QUANTIFICATION OF THE GEOTECHNICAL AND ECONOMIC RISK IN TUNNELING

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ABSTRACT

This paper discusses a consistent procedure to quantify geological, geotechnical and economic risk in tunneling. For an underground excavation a sound rock mass model and a systematic and quantitative rock mass characterization has to be developed. After defining key parameters, Rock Mass Types are determined and combined with influencing factors to obtain the behavior of the rock mass after excavation. A support and excavation concept is assigned to each Behavior Type, which allows an estimate of time requirement and costs. The probabilistic processing of distributed input data allows the determination of probability distributions for time and costs of a tunnel excavation based on the geotechnical risk and the variation of time and costs of different Excavation Classes.

INTRODUCTION

Many decisions during the design and the construction of a tunnel are based on a geological model and the geological and geotechnical parameters (Dudt & Descoeudres (1)). Throughout the development of a tunnel project the quantity and quality of the available data changes as well as the influence of different parameters. Additionally various kinds of data like observed, calculated, or estimated data have to be processed.

A key element in the development of a tunnel project is the knowledge of the costs (Vavrovsky (2)). To quantify a realistic range of time and costs in each stage of the design it is necessary to use distributions instead of singular deterministic values. Only a continuous probabilistic collection and processing of geological and geotechnical data allows a realistic determination of the distribution of time and costs in each design stage. This process includes geological modeling as well as rock mass characterization, the tunnel design, and the assignment of time and costs. The geotechnical risk can be evaluated based on the variation and the probability of the geological and geotechnical data.

PROCEDURE

A consistent procedure has been developed to perform a probabilistic risk assessment for a underground excavation. Figure 1 shows a flow chart developed for this procedure which consists of three major elements: the definition and determination of geological and geotechnical parameters, the determination of the rock mass behavior and assignment of time and costs to the different Behavior Types. This procedure conforms to the Austrian guideline for the geomechanical design for conventional tunneling. This guideline has been published by the ÖGG (3) in combination with the Austrian standard ON B2203-1 (4) and describes a consistent method for the excavation and support determination for the design and construction of tunnels (Schubert et al (5)).
The first step is to characterize and quantify the rock mass and its parameters. The reliability of the geological prediction depends on the investigation strategy, the quality and quantity of the subsurface investigation and has a significant influence on all further evaluations. A longitudinal profile along the alignment has to be derived from the developed three-dimensional geologic model. Geotechnically homogeneous units based on the expected geology, the geological architecture and the groundwater situation have to be carefully determined. Key parameters obtained from field investigation and laboratory tests are defined to characterize the rock mass (Riedmüller & Schubert (6), Steidl et al (7)).

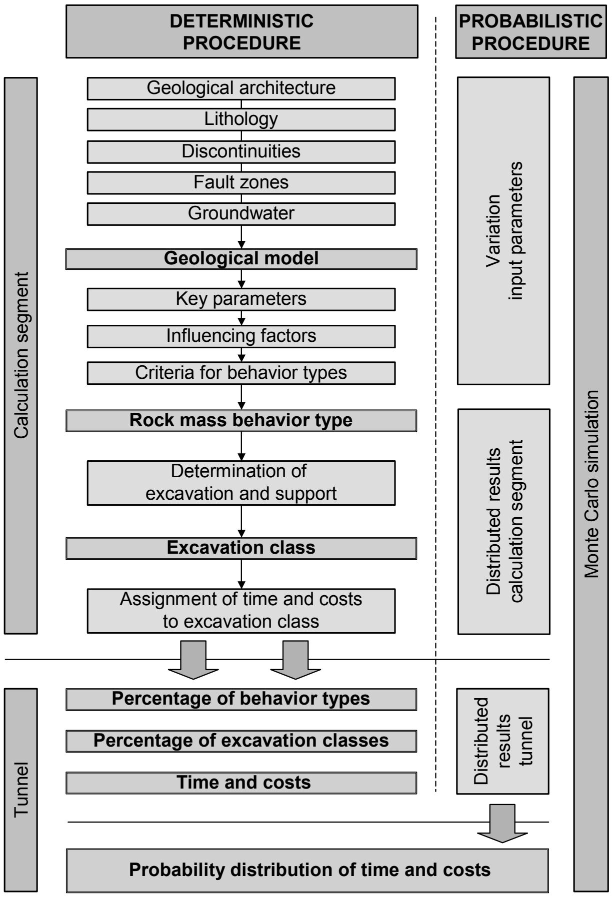

Figure 1 Procedure for the determination of the geotechnical risk

By combining this data 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 the behavior of the rock mass around the unsupported excavation can be determined. Corresponding to the various rock mass properties and the actual system factors different analytical models can be used to evaluate the rock mass behavior. After defining delimiting criteria Behavior Types can be assigned to the eleven categories of basic Behavior Types distinguished in the guideline (3) or sub Behavior Types defined.

The next step after establishing project specific requirements - such as the allowable surface settlement magnitudes for shallow tunnels in urban areas or the allowable load in the lining for deep tunnels - is the design of the excavation and support. Different methods can be used to determine the rock mass-support interaction that has to correspond to the required project goals. With the predicted round length and the support the support classes can be calculated for each Behavior Type.

In the Austrian standard ON B2203-1, which deals with contractual matters, an excavation is divided into different Excavation Classes. An Excavation Class is defined by a range of round length (e.g. 1.3 - 1.7m) and the required support.

For each Excavation Class the costs for one excavation cycle have to be determined. Parameters, such as drilling time, time for mucking etc. and the exact length of one round are assigned and the excavation-time is calculated.

The whole process, as described above, can be split into two parts of discrete analytical modeling. The first part is the calculation of homogenous segments along the tunnel alignment, the calculation segments. In the second part all data and results are calculated for the entire length of the tunnel.

By using a Monte Carlo simulation during the complete analytical process the distribution of input parameters can be considered. This leads to probabilistic results such as the probability of the distribution of Behavior Types along the tunnel alignment or the probability distribution of time and costs of the whole tunnel. With this method of data processing the risk for varying geological and geotechnical conditions can be quantified and evaluated.

QUANTIFICATION OF GEOLOGICAL PARAMETERS

A sound geological model together with carefully investigated and reasonably selected key rock mass parameters build the basis for all further probabilistic investigations. Based on the evaluation of the results from geological site investigations, which may consist of core logs, laboratory and in-situ test results, geological maps, outcrop studies, project specific Rock Mass Types (RMT) are defined by selecting and quantifying relevant geological key parameters.

In addition to the lithological discrimination between rock types, significant differences within a certain rock type e.g. bedding plane spacing, joint frequency, matrix characteristics and the uniaxial compressive strength are used to establish Rock Mass Types. These Rock Mass Types cover all relevant engineering geological characteristics known at that stage of the design phase.

The key parameters can be described either by using singular deterministic values or, better, by frequency distributions. For example, the spacing of discontinuities can be obtained by applying scanline- or window mapping techniques on selected outcrops or along rock cores (Priest (8)). Also the results of laboratory tests, which are usually performed in great numbers on rock core samples to evaluate mechanical and mineralogical properties, can be presented by frequency

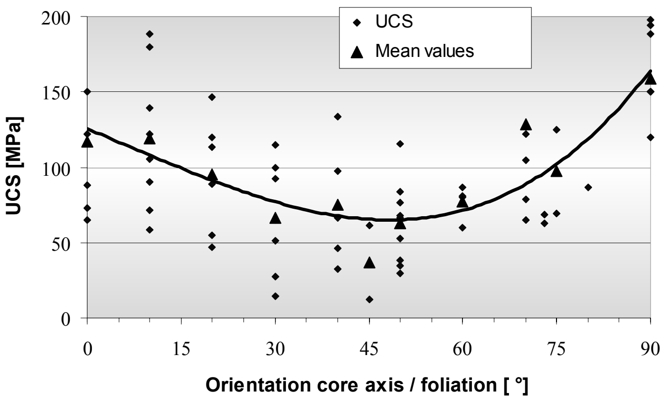

Figure 2 Evaluation of laboratory test results

distribution. When a sufficient, large number of data can not be obtained, the parameter distribution can be estimated by using statistical methods (Thurner (9)).
Geological singularities such as faults, lithologic boundaries, and aquifers, have a significant influence on tunnel projects. The most suitable aid to handle the uncertainties in prediction are probabilistic distributions. For example, the thickness distributions of fault zones for each geotechnical unit can be determined from the result of core logging and the evaluation of optical scanner measurements. In addition, the density of fault zones can be derived from detailed engineering geological maps or spatial geological models by applying scanline techniques.

QUANTIFICATION OF ROCK MASS BEHAVIOR TYPES

An important element in the quantitative rock mass characterization is the classification of Rock Mass Types into Rock Mass Behavior Types. These Behavior Types are defined as the potential failure modes of the unsupported tunnel, such as gravity controlled sliding of blocks, or shear failures in the rock mass. In this procedure analytical methods to determine the rock mass behavior are used. To improve the accuracy of the results the analytical model can be adjusted to the results of numerical calculations or the experience gained from previous projects under similar conditions. The advantage of analytical models is the possibility to use simple statistical methods such as Monte Carlo simulation (Schneider (10)).
The main influencing factors for the determination of the Rock Mass Behavior Types besides the Rock Mass Type are the 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. According to their appearance in nature these input parameters have to be computed as deterministic values or probabilistic parameters with various distributions.
The tunnel alignment is divided into segments with homogeneous geotechnical properties and the input parameters are assigned to these units. Due to the rock mass properties and the predominant influencing factors different analytical methods can be used (Hoek (11), (12), Feder (13), Goodman & Shi (14), etc.). Independent of the selected method the result of the calculation has to be a rock mass behavior. Delimiting criteria are established to delimit the different calculated failure modes. With help of the defined criteria, the obtained rock mass behavior of the particular calculation segments can be classified into the predefined eleven basic Behavior Type categories as specified in the Austrian guideline (3).
Due to the large number of calculations it is possible to evaluate the influence of the scatter and the uncertainties of the input parameters on the results. By using a

Monte Carlo simulation the probability of occurrence for each Rock Mass Type in every single calculation segment is received as well as the distribution of the percentage of one RMT along the whole tunnel alignment.
Figure 3 shows a detailed flow chart of the described process and a chart, which shows the probability distribution of the calculated Rock Mass Behavior Types by variation of the input parameters within one homogeneous section of a tunnel.

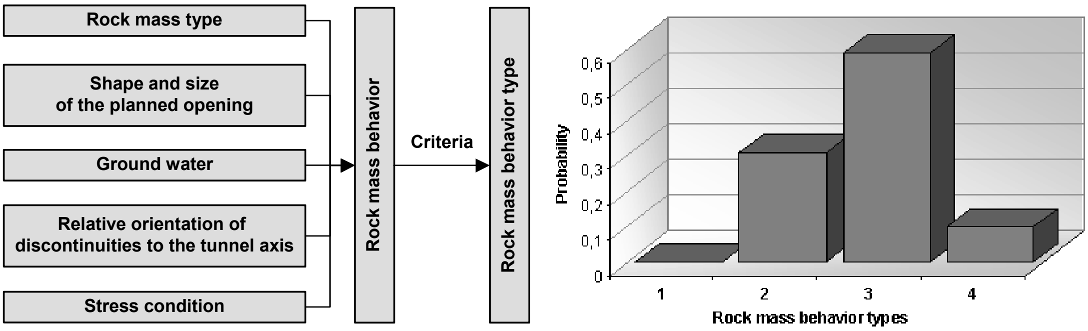

Figure 3 Probability of occurrence of determined Behavior Types for one calculation segment

Based on the RMT the excavation and support concepts can be determined. The detailed process and the implementation of probabilistic concepts (Thurner (9), Pöttler et al (15)) are not discussed in this paper.

COSTS AND COMPENSATION

Because of the compensation-model which is used in the Austrian Standard ON B2203-1 (4) commercial risk in tunneling is allocated to two different spheres – contractor's- and employer's sphere. For the better understanding of the following procedures, this compensation-model is explained.
When creating a bill of quantities, the designer of a tunnel has to link each rock mass Behavior Type to an Excavation Class (EC). Thus, the whole tunnel length is divided into ECs. Every EC is defined by two numbers. The first number specifies the spread of round lengths. The second number is defined by the necessary support such as bolts or shotcrete lining for this EC.
The contractor has to estimate the required time for the excavation and support for one round in each EC. By summing up the estimated time over all ECs the contractor gets a forecasted time schedule for the excavation, which becomes part of the contract.
Compensation of work is split into two parts, the first is time based (tunneling equipment, tunnellers wages, etc.) and the second is based on unit prices (blots [m^1], shotcrete [m^2], etc.)
When, during excavation, the distribution of ECs changes, which is the normal case, the contractual excavation time changes. According to the model of ON B2203-1 the compensation of the time based parts in the bill of quantities in- or de-creases. This shows, that the geological risk – expressed in terms of distributions of ECs With this definition of compensation, the possible differences between the predicted and encountered EC's constitutes a commercial risk for the employer.

The risk of the contractor is the possible variation between estimated and actual performance within one single EC which can be estimated by the most influencing parameters like the drilling-time, or costs incidental to wages, costs for construction equipment and costs for materials (ON B2061 (16)).
To achieve an estimation of the distribution of time and costs for one EC a Monte Carlo simulation is used after assigning reasonable types of distributions and plausible limits to all described parameters (Dudt & Descoeudres (1)).

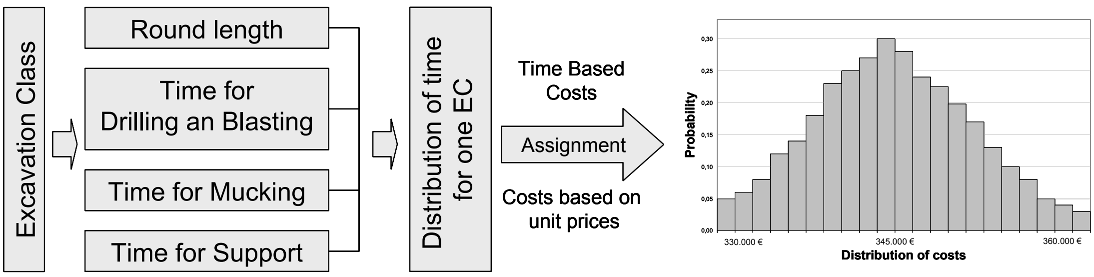

Figure 4 Procedure to determine the distribution of cost and time for one Excavation Class

EXAMPLE

In this example the practical applicability of the discussed procedure including the use of statistical and probabilistical methods is shown briefly.
To define the Rock Mass Types the following key parameter were defined and invested: lithology, foliation/anisotropy, block size, discontinuity parameters such as persistence, surface properties and aperture as well as mechanical intact rock properties like uniaxial compressive strength, cohesion, friction angle or elasticity parameters. The strength characteristics of the rock mass were estimated on the basis of the Geological Strength Index (Hoek & Brown (11)). Figure 5 shows the results of a statistical evaluation of data obtained from one drill core log. The rock mass along the 165,5 m deep drill hole was divided by the degree of weathering and grouped into classes of different fracturing. The diagram shows a changing distribution for weathered and unweathered rock mass and underlines the importance of statistical data evaluation.

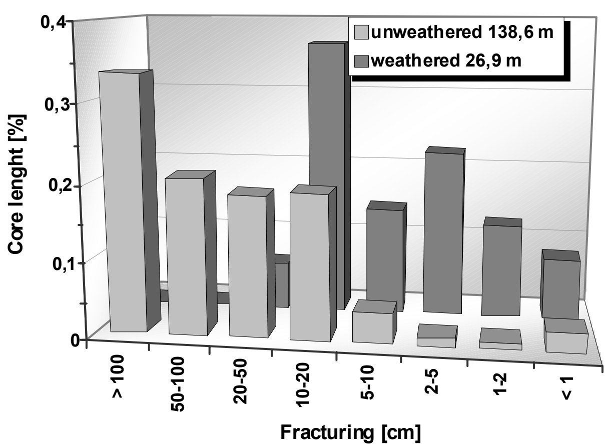

Figure 5 Statistical evaluation of a drill core log

The tunnel alignment was divided into homogenous sections with a length of 20 m, the so-called calculation segments. The assigned Rock Mass Types were then combined with the influencing factors, which are the default tunnel geometry as a deterministic parameter, the

estimated primary stresses as probabilistic parameter with an estimated distribution, or the measured relative orientation of the main discontinuities to the tunnel axis as a natural distributed parameter. An analytical model based on the Geological Strength Index by Hoek (12) was used to calculate the rock mass behavior such as depth of broken zone or radial displacement. Due to the delimiting criteria different Behavior Types were computed for the calculation segments.
The software @RISK (17) was used to realize the Monte Carlo simulation. Figure 6 shows results of the calculation for one calculation segment and the distributed percentage of one Behavior Type along the whole tunnel alignment. With the designed excavation and support, the Excavation Classes were calculated and assigned to the Behavior Types. Time and costs for each Excavation Class were determined probabilistically and combined with distributions of the Excavation Classes along tunnel alignment. This resulted in the probabilistic distribution of costs for the whole tunnel.

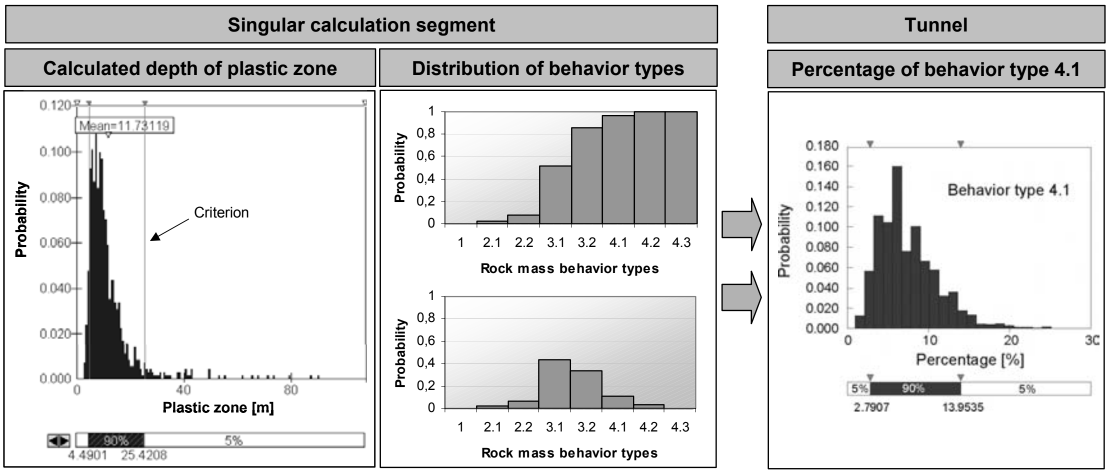

Figure 6 Results of different steps of the calculation

CONCLUSION

In this paper a consistent method for the probabilistic determination of time and costs of tunnels is outlined. The geotechnical and economic risk can be quantified using distributions for input data, a consistent procedure for rock mass characterization as well as excavation and support determination, an assignment of time and costs, and Monte Carlo Simulations. When following this procedure the significant influence of the geological and geotechnical uncertainties can be considered and its sensitivity to time and costs can be assessed.

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