Contents

Preface xi

Introduction xv

I.1. Background xv
I.2. Main assumptions xvii
I.3. Key of the multi-scale approach: the internal actions, a new tensor concept xviii

Notations xxi

Chapter 1. Fundamentals: The Tensor Structures Induced by Contact Friction 1

1.1 Microscopic scale: the elementary inter-granular contact 3
1.1.1. Vector formulation of energy dissipation 3
1.1.2. Tensor formulation of energy dissipation 3
1.1.3. Physical significance – algebraic and geometrical representations 5
1.2. Mesoscopic scale: the discontinuous granular mass 7
1.2.1. Vector formulation of energy dissipation 7
1.2.2. Tensor aspects of energy dissipation 8
1.2.3. A key population effect in energy exchanges: the internal feedback interaction 9
1.2.4. The mesoscopic equation of energy dissipation by contact friction 12
1.2.5. Minimal dissipation and ordered structures 13
1.2.6. Maximal dissipation and disordered structures 15
1.2.7. General solutions of dissipation equation with $0 \leq R(A) \leq 1$ – some key properties and geometrical representation 18

1.2.8. Practical situations: theoretical and practical minimum dissipation rule 20
1.2.9. Practical situations: the apparent inter-granular friction 21
1.3. Macroscopic scale: the equivalent pseudo-continuum 22
1.3.1. Previous works on a tensor formulation of energy dissipation . . . 22
1.3.2. Correspondence between equivalent pseudo-continuum and discontinuous granular mass 23
1.3.3. The macroscopic equation of energy dissipation by contact friction 25
1.3.4. Coaxial situations: the six allowed strain modes and their physical meaning 27

Chapter 2. Natural Compatibility With Mechanical Heterogeneity 31

2.1. Compatibility with the heterogeneity of internal actions 32
2.1.1. Discontinuous granular mass in motion near minimal dissipation 32
2.1.2. Relationship on statistical distributions of contact action orientation 34
2.1.3. Equivalent pseudo-continuum in motion near minimal dissipation 42
2.1.4. Conclusions on the compatibility with the heterogeneity of internal actions 44
2.2. Compatibility with the heterogeneity of internal forces and internal movement distributions (stress and strain rates) 46
2.2.1. Case of coaxiality – compatibility with heterogeneity of stresses and strain rate distributions 47
2.2.2. General situations near minimal dissipation 53
2.2.3. Conclusions on heterogeneity of stresses and strain rates 57

Chapter 3. Strain Localization and Shear Banding: The Genesis of Failure Lines 59

3.1. Background and framework of the analysis 59
3.2. Shear bands orientation 61
3.2.1. Constant volume motion (critical state) 61
3.2.2. Variable volume motion 64
3.3. Shear bands internal structure 66
3.3.1. Kinematic stationary structures in shear bands 67
3.3.2. Confrontation with key experimental results of Nemat-Nasser and Okada 69
3.3.3. The dissipative microstructure inside of shear bands 72
3.3.4. Consequences on the development of shear bands 76

3.4. Localization criterion 80
3.4.1. Conditions for heterogeneity development 80
3.4.2. The localization criterion 82
3.5. Shear band evolution: the formation of failure lines 84
3.5.1. Evolution of a single shear band 87
3.5.2. Evolution of a set of parallel shear bands 87
3.5.3. Conclusions 88

Chapter 4. Failure Criterion: The Micromechanical Basis of Coulomb Criterion 91

4.1. Background and framework of the analysis 92
4.2. Failure criterion at a critical state: the Coulomb Criterion 94
4.2.1. Specificity of "failure" under large shear strains – an analytical framework… 94
4.2.2. The criterion of least shear resistance 95
4.2.3. Link with least dissipation criterion 100
4.2.4. Incidence of small deviations from least shear resistance solution 108

Chapter 5. Coupling Between Shear Strength and Volume Changes: Generalized 3D Stress–Dilatancy Relations 111

5.1. Framework of the analysis 111
5.2. Definition of a general 3D dilatancy rate 112
5.3. Generalized stress–dilatancy relationships for relevant strain modes 115
5.4. Simplification into Rowe's relations for particular conditions 117
5.5. Failure criterion at peak strength with dilation 118
5.5.1. The least shear strength criterion: the Coulomb failure criterion … 118
5.5.2. Incidence of small deviations from the minimal solution 120
5.6. Incidence of strain reversals on volume change rates 120
5.7. 3D Characteristic state 122
5.7.1. Framework of the analysis… 122
5.7.2. Key results 122
5.8. Nature of the six allowed strain modes regarding volume changes and motion sustainability 123
5.9. A direct link with fluid mechanics 125
5.10. Conclusions 126

Chapter 6. Experimental Validations 129

6.1. Validations from classical "triaxial" test results 130
6.1.1. Triaxial compression … 130

6.1.2. Triaxial extension and cyclic triaxial 132
6.2. Validations from simple shear experimental results 133
6.3. Validations from true 3D compression apparatus results 135
6.4. Validation from cyclic torsional shear tests data 137
6.5. Validations from detailed numerical simulations with realistic discrete particles 139
6.6. Measurement of apparent inter-granular friction – typical values of the parameters 141

Chapter 7. Cyclic Compaction Under Alternate Shear Motion 145

7.1. Background and framework of the analysis 145
7.2. Key results 147
7.3. The cyclic compaction ratio versus the principal stress ratio 149
7.4. Energy efficiency of compaction 150
7.5. Limit of cyclic compaction when apparent inter-granular friction vanishes 151

Chapter 8. Geostatic Equilibrium: The K_0 Effect 153

8.1. Background and framework of the analysis 153
8.2. The micromechanical process of geostatic stress-building in the soil mass 155
8.3. The solutions provided by the multi-scale approach 156
8.4. The resulting K_0 formula based on micromechanics 158
8.5. Comparison with empirical Jaky formula 159
8.6. The two limits of geostatic equilibrium 160
8.7. Limit of geostatic equilibriums when apparent inter-granular friction vanishes 161

Chapter 9. Scale Effects in Macroscopic Behavior Due to Grain Breakage 163

9.1. Introduction to grain breakage phenomenon: a framework of the analysis 163
9.1.1. Elementary grain breakage 164
9.1.2. Statistical representations 165
9.1.3. Central trend in the statistics of mineral particle failures 166
9.2. Scale effects in shear strength 167
9.2.1. Shear strength of rockfill 167
9.2.2. Evidence of scale effect 168
9.2.3. Scale effect rule on shear strength envelope (failure criterion) . . . 171

Chapter 10. Practical Applications of Scale Effects to Design and Construction 175

10.1. A new method for rational assessment of rockfill shear strength envelope 176
10.2. Incidence of scale effects on rockfill slopes stability. 178
10.2.1. The question of stability assessment 178
10.2.2. Explicit scale effect in safety factors. 179
10.2.3. Scale effect compensation 182
10.3. Scale effects on deformation features and settlements. 184
10.3.1. Scale effects on deformation features 184
10.3.2. Scale effects in rockfill apparent rigidity modulus. 187
10.3.3. Scale effects in settlements 190

Chapter 11. Concluding Remarks 195

11.1. Concluding remarks on features resulting from energy dissipation by friction 195
11.1.1. Tensor structures induced by contact friction on internal actions 196
11.1.2. Relevance of minimum dissipation rule 197
11.1.3. Compatibility with heterogeneity. 198
11.1.4. Localization and shear banding 198
11.1.5. Failure criterion 199
11.1.6. Experimental validations. 200
11.1.7. Coaxiality assumption in macroscopic properties 200
11.1.8. Tracks for further developments 201
11.2. Concluding remarks on features resulting from grain breakage 202
11.3. Final conclusions. 203

Appendices 205

References 267

Index 275