Walter Wittke

# Rock Mechanics Based on an Anisotropic Jointed Rock Model (AJRM)

- für den Entwurf und Bau von Tunneln, Dämmen und Böschungen in geklüftetem und anisotropem Fels
- mit praxisnahen Fallbeispielen

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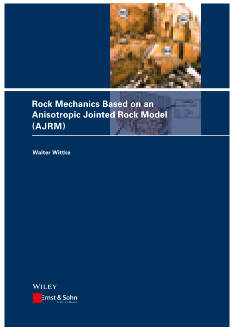



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## ÜBER DAS BUCH

Dieses Buch konzentriert sich auf die Grundlagen der Felsmechanik als Basis für den sicheren und wirtschaftlichen Entwurf und Bau von Tunneln, Dämmen und Böschungen in geklüftetem und anisotropem Fels.

Es ist in vier Hauptteile gegliedert:
- Grundlagen und Modelle
- Berechnungs- und Entwurfsmethoden
- Erkundungen, Versuche, Messung und Beobachtung
- Anwendungen und Fallbeispiele

Die felsmechanischen Modelle berücksichtigen den Einfluss von Trennflächen auf das Spannungs-Dehnungs-Verhalten und die Durchlässigkeit von geklüftetem Fels.

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# Preface

In 1984, my book on Rock Mechanics was published. Some years later, it was translated into English and Chinese and to a larger part also into Russian.

Since then, together with my co-workers, I have extended our anisotropic jointed rock model (AJRM) and the corresponding analysis methods to a wider spectrum of rock types. Furthermore, our design approach has been applied to many projects in tunneling, dam and slope design. Monitoring and back analyses have helped us to gain a far better understanding of rock mass behavior and to assess the corresponding properties.

Therefore, I decided to publish a new book with the title

Rock Mechanics
based on an
Anisotropic Jointed Rock Model
AJRM

I hope that many colleagues will follow this design method in order to achieve safer and more economic solutions.

In Part A, the fundamentals of our modeling concept are outlined and in part B our means of analyzing structures in and on jointed rock are presented. Part C is devoted to exploration, testing and monitoring and in Part D applications and case studies are presented.

I would like to thank Dr.-Ing. Dipl.-Phys. Johannes Kiehl for his valuable contribution to this book. He has carefully studied and summarized the recent literature related to a number of chapters of parts A and C, and he has compiled the material gathered in WBI Worldwide Engineering over many years.

Furthermore, I would like to thank Dipl.-Ing. Christa Mühlen-Senz for contributing the excellent figures to this book and Mrs. Ute Kratz for compiling the whole manuscript.

My thanks also go to my former and present colleagues in the WBI Company for their contributions to the development of models and computer programs and to the design of the related engineering projects.

In this context, I would specially mention Dr.-Ing. Bernd Pierau, Dr.-Ing. Claus Erichsen, Dr.-Ing. Bettina Wittke-Schmitt, Dr.-Ing. Patricia Wittke-Gattermann, Dr.-Ing. Martin Wittke, as well as Dipl.-Ing. Dieter Schmitt and Dipl.-Ing. Meinolf Tegelkamp.

Finally, I want to thank my wife Lilian for the many years of personal support and understanding.

*Walter Wittke*

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*Walter Wittke*

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## Part B: Analysis and Design Methods

## Part C: Exploration, Testing and Monitoring

## Part D: Applications and Case Histories

## 2.7 Rock Mass

### 2.7.1 Examples

Figure 2.14 shows a granite in which the jointing in preferred directions is clearly visible.

The sandstone represented in Fig. 2.15 exhibits horizontal, persistent and closed bedding-parallel discontinuities, as well as vertical joints that frequently terminate at the bedding-parallel discontinuities. Locally, open joints appear.

Fig. 2.16 shows a closely bedded claystone with vertical joints. After drying and subsequent contact with water, such a rock may become a mud. A rock mass with such a behavior is called “slaking”.

A sedimentary rock mass often consists of an alternating sequence of different intact rocks. In the example illustrated in Fig. 2.17, between sandstone and siltstone layers bedding-parallel shear zones appear.

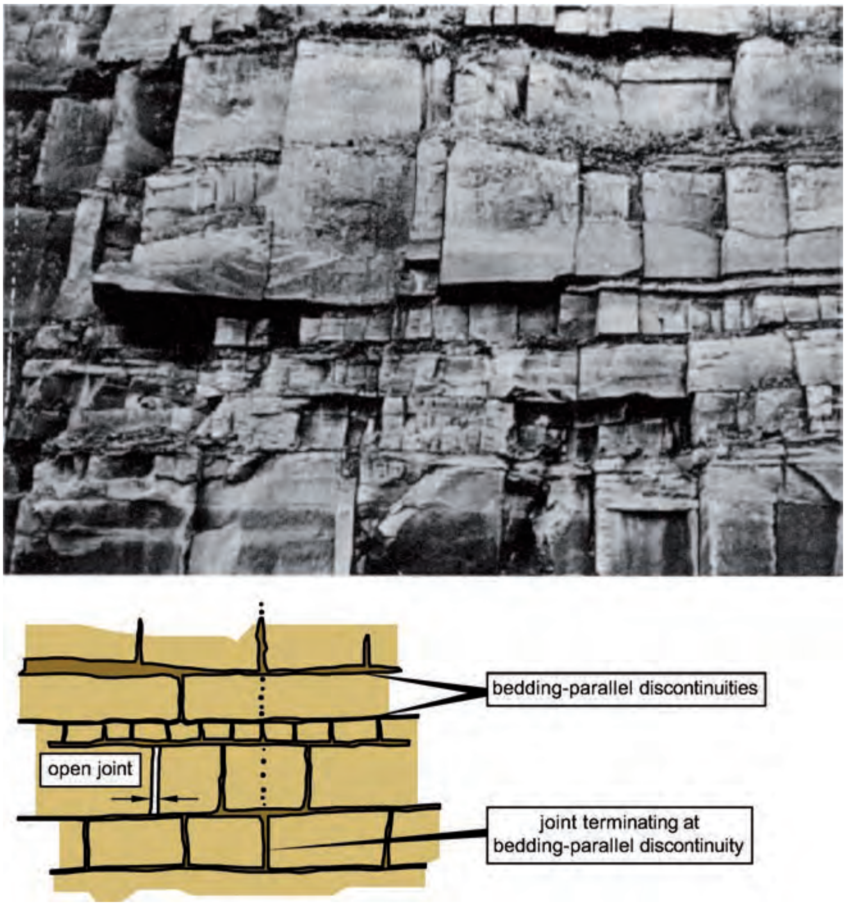


**Figure 2.15** Bunter (sandstone), near Fulda (Germany)

The clay slate represented in Fig. 2.18 is an example of a rock mass with an orthogonal system of vertical discontinuities (D1 and D2) and horizontal schistosity-parallel discontinuities (Sch), which in this particular case have the same orientation as the bedding.

Fig. 2.19 illustrates a tuff, as an example for a pyroclastic sediment. Such a rock mass often exhibits practically no discontinuities. The same is true for the rock salt represented in Fig. 2.20 as an example for a chemical sediment.

The water solubility of chemical sediments can lead to large openings in the ground. Figure 2.21 shows a schematic section through the White Jurassic formation at the Swabian Alb. In the banked limestone, which has been subjected to the Rhenanian karst formation, various karst structures appear, such as karstified master joints (Fig. 2.22) and large karst channels (Fig. 2.23). In the overlying massive limestones of the Danubian karst formation major karst structures such as horizontal and vertical caves, holes and larger cavities can be found (Fig. 2.21).

**Figure 2.16** Claystone, Black Jurassic (Lias $\alpha$), Stuttgart (Germany)

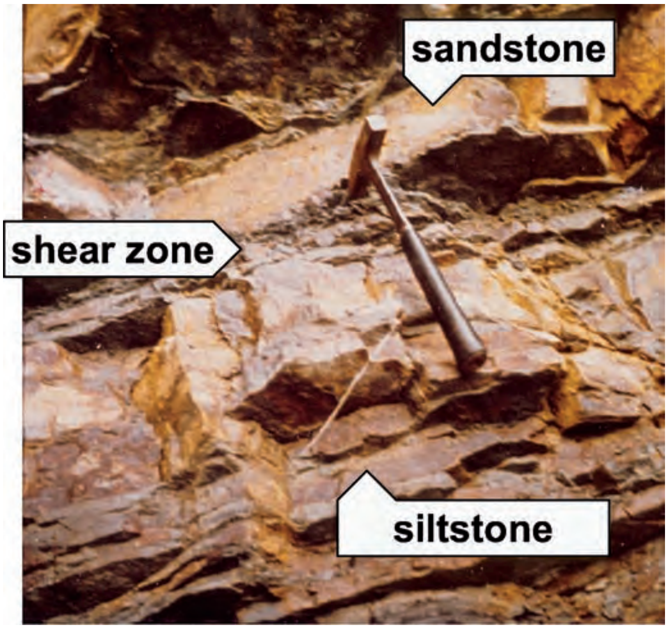


**Figure 2.17** Alternating sequence of sandstones and siltstones (Waichecheng Series), bedding-parallel shear zones, near Taichung (Republic of China)

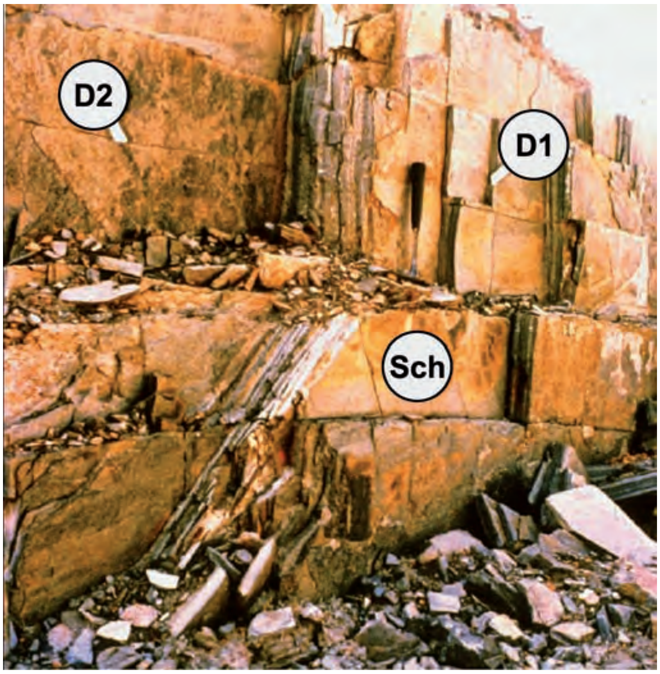


**Figure 2.18** Clay slate, Selingue project (Mali)

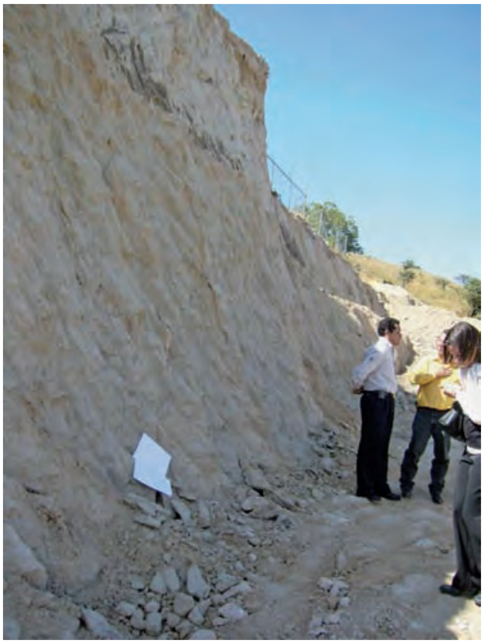

**Figure 2.19** Tuff, Guadalajara (Mexico)

**Figure 2.20** Rock salt, drift, salt mine near Morsleben (Germany)

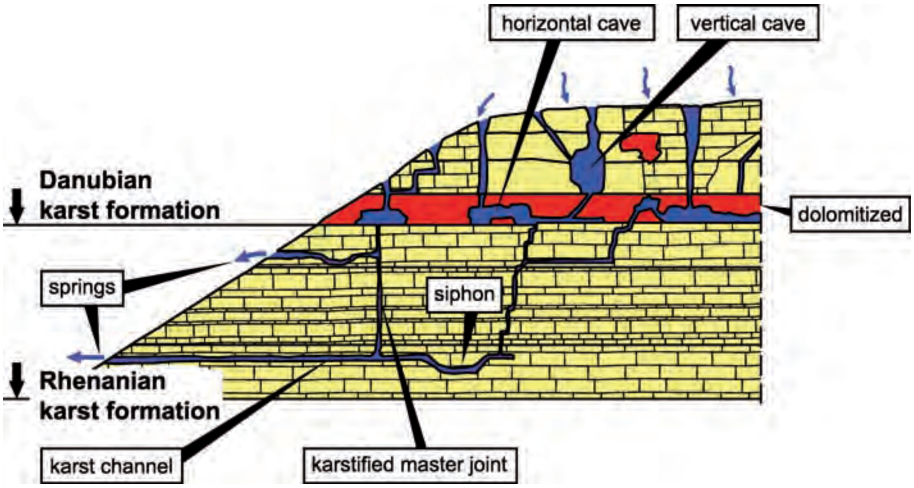


**Figure 2.21** Types of karst formation, White Jurassic, Swabian Alb (Germany)

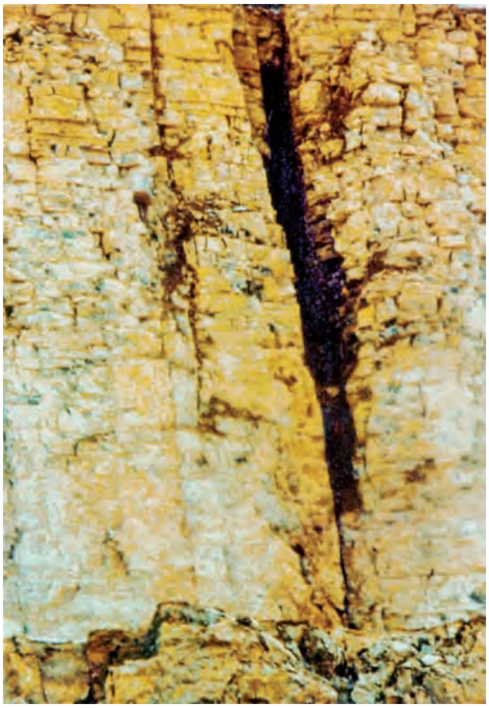

**Figure 2.22** Karstified master joint, White Jurassic, Swabian Alb (Germany)

**Figure 2.23** Karst channel "Mordloch" (L ≈ 4.3 km) White Jurassic, Swabian Alb (Germany)

Also in rock salt water solubility can lead to major karst structures known as "saliniferous karst". The existence of such structures may be indicated by dolines and sinkholes which can be observed, for example, around the Dead Sea (Fig. 2.24).

**Figure 2.24** Sinkholes near Wadi Rahaf, Dead Sea (Israel)

## 2.7.2 Description of Discontinuities

Discontinuities usually occur as sets or families with more or less parallel orientation. The whole assemblage of discontinuities present in a rock mass is called a "disconti-

# 12 Design Methods

## 12.1 Introduction

There are different views with regard to rock engineering design. The most frequently applied design methods are based on:

– rock mechanical models
– assessment of the rock mass behavior
– classification systems.

The first design method is mainly based on the results of comprehensive geotechnical investigations, stability analyses and monitoring results during construction (Section 12.2). This design method has been successfully applied for several decades by WBI (Wittke 1990, Wittke 2000b, Wittke et al. 2002, Wittke et al 2006) and other designers and consultants. One of the main objectives of this book is to provide the fundamentals of this design method. Examples of completed projects carried out according to this design method are presented in Part D of this book.

The second kind of design method is based on rock mass behavior types and hazard scenarios and is applied mainly in Austria and Switzerland (Section 12.3).

A characteristic attribute of the third design method, based on classification systems, is that rock mass properties and other influencing factors such as stresses and groundwater conditions are condensed to a single numerical value referred to the "rock mass rating index". As stated by Bieniawski (1989), the developer of the "rock mass rating (RMR)" system, which was one of the first empirical classification systems, "a classification system is not intended to replace analytical modeling, site investigations and monitoring but should be used in conjunction with these tools of rock engineering design" (Bieniawski 1989). According to this view, classification systems should not be used as self-contained design methods. However, the development and promotion of a number of new and more refined classification systems in the recent past has given rise to their use as self-contained design methods (Section 12.4). The risks that are associated with the use of classification methods as self-contained design methods are emphasized in Sections 12.5 to 12.7.

## 12.2 Design Based on Rock Mechanical Models

A characteristic feature of rock engineering design is the iterative procedure in which individual phases of work may be repeated several times, if necessary.

The design has to be adjusted to the type of rock mass and local conditions in the project area. The following instructions must therefore be treated as general guidelines.

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Figure 12.1 illustrates the basic steps for the design of tunnels according to the tunneling study group of the German Geotechnical Society (DGGT 1995) and the European Regional Technical Committee no. 9 for tunneling and underground construction (ERTC9 1997). These can also be transferred to the design of other rock engineering structures. The linking arrows show the connections and sequence of work as well as possible and perhaps necessary feedback in order to revise or modify the design in certain phases.

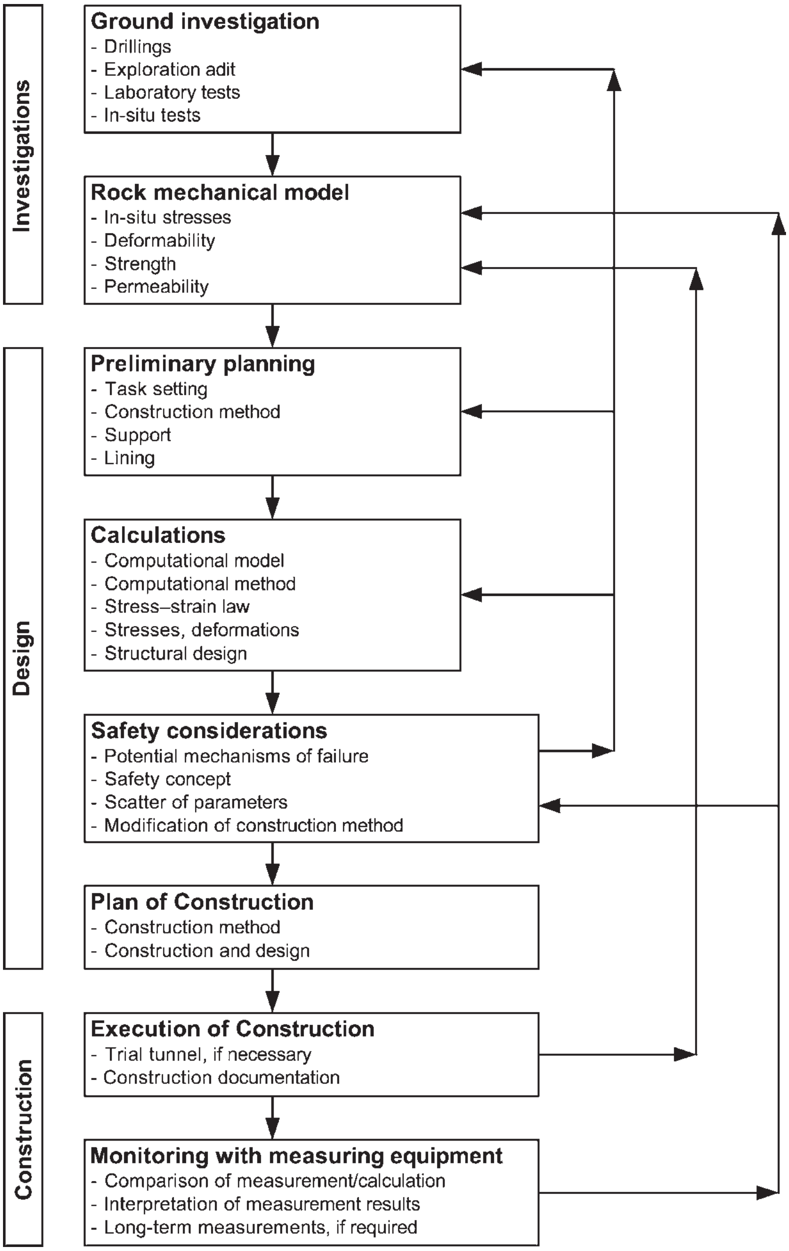


**Figure 12.1** Design based on rock mechanical models (ERTC9 1997)

Site investigation and simultaneous testing for determining the rock mechanical parameters and the in-situ stress state (Chapters 13, 14, 15, 16 and 19) have to be carried out at an early stage of project. The investigation program should be flexible and adjusted to the state of knowledge and the envisaged construction methods.

A rock mechanical model has to be established in due time. This covers structural models (Section 2.7.2), mechanical models (Chapters 3, 5 and 8) and hydraulic models (Chapter 6). The rock mechanical parameters describing deformability, strength and permeability (Chapters 3 and 6) as well as the in-situ stress state (Chapter 9) that are required for stability analyses (Chapter 10) must be derived for the rock mass units encountered in the project area from the results of site investigations, laboratory and in-situ testing, previous experience as well as engineering and geological judgement. Then the results of laboratory and in-situ tests should be reviewed critically in view of their significance for real conditions (DGGT 1995).

On this basis a suitable construction method is specified as part of the preliminary planning. The means of temporary and permanent support such as the tunnel lining have to be designed for the selected construction method.

Stability analyses and serviceability proofs are required that cover all the critical stages of construction and loading. The applied analysis method should allow a realistic consideration of geometric conditions, the rock-structure interaction accounting for suitable stress-strain relationships and other influences. This is best done by means of the FEM (Chapter 10). Supplementary analyses with regard to the stability of rock wedges (Chapter 11) may also become necessary. A safety concept which is based on potential failure mechanisms can contain criteria such as stresses, strains, displacements or strength. Parameter variations should be undertaken accounting for simplifications and uncertainties in the choice of the analysis model and the analysis method. On this basis the final design is then carried out.

During construction, documentation of all construction phases has to be carried out. To verify the design with the aid of measurements and the comparison with analysis results and design criteria, a monitoring program has to be established from the very beginning of the construction works. If little or no experience with the encountered rock mass is available, the vault of a tunnel or cavern or even the entire cross-section may be excavated in advance over a certain length as test excavation (Sections 13.7 and 13.8), equipped with monitoring devices (Chapter 17). In addition, geotechnical mapping of exposed rock surfaces such as the temporary face should also be carried out (Section 13.9).

If the monitoring results differ significantly from the analysis results then modifications of the support measures and/or the construction method will be necessary. The analysis model and the parameters sometimes have to be adjusted to the ground conditions by means of back analyses of monitoring results. Thus, the rock mechanical model on which the design is based is checked and, if necessary, it can be adapted or modified during construction.

Not all load cases actually occur during the construction works (e.g. water pressure, swelling pressure or traffic loads). In such cases long-term measurements should be envisaged, that is, monitoring needs to be continued after construction has been completed.

The rock mechanical model, the analysis model, the analysis method and the safety considerations should be understood as a unity. Inaccuracies and too many simplifications in one part of the model have a negative influence on the reliability of the entire model and thus on the safety concept too. Therefore the demands on accuracy should be well balanced for all parts of the design (DGGT 1995, ERTC9 1997).

Unlike the design methods described below, this method does not need to define a rock mass classification scheme. A classification is only introduced in tunneling. Here, the excavation method and the amount of support are classified into so-called "excavation classes" that are specified according to the expected rock mass conditions (DIN 18312 2002). The latter are described by so-called "homogeneous areas" – rock mass units with a more or less uniform behavior in terms of the homogeneous model.

## 12.3 Design Methods Based on the Assessment of the Rock Mass Behavior

In tunneling and mining the rock mass classification on the basis of rock mass behavior has a more than 200 year long tradition, mainly in Austria (Bierbaumer 1913, Rabcewicz 1944, Terzaghi 1946, Stini 1950, Rabcewicz 1957, Lauffer 1958, Pacher et al. 1974, Lauffer 1988).

The guidelines of the Austrian Geomechanical Society (ÖGG 2001) led to the preparation of the Austrian standard ÖNORM B2203-1 (2001) that is based on so-called "rock mass behavior types". A rock mass behavior type describes the mechanical and hydraulic behavior of the rock mass, including influencing factors such as groundwater conditions, in-situ stress state and orientations of discontinuity sets with respect to an underground structure. Also size, shape and location of the structure are incorporated in the definition of project-specific behavior types. These are defined as the rock mass response to the excavated underground structure without any support measures. In the Austrian standard ÖNORM B2203-1 (2001) 11 main rock mass behavior types are defined with the possibility of further subdivision representing a classification scheme. Each rock mass unit is then assigned to one or a combination of these behavior types. Examples and a detailed description of these behavior types can be found, for example, in Goricki (2007).

Based on the rock mass behavior types the support measures are specified. The rock-structure interaction, which is referred to as "system behavior", is derived from the results of numerical and analytical analyses or from experience gained from other projects. The evaluated system behavior for each rock mass unit then leads to design requirements which depend on the corresponding behavior type.

The design method used in Switzerland, instead of rock mass behavior types, introduces potential hazard scenarios in order to obtain a basis for the assessment of rock mass behavior (SIA199 1998). They include water inflows, gas explosions and possible failure modes. Rock mass units with the same or similar potential hazard scenarios are classified with respect to their level of risk, including a specification of the required support measures.

## 12.4 Design Based on Classification Systems

In principle, all classification systems follow the procedure outlined in Fig. 12.2. Rock mechanical parameters, in-situ stresses, groundwater conditions and so on, evaluated from geotechnical investigations are described in a simplifying manner by coefficients. Tables, formulas, diagrams and combinations of them are used to obtain ratings for these coefficients. By means of an empirical function, the so-called "rock mass rating index" is calculated from these coefficients. On the basis of this single index, recommendations for support measures denoted as "support classes" and further specifications for the design are given.

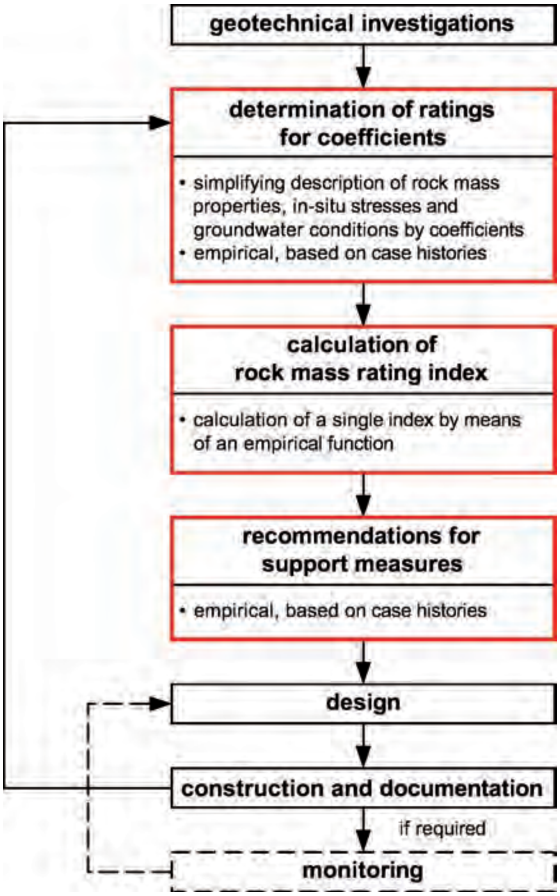


**Figure 12.2** Design based on classification systems (Sommer & Wittke 2011)

During construction documentation of the construction phases is carried out, and a monitoring program is established (Fig. 12.2) whereupon the latter is not always considered necessary (Barton & Grimstad 2004). On the basis of the encountered rock mass conditions the rock mass rating index is reviewed. If no agreement is obtained then the rock mass rating index needs to be re-evaluated, which may lead to a modification of the support classes.

The basis of each classification system is empirical. This means that the selection of the influencing variables, their rating and the recommended support classes are based on the experience of the developer, gained from practical cases. As a consequence, classification systems generally have a subjective aspect. In order to overcome this shortcoming and to detect misjudgements, the users of classification systems are recommended to apply more than one system in parallel and to compare their results (Bieniawski 1988, Trunk & Hönisch 1990, Alber 2001).

A comprehensive description of classification systems can be found in Bieniawski (1989), Afrouz (1992) and Singh & Goel (1999). Also, Sommer (2009) provides an over-

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