

Table of Contents

Preface	V
1 Introduction	1
Part A: Fundamentals and Models	
2 Structure of Rock	5
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
3 Stress-Strain Behavior of Jointed Rock	39
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
4 Squeezing Rock	91
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
5	Rock Salt	115
5.1	Introduction	115
5.2	Stress-Strain Behavior	115
5.3	Validation of Model	124
6	Permeability and Seepage Flow	127
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
7	Coupling of Stress-Strain Behavior and Seepage Flow	165
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
8	Swelling Rock	181
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
9	Rock Mass In-Situ Stress	209
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

10	Finite Element Method (FEM)	225
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
11	Stability of Rock Wedges and Excavation Surfaces.....	287
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
12	Design Methods	331
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

13	Site Investigation	353
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
14	Laboratory Tests	403
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

15	Field Tests	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
16	Stress Measurements	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
17	Monitoring	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
18	Evaluation of Rock Mechanical Parameters	587
18.1	General Procedure	587
18.2	Examples	590
19	Examples of Testing and Monitoring Programs	607
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

20	NATM Tunneling	619
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 α 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
21	TBM Tunneling	663
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
22	Powerhouse Cavern Estangento-Sallente	725
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
23	Tunneling in Swelling Rock	753
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
24	Rehabilitation of Urft Dam	771
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
25	Stabilization of a Rock Mass Slide	803
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
References	819
Index	865