Basics and Application of the Austrian Guideline for the Geomechanical Design of Underground Structures

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ABSTRACT: Currently excavation and support determination for underground projects 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 the step-by-step procedure outlined in the Guideline for Geomechanical Design of Underground Structures (OeGG, 2001) is briefly introduced and its application shown. The guideline does not prescribe certain techniques for design, but rather describes the single tasks to be performed during design and their appropriate sequence, promoting an engineering approach. The techniques applied should be appropriate to the project, the phase of the project, the rock mass types expected, and the boundary conditions. After some three years of effectiveness of the guideline a review seems to be appropriate if the targets set out have been reached, and where the problems in the application showed.

1 INTRODUCTION

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 (Bieniawski, 1974, 1989, Barton et al., 1974, Barton, 1998). Additionally, the on site decisions on excavation and support modifications are frequently based more on intuition than on analyses.

To overcome the shortcomings of the current practice during design and construction, a guideline for the geomechanical design of underground openings was developed and published by the Austrian Society of Geomechanics (OeGG, 2001). The concept recently was extended to risk analyses, considering the uncertainty in the geological model and the natural spread of geotechnical parameters (Goricki, 2003).

In the following the basic procedure during design and construction will be briefly outlined and some points, which occasionally lead to misunderstandings are discussed in more detail.

2 PROCEDURE DURING DESIGN

The basic procedure consists 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).
The five steps to be followed are outlined below.

2.1 *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 selection of parameters used should focus on such parameters, which are expected to dominate the behaviour of the rock mass and have a significant influence on the construction method, time and costs (Liu et al., 2001). A Rock Mass Type is a group of rock masses having similar physical and/or hydraulic parameters. Not necessarily each lithological unit leads to a separate Rock Mass Type, if the properties of different units are the same within acceptable limits. In general also alternating layers of different rock types are grouped in one RMT. The number of Rock Mass Types elaborated depends on the project specific geological conditions and on the stage of the design process.

Special care has to be taken when evaluating rock mass parameters. With empirical relationships, which frequently are based on ratings, completely unrealistic results for the rock mass strength and deformability are obtained under certain circumstances. A check on the plausibility of the results is thus advisable.

2.2 *Step 2 – Determination of Rock Mass Behavior*

The second step involves evaluating the potential rock mass response to tunnel excavation considering Rock Mass Type and local influencing factors, including the relative orientation of relevant discontinuities to the excavation, ground water conditions, stress situation, etc. This process results in the definition of project specific Rock Mass Behaviours. Rock Mass Behaviour in this context is defined as the reaction of the rock mass to the excavation of the underground opening without consideration of sequential excavation steps and support.

One starts with dividing the alignment into geotechnical units or sections, which exhibit same rock mass types, influencing factors and boundary conditions. The rock mass response to the excavation is then analysed in each section. The knowledge of the rock mass behaviour without the influence of construction measures is an important basis for the design of appropriate excavation and support methods.

The sophistication of analysis methods depends on the stage of the project and the complexity of the expected rock mass behaviour. In early project stages and for rather homogeneous rock mass conditions, closed form solutions (Feder, 1978, Hoek, 1999) will be sufficient, while for the detail design or strongly anisoptropic materials appropriate numerical methods will have to be used. Systematically each section is checked against all possible failure modes. This in general requires applying different methods of analysis. For example jointed rock masses will show a tendency to severe overbreak up to chimney type failure in a low stress environment. The same rock mass may be perfectly stable under medium stress, while other failure modes, like spalling or shearing will have to be expected under high stresses.

Each characteristic behaviour identified is described with respect to applicable Rock Mass Types, ground water conditions, failure mode or combined failure modes, and quality and quantity of displacements. In the Guideline eleven basic categories of Behaviour Types are listed. For the ease of communication, the behaviours evaluated should be assigned to one of the basic categories. Distinct delimiting criteria for each Behaviour Type evaluated have to be used. For example the volume of overbreak may serve as criterion for distinguishing between different behaviours within the basic category “discontinuity controlled overbreak”. The depth of expected failure zone may serve as a criterion to distinguish between the category “shallow stress induced failures” and “deep seated stress induced failures". The delimiting criteria have to be shown in the geotechnical report. It is quite obvious, that combinations of failure modes can occur, for example overbreak combined with swelling, or shear failure combined with overbreak.

2.3 *Step 3 – Determination of excavation and support and evaluation of System Behaviour*

Based on the defined project specific Behaviour Types, different excavation and support measures are evaluated and acceptable methods 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 within one project. A shallow tunnel in weak ground may serve as example. When built in open space, surface settlements will be a minor issue and the excavation and support can be optimised with respect to construction costs. In built up areas the excavation and support methods have to be designed to limit surface settlements. Methods of excavation and support and costs will be quite different in both cases.

Regulations with respect to safety factors, loads to be assumed, life cycle of primary support, etc. vary strongly in different countries. This also must lead to different designs for the same rock mass behaviour in different environments.

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.

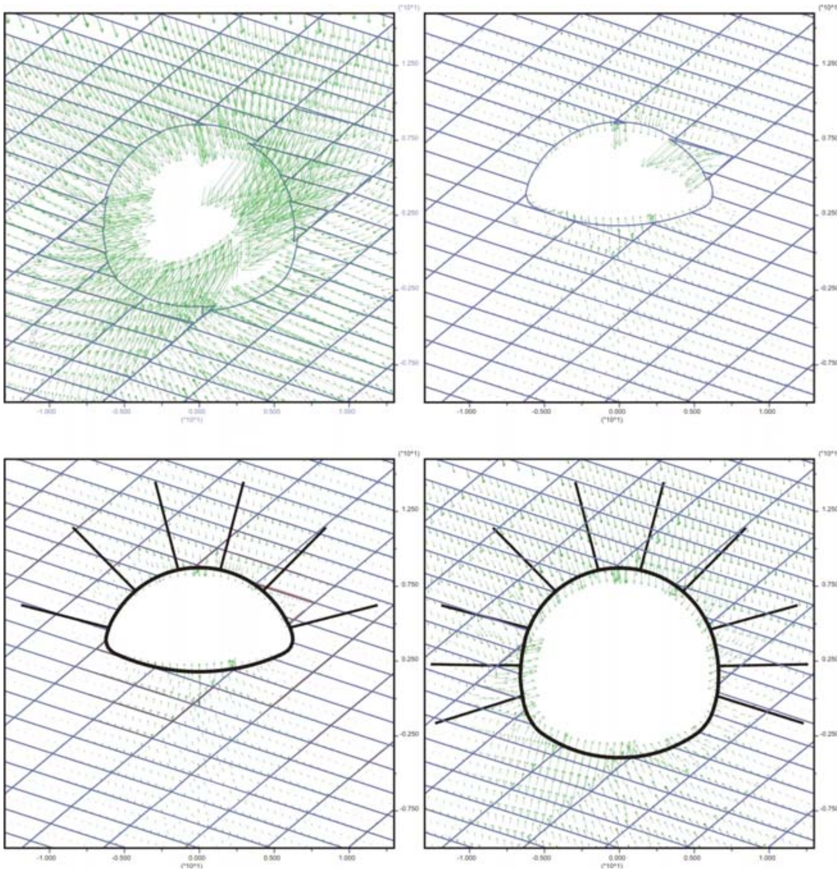

Figure 1. Result of a numerical simulation to determine the Rock Mass Behaviour (upper left), the System Behaviour after dividing the face into two sequential excavtion steps (upper right), the System Behaviour after installation of support in the top heading (lower left), and the System Behaviour after excavation of bench and installation of support (lower right)

2.4 *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 for the case when acceptable limits of behaviour are exceeded.

2.5 *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 excavation classes along the alignment of the underground structure provides the basis for establishing the bill of quantities and the bid price during tender.

3 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. The procedure during construction basically is similar to that during design. Important tasks during construction are the continuous updating of the model, short term prediction of ground conditions ahead, selection of appropriate excavation and support methods, prediction of System Behaviour and the control of the System Behaviour.

3.1 *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 key parameters. 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 behavior). Up to date methods of data collection (Gaich et al., 2001) and evaluation support the continued geological modeling. Criteria defined during the design phase are used to identify the Rock Mass Type at hand. Basically the same criteria for distinguishing the Rock Mass Types are used on site, as they were used during design. It may be advisable to subdivide the previously defined types, as more information is obtained during construction.

3.2 *Step 2 – Determination of the actual Rock Mass Behavior Type*

It is obvious that the rock mass behaviour as defined in the design stage (unsupported and excavation in full pofile) cannot be observed during construction, but the System Behaviour. Both excavation and support, to a major extent, have to be determined prior to the excavation. After the excavation only minor modifications are possible. This fact stresses the importance of a continuous short-term prediction and identification of potential behaviours. To assign the appropriate excavation and support it is necessary to determine the Behaviour Type on the basis of the identified Rock Mass Type and the influencing factors, like stresses, ground water conditions, and orientation of the relevant discontinuities, using the criteria specified during design. 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 and support the determination of the Behaviour Type. Advanced methods of displacement monitoring data evaluation (Steindorfer, 1998, Schubert et al., 2004) should be used to improve the quality of the short term-prediction of the geotechnical conditions ahead of the face. Once the ground model is established and the influencing factors determined, the actual Behaviour Type expected on the next rounds can be derived on the basis of the design.

3.3 *Step 3 – Determination of excavation and support*

Excavation and support layout are chosen in a way to prevent failure and guarantee stability in all construction phases. In many cases more than one method is available to achieve this goal. Then preferably the method is chosen, which provides the economical optimum at an acceptable safety level.

As an example a tunnel in weak rock with high overburden may serve. In order to keep the strains of the lining within acceptable limits, heavy supports and reinforcement by a dense rock bolting might be feasible. Another solution for the same conditions is to use a ductile support system (Moritz 1999, Schubert et al., 2000), allowing for more deformation of the rock mass without of the danger of lining failure. Which solution eventually is applied, depends on the technical feasibility and economical impact.

Based on the evaluated Behaviour Type, and the excavation and support layout determined, the System Behaviour for each section has to be predicted (Sellner, 2000). Analyses performed during design and experience from similar situations can be used on site. For conditions not considered in the design, additional analyses will be required.

3.4 *Step 4 – Verification of System Behavior*

By monitoring the behaviour of the excavated and supported section, the actual System Behaviour is compared to the predicted one. It is advisable to use monitoring data evaluation software, which allows a continuous comparison, even if the progress is other than anticipated (Sellner et al., 2002). The reason for deviations of the actual System Behaviour from the predicted one can have its roots in unexpected geological features, a misjudgement of the Rock Mass Type or simply in a not appropriate assignment of excavation and support methods to the behaviour. In all cases a thorough review of the situation is required. Lessons learned from the continuous geotechnical evaluation improve the accuracy of the decision making process, thus reducing risks and costs.

An integral part of the verification of the System Behaviour is the observation of warning criteria and alarm levels. In case of less favourable System Behaviour than predicted improvement measures (like increase of support) may be necessary. To prevent escalation of unfavourable situations, an appropriate site organization and safety management concept are required to allow for quick and competent decisions.

4 EXPERIENCE WITH THE APPLICATION

In the past three years after the guideline became effective, several projects have been designed following the ideas outlined there. Generally the procedure was well accepted, contributing to a more transparent design of underground structures. Problems encountered mainly were associated with the difficulty to break with old habits. In the past the term "Rock Mass Behaviour" was poorly defined, not explicitly separating rock mass behaviour and the influence of excavation and support on the system's behaviour. This resulted in different "rock mass behaviours" for different excavation and support methods. It is hoped that this confusion is eliminated with the clear definition of the term "Rock Mass Behaviour" and the introduction of the term "System Behaviour", describing the behaviour of the system under the influence of excavation and support measures, as well as auxiliary measures like ground water lowering, ground improvement etc..

The requirement of the guideline to coherently document each step has also demonstrated the deficits in the determination of rock mass characteristics and methods of analysis. Current methods of determination of rock mass properties in some cases yield unrealistic results, and not always the methods used for analysis are adequate to capture the characteristic behaviour of the rock mass.

The experience with the on site application presently is not sufficient to be able to report on it. It can be expected that the engineering approach will benefit the projects.

5 CONCLUSION

Instead of support decisions being based on standardized rock mass classification systems the procedure outlined incorporates the evaluation 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 and audible 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. The documentation of the decision making process will also support further advances in tunnel engineering, as results from different sites and different conditions can be compared objectively.

Despite some minor problems in the phase of implementation the procedure has been well accepted and it is hoped that engineering in underground construction regains its important role.

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