Excavation and Support Determination for the Design and Construction of Tunnels

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ABSTRACT: Our procedure, developed from considerable experience, promotes an engineering approach to design and construction of tunnels. In the pre-construction phase support concepts are based on Rock Mass Behavior Types developed from Rock Mass Types and influencing factors. The System Behavior describes the rock mass-support interaction which is based on numerical simulations and previous experience (data base knowledge). During construction geological face mapping, geotechnical monitoring, and observations allow the support and excavation methods to be finalized. The observed and predicted behavior are compared by evaluating displacement monitoring, support utilization, and overbreak volume. Deviations between the observed and predicted behavior lead to a reevaluation of the process resulting in modifications to the support and excavation methods. Our experience shows that this procedure, demonstrated by two case studies from the Austrian Alps, contributes to the optimization of tunnel construction.

1 INTRODUCTION

A sound and economical tunnel design heavily relies on a quality rock mass characterization. In the past, tunnel design was primarily based on experience, basic empirical calculations, and standardized rock mass classification systems. Due to uncertainties in the rock mass behavior, the final excavation and support design should continue through the construction process. This is especially true for tunnels with high overburden and poor ground conditions where limited information is available in the pre-construction phase.

The quantitative rock mass classification systems presently in use (Bieniawski 1974, 1989, Barton et al. 1974, 1998) have severe shortcomings. One of the main deficiencies is that the classification parameters are universally applied to all rock mass types. 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 for the ground-support interaction (Riedmüller & Schubert. 1999).

The 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.

For this reason, we decided to outline a consistent method for tunnel design, from the pre-construction phase through the tunnel construction, applicable to all rock mass conditions. When the final design process continues into the construction phase we have developed a procedure that defines an objective and unbiased decision making process used to guide the final design. We first briefly describe the procedure for the design phases, then discuss procedures for the construction phase. Each process is demonstrated with a case history.

2 PROCEDURE DURING DESIGN

2.1 *Rock Mass Characterisation*

2.1.1 *Rock mass types*

The first step in characterizing the rock mass is to define Rock Mass Types (RMT). The Rock Mass Types are defined by lithology, laboratory tests, and field observation data. Statistical methods are used to assign the parameter range for each rock mass type. Different rock types have different characteristics that effect their behavior; therefore it is important to define key parameters that specifically describe each rock type. For example, the uniaxial strength and joint intensity control the behavior of granite, while the behavior of foliated rock is dominated by the foliation planes orientation, anisotropy and shear strength.

The rock mass types definition, in our approach, is project specific. For projects with rather uniform conditions only a few rock mass types will be necessary, while in complex geological conditions many rock mass types may emerge from the analyses. Site data from previous projects, stored in the data base system DEST, we have recently developed (Liu et al. 1997, 1999), support the determination of Rock Mass Types. Systematic evaluation of those data allows one to identify key parameters for each Rock Mass Type (Liu et al. 2001).
Procedures to arrive at rock mass parameters include the GSI concept (Hoek 1999) or numerical simulations of a representative rock mass volume (Barton & Bandis 1982, Bhasin & Hoeg 1998).

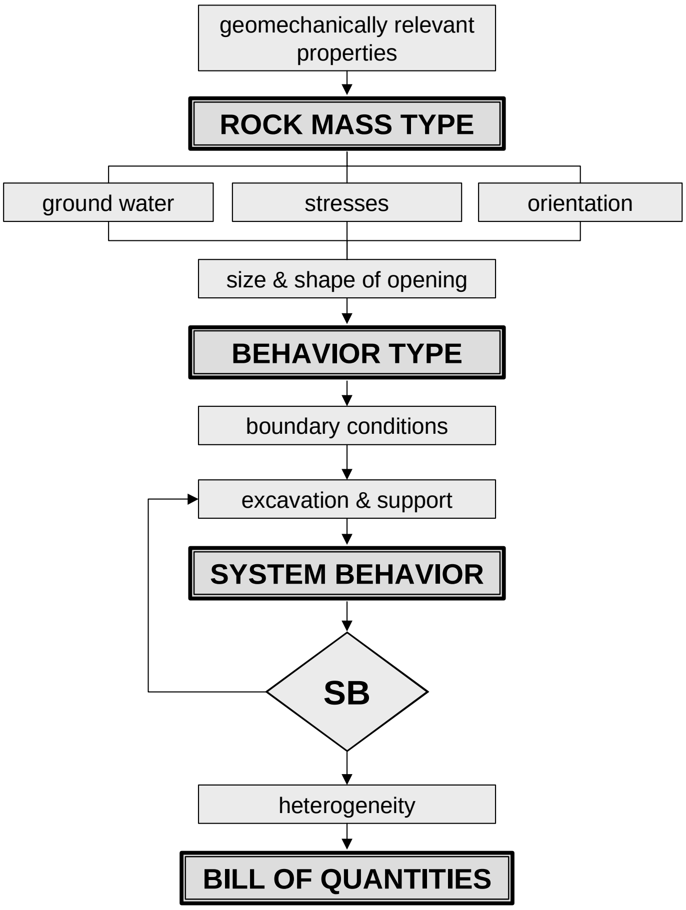


Figure 1. Flow chart of basic procedure of excavation and support design for tunnels

2.1.2 *Rock Mass Behavior Types*

The second step in the process is to define Rock Mass Behavior Types (BT). The Behavior Types are developed by combining the previously defined RMT with system factors such as stress conditions, relative orientation of discontinuities to the tunnel axis, the influence of ground water, as well as shape and size of the planned opening.

Potential failure modes are identified, such as gravity controlled sliding of blocks, or shear failures in the rock mass, and the displacement magnitude is estimated. A single rock mass type when combined with the system factors can yield different behavior types. Likewise, a single behavior type can represent many rock mass types. A careful investigation of the failure modes is essential in this phase in order to arrive at efficient support concepts during subsequent steps.

Analytical or numerical simulations in this phase of the project supplement the experience gained from previous projects under similar conditions.

Eleven basic categories of Behavior Types have been distinguished so far (Table 1). It is emphasized that combinations of basic Behavior Types may occur.

Basic Behavior Type		**Description**
1	Stable	Stable rock mass with small local gravity induced falling or sliding of blocks
2	Stable with the potential of discontinuity controlled block fall	Deep reaching discontinuity controlled, gravity induced falling and sliding of blocks, occasional local shear failure
3	Shallow shear failure	Shallow stress controlled shear failures in combination with discontinuity and gravity controlled failure of the rock mass
4	Deep seated shear failure	Deep seated, stress induced shear failures and large deformations
5	Rock burst	Sudden and violent failure of the rock mass, caused by highly stressed rock and the rapid release of accumulated strain energy
6	Buckling failure	Buckling of rocks with a narrowly spaced discontinuity set, frequently associated with shear failure
7	Shear failure under low confining pressure	Potential for excessive overbreak and progressive shear failure with the development of dead loads, caused mainly by a deficiency of side pressure
8	Ravelling ground	Flow of cohesionless dry or moist material
9	Flowing ground	Flow of material with high water content
10	Swelling	Time dependent volume increase of the rock mass, caused by physical-chemical reactions of rock and water in combination with stress relief, leading to inward movement of the tunnel perimeter
11	Rock mass with frequently changing deformation characteristics	Rapid variations of stresses and deformations, caused by block-in matrix situation of a tectonic melange (brittle fault)

Table 1: Basic Rock Mass Behavior Types

2.1.3 *System Behavior*

The final step in the characterization process is to determine the System Behavior (SB). The rock mass-support interaction is analyzed defining the System Behavior. The predicted System Behavior is compared to the required project goals. Various parameters have to be considered in this process to meet project specific requirements. For example, such parameters can be the allowable surface settlement magnitudes for shallow tunnels in urban areas, while for deep tunnels the allowable load in the lining, or compatibility of support ductility with expected displacements may control the design decisions.

Naturally there is more than one way to meet the specified requirements. To technically and economically optimize the tunnel construction various solutions have to be analyzed and compared. In this process local regulations and contractor capabilities also have to be considered. For example, the speed of excavation and support installation in poor ground may influence the system behavior considerably. Thus, the experience of the crews working on the project must be taken into account when designing excavation and support.

More frequently numerical simulation methods are used to determine the System Behavior, supplementing experience and analytical solutions. Improved hard- and software performance has allowed simulations to be performed in reasonable time and at acceptable costs. Cross-checks of the results with carefully worked case studies are always recommended.

The final stage in the design process is to establish the bill of quantities. When determining the distribution of excavation classes, one has to consider, that in practice the decision making process to change excavation and support takes some time. For example in heterogeneous ground when better rock mass conditions are encountered, the decision to increase round length and decrease support always takes longer than reducing round length and increasing support when running into poor ground. Thus, the distribution of the excavation classes always will shift to the more “poor” side than theoretically necessary.

2.2 *Case study - Semmering base tunnel*

The tunnel is part of the modernization program of the Austrian Federal Railways on the so-called Pontebbana line, linking Vienna with Trieste. The tunnel is situated in eastern Austria and has a length of approximately 22 km with a maximum overburden of about 900 m. A report on the investigation is given by Riedmüller et al. (2000) and Riedmüller & Schubert (2001).

2.2.1 *Rock Mass Types*

For the tender design of the Semmering base tunnel a total of 21 different Rock Mass Types were identified and described. Table 2 shows the parameters for two of the Rock Mass Types distinguished. Parameters were obtained from laboratory testing and observations during excavation of a pilot tunnel, which was constructed over approximately 20% of the total tunnel length.

Mean values and standard deviation are shown for each parameter, as well as the number of samples tested.

	RMT 1	**RMT 12**
Lithology	marble	phyllite
Foliation/Anisotropy	massive	foliated, highly anisotropic
Block size	> 20 cm	< 20 cm
Joint condition	mainly rough	coated with clay
Persistence	low	dominating low
Aperture	closed	dominating closed
	Intact rock	
	μ / σ / no. of samples	
UCS [Mpa]	102,6 / 29,0 / 26	28,2 / 13,6 / 19
c [MPa]	24,2 / 8,2 / 20	8,0 – 14,2 / 3
φ [°]	40,7 / 4,9 / 20	30,1 – 33,1 / 3
E [GPa]	68,3 / 17,6 / 23	26,7 / 19,1 / 18
CAI (Abrasivity)	1,4 / 0,4 / 18	no values
ν [ ]	0,19 / 0,4 / 18	0,3 – 0,55 / 2
mi [ ]	13,4 / 6,2 / 20	8,0 – 19,9 / 3
	Rock mass	
	μ / σ	
GSI	70 / 10	40 / 5
UCS [Mpa]	33,2 / 12,1	3,9 / 2,0
c [MPa]	8,0 / 2,8	1,1 / 0,5
φ [°]	37,7 / 4,7	31,3 / 3,6
E [GPa]	35,0 / 19,4	3,0 / 1,0
	Joint properties	
	estimated values.	μ / σ / no. of samples
φ [°]	35 – 45	33,7 / 6,3 / 15
φ res [°]	30 – 40	28,5 / 5,6 / 23

Table 2: Example of description of two rock mass types for the Semmering base tunnel (μ = mean value, σ = standard deviation)

To evaluate rock mass parameters estimated GSI values were used together with back analyses of the pilot tunnels monitoring results. The point estimate method (Rosenblueth 1975) was used to obtain the distribution of the rock mass parameters with the given variation of the intact rock and joint properties.

2.2.2 *Rock Mass Behavior Types*

After a careful evaluation of the local conditions along the tunnel alignment, Behavior Types were defined using analytical and numerical models.

With analytical models (Feder 1977, 1978, Hoek 1999) the displacements order of magnitude and the depth of failure zone were evaluated, while the numerical models were used to study failure mechanisms (figure 2).

A total of 14 BTs were distinguished. Each BT was described with respect to rock mass condition, stress and groundwater situation, rock mass behavior, and expected deformations. Remarks on excavation method and appropriate support complete the description in table form for each BT. An example is shown in figure 3.

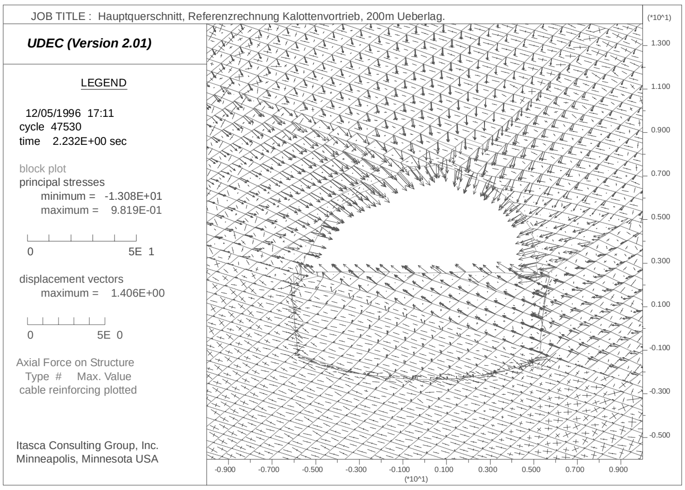
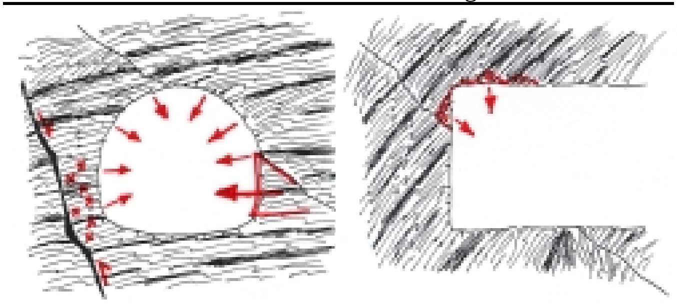


Figure 2. Numerical study of an unlined tunnel in foliated rock (RMT 13). Extensive shearing along foliation (BT 4)

ROCK MASS BEHAVIOR TYPE 3/2	
Rock mass type	RMT 12 and 13 (quartz phyllite)
Main discontinuity orientation	The foliation strikes perpendicular to the tunnel, dip angle 45° - 75°
Stress conditions	Stress redistribution is governed by steeply dipping foliation planes. Stress ratio around 1
Groundwater conditions	Little to no groundwater inflow
Rock mass behavior (excavatability, failure mechanisms)	Highly anisotropic rock mass with relatively uniform deformations. Small block failures controlled by foliation. Shear along foliation planes. Favorable face stability for foliation dipping into the face, potential block slides for foliation dipping into the excavation
Recommended excavation method	Drill and blast, (roadheader)
Support recommendation	Systematic bolting with medium length and density to control and minimize overbreak and stress induced failures. If necessary use ductile support elements within gaps in the shotcrete lining to allow for larger deformations. To avoid excessive overbreak in the crown forepoling may be necessary
Deformation characteristics	Initial deformation rates are relatively high. Radial deformations are expected to stabilize in the range of 15 to 25 cm



Symbolic diagram for quartz phyllite (excavation towards NE)

Figure 3. Description of Behavior Type 3/2 for the Semmering base tunnel

With the numerical models different support types were tested for each BT in order to optimize the support effectiveness.

3 PROCEDURE DURING CONSTRUCTION

Although the rock mass characteristics during the design may be well described, to achieve an optimal technical and economical result the final excavation and support "fine-tuning" must be performed during construction.

Additional data including the results from geological face mapping, monitoring, and observations made during the excavation are available. For most cases the support will be in place, therefore only the System Behavior (SB) is observed. The determination of the support and excavation method during construction is based on continually updating the geologic model by extrapolating observed data.

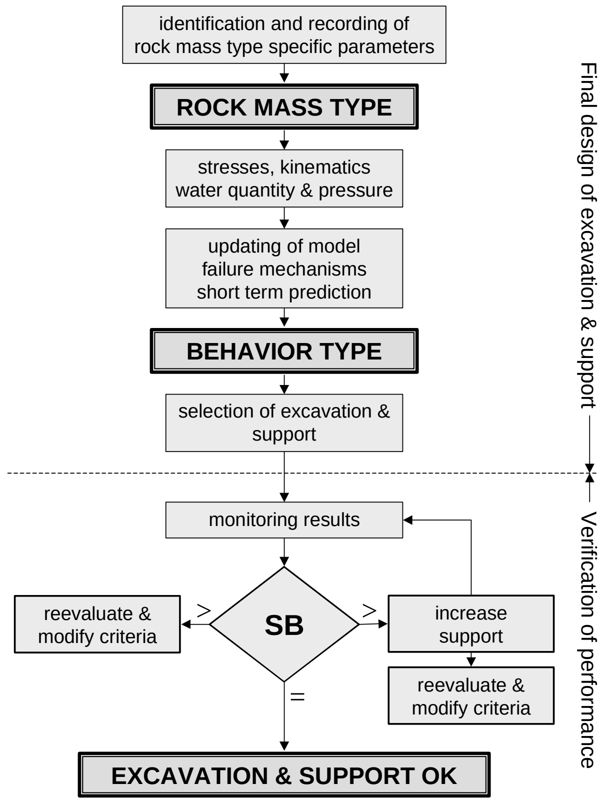


Figure 4. Flow chart of basic procedure for excavation and support selection and verification during construction

3.1 *Determination of Rock Mass and Behavior Types*

For the expected Rock Mass Types relevant key parameters are defined during design that are easily obtained at the face. More advanced analyses may be performed using digital face mapping and analyses (Gaich et al. 1999, 2001)

Face logging concentrates on collecting relevant geotechnical parameters and on assessing the rock mass structure. Due to heterogeneity, the face has to be divided into homogeneous regions. For each region the key parameters and the subsequent Rock Mass Type have to be determined.

The rock mass Behavior Type is determined by assessing potential failure mechanisms using the influencing factors, the updated geologic model, observations made during the excavation, and monitoring results (Schubert & Budil 1995, Steindorfer 1998, Golser et al. 2000).

3.2 *Final Excavation and Support Class Selection*

Once the Behavior Type is predicted the appropriate excavation and support class is selected from the design options. Monitoring results and short-term predictions ahead of the face are used to "fine tune" the support layout to the encountered geotechnical situation.

For this process numerical simulations, including back- and forward-analyses, and/or kinematic analysis may be used to support the decision.

3.3 *Observation of System Behavior*

To evaluate the suitability of the selected excavation method and the installed support the system behavior must be quantified by observations and measurements. This process includes advanced evaluation of displacement monitoring, determining the utilization of the support, and measuring overbreak volumes (Steindorfer 1998, Sellner 2000, Rokahr & Zachow 1997, Hellmich et al. 1999)

Next, the observed and predicted system behaviors are compared. If the observed behavior deviates from the predicted behavior reevaluations are required. The reevaluation involves reviewing the complete decision process, focussing on the observed deformations, Rock Mass Type - Behavior Type determination, and the support utilization.

If the rock mass stabilization process does not meet the requirements support may be reinforced, and/or the subsequent excavation sequence modified (bench heading, temporary or final invert, etc.). If displacements and support utilization are less than the expected range, the information is incorporated into the evaluation of the System Behavior predictions. With this procedure a continuous learning process is incorporated into the design.

It has shown that plotting the observed vs. predicted BT and SB for each successive round is very helpful. This is done to account for the heterogeneity along the alignment. Support will not be changed every round, but only if the behavior change is expected to last over several rounds.

3.4 *Case study - Blisadona tunnel*

This process of support and excavation determination during construction was first applied at the Blisadona railway tunnel in western Austria. The overburden reaches several hundred meters. Limestone, dolomite, marl and shale prevail along the alignment. Fault zones consisting of coarse grained cataclasite frequently intersect the alignment.

area	lithology	bedding thickn. a	b	c	deg. of fract. low	med.	high	apert. +/-	R. M. Type
A	MS		X			X		+	9
B	LD	X				X		+	2
C	LD	X				X		+	2
D	LD		X			X		+	3

area	interlocked yes	no	water inflow no	< 5	> 5	Behav. Type local
A		X	X			4
B	X		X			2
C		X	X			3
D		X	X			4

dominating regions: A,C

Displacement category (cm)

<5   5-10   >10

Behavior Type 2
rock mass with potential for systematical
and voluminous overbreak,
no stress induced failures

Support & Excavation Concept
round length: 1.3 m
support type: ST 3

Figure 5. Application example of the procedure for determination of excavation and support at the Blisadona tunnel

In some of the fault zones considerable water inflow under high pressure was encountered. Observed rock mass behavior was characterized by gravity and water pressure induced overbreak.

The Rock Mass Types were determined for homogeneous regions in the face. The key parameters included the rock type, bedding thickness, degree of fracturing, and discontinuity aperture.

Observations during excavation and scaling, like block interlocking, water inflow rate, and joint water pressure were additionally used to determine the local Behavior Type for each homogeneous region.

The on-site geotechnical engineer determined the representative Behavior Type for the section. Parameters used included the local behavior types, the updated geo-logic model, the potential failure mechanisms and the monitoring results from previous rounds as well as from comparable rock mass conditions.

Based on the Behavior Type the predetermined excavation and support concepts were implemented. Performance was routinely verified by displacement monitoring. Figure 5 shows an example of the application using a standardized form including the face map, parameter log and displacement category.

The method allowed for the successful construction of the tunnel. The decision making process was documented transparently and consistently. The geotechnical team on site was trained to apply a systematic and unbiased observation process to determine the relevant geotechnical parameters and continuously analyze the rock mass behavior.

4 CONCLUSION

We have outlined a method to determine support and excavation sequence for the design and construction of tunnels. Instead of support decisions based on standardized rock mass classification systems this project tailored procedure incorporates the observation of the rock mass behavior and the rock mass-support interaction in a transparent and consistent way. Experience gained with this procedure is incorporated in the data base system DEST eventually leading to an Expert System.

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