# Contents

Preface and acknowledgements xiii  
About the editors xv  

## 1 Introduction 1

*Peter Stacey and Derek Martin*

1.1 Background 1  
1.2 General descriptions and definitions for weak rocks 2  
  1.2.1 Cemented sediments 3  
  1.2.2 Weak sedimentary rocks 4  
  1.2.3 Saprolites: weathered rock and residual soil 5  
  1.2.4 Soft iron ores and leached rocks 7  
  1.2.5 Hydrothermally altered rocks 7  
1.3 Slope design terminology 8  
  1.3.1 Slope configurations 8  
  1.3.2 Instability 9  
1.4 Design implications 10  
1.5 Design implementation 12  

## 2 Field data collection and methodology 13

*Peter Stacey and Derek Martin*

2.1 Introduction 13  
2.2 General field descriptions 14  
  2.2.1 Field estimate of strength 14  
  2.2.2 Weathering and alteration 15  
  2.2.3 Moisture-sensitive weak rocks 15  
  2.2.4 Residual soils and weathered rocks 16  
2.3 Field mapping 17  
2.4 Core logging, sampling and sample preservation 17  
  2.4.1 Core boxing and photography 17  
  2.4.2 Core logging 17  
  2.4.3 Discontinuities and bedding plane shears 19  
  2.4.4 Sampling 20  
2.5 Laboratory testing 22  
  2.5.1 Routine test methods 22  
  2.5.2 Characterisation tests 23  
  2.5.3 Strength testing 27  
2.6 *In-situ* borehole characterisation 28  
  2.6.1 Borehole strength and stiffness methods 29  
  2.6.2 Geophysical methods 29  
  2.6.3 Geochemical testing 29  
2.7 Summary 30  

## 3 Weak rock strength models 33

*Derek Martin and Peter Stacey*

3.1 Introduction 33  
3.2 Geological and structural models 33
3.2.1 Lithology and alteration 34
3.2.2 Major structures 36
3.2.3 Structural fabric 37
3.2.4 Seismicity 37
3.3 Role of rock mass classifications systems 37
3.4 Shear strength and failure criteria of weak rocks in laboratory tests 39
3.4.1 Shear strength and failure envelopes 39
3.4.2 Stresses and stress path during open pit excavation 41
3.4.3 Factors affecting weak rock strength 43
3.4.4 Laboratory testing of weak rock 46
3.4.5 Weak rock behaviour 50
3.4.6 Anisotropic shear strength 56
3.4.7 Partially saturated strength 57
3.4.8 Coupled hydromechanical response during mining 60
3.5 Erodibility/degradability 62

4 The role of water in slope design for weak rocks 63
Geoff Beale

4.1 Introduction 63
4.2 Hydrogeological background 64
4.2.1 General classification 64
4.2.2 Discussion of basic parameters 65
4.2.3 Unconfined and confined groundwater 68
4.2.4 Pore pressure 69
4.2.5 Hydromechanical coupling 71
4.2.6 Piping 72
4.2.7 Fault gouge 72
4.3 Groundwater characterisation 73
4.3.1 General 73
4.3.2 Defining the goals 73
4.3.3 Data collection and compilation 74
4.4 Development of a conceptual hydrogeological model 80
4.4.1 General 80
4.4.2 Regional- and mine-scale model 80
4.4.3 Sector-scale model 81
4.5 Analysis and modelling of pore pressure 82
4.5.1 Defining the goals 82
4.5.2 Pore pressure input to the geotechnical analysis 83
4.5.3 Analysis of pore pressures 83
4.5.4 Planning of numerical models 84
4.5.5 Inclusion of hydromechanical coupling 85
4.5.6 Development of numerical models 86
4.6 Depressurisation of weak rocks 87
4.6.1 Importance of time 87
4.6.2 Importance of recharge 87
4.6.3 Methods for depressurisation of weak rock units 88
4.7 Characterisation of surface water 93
4.7.1 Sources of surface water 94
4.7.2 Estimating flow rates 95
5 Slope design considerations 97
Derek Martin, Loren Lorig and Peter Stacey

5.1 Introduction 97
5.2 Modes of failure 99
  5.2.1 Primary modes 99
  5.2.2 Secondary modes 101
5.3 Instability mechanisms 101
  5.3.1 Cohesion-loss processes 101
  5.3.2 Weak planes in bedded deposits 103
  5.3.3 Collapse in high porosity weak rocks 104
  5.3.4 Summary of instability mechanisms 105
5.4 Stability analyses and predictions 106
  5.4.1 Approaches 106
  5.4.2 Seismic analysis 108
5.5 Limit equilibrium analyses 108
  5.5.1 LEM methods 108
  5.5.2 Role of Factor of Safety 110
  5.5.3 Deformations and Factor of Safety 110
  5.5.4 The postulated slip surface 111
  5.5.5 Anisotropy 111
5.6 Numerical approaches 111
  5.6.1 Role of numerical models 111
  5.6.2 Continuum models 112
  5.6.3 Discontinuum models 113
  5.6.4 Simulating common behaviour modes in numerical models 113
  5.6.5 Pore water pressures 115
  5.6.6 Shear strength reduction 118
  5.6.7 Application of numerical models 119
  5.6.8 Summary of numerical approaches 123
5.7 Role of back analyses 123
5.8 Acceptance criteria 124
  5.8.1 Limit-based design (pre-feasibility) 125
  5.8.2 Performance-based design during operations 125
5.9 Summary 126

6 Cemented sediments 127
Derek Martin and Peter Stacey

6.1 Introduction 127
6.2 General geological setting 127
  6.2.1 Geology 127
  6.2.2 Structural geology 128
6.3 Hydrogeology 129
  6.3.1 Basin and range deposits 129
  6.3.2 Cemented bedded sediments: Carlin Formation 130
6.4 General geotechnical properties 131
  6.4.1 Cemented bedded sediments 131
  6.4.2 Cemented gravels 131
6.5 Slope design considerations 132
6.6 Goldstrike Betze-Post open pit, Nevada: instability in the Carlin Formation

6.6.1 Introduction
6.6.2 Geology
6.6.3 East wall development history
6.6.4 Engineering geology
6.6.5 Hydrogeology
6.6.6 Laboratory testing and material and strength properties
6.6.7 North-east layback slope analysis and design
6.6.8 Numerical modelling of deep-seated slope deformation
6.6.9 Carlin Formation instability
6.6.10 Continued instability, monitoring, and remediation
6.6.11 Control of slope movement in the Carlin Formation
6.6.12 Conclusions

6.7 Nine Points slope failure at Newmont’s Gold Quarry open pit

6.7.1 Introduction
6.7.2 Geology
6.7.3 Hydrogeology
6.7.4 Midway slope instability
6.7.5 April 2009 Nine Points slope instability
6.7.6 Post-April 2009 Nine Points instability behaviour
6.7.7 December 2009 failure event
6.7.8 Geological investigation and model update
6.7.9 Initial slope modelling results
6.7.10 Geotechnical drilling results
6.7.11 Hydrogeology results
6.7.12 Material strength results
6.7.13 Slope remediation design
6.7.14 Summary of lessons learned

6.8 Overview of open pit experience in cemented (alluvium) gravels found in south-western United States

6.8.1 General
6.8.2 Geological setting for cemented gravels of the south-western United States
6.8.3 Material properties characterisation
6.8.4 Hydrogeology
6.8.5 Pit slope performance
6.8.6 Design considerations
6.8.7 Operational considerations
6.8.8 Slope performance

6.9 Ministro Hales Mine, Codelco: bench failure in massive gravels

6.9.1 Background
6.9.2 Characterisation
6.9.3 Failure description
6.9.4 Back analysis
6.9.5 Proposed change in bench geometry
6.9.6 Conclusions and recommendations

Acknowledgements

7 Weak sedimentary mudrocks

7.1 Introduction
7.2 General geological setting
7.2.1 Geology
7.2.2 Structural geology
7.3 Hydrogeology 170
  7.3.1 Mudrocks 170
  7.3.2 Borates 171

7.4 General geotechnical properties 171
  7.4.1 Terminology 171
  7.4.2 Micro-fabric, macro-fabric, fissures and bedding plane shears 171
  7.4.3 Mineralogy and plasticity 172
  7.4.4 Strength, modulus and moisture 173
  7.4.5 Swelling, softening and time-dependent deformations 174
  7.4.6 Classification parameters 175

7.5 Slope design considerations 175
  7.5.1 Failure kinematics 175
  7.5.2 Design process 176

7.6 Voorspoed Mine, South Africa: open pit diamond mining in weak mudrock 176
  7.6.1 Introduction 176
  7.6.2 Geological setting 176
  7.6.3 Slope performance 178
  7.6.4 Feasibility study and current geotechnical domains 180
  7.6.5 Laboratory testing database and core logging information 181
  7.6.6 Precipitation and groundwater 184
  7.6.7 Hypothesised failure mechanisms 184
  7.6.8 Summary of Voorspoed failure mechanisms and consequence on design 187
  7.6.9 Risk management strategy 187
  7.6.10 Future design and mining strategy 188
  7.6.11 Conclusions 190

7.7 Rio Tinto Minerals Boron operation: design considerations for weak lakebed sedimentary rocks 191
  7.7.1 Introduction 191
  7.7.2 Geology 191
  7.7.3 Hydrogeology 192
  7.7.4 Rock mass strengths and design considerations 193
  7.7.5 Design considerations 195
  7.7.6 Conclusions 200

Acknowledgements 201

8 Weak sedimentary coal, chalk and limestone 203

John Simmons, Patrick Ebeling and Peter Stacey

8.1 Introduction 203

8.2 General geological setting 203
  8.2.1 Geology 203
  8.2.2 Structural geology 203
  8.2.3 Material properties 204

8.3 Slope design considerations 204
  8.3.1 Typical failure modes 204
  8.3.2 Slope designs 205

8.4 Weak coal measures 205
  8.4.1 Overview 205
  8.4.2 Derivation of empirical rock mass shear strength models 206
  8.4.3 Interpretation of groundwater conditions with coal measures rock masses 207
  8.4.4 Large-scale open pit mining in low-strength rock masses at the PT Kaltim Prima Coal Sangatta and Bengalon Projects 209
8.4.5 Geotechnical conditions for mining the coal measures rocks of the Western Canada Sedimentary Basin 219

8.5 Chalk and weak limestones 223
8.5.1 Introduction 223
8.5.2 General geology and classification 223
8.5.3 Sampling 225
8.5.4 Material properties 225
8.5.5 Hydrogeology 228
8.5.6 Case histories 228
8.5.7 Slope designs 230
8.5.8 Design implementation 231

9 Saprolite: weathered rock and residual soil 233
  Derek Martin and Peter Stacey

9.1 Introduction 233
9.2 Terminology 234
  9.2.1 Saprolith 235
  9.2.2 Pedolith 235

9.3 Weathering processes and geology 236
  9.3.1 Chemical weathering 236
  9.3.2 Physical weathering 236
  9.3.3 Weathering rates 237
  9.3.4 Influence of parent rock 237
  9.3.5 Weathering profile examples 239

9.4 General geotechnical properties 240
  9.4.1 Weathering descriptions 241
  9.4.2 Composition and structure with depth 242
  9.4.3 Effect of weathering on strength 242

9.5 Hydrogeology 247
  9.5.1 Typical hydrogeology profiles 247
  9.5.2 Dewatering 248
  9.5.3 Hydrogeology observations at Rosebel Gold Mine 250

9.6 Slope design considerations 251
  9.6.1 Failure kinematics 251
  9.6.2 Design process 251
  9.6.3 Design implementation 253

9.7 Cowal Gold Mine: back analysis 253
  9.7.1 Introduction 253
  9.7.2 Geology 254
  9.7.3 Slope stability assessments (pre-mining) 254
  9.7.4 Mining 256
  9.7.5 East wall instability 256
  9.7.6 Back analysis 257
  9.7.7 Discussion of back analysis results 258
  9.7.8 Conclusions 259

9.8 Newmont Boddington Gold: slope design optimisation in oxide/saprolite 260
  9.8.1 Introduction 260
  9.8.2 Site condition 261
  9.8.3 Oxide material at NBG 263
  9.8.4 Historical slope failures in oxide slopes at NBG 263
  9.8.5 Laboratory testing of oxide/saprolite at NBG 264
9.8.6 Groundwater conditions 265
9.8.7 Geotechnical assessment for oxide/saprolite slope design 266
9.8.8 Slope design optimisation for oxide/saprolite slopes at NBG 267
9.8.9 Surface drainage in oxide slopes 267
9.8.10 Summary 268
Acknowledgements 268

10 Soft iron ores and other leached rocks 269
Paulo Franca, Teófilo Costa and Peter Stacey

10.1 Introduction 269
10.2 Background 269
10.3 Soft iron ores: geology 270
  10.3.1 Lithology 270
  10.3.2 Alteration 271
  10.3.3 Structure 272
10.4 Soft iron ores: geotechnical characteristics 272
  10.4.1 Definitions 273
  10.4.2 Field characterisation 274
  10.4.3 Laboratory characterisation and testing 276
  10.4.4 Conclusions 283
10.5 Weathered country rocks 283
  10.5.1 Weathering and strength 283
  10.5.2 Characterisation 285
  10.5.3 Strength parameters 288
10.6 Hydrogeology of soft iron ores and associated rocks 291
  10.6.1 Hydrogeology in the Iron Quadrangle of Brazil 291
  10.6.2 Dewatering and slope depressurisation 294
  10.6.3 Carajás hydrogeology 294
10.7 Leached quartzites and quartzitic sediments 295
10.8 Slope performance and case histories 295
  10.8.1 Introduction 295
  10.8.2 Patrimônio: back analysis 296
  10.8.3 Carajás: failures of the south and south-east walls of the N4E pit 299
  10.8.4 Pau Branco Mine – Iron Quadrangle, State of Minas Gerais: weathered phyllites associated with soft iron ores 300
  10.8.5 Pico Mine: an assessment of the mechanism of flexural toppling in weak phyllite 303

11 Hydrothermally altered rocks 309
Peter Stacey and Derek Martin

11.1 Introduction 309
11.2 General geological setting 309
  11.2.1 Igneous deposits 310
  11.2.2 Epithermal deposits 310
  11.2.3 Structural geology 310
11.3 Geotechnical properties 311
  11.3.1 Description and classification 311
  11.3.2 Strength and deformation 312
11.4 Hydrogeology 313
11.5 Slope stability and engineering geology at the Pierina Mine 314
  11.5.1 Introduction 314
  11.5.2 Engineering geology 314
  11.5.3 Slope stability experience 315
  11.5.4 Stability analysis and disturbance factor (D) 319
  11.5.5 Surface runoff and hydrogeology 319
  11.5.6 Pit slope monitoring 320
  11.5.7 Results and conclusions 321

11.6 Instability in weak rocks, El Tapado Pit north wall, Yanacocha Operation 321
  11.6.1 Introduction 321
  11.6.2 Site conditions 321
  11.6.3 Phase 2 El Tapado Pit 324
  11.6.4 Deep-seated instability in north wall 327
  11.6.5 Completion of mining 330
  Acknowledgements 333

11.7 Lihir Open Pit Mine in argillic materials 333
  11.7.1 Introduction 333
  11.7.2 Engineering properties of argillic materials 335
  11.7.3 Gw28 slope 336
  11.7.4 Western Stockpile 338
  11.7.5 Conclusions 342

12 Design implementation and operational considerations 343
  Peter Stacey, Paulo Franca and Geoff Beale

  12.1 Introduction 343
  12.2 Mine planning 343
    12.2.1 Pre-mining (Levels 1 and 2) 344
    12.2.2 Feasibility level and detailed design 344
  12.3 Design implementation 345
    12.3.1 Excavation and scaling 347
    12.3.2 Blasting 348
  12.4 Surface water control 349
    12.4.1 Surface water diversion 349
    12.4.2 Collection of runoff water on catch benches and haul ramps 350
    12.4.3 Control of recharge 352
    12.4.4 Managing large surface flow volumes 353
    12.4.5 Maintenance of surface water management systems 353
    12.4.6 Case history 353
  12.5 Slope protection 354
  12.6 Performance assessment and monitoring 356
    12.6.1 Geotechnical model validation 357
    12.6.2 Slope performance 357
    12.6.3 Slope movement monitoring 358
    12.6.4 Mine water monitoring 360
  12.7 Ground control management plans 363
  12.8 Mine closure 364
    12.8.1 Slope stability considerations 364
    12.8.2 Hydrogeological considerations 365
    12.8.3 Post-closure monitoring 367

  References 369
  Index 383