

# The Guideline for the Geomechanical Design of Underground Structures with Conventional Excavation

By Wulf Schubert, Andreas Goricki and Gunter Riedmüller

**C**urrently, there are no standardized procedures to determine excavation and support for underground openings. This lack of consistency makes it difficult to technically review or audit designs, collect, evaluate, and compare data from different sites and designs.

A sound and economical tunnel design depends on a realistic geological model (2), a quality rock mass characterization, and the assessment of influencing factors such as primary

stresses, groundwater, and the size of underground opening. Despite this requirement it is still current practice to base the tunnel design primarily on experience, basic empirical calculations, and standardized rock mass classification systems. Additionally, the on site decisions on excavation and support modifications are frequently based more on intuition than on analyses. This is especially true for tunnels with high overburden in complex geological conditions

## Richtlinie für die geomechanische Planung von Untertagebauarbeiten mit zyklischem Vortrieb

*Die Werkvertragsnorm ÖNORM B2203 regelt die vertraglichen Belange im Untertagebau. Die Fassungen von 1983 und 1994 enthalten auch Elemente der Gebirgstypisierung. Im Zuge der Überarbeitung der ÖN B2203 im Jahr 2001 wurden alle Belange der Gebirgscharakterisierung aus der Werkvertragsnorm eliminiert. Eine Arbeitsgruppe der Österreichischen Gesellschaft für Geomechanik erstellte eine Richtlinie für die geomechanische Planung von Untertagebauarbeiten mit zyklischem Vortrieb, die im Oktober 2001 erschien und auf welche die ÖNORM B2203-1 Bezug nimmt. Die Richtlinie beschreibt die für eine Planung und Bauausführung von Untertagebauten erforderlichen Schritte aus technischer Sicht. Der in der Richtlinie skizzierte schrittweise Vorgang soll einen ingeniermäßigen Zugang zur Thematik fördern.*

*In der Planungsphase basieren die Vortriebs- und Ausbaukonzepte auf Gebirgsverhaltenstypen, die aus den Gebirgsarten und den das Verhalten beeinflussenden Faktoren abgeleitet werden. Das Systemverhalten beschreibt das Verhalten des Systems Ausbau-Gebirge. Die Ermittlung des Systemverhaltens stützt sich auf Datenauswertung ausgeführter Projekte und wird durch numerische Simulationen an geeigneten Modellen unterstützt. Während des Baus wird die Planung mithilfe von geologischen Aufnahmen, Beobachtungen und Auswertung von Messungen verfeinert. Das vorhergesagte und beobachtete Verhalten wird laufend verglichen. Treten Abweichungen zwischen prognostiziertem und beobachtetem Verhalten auf, ermöglicht die systematische Vorgangsweise eine umfassende Analyse. Damit wird eine ständige Weiterentwicklung des Tunnelbaus ermöglicht und gefördert.*

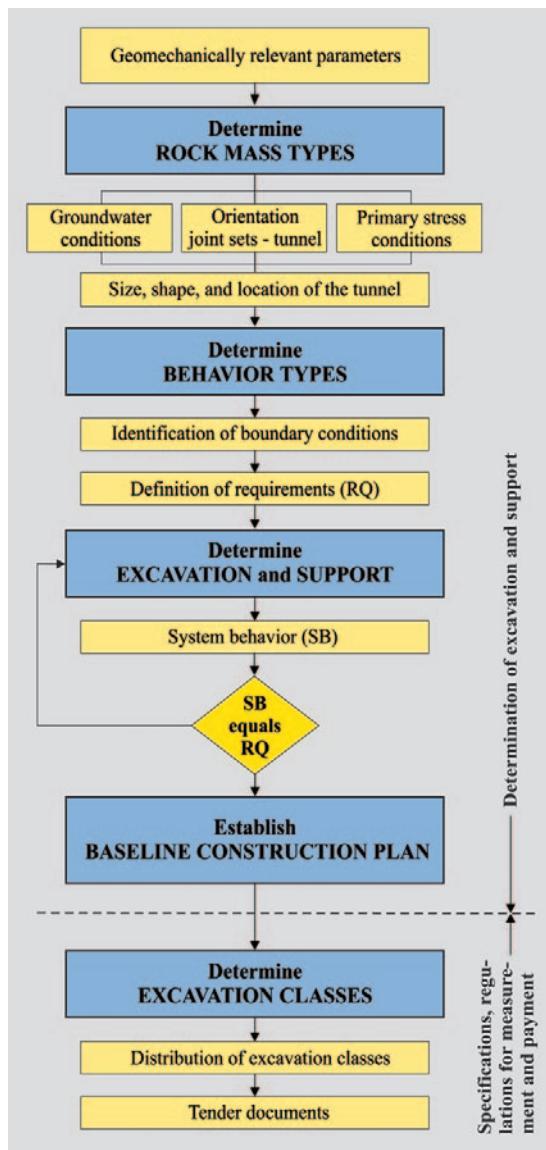
*Bei Einhaltung des in der Richtlinie vorgegebenen Ablaufs ist eine relativ einfache technische Überprüfung der Planung möglich. Die in der Richtlinie geforderte durchgängige Dokumentation sollte zudem ermöglichen, die*

*Erfahrungen verschiedener Bauwerke besser nutz- und vergleichbar zu machen, was auf längere Sicht zu einer Verbesserung von Planungs- und Baumethoden führen sollte.*

The Austrian Standard B2203 regulates the contractual procedure for underground works. The versions of 1983 and 1994 contained descriptions of rock mass types. In the course of updating the Standard in 2001 it was decided to remove all rock mass characterization issues from the Standard. A working group of the Austrian Society for Geomechanics (OGG) established a guideline for the geomechanical design of underground structures, which was published in October 2001, and to which the Standard B2203-1 refers (1). The main topic of the guideline is the development of a consistent procedure for the determination of excavation and support. The outlined step by step procedure promotes an engineering approach to the design and construction of tunnels.

In the pre-construction phase support concepts are based on rock mass behaviour types developed from rock mass types and influencing factors. The system behaviour describes the rock mass-support interaction which is based on previous experience (including data base knowledge), analytical and numerical simulations. During construction, geological face mapping, geotechnical monitoring, and observations allow the design of support and excavation methods to be completed. The observed and predicted behaviours are compared by evaluating monitored deformations, support utilization, and overbreak volume. Deviations between the observed and predicted behaviour lead to a re-evaluation of the process resulting in modifications to the support and excavation methods.

The consistent procedure allows designs to be technically reviewed and audited. The standardized approach should also allow the establishment of knowledge based expert systems, which in the long run will improve design and construction methods.



**Fig. 1** Flow chart of the basic procedure of excavation and support design for underground structures.

## **Bild 1** Flussdiagramm der grundsätzlichen Vorgangsweise zur geotechnischen Planung von Ausbrüchen und Stützung von Untertagegebäuden.

where limited information is available in the pre-construction phase.

On the other hand, the quantitative rock mass classification systems presently in use (3, 4, 5, 6) have severe shortcomings. One of the main deficiencies is that the classification parameters are universally applied to all rock mass types. Especially in heterogeneous and poor ground conditions these classification methods may provide misleading results, while other shortcomings include the lack of consideration for different rock mass failure modes and ground-support interaction (7). These schematic procedures have the potential to make tunnel design appear rather simple. Frequently, a few specific parameters are determined and simple classification formulas are applied to achieve a rating. Then with a design chart a support method is determined. No reference is made to project specific requirements or to boundary conditions.

For this reason, it was decided to develop a consistent method for tunnel design, from the pre-construction phase through the tunnel construction, applicable to all rock mass conditions. In general, the final design process continues

into the construction phase. The procedure developed describes a transparent and unbiased decision making process and was published in the form of a guideline (8).

The guideline clearly distinguishes between rock and rock mass descriptions, behaviour of the rock mass as a result of the excavation, and the system behaviour resulting from excavation and support. The minimum requirements for the documentation of each step are given in the guideline.

First the procedure for the design phases is briefly described, and then the procedures for the construction phase are discussed, as they are outlined in the guideline.

## **Procedure during design**

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 (9).

The flow chart (Figure 1) shows the basic procedure, consisting of five general steps, to develop the geotechnical design, beginning with the determination of the rock mass types and ending with the definition of excavation classes. During the first two steps statistical or probabilistic analyses should be used to account for the variability and uncertainty in the key parameter values and influencing factors, as well as their distribution along the projects route (10). The probabilistic analyses are then continued throughout the entire process as necessary, resulting in both a risk analysis and a distribution of excavation classes on which the tender documents can be based (11).

### **Step 1 – determination of rock mass types (RMT)**

The first step starts with a description of the basic geologic architecture and proceeds by defining geotechnically relevant key parameters for each ground type. The key parameters values and distributions are determined from available information or estimated with engineering and geological judgment. Values are constantly updated as pertinent information is obtained. Rock mass types are then defined according to their key parameters. The number of rock mass types elaborated depends on the project specific geological conditions and on the stage of the design process.

Physical and hydraulic parameters have to be established for each rock mass type (12, 13, 14).

## **Step 2 – determination of rock mass behaviour types (BT)**

The second step involves evaluating the potential rock mass behaviours considering each rock mass type and local influencing factors, including the relative orientation of relevant discontinuities.

nuties to the excavation, ground water conditions, stress situation, etc. (15, 16, 17). This process results in the definition of project specific behaviour types.

The rock mass 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.

Eleven general categories are listed in the guideline (Table). In case more than one behaviour type is identified in one of the general categories, sub types have to be assigned. A concise description of the applicable rock mass types, the influencing factors, the specific behaviour, failure modes, as well as estimates of the displacements for each behaviour type is required.

The rock mass behaviour types form the basis for determining the excavation and support methods as well as assist in evaluating monitoring data during the excavation.

### Step 3 – determination of the excavation and support

Based on the defined project specific behaviour types, different excavation and support measures are evaluated and acceptable methods are determined. The system behaviour (SB) is a result of the interaction between the rock mass behaviour and the selected excavation and support schemes. The evaluated system behaviour has to be compared to the defined requirements. If the system behaviour does not comply with the requirements, the excavation or support scheme has to be modified until compliance is obtained. It is emphasized, that different boundary conditions or different requirements may lead to different support and excavation methods for the same behaviour type even within one project.

Figure 2 illustrates the process of determination of the behaviour type on the full, unsupported cross section, and the influence of the reduction of the face height, and finally the system behaviour of the supported top heading. Once the acceptable excavation and support methods have been determined both risk and economic analyses should be performed to allow appropriate assessments during the tender process (11).

**Table** General categories of rock mass behaviour types.

**Tabelle** Übergeordnete Kategorien von Gebirgsverhaltenstypen.

| Behaviour type (BT)  | Description of potential failure modes/mechanisms during excavation of the unsupported rock mass   |
|--|--|
| 1 Stable   | Stable rock mass with the potential of small local gravity induced falling or sliding of blocks  |
| 2 Stable with the potential of discontinuity controlled block fall | Deep reaching, discontinuity controlled, gravity induced falling and sliding of blocks, occasional local shear failure   |
| 3 Shallow shear failure  | Shallow stress induced shear failures in combination with discontinuity and gravity controlled failure of the rock mass  |
| 4 Deep seated shear failure  | Deep seated stress induced shear failures 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 failure   | Buckling of rocks with a narrowly spaced discontinuity set, frequently associated with shear failure   |
| 7 Shear failure under low confining pressure                       | Potential for excessive overbreak and progressive shear failure with the development chimney type failure, caused mainly by a deficiency of side pressure                                    |
| 8 Ravelling ground   | Flow of cohesionless dry or moist, intensely fractured rocks or soil   |
| 9 Flowing ground   | Flow of intensely fractured rocks or soil with high water content  |
| 10 Swelling  | Time dependent volume increase of the rock mass caused by physical-chemical reaction of rock and water in combination with stress relief, leading to inward movement of the tunnel perimeter |
| 11 Frequently changing behaviour                                   | Rapid variations of stresses and deformations, caused by heterogeneous rock mass conditions or block-in-matrix rock situation of a tectonic melange (brittle fault zone)                     |

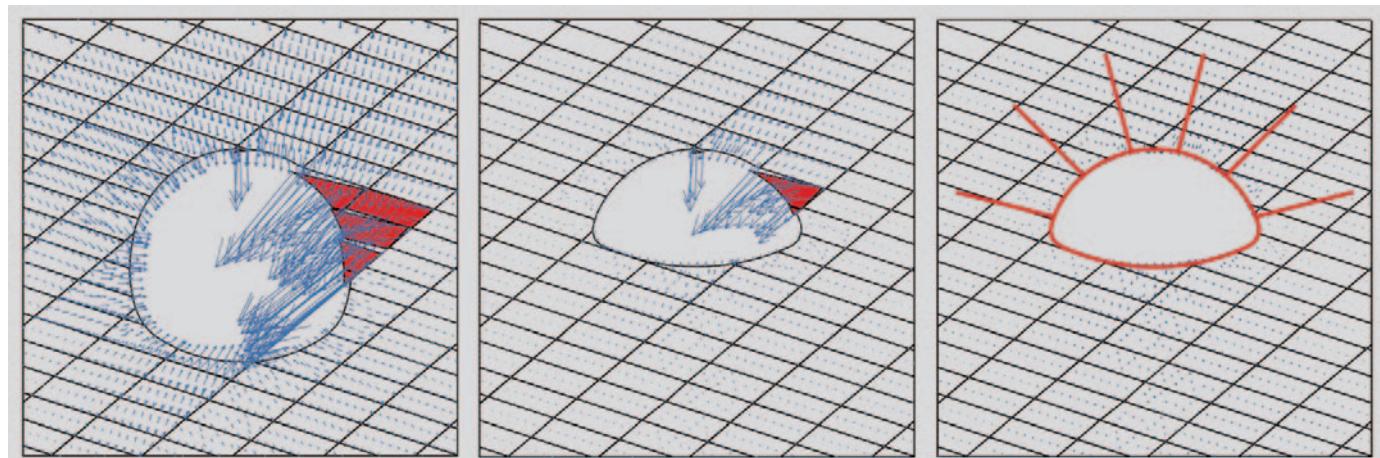
### Step 4 – geotechnical report – baseline construction plan

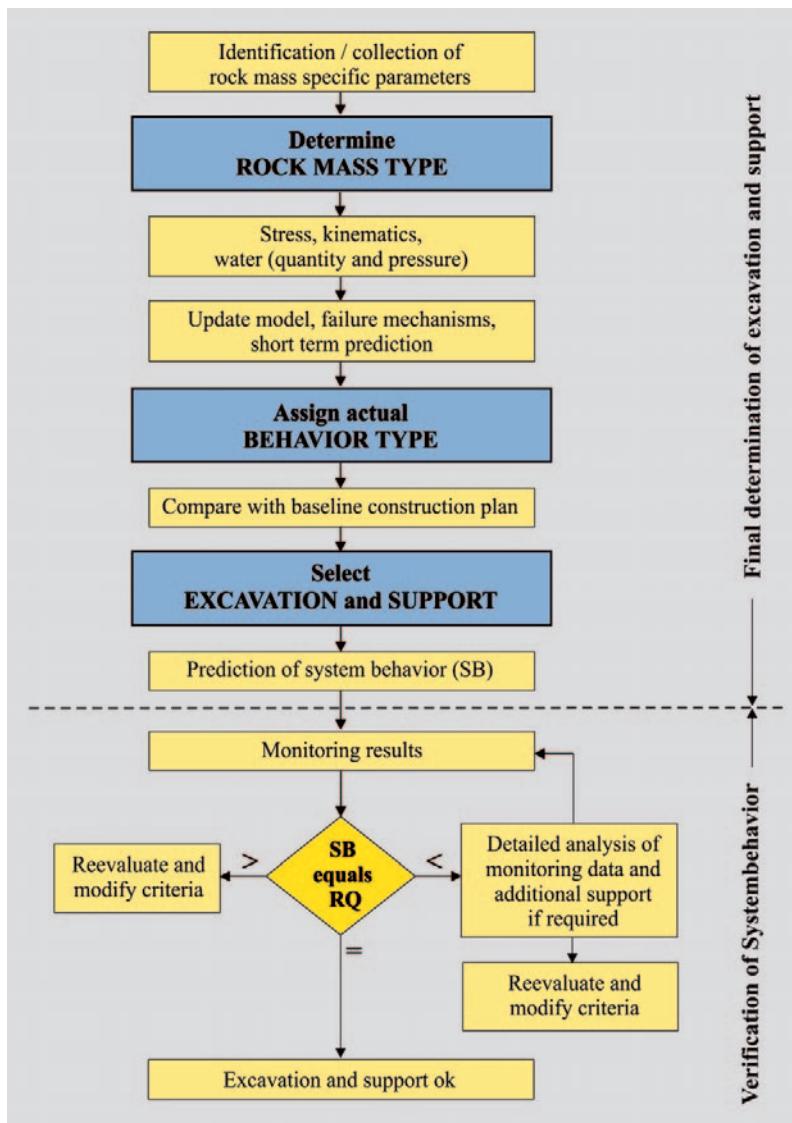
Based on steps 1 through 3 the alignment is divided into "homogeneous" regions with similar excavation and support requirements. The baseline construction plan indicates the excavation and support methods available for each region, and contains limits and criteria for possible variations or modifications on site. The plan summarizes the geotechnical design and should contain following information:

- ⇒ Geological model with distribution of rock mass types and behaviour types in a longitudinal section,

**Fig. 2** Numerical analysis of the rock mass behaviour for a full section (left); the influence of a reduced face height (centre), and the system behaviour with installed support (right).

**Bild 2** Numerische Analyse des Gebirgsverhaltens am vollen Querschnitt (links), des Einflusses einer reduzierten Ausbruchhöhe (Mitte) sowie des Systemverhaltens mit Ausbau (rechts).





**Fig. 3** Flow chart of basic procedure for excavation and support selection and verification of the system behaviour during construction

**Bild 3** Flussdiagramm der grundsätzlichen Vorgangsweise bei der Festlegung von Ausbruch und Stützung und Überprüfung des Systemverhaltens während des Baus.

- Sections, where specific requirements for construction have to be observed,
- Fixed excavation and support types (round length, excavation sequence, overexcavation, invert distance, support quality and quantity, ground improvements, etc.),
- List of measures to be determined on site (support ahead of the face, face support, ground improvement, drainage),
- Description of system behaviour (behaviour during excavation, deformation characteristics, utilization of supports),
- Warning criteria and levels, as well as contingency measures according to the safety management plan.

This is the final step in the geotechnical design process. All possible geological conditions should be addressed with a defined range of excavation and support methods as well as the probability or likelihood of occurrence.

#### Step 5 – determination of excavation classes

In the final step of the design process the geotechnical design must be transformed into a cost and time estimate for the tender process. Exca-

vation 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 evaluation of excavation classes is based on the regulations in ONORM B2203-1. In other locations the local or agreed upon regulations should be used.

The distribution of the expected behaviour types and the excavation classes along the alignment of the underground structure provides the basis for establishing the bill of quantities and the bid price during tender.

#### Procedure during construction

Due to the fact, that in many cases the rock mass 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 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 followed. Figure 3 shows the basic procedure to be followed for each section.

#### Step 1 – determination of the encountered rock mass type

To be able to determine the encountered rock mass type, the geological investigation (documentation) during construction has to be targeted to collect and record the relevant parameters that have the greatest influence on the rock mass behaviour (18, 19, 20). The geological and geotechnical data collected and evaluated on site are the basis for the extrapolation and prediction of the rock mass conditions into a representative volume (rock mass volume, which determines the behaviour). In addition to recording the face conditions, geologists need to predict the conditions in the volume of rock that controls the behaviour.

Predefined criteria and weighted parameters are used to identify the appropriate rock mass type.

#### Step 2 – determination of the actual rock mass behaviour type

Observations during excavation, such as signs of excessive stress, deformation pattern and observed failure mechanisms, and results from probing ahead are used to continuously update the geotechnical model. The reaction of the ground to the excavation has to be observed, using appropriate geotechnical monitoring methods and layouts. Based on observations and measurement results during construction a short-term prediction is made, and the actual rock mass behaviour type for the coming excavation step is determined (21, 22).

### Step 3 – determination of excavation and support

To determine the appropriate excavation and support the criteria laid out in the baseline construction plan have to be followed. Consequently, the actual rock mass conditions (RMT, BT) continuously have to be compared to the prediction for compliance. A continuous detailed analysis of the rock mass behaviour is used to update the geotechnical model. 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.

Based on the evaluated behaviour type, and the excavation and support layout determined according to the defined criteria, the system behaviour for each section has to be predicted (23).

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.

Figure 4 shows an example for the determination of excavation and support on site. To determine the rock mass type, the rock type, strength of the rock, spacing of foliation planes and slickensides, joint fillings and contact, thickness of cataclastic zones, and weathering are used. Parameters for the determination of the behaviour type are the geometry of the excavation, the stress conditions, the ground water, and the relative orientation of discontinuities to the tunnel axis.

For the determination of the excavation and support two different scenarios are anticipated. In the first case no limitations in blasting vibrations and no restrictions in the surface settlements have to be observed. This allows a round length of 2.5 m, while for support shotcrete, rock bolts, and steel arches are used. In the second case the boundary conditions are different, with restrictions both in blasting vibrations and surface settlements due to an adjacent building. In this case the round length is reduced to 1.3 m to reduce blasting vibrations and displacements. In addition forepoling is used to reduce loosening. This example is used to demonstrate, that different requirements strongly can influence the excavation and support design.

### Step 4 – verification of system behaviour

By monitoring the behaviour of the excavated and supported section the compliance with the requirements and criteria defined in the geotechnical safety management plan can be checked. When differences between the observed and predicted behaviour occur, the parameters and criteria used during excavation for the determination of rock mass 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 improvement measures (like increase of support) ordered (24, 25). In case the system behaviour is

**Fig. 4** Example of the sequence for determination of excavation and support with different requirements.

**Bild 4** Beispiel für die Bestimmung von Ausbruch und Stützung bei unterschiedlichen Anforderungen.

| Rock Mass Type - RMT         |                              | Behavior Type - BT |                                   | System Behavior - SB |   |  |   |
|------------------------------|------------------------------|--------------------|-----------------------------------|----------------------|---|--|---|
|                              |                              |                    |                                   |                      |   |  |   |
| Relevant parameters          |                              | RMT                | Factors of influence              | BT                   | RQ  | E&S  | SB  |
| Pyllite                      | UCS 20-50 MPa                |                    |                                   |                      | Limited surface settlements and blasting vibrations           | Round length 1.3 m, spiles, girder, shotcrete, rock bolt | Surface settlement <1cm                                   |
| Spacing of foliation 2-20 cm | Clay coated foliation planes |                    |                                   |                      | No limitation for surface settlements and blasting vibrations | Round length 2.5 m, girder, shotcrete, rock bolt         | General stable conditions with overbreak in certain areas |
| Block size 6-20 cm           | Partially open joints        |                    |                                   |                      |   |  |   |
| Slickensides 1-3 m           | Cataclastic zones <30 cm     |                    |                                   |                      |   |  |   |
| No weathering                |                              |                    |                                   |                      |   |  |   |
|                              |                              | 2                  | Overburden < 30 m                 | 3                    |   |  |   |
|                              |                              |                    | No water                          |                      |   |  |   |
|                              |                              |                    | Foliation parallel to tunnel axis |                      |   |  |   |

more favourable than expected, the reasons have to be analysed as well, and the findings used to better calibrate the geotechnical model and the delimitating criteria and parameters.

## Conclusion

The Guideline for the "Geomechanical Design of Underground Structures with Conventional Excavation" of the OGG outlines a method to determine support and excavation sequence for the design and construction of tunnels. Instead of support decisions based on standardized rock mass classification systems this project tailored procedure incorporates the observation of the rock mass behaviour and the rock mass support interaction in a transparent and consistent way.

There are several goals that are hoped to be reached by applying of this procedure:

- ▷ Optimized exploratory investigation programmes by concentrating on the collection of rock mass and project specific key parameters,
- ▷ Consistent designs meeting project specific requirements,
- ▷ Optimized construction by providing clear procedures to support the decisions on site,
- ▷ Continuous documentation of the decision making process,
- ▷ Promote technical advances in tunnelling by evaluating comparable data from various sites.

Most of the owners in Austria meanwhile specify the Guideline as a basis for geomechanical designs. The response from owners and designers is very positive. The practical application of the Guideline has shown that a few points need clarification. Currently a revision of the Guideline is under preparation, which will appear later in 2003. Parallel to this, the Guideline is translated into English, allowing a wider distribution.

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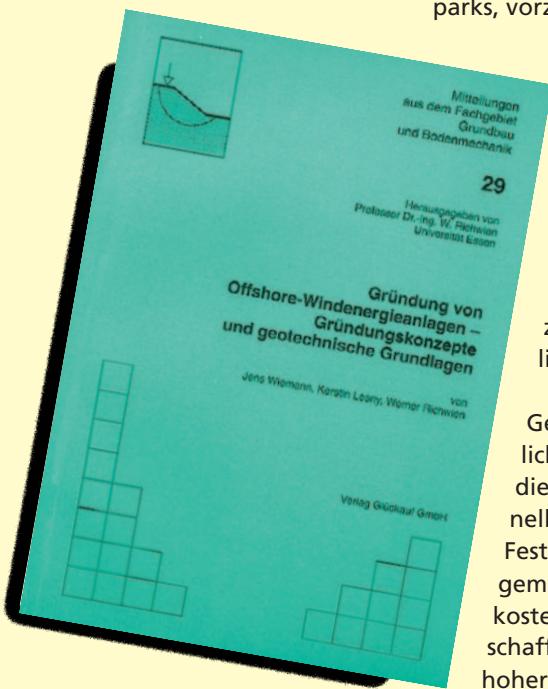
# Gründung von Offshore-Windenergieanlagen

## Gründungskonzepte und geotechnische Grundlagen

von Jens Wiemann, Kerstin Lesny und Werner Richwien

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### Inhalt und Zielgruppe

Ein weiterer Ausbau der Windenergie an Land ist nur noch in einem gerin- gen Umfang möglich, weil geeignete Standorte kaum noch vorhanden und vor allem nicht mehr genehmigungs-fähig sind. Stattdessen sollen die ener-giepolitischen Ziele (Vorrang erneuer-barer Energien) durch intensive Nut-zung des Windenergiopotenzials in der Deutschen Bucht und der Ostsee genutzt werden. In Offshore-Wind-parks, vorzugsweise in der ausschließ-lichen Wirtschaftszone (AWZ) der Bundesrepu-blik Deutschland, sollen bis zum Jahr 2030 rd. 25 000 bis 30 000 MW Leistung in Offshore-Windparks mit mehreren hundert Anlagen pro Park und einer Leistung von bis zu 5 MW pro Anlage instal-liert werden.

Generell entfällt ein wesent-licher Teil der Baukosten auf die Gründung. Bei konven-tionellen Bauwerken auf dem Festland sind dies erfahrungs-gemäß 10 bis 30 % der Rohbau-kosten, je nach Baugrundbe-schaffenheit. Bei Bauwerken auf hoher See kann der Anteil auf-

grund der besonderen Randbedin-gungen noch höher sein. Der Erkun-dung der Baugrundeigenschaften und der optimalen Auswahl der Gründung kommt also eine hohe wirtschaftliche und technische Bedeu-tung zu. Für eine wirtschaftliche Rea-lisierung der Offshore-Windparks folgt daraus, dass vor allem Grün-dungsarten zu entwickeln sind, die sich trotz eines hohen Grads an Vor-fertigung an die jeweiligen grün-dungstechnischen Randbedingungen vor Ort anpassen lassen. Dies erfor-deret in allen Planungsphasen hinreichende Kenntnisse über die Bau-grundeigenschaften und deren Um-setzung im Rahmen der Gründungs-planung. Hierzu soll das vorliegende Heft eine Arbeitshilfe sein.

Dieses Werk fasst die bisherigen Er-kenntnisse über die geologische Ent-wicklung der Böden in der Deutschen Bucht zusammen und enthält für typische Bodenarten Bandbreiten der maßgebenden Baugrundkennwerte. Die Methoden der Baugrundunterkun-dungen werden vorgestellt und die derzeit für den Entwurf und die Be-messung maßgebenden Regeln und Ansätze diskutiert. Das Werk richtet sich nicht nur an Geotechniker, son-dern an alle an der Planung der Windparks beteiligten Fachleute und enthält daher zusätzlich ein Glos-sar typischer geotechnischer Fachbe-griffe.

Die Publikation ist aus der Mitwir-kung der Autoren in der Forschungs-gruppe Gigawind an der Universität Hannover – Bau- und umwelttechni-sche Aspekte von Offshore-Windener-gieanlagen – mit Unterstützung des Bundesministeriums für Wirtschaft und Technologie entstanden.

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Datum

Unterschrift