Computer Aided Hierarchical Ground Characterization for Underground Structures

A. Steiner & W. Schubert
Graz University of Technology, Institute for Rock Mechanics and Tunneling, Austria

ABSTRACT: The characterization of the ground comprises an integral part in the design of an underground structure. For this reason several classification systems have been developed in the past. They were derived from specific project conditions. The Austrian "Guideline for the Geomechanical Design of Underground Structures with Conventional Excavation" describes a consistent procedure for the characterization of the ground and determination of excavation and support. The software GEOCLASS has been developed in order to accelerate the calculation process following this guideline. GEOCLASS allows dealing with Ground Types, failure mechanisms, and ground behavior. The result of the calculation is a classification of identified ground behaviors into Ground Behavior Types. It allows the application of deterministic and probabilistic methods due to the automatic processing of the data. The results are used to determine excavation and support, as well as costs, time and risks of the construction works.

1 INTRODUCTION

The development of a tunnel project contains several investigations and design phases. Those start with a preliminary site assessment and typically end with a final design. The particular investigation and design steps are usually executed by various companies and/or working groups. Results from these subsequent steps lead to continuous increase of knowledge on the tunnel project and finally end with the final design.

The Austrian "Guideline for the Geomechanical Design of Underground Structures with Conventional Excavation" (ÖGG 2001) illustrates a coherent procedure for both the design- as well as the construction stage of a tunnel. The procedure for the design phase includes the following intermediate stages: definition of Ground Types (GT), assessment of ground behavior and classification into Ground Behavior Types (BT), evaluation of System Behavior (SB), and determination of excavation and support methods.

Reliable results require sufficient and representative data sets for input, which have to be processed by using predefined rules and definitions. Due to the large amount of data obtained from investigation campaigns, this analysis calls for an efficient, automated processing, accelerating the entire process. For this reason, the program GEOCLASS was created following the procedure illustrated in the previously mentioned Austrian Guideline. In this paper, the computer aided data processing is presented up to the determination of the Ground Behavior Types comprising the basic result of the ground characterization.

2 GUIDELINE FOR THE GEOMECHANICAL DESIGN OF UNDERGROUND STRUCTURES WITH CONVENTIONAL EXCAVATION

The guideline considers two main phases, the design phase the construction phase. The procedures described in the design phase lead to a coherent determination and characterization of support and excavation methods related to the expected ground conditions. The expected ground, excavation and support interaction is assessed (System Behavior) (ÖGG 2001, Goricki 2003). Additionally during the design process, the natural spread of the input parameters is considered.

During the construction phase, the observed System Behavior can be compared to the behavior that was determined for the associated Ground Type during the design phase. When all concepts, considerations, and decisions are documented during both phases, the systematic procedure described in the guideline allows a review of the decision making process, whenever new findings from the site are gained.

The design phase consists of five general steps: determination of Ground Types, assessment of

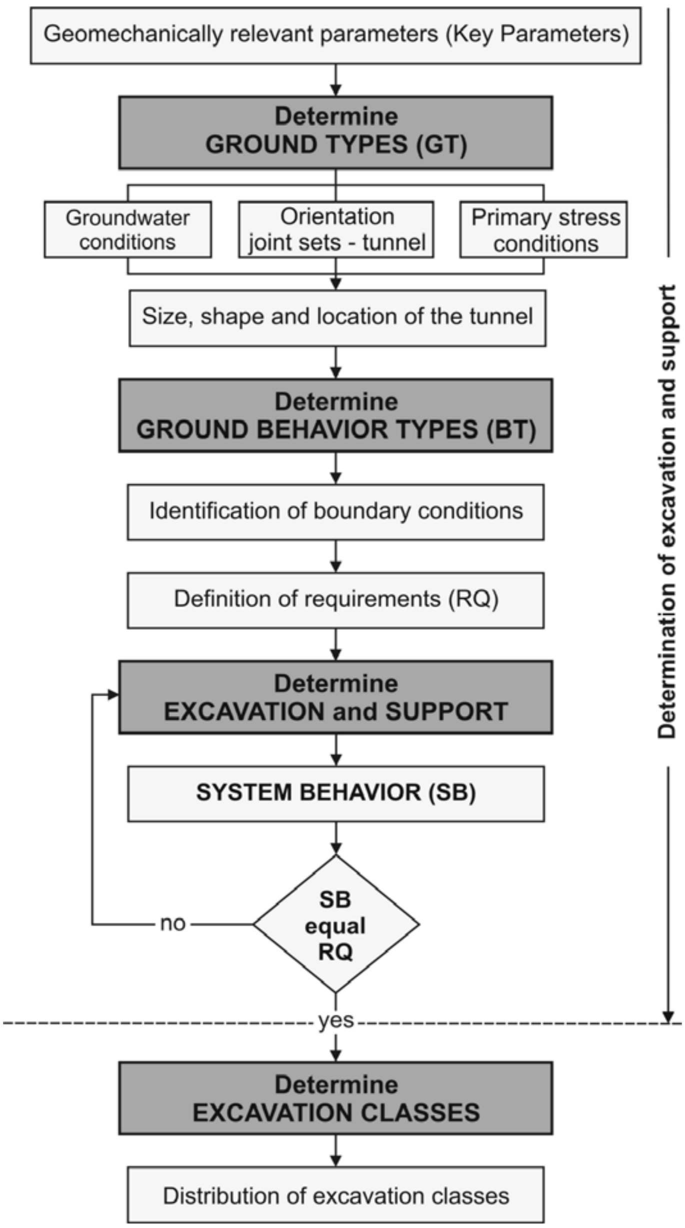

Figure 1. Fundamental design procedure based on ground characterization and classification according to the Austrian Society for Geomechanics (ÖGG 2001, Goricki 2003) modified by Steiner (2005).

ground behavior and classification into Ground Behavior Types, evaluation of System Behavior, Baseline Construction Plan, and determination of excavation classes (Figure 1). In order to account for the variability of the input parameters they should be described with statistical values to enable the evaluation with probabilistic procedures later on.

The basis for the determination of the Ground Types is the geological model for the project area. The information about the geological architecture allows correlating geological units with geomechanically relevant parameters (key parameters). The key parameters describe the relevant properties of the ground within a geological unit. Ground Types are defined by similar material and properties. The number of necessary Ground Types for one geological unit is dominated by the variation of the key parameter values.

The ground behavior is the response of the ground to the excavation a tunnel without consideration of excavation and support methods as well as auxiliary measures. It considers the specific local influencing factors (primary stress situation, ground water conditions, discontinuity orientation relative to the excavation direction, etc.). These analyses evaluate only involved failure mechanisms. The observed mechanisms characterize the behavior caused by the excavation. Similar behavior is subsequently grouped into the Ground Behavior Types. The basic Ground Behavior Types, mentioned in the Guideline, are presented in Table 1.

The evaluated ground behaviors form the basis for the determination of excavation and support methods as well as auxiliary measures (Schubert et al. 2000). Several combinations of excavation and support methods may result in a stable excavation fulfilling all project requirements but only one regarding to economical and safety issues has to be chosen. Based on this result the Baseline Construction Plan is developed. The Baseline Construction Plan defines the excavation and support measures for each tunnel section.

The final step in the design phase includes the preparation of the tender documents as well as costs and construction times estimated for the entire project consistent with the determined amount of excavation and support measures.

Since the input parameters have a natural spread, the influence of varying key parameters on the ground and System Behavior has to be assessed for a realistic risk assessment in the design, the use of probabilistic methods is recommended and described in this paper.

3 COMPUTER AIDED DESIGN PROCEDURE

The Austrian guideline describes a consecutive approach for the design of an underground structure. Due to the consideration of the natural spread in the input parameters via statistical and probabilistic approaches, calculation and time efforts increase for the design process. To optimize these time consum-

Table 1. Eleven general Ground Behavior Types (ÖGG 2001), for a detail description (Goricki 2003).

Number	Ground Behavior Types
1	Stable
2	Discontinuity controlled block failure
3	Shallow stress induced failure
4	Deep seated stress induced failure
5	Rock burst
6	Buckling failure
7	Shear failure under low confining pressure
8	Raveling ground
9	Flowing ground
10	Swelling
11	Frequently changing behavior

ing processes the program GEOCLASS was developed for the evaluation of the first two steps in the design procedure.

The core of GEOCLASS is the determination of the response of the ground using empirical and closed-form solutions for 2D failure mechanisms under current boundary conditions.

3.1 *Basic procedure in GEOCLASS*

GEOCLASS requires for computation the definition of several input parameters, which are related to the implemented approaches, and the assignment of boundary conditions. The parameter values are simultaneously processed with all models resulting in specific output values for each model. Typical output categories are depth of the failure zone, rock burst potential, or displacement magnitudes. Each of the output categories is characteristic for a particular ground behavior. The output values of each category are used to classify the ground into a particular Ground Behavior Type. Due to the use of several calculation models, it is possible that for a particular ground several Ground Behavior Types apply. Therefore, it is necessary to assign the dominating Ground Behavior Type with a hierarchical sequence.

3.1.1 *Input*

At the beginning, the mechanical ground properties are assigned to the predefined Ground Types. Typical properties used in the program are uniaxial compressive strength, Hoek’s constant, Young’s modulus, Poisson’s ratio, etc. These parameters describe the properties of the intact ground. They are usually determined by laboratory tests, and additionally by field tests, index tests, or from literature.

The influence of the ground structure has to be considered, in order to enable the determination of ground properties from the intact rock values. Presently the GSI model (Hoek et al. 1998, Marinos & Hoek 2001) is implemented in the software to account for fracturing, block interlocking, weathering, etc. of the ground. Appropriate GSI values are assigned for each Ground Type.

When the Ground Types have been determined, the project related geometry and other influencing factors have to be defined. The project geometry includes the geometry of the excavation (size, shape, and length), the corresponding overburden, and the assignment of the Ground Types along the tunnel axis according to the geological model. For the calculation, it is necessary to assign the Ground Types to discrete locations, so called calculation segments. One characteristic parameter set is assigned for each calculation segment. The length of the calculation segments is project specific and depends on the complexity of the geological architecture. Typical length values range between 10 – 50 m. Singular structures such as faults can be individually discredited. Other project dependent influencing factors are also assigned directly to the calculation segments, such as ground water conditions, the lateral confining coefficient, discontinuity orientation relative to the tunnel direction, etc.

In order to enable the software to classify automatically different Ground Behavior Types the input of delimiting criteria are necessary. The delimiting criteria are compared with the output parameters of the calculation models. Delimiting criteria are given, for instance, for rock burst potential, depth of the failure zone, overbreak, etc. Reasonable delimiting criteria should be based on a geotechnical model and take into account practical relevance.

Finally, a hierarchy of Ground Behavior Types has to be defined because the analysis can result in several Ground Behavior Types for each calculation segment. However, the following automated processing only considers one Ground Behavior Type per calculation segment. For this reason, the dominating Ground Behavior Type has to be defined for each particular calculation segment, though secondarily defined Ground Behavior Types have an impact on later steps of the design procedure (e.g. swelling).

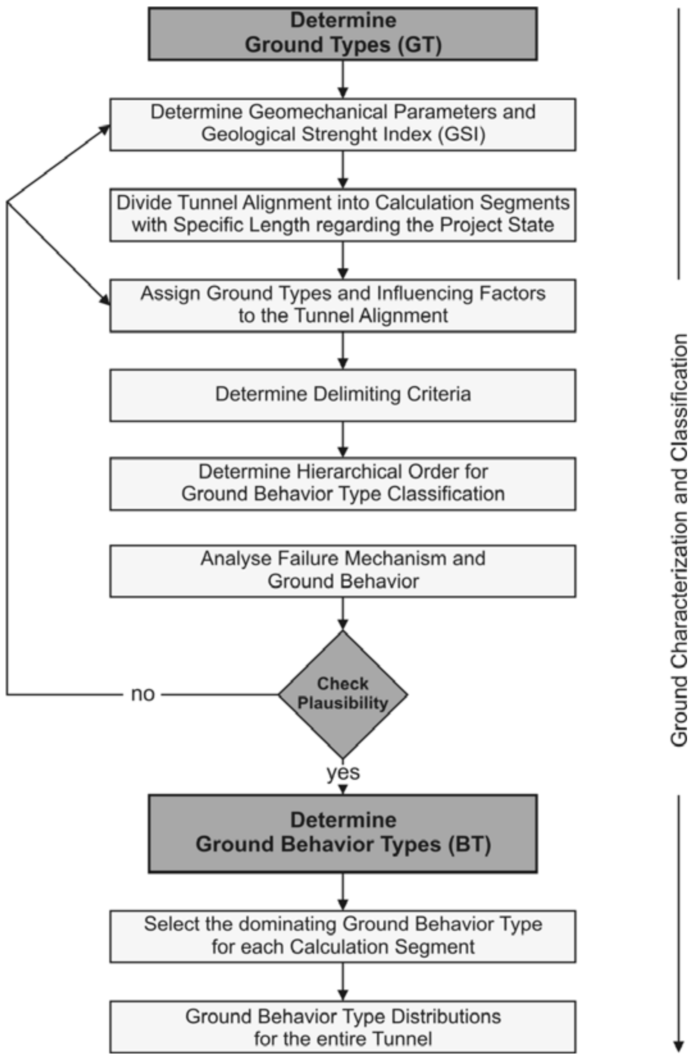

Figure 2. Deterministic procedure for the ground characterization and classification implemented in GEOCLASS.

3.1.2 *Data processing*

In the first step, the defined intact ground properties of the Ground Types are processed into ground properties. Presently GEOCLASS uses for the up-scaling process of intact properties to ground properties the GSI system (Hoek et al. 2002).

Using the ground properties and the boundary conditions assigned to each calculation segment the response of the ground to the excavation is determined based on the analytical models implemented in the software. For example, GEOCLASS includes two models for the determination of the failure zone depth and the displacements (Carranza-Torres 2003, Feder & Arwanitakis 1976), one model for rock burst potential (Wang & Park 2001), as well as one model for determining dome and chimney type failures (Feder 1980). The models are simultaneously applied for each calculation segment.

The results of the analysis are compared to the defined delimiting criteria. For a particular parameter, whose magnitude complies with the range of the delimiting criteria, the corresponding Ground Behavior Type is assigned to the calculation segment. Several Ground Behavior Types can be assigned due to the simultaneous use of different calculation models. The relevant BT is determined according to the previously defined BT hierarchy (Figure 2).

3.1.3 *Results*

In order to judge the results of the ground characterization, several tables and visualizations can be created. The obtained BT for all calculation segments can be visualized in a longitudinal tunnel section. This way of illustrating the results descriptively shows the different BT location, as well as their variation along the tunnel, and geotechnical units can be derived. Based on these units the conceptual layout of the excavation and support is established.

Diagrams, showing the displacement magnitudes and depth of failure zone can also be created. All diagrams are generated relative to the geometric project layout (Figure 3). All these visualizations allow the engineer a fast and clear judgment of the analysis and provide valuable input for the subsequent design of excavation and support.

3.2 *Exemplary calculation for Ground Behavior Type 7*

Practically input parameters are determined by laboratory tests and measurements during the geological investigations. In GEOCLASS the parameters UCS_{intact} and Hoek's constant (m_i) describe the intact ground and the GSI value is used to consider the discontinuity condition. These input parameters result in the parameters describing the homogenized ground (UCS_{rm}, E_{rm}, c_{rm} and φ_{rm}).

These parameters can be used to classify the Ground Behavior Type 7. The analysis of the BT 7

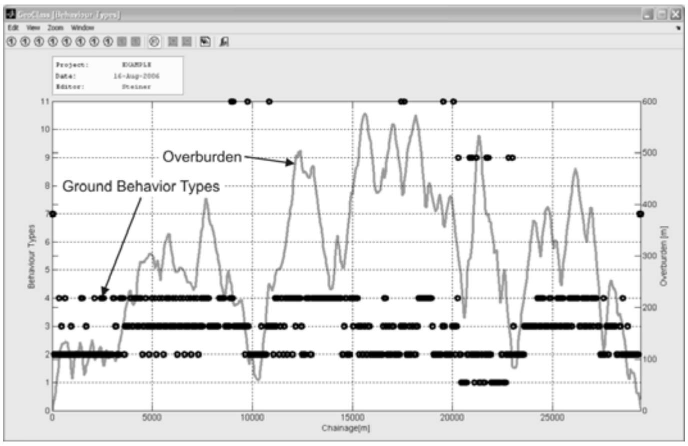

Figure 3. Distribution of the Ground Behavior Types in the longitudinal direction of a project; with the associated overburden.

(Formula 1-3) considers a failure criterion delimiting a chimney type failure from stable conditions (Feder 1980).

$$T_{shear} = \frac{h_{overburden}{}^{2} * \gamma_{rm}}{2} * K_0 * \tan(\varphi_{rm}) \quad (1)$$

$$G_{block} = h_{overburden} * \gamma_{rm} * D_{tunnel} \quad (2)$$

$$2 * T_{shear} \leq G_{block} \quad (3)$$

where T_{shear} =shear force in the sliding plane; $h_{overburden}$ =overburden; γ_{rm} =specific weight of the ground; K_0 =lateral confining coefficient; φ_{rm} =friction angle of the ground; G_{block} =weight of the block over the excavation; D_{tunnel} =excavation diameter.

3.3 *Exemplary calculation for Ground Behavior Type 1/3/4*

For the classification between Ground Behavior Type 1, 3, and 4, the UCS_{rm} is used in the calculation model from both Feder & Arwanetakis (1976) as well as Carranza-Torres (2003). The second one is limited to hydrostatic stress situations.

The result of this calculation is the size and shape of the failure zone (secondary stress condition > UCS_{rm}). The delimiting criterion between BT 3 and 4 is determined depending on project conditions and practical issues. In GEOCLASS an empirical formula (4), which is primarily based on the size of the excavation, is used for the classification (Figure 4).

$$DBZ_{limit} = 2.5 * \sqrt{R_{equivalent}} \quad (4)$$

where DBZ_{limit} =delimiting depth of failure zone; $R_{equivalent}$ =equivalent radius of excavation.

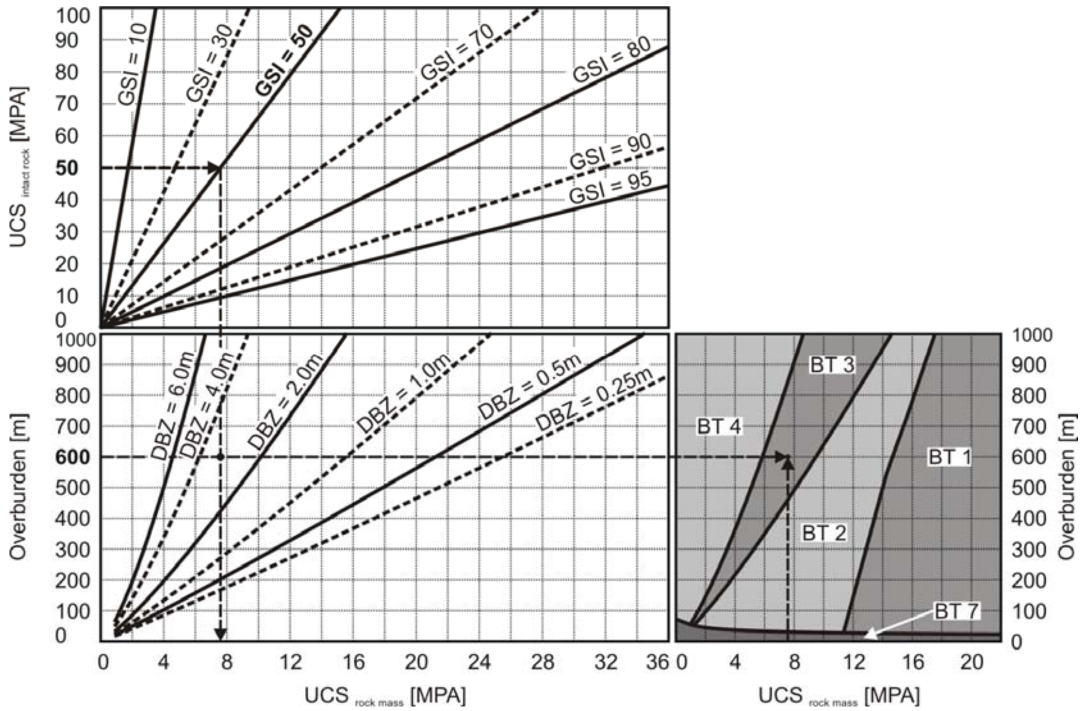

Figure 4. Nomogram for the Ground Behavior Types classification based on uniaxial compressive strength (intact rock), geological strength index, and overburden including different delimiting criteria; excavation diameter=10 m; Hoek's constant=10.

4 PROBABILISTIC APPROACH

In contrast to the deterministic calculation that proceeds with one representative parameter set during the entire calculation, the probabilistic approach uses a number of such calculations with varying input parameter sets. Those input parameter sets are determined by the natural spread of the values for each GT. The probabilistic approach results in a statistical distribution for the calculation results, hence also for the Ground Behavior Types after a sufficient high number of calculations (Figure 6).

At the ideal case, a number of laboratory results for each geotechnical unit can be used for the determination of the statistic distribution type and its characteristic values. If there is a lack of laboratory results, the determined input parameters can be used as average values. In this case, expert knowledge can be used to assume a realistic distribution. Now the random input values can be determined. In GEOCLASS this determination is done by using the Monte Carlo Simulation (Haldar & Mahadevan 2000).

The previously described deterministic calculation is executed with each of these random parameter sets, which represent the natural spread of the ground properties. The evaluation of the probabilistically determined results offers relevant conclusions (e.g. risk assessment, ect.).

During the following steps in the design procedure, each Ground Behavior Type is assigned with specific excavation and support measures. Those

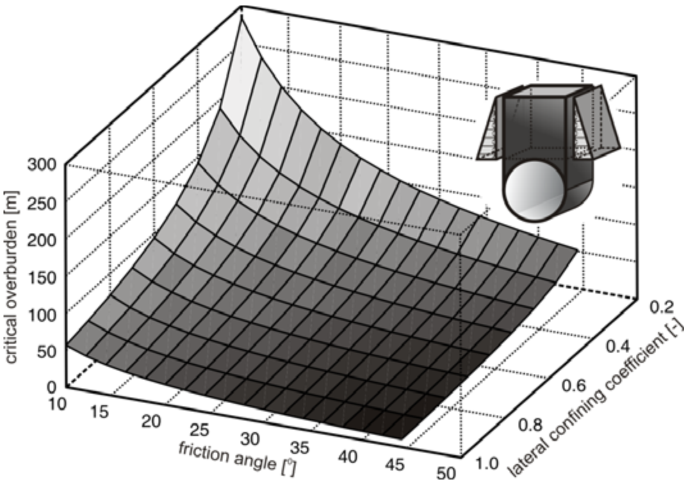

Figure 5. Delimiting criteria to determine the critical overburden depending on the friction angle and the lateral confining coefficient.

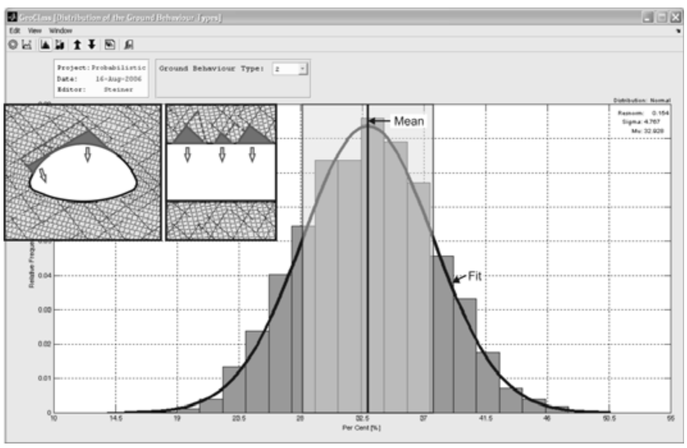

Figure 6. Histogram of the Ground Behavior Type 2 with a sketch of the appropriate failure mechanism.

measures result in costs and time. The distribution, showing the expected length of each Ground Behavior Type, is later used for the determination of the costs and their possible spread.

Even when the natural spread of the input parameters is used for the calculation, some calculation segments can clearly be assigned to one expected Ground Behavior Type. Others may possibly be assigned to several Ground behavior types. In early stages of a project, these may indicate a lack of information about the ground conditions possibly resulting in further ground investigations. During final design these results represent the natural spread inherent in the explored data sets.

5 CONCLUSION

The estimation of costs and time requires rules for the determination of excavation and support during design stage. Both depend on the ground behavior. For this reason characterization systems were developed (GSI, RMR, RMi, RSR, Q-System, etc.). These systems are mostly based on measurable and/or observable values, which are used to classify the ground quality. The determined ground quality is then used to associate support methods without considering the ground behavior (Edelbro 2004, Goricki 2003).

The complexity of projects effort a lot of calculation works, so a program (GEOCLASS) was developed to accelerate the design procedure following the rules of the Austrian Guideline for the Geomechanical Design of Underground Structures with Conventional Excavation (ÖGG 2001). In the program, different approaches can be used to analyze the ground behavior. The simple illustrations of the results allow a continuous engineering judgment of the results during the first steps of the design process. Normally only deterministic procedures are used to analyze project conditions. The implementation of the Monte Carlo Simulation in GEOCLASS additionally provides the use of probabilistic procedures for the entire procedure.

The results of the probabilistic approach contain the natural spread and/or variability of the ground. When this statistic results are used for the determination of excavation and support, the variability of expected costs, and time can also be determined.

By the consideration of the natural spread inherent in the input parameters, the results for the design process are more significant in each project stage.

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