Geotechnical Risk Assessment as the Basis for Cost Estimates in Tunneling

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ABSTRACT:

Geological and geotechnical data are essential for the determination of time and cost of a planned tunnel excavation. A distinct geological model, the selection of relevant parameters and a systematic and quantitative rock mass characterization form the basis for all further probabilistic evaluations. After the definition of key parameters and factors of influence it is important to evaluate the spread of parameters and to quantify the probability of the geological prediction.

To estimate the required excavation and support concepts the rock mass is divided into sections of similar properties. Based on geotechnical key parameters the rock mass is classified into different Rock Mass Types (RMT) and based on the behavior after excavation of the tunnel into different Behavior Types (BT). Different analytical methods are used to determine the rock mass behavior depending on the combination of rock mass parameters. The probabilistic processing of the input data leads to the probability of occurrence and the distributed percentage of the Behavior Types along the tunnel alignment.

The choice of the appropriate excavation- and support method highly depends on the geotechnical properties of the rock mass and its behavior. The probabilistic evaluation allows an evaluation of the applicability and the technical risk of different excavation- and support methods.

By assigning excavation and support classes to the Behavior Types and by evaluating them monetarily it is possible to determine the distributed costs of a tunnel based on the geotechnical risk.

Examples illustrate the procedure of determining the geotechnical risk of tunnel excavations.

Introduction

Many decisions during the design and the construction of a tunnel are based on a geological model and on its geological and geotechnical parameters (1, 2). Throughout the development of a tunnel project the quantity and quality of the available data change as well as the influence of different parameters. Additionally various kinds of data such as 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 (3). 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 collection and probabilistic processing of geological and geotechnical data allows a reasonable 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 - as the range of possible values of tunnel costs and their likelihood of occurrence - can be evaluated based on the variation and the probability of the geological and geotechnical data. Additional to the natural distribution of the values of the single parameters the reliability of the prediction has to be quantified by describing the probability of the geological model.

1. Procedure A consistent procedure has been developed to perform a probabilistic risk assessment for an 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 (4) and describes a consistent method for the excavation and support determination for the design of tunnels (5).

The first step is to characterize and quantify the rock mass and its parameters. Based on results from site investigations a three-dimensional geological model is developed. This model includes the expected lithology, geological architecture, intact rock, discontinuity, and hydraulic properties, fault zones and groundwater situation. Rock Mass Types – rock masses with similar properties - are determined by selecting and quantifying relevant geotechnical key parameters for tunneling from field investigations and laboratory tests (6, 7).

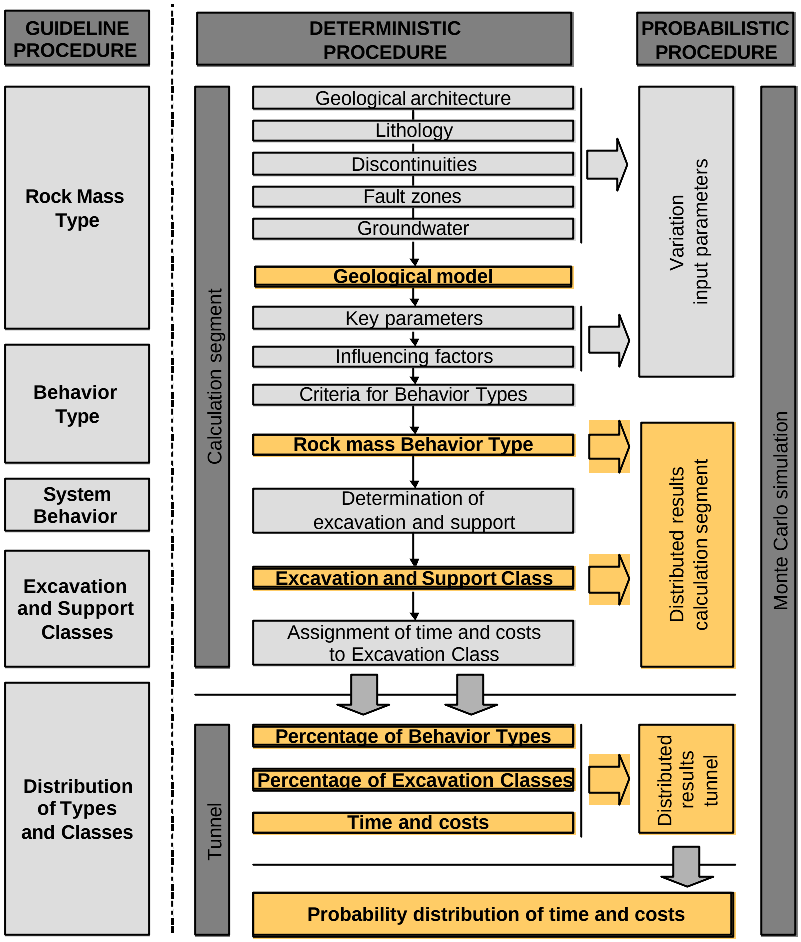

Fig. 1 Procedure for the determination of the geotechnical risk
Bild 1 Ablaufdiagramm zur Ermittlung des geotechnischen Risikos

By combining these 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 (BT) can be assigned to the eleven categories of basic Behavior Types distinguished in the guideline (4) or to newly defined project specific sub Behavior Types.

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

After defining project specific requirements the excavation and support of the tunnel is designed. With the determined and calculated round length and support measures the excavation classes can be calculated for each Behavior Type. By determining and assessing time and costs for each excavation class the costs for the entire tunnel can be calculated.

By using statistical methods 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 - the geotechnical risk of the tunnel (8). With this method of data processing the risk for varying geological and geotechnical conditions can be quantified and evaluated.

2 Geological model and Rock Mass Types

A sound geological model together with carefully investigated and reasonably selected rock mass parameters build the basis for all further probabilistic investigations. Based on the evaluation of the results from geological site investigations, which may be core drillings, laboratory and in-situ tests, detailed geological mapping, outcrop studies and geophysical surveys, a three-dimensional rock mass model is developed and geotechnically homogenous areas are defined.

Geological singularities of this rock mass model such as faults, lithologic boundaries and aquifers have a significant influence on tunnel projects. A very suitable aid to handle the uncertainties in prediction is the use of probabilistic distributions. The necessary data to describe these singularities can be either measured in boreholes, outcrops, aerial and satellite images or estimated. In any case, these results have to be reconsidered after each new investigation campaign.

In addition to the lithologic discrimination between rock types, significant differences within a certain rock type e.g. spacing and frequency of discontinuity sets, matrix characteristics and the uniaxial compressive strength, are used to define project specific 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 (9). 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 statistically (Fig. 2). When a sufficiently large number of data cannot be obtained, the parameter distribution can be estimated by using statistical methods (10).

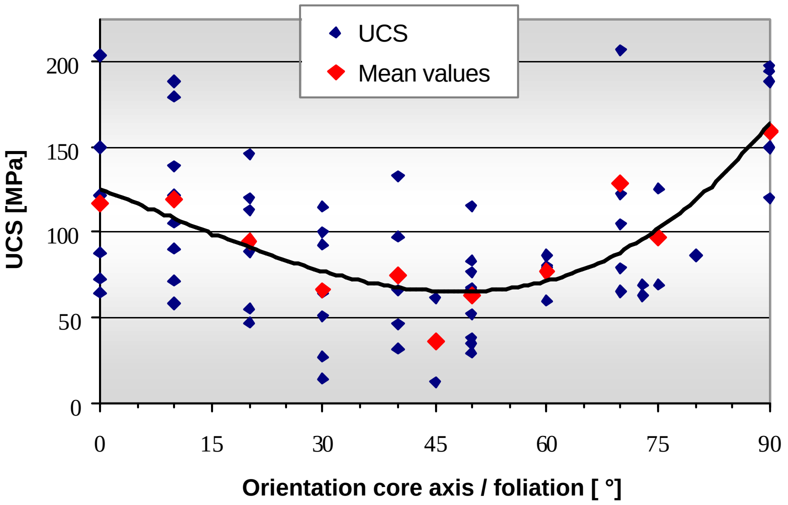

Fig. 2 Statistical data evaluation of laboratory test results
Bild 2 Statistische Datenauswertung von Versuchsergebnissen

3. 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, rock burst, or shear failures in the rock mass. To determine the rock mass behavior analytical methods are used. To improve the accuracy of the results, the analytical model can be adjusted to the results of numerical calculations or to 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 simulations.

The main influencing factors for the determination of the Behavior Types are the Rock Mass Types, the stress conditions, relative orientations of the main discontinuity sets 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. Especially in the early stage of a project parameters with a low reliability can be implemented into the analytical process with wide distributions. The probabilistic data processing gives an idea about the sensitivity of the result to the input parameters and helps to identify the necessity for further specific field and/or laboratory investigations.

Depending on the rock mass properties and the predominant influencing factors different kinds of rock mass behavior are evaluated:

- Displacements, depth of failure and plastic zone
- Volume and depth of overbreak
- Potential for rock burst and/or spalling
- Progressive roof and/or shear failure
- Influence of groundwater
- Swelling
- Time dependence
- Frequently changing deformation characteristics.

Delimiting criteria are established to limit the different calculated failure modes. With these criteria, the obtained rock mass behavior of the particular calculation segments can be classified into the predefined Rock Mass Behavior Types.

4. Probabilistic data processing and results

The tunnel alignment is divided into segments of homogeneous geotechnical properties based on Rock Mass Types or zones of similar influencing factors such as tunnel shape or primary stress conditions. All deterministic and/or probabilistic input parameters, like laboratory data or fault zone thickness are assigned to the segments and the Behavior Types are determined for each of these units using analytical methods as described above.
To evaluate the influence of the scatter and the uncertainties of the input parameters on the results Monte Carlo simulations are used. The Monte Carlo simulation is an analytical technique in which a large number of simulations are run using random quantities for uncertain variables. The result of the simulation is a histogram of the calculated values that can be reduced to a most likely value or a statistical distribution. The method is adaptable, accurate, and very simple to use (11).
Due to the probabilistic input data of the geotechnical properties the rock mass model along the tunnel alignment changes geometrically and/or mechanically in each run of the simulation. This can lead to different Behavior Types in each calculation segment from one run to the other. Due to the large number of calculation cycles it is possible to obtain the probability of occurrence of each Rock Mass Type in every single calculation segment or, by considering the length of the calculation segments, the distribution of the percentage of one ROCK MASS TYPE along one rock mass unit or the entire tunnel alignment.
Fig. 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.

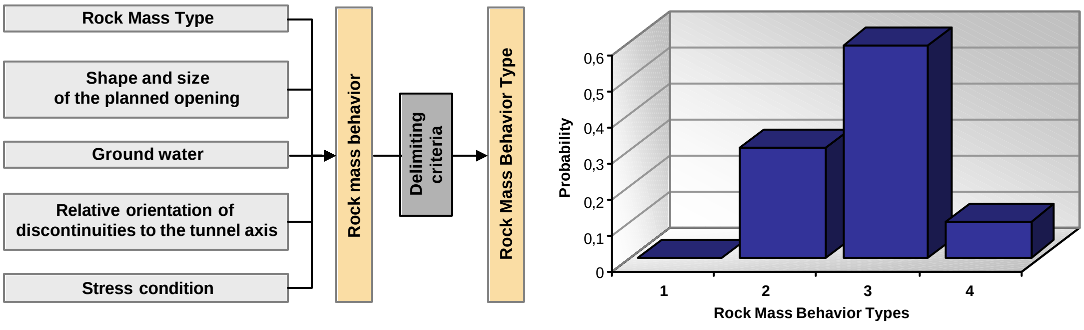

Fig. 3 Probability of occurrence of determined Behavior Types for one calculation segment
Bild 3 Eintrittswahrscheinlichkeit der ermittelten Gebirgsverhaltenstypen in einem Berechnungssegment

Based on the Behavior Type the excavation and support concepts can be determined and time and costs can be assigned. This results in a probabilistic distribution of costs for the entire tunnel. The integration of probabilistic concepts into this process is not discussed in this paper.

5. Application of geotechnical risk determination

In this chapter an example is given to show the practical applicability of the discussed procedure including the use of statistical and probabilistic methods for a tunnel project.

Based on the results of site investigations a spatial rock mass model was developed and the expected lithology, geological architecture, fault zones and ground water situation was characterized. The key parameters of the rock mass model were determined and their values presented by probabilistic distributions. For example, fault zones were described by fault zone frequency and fault zone thickness.

The distributions of fault zone thickness for each geotechnically homogenous area were determined from the results of core logging and the evaluation of optical scanner measurements. The density of major fault zones (thickness greater than 5 meters) was derived from the results of detailed geological mapping by applying scanline and window mapping techniques (Figure 4).

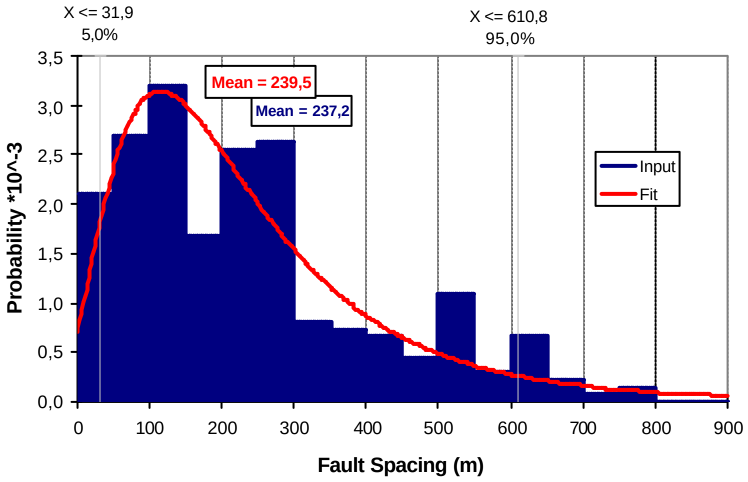

Fig. 4 Distribution of fault zone frequency
Bild 4 Verteilung der Abstände von Störungszonen

The Rock Mass Types were defined by the following key parameters: lithology, anisotropy, block size, weathering and karst phenomena, discontinuity parameters such as spacing, persistence and surface properties as well as mechanical intact rock properties like uniaxial compressive strength, cohesion, friction angle or elasticity parameters (9, 12). The strength characteristics of the rock mass were estimated on the basis of the Geological Strength Index (13).

Fig. 5 shows the results of a statistical evaluation of fracturing and weathering data obtained from rock cores in a 166 m deep borehole. The diagram shows a changing distribution for weathered and unweathered rock mass.

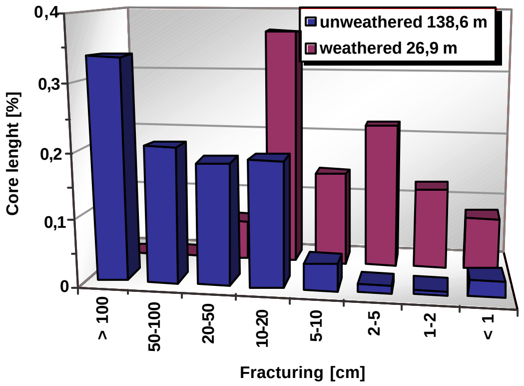

Fig. 5 Statistical evaluation of a drill core log
Bild 5 Statistische Auswertung einer Bohrkernaufnahme

The borders of the lithological units and the fault zones divided the tunnel alignment into homogenous sections, the so-called calculation segments. The values of the key parameters were assigned and the combination of the different parameter values resulted in a Rock Mass Type for each calculation segment. These Rock Mass Types were then combined with the influencing factors, which are the default tunnel geometry as a deterministic parameter, the estimated primary stresses and groundwater inflow as probabilistic parameters with an estimated distribution, and the measured relative orientation of the main discontinuities to the tunnel axis as a naturally distributed parameter.

Based on the different rock mass properties and the occurring combinations of influencing factors different analytical models were used to calculate the rock mass behavior. The deformations of the unlined tunnel and the depth of plastic zones were calculated with models by Feder (14, 15) and Hoek (16). The volume and depth of overbreak for blocky rock masses was determined with the geometrical key block model by Goodman & Shi (17) in combination with joint properties and the influence of the secondary stress regime around the excavation (18, 19). The potential of rock burst was evaluated by investigating the property and characteristics of strain energy accumulation in the rock (20) including the potential energy in elastic strain, the rock brittleness, the stress level and the fracturing of the rock mass. Brittle failure of the rock mass was estimated based on the failure criteria for spalling (21). For other Rock Mass Types the cohesion, the pore water pressure or the percentage of swelling minerals dominates the rock mass behavior.
In sections of heterogeneous ground the influence of the variation of stiff and soft zones was quantified by assessing the stress redistribution and the deformations based on three-dimensional numerical studies (22) and the evaluation of the geotechnically significant zone length, as described by Medley (23).

Delimiting criteria have been defined to classify the calculated rock mass behavior into one of the eleven basic Behavior Types distinguished by the Austrian Guideline (4) and the defined sub Behavior Types, for example a certain value of over break volume is used to differentiate between Behavior Type 1 and Behavior Type 2. Due to these delimiting criteria the different Behavior Types were computed for the calculation segments.

The software @RISK (24) was used to realize the Monte Carlo simulation. Figure 6 shows the calculated depth of plastic zone and the distribution of the project specific defined sub Behavior Types for one calculation segment on the left hand side and the distributed percentage of the Behavior Type 4.1 for the entire tunnel on the right hand side. Fitting them to distribution functions or reducing them to probable ranges of values by truncating the distribution can simplify these result data.

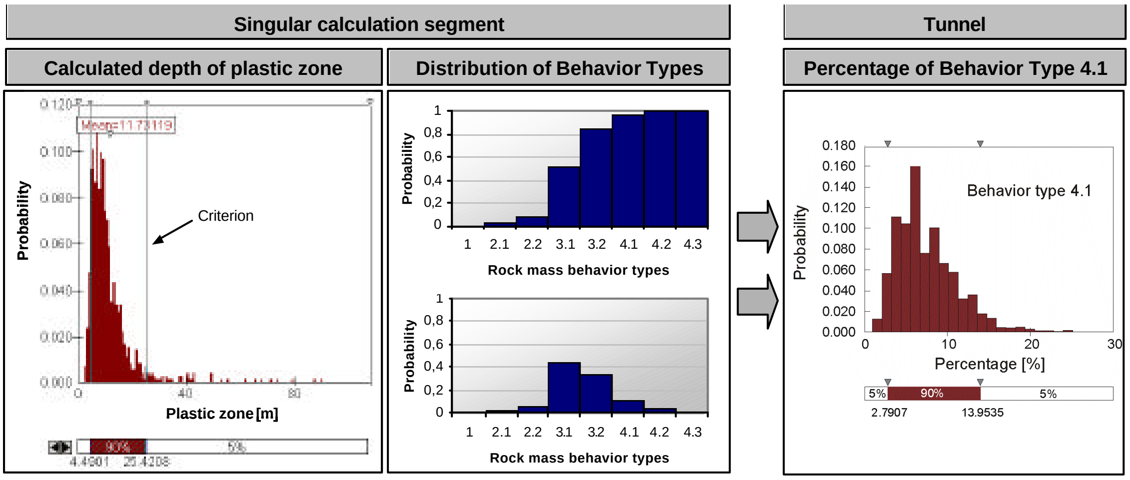

Fig. 6 Results of individual calculation phases
Bild 6 Ergebnisse aus verschiedenen Berechnungsphasen

6. Geotechnical risk relevancy due to the excavation- and support method

The variation in the geotechnical risk for each potential excavation and support method must be evaluated.

Figure 7 clearly shows the consequence of the specific risk-relevant behavior.

It shows the difference in geotechnical risk for two excavation methods (D&B and TBM) for a railway tunnel project in Austria in very heterogeneous ground with high overburden, where both methods were compared. The conventional method shows a wide deviation and lower basic costs whereas the mechanical method shows a narrow deviation at higher basic costs. The higher flexibility of the conventional method allows a variation of the measures to be applied depending on the rock mass behavior encountered on site. With the mechanical excavation method higher basic investments into the technology are required to cope with the expected rock mass behavior on the major part of the tunnel with small variations in excavation and support. The costs of the TBM excavation are further increased in this project, as in some sections the high risk identified would require a conventional excavation.

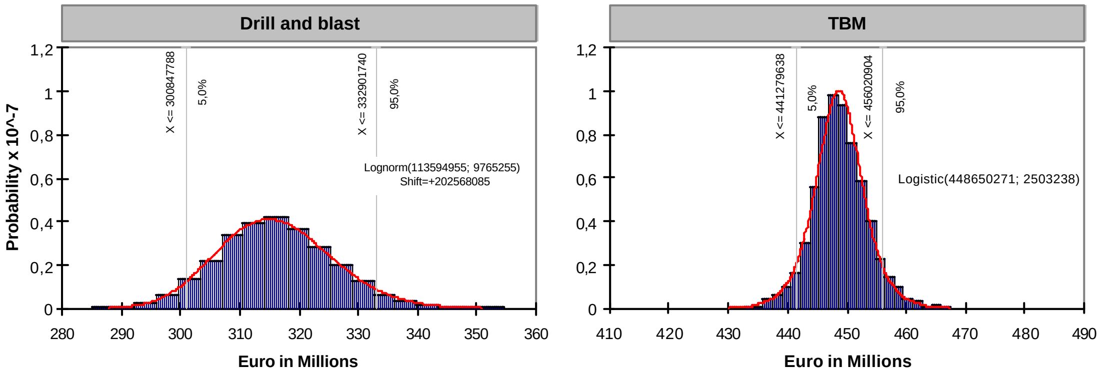

Fig. 7 Example for distribution of costs for conventional and mechanical excavation method

Bild 7 Beispiel für die Kostenverteilung für konventionellen und mechanischen Vortrieb

Figure 8 shows the interdependence between rock mass behavior, time dependence, advance rate and the technological (geometrical) restrictions of a TBM-system. Variations in the rock mass parameters spread the characteristic line, which results in different time-displacement lines. It also shows, that the required advance rate for an open TBM is considerably smaller than for a DS-TBM with the same displacements and support due to the length of the shield. Support installation slows down a DS-TBM less than an open TBM. In order to prevent disintegration of the rock mass or trapping of the shield by squeezing, the advance rate must be relatively high. Consequently, considerable care has to be taken in the decision on a system depending on the geotechnical hazard.

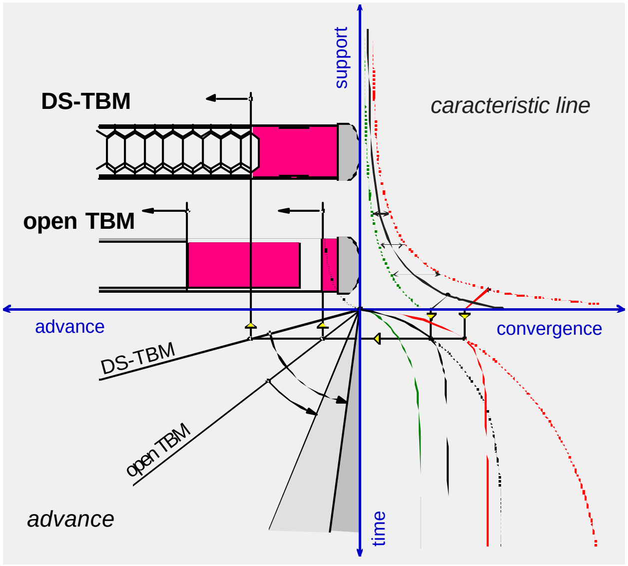

Fig. 8 Interdependence between rock mass and TBM parameters (modified from (25))

Bild 8 Zusammenhang zwischen Gebirgs- und TBM Parametern (nach (25))

7. Conclusion

In this paper a coherent method for the probabilistic determination of the geotechnical risk is outlined. Using distributions for input data, a consistent procedure for rock mass characterization and excavation and support determination, and by assigning time and costs to the construction the geotechnical and consequently the economic risk can be quantified. Monte Carlo simulations are used to achieve probabilistic results. Following this procedure the significant influence of the geological and geotechnical uncertainties can be considered and its sensitivity to time and costs of a tunnel can be assessed.

8. References

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