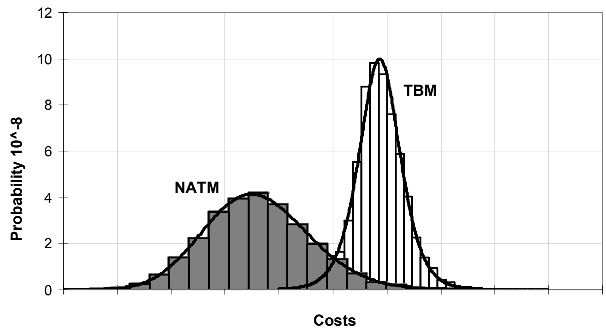


**Figure 4.** Typical distributions of construction costs for different construction methods

Figure 4 shows the difference in the distributions of costs for the excavation methods compared. Due to the high complexity of the geological situation and the higher flexibility and the lower basic investments the conventional method shows a wide deviation with lower basic costs.

# CONCLUSIONS

Instead of support decisions being based on standardized rock mass classification systems the procedure outlined incorporates the observation of the rock mass behaviour and the rock mass-support interaction in a transparent and consistent way.

The goals reached by application of this procedure include the optimization of investigation programs by concentrating on the collection of rock mass and project specific key parameters, consistent designs meeting project specific requirements, optimized construction by providing clear procedures to support the decisions on site, and a continuous documentation of the decision making process. Another target is to promote technical advances in tunnelling by evaluating comparable data from various sites.

# REFERENCES


Barton, N. 1998. NMT support concepts for tunnels in weak rocks. In A. Negro Jr., A.A. Feirreira (eds.), Tunnels and Metropolises; Proc. intern. symp., Sao Paulo: 273-279. Balkema.

Barton, N., Lien, R. & Lunde, J. 1974. Engineering classification of rock masses for the design of tunnel support. Rock Mechanics 6(4): 189-236.

Bieniawski, Z.T. 1974. Geomechanics classify-cation of rock masses and its application in tunnelling. Adv. in rock mech. 2(A): 27-32.

Bieniawski, Z.T. 1989. Engineering rock mass classifications. 251 pp. New York: Wiley.

Feder, G. 1978. Versuchsergebnisse und analytische Ansätze zum Scherbruch-mechanismus im Bereich tiefliegender Tunnel. Rock Mechanics (6): 71-102.

Gaich, A., Fasching, A. & Schubert, W. 2001. Geotechnical data collection supported by computer vision. In P. Särkkä, (ed.), Rock Mech;A Challenge for Society: Balkema 65-70.

Goricki, A. 2003. Classification of Rock Mass Behaviour based on a hierarchical Rock Mass Characterization for the Design of Underground Structures. Doctoral thesis, TU-Graz

Goricki, A., Schick, K.J., Steidl, A., 2002. Quantification of the Geotechnical and Economic Risk in Tunneling. Probabilistics in Geotechnics: Technical and Economic Risk Estimation, 2002. pp. 483-490. VGE.

Hoek, E., 1999. Support for very weak rock associated with faults and shear zones. Proc. Int. Symp. Rock Support and Reinforcement Practice in Mining, Kalgoorlie, Australia, 14-19

Liu, Q., Riedmueller, G., Klima, K., 2001. Quantification of parameter relationships in tunnelling. In P. Särkkä, (ed.), Rock mechanics; A challenge for society. Balkema. 357 -362

ONORM 2203-1, 2001. Untertagebauarbeiten – Werkvertragsnorm. Teil 1: Zyklischer Vortrieb. Austrian Standards Institute (ON)

Riedmüller, G. & Schubert, W. 2001. Project and rock mass specific investigation for tunnels. In P. Särkkä, P. Eloranta (eds.), Rock Mechanics a Challenge for Society: 369-376. Balkema.

Riedmüller, G., Schubert, W. 1999. Critical comments on quantitative rock mass classifications. Felsbau 17(3): 164-167.

Schubert, W. et al., 2001. Method for a Consistent Determination of Excavation and Support for Design and Construction of Tunnels. In P. Särkkä (ed.), Rock mechanics; A challenge for society. Balkema. 383 -388.

Sellner, P. 2000. Prediction of displacements in tunneling. Publication Series of Geotechnical Group Graz (9).

Steindorfer, A. 1998. Short Term Prediction of Rock Mass Behavior in Tunnelling. Publication Series of Geotechnical Group Graz (1).