Contents

Preface xi

1 Introduction 1

1.1 Overview 1
1.2 Background 2
1.3 Closed-form solutions 3
1.4 Engineering judgement 4
1.5 Ground model 5
1.6 Status quo 5
1.7 Ground investigation 8
1.8 Design parameters 9
1.9 Groundwater regime 9
1.10 Design methodology 9
1.11 Case histories 10

2 Basic slope stability analysis methods 17

2.1 Introduction 17

2.1.1 Types of stability analyses 17
2.1.2 Definition of the factor of safety 17

2.2 Slope stability analysis: limit equilibrium method 20

2.2.1 Limit equilibrium formulation of slope stability analysis methods 23

2.2.1.1 Force equilibrium 25
2.2.1.2 Moment equilibrium equation 27

2.2.2 Interslice force function 28

2.2.3 Reduction to various methods and discussion 30

2.2.4 Solution of non-linear factor of safety equation 35

2.2.5 Examples of slope stability analysis 38
2.3 Miscellaneous considerations on slope stability analysis 41
2.3.1 Acceptability of the failure surfaces and results of the analysis 41
2.3.2 Tension crack 42
2.3.3 Earthquake 42
2.3.4 Water 43
2.3.5 Saturated density of soil 45
2.3.6 Moment point 45
2.3.7 Use of soil nail/reinforcement 46
   2.3.7.1 Advantages of soil nailing 46
2.3.8 Failure to converge 50
2.3.9 Location of the critical failure surface 51
2.3.10 Three-dimensional analysis 51
2.4 Limit analysis method 52
2.4.1 Lower bound approach 53
2.4.2 Upper bound approach 54
2.5 Rigid element method 58
2.5.1 Displacements of the rigid elements 59
2.5.2 Contact stresses between rigid elements 61
2.5.3 Principle of virtual work 62
2.5.4 Governing equations 64
2.5.5 General procedure of REM computation 65
2.6 Relation between the REM and the slice-based approach 65
2.7 Uses of design figures and tables for simple problems 70
2.8 Finite element method 72
2.9 Distinct element method 78
2.9.1 Force displacement law and the law of motion 82
2.9.2 Limitations of the distinct element method 83
2.9.3 Case studies for slope stability analysis using PFC 84
2.9.4 Three-dimensional model and distinct element studies of a slope under a patch load 89
   2.9.4.1 Laboratory test on a model slope 90
   2.9.4.2 Three-dimensional distinct numerical modelling of slope under local surcharge 93

3 Location of critical failure surface, convergence and advanced formulations 99
3.1 Difficulties in locating the critical failure surface 99
3.2 Generation of trial failure surface 103
3.3 Global optimization methods 108
  3.3.1 Simulated annealing algorithm 108
  3.3.2 Genetic algorithms 109
  3.3.3 Particle swarm optimization algorithm 112
  3.3.4 Simple harmony search algorithm 114
  3.3.5 Modified harmony search algorithm 118
  3.3.6 Tabu search algorithm 120
  3.3.7 Ant colony algorithm 121
  3.3.8 Hybrid optimization algorithm 124

3.4 Verification of the global minimization algorithms 128

3.5 Presence of Dirac function 131

3.6 Numerical studies of the efficiency and effectiveness of various optimization algorithms 132

3.7 Sensitivity of global optimization parameters in the performance of the global optimization methods 140

3.8 Convexity of critical failure surface 145

3.9 Lateral earth pressure determination from slope stability analysis 146

3.10 Convergence problem due to iterative solution of FOS 148
  3.10.1 Parametric study of convergence 153
  3.10.2 Combined impact of optimization and double QR analysis 158
  3.10.3 Reasons for failure to converge 159

3.11 Importance of the methods of analysis 162

3.12 Solution of the inter-slice force function and fundamental investigation into the problem of convergence 163
  3.12.1 Determination of bounds on FOS and f(x) 165
  3.12.2 Numerical studies and comparisons with classical methods of analysis 168
  3.12.3 Study of convergence by varying f(x) 171
  3.12.4 Validation of maximum extremum principle 175

3.13 Variable FOS formulation in LEM 177
  3.13.1 Basic formulation for variable FOS formulation 178
  3.13.2 Analysis of variable FOS approach 184
  3.13.3 Discussion on variable FOS approach 185

3.14 Use of internal/external variables in slope stability analysis and relation of slope stability problem to other geotechnical problems 187
3.14.1 Basic methods in formulation 187
3.14.2 Inter-slice force function f(x) and thrust line for horizontal slope problem 190
3.14.3 Boundary forces in LEM 202
3.14.4 Lower bound solution and the maximum extremum from limit equilibrium analysis 203

4 Finite-element methods for slope stability analysis and comparisons with limit equilibrium analysis 209

4.1 Comparisons between SRM and LEM 209
4.2 Stability analysis for a simple and homogeneous soil slope using LEM and SRM 210
4.3 Stability analysis of a slope with a soft band 217
4.4 Local minimum in LEM 224
4.5 Effect of water on slope stability analysis 227
4.6 Soil nailed slopes by SRM and LEM 229
   4.6.1 Distribution of the nail tension force and the critical slip surface by SRM 235
4.7 Stabilization of slope with piles using SRM 239
4.8 Discussion and conclusion 251

5 Three-dimensional slope stability analysis 255

5.1 Limitations of the classical three-dimensional limit equilibrium methods 255
5.2 New formulation for 3D slope stability analysis in Bishop, Janbu and Morgenstern–Price methods by Cheng and Yip 259
   5.2.1 Basic formulation with consideration of sliding direction 259
   5.2.2 Reduction to 3D Bishop and Janbu simplified methods 267
   5.2.3 Numerical implementation of Bishop, Janbu and MP methods 269
   5.2.4 Numerical examples and verification 270
   5.2.5 Comparison between Huang’s method and the present methods for transverse earthquake load 274
   5.2.6 Relation of proposed 3D slope stability method with classical 3D methods 278
   5.2.7 Problem of cross-section force/moment equilibrium for MP method 278
5.2.8 Discussion on $\lambda_{xy}$ for MP analysis 284
5.2.9 Discussion on 3D limit equilibrium stability formulation 284

5.3 Three-dimensional limit analysis 286
5.3.1 Three-dimensional bearing capacity problem with an inclined slope 290
5.3.1.1 Failure mechanism of the patched load acting on the top surface of a slope ($D=0\ m$) 291
5.3.1.2 Work done rate produced along load length $L$ 291
5.3.1.3 Work done rate produced at the two end-failure zones of the footing 295
5.3.1.4 Determining the value of the safety factor 299
5.3.1.5 Failure mechanism of the patched load acting at an embedded depth from the top surface of slope ($D>0\ m$) 300
5.3.1.6 Work done rate produced along footing length $L$ 300
5.3.1.7 Work done rate produced at two end failures of the buried load 302
5.3.1.8 Comparison of Cheng's method with other analytical solutions 304

5.4 Location of general critical non-spherical 3D failure surface 309
5.4.1 Three-dimensional NURBS surfaces 310
5.4.2 Spherical and ellipsoidal surface 313
5.4.3 Selection of sliding surfaces 314
5.4.4 Optimization analysis of NURBS surface 316

5.5 Case studies in 3D limit equilibrium global optimization analysis 316

5.6 Effect of curvature on FOS 323
5.7 Three-dimensional SRM analysis 325

6 Implementation

6.1 Introduction 333
6.2 FRP nail 335
6.3 Drainage 339
6.4 Construction difficulties 340
7 Routine assessment of feature and design of landslip preventive measures

7.1 Introduction 341
7.2 Geotechnical assessment 342
7.3 Desk study 342
7.4 Aerial photograph interpretation and ground-truthing 343
7.5 GI and field testing 344
7.6 Laboratory testing 345
7.7 Man-made features 345
7.8 Rainfall records 345
7.9 Groundwater regime 346
7.10 Stability assessment of the existing feature 347
7.11 Design of landslip preventive works 348
7.11.1 Design options for masonry retaining walls 348
7.11.2 Design options for fill slopes 349
7.11.3 Design options for cut slopes 351
7.12 Soil nailing 351
7.13 Soil nailing in loose fill 354
7.14 Surface and sub-soil drainage 355
7.15 Surface erosion control and landscaping 356
7.16 Site supervision during implementation 357
7.17 Corrosiveness assessment 357
7.18 Precautionary measures and other considerations 358
7.19 Long-term maintenance 358

8 Numerical implementation of slope stability analysis methods

8.1 Numerical procedures for simplified limit equilibrium methods 359
8.2 Numerical procedures for "rigorous" limit equilibrium methods 368
8.2.1 Spencer and Morgenstern–Price method 368
8.2.2 Janbu rigorous method 372
8.2.3 Sarma method 375
8.3 Three-dimensional analysis 381

Appendix 387
References 399
Index 415