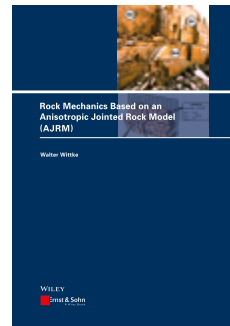


Walter Wittke

# 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



2014 · 876 Seiten · 900 Abbildungen ·  
42 Tabellen

Hardcover

ISBN 978-3-433-03079-0

€ 155\*

WILEY

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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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## BESTELLUNG

Anzahl	ISBN /	Titel	Preis
	978-3-433-03079-0	Rock Mechanics Based on an Anisotropic Jointed Rock Model	€ 155*

## BESTELLEN

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\* Der €-Preis gilt ausschließlich für Deutschland. Inkl. MwSt.

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Irrtum und Änderungen vorbehalten. Stand: 7/2021

## 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  
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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.

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# Table of Contents

<b>Preface</b> .....	<b>V</b>
<b>1 Introduction</b> .....	<b>1</b>
<b>Part A: Fundamentals and Models</b>	
<b>2 Structure of Rock</b> .....	<b>5</b>
2.1 Introduction .....	5
2.2 Rock Groups .....	5
2.3 Intact Rock .....	7
2.4 Faults .....	12
2.5 Folds .....	13
2.6 Discontinuities .....	15
2.7 Rock Mass .....	17
2.7.1 Examples .....	17
2.7.2 Description of Discontinuities .....	22
2.7.3 Structural Models .....	32
<b>3 Stress-Strain Behavior of Jointed Rock</b> .....	<b>39</b>
3.1 Introduction .....	39
3.2 Intact Rock .....	39
3.2.1 Elastic Behavior .....	39
3.2.2 Strength and Failure Criteria .....	46
3.2.3 Post-Failure Behavior .....	53
3.2.4 Intact Rocks with Deviations from Elastic-Viscoplastic Stress-Strain Behavior .....	57
3.3 Discontinuities .....	58
3.3.1 Types of Discontinuities .....	58
3.3.2 Stress-Displacement Behavior of Discontinuities Loaded by a Normal Compressive Stress .....	58
3.3.3 Strength and Failure Criteria .....	60
3.3.4 Stress-Displacement Behavior of Discontinuities Loaded by a Normal Stress and a Shear Stress .....	74
3.4 Rock Mass .....	75
3.4.1 Discrete Model .....	75
3.4.2 Homogeneous Model .....	77
3.4.3 Combination of the Homogeneous Model with Discrete Models of Individual Discontinuities .....	89
<b>4 Squeezing Rock</b> .....	<b>91</b>
4.1 Introduction .....	91
4.2 Phenomenon .....	93

4.3	Yielding Support. . . . .	93
4.4	Convergence-Confinement Method . . . . .	97
4.5	Example of a Tunnel in Squeezing Rock . . . . .	99
4.5.1	Statement of Problem, Analysis Model, Parameters and Analyzed Cases. . . . .	99
4.5.2	Reference Case . . . . .	103
4.5.3	Influence of Residual Strength. . . . .	106
4.5.4	Influence of Discontinuities . . . . .	107
4.5.5	Influence of Supporting Pressure. . . . .	109
4.5.6	Conclusions . . . . .	113
<b>5</b>	<b>Rock Salt . . . . .</b>	<b>115</b>
5.1	Introduction . . . . .	115
5.2	Stress-Strain Behavior . . . . .	115
5.3	Validation of Model. . . . .	124
<b>6</b>	<b>Permeability and Seepage Flow . . . . .</b>	<b>127</b>
6.1	Introduction . . . . .	127
6.2	Porous Intact Rock . . . . .	128
6.2.1	Porosity. . . . .	128
6.2.2	Darcy's Law and Permeability . . . . .	129
6.3	Discontinuities . . . . .	131
6.3.1	Laminar Flow. . . . .	131
6.3.2	Turbulent Flow. . . . .	136
6.4	Rock Mass . . . . .	138
6.4.1	Discrete Model. . . . .	138
6.4.2	Homogeneous Model. . . . .	139
6.4.3	Seepage Force and Hydrostatic Uplift. . . . .	161
<b>7</b>	<b>Coupling of Stress-Strain Behavior and Seepage Flow . . . . .</b>	<b>165</b>
7.1	Introduction . . . . .	165
7.2	Permeability of a Discontinuity as a Function of Stress. . . . .	168
7.2.1	Permeability of a Discontinuity as a Function of Normal Stress. . . . .	168
7.2.2	Permeability of a Discontinuity as a Function of Normal Compressive Stress and Shear Stress . . . . .	170
7.3	Rock Mass . . . . .	173
7.3.1	Discrete Model. . . . .	173
7.3.2	Homogeneous Model. . . . .	173
<b>8</b>	<b>Swelling Rock . . . . .</b>	<b>181</b>
8.1	Introduction . . . . .	181
8.2	Swelling Mechanisms . . . . .	185
8.3	Water Uptake . . . . .	188
8.4	Swelling. . . . .	191
8.5	Coupled Model. . . . .	193

8.6	Characteristic Parameters of the Gypsum Keuper . . . . .	196
8.7	Gypsum Keuper in its Natural Condition . . . . .	201
8.8	Calibration of Model . . . . .	202
<b>9</b>	<b>Rock Mass In-Situ Stress . . . . .</b>	<b>209</b>
9.1	Introduction . . . . .	209
9.2	Stresses due to Gravity . . . . .	209
9.2.1	Horizontal Ground Surface . . . . .	209
9.2.2	Influence of Topography . . . . .	213
9.3	Tectonic Stresses . . . . .	215
9.4	Stresses due to Pre-loading and Subsequent Unloading . . . . .	219
9.5	Residual Stresses . . . . .	221
9.6	Effect of Rock Mass Inhomogeneity . . . . .	221

## Part B: Analysis and Design Methods

<b>10</b>	<b>Finite Element Method (FEM) . . . . .</b>	<b>225</b>
10.1	Introduction . . . . .	225
10.2	The Principle of FEM . . . . .	225
10.3	Element Types . . . . .	232
10.3.1	Three-Dimensional Isoparametric Elements . . . . .	232
10.3.2	Truss Elements . . . . .	234
10.3.3	Spring Elements . . . . .	234
10.4	Computation Section . . . . .	235
10.5	Stress-Strain Analyses . . . . .	238
10.5.1	Boundary Conditions . . . . .	238
10.5.2	Simulation of Construction Stages . . . . .	246
10.5.3	Evaluation of Stress Resultants . . . . .	252
10.5.4	Simulation of Support Measures . . . . .	254
10.5.5	Representation of Results . . . . .	259
10.5.6	Examples . . . . .	269
10.6	Seepage Flow Analyses . . . . .	276
10.6.1	Boundary Conditions . . . . .	276
10.6.2	Representation of Results . . . . .	279
10.6.3	Example . . . . .	279
10.7	FEM Program Systems and Related Modules Provided by WBI . . . . .	283
10.7.1	Program System FEST03 . . . . .	283
10.7.2	Program System HYD03 . . . . .	285
<b>11</b>	<b>Stability of Rock Wedges and Excavation Surfaces . . . . .</b>	<b>287</b>
11.1	Introduction . . . . .	287
11.2	Potential Failure Modes of Rock Wedges . . . . .	287
11.3	Stability of Rock Wedges against Sliding . . . . .	290
11.3.1	Two-Dimensional Rock Wedges . . . . .	290
11.3.2	Three-Dimensional Rock Wedges . . . . .	308

11.4	Stability of Rock Wedges against Rotation . . . . .	319
11.5	Stability of Multiple Rock Blocks . . . . .	325
11.6	Stability of Rock Columns and Layers against Buckling . . . . .	327
<b>12</b>	<b>Design Methods. . . . .</b>	<b>331</b>
12.1	Introduction . . . . .	331
12.2	Design Based on Rock Mechanical Models. . . . .	331
12.3	Design Methods Based on the Assessment of the Rock Mass Behavior. . .	334
12.4	Design Based on Classification Systems . . . . .	334
12.5	Flaws and Deficiencies of Classification Systems . . . . .	340
12.6	Case History Road Tunnel Österfeld . . . . .	346
12.7	Conclusions. . . . .	349

## Part C: Exploration, Testing and Monitoring

<b>13</b>	<b>Site Investigation . . . . .</b>	<b>353</b>
13.1	Introduction . . . . .	353
13.2	Evaluation of Documents . . . . .	353
13.3	Rock Exposures . . . . .	356
13.4	Test Pits. . . . .	356
13.5	Boreholes . . . . .	357
13.5.1	Core Drilling. . . . .	357
13.5.2	Observation of Borehole Walls . . . . .	365
13.5.3	Borehole Direction. . . . .	368
13.5.4	Geophysical Logging . . . . .	369
13.6	Exploration Adits and Shafts. . . . .	372
13.7	Test Excavations . . . . .	374
13.8	Exploration During Construction . . . . .	374
13.9	Mapping of Rock Surfaces. . . . .	376
13.9.1	Mapping Techniques . . . . .	376
13.9.2	Mapping Evaluation. . . . .	387
13.10	Evaluation of a Structural Model . . . . .	397
<b>14</b>	<b>Laboratory Tests . . . . .</b>	<b>403</b>
14.1	Introduction . . . . .	403
14.2	Petrographic Investigations . . . . .	403
14.3	Water Content, Density, Porosity and Related Properties. . . . .	404
14.4	Deformability and Strength of Intact Rock. . . . .	408
14.4.1	Uniaxial Compression Test . . . . .	408
14.4.2	Triaxial Compression Test . . . . .	416
14.4.3	Brazilian Test . . . . .	422
14.4.4	Other Tests . . . . .	424
14.5	Shear Strength of Discontinuities . . . . .	434
14.6	Swelling. . . . .	439
14.7	Slake Durability and Disintegration Resistance . . . . .	444
14.8	Abrasiveness . . . . .	446



<b>15</b>	<b>Field Tests</b>	451
15.1	Introduction	451
15.2	Borehole Expansion Tests	451
15.2.1	Isotropic Rock Mass	451
15.2.2	Transversely Isotropic Rock	460
15.3	Plate Loading Tests	465
15.4	Flat Jack Tests	469
15.4.1	Isotropic Rock Mass	469
15.4.2	Transversely Isotropic Rock Mass	473
15.5	Triaxial Tests	480
15.6	Gallery Tests	484
15.7	Direct Shear Tests	485
15.8	Permeability Tests	490
15.8.1	Standard Packer Tests (Lugeon Tests)	490
15.8.2	Other Methods of Permeability Testing	497
<b>16</b>	<b>Stress Measurements</b>	509
16.1	Introduction	509
16.2	Stress Relief	510
16.2.1	Triaxial Cells	510
16.2.2	Borehole Deformation Cells	518
16.2.3	Doorstopper	521
16.2.4	Conical Strain Cell	522
16.2.5	Borehole Slotter	523
16.2.6	Borehole Wall Stress Relief Method	524
16.3	Stiff Inclusion	524
16.4	Compensation Method	525
16.5	Hydraulic Methods	527
16.5.1	Hydraulic fracturing (HF)	527
16.5.2	Hydraulic Testing of Pre-Existing Fractures (HTPF)	534
16.6	Methods of Large-Scale In-situ Stress Determination	535
16.7	Case Studies	537
16.7.1	Underground Powerhouse Cavern	537
16.7.2	Construction Pit	542
16.8	The World Stress Map Project – Results of Stress Measurements	548
<b>17</b>	<b>Monitoring</b>	553
17.1	Introduction	553
17.2	Geodetic Measurements	554
17.3	Monitoring of Vertical Displacements on the Ground Surface	556
17.4	Monitoring of Rock Displacements along Boreholes	558
17.4.1	Monitoring of Displacements Parallel to the Borehole Axis	558
17.4.2	Monitoring of Displacements Normal to the Borehole Axis	565
17.4.3	Three-Dimensional Monitoring of Displacements along Boreholes	569



17.5	Monitoring of Relative Displacements between Rock Surfaces . . . . .	570
17.6	Pressure Monitoring . . . . .	572
17.7	Anchor Force Measurements . . . . .	576
17.8	Monitoring of Water Level and Water Pressure . . . . .	578
17.9	Automatic Data Acquisition . . . . .	579
17.10	Examples . . . . .	581
17.10.1	Monitoring Section in a Tunnel . . . . .	581
17.10.2	Monitoring Program for the Observation of a Rock Slide . . . . .	583
<b>18</b>	<b>Evaluation of Rock Mechanical Parameters . . . . .</b>	<b>587</b>
18.1	General Procedure . . . . .	587
18.2	Examples . . . . .	590
<b>19</b>	<b>Examples of Testing and Monitoring Programs . . . . .</b>	<b>607</b>
19.1	Introduction . . . . .	607
19.2	Urban Railway Stuttgart, Hasenberg Tunnel, Construction Lot 15, Exploration Shaft and Adits . . . . .	607
19.3	Urban Railway Stuttgart, Construction Lot 11, Exploration Shaft and Adit . . . . .	610

## Part D: Applications and Case Histories

<b>20</b>	<b>NATM Tunneling . . . . .</b>	<b>619</b>
20.1	Introduction . . . . .	619
20.2	Fundamentals of the NATM . . . . .	619
20.2.1	Excavation Classes . . . . .	619
20.2.2	Construction of the Shotcrete Membrane . . . . .	621
20.2.3	Shotcrete . . . . .	624
20.2.4	Steel Sets . . . . .	628
20.2.5	Rock Bolts . . . . .	628
20.2.6	Advancing support . . . . .	634
20.3	Tunneling under Stuttgart Airport Runway . . . . .	642
20.3.1	Project . . . . .	642
20.3.2	Ground and Groundwater Conditions . . . . .	645
20.3.3	Experience Gained from Other Tunnels Located in the Lias $\alpha$ Formation . . . . .	647
20.3.4	Fundamentals of the Design . . . . .	649
20.3.5	Stability Analyses . . . . .	651
20.3.6	Excavation and Support . . . . .	654
20.3.7	Back Analyses of Monitoring Results . . . . .	656
20.3.8	Conclusions . . . . .	660
<b>21</b>	<b>TBM Tunneling . . . . .</b>	<b>663</b>
21.1	Fundamentals . . . . .	663
21.1.1	Introduction . . . . .	663
21.1.2	Shielded TBM . . . . .	664

21.1.3	Gripper TBM .....	670
21.1.4	Lining Concepts .....	673
21.2	Stability of the Temporary Face and Shield Design, Example .....	674
21.2.1	Project .....	674
21.2.2	Ground and Groundwater Conditions .....	675
21.2.3	Project History .....	677
21.2.4	Contract, Technology and Problems .....	679
21.2.5	Reasons for the Delay and Cost Increase .....	680
21.2.6	Measures for Improvement .....	683
21.2.7	Conclusions .....	688
21.3	Shield Design, Example .....	689
21.3.1	Statement of Problem .....	689
21.3.2	Investigated Cases .....	690
21.3.3	Seepage Flow Analysis, Assumptions .....	691
21.3.4	Stability Analyses, Assumptions and Computation Steps .....	692
21.3.5	Analysis Results .....	695
21.3.6	Conclusions .....	697
21.4	Stability and Permeability Changes of the Rock Mass in the Machine Area, Example .....	698
21.5	Design of the Segmental Lining, Examples .....	703
21.5.1	Design of the Segmental Lining for Five Machine-Driven Rock Tunnels .....	703
21.5.2	Loading and Bedding of the Segmental Lining .....	713
<b>22</b>	<b>Powerhouse Cavern Estangento-Sallente .....</b>	<b>725</b>
22.1	Project .....	725
22.2	Site Investigation and Testing Prior to Construction .....	729
22.2.1	Site Investigation .....	729
22.2.2	Discontinuities .....	730
22.2.3	Testing .....	731
22.3	Location of the Powerhouse Cavern .....	733
22.4	Rock Mechanical Model .....	734
22.5	Stability Analyses .....	735
22.6	Monitoring Program .....	736
22.7	Mapping and Monitoring Results during Excavation of Vault .....	738
22.8	Support of the Cavern Walls .....	740
22.9	Mapping and Monitoring Results during Excavation of Benches .....	742
22.10	Back Analyses .....	750
22.11	Conclusions .....	752
<b>23</b>	<b>Tunneling in Swelling Rock .....</b>	<b>753</b>
23.1	Introduction .....	753
23.2	Influence of the Elevation of the Anhydrite Surface on Swelling Pressure and Heaving .....	753
23.2.1	Anhydrite Surface above the Tunnel Roof .....	753
23.2.2	Anhydrite Surface underneath and in the Area of the Tunnel Invert .....	756

23.2.3	Anhydrite Surface in the Middle of the Tunnel Cross-Section ..	761
23.2.4	Conclusions .....	762
23.3	Urban Railway Tunnel in Stuttgart, Construction Lot 12 .....	762
23.3.1	Project .....	762
23.3.2	Ground Conditions .....	764
23.3.3	Stability Analyses for the Phase of Construction .....	764
23.3.4	Excavation of the Tunnel .....	764
23.3.5	Internal Lining .....	766
23.3.6	Long-Term Stability of the Tunnel .....	767
23.3.7	Recommendations for the Construction of Tunnels in Swelling Rock .....	769
<b>24</b>	<b>Rehabilitation of Urft Dam .....</b>	<b>771</b>
24.1	Introduction .....	771
24.2	Project .....	771
24.3	Rehabilitation Concept .....	774
24.4	Site Investigation and Testing .....	775
24.4.1	Program .....	775
24.4.2	Masonry Dam .....	776
24.4.3	Foundation Rock .....	781
24.5	Rehabilitation Works .....	786
24.5.1	Overview .....	786
24.5.2	Inspection Galleries .....	788
24.5.3	Drainage .....	789
24.6	Monitoring .....	790
24.6.1	Program .....	790
24.6.2	Temperatures .....	790
24.6.3	Pore Pressures and Quantities of Seepage Water .....	791
24.6.4	Displacements .....	793
24.7	Back Analyses .....	795
24.8	Stability Proof .....	797
24.9	Conclusions .....	800
<b>25</b>	<b>Stabilization of a Rock Mass Slide .....</b>	<b>803</b>
25.1	Original Design .....	803
25.2	Revised Design .....	806
25.2.1	Further Explorations .....	806
25.2.2	Stability Analyses .....	807
25.2.3	Installation of Tendons and Drainage .....	807
25.2.4	Monitoring .....	811
25.3	Back Analysis of Monitoring Results .....	814
25.4	Installation of Additional Tendons .....	817
25.5	Long-Term Monitoring .....	818
	<b>References .....</b>	<b>819</b>
	<b>Index .....</b>	<b>865</b>

## 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.

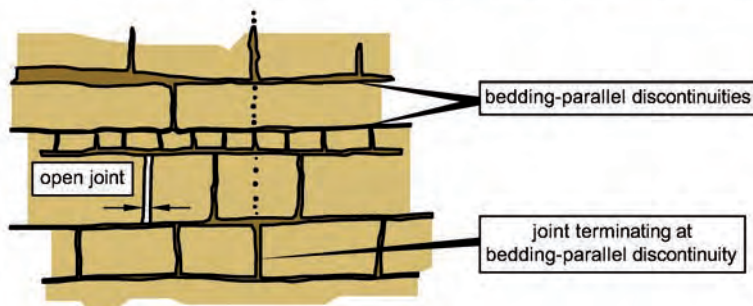
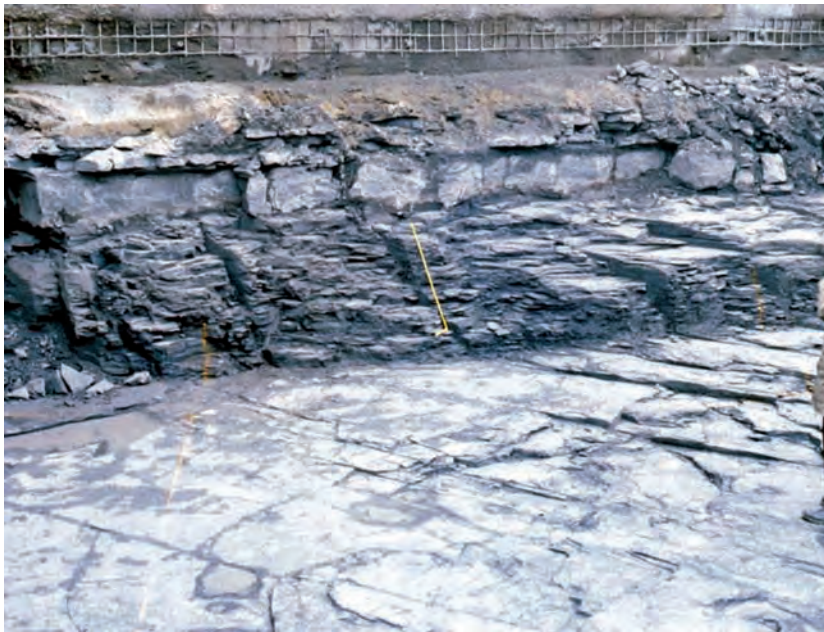


Figure 2.15 Bunter (sandstone), near Fulda (Germany)

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.

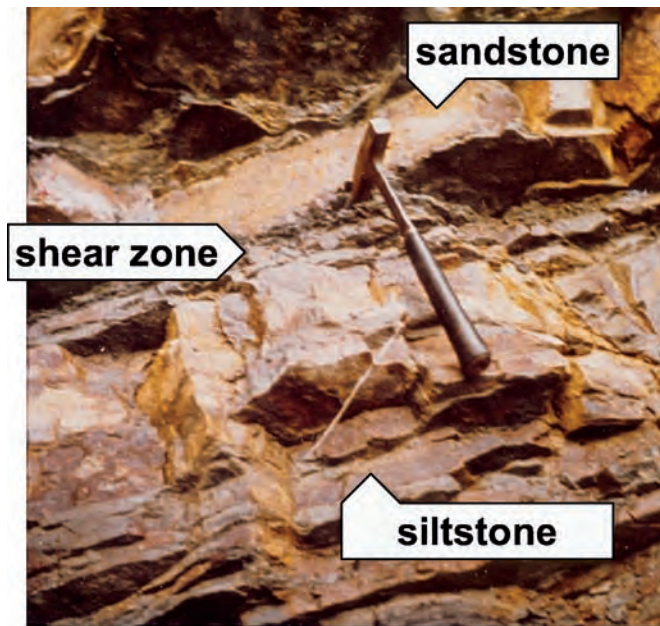
Fig. 2.19 illustrates a tuff, as an example for a pyroclastic sediment. Such a rock mass often exhibits practically no discontinuities. The same is true for the rock salt represented in Fig. 2.20 as an example for a chemical sediment.

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)

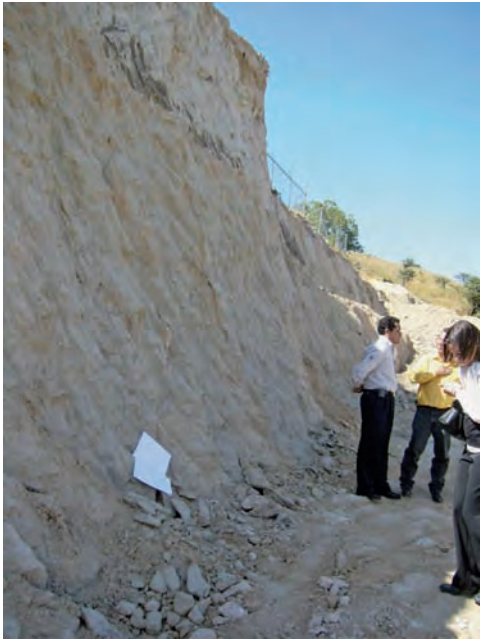


Figure 2.19 Tuff, Guadalajara (Mexico)



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



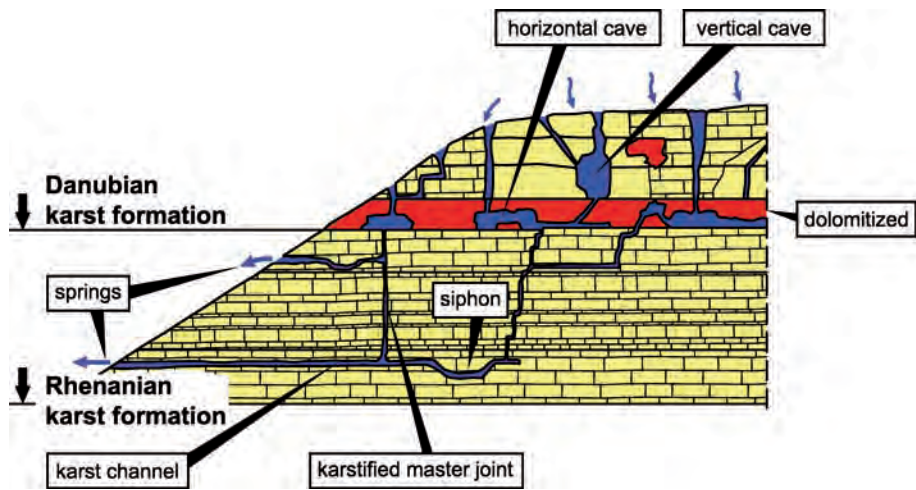


Figure 2.21 Types of karst formation, White Jurassic, Swabian Alb (Germany)



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



**Figure 2.23** Karst channel “Mordloch”  
( $L \approx 4.3$  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.

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.

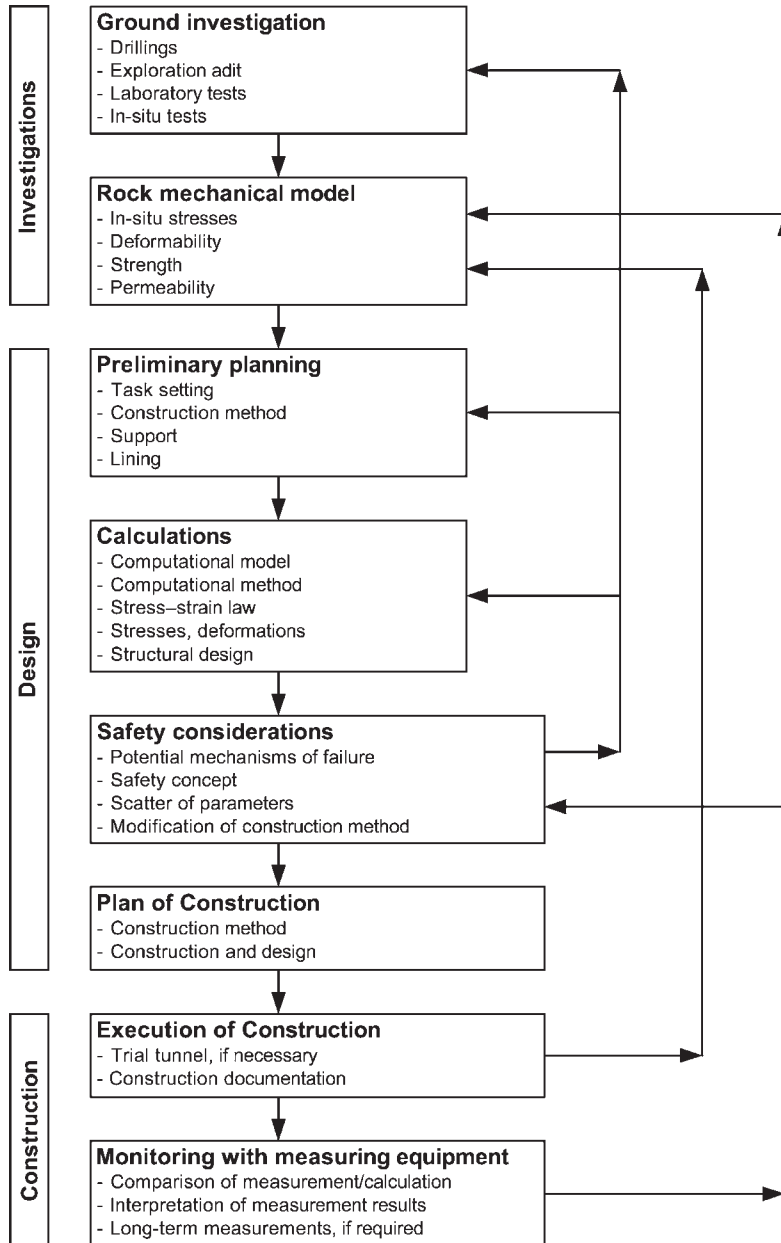


Figure 12.1 Design based on rock mechanical models (ERTC9 1997)

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).

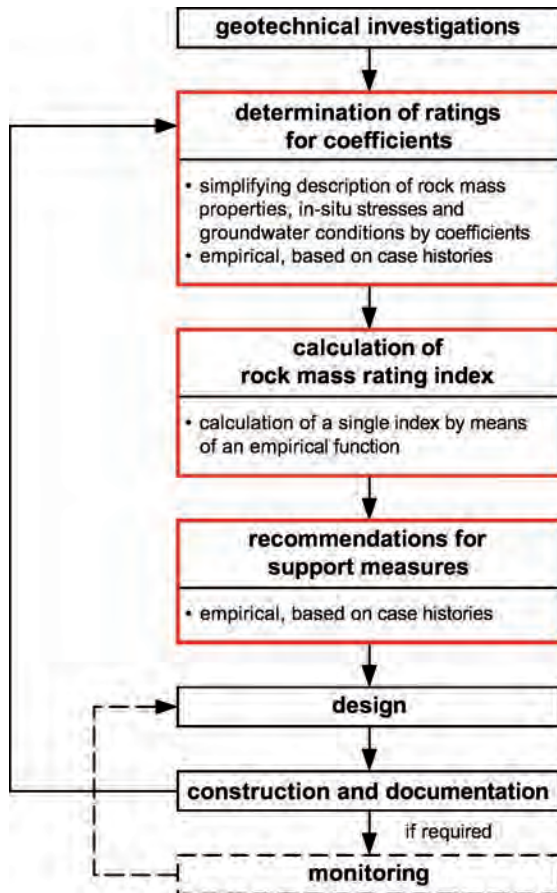
Based on the rock mass behavior types the support measures are specified. The rock-structure interaction, which is referred to as “system behavior”, is derived from the results of numerical and analytical analyses or from experience gained from other projects. The evaluated system behavior for each rock 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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