Finite element analysis in geotechnical engineering

Application

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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

ii / Finite element analysis in geotechnical engineering: Application

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

Preface

While the finite element method has been used in many fields of engineering practice for over thirty years, it is only relatively recently that it has begun to be widely used for analysing geotechnical problems. This is probably because there are many complex issues which are specific to geotechnical engineering and which have only been resolved relatively recently. Perhaps this explains why there are few books which cover the application of the finite element method to geotechnical engineering.

For over twenty years we, at Imperial College, have been working at the leading edge of the application of the finite element method to the analysis of practical geotechnical problems. Consequently, we have gained enormous experience of this type of work and have shown that, when properly used, this method can produce realistic results which are of value to practical engineering problems. Because we have written all our own computer code, we also have an in-depth understanding of the relevant theory.

Based on this experience we believe that, to perform useful geotechnical finite element analysis, an engineer requires specialist knowledge in a range of subjects. Firstly, a sound understanding of soil mechanics and finite element theory is required. Secondly, an in-depth understanding and appreciation of the limitations of the various constitutive models that are currently available is needed. Lastly, users must be fully conversant with the manner in which the software they are using works. Unfortunately, it is not easy for a geotechnical engineer to gain all these skills, as it is very rare for all of them to be part of a single undergraduate or postgraduate degree course. It is perhaps, therefore, not surprising that many engineers, who carry out such analyses and/or use the results from such analyses, are not aware of the potential restrictions and pitfalls involved.

This problem was highlighted four years ago when we gave a four day course on numerical analysis in geotechnical engineering. Although the course was a great success, attracting many participants from both industry and academia, it did highlight the difficulty that engineers have in obtaining the necessary skills required to perform good numerical analysis. In fact, it was the delegates on this course who urged us, and provided the inspiration, to write this book.

The overall objective of the book is to provide the reader with an insight into the use of the finite element method in geotechnical engineering. More specific aims are:

- To present the theory, assumptions and approximations involved in finite element analysis;
- To describe some of the more popular constitutive models currently available and explore their strengths and weaknesses;
- To provide sufficient information so that readers can assess and compare the capabilities of available commercial software;
- To provide sufficient information so that readers can make judgements as to the credibility of numerical results that they may obtain, or review, in the future;
- To show, by means of practical examples, the restrictions, pitfalls, advantages and disadvantages of numerical analysis.

The book is primarily aimed at users of commercial finite element software both in industry and in academia. However, it will also be of use to students in their final years of an undergraduate course, or those on a postgraduate course in geotechnical engineering. A prime objective has been to present the material in the simplest possible way and in manner understandable to most engineers. Consequently, we have refrained from using tensor notation and have presented all theory in terms of conventional matrix algebra.

When we first considered writing this book, it became clear that we could not cover all aspects of numerical analysis relevant to geotechnical engineering. We reached this conclusion for two reasons. Firstly, the subject area is so vast that to adequately cover it would take many volumes and, secondly, we did not have experience with all the different aspects. Consequently, we decided only to include material which we felt we had adequate experience of and that was useful to a practising engineer. As a result we have concentrated on static behaviour and have not considered dynamic effects. Even so, we soon found that the material we wished to include would not sensibly fit into a single volume. The material has therefore been divided into theory and application, each presented in a separate volume.

Volume 1 concentrates on the theory behind the finite element method and on the various constitutive models currently available. This is essential reading for any user of a finite element package as it clearly outlines the assumptions and limitations involved. Volume 2 concentrates on the application of the method to real geotechnical problems, highlighting how the method can be applied, its advantages and disadvantages, and some of the pitfalls. This is also essential reading for a user of a software package and for any engineer who is commissioning and/or reviewing the results of finite element analyses.

Volume 1 of this book consists of twelve chapters. Chapter 1 considers the general requirements of any form of geotechnical analysis and provides a framework for assessing the relevant merits of the different methods of analysis currently used in geotechnical design. This enables the reader to gain an insight into the potential advantage of numerical analysis over the more 'conventional' approaches currently in use. The basic finite element theory for linear material behaviour is described in Chapter 2. Emphasis is placed on highlighting the

assumptions and limitations. Chapter 3 then presents the modifications and additions that are required to enable geotechnical analysis to be performed.

The main limitation of the basic finite element theory is that it is based on the assumption of linear material behaviour. Soils do not behave in such a manner and Chapter 4 highlights the important facets of soil behaviour that ideally should be accounted for by a constitutive model. Unfortunately, a constitutive model which can account for all these facets of behaviour, and at the same time be defined by a realistic number of input parameters which can readily be determined from simple laboratory tests, does not exist. Nonlinear elastic constitutive models are presented in Chapter 5 and although these are an improvement over the linear elastic models that were used in the early days of finite element analyses, they suffer severe limitations. The majority of constitutive models currently in use are based on the framework of elasto-plasticity and this is described in Chapter 6. Simple elasto-plastic models are then presented in Chapter 7 and more complex models in Chapter 8.

To use these nonlinear constitutive models in finite element analysis requires an extension of the theory presented in Chapter 2. This is described in Chapter 9 where some of the most popular nonlinear solution strategies are considered. It is shown that some of these can result in large errors unless extreme care is exercised by the user. The procedures required to obtain accurate solutions are discussed.

Chapter 10 presents the finite element theory for analysing coupled problems involving both deformation and pore fluid flow. This enables time dependent consolidation problems to be analysed.

Three dimensional problems are considered in Chapter 11. Such problems require large amounts of computer resources and methods for reducing these are discussed. In particular the use of iterative equation solvers is considered. While these have been used successfully in other branches of engineering, it is shown that, with present computer hardware, they are unlikely to be economical for the majority of geotechnical problems.

The theory behind Fourier Series Aided Finite Element Analysis is described in Chapter 12. Such analysis can be applied to three dimensional problems which possess an axi-symmetric geometry but a non axi-symmetric distribution of material properties and/or loading. It is shown that analyses based on this approach can give accurate results with up to an order of magnitude saving in computer resources, compared to equivalent analyses performed with a conventional three dimensional finite element formulation.

This volume of the book (i.e Volume 2) builds on the material given in Volume 1. However, the emphasis is less on theory and more on the application of the finite element method in engineering practice. It consists of nine chapters.

Chapter 1 considers the problems involved in obtaining geotechnical parameters. These are necessary to define the constitutive models and initial conditions for an analysis. The relative merits of laboratory and field testing are discussed and the parameters that can be obtained from the various tests examined.

The analyses of tunnel construction is considered in Chapter 2. Emphasis is

placed on simulating the construction process and how this can be achieved in a two dimensional analysis. Modelling of the tunnel lining, the choice of an appropriate constitutive model for the soil and the selection of appropriate hydraulic boundary conditions are considered.

Chapter 3 considers the analysis of earth retaining structures. In particular the analysis of gravity, embedded and reinforced/anchored walls are examined. Emphasis is placed on modelling the structural elements, choosing appropriate constitutive models and simulating construction.

Cut slopes are considered in Chapter 4. The concepts behind progressive failure are introduced. Its role in slope stability is then examined and in particular its interaction with the long term dissipation of excess pore water pressures.

The analysis of embankments is discussed in Chapter 5. Embankments built of earthfill and rockfill and those built on weak and strong foundations are considered. The choice of appropriate constitutive models is discussed at some length as are the appropriate hydraulic boundary conditions and the role of progressive failure. For embankments on soft ground, single and multi-staged construction and the benefits of reinforcement are examined.

Chapter 6 considers shallow foundations. To begin with, simple surface foundations are considered and comparisons with the classical bearing capacity solutions made. The ability of numerical analysis to advance the current state of the art is then demonstrated by considering some of the weaknesses in current bearing capacity theory. For example, the effect of self weight on drained bearing capacity, the effect of foundation shape and its depth below the soil surface are considered. The effects of anisotropic soil strength and of pre-loading on bearing capacity are also examined. The analysis of tall towers and the difference between bearing capacity failure and leaning instability is discussed. Analysis of the leaning Tower of Pisa is then used to demonstrate the power of numerical analysis.

Deep foundations are considered in Chapter 7. The analyses of single piles and pile groups subjected to combined vertical, lateral and moment loading are considered. The behaviour of suction caissons and the possible detrimental effects of neglecting anisotropic soil strength are discussed.

Benchmarking and validation of numerical analyses are discussed in Chapter 8. The various options, their deficiencies and results from some recent benchmarking exercises are described.

Chapter 9 describes many of the restrictions and pitfalls that the authors have experienced. In particular, restrictions implicit in modelling problems as plane strain, problems associated with initial conditions and pitfalls associated with the use of some of the more common constitutive models are discussed.

Emphasis throughout this volume of the book is placed on explaining how the finite element method should be applied and what are the restrictions and pitfalls. In particular, the choice of suitable constitutive models for the various geotechnical boundary value problems is discussed at some length. To illustrate the material presented, examples from the authors experiences with practical geotechnical problems are used.

All the numerical examples presented in both this volume and Volume 1 of this book have been obtained using the Authors' own computer code. This software is not available commercially and therefore the results presented are unbiased. As commercial software has not been used, the reader must consider what implications the results may have on the use of such software.

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Authorship

This volume has been edited and much of its content written by David Potts and Lidija Zdravković. Several of the chapters involve contributions from colleagues at Imperial College and the Geotechnical Consulting Group (GCG). In particular:

Dr Trevor Addenbrooke (Imperial College) wrote a large part of Chapter 2 (Tunnels);

Mr Kelvin Higgins (GCG) wrote Chapter 8 (Benchmarking) and contributed to Chapter 3 (Earth retaining structures);

Dr Nebojša Kovačević (GCG) wrote large parts of Chapter 4 (Cut slopes) and Chapter 5 (Embankments).

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