Contents

General symbols xv
Preface xxv

1 Origin and classification of soils 1
1.1 Introduction: what is soil mechanics? 1
1.1.1 Objectives 3
1.2 Structure of the earth 3
1.3 Origin of soils 5
1.3.1 Transport processes and depositional environments 6
1.3.1.1 Water 6
1.3.1.2 Wind 8
1.3.1.3 Ice 8
1.3.1.4 Ice and water 8
1.4 Soil mineralogy 9
1.4.1 Composition of soils 9
1.4.2 Clay minerals 10
1.4.2.1 Kaolinite 10
1.4.2.2 Montmorillonite 12
1.4.2.3 Illite 12
1.4.2.4 Other clay minerals 12
1.4.3 Non-clay minerals 12
1.4.4 Surface forces 13
1.4.5 Organic or non-mineral soils 14
1.5 Phase relationships for soils 14
1.6 Unit weight 18
1.6.1 Measuring the particle relative density Gs 20
1.7 Effective stress 22
1.7.1 Calculating vertical stresses in the ground 23
1.8 Particle size distributions 27
1.9 Soil filters 32
1.10 Soil description 39
1.11 Index tests and classification of clay soils 41
1.12 Compaction 43
1.13 Houses built on clay 49
Key points 54
2 Soil strength

2.1 Introduction 59
  2.1.1 Objectives 59

2.2 Stress analysis 60
  2.2.1 General three-dimensional states of stress 60
  2.2.2 Principal stresses 60
  2.2.3 Plane strain 61
  2.2.4 Axisymmetry 62
  2.2.5 Mohr circle of stress 62
  2.2.6 Mohr circle of strain 64

2.3 Soil strength 67

2.4 Friction 68

2.5 Shearbox or direct shear apparatus 71

2.6 Presentation of shearbox test data in engineering units 73

2.7 Volume changes during shear 74

2.8 Critical states 76

2.9 Peak strengths and dilation 79

2.10 Shearbox tests on clays 85

2.11 Applications 87

2.12 Stress states in the shearbox test 90
  2.12.1 Conventional interpretation 90
  2.12.2 Alternative interpretation 91
  2.12.3 Undrained tests on clays 93

2.13 Simple shear apparatus 94

Key points 100

Self-assessment and learning questions 100

Shearbox test 100
  Development of a critical state model 101
  Determination of peak strengths 101
  Use of strength data to calculate friction pile load capacity 102
  Stress analysis and interpretation of shearbox test data 102

References 103

3 Groundwater flow and control

3.1 Introduction 105
  3.1.1 Objectives 105
3.2 Pore water pressures in the ground 106
  3.2.1 Artesian conditions and underdrainage 106
  3.2.2 Effect of construction activities 109
  3.2.3 Pore water pressures above the water table 110
3.3 Darcy's law and soil permeability 111
3.4 Laboratory measurement of permeability 115
  3.4.1 Constant head permeameter 115
  3.4.2 Falling head permeameter 117
3.5 Field measurement of permeability 119
  3.5.1 Well pumping test in an ideal confined aquifer 120
  3.5.2 Well pumping test in an ideal unconfined aquifer 122
3.6 Permeability of laminated soils 123
3.7 Mathematics of groundwater flow 126
3.8 Plane flow 128
3.9 Confined flownets 129
3.10 Calculation of pore water pressures using flownets 136
3.11 Quicksand 137
3.12 Unconfined flownets 139
3.13 Distance of influence 141
3.14 Soils with anisotropic permeability 142
3.15 Zones of different permeability 145
3.16 Boundary conditions for flow into drains 146
3.17 Application of well pumping formulae to construction dewatering 148
3.18 Numerical methods 150
3.19 Groundwater control 150
  3.19.1 Wellpoint system 151
  3.19.2 Deep wells 152
  3.19.3 Ejectors 153
  3.19.4 Well design 153
  3.19.5 Electro-osmosis 153
  3.19.6 Ground freezing 158
  3.19.7 Grouting 160
3.20 Unsaturated soils 160
  3.20.1 Unsaturated soil as a three-phase material 160
  3.20.2 Relationship between soil suction and water content 161
  3.20.3 Permeability of unsaturated soils 163
  3.20.4 Water flow in unsaturated soils 164

Key points 165
Self-assessment and learning questions 165
Laboratory measurement of permeability; fluidisation; layered soils 165
Well pumping test for field measurement of permeability 167
Confined flownets and quicksand 167
Unconfined flownet 169
Flownets in anisotropic soils 169
Notes 170
References 171
4 One-dimensional compression and consolidation

4.1 Introduction and objectives 173
  4.1.1 Objectives 174
4.2 One-dimensional compression: the oedometer test 175
4.3 One-dimensional consolidation 184
4.4 Properties of isochrones 186
4.5 One-dimensional consolidation: solution using parabolic isochrones 187
4.6 Determining the consolidation coefficient $c_v$ from oedometer test data 191
4.7 Application of consolidation testing and theory to field problems 193
  4.7.1 Consolidation due to an increase in effective stress following groundwater lowering 194
  4.7.2 Underdrainage of a compressible layer 196
  4.7.3 Vertical compression due to plane horizontal flow 201
  4.7.4 Self-weight consolidation: hydraulic fill 205
4.8 One-dimensional consolidation: exact solutions 208
  4.8.1 Derivation of the differential equation governing one-dimensional consolidation 208
  4.8.2 General solution to the consolidation equation 210
  4.8.3 Solutions for particular boundary conditions using Fourier series 211
4.9 Radial drainage 218
4.10 Limitations of the simple models for the behaviour of soils in one-dimensional compression and consolidation 221
  4.10.1 Model for one-dimensional compression and swelling: specific volume against $\ln(o\sigma')$ 221
  4.10.2 One-dimensional consolidation solutions 221
  4.10.3 Horizontal stresses in one-dimensional compression and swelling 222

Key points 223
Self-assessment and learning questions 224
Analysis and interpretation of one-dimensional compression test data 224
Analysis of data from the consolidation phase 225
Application of one-dimensional compression and consolidation theory to field problems 226

Notes 228
References 229

5 Triaxial test and soil behaviour

5.1 Introduction 231
  5.1.1 Objectives 231
5.2 Triaxial test 232
  5.2.1 Apparatus 232
  5.2.2 Procedures 234
5.3 Stress parameters 235
  5.3.1 Stress invariants 235
  5.3.2 Notation 237
5.4 Stress analysis of the triaxial test 238
5.4.1 Assumptions 238
5.4.2 Measured quantities 238
5.4.3 Converting measurements to stress, strain and state parameters 239
5.4.4 Mohr circles of stress 241
5.4.5 Mohr circles of strain 242
5.4.6 Other ways of presenting shear test data 242
5.5 Determining the effective angle of shearing resistance $q'$ from triaxial shear tests 245
5.6 Undrained shear strengths of clay soils 250
5.7 Isotropic compression and swelling 253
5.8 Specimen preparation by one-dimensional compression and swelling: $K_0$ consolidation 254
5.9 Conditions imposed in shear tests 255
5.10 Critical states 257
5.10.1 Relation between $M$ and $q'_{\text{crit}}$ 258
5.11 Yield 260
5.12 State paths during shear: normally consolidated and lightly overconsolidated clays 268
5.12.1 Drained tests 268
5.12.2 Undrained tests 270
5.13 Peak strengths 278
5.13.1 Predictions using Cam clay 278
5.13.2 Hvorslev rupture and tensile fracture 279
5.13.3 Interpreting peak strength data 280
5.13.4 Stress ratio-rate of dilation plots 280
5.14 Residual strength 282
5.15 Sensitive soils 283
5.16 Correlation of critical state parameters with index tests 285
5.17 Creep 286
5.18 Anisotropy 288
5.19 Unsaturated soils 289
5.20 Critical state model applied to sands 291
5.21 Non-linear soil models 292
5.22 Repeated or cyclic loading 295
Key points 297
Self-assessment and learning questions 298
Interpretation of triaxial test results 298
Determination of critical state and Cam clay parameters 299
Analysis and prediction of state paths using Cam clay concepts 300
Notes 302
References 303

6 Calculation of soil settlements using elasticity methods 307
6.1 Introduction 307
6.1.1 Objectives 308
6.2 Selection of elastic parameters 309
  6.2.1 Approximations and shortcomings of a simple elastic model 309
  6.2.2 Relationships between elastic constants 311
  6.2.3 Determining elastic moduli from triaxial compression test data 313

6.3 Boussinesq’s solution 314

6.4 Newmark’s chart and estimation of vertical stress 316

6.5 Settlements due to surface loads and foundations 320

6.6 Influence factors for stress 323

6.7 Standard solutions for surface settlements on an isotropic, homogeneous, elastic half-space 327

6.8 Estimation of immediate settlements 328

6.9 Effect of heterogeneity 329

6.10 Cross-coupling of shear and volumetric effects due to anisotropy 330

Key points 331

Self-assessment and learning questions 332

Determining elastic parameters from laboratory test data 332

Calculation of increases in vertical effective stress below a surface surcharge 333

Calculation of increases in vertical effective stress and resulting soil settlements 334

Use of standard formulae in conjunction with one-dimensional consolidation theory (Chapter 4) 335

References 336

7 Plasticity and limit equilibrium methods for earth pressures and retaining walls 337

7.1 Engineering plasticity 337
  7.1.1 Objectives 338

7.2 Upper and lower bounds (safe and unsafe solutions) 339

7.3 Failure criteria for soils 340
  7.3.1 \( \tau / \sigma' \) \(_{\text{max}} = \tan \phi' \) failure criterion 340
  7.3.2 \( \phi'_{\text{crit}} \) or \( \phi'_{\text{peak}} \) 342
  7.3.3 \( \tau_{\text{max}} = \tau_u \) failure criterion 342

7.4 Retaining walls 344

7.5 Calculation of limiting lateral earth pressures 349

7.6 Development of simple stress field solutions for a propped embedded cantilever retaining wall 351
  7.6.1 \( \tau / \sigma' \) \(_{\text{max}} = \tan \phi' \) failure criterion 352
  7.6.2 \( \tau_{\text{max}} = \tau_u \) failure criterion 356

7.7 Soil/wall friction 361

7.8 Mechanism-based kinematic and equilibrium solutions for gravity retaining walls 362

7.9 Reinforced soil walls 384

7.10 Compaction stresses behind backfilled walls 387
  7.10.1 Free-draining soils 387
  7.10.2 Clays 392
8 Foundations and slopes

8.1 Introduction and objectives 405
8.1.1 Objectives 405

8.2 Shallow strip foundations (footings): simple lower bound (safe) solutions 406
8.2.1 Effective stress analysis: \( (\tau/\sigma')_{\text{max}} = \tan\phi \) failure criterion 406
8.2.2 Short-term total stress analysis: \( \tau_{\text{max}} = \tau_u \) failure criterion 407

8.3 Simple upper bound (unsafe) solutions for shallow strip footings 408
8.3.1 Short-term total stress analysis: \( \tau_{\text{max}} = \tau_u \) failure criterion 408
8.3.2 Effective stress analysis: \( (\tau/\sigma')_{\text{max}} = \tan\phi \) failure criterion 411

8.4 Bearing capacity enhancement factors to account for foundation shape and depth, and soil weight 414
8.4.1 Effective stress analysis: \( (\tau/\sigma')_{\text{max}} = \tan\phi \) failure criterion 414
8.4.2 Short-term total stress analysis: \( \tau_{\text{max}} = \tau_u \) 415

8.5 Shallow foundations subjected to horizontal and moment loads 417

8.6 Simple piled foundations: ultimate axial loads of single piles 425
8.7 \( \phi'_{\text{crit}} \) or \( \phi'_{\text{peak}} \) 428

8.8 Pile groups and piled rafts 433

8.9 Lateral loads on piles 435
8.9.1 Effective stress analysis: \( (\tau/\sigma')_{\text{max}} = \tan\phi \) failure criterion 436
8.9.2 Total stress analysis: \( \tau_{\text{max}} = \tau_u \) failure criterion 437

8.10 Introductory slope stability: the infinite slope 439

8.11 Analysis of a more general slope 443
8.11.1 Total stress analysis for undrained stability of slopes in clays 444
8.11.2 Effective stress analysis of a general slope with a circular slip surface 446
8.11.2.1 Swedish method: Fellenius (1927) 447
8.11.2.2 Bishop's simplified or routine method: Bishop (1955) 449
8.11.3 Non-circular slips 451

8.12 Laterally loaded piles for slope stabilisation 454

Key points 458
Self-assessment and learning questions 459
Shallow foundations 459
Deep foundations 461
Laterally loaded piles 463
Slopes 464
References 466
9 In-ground retaining structures: embedded walls and tunnels

9.1 Introduction and objectives 469
9.1.1 Objectives 469

9.2 Limit equilibrium stress distributions for embedded retaining walls 470
9.2.1 Long-term pore water pressures 470
9.2.2 Unpropped embedded walls; fixed earth support conditions 472
9.2.3 Embedded walls propped at the crest: free and fixed earth support conditions 473

9.3 Earth pressure coefficients taking account of shear stresses at the soil/wall interface 475
9.3.1 Effects of soil/wall friction 475
9.3.2 Effects of soil/wall adhesion 478

9.4 Limit equilibrium calculations for embedded retaining walls and ultimate limit state design 479
9.4.1 Brief history of embedded retaining wall design 479
9.4.2 ULS limit equilibrium calculations 482

9.5 Calculation of bending moments and prop loads: serviceability limit states 492

9.6 Embedded walls retaining clay soils 493
9.6.1 Time-scale over which undrained conditions apply 493
9.6.2 Effect of high in situ lateral stresses 494

9.7 Geostructural mechanism to estimate wall movements 497

9.8 Effect of relative soil: wall stiffness 501
9.8.1 Early work by Rowe 501
9.8.2 Modern approach 503

9.9 Strip loads 509

9.10 Multi-propped embedded walls 510

9.11 Tunnels 510
9.11.1 Stress analysis of a tunnel of circular cross-section 514
9.11.2 Collapse of tunnels in clay: short-term total stress analysis 515
9.11.3 Collapse of tunnels: effective stress analysis 515
9.11.4 Collapse of tunnel headings 517
9.11.5 Ground movements due to tunnelling 518

Key points 520
Self-assessment and learning questions 521
Embedded retaining walls and ULS design 521
Tunnels 526
Note 527
References 527

10 Calculation of improved bearing capacity factors and earth pressure coefficients using plasticity methods

10.1 Introduction and objectives 531
10.1.1 Objectives 532
10.2 Stress discontinuities and their use to calculate improved bearing capacity factors for a shallow foundation subjected to a vertical load: effective stress ($q'$) analysis 533
10.3 Stress discontinuities and their use to calculate improved bearing capacity factors for a shallow foundation subjected to a vertical load: total stress ($\tau_w$) analysis 539
10.4 Application to stress analysis 543
  10.4.1 General approach 543
  10.4.2 Visualization of stress fields using characteristic directions 544
10.5 Shallow foundations subjected to inclined loads 545
  10.5.1 Effective stress ($q'$) analysis 546
  10.5.2 Total stress (undrained shear strength, $\tau_w$) analysis 551
  10.5.3 Interaction diagrams for eccentric vertical loading (combined vertical and moment loading): a simplified approach 556
10.6 Calculation of earth pressure coefficients for rough retaining walls 557
  10.6.1 Wall friction: effective stress $q'$ analysis 557
  10.6.2 Wall adhesion: total stress ($\tau_w$) analysis 562
10.7 Sloping backfill 567
  10.7.1 Effective stress ($q'$) analysis 567
  10.7.2 Total stress ($\tau_w$) analysis 568
10.8 Wall with a sloping (battered) back 569
  10.8.1 Effective stress ($q'$) analysis 570
  10.8.2 Total stress ($\tau_w$) analysis 570
10.9 Improved upper bounds for shallow foundations 573
  10.9.1 Total stress ($\tau_w$) analysis 573
  10.9.2 Effective stress ($q'$) analysis 580
Key points 581
Self assessment and learning questions 582
Bearing capacity of foundations 582
Retaining walls and earth pressures 584
References 585

11 Site investigation, in situ testing and modelling 587

11.1 Introduction and objectives 587
  11.1.1 Objectives 588
11.2 Site investigation 588
  11.2.1 Planning the investigation 588
  11.2.2 Developing the ground model 590
  11.2.3 Soil sampling and testing 593
11.3 In situ testing 594
  11.3.1 Standard penetration test 594
  11.3.2 Cone penetration test 598
  11.3.3 Pressuremeter tests 603
    11.3.3.1 General description 603
    11.3.3.2 Stress analysis 606
11.3.4 Vane shear test 615
11.3.5 Plate bearing test 618
11.4 Modelling 618
11.4.1 Numerical modelling 619
11.4.2 Physical modelling: geotechnical centrifuge testing 626
11.5 Ground improvement 631
11.5.1 Grouting 631
11.5.2 Preloading 632
11.5.3 Surface compaction 633
11.5.4 Heavy tamping 633
11.5.5 Cement and lime stabilization 634
11.5.6 Soil reinforcement 635
11.5.7 Assessing the success of ground improvement techniques 637

Key points 637
Self-assessment and learning questions 638
In situ testing 638
Modelling 639
Ground improvement 639
Notes 639
References 640

Index 645