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Consistent Excavation and Support Determination for the Design and Construction of Tunnels

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ABSTRACT: Currently excavation and support determination in tunneling is mainly based on experience, supplemented by simplified models and calculations. 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.

Parallel to the recent updating of the Austrian standard ÖNORM B 2203-1 a consistent procedure for the determination of excavation and support was developed. Guidelines describing this procedure have been produced in a small working group of the Austrian Society of Geomechanics. The outlined step by step procedure promotes an engineering approach to the 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 previous experience (including data base knowledge) and numerical simulations. During construction geological face mapping, geotechnical monitoring, and observations allow the support and excavation methods to be completed. 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 re-evaluation 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.

KURZFASSUNG: Die Festlegung von Ausbruch und Stützung im Tunnelbau erfolgt in vielen Fällen rein empirisch. In manchen Fällen wird die Entscheidung durch Berechnungen an stark vereinfachten Modellen unterstützt. Eine einheitliche Vorgangsweise bei der Bestimmung von Ausbruch und Stützung fehlt weitgehend. Dies erschwert die Überprüfung von Planungen, das strukturierte Sammeln und Auswerten von Daten sowie das Vergleichen von Daten verschiedener Baustellen.

Im Zuge der kürzlich erfolgten Überarbeitung der Werkvertragsnorm ÖNORM B 2203-1 wurde beschlossen, begleitend zur Norm eine Richtlinie für die Vorgangsweise zur Festlegung von Ausbruch und Stützung im Untertagebau auszuarbeiten. Die Richtlinie wurde in einer kleinen Arbeitsgruppe der Österreichischen Gesellschaft für Geomechanik erstellt und wird von dieser herausgegeben. Der in der Richtlinie skizzierte schrittweise Vorgang soll einen ingenieurmäßigen Zugang zur Thematik fördern.

In der Planungsphase basieren die Vortriebs- und Ausbaukonzepte auf Gebirgsverhaltenstypen, welche wiederum aus den Gebirgsarten und den das Verhalten beeinflussenden Faktoren abgeleitet werden. Das Systemverhalten beschreibt das Verhalten des Systems Ausbau und Gebirge. Die Ermittlung des Systemverhaltens stützt sich auf Datenauswertung ausgeführter Projekte und wird durch numerische Simulationen an geeigneten Modellen unterstützt. Während des Baues wird die Planung mit Hilfe von geologischen Aufnahmen, Beobachtungen und Auswertung von Messungen verfeinert. Das vorhergesagte und beobachtete Verhalten wird laufend verglichen. Treten Abweichungen zwischen prognostiziertem und beobachtetem Verhalten auf, ermöglicht die systematische Vorgangsweise eine umfassende Analyse. Damit wird eine ständige Weiterentwicklung des Tunnelbaues ermöglicht und gefördert.

1 INTRODUCTION

A sound and economical tunnel design depends on a quality rock mass characterization and the assessment of influencing factors such as primary stresses, groundwater and kinematics. Despite this coherent 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 and poor ground conditions where limited information is available in the pre- construction phase.

On the other hand the quantitative rock mass classification systems presently in use (1, 2, 3, 4) 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 for the ground-support interaction (5). 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.

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. A procedure was developed that allows an objective and unbiased decision making process during construction.

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 lithological descriptions and physical as well as hydraulic parameters obtained by 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 the definition of 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 (6, 7), support the determination of Rock Mass Types. Systematic evaluation of those data allows one to identify key parameters for each Rock Mass Type (8).

Procedures to arrive at rock mass parameters may include the GSI concept (9) or numerical simulations of a representative rock mass volume (10, 11).

Fig 1 Flow chart of basic procedure of excavation and support design for tunnels
Bild 1 Flußdiagramm der grundsätzlichen Vorangsweise zur geotechnischen Planung von Ausbruch und Stützung von Untertagebauten

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 of the unsupported tunnel 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 a number of rock mass types when combined with different system factors. 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.

Table 1 Basic Rock Mass Behavior Types
Tabelle 1 Übergeordnete Kategorien von Gebirgsverhaltenstypen

3. Excavation and support design

3.1 Design requirements

Prior to the design of the excavation and support the design requirements have to be established. Parameters have to be identified, which influence 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.

3.2 System Behavior

The next step 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.

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.

Numerical simulation methods are increasingly 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.

3.3 Case study - Semmering base tunnel

This 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 (12) and (13).

3.3.1 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.

To evaluate rock mass parameters estimated GSI values were used together with back analyses of the pilot tunnels monitoring results. The point estimate method (14) was used to obtain the distribution of the rock mass parameters with the given variation of the intact rock and joint properties.

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

Tabelle 2 Beispiel für die Angaben zu zwei Gebirgsarten beim Semmeringbasistunnel (μ = Mittelwert, $\sigma =$ Standardabweichung)

3.3.2 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 (15, 16,17,18) 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).

Figure 2 Numerical study of an unlined tunnel in foliated rock (RMT 13)
Bild 2 Numerische Analyse des ungestützten Tunnels in geschiefertem Gebirge

A total of 14 Behavior Types (BT) 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. With the numerical models different support types were tested for each BT in order to optimize the support effectiveness.

Figure 3 Description of Behavior Type 3/2 for the Semmering base tunnel
Bild 3 Beschreibung des Gebirgsverhaltenstyps 3/2 beim Semmering Basistunnel

4 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. It has to be kept in mind, that the determination of the support and excavation method during construction is based on continually updating the geologic model by extrapolating observed data to the rock mass ahead of the face. Monitoring results and short-term predictions ahead of the face are used to improve the geotechnical model (19, 20, 21). The basic procedure during construction is shown in figure 4.

Figure 4 Flow chart of basic procedure for excavation and support selection and verification of the System Behavior during construction
Bild 4 Flußdiagramm der grundsätzlichen Vorgangsweise bei der Festlegung von Ausbruch und Stützung und Überprüfung des Systemverhaltens während des Baues

4.1 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 (22, 23).

Face logging focuses on collecting relevant geotechnical parameters and on assessing the rock mass structure. The key parameters are recorded for each individual Rock Mass Type. In case of heterogeneous conditions, the face has to be divided into homogeneous regions and the local Behavior Types determined.

The dominating rock mass Behavior Type is determined by analyzing the interaction between the local Behavior Types and the influencing factors.

4.2 Final Excavation and Support Class Selection

Once the Behavior Type is predicted the appropriate excavation and support class is selected from the design options. To "fine tune" the support layout numerical simulations, including back- and forward-analyses, kinematic analyses, and/or previous observations of the system behavior in comparable conditions may be used.

4.3 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 (20, 24, 25,26)

Next, the observed and predicted system behaviors are compared. If the observed behavior deviates from the predicted behavior re-evaluations are required. The re-evaluation involves reviewing the complete decision process, focusing 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, the 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 versus 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.

4.4 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 is up to several hundred meters. Limestone, dolomite, marl and shale prevail along the alignment. Fault zones consisting of coarse grained cataclasite frequently intersect the alignment.

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 geologic 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.

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

Bild 5 Anwendungsbeispiel während der Ausführung am Blisadonatunnel

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.

5 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.

There are several goals that we hope will be reached by application of this procedure:

- Optimize exploratory investigation programs by concentrating on the collection of rock mass and project specific key parameters
- Consistent designs meeting project specific requirements
- Optimize construction by providing clear procedures to support the decisions on site
- Documentation of the decision process
- Promote technical advances in tunneling by evaluating comparable data from various sites

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