Austrian Society for Geomechanics

Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation

Ground characterization
and coherent procedure for the determination
of excavation and support during design and construction

Translated from version 2.1

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1 INTRODUCTION

One goal of the Austrian Society of Geomechanics is to improve the communication between clients, geologists, engineers, and contractors in the field of geotechnical engineering, as well as the improvement of design and design procedures for projects involving rock and soil.

The Guideline has first been established in conjunction with the new edition of the Austrian Standard ONORM B2203-1 [1] in 2001. This standard deals with contractual matters for underground construction with conventional excavation. All subjects related to ground characterization and behaviour evaluation have been summarized in the Guideline published by the OGG, which the Standard ONORM B2203-1 refers to. The Guideline cannot be used as a basis for contractual matters. The Guideline was revised in 2008 and replaces the edition from 2001.

The stability of underground structures is a key issue during design and construction. Depending on the geotechnical conditions and influencing factors, different failure modes can be expected. Depending on the potential failure modes, project specific requirements and boundary conditions, specific construction measures to ensure stability have to be chosen.

Due to the variation in the geotechnical conditions (the static system and the capacity of ground and supports) the design of an underground structure cannot be compared to a structural design of other buildings, where the loads, the system, and the characteristics of the materials used are known.

In underground construction the risks associated with construction cannot be precisely defined due to the uncertainties of the geotechnical model. This circumstance requires a continuous adaptation of the construction method to the actual ground conditions, and the implementation of a safety management system [2, 3].

The safety management system has to cover following topics:

- A design concept for the determination of excavation and support
- Criteria for the assessment of the stability based on the knowledge of the ground conditions during design
- A monitoring concept with all technical and organizational provisions to allow a continuous comparison between the expected and actual conditions
- A management concept for cases where the actual conditions deviate from the expected range, both in unfavourable and favourable direction

In underground engineering there are two major aspects that must be addressed during the design phase. The first and most important is developing a realistic estimate of the expected ground conditions and their potential behaviours as a result of the excavation. The second is to design an economic and safe excavation and support method for the determined ground behaviours. The design process begins with the feasibility study and continues through the preliminary design, the detail design, the tender design, and throughout the construction. The design is constantly updated during each stage, as more information is available. This requires the involvement of geological and geotechnical experts in all phases of a project.

A central issue for all geotechnical designs is the ground-structure interaction. This not only includes the final state, but also the transient effects of the construction processes, as well as time and stress dependent ground properties.

During the design phases the inherent complexity and variability in many geological settings prohibits a complete picture of the ground structure and quality to be excavated. The geotechnical design is targeted to a continuous refinement of the models and decision criteria. Besides a high professional standard, a systematic and consistent, well documented evaluation and decision process is of paramount importance. Uncertainties in the ground model shall be considered in the design.

Depending on the ground properties and the boundary conditions of a project, the importance of the geomechanical design and the structural design will vary. Most countries have regulations regarding the structural design of underground structures, especially in urban areas. The Austrian guideline RVS 09.01.42 may serve as an example.

The Guideline contains a description of the general procedure to be followed for the geotechnical design. It addresses everybody involved in an underground project, and assists in efficiently preparing and organizing the geotechnical design during all phases of a project. The Guideline does not contain distinct stipulations for engineering tasks.

Contractual matters, like sharing of geological risk, matters of responsibility or site organization are not addressed in this technical guideline, as the conditions will vary from project to project.

2 TARGETS

The main task of the geotechnical design is the economic optimization of the construction considering the ground conditions as well as safety, long term stability, and environmental requirements.

The variability of the geological architecture including the local ground structure, ground parameters, stress and ground water conditions requires that a consistent and specific procedure be used during the design process. The key influences governing the geotechnical design are the ground conditions and ground behaviour.

Existing schematic rating systems and their recommendations for excavation and support have been developed from experience under specific conditions. A generalization for other ground and boundary conditions frequently leads to inadequate design [4]. Consequently a technically sound and economical design and construction can be achieved only by applying a project and ground specific procedure.

In spite of all uncertainties in the description of the ground conditions, underground engineering needs a strategy, allowing a consistent and coherent design procedure that is traceable throughout the entire project, and an optimal adjustment of the construction to the actual ground conditions encountered on site.

Two main phases can be distinguished:

Phase 1: Design

This phase involves determining the expected ground properties, the classification into Ground Types (GT), the assessment of the Ground Behaviours, its categorization into Ground Behaviour Types (BT), as well as the determination of construction measures derived from the ground behaviour under consideration of the project specific boundary conditions. On this basis the expected System Behaviour is predicted. Tunnelling classes are then determined according to the rules stipulated in ONORM B2203-1.

The results of all phases of the geotechnical design are summarized in a geotechnical report. The geotechnical report clearly has to show, on which ground conditions, boundary conditions, and other assumptions the design is based. The framework plan is part of the geotechnical report. This plan has to contain clear application criteria, and shall indicate which measures shall not be modified during construction without consent of the designer, as well as the criteria for possible modifications and adjustments during construction.

Phase 2: Construction

During construction geotechnical relevant ground parameters have to be collected, recorded, and evaluated to determine the ground type. Under consideration of the influencing factors the actual System Behaviour in the excavation area is assessed according to the stipulations of the design. Excavation and support measures have to be chosen based on the criteria laid out in the framework plan and the safety management plan.

The geotechnical design and the framework plan have to be continuously updated based on the findings on site. The improved quality of the geotechnical model allows an optimization of the construction while observing all safety and environmental requirements.

The relevant data and assumptions made for all decisions during design and construction have to be recorded. Relevant information in connection with the ground properties, ground and system behaviour has to be collected, evaluated and analyzed in both phases.

The guideline shall help to follow a systematic procedure. All concepts, considerations and decisions shall be recorded in a way, that a review of the decision making process is possible.

3 DEFINITIONS

GROUND	Part of the earths crust, composed of rock and/or soil, frequently with anisoptopic properties, including discontinuities, and voids filled with liquids o gases.
ROCK	Aggregate, consisting of mineral components, developed from natural processes, characterized by the types and amount of the minerals and grain structure.
SOLID ROCK	Mineral aggregate, whose properties predominantly are determined by the physical/chemical bond.
SOIL	Accumulation of anorganic solid varigrained particels with occasional organic admixtures. The properties are predomonantely governed by the granulometric composition, the compaction, and the water content
DISCONTINUITY	General term for any mechanical discontinuity in a rock mass having zero or low tensile strength. Collective term for most types of joints, weak bedding planes, weak schistosity planes, weakness zones and faults.
ROCK TYPE	Soil or rock with similar properties
GROUND TYPE (GT)	Ground with similar properties.
GROUND BEHAVIOUR	Reaction of the ground to the excavation of the full profile without consideration of sequential excavation and support
BEHAVIOUR TYPE (BT)	General categories describing similar Ground Behaviours with respect to failure modes and displacement characteristics
SYSTEM BEHAVIOUR (SB)	Behaviour resulting from the interaction between ground, excavation, and support, separated in: system behaviour in the respective excavation section system behaviour in the supported section system behaviour in the final state
BOUNDARY CONDITIONS	Conditions, which influence construction process and methods due to other than geotechnical reasons
FRAMEWORK PLAN	Summary of the Geotechnical Design, including relevant parameters used in the design, and application criteria for the assignment of excavation and support methods
REQUIREMENTS	Definition of required parameters to safeguard serviceability, safety, and environmental issues

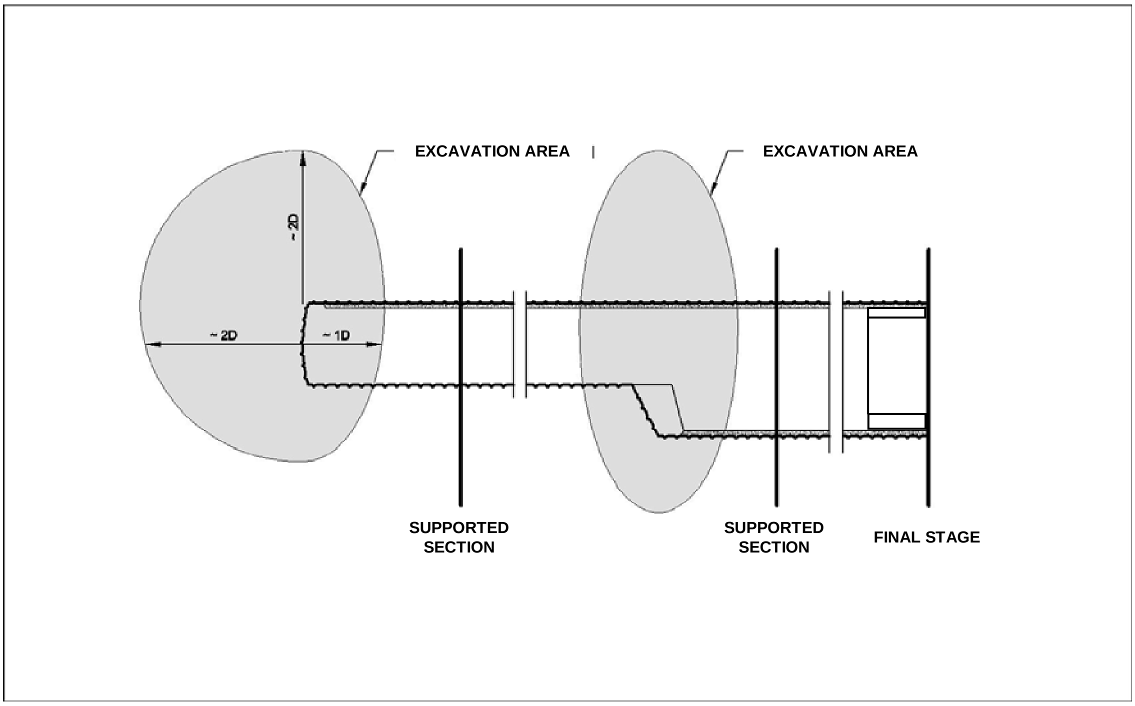

Figure 1: Allocation of system behaviour to different sections

4 PHASE 1 - DESIGN

4.1 Basic Procedure

The geotechnical design, as part of the tunnel design, serves as a basis for approval procedures, the tender documents (determination of excavation classes and their distribution), and the determination of the excavation and support methods used on site [5].

The flow chart (Figure 2) shows the basic procedure to develop the geotechnical design, beginning with the determination of the ground types and ending with the definition of excavation classes. Statistical and/or probabilistic analyses should be used to account for the variability and uncertainty in the parameter values and influencing factors, as well as their distribution along the projects route. The analyses may serve as a basis for a risk analysis.

The procedure incorporates following steps:

Step 1 – Determination of Ground Types

The first step starts with a description of the basic geologic model and proceeds by defining geotechnically relevant parameters for each ground type. The key parameters values and distributions are determined from available information and/or estimated with engineering and geological judgement. Ground with similar properties is classified into Ground Types (GT). The number of Ground Types elaborated depends on the project specific geological conditions.

Step 2 - Determination of Ground Behaviour and Assignment to Ground Behaviour Types

The second step involves evaluating the potential ground behaviours considering each ground type and local influencing factors, including the relative orientation of relevant discontinuities to the excavation, ground water conditions, stress situation, etc. For each section, which has similar ground properties and influencing factors, the Ground Behaviour is analyzed.

The ground behaviour has to be evaluated for the full cross sectional area without considering any modifications including the excavation method or sequence and support or other auxiliary measures.

The evaluated project specific ground behaviours shall be assigned to basic Ground Behaviour Types (table 2). Project specific conditions may require a further subdivision of the Ground Behaviour Types, as well as a detailed description of the single expected behaviours.

Step 3 – Selection of construction concept

Based of the ground characteristics and the determined ground behaviour for each characteristic situation a feasible construction concept is chosen, consisting of excavation method, sequence of excavation, support and auxiliary methods.

Step 4 – Assessment of system behaviour in the excavation area

Under consideration of the construction concept, including sequence of construction, stability of the face and perimeter, and the spatial stress distribution, the system behaviour in the excavation area is assessed.

Step 5 – Detailed determination of the excavation and support method and evaluation of system behaviour in the supported area

The excavation and support methods are fixed in quality and quantity, considering probable further excavation steps, and the system behaviour determined. The evaluated system behaviour is then compared to the requirements.

Step 6 - Geotechnical report-framework plan

Based on steps 1 through 5 the alignment is divided into sections with similar excavation and support requirements. The framework plan indicates the excavation and support methods available for each section, and contains limits and criteria for possible variations or modifications on site.

Step 7 - Determination of excavation classes

In the final step of the design 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 definition of tunnelling classes is based on the regulations in ONORM B2203-1.

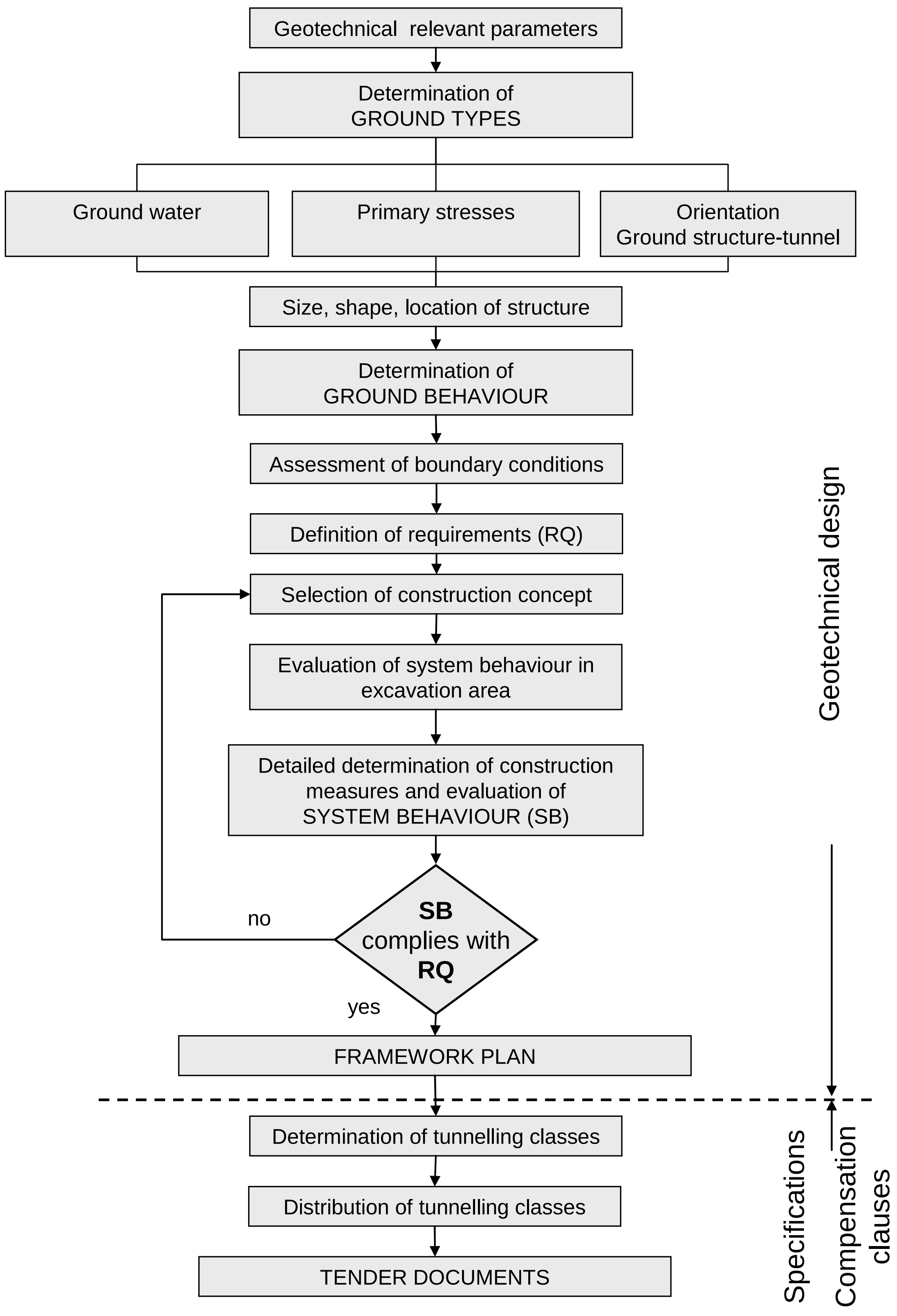

Figure 2: Schematic procedure of the geotechnical design

4.2 Determination of Ground Types

A Ground Type is defined as a geotechnical relevant ground volume, including matrix, discontinuities and tectonic structures, which is similar with respect to following properties

- in rock: mechanical properties (intact rock – rock mass), discontinuity characteristics and properties, rock type, rock- and rock mass conditions hydraulic properties
- in soil: mechanical properties, grain size distribution, density, mineral composition, parameters of the soil components, matrix parameters, water content and hydraulic properties

Different Ground Types have different characteristic parameters that influence their mechanical behaviour. To determine different ground types relevant key parameters have to be evaluated and defined. Different ground masses with similar combinations of relevant parameters are defined as one Ground Type.

The definition of the Ground Types has to be based on the current knowledge in each project stage, considering their importance for the successful completion of the project. The number of defined Ground Types is project specific and depends on the design phase, as well as on the complexity of the geological conditions in the project area. In general, in early design phases, a rough discrimination will be sufficient, with increased information in subsequent design phases the distinction of the single Ground Types will be, and has to be more precise.

The final task in this step is to assign the Ground Types to the alignment.

4.2.1 Method

Selected key parameters describe the geotechnical relevant properties of the ground [6]. Table 1 is intended to provide assistance for the selection of the relevant parameters for different rock types. Depending on project specific boundary conditions, other or additional parameters may have to be determined. In any case it has to be checked if the selected parameters are sufficient to adequately describe the ground properties [7, 8].

Appendix A contains a list of soil, rock, discontinuity, and ground parameters and relevant references.

The determination of the various parameters shall be based on local standards and regulations. The reasons for the use of other standards or procedures have to be clearly explained.

In all project stages the used data, the method of evaluation and the spread of the parameters have to be listed.

Different key parameters may be required depending on the type and use of the under-ground structure. The number of parameters used for the definition of the Ground Types and their mode of classification can change as the project progresses. For the determination of ground types the mechanical and hydraulic properties of the ground have to be determined.

Preferably the collection of the relevant geotechnical parameters and influencing factors is done during the preliminary design. Investigations during the tender design should concentrate on reducing the uncertainty or risk in geotechnical critical areas.

Simple rating methods ([9, 10]) can be used in early project phases (feasibility study, preliminary design). Frequently in these phases parameters from literature or previous experience have to be used due to lack of data from the project area. The origin of the used data has to be shown.

Empirical [11, 12, 13, 14] and numerical methods [15, 16]), as well as in situ tests may be used in later project phases (project approval, tender design) for the determination of the properties of the ground.

Ground strength, deformation characteristics, hydraulic properties, as well as specific properties (for example pronounced anisotropy [17], low friction of discontinuities, time dependent behaviour, intercalation of other rock types, etc.) have to be evaluated and shown in the documents.

BASIC ROCK TYPES		KEY PARAMETERS																		
		INTACT ROCK PROPERTIES													DISCONTINUITIES					
		Mineral Composition	Clay Mineral Composition (qualitative)	Clay Mineral Composition (quantitative)	Cementation	Grain Size	Texture	Ratio Matrix/Fraoments	Porosity	Alteration/Weatherino	Solution Phenomena	Swelling Properties	Strenoth Properties	Anisotropy	Block Shape	Block Size	Persistence	Aperture	Shear Strength/Roughness	Infilling
ROCKS	Plutonic Rocks	■				■	■			□			■		■	■	□	■	□	□
ROCKS	Volcanic Rocks (massive)	□					□		■	■			■		■	■	□	■	□	■
ROCKS	Volcano-Clastic Rocks	□	□		□	□		■	■	■		□	□							
ROCKS	Coarse-grained Clastic Rocks (massive)	□		□	■	■	□	■	□	□			■		□	□	□	□		
ROCKS	Fine-grained Clastic Rocks (massive)		■	■	■	■				□		■	□		□	□				
ROCKS	Coarse-orained Clastic Rocks (bedded)	□		□	■	■		■	□	□			■	■					■	
ROCKS	Fine-orained Clastic Rocks (bedded)		■	■	■	■				□		■		■					■	□
ROCKS	Carbonatic Rocks (massive)	■									■		■		□	■	□	■		□
ROCKS	Carbonatic Rocks (bedded)	■									■		■		■				□	□
ROCKS	Sulfatic Rocks	■									■	■	□							
ROCKS	Metamorphic Rocks (massive)	■				■	■			□			■		■	■	□	■		
ROCKS	Metamorphic Rocks (bedded)	■				■	■			□			■	■	■	■	□		■	■
ROCKS	Fault Rocks	□	■	■	■			■		□		■	■							
SOILS	Coarse-grained Soils (gravel)					■		■	□				■							
SOILS	Coarse-grained Soils (sand)					■		□	□				■							
SOILS	Coarse-grained Soil Mixtures	□		■		■		■	□			□	■							
SOILS	Fine-grained Soils (silt)					■			□				■							
SOILS	Fine-grained Soils (clay)	□		■		■			□			■	■							

Legend ■ Significant Parameter □ Less Important Parameter

Table 1. Example of selected key parameters for different general rock types. The selection of key parameters may vary depending on the project conditions and requirements.

4.2.2 Records

All parameters used for the determination of ground types have to be described and shown in the documents in the form of a table.

4.3 Determination of Ground Behaviour

The ground behaviour describes the response of the ground to full face excavation, considering ground type and influencing factors without the influence of supports, division of face or auxiliary measures.

First the orientation of relevant discontinuity sets relative to the axis of the underground structure must be determined; the appropriate stress conditions defined, as well as the local ground water conditions for each section along the alignment. After assigning all relevant properties and influencing factors to each section, the ground behaviour is evaluated for each section of the underground structure. The expected ground behaviour is then categorized into the general types listed in table 2, and the distribution along the alignment determined.

4.3.1 Method

When considering long underground structures (tunnels) an unsupported cavity without supporting influence of the face has to be assumed. Sequential excavation steps are not considered in this phase.

The following influencing factors are usually considered for the evaluation of the Ground Behaviour:

- Ground Type (GT)
- Virgin stress conditions
- Shape and size of the underground structure (final shape and size)
- Position of underground structure in relation to surface or existing structures
- Relative orientation of the underground structure and discontinuities as a basis for kinematical analyses, and the assessment of the stress redistribution
- Boundaries between different ground types
- Ground water, seepage force, hydraulic head

For the determination of the ground behaviour the following evaluations are recommended:

- Kinematics: Kinematical analyses for the determination of discontinuity controlled overbreak and sliding of wedges
  Methods: Key Block Theory [18], analyses using stereographic projection [19, 20]
- Ground utilization: evaluation of the ratio between the strength of the ground and the spatial stress situation in the vicinity of the underground opening. Methods: analytical and numerical methods [21, 22, 23], 24]
- Failure mechanisms: possible failure mechanisms of the ground have to be analyzed and described at least qualitatively (for example: spalling, shearing along discontinuities as result of stress release, shear failure, etc.)

Methods: model tests, analytical analyses, numerical analyses, which allow the modelling of discrete failure planes, case histories.

When influencing factors cannot be determined with sufficient accuracy, a parametric study considering the spread of parameters shall be made.

Analytical and/or numerical methods are to be used, which provide appropriate modelling methods for the characteristics of the ground types under the given boundary conditions.

The Ground Behaviours resulting from the analyses have to be assigned to one of the categories listed in Table 2. In case more than one Behaviour Type is identified in one of the general categories, sub types have to be assigned (for example 2/1, 2/2 for a ground with a different potential for overbreak with different combinations of joint sets or orientations). If combinations of behaviours are identified in the same section, all behaviours have to be shown. The assignment to the general categories is done according to the behaviour type considered dominating (for example: discontinuity controlled overbreak and swelling of invert BT 2+10). Ground with frequently changing strength and deformation characteristics, as can be found in fault zones are assigned to the general behaviour category 11. The characteristics and behaviours have to be described project specifically.

Basic categories of Behaviour Types (BT)		Description of potential failure modes/mechanisms during excavation of the unsupported ground
1	Stable	Stable ground with the potential of small local gravity induced falling or sliding of blocks
2	Potential of discontinuity controlled block fall	Voluminous discontinuity controlled, gravity induced falling and sliding of blocks, occasional local shear failure on discontinuities
3	Shallow failure	Shallow stress induced failure in combination with discontinuity and gravity controlled failure
4	Voluminous stress induced failure	Stress induced failure involving large ground volumes and large deformation
5	Rock burst	Sudden and violent failure of the rock mass, caused by highly stressed brittle rocks and the rapid release of accumulated strain energy
6	Buckling	Buckling of rocks with a narrowly spaced discontinuity set, frequently associated with shear failure
7	Crown failure	Voluminous overbreaks in the crown with progressive shear failure
8	Ravelling ground	Ravelling of dry or moist, intensely fractured, poorly interlocked rocks or soil with low cohesion
9	Flowing ground	Flow of intensely fractured, poorly interlocked rocks or soil with high water content
10	Swelling ground	Time dependent volume increase of the ground caused by physical-chemical reaction of ground and water in combination with stress relief
11	Ground with frequently changing deformation characteristics	Combination of several behaviours with strong local variations of stresses and deformations over longer sections due to heterogeneous ground (i.e. in heterogeneous fault zones; block-in-matrix rock, tectonic melanges)

Table 2: General categories of Ground Behaviours

4.3.2 Records

The description of each Ground Behaviour Type has to contain at least:

- Ground Type(s)
- Orientation of relevant discontinuities relative to the underground structure
- Utilization of ground strength at tunnel perimeter and in representative volume
- Ground water, limits of ground water quantity/pressure under which ground behaviour type applies
- Sketch of expected ground structure
- Description of ground behaviour (type of failure mechanism, long term behaviour, etc.)
- Displacements, estimate of magnitude, orientation, and development over time

4.4 Selection of construction concept and evaluation of System Behaviour in the excavation area

After the Ground Types and the Behaviour Types have been determined, an appropriate construction concept is chosen for each characteristic situation.

The tunnelling concept in general contains:

- Ground improvement methods
- Dewatering methods
- Excavation method
- Excavation and support sequence
- Pre-supports
- Support concept
- Possible round length

Based on the tunnelling concept the system behaviour under consideration of the influencing factors in the excavation area is determined.

Influencing factors are:

- The ground behaviour
- Shape and size of underground opening, considering intermediate construction steps
- Round length
- Excavation method
- Spatial stress condition
- Ground water
- Subdivision of excavation cross sesction
- Support elements, as far as they influence the system behaviour in the excavation area

The system behaviour in the excavation area has to be shown in a graphical representation with indication of potential failure modes.

4.5 Detailed determination of construction measures and evaluation of system behaviour in supported area

After evaluating the system behaviour in the excavation area the construction measures are designed in detail. The stability of the face and the perimeter, subsequent construction steps, and boundary conditions have to be considered.

The next step involves the evaluation of the system behaviour (interaction between ground, support, additional measures, and construction sequence) and its comparison to the requirements.

4.5.1 Influencing factors

In addition to the above mentioned influencing factors, following factors have to be considered for the evaluation of the system behaviour in the supported area:

- Time and position of installation of support, as well as their time dependent properties
- Time dependent properties of the ground
- Subsequent excavation steps

4.5.2 Method

The method of analysis depends on the specific boundary conditions of the underground structure. Following methods are applicable:

- Closed form solutions
- Numerical simulations
- Experience from similar structures under comparable conditions

4.5.3 Analyses and Proofs

The system behaviour shall be analyzed and compared to the requirements.

Following has to be proven:

- the stability in all construction stages and the servicability in the final stage
- the compliance with environmental requirements (surface settlements, vibrations, ground water disturbance, etc.)
- displacements are within acceptable limits (admissible displacements, serviceability; system compatibility, etc.)

All analyses have to be documented in a traceable and auditable form.

The spread of the influencing factors, as well as the influence of the construction on the environment has to be considered. In general influencing factors are not available as deterministic values, but rather as a range or distribution. The influence of the spread of critical parameters on the system behaviour shall be analysed by means of a parametric study.

As the chosen construction measures strongly influence the system behaviour, an optimal choice of construction sequence and support measures a priori is the exception. Generally construction sequence and support measures have to be varied until a safe and economical construction process is obtained.

In case the required parameters cannot be determined with sufficient accuracy in advance, a geotechnical safety management plan has to be developed. This plan shall prescribe methods and procedures for the verification of assumptions, for assessment of the stability, for compliance with the environmental requirements, and for the determination of the appropriate construction and support methods.

4.5.4 Records

For characteristic conditions (for example ground conditions, section of tunnel, different sequence, support method, etc.) the expected system behaviour has to be described in a way that it can be verified during construction.

Typically this includes, but is not limited to:

- Amount, orientation, and development of displacements with time/distance to the face in all construction stages
- Required face support
- Subsidence in case of shallow tunnels
- Behaviour of supports (utilization of lining, deformation of bolt plates and yielding elements, etc.)

Above information serves also as input in the safety management plan.

4.6 Determination of tunnelling classes

For characteristic combinations of support measures and construction sequences the tunnelling classes are determined according to the Austrian standard ÖNORM B2203-1.

To establish the bill of quantities a prediction of the distribution of excavation classes is required. This distribution has to be established for the most probable case, as well as the spread in the distribution resulting from the spread of ground parameters and influencing factors. When establishing the distribution of excavation classes along the alignment not only the geological and geotechnical conditions, but also the heterogeneity of the ground has to be considered. In very heterogeneous ground, frequently changing the excavation and support methods in many cases will be technically and economically unfeasible. If the distribution of excavation classes is “homogenized”, the reasons have to be explained.

4.7 Geotechnical report

The results of the geotechnical design have to be summarized in a geotechnical report. In this report the single steps described in this guideline have to be described in a comprehensible and auditable form.

The geotechnical report shall be compiled in joint co-operation between designer, geologist and geotechnical engineer.

4.7.1 Contents

- A summary of the results of geological and geotechnical investigations, and the interpretation of the results
- A description of the Ground Types and the associated key parameters

- A description of the predicted Ground Behaviour Types, the relevant influencing factors, the analyses performed, and the geotechnical models used for determination of the behaviours
- A report on the determination of excavation and support, relevant scenarios considered (for example stability of unsupported area and face), analyses conducted, and design results
- Definition of the criteria for assignment of excavation and support method to the system behaviour in the excavation area
- Description of system behaviours in all construction stages
- The framework plan
- Distribution of tunnelling classes along the alignment

4.7.2 Contents of the Framework Plan

The framework plan shall contain following information:

- Geological model with expected distribution of Ground Types in a longitudinal section
- Expected system behaviour in the excavation area for the respective ground types and influencing factors (e.g. overburden, orientation between discontinuities and structure)
- Criteria for the determination of construction measures on site with respect to system behaviour in the excavation area
- Fixed excavation and support types (round length, excavation sequence, overexcavation, invert closure distance, support quality and quantity, etc.)
- Measures to be determined on site (support ahead of the face, face support, ground improvement, drainage, etc.)
- Description of expected System Behaviour in supported section (deformation characteristics, utilization of supports, etc.)
- Warning criteria and levels, as well as remedial measures according to the safety management plan

5 PHASE 2 - CONSTRUCTION

5.1 Basic procedure

Due to the fact, that in many cases the ground 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 detailed analyses of the system behaviour during construction serve as a basis for refining the geotechnical model. Conclusions shall be used for the determination of the construction measures. For geotechnical difficult projects a geotechnical engineer shall be employed on site.

The final determination of excavation methods, as well as support type and quantity in most cases is possible only on site. In order to guarantee the required safety, a safety management plan needs to be established.

Figure 3 shows the basic procedure to be followed for each section

Step 1 – Determination of the encountered Ground Type and prediction of ground characteristics

To be able to determine the encountered Ground Type, the geological documentation during construction has to be targeted to collect and record the relevant parameters specified in the design. Additional observations, like indications of overstressing, deformation and failure mechanisms, as well as results from probing ahead and the evaluation of the geotechnical monitoring are used to update the ground model and predict the conditions ahead of the face.

Step 2 – Assessment of system behaviour in excavation area

Based on the predicted ground conditions the system behaviour in the section ahead has to be assessed under consideration of the influencing factors, and compared to the framework plan. Particular attention has to be paid on potential failure modes.

Step 3 – Determination of excavation and support measures and prediction of System Behaviour in supported section

To determine the appropriate excavation and support the criteria laid out in the framework plan have to be followed. Consequently, it has to be checked if the actual ground conditions (ground type, system behaviour) comply with the prediction. The additional data obtained during construction form the basis for the determination of the applied excavation and support methods. The goal is to achieve an economical and safe tunnel construction.

The system behaviour has to be predicted for the next excavation section, considering ground conditions, and the chosen construction measures. Records have to be kept on this process.

Note: Both, excavation and support, to a major extent, have to be determined prior to the excavation. After the initial excavation only minor modifications, like additional bolts, are possible. This fact stresses the importance of a continuous short-term prediction.

Step 4 – Verification of System Behaviour

By monitoring the system behaviour (visually and by measurements) the compliance with the requirements and criteria defined in the geotechnical safety management plan is checked. When differences between the observed and predicted behaviour occur, the parameters and criteria used during excavation for the determination of the ground type and the excavation and support have to be reviewed. When the displacements or support utilization are higher than predicted, a detailed investigation into the reasons for the different system behaviour has to be conducted, and if required mitigation measures (like increase of support) ordered. In case the system behaviour is more favourable than expected, the reasons have to be analyzed as well, and the used parameters modified if appropriate. This allows for a continuous improvement and refinement of the method for assignment of excavation and support methods.

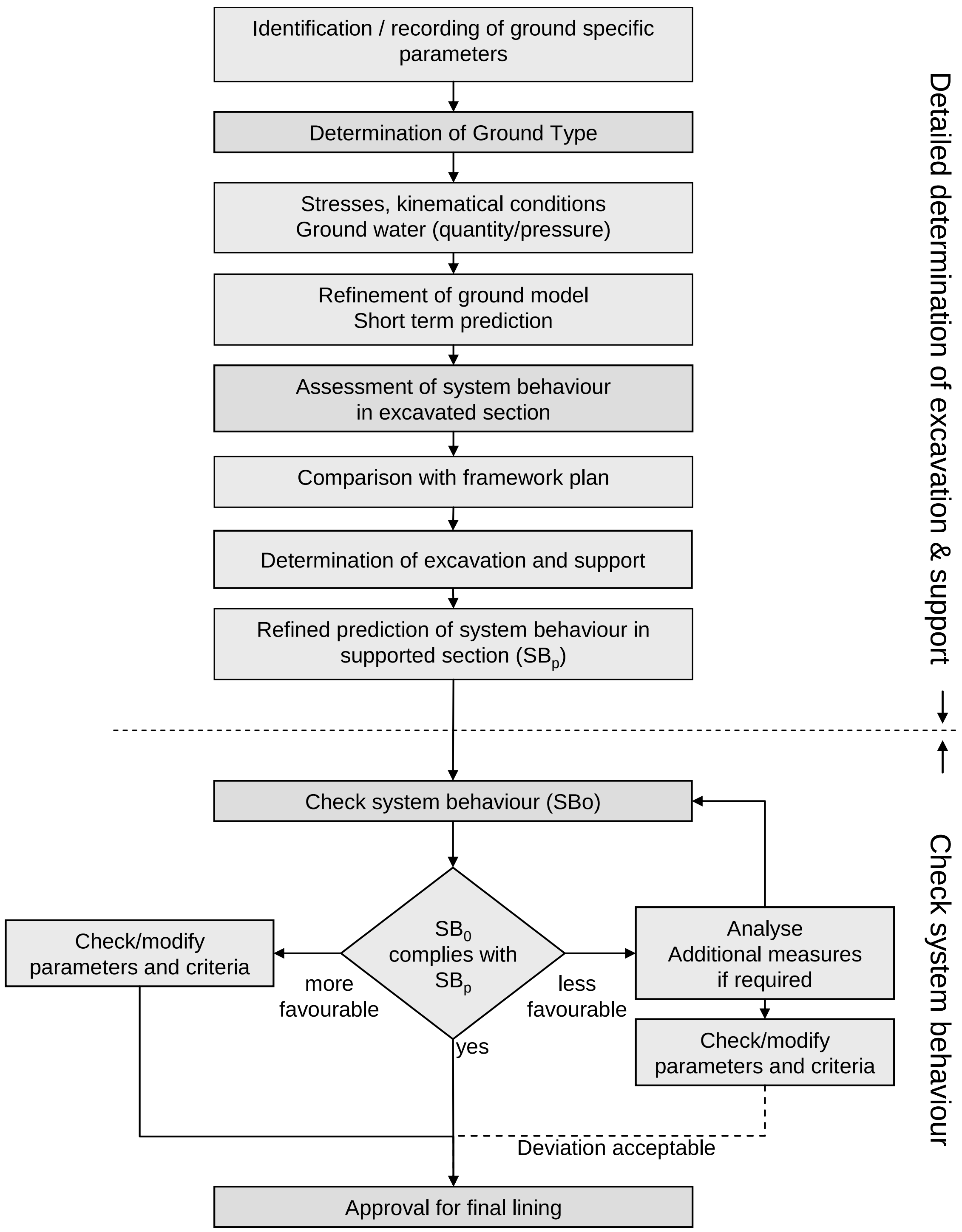

Figure 3: Basic procedure of determination of construction measures and check of system behaviour during construction (SB_p = predicted system behaviour, SB_o = observed system behaviour)

5.2 Determination of actual ground type

5.2.1 Preparation and method

During design key parameters had been defined for the identification of each ground type, considering that those can be recorded during construction. If required the recording of additional parameters, relevant for the system behaviour can be required during construction. The use of additional parameters has to be justified and agreed upon by all parties involved. Appropriate documentation is required.

Each of the key parameters is categorized. Whenever feasible, numerical values shall be used rather than descriptive data, like spacing, joint opening, strength, etc. Due to practical reasons some of the required parameters can only be described qualitatively.

Using predefined criteria the parameters are weighted and combined, allowing the appropriate Ground Types to be identified. A correlation matrix shall be used.

5.2.2 Collection of parameters on site and determination of ground type

Data collection on site has to concentrate on collecting relevant geological and geotechnical data and on observing and recording the ground structure. The data collected are recorded in prepared forms. With the criteria defined during the design, the Ground Type is determined. In heterogeneous ground conditions, the ground has to be divided into several sections, and the appropriate key parameters have to be collected for each section separately.

The geological and geotechnical data collected and evaluated on site are the basis for the extrapolation and prediction of the ground conditions into a representative volume. The geological work thus is not limited to recording the face conditions, but also has to involve predicting the conditions in the volume of rock that controls the ground response.

5.3 Assessment of system behaviour in the excavation area

5.3.1 Method

In addition to the parameters required to determine the Ground Type(s), influencing factors, like ground water conditions, ground structure, estimated stress situation, and kinematical conditions, as well as observations of the system behaviour in the excavation area shall be recorded.

The reaction of the ground to the excavation and support are observed by using an appropriate monitoring system.

Continuous evaluation of the mechanical processes in the excavated sections allows assessing the ground conditions outside the visible volume. Besides the geological prediction, an extended evaluation of monitoring data can help in modelling the ground conditions in a representative ground volume.

Applicable methods of analyses using the results of displacement measurements are:

- Analysis of the spatial stress redistribution by using deflection curves [25, 26]

- Extrapolation of displacement trends [27]
- Analysis of the displacement vector orientations and/or ratios of displacements of different monitoring points [28, 29, 30, 31, 32]
- Analysis of additional monitoring results (extensometers, inclinometers, etc.) [33]

The predicted ground structure in combination with the on site observations and monitoring results is used to predict the ground behaviour for the sections to be excavated next.

5.4 Determination of excavation and support and prediction of System Behaviour

5.4.1 Comparison with the Framework plan

For the final determination of the excavation and support method, it must be checked if the ground conditions and system behaviour observed on site conform to the design assumptions (according to the framework plan). When the observed conditions conform to the predicted ones, stipulations in the framework plan have to be followed when determining the construction measures. Additional locally required measures have to be set, even if those are not required explicitly in the framework plan.

In case of a deviation exceeding the specified tolerance in the framework plan, the designer has to be informed to allow for an adaptation of the prediction, based on new findings. The designer shall agree with the required additional measures in due time, and update the framework plan accordingly.

5.4.2 Decisions on site

The final decisions on the construction measures applied are based on the design and additional information gained during construction. The goal is a safe and economical construction. The decisions have to be coherently explained and documented, for example in an appendix to the excavation and support sheet.

5.4.3 Refinement of correlation criteria

During the design construction measures are assigned to each Ground Behaviour Type. The increase in information during the construction allows refining the criteria. In order to allow more accurate decisions on site, the categories for each parameter can be increased, or additional parameters defined. Changes in the criteria or parameter categories have to be supported with site data and evaluations. Changes in the parameter categories or criteria require an update of the framework plan.

5.4.4 Refinement of the prediction of the System Behaviour

With the increase in available information the actual ground behaviour and system behaviour can be predicted more precisely. The prediction generally is done for a section 10 to 20 m ahead of the actual face position.

The prediction of the system behaviour should contain (minimum requirements):

- Expected magnitude and orientation of the tunnel displacements, and the surface (if applicable), including the displacements spatial and time dependent development [32, 34, 35]
- Expected utilization factor of the support

5.5 Check of System Behaviour

Using observations of the system behaviour during excavation and evaluation and analysis of the measurement results, the actual system behaviour in the supported area and in the final stage is compared to the predicted, and checked, whether the behaviour is within the specified limits of the warning criteria. Additional measurements or evaluations may be required to determine for example the utilization of the lining [36, 37].

Deviations between the expected and the observed behaviours have to be analyzed and documented. The result of the analysis is basis for further decisions.

Observed system behaviour deviates from predicted

A discrepancy between observed and predicted system behaviours can have following reasons:

- Different geological or geotechnical conditions
- Actual ground behaviour different from the predicted
- Inappropriate parameter selection
- Wrong assumptions of the influencing parameters

The reasons for the deviation in behaviour have to be analyzed. In case the assumptions regarding the influencing factors are inappropriate, the parameters have to be modified. The modifications have to be supported by appropriate data and analyses and documented in an updated framework plan.

In case the ground quality is **better** than predicted, the geotechnical model has to be revised. In case of a significant deviation, the criteria for the determination of excavation and support have to be modified.

In case the ground quality is **worse** than predicted and warning levels exceeded, contingency measures according to the safety management plan have to be implemented, and excavation and support adjusted accordingly. This can be done for example by additional bolting, installation of a temporary invert, etc. In some cases the installation of a stronger support in the following rounds may be sufficient to achieve the target.

In case of significant deviations, the geotechnical model has to be revised. In case of a significant deviation, the criteria for the determination of excavation and support have to be modified. This generally requires that the framework plan is updated.

5.6 Updating of design

Due to limited information available during design, a number of assumptions and simplified models have to be used to arrive at a design, which is the basis for the framework plan and the tender documents.

To achieve the goal of a safe and economical construction it is required to continuously update the geotechnical design with the increasing level of information.

This applies to the determination of the ground types, the assignment and calibration of key parameters and criteria, as well as for the determination of the system behaviour. The refinement of parameter categories, the introduction of additional criteria, etc. help in improving the geotechnical model.

The geotechnical engineer on site has to report to the designer in case of significant deviations of the actual geological/geotechnical situation or system behaviour from the predicted ones, as outlined in the framework plan. A detailed report, containing all relevant information and coordinated with the site geologist and the representatives of the owner and contractor has to be prepared and submitted. After consideration of the facts, the designer has to update the framework plan. This has to be documented in a supplement to the geotechnical report.

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Appendix

Soil, rock, and ground parameters

Table of Contents

The following listing of parameters and references does not claim to be complete or exclusive. Actually decisive parameters of ground types have to be selected and evaluated according to the specific requirements of a geotechnical project.

1 INTACT ROCK

1.1 Description

- Rock name
  Applied classification system: [1, 2, 3, 4, 5, ÖNORM B 4401/3]
- Geotechnically relevant components, intercalations and variations should be given in percent per volume (vol.-%) and frequency.
- Mineral assemblage
  main and minor constituents (vol.-%), accessory minerals; cement, composition of components and matrix, contents/distribution of clay minerals qualitatively/quantitatively; (EN 12407, EN 12470, EN 12440, EN ISO 14689, [1, 2, 6, 7, 8, 9]
- Potential for swelling or aggressive behaviour: [9,10, 11]

1.2 Micro-Fabric

- Texture, micro-structure
- grain size, interlocking
- Micro-fractures [12, 13]
- Ratio of components to matrix, porosity, quantitative indices on grain fabrics ([2, 4, 5, 14, 15, 16, 17]

1.3 Condition of Rock and Rock Mass

- Tectonic or hydro-thermal alteration, disintegration
  cataclasis: [18, 19]
- Type of weathering
  applied classification system; discoloration, influence on material stregth, grain bonding, effect on discontinuity properties. [1, 2, 6, 20] 21, 22, 23, 24, 25, 26]
- Dissolution – transformation – neoformation of constituents or parts of rock mass (subrosion, karst formation)

1.4 Discontinuities, Macro-Fabric

- Macro structure
  (folding, bedding. Layering, schistosity, cleavage), type of discontinuity, age relationships, genensis
- Number and geometrical pattern of dominant discontinuity sets, size and shape of discontinuity-bounded blocks. [1, 2, 6, 17, 22, 26, 27])

1.5 Discontinuity properties

- Size measures (trace length – persistence, area)
  set-related distance, aperture, termination; [26, 28, 29]
- Alteration on discontinuities, filling, coating [22]
- Waviness - roughness, dilation angle, parameters of shear strength and stiffness of discontinuities [22, 28, 30, 31, 32]
- Characteristic measures of discontinuity intensity – density, rock mass permeability [6, 17, 29, 33, 34, 35] 36]

1.6 Strength Characteristics of Rock, Rock Mass

- Rock strength in shear, compression, tension, [37, 38]
- Elastic constants (e.g.: E, ν, G, V)
- Coulomb/Hoek-Brown parameters (e.g.: c, φ, mi, s, GSI): [32, 35, 39, 40, 41, 42, 43, 44]
- Point load-, Brazilian-, elastic rebound index values, [26, 45 46, 47, 48, 49, 50]
- Anisotropy with respect to rock or rock mass strength and deformability [22, 31, 51, 52, 53]
- Abrasivity, cuttability, ease of excavation, [15, 26, 54, 55, 56, 57, 58, 59, 60]
- Stability against wear, temperature changes, weathering and immersion. [11, 61, 62, 63], EN 1367/1, ÖNORM B3126/1-2, B 3128

2 SOIL

2.1 Soil Classification

- Definition of grain size classes
- Grain size distribution
- Properties of plasticity
- Constituents of organic origin [64, [65]

2.2 Parameters of the composite

- Specific weight, unit weight, density (ÖNORM B 4413, B 4414/1/2, DIN 18124, DIN 18125 T1/T2, DIN 18126, ASTM D 854)
- Grain size distribution (ÖNORM B 4412/1/2, B4401/3, B 3120, DIN 8196, DIN18123, DIN 4021 T1, ASTM D 2487, ASTM D 3282, ASTM D 422, EN 932/3/4, EN 933/1-6, [2], [5], EN ISO 14688)
- Porosity, structure - texture
- (ratio of components to matrix, kind and arrangement of the component framework (EN 1097/3-4, [5])
- Properties (and potential direction-dependence) of strength and deformability (ÖNORM B 4420, B 4416, B 4415, B 4411, DIN 18122 T1/T2, DIN 18127, ASTM 4318, ASTM 2435, ASTM D 2166, ASTM D 2850, ASTM D 3080)

2.3 Parameter of components

- Mineralogical composition of the main constituents, grain shape, see 1.1, 1.2, ÖNORM B4401/3, ASTM 2488, [5, 66]
- • State of components (e.g. weathering, alteration): see section 1.3, EN 1097/1-2, [6], ÖNORM B 3128
- Mineralogical composition of the main constituents, grain shape, see 1.1, 1.2, ÖNORM B4401/3, ASTM 2488, [5]
- State of components (e.g. weathering, alteration): see section 1.3, EN 1097/1-2, [6], ÖNORM B 3128

2.4 Parameters of matrix

- Mineralogical composition, contents of clay minerals and organic material, cementation [5], [9], EN 933/8-10

2.5 Permeability

ÖNORM B 4410, B4422/1/2, DIN18130 T1, ASTM: D 4643, D 4944, D 2434

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