Guideline for Geomechanical Design for Underground Structures with Continuous Excavation

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Richtlinie für die geomechanische Planung von Tunneln mit kontinuierlichem Vortrieb

Nachdem vor zwei Jahren die Richtlinie zur geomechanischen Planung (zyklischer Vortrieb) erschienen ist, wird zur Zeit eine ähnliche Richtlinie für den kontinuierlichen Vortrieb erarbeitet. Die ersten Schritte (Bestimmung von Gesteinsart, Gebirgsart und Gebirgsverhalten) entsprechen weitgehend dem zyklischen Vortrieb, während vor allem das Systemverhalten (in Planung und Ausführung) sowie teilweise die geologische und geotechnische Dokumentation je nach Maschinentyp wesentlich unterschiedliche Vorgangsweisen verlangen.

The Austrian "Guideline for the Geomechanical Design of Underground Structures with Conventional Excavation" has been valid for two years. A similar guideline for continuous advance (by TBM) is now in preparation. The first steps (determination of rock type and rock mass behaviour types) are quite similar to the cyclic excavation, the system behaviour, however, and the geotechnical and geological documentation diverge depending on the type of machine, thus requiring different measures.

Parallel to the development of the Austrian Standard B2203-2 (tunnelling by TBM) (1) the "Guideline for Geomechanical Design for Underground Structures with Continuous Excavation (TBM)" will be prepared by a working group of the ÖGG (Austrian Society for Geomechanics) (2). This guideline will be an integrative part of the new standard and will describe the procedure for the geomechanical design for underground structures within the different project phases. This paper describes the targets and the main elements of the guideline which is currently under preparation.

In general, this guideline will be structured according to the existing ÖGG-guideline for conventional excavation (2). The elements and procedures which are correlated to continuous tunnelling had to be adapted or extended. The choice of the excavation system that is feasible or best suitable for the expected ground conditions has to be made in an early stage with fundamental consequences for the total project and therefore has to be considered seriously. The same is true for the lining system which also must be decided on in an early stage and adaptations in a later stage can be rather restricted.

Table 1 Steps during design and planning – compared with the guideline for conventional excavation (2).

Tabelle 1 *Schritte während der Planung – verglichen mit der Richtlinie für den zyklischen Vortrieb (2).*

Main steps during design and planning	Remaining/changing
Step 1: rock mass type (RMT)	Will remain in principle but will focus or will be extended in view to parameters which are relevant for continuous excavation
Step 2: rock mass behaviour type (RMBT)	Will remain in principle
Step 3: excavation and support; system behaviour types (SBT)	Will remain in principle but will consider in detail the features of the continuous excavation and support system in view to "temporary system support" (TSS)
Step 4: baseline construction plan	Will remain in principle but will focus on "advance relevant parameters" and special or additional measures
Step 5: rock mass classes	Will remain in principle but will follow the Austrian standards ON B2203/2

The aim is to keep within the main steps of the guideline established for conventional excavations which has provided good results in practice, but to focus to the special requirements of continuous excavation and related lining systems.

As a design instrument the consistent procedure integrates the rock mass characterization and the excavation and support determination into the design and construction stages of an underground structure.

This leads to a sound and transparent geomechanical design which is the basis for safety and risk management during the entire process of project development. Additionally, the systematic approach simplifies the communication between the different people involved in design and construction and allows different projects to be compared.

What are the main differences compared with the guideline for conventional excavation?

The basic procedure for the geomechanical design as outlined in the "Guideline for the Geomechanical Design of Underground Structures with Conventional Excavation" (2) consists of the following key elements:

- Rock mass characterization based on geomechanically relevant key parameters,
- Determination of the rock mass behaviour for the unsupported tunnel,
- Determination of the excavation and support method and determination/evaluation of the behaviour of the system "rock mass, excavation and support".

This basic concept is implemented into procedures for design and construction and builds the basis for the definition of minimum requirements of documentation or safety management (3, 4).

The consistent procedure provides transparency in rock mass characterization and classification throughout the entire design process and leads to comparability between various projects. It supports data acquisition and data processing with focus on the rock mass behaviour which allows the engineering assessment of the results.

Considering the main steps of the design guideline the main changes or alterations compared with the guideline for conventional excavation are outlined in Table 1 for the design stages and for the construction Table 2.

Phases of the "design stage"

The flowchart for design for continuous excavation (Figure 1) shows the main steps of the design process. The flowchart is, in principle, based on the design process for conventional excavation.

The main difference is that the determination of excavation and support is not only restricted to the adequate measures, but also to the adequate system. This means, that the decision for the feasibility of continuous (TBM-) excavation in general, as well as the decision for the type of the excavation system (open type TBM with conventional support, shielded TBM with segmental lining or a system working under pressure like Slurry or EPB) has to be taken in an early design stage.

Rock mass types (RMT)

The definition of rock and rock mass types is similar to the cyclic advance. However, with a continuous excavation TBM-specific parameters are considered more intensely, e.g.:

- Parameters influencing the penetration (grain texture, mineral boundary forces, abrasive minerals, anisotropy due to schistosity and cleavage, compressive and tensile strength, degree of separation),
- Parameters concerning the geotechnical properties of the rock mass concerning stability,

Table 2 Steps during construction – compared with the guideline for conventional excavation (2).

Tabelle 2 *Schritte während der Bauausführung – verglichen mit der Richtlinie für den zyklischen Vortrieb (2).*

Main steps during construction	Remaining / changing
Step 1: actual rock mass type (RMT-actual)	Will remain in principle but will be mainly be based on indirect methods derived from data from the excavation system
Step 2: actual rock mass behaviour type (RMBT-actual)	Will remain in principle but will be mainly be based on indirect methods derived from data from the excavation system
Step 3: actual excavation and support; actual system behaviour type (SBT-actual)	Will remain in principle but will mainly focus on requirements for additional or special measures
Step 4: actual baseline construction plan	will remain in principle but will mainly focus on requirements for additiona or special measures
Step 5: geotechnical safety- and risk management	Will remain in principle but will mainly focus on "learning" to avoid unfavourable interruptions of advance

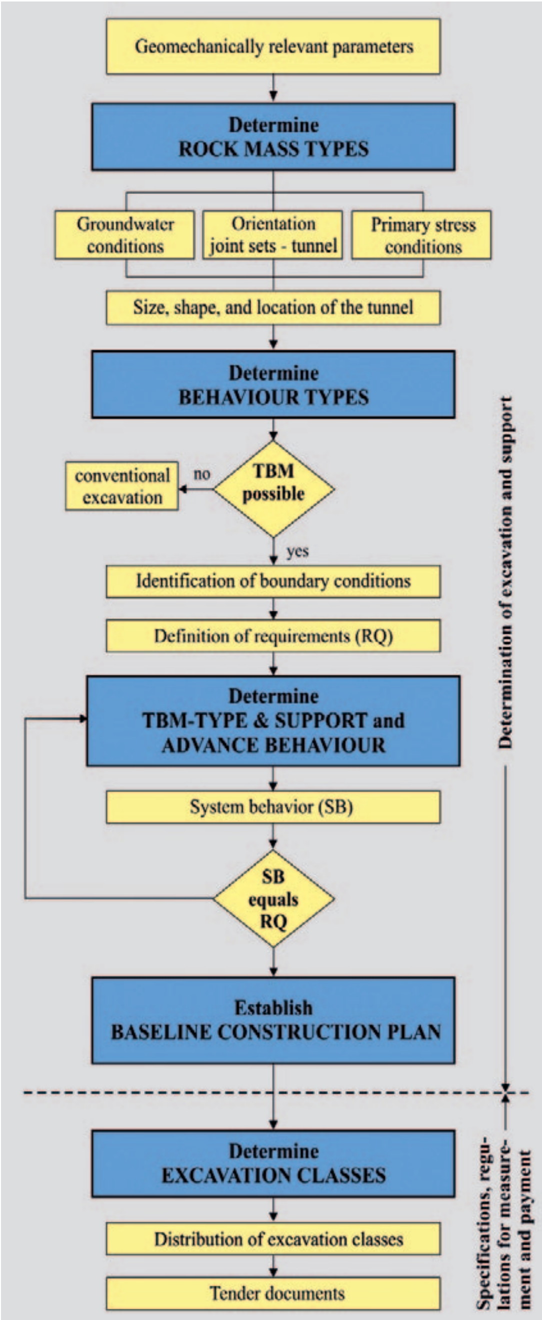

Fig. 1 Flowchart for the geomechanical design for continuous excavation.

Bild 1 *Ablaufdiagramm für die geomechanische Planung bei kontinuierlichem Vortrieb.*

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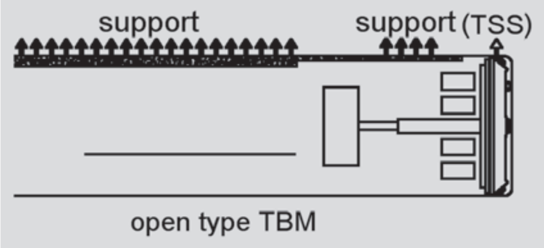

Fig. 2 Open type TBM with associated temporary support and temporary system support.

Bild 2 *Offene TBM mit zugehörigem Ausbau und Ausbauwirkung aus Vortriebssystem.*

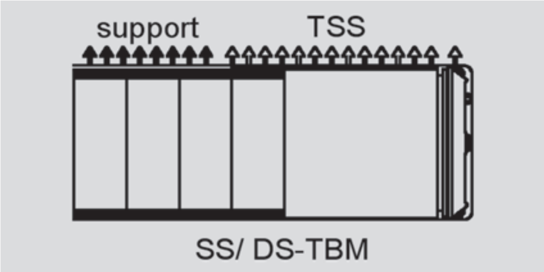

Fig. 3 Single- or double shield TBM with associated support and temporary system support.

Bild 3 *Einfach- oder Doppelschild TBM mit zugehörigem Ausbau und Ausbauwirkung aus Vortriebssystem.*

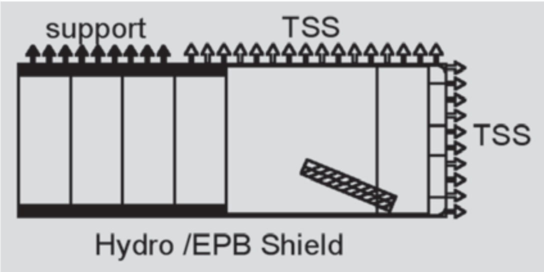

Fig. 4 Hydro- or EPB shield TBM with associated support and temporary system support.

Bild 4 *Flüssigkeits- oder erddruckgestützte Schild-TBM mit zugehörigem Ausbau und Ausbauwirkung aus Vortriebssystem.*

standup-time or the time dependent behaviour,

- Parameters which indicate the changing potential of the rock mass together with time, deformation and water, like post failure properties,
- Parameters which might give rise to special measures together with e.g. mixed face conditions, greater fault zones, propensity to stick, liquefaction potential.

Parameters obtained by semiquantitative rating systems (5, 6) make sense in the first phase for the first evaluations or for the comparison of route corridors, penetration rates or utilization grades should not be derived by these methods.

Rock mass behaviour types (RMBT)

The rock mass behaviour types generally are the same as in the conventional advance. They serve to indicate the geotechnical behaviour of the rock mass types during excavation. It is a theoretical step to consider the unsupported rock mass behaviour to gain adequate support requirements.

Indicators for the rock mass behaviour must be defined which might be representative for the overall behaviour. Such parameters can be:

- Stress/strength factor at the tunnel wall after excavation which is indicating the potential of overstressing and rock mass disintegration during excavation,
- Unsupported deformation potential,
- Radius of “plastification” or depth of unsupported rock mass disintegration,
- Unsupported face stability factor.

The rock mass behaviour types provide the basis for the selection of the excavation- and support system most appropriate for ensuring stability and achieving the best advance rates with the lowest risk related to the complete tunnel length.

Excavation and support system behaviour

The step to decide for the adequate excavation- and support system is the most important step within the design phase. The decision has to consider the following aspects:

- Adequate excavation system to deal with the rock and rock mass properties to achieve high adequate advance rates (hard rock TBM, soft rock TBM, mixed system, system to be adapted)
- Need and extension of a temporary system support (TSS) and adequate choice of the type of TBM,
- Geometrical properties and restrictions together with the advance behaviour of the system (location and time for 1st support),
- Compatibility and restrictions for deformations of the rock mass (convergences) related to preconvergences, overcutting and convergence restrictions within the support area,
- Bearing capacity of the system components (shield, rear shield) and the support or lining elements as well,
- Applicability and capacity of additional and special measures to be applied under extraordinary conditions.

The most suitable excavation system concept has to be chosen from the three available basic types:

- More or less no temporary system support (open type TBM, Figure 2),
- With temporary system support within the shield range where the support- or lining system is installed (Single- or double shield TBM, Figure 3),
- With temporary system support within the shield range as well as at the face (Slurry, EPB, Figure 4).

The “advance/support” character of the individual system must be considered within the step of determining the "TBM-type/support and advance behaviour".

Due to the development of TBM-tunnelling in rock, the excavation and lining systems are tending to become more and more universal. The result is that an increasing range of rock mass behaviours can be managed more or less at the full capacity of the system. Therefore, it becomes less important to classify within this universal range (7, 8).

The definition of the charact eristics and relevant parameters of fault zones that may limit the TBM-advance become crucially important.

Baseline construction plan and classification for excavation

The “baseline construction plan” in principle contains the prognosis of the main geological, geotechnical and hydrogeotechnical properties, together with the measures to excavate, to support, to treat and finally to line the tunnel. It is prepared in form of a longitudinal tunnel section and is subdivided into certain "homogeneous" regions with "similar" properties.

The subdivision into "homogeneous" sections is based on the geological (RMT) and the geotechnical (RMBT) characteristics of a single section and is made with regard to the expected "homogeneous" excavation and boring conditions. The subdivision is made in line with the standards for continuous excavation (1).

Within each range, the prognosis for the "regular", the "additional" and the "special" measures is given:

- The "regular" measures contain the common excavation and support conditions within each range which has been the primary basis for design or choice of the excavation and support system.
- The "additional" measures must be seen as an extension of the regular measures to overcome conditions which might decrease the regular advance. Anyhow, the excavation and support system must be prepared to carry out "additional" measures without complications.
- The "special" measures are designed to overcome extraordinary and singular situations. They are expected to occur with a certain probability that is determined during risk assessment. Such "special" measures normally require more or less intense interruptions of the regular advance.

The general aim of the baseline construction plan is to provide all measures required, together with their deviation, to overcome the complete tunnel length.

Phases of the construction stage

During construction when continuous excavation methods are utilized the excavation and lining system in general must be accepted as it behaves and can be adapted only within certain limits. More or less the only variability to react to adverse geological and geotechnical conditions is to implement "additional" or "special" measures. To provide sufficient time for the implementation of these measures the adverse conditions have to be detected and evaluated as early as possible.

For the identification of the actual rock mass type the following parameters (like for the rill and blast excavations) have to be determined:

- Hard rock mass: rock type, grain texture, strength parameters of intact rock and rock mass, degree of fracturing, boreability, abrasivity, joint quality,
- Soft rock: rock type, grain parameters , parameters of the components, parameters of the matrix, packing density, water content.

However, one problem that arises in determining the encountered rock mass types, as well as the rock mass behaviour types, is that they cannot be directly observed because access is restricted by the chosen excavation system. Therefore, indirect methods must serve to complete the direct information about the rock mass.

A second problem is that in case of continuous excavation at high advance rates, the actual rock mass parameters cannot be determined metre by metre but must be determined as statistical values with their statistical parameters.

"Actual" rock mass behaviour

In case of continuous excavation unsupported areas are well provided and unsupported behaviour can well be detected to check the proposed "unsupported" rock mass behaviour (RMBT). By that way the actual rock mass behaviour becomes the most important indicator to determine the adequacy of the regular support system considered and the special and additional measures required.

For the determination of the actual rock mass behaviour the following observations can be used:

- Rock mass disintegration at the tunnel walls,
- Actual (unsupported) convergence development,
- Squeezing phenomena,
- Rock mass disintegration at the tunnel face (blocky face),

- Actual (time dependent) face stability.

The observation of the relevant data can be achieved by direct and indirect methods as well.

"Actual" behaviour of the excavation and support system

By quantifying the actual behaviour of the excavation and support system it can be determined if the chosen method was adequate or not, as well as where and when the additional or special measures have to be applied.

Together with the determination of the actual rock mass behaviour as outlined above, the main goals of the evaluation of the actual system behaviour are the following:

- Determination of the unsupported behaviour (deformation behaviour and stability behaviour of the tunnel face and the tunnel walls),
- Behaviour of the temporary support system (TSS) together with the advance (time dependent loads on the temporary support system),
- Behaviour of the permanent support (utilization, deformation),
- Behaviour and effect of the additional measures,
- Behaviour and effect of the special measures.

The indications about the above behaviour must be gained from a combination of direct and indirect methods.

Additional and special support measures

Additional and special measures are the major tools to react to special conditions which should be restricted to small and certain ranges (additional measures) or to extraordinary cases (special measures) only. The only indicator is the rock mass and system behaviour.

Since the excavation and support system is highly, but individually linked to the rock mass to be excavated and supported, there is always a kind of learning process until the "answer" of the system to the "language" of the rock mass is well acknowledged, interpreted and understood. Therefore a learning process must always be considered until the additional and special measures can be applied with their adequate efficiency.

As a kind of "learning" instrument the baseline construction plan must permanently be adapted to the actual findings. In detail this means the documentation of:

- Actual geological properties and actual rock mass behaviour (as far as possible),
- Actual advance,
- Actual need for additional measures,
- Actual need for special measures.

Shield TBMs allow only an indirect assessment of geological or geotechnical parameters of the rock mass mainly by chips, calculation of the machine parameters (10, 11), pressure cells at the tubings, gap filling and so on.

The actualization of the baseline construction plan is clearly working out the gap between the design and the actual requirements. Since the adoption to the actual needs or requirements is part of design, safety and risk management the baseline construction plan is an integrative part of these tools.

Geotechnical safety and risk management

As already lined out in the guideline for conventional excavation, the geotechnical safety and risk management is an integrative part of a self-learning system which tunnelling always will remain.

For continuous excavation methods this self-learning system must be extraordinary sensitive due to the following facts:

- The major length of the tunnel must be overcome with the regular system which requires more or less no special reaction (effect of no training for the risk management),
- At high and steady advance rates a number of problems do not appear which otherwise become rather relevant when the advance is disturbed or interrupted (hysteresis effect),
- The relevant safety or risk scenarios mostly become due as a combination of geological, hydrogeological but also logistic matters (effect of combined origin).

For that reason attention must be paid to the individual indicators of the safety and risk management in a special way (12, 13, 14):

- "normal behaviour": also under normal conditions the degree of safety and the tendency to get out of the normal range must be permanently monitored,
- "reaction-phase": the reaction must be turned into prevention as soon as this is indicated by a unfavourable tendency – the goal is to remain under steady advance,
- "extraordinary situation": if extraordinary situations will appear the application of the special measures must be well prepared.

In this sense special treatment and assessment of fault zones and their properties is necessary (e.g. thickness, intensity of separation, water load, stress conditions, mixed face) and are the main influence to the risk distribution (14, 15, 16).

Conclusions

The guideline under preparation should provide a proper tool for the design procedure for continuous (TBM) tunnelling during all stages. The concept, in general, is similar to the concept of the existing guideline for conventional excavation which has proved to work quite well. But anyhow the new guideline considers the very special character of continuous or TBM tunnelling; thus, because steady interactions between machine and support measures take place.

As the main measures are fixed and variations are limited, a careful investigation especially of the risk parameters has to be completed in the design stage (17).

The concept which is presented within this paper is under final preparation and will be completed by examples which already have been designed following the concept above. It is planned to finish the guideline in time with the Austrian standard.

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