# Engineering in Rock Masses

Edited by



With specialist contributions





# Contents

Preface ix List of contributors xi

# 1 Properties and behaviour of rocks and rock masses 1

- 1.1 Geological aspects: igneous rocks 1
- 1.2 Geological aspects: metamorphic rocks 3
- 1.3 Geological aspects: sedimentary rocks 5
- 1.4 Factors controlling the mechanical behaviour of rocks 10
- 1.5 Deformation and failure of rocks 14
- 1.6 Strength of discontinuous rock masses and its assessment 19 References 24

#### 2 Influence of weathering and discontinuities on the behaviour of rock masses 27

- Weathering 27
- 2.1 Rate of weathering 27
- 2.2 Mechanical weathering 28
- 2.3 Chemical and biological weathering 30
- 2.4 Slaking and swelling of mudrocks 33
- 2.5 Engineering classification of weathering 33 Discontinuities 41
- 2.6 Nomenclature of joints 41
- 2.7 Origins of joints 42
- 2.8 Description of jointed rock masses 44
- 2.9 Discontinuities and rock quality indices 46
- 2.10 Recording discontinuity data 48 References 52

# 3 Description and classification of rock masses 54

- 3.1 Description of rocks and rock masses 54
- 3.2 Properties of rocks and rock masses 54
- 3.3 Basic geotechnical description of ISRM 62
- 3.4 Principles of classification 63
- 3.5 Review of classifications 65
- 3.6 The rating concept 67 References 76

# 4 Groundwater in rock masses 78

- 4.1 Basic concepts 78
- 4.2 Hydrodynamics of porous and equivalent media 82
- 4.3 Discontinuous media 89
- 4.4 Hydromechanical coupling 97 References 100

# 5 Block theory in rock engineering 101

- 5.1 Properties of a rock mass and computational possibilities 101
- 5.2 Stereographic projection 102
- 5.3 Block theory 103

- 5.4 Case I: Analysis given only the orientations of the joints 104
- 5.5 Case II: Further analysis given the joint friction angles 106
- 5.6 Case III: Further analysis to define real keyblocks given the locations of joint traces 108
- 5.7 Case IV: Further analysis for known initial stress, joint dilatancy or rock permeability – the block reaction curve 110
- 5.8 An example 112
- 5.9 Conclusions 114 References 116

# 6 Stress analysis for rock masses 117

- 6.1 Purpose 117
- 6.2 In situ state of stress 117
- 6.3 Classical stress analysis 118
- 6.4 Zone of influence of an excavation 121
- 6.5 Excagvation shape and boundary stresses 122
- 6.6 Rock structure and boundary stresses 123
- 6.7 Computational methods of stress analysis 125
- 6.8 Boundary element method 126
- 6.9 Finite difference and distinct element methods 129
- 6.10 Finite element method 131 References 133

# 7 Exploration and investigation of rock masses 134

- 7.1 Introduction 134
- 7.2 Methodology for rock-mass investigation 134
- 7.3 Methods for the study of rock masses 135 References 150 Further reading 150
- 8 Laboratory testing of rocks 151
  - 8.1 Density and porosity 151
    - 8.2 Water sorption and capillarity 153
  - 8.3 Permeability 155
  - 8.4 Durability of weak rocks 156
  - 8.5 Compressive and shear strength 157
  - 8.6 Hardness 164
  - 8.7 Elastic properties 166 References 168

# 9 Rock-mass assessment using geophysical methods 170

- 9.1 Geomechanical properties 170
- 9.2 Geophysical properties 171
- 9.3 Surface geophysical methods 172
- 9.4 Drillhole geophysical methods 177
- 9.5 Geophysical classification 184 References 187

#### 10 Instrumentation in rock masses 191

- 10.1 Introduction 191
- 10.2 Measurement of groundwater level and pore water pressure 191
- 10.3 Measurement of stress and strain in rock masses 194
- 10.4 Stress-change measurements 198
- 10.5 Measurement of displacement 201 References 207 Acknowledgment 207

# 11 Slope stability and rockfall problems in rock masses 209

- 11.1 Introduction 209
- 11.2 Slope stability in rock masses 209
- 11.3 Rockfalls 217
- 11.4 Conclusions 228 References 229

# 12 Settlement and bearing capacity of rock masses 231

- 12.1 Introduction 231
- 12.2 Geological characterization 231
- 12.3 Geomechanical models 232
- 12.4 Settlement of foundations on rock 232
- 12.5 Axial compression capacity of foundations 236
- 12.6 Uplift capacity 242
- 12.7 Lateral capacity 242
- 12.8 Acknowledgements 245 References 245

# 13 Subsidence in rock masses 246

- 13.1 Introduction 246
- 13.2 Subsidence due to coal mining 246
- 13.3 Subsidence in metalliferous mining 252
- 13.4 Subsidence due to the abstraction of fluids 255
- 13.5 Methods of subsidence prediction 258 References 269

# 14 Seismic movements and rock masses 272

- 14.1 Introduction 272
- 14.2 Basic principles of seismic action 273
- 14.3 Analysis an overview 278
- 14.4 Earthquakes and foundations in rock 281
- 14.5 Earthquakes and natural rock slopes 283
- 14.6 Earthquakes and open-pit mining 291
- 14.7 Earthquakes, caverns and tunnels 291
- 14.8 Design to improve resistance to earthquakes 297 References 299

# 15 Control of groundwater in rock masses by pumping systems 304

- 15.1 Introduction 304
- 15.2 The overburden and open-cast mining 304
- 15.3 Some aspects of soil structure of alluvials 309
- 15.4 Rock types and groundwater 311
- 15.5 Engineering precautions 311
- 15.6 Initial investigation 313
- 15.7 Underground water in rocks 315
- 15.8 System design guidelines 317
- 15.9 Summary 319 Acknowledgements 319 References 319

#### 16 Ground freezing 321

- 16.1 Introduction 321
- 16.2 Freezing methods 322
- 16.3 Hydrogeology and ground freezing 325
- 16.4 Design of a frozen wall 326
- 16.5 Placing concrete against frozen ground 332
- 16.6 Monitoring frozen ground 332 References 333

# 17 Grouting in rock masses 334

- 17.1 Nature and purposes of grouting 334
- 17.2 Site investigation 334
- 17.3 When is grouting necessary? 337
- 17.4 Types of grout 338
- 17.5 Cement grouting equipment 338
- 17.6 Stage grouting and methods 342
- 17.7 Closure grouting 342
- 17.8 Grout curtain design 344
- 17.9 Grout pressures 344
- 17.10 The nature of grout penetration in cracks 346
- 17.11 Water : cement ratio and its effect on durability 348
- 17.12 Grouting of fine cracks 348
- 17.13 Grouting of stressed rock 348
- 17.14 Assessment of grouting 349
- 17.15 Some words of caution and encouragement to the inexperienced 349 Acknowledgment 349 References 350 Bibliography 350

#### 18 Reinforcement and support of rock masses 351

- 18.1 Introduction 351
- 18.2 Dowels 352
- 18.3 Rockbolts 354
- 18.4 Sprayed mortar and concrete 363 Acknowledgment 369 References 369

# 19 Rock anchors 370

- 19.1 General approach to anchoring 370
- 19.2 The components of an anchor system 371
- 19.3 The tendon system 372
- 19.4 The mechanics of load mobilization 372
- 19.5 Anchors in soft rocks 375
- 19.6 Anchor construction 378
- 19.7 Anchor testing 378
- 19.8 Anchor performance 380
- 19.9 Anchor monitoring 382
- 19.10 Anchor maintenance 383
- 19.11 Uncertainty in anchor use 383 References 383

# 20 Drilling and blasting of rock masses 385

- 20.1 Drilling of rock masses 385
- 20.2 Blasting of rock masses 389
- 20.3 Explosives 395 Symbols 398
  - Bibliography 399

# 21 Open excavation in rock masses 400

- 21.1 Introduction 400
- 21.2 Groundwater and excavation 400
- 21.3 Methods of excavation: drilling and blasting 403

- 21.4 Methods of excavation: ripping 415
- 21.5 Diggability 421
- References 421

# 22 Tunnelling in rock masses 443

- 22.1 General approach for tunnelling projects 443
- 22.2 Site investigations and ground probings 424
- 22.3 Excavation and support methods for rock tunnelling 426
- 22.4 Structural design of tunnels 429
- 22.5 In situ monitoring and its interpretation 435
- 22.6 Structural detailing of the lining 437 22.7 Documents for tunnelling 437
- References 439

# 23 Underground chambers in hard rock masses 440

- 23.1 Introduction 440
- 23.2 Benefits of underground chambers 440
- 23.3 Design and construction procedure for underground chambers 442
- 23.4 Site characterization 443
- 23.5 Rock-mass classification 449
- 23.6 Rock-engineering considerations 449
- 23.7 Rock support and reinforcement 455
- 23.8 Application of design and construction procedure to an intermediate storage facility for spent nuclear fuel 459 References 463

# 24 Shafts and raises in rock masses 465

- 24.1 Introduction 465
- 24.2 Shaft and raise design 468
- 24.3 Shaft and raise construction 480

24.4 Scenario of shaft and raise construction 502 References 506

#### 25 Socketed foundations in rock masses 509

- 25.1 Introduction 509
- 25.2 Axial loading 510
- 25.3 Lateral loading 522
- 25.4 Design example 526 Acknowledgments 529 References 529

# 26 Retaining structures for rock masses 530

- 26.1 Introduction: general aspects 530
- 26.2 Failure modes in rock masses 530
- 26.3 Strength parameters 531
- 26.4 Lateral pressures on retaining structures 532
- 26.5 Effects of surcharge loading 540
- 26.6 Effect of slope creep 545
- 26.7 Stability of retaining structures 546
- 26.8 Monolithic retaining walls 550
- 26.9 Special types of retaining walls 551
- 26.10 Composite retaining structures 558
- 26.11 Rock reinforcement, rock anchoring 560
- 26.12 Dowelling of rock bodies 565
- 26.13 Rock grouting 569
- 26.14 Spaced and single restraining structures 569
- 26.15 Protective structures for bridges and masts 570
- 26.16 Accompanying measures 570
- 26.17 Final remarks 570

References and further reading 571

Index 573