

## Table of Contents

Preface to the English Edition .....	xi
Preface to the French .....	xiii
<b>Chapter 1. The Main Classes of Constitutive Relations .....</b>	<b>1</b>
Félix DARVE	
1.1. Introduction .....	1
1.2. The rheological functional .....	3
1.3. Incremental formulation of constitutive relations .....	5
1.4. Rate-independent materials .....	6
1.4.1. Non-linearity of G and H .....	7
1.4.2. Anisotropy of G and H .....	7
1.4.3. Homogeneity of degree 1 of G and H .....	8
1.5. Notion of tensorial zones .....	9
1.6. The main classes of rate-independent constitutive relations .....	11
1.6.1. Constitutive relations with one tensorial zone .....	11
1.6.2. Constitutive relations with two tensorial zones .....	12
1.6.3. Constitutive relations with four tensorial zones .....	19
1.6.4. Constitutive relations with n tensorial zones ( $n > 4$ ) .....	23
1.6.5. Constitutive relations with an infinite number of tensorial zones .....	23
1.6.6. Conclusion .....	24
1.7. The main constitutive relations for rate-dependent materials .....	25
1.7.1. First class of incremental strain decomposition .....	25
1.7.2. Second class of incremental strain decomposition .....	26
1.8. General conclusions .....	27
1.9. References .....	28
<b>Chapter 2. Mechanisms of Soil Deformation .....</b>	<b>31</b>
Jean BIAREZ and Pierre-Yves HICHER	
2.1. Introduction .....	31
2.2. Remolded soil behavior .....	32

2.3. Relationships between discontinuous and continuous medium . . . . .	44
2.3.1. Granular materials . . . . .	47
2.3.2. Remolded clayey materials . . . . .	48
2.3.3. Granular materials with intergranular glue . . . . .	51
2.4. Natural soils . . . . .	55
2.5. Conclusion . . . . .	73
2.6. References . . . . .	73
<b>Chapter 3. Elastoplastic Modeling of Soils: Monotonous Loadings . . . . .</b>	<b>77</b>
Philippe MESTAT, Emmanuel BOURGEOIS and Philippe REIFFSTECK	
3.1. Introduction . . . . .	77
3.2. Elastoplasticity equations . . . . .	78
3.2.1. Basic concepts . . . . .	78
3.2.2. Yield surface and elastic domain . . . . .	79
3.2.3. Plastic flow rule . . . . .	80
3.2.4. Incremental relations for one plastic mechanism model . . . . .	81
3.2.5. Incremental relationships for multi-mechanism elastoplasticity . . . . .	83
3.3. Constitutive laws and laboratory tests . . . . .	84
3.4. Characterization of natural cohesive soil behavior . . . . .	86
3.4.1. Analysis of triaxial test results . . . . .	86
3.4.2. Analysis of oedometer tests . . . . .	87
3.4.3. Elasto-viscoplasticity or elastoplasticity? . . . . .	88
3.5. Characterization of frictional soil behavior . . . . .	88
3.5.1. Analysis of triaxial test results . . . . .	88
3.5.2. Elastoplasticity framework for frictional soils . . . . .	91
3.6. Principles for the derivation of elastoplastic models . . . . .	92
3.6.1. Elastic behavior . . . . .	92
3.6.2. Estimation of the plastic behavior . . . . .	96
3.6.3. Failure surface . . . . .	97
3.6.4. Total and plastic strains . . . . .	102
3.6.5. Plastic potential . . . . .	103
3.6.6. Yield surface . . . . .	107
3.7. Three-dimensional aspect of the models and calculation of geotechnical works . . . . .	116
3.8. Examples of perfect elastoplastic models . . . . .	117
3.8.1. The Mohr-Coulomb model . . . . .	117
3.8.2. The Drucker-Prager model . . . . .	121
3.9. Examples of elastoplastic models with hardening . . . . .	124
3.9.1. University of Cambridge models (Cam-Clay models) . . . . .	124
3.9.2. Nova model (1982 version) . . . . .	129
3.9.3. Mélanie model . . . . .	131
3.10. Conclusions . . . . .	136

3.11. Notations . . . . .	138
3.12. References . . . . .	138
<b>Chapter 4. Elastoplastic Modeling of Soils: Cyclic Loading . . . . .</b>	<b>143</b>
Bernard CAMBOU and Pierre-Yves HICHER	
4.1. Soil behavior under drained loading . . . . .	143
4.1.1. Isotropic and oedometric cyclic loading. . . . .	143
4.1.2. Cyclic triaxial loading . . . . .	144
4.1.3. Influence of rotating principal axes . . . . .	148
4.2. Isochoric triaxial tests . . . . .	149
4.3. Modeling soil cyclic behavior . . . . .	154
4.3.1. Difficulties involved in the modeling of the soil cyclic behavior in the framework of elastoplasticity . . . . .	155
4.3.2. The Masing model. . . . .	157
4.4. Models based on one or several independent yield surfaces . . . . .	160
4.4.1. The CJS model . . . . .	161
4.5. Models based on nested yield surfaces . . . . .	166
4.5.1. Models with nested yield surfaces: the Mroz model . . . . .	167
4.5.2. Model with infinite yield surfaces: the Hujeux model . . . . .	168
Deviatoric mechanisms ( $k = 1, 2, 3$ ) . . . . .	169
4.5.3. Models with two yield surfaces: the Dafalias model . . . . .	176
4.5.4. Models with two yield surfaces: the Hashigushi model . . . . .	178
4.5.5. Models with two yield surfaces: CJS 4 model. . . . .	179
4.6. Generalized plasticity models. . . . .	181
4.7. Parameter identification for cyclic plasticity models . . . . .	182
4.8. Conclusion . . . . .	183
4.9. References . . . . .	183
<b>Chapter 5. Elastoplastic Behavior of Ductile Porous Rocks . . . . .</b>	<b>187</b>
Jian-Fu SHAO and Shou-Yi XIE	
5.1. Introduction . . . . .	187
5.2. Review of typical mechanical behavior of porous rocks . . . . .	188
5.3. Formulation of the constitutive model. . . . .	192
5.3.1. Plastic pore collapse model. . . . .	194
5.3.2. Plastic shearing model . . . . .	195
5.4. Examples of numerical simulations . . . . .	198
5.5. Influence of water saturation . . . . .	200
5.6. Creep deformation . . . . .	204
5.7. Conclusion . . . . .	206
5.8. References . . . . .	207

<b>Chapter 6. Incremental Constitutive Relations for Soils . . . . .</b>	211
René CHAMBON, Félix DARVE and Farid LAOUAFA	
6.1. Incremental nature of constitutive relations . . . . .	211
6.2. Hypoplastic CloE models . . . . .	213
6.2.1. Irreversibility in hypoplasticity . . . . .	214
6.2.2. Limit states . . . . .	216
6.2.3. A simple example: the 2D Mohr-Coulomb model . . . . .	219
6.2.4. Use in boundary value problems . . . . .	221
6.2.5. Explicit criterion of localization . . . . .	222
6.2.6. Induced anisotropy . . . . .	224
6.2.7. Extension to media with internal length . . . . .	225
6.2.8. Examples of application . . . . .	226
6.3. Incrementally non-linear constitutive relations . . . . .	229
6.3.1. Formalism . . . . .	229
6.3.2. Continuous transition between non-linear and octo-linear interpolations . . . . .	234
6.3.3. Significant degenerations . . . . .	238
6.3.4. Applications . . . . .	240
6.3.5. Conclusions . . . . .	255
6.4. General conclusion . . . . .	255
6.5. References . . . . .	257
<b>Chapter 7. Viscoplastic Behavior of Soils . . . . .</b>	261
Pierre-Yves HICHER and Isam SHAHROUR	
7.1. Introduction . . . . .	261
7.2. Laboratory testing . . . . .	262
7.2.1. Strain rate influence . . . . .	262
7.2.2. Creep tests . . . . .	265
7.3. Constitutive models . . . . .	277
7.3.1. Modeling framework . . . . .	277
7.3.2. Perzyna's formulation . . . . .	278
7.4. Numerical integration of viscoplastic models . . . . .	280
7.5. Viscoplastic models for clays . . . . .	281
7.5.1. Choice of the viscoplastic mechanisms . . . . .	281
7.5.2. Viscoplastic models derived from the elastoplastic Cam-Clay model . . . . .	284
7.5.3. Cyclic viscoplastic modeling . . . . .	294
7.6. Conclusion . . . . .	295
7.7. References . . . . .	296
<b>Chapter 8. Damage Modeling of Rock Materials . . . . .</b>	299
André DRAGON	
8.1. Introduction . . . . .	299

8.2. Modeling of damage by mesocracks and induced anisotropy . . . . .	302
8.2.1. Preliminaries: damage variables and some micromechanical bases.	302
8.2.2. Anisotropic damage model (basic model - level (i)) . . . . .	306
8.2.3. Comments on the identification of the model's parameters and on its prediction capability . . . . .	314
8.3. Taking into account mesocrack closure effects: restitution of moduli and complex hysteretic phenomena. . . . .	322
8.3.1. Normal unilateral effect . . . . .	322
8.3.2. Introduction of friction . . . . .	329
8.4. Numerical integration and application examples – concluding notes . .	336
8.5. References . . . . .	342
<b>Chapter 9. Multiscale Modeling of Anisotropic Unilateral Damage in Quasi-brittle Geomaterials: Formulation and Numerical Applications . . . . .</b>	<b>347</b>
Djimédo KONDO, Qizhi ZHU, Jian-Fu SHAO and Vincent PENSEE	
9.1. Introduction . . . . .	347
9.2. Homogenization of microcracked materials: basic principles and macroscopic energy. . . . .	349
9.3. Formulation of the multiscale anisotropic unilateral damage model . .	354
9.3.1. Constitutive equations . . . . .	354
9.3.2. Friction-damage coupling and evolution laws. . . . .	358
9.4. Computational aspects and implementation of the multiscale damage model. . . . .	360
9.4.1. Determination of the tangent matrix . . . . .	360
9.4.2. Local integration of the model . . . . .	361
9.5. Illustration of the model predictions for shear tests . . . . .	363
9.6. Model's validation for laboratory data including true triaxial tests. .	364
9.6.1. Validation by comparison with conventional triaxial compression tests . . . . .	365
9.6.2. Simulations of true triaxial compression tests . . . . .	367
9.7. Application on an underground structure: evaluation of the excavation damage zone (EDZ). . . . .	369
9.8. Conclusions . . . . .	373
9.9. References . . . . .	374
<b>Chapter 10. Poromechanical Behavior of Saturated Cohesive Rocks . . . . .</b>	<b>377</b>
Jian-Fu SHAO and Albert GIRAUD	
10.1. Introduction . . . . .	377
10.2. Fundamentals of linear poroelasticity . . . . .	378
10.3. Fundamentals of poroplasticity. . . . .	382
10.4. Damage modeling of saturated brittle materials . . . . .	385
10.4.1. Experimental characterization . . . . .	386

x	Constitutive Modeling of Soils and Rocks	
10.4.2. Numerical modeling . . . . .	394	
10.5. Conclusion . . . . .	401	
10.6. References . . . . .	402	
<b>Chapter 11. Parameter Identification . . . . .</b>	<b>405</b>	
Pierre-Yves HICHER and Jian-Fu SHAO		
11.1. Introduction . . . . .	405	
11.2. Analytical methods . . . . .	407	
11.3. Correlations applied to parameter identification . . . . .	407	
11.4. Optimization methods . . . . .	413	
11.4.1. Numerical formulation . . . . .	414	
11.4.2. Examples of parameter identification by means of laboratory testing . . . . .	416	
11.4.3. Parameter identification from <i>in situ</i> testing . . . . .	418	
11.5. Conclusion . . . . .	430	
11.6. References . . . . .	430	
List of Authors . . . . .	433	
Index . . . . .	437	