



Finite element analysis in geotechnical engineering application

David M Potts and Lidija Zdravković

Contents

Preface	xi
Authorship	xvi
Acknowledgements	xvi
1. Obtaining geotechnical parameters	1
1.1 Synopsis	1
1.2 Introduction	1
1.3 Laboratory tests	2
1.3.1 Introduction	2
1.3.2 Oedometer test	3
1.3.3 Triaxial test	6
1.3.4 True triaxial test	11
1.3.5 Direct shear test	12
1.3.6 Simple shear test	14
1.3.7 Ring shear test	15
1.3.8 Hollow cylinder test	16
1.3.9 Directional shear cell	20
1.3.10 Geophysical techniques	20
1.3.11 Permeameters	22
1.4 In-situ tests	23
1.4.1 Introduction	23
1.4.2 Standard penetration test (SPT)	23
1.4.3 Cone penetration test (CPT)	27
1.4.4 Pressuremeter testing	30
1.4.5 The plate loading test	32
1.4.6 Pumping tests	35
1.5 Summary	35
2. Tunnels	38
2.1 Synopsis	38
2.2 Introduction	38
2.3 Tunnel construction	39

2.3.1	Introduction	39
2.3.2	Open faced shield tunnelling	40
2.3.3	Tunnel Boring Machines (TBM), including slurry shields and Earth Pressure Balance (EPB) tunnelling	40
2.3.4	The sprayed concrete lining (SCL) method	41
2.3.5	Ground response to tunnel construction	41
2.4	Simulation of the construction process	43
2.4.1	Introduction	43
2.4.2	Setting up the initial conditions	44
2.4.3	Important boundary conditions	45
2.4.4	Modelling tunnel excavation	45
2.4.5	Modelling the tunnel lining	48
2.5	Modelling time dependent behaviour	52
2.5.1	Introduction	52
2.5.2	Setting up the initial conditions	52
2.5.3	Hydraulic boundary conditions	54
2.5.4	Permeability models	55
2.5.5	A parametric study of the effect of permeable and impermeable tunnel linings	57
2.6	Choice of soil model	59
2.6.1	Introduction	59
2.6.2	Results from a parametric study	59
2.6.3	Devices for improving the surface settlement prediction	60
2.7	Interaction analysis	63
2.7.1	The influence of building stiffness on tunnel-induced ground movements	63
2.7.2	The Treasury building - a case study	66
2.7.3	Twin tunnel interaction	70
2.8	Summary	72
3.	Earth retaining structures	74
3.1	Synopsis	74
3.2	Introduction	74
3.3	Types of retaining structure	75
3.3.1	Introduction	75
3.3.2	Gravity walls	75
3.3.3	Reinforced/anchored earth wall	76
3.3.4	Embedded walls	76
3.4	General considerations	77
3.4.1	Introduction	77
3.4.2	Symmetry	77
3.4.3	Geometry of the finite element model	79
3.4.4	Support systems	82

3.4.5	Choice of constitutive models	84
3.4.5.1	Structural components	84
3.4.5.2	Soil	85
3.4.6	Initial ground conditions	88
3.4.6.1	General	88
3.4.6.2	'Greenfield' conditions	88
3.4.6.3	Modified initial soil stresses	89
3.4.7	Construction method and programme	91
3.4.7.1	General	91
3.4.7.2	Construction method	91
3.4.7.3	Time related movements	92
3.4.7.4	Ground water control	93
3.5	Gravity walls	93
3.5.1	Introduction	93
3.5.2	Earth pressure due to compaction	94
3.5.3	Finite element analysis	95
3.6	Reinforced earth walls	96
3.6.1	Introduction	96
3.6.2	Finite element analysis	99
3.7	Embedded walls	103
3.7.1	Introduction	103
3.7.2	Installation effects	104
3.7.2.1	General	104
3.7.2.2	Field measurements	104
3.7.2.3	Analysis	105
3.7.2.4	Comments	106
3.7.3	Modelling of walls	107
3.7.3.1	Element type	107
3.7.3.2	Wall stiffness	109
3.7.3.3	Interface behaviour	111
3.7.3.4	Wall permeability	111
3.7.4	Support systems	112
3.7.4.1	Introduction	112
3.7.4.2	Support stiffness	112
3.7.4.3	Connection details	113
3.7.4.4	Active support systems	114
3.7.4.5	Berms	115
3.7.4.6	Ground anchors	115
3.7.4.7	Relieving slabs	116
3.7.5	Long term behaviour and post construction effects	118
3.7.6	Adjacent structures	119
3.8	Summary	122
	Appendix III.1	123

4. Cut slopes	125
4.1 Synopsis	125
4.2 Introduction	125
4.3 'Non-softening' analyses	126
4.3.1 Introduction	126
4.3.2 Cut slopes in stiff 'non-softening' clay	127
4.3.2.1 Introduction	127
4.3.2.2 Soil parameters	127
4.3.2.3 Finite element analyses	127
4.3.2.4 Results of analyses	128
4.3.3 Cut slopes in soft clay	131
4.3.3.1 Introduction	131
4.3.3.2 Soil parameters	132
4.3.3.3 Finite element analyses	136
4.3.3.4 Results of analyses	138
4.4 Progressive failure	141
4.5 'Softening' analyses	145
4.5.1 Introduction	145
4.5.2 Choice of constitutive model	146
4.5.3 Implications for convergence	147
4.5.4 Cut slopes in London Clay	147
4.5.4.1 Introduction	147
4.5.4.2 Soil parameters	148
4.5.4.3 Finite element analyses	150
4.5.4.4 Results of a typical analysis	150
4.5.4.5 Effect of coefficient of earth pressure at rest	153
4.5.4.6 Effect of surface boundary suction	155
4.5.4.7 Effect of slope geometry	155
4.5.4.8 Effect of surface cracking	156
4.5.4.9 Effect of subsequent changes to slope geometry	158
4.5.4.10 Further discussion	160
4.6 Construction of cut slope under water	162
4.7 Summary	163
5. Embankments	166
5.1 Synopsis	166
5.2 Introduction	166
5.3 Finite element analysis of rockfill dams	167
5.3.1 Introduction	167
5.3.2 Typical stress paths	167
5.3.3 Choice of constitutive models	168
5.3.3.1 Linear elastic analysis	169

5.3.3.2	'Power law' models	169
5.3.3.3	Hyperbolic model	170
5.3.3.4	K-G model	171
5.3.3.5	Elasto-plastic models	171
5.3.4	Layered analysis, stiffness of the simulated layer and compaction stresses	173
5.3.5	Example: Analysis of Roadford dam	175
5.3.5.1	Introduction	175
5.3.5.2	Material parameters	175
5.3.5.3	Finite element analysis	177
5.3.5.4	Comparison with observations	179
5.3.6	Example: Analysis of old puddle clay core dams	180
5.3.6.1	Introduction	180
5.3.6.2	Dale Dyke dam	181
5.3.6.3	Ramsden dam	183
5.4	Finite element analysis of earth embankments	185
5.4.1	Introduction	185
5.4.2	Modelling of earthfill	186
5.4.3	Example: Road embankments on London Clay	186
5.4.3.1	Introduction	186
5.4.3.2	Material properties	187
5.4.3.3	Finite element analysis	188
5.4.4	Example: Failure of Carsington embankment	189
5.4.4.1	Introduction	189
5.4.4.2	Material parameters and soil model used	190
5.4.4.3	Finite element analysis	191
5.4.4.4	Original Carsington section	191
5.4.4.5	Effect of the core geometry on progressive failure	192
5.4.4.6	Effect of berm in improving the stability	193
5.5	Finite element analysis of embankments on soft clay	194
5.5.1	Introduction	194
5.5.2	Typical soil conditions	195
5.5.3	Choice of constitutive model	196
5.5.4	Modelling soil reinforcement	198
5.5.5	Example: Effect of a surface crust	198
5.5.5.1	Introduction	198
5.5.5.2	Soil conditions	198
5.5.5.3	Finite element analysis	199
5.5.5.4	Results	200
5.5.6	Example: Effect of reinforcement	200
5.5.6.1	Introduction	200
5.5.6.2	Soil conditions	201
5.5.6.3	Results	201

5.5.7	Example: Staged construction	202
5.5.7.1	Introduction	202
5.5.7.2	Soil conditions	203
5.5.7.3	Finite element analysis	204
5.5.7.4	Results	205
5.5.8	Example: Effect of anisotropic soil behaviour	206
5.5.8.1	Introduction	206
5.5.8.2	Geometry	206
5.5.8.3	Soil conditions	207
5.5.8.4	Finite element analysis	207
5.5.8.5	Results	208
5.6	Summary	211
6.	Shallow foundations	214
6.1	Synopsis	214
6.2	Introduction	214
6.3	Foundation types	215
6.3.1	Surface foundations	215
6.3.2	Shallow foundations	215
6.4	Choice of soil model	215
6.5	Finite element analysis of surface foundations	216
6.5.1	Introduction	216
6.5.2	Flexible foundations	218
6.5.3	Rigid foundations	218
6.5.4	Examples of vertical loading	219
6.5.4.1	Introduction	219
6.5.4.2	Strip footings on undrained clay	219
6.5.4.3	Effect of footing shape on the bearing capacity of undrained clay	223
6.5.4.4	Strip footings on weightless drained soil	225
6.5.4.5	Strip footings on a drained soil	227
6.5.4.6	Circular footings on a weightless drained soil	230
6.5.4.7	Circular footings on a drained soil	232
6.5.5	Undrained bearing capacity of non-homogeneous clay	233
6.5.5.1	Introduction	233
6.5.5.2	Constitutive model	234
6.5.5.3	Geometry and boundary conditions	236
6.5.5.4	Failure mechanisms	236
6.5.6	Undrained bearing capacity of pre-loaded strip foundations on clay	238
6.5.6.1	Introduction	238
6.5.6.2	Constitutive model	239

6.5.6.3	Geometry and boundary conditions	240
6.5.6.4	Results of the analyses	240
6.5.6.5	Concluding remarks	243
6.5.7	Effect of anisotropic strength on bearing capacity	243
6.5.7.1	Introduction	243
6.5.7.2	Soil behaviour	244
6.5.7.3	Behaviour of strip footings	246
6.5.7.4	Behaviour of circular footings	247
6.6	Finite element analysis of shallow foundations	248
6.6.1	Introduction	248
6.6.2	Effect of foundation depth on undrained bearing capacity	248
6.6.3	Example: The leaning Tower of Pisa	252
6.6.3.1	Introduction	252
6.6.3.2	Details of the Tower and ground profile	253
6.6.3.3	History of construction	254
6.6.3.4	History of tilting	255
6.6.3.5	The motion of the Tower foundations	256
6.6.3.6	Stability of tall towers	256
6.6.3.7	Soil properties	259
6.6.3.8	Finite element analysis	263
6.6.3.9	Simulation of the history of inclination	265
6.6.3.10	Temporary counterweight	267
6.6.3.11	Observed behaviour during application of the counterweight	269
6.6.3.12	Permanent stabilisation of the Tower	271
6.6.3.13	Soil extraction	271
6.6.3.14	The response of the Tower to soil extraction	275
6.6.3.15	Comments	276
6.7	Summary	278
7.	Deep foundations	280
7.1	Synopsis	280
7.2	Introduction	280
7.3	Single piles	282
7.3.1	Introduction	282
7.3.2	Vertical loading	282
7.3.3	Lateral loading	287
7.4	Pile group behaviour	289
7.4.1	Introduction	289
7.4.2	Analysis of a pile group	291
7.4.3	Superposition	291
7.4.3.1	Simple superposition	292

	7.4.3.2 Pile displacements with depth	293
7.4.4	Load distribution within a pile group	294
	7.4.4.1 Obtaining an initial trial division of the applied loads	296
	7.4.4.2 Evaluating pile head displacements	297
	7.4.4.3 Checking the rigid pile cap criterion	297
7.4.5	Pile group design	298
	7.4.5.1 Matrix formulation of the pile group response	298
	7.4.5.2 Superposition of loads	299
	7.4.5.3 Evaluating the solution displacements and rotations	302
7.4.6	Magnus	304
	7.4.6.1 Introduction	304
	7.4.6.2 Soil properties and initial conditions	304
	7.4.6.3 Finite element analyses	308
	7.4.6.4 Design of Magnus foundations	309
	7.4.6.5 Environmental loading	314
7.5	Bucket foundations	317
	7.5.1 Introduction	317
	7.5.2 Geometry	318
	7.5.3 Finite element analysis	318
	7.5.4 Modelling of the interface between top cap and soil	320
	7.5.5 Isotropic study	321
	7.5.5.1 Soil conditions	321
	7.5.5.2 Parametric studies	322
	7.5.5.3 Results	322
	7.5.6 Anisotropic study	326
	7.5.6.1 Introduction	326
	7.5.6.2 Results	326
	7.5.7 Suction anchors	327
	7.5.7.1 Introduction	327
	7.5.7.2 Geometry	327
	7.5.7.3 Results	329
7.6	Summary	329
8.	Benchmarking	332
8.1	Synopsis	332
8.2	Definitions	332
8.3	Introduction	333
8.4	Causes of errors in computer calculations	334
8.5	Consequences of errors	335
8.6	Developers and users	336
	8.6.1 Developers	336

8.6.2	Users	337
8.7	Techniques used to check computer calculations	339
8.8	Benchmarking	339
8.8.1	General	339
8.8.2	Standard benchmarks	340
8.8.3	Non-standard benchmarks	341
8.9	The INTERCLAY II project	341
8.10	Examples of benchmark problems - Part I	342
8.10.1	General	342
8.10.2	Example 1: Analyses of an ideal triaxial test	343
8.10.3	Example 2: Analysis of a thick cylinder	344
8.10.4	Example 3: Analyses of an advancing tunnel heading	346
8.10.5	Example 4: Analysis of a shallow waste disposal	348
8.10.6	Example 5: Simplified analysis of a shallow waste	351
8.11	Examples of benchmark problems - Part II (German Society for Geotechnics benchmarking exercise)	353
8.11.1	Background	353
8.11.2	Example 6: Construction of a tunnel	353
8.11.3	Example 7: Deep excavation	355
8.11.4	General comments	356
8.12	Summary	357
Appendix VIII.1	Specification for Example 1: Analyses of an idealised triaxial test	358
VIII.1.1	Geometry	358
VIII.1.2	Material properties and initial stress conditions	358
VIII.1.3	Loading conditions	358
Appendix VIII.2	Specification for Example 2: Analysis of a thick cylinder	358
VIII.2.1	Geometry	358
VIII.2.2	Material properties	358
VIII.2.3	Loading conditions	359
Appendix VIII.3	Specification for Example 3: Analysis of an advancing tunnel heading	359
VIII.3.1	Geometry	359
VIII.3.2	Material properties	359
VIII.3.3	Loading conditions	359
Appendix VIII.4	Specification for Example 4: Analysis of a shallow waste disposal	360
VIII.4.1	Geometry	360
VIII.4.2	Material properties	360
VIII.4.3	Loading conditions	361
Appendix VIII.5	Specification for Example 5: Simplified analysis of a shallow waste disposal	361

VIII.5.1	Geometry	361
VIII.5.2	Material properties	361
VIII.5.3	Loading conditions	361
VIII.5.4	Additional boundary conditions	362
Appendix VIII.6	Specification for Example 6: Construction of a tunnel	362
VIII.6.1	Geometry	362
VIII.6.2	Material properties	362
Appendix VIII.7	Specification for Example 7: Deep excavation	362
VIII.7.1	Geometry	362
VIII.7.2	Material properties	362
VIII.7.3	Construction stages	363
9.	Restrictions and pitfalls	364
9.1	Synopsis	364
9.2	Introduction	364
9.3	Discretisation errors	365
9.4	Numerical stability of zero thickness interface elements	368
9.4.1	Introduction	368
9.4.2	Basic theory	368
9.4.3	Ill-conditioning	370
9.4.4	Steep stress gradients	373
9.5	Modelling of structural members in plane strain analysis	376
9.5.1	Walls	376
9.5.2	Piles	377
9.5.3	Ground anchors	378
9.5.4	Structural members in coupled analyses	380
9.5.5	Structural connections	380
9.5.6	Segmental tunnel linings	381
9.6	Use of the Mohr-Coulomb model for undrained analysis	382
9.7	Influence of the shape of the yield and plastic potential surfaces in the deviatoric plane	384
9.8	Using critical state models in undrained analysis	386
9.9	Construction problems	387
9.10	Removal of prescribed degrees of freedom	388
9.11	Modelling underdrainage	389
9.12	Summary	394
References		396
List of symbols		410
Index		415