

## Table of Contents

<b>Foreword</b> . . . . .	xiii
<b>Introduction</b> . . . . .	xvii
<b>Chapter 1. Geophysical Detection and Characterization of Discontinuities in Rock Slopes</b> . . . . .	1
Jacques DEPARIS, Denis JONGMANS, Stéphane GARAMBOIS, Clara LÉVY, Laurent BAILLET and Ombeline MERIC	
1.1. Introduction . . . . .	1
1.2. Geophysical parameters and methods . . . . .	2
1.2.1. Introduction . . . . .	2
1.2.2. Seismic velocity . . . . .	4
1.2.3. Electrical resistivity . . . . .	7
1.2.4. Dielectrical permittivity . . . . .	10
1.2.5. Resonance frequency . . . . .	14
1.3. Applications . . . . .	19
1.3.1. Introduction . . . . .	19
1.3.2. Plateau survey: Ravin de l'Aiguille . . . . .	20
1.3.3. Cliff survey: Gorge de la Bourne . . . . .	23
1.3.4. Column survey: Chamousset . . . . .	28
1.4. Conclusions . . . . .	31
1.5. Acknowledgments . . . . .	32
1.6. Bibliography . . . . .	33

<b>Chapter 2. Remote Sensing and Monitoring Techniques for the Characterization of Rock Mass Deformation and Change Detection</b> . . . . .	39
Marc-Henri DERRON, Michel JABOYEDOFF, Andrea PEDRAZZINI, Clément MICHOU and Thierry VILLEMIN	
2.1. Introduction . . . . .	39
2.2. Main issues . . . . .	40
2.3. Investigation and monitoring techniques . . . . .	41
2.3.1. Geotechnical instrumentation: crackmeter, extensometer, tiltmeter . . . . .	41
2.3.2. Distancemeter . . . . .	44
2.3.3. Laser scanning . . . . .	44
2.3.4. High resolution imaging and photogrammetry . . . . .	46
2.3.5. Synthetic aperture radar interferometry (InSAR) . . . . .	46
2.3.6. Global navigation satellite system (GNSS) . . . . .	48
2.4. Examples of applications . . . . .	48
2.4.1. Detection of rock slope instabilities . . . . .	50
2.4.2. Geometry and structure analysis . . . . .	51
2.4.3. Movement detection and characterization . . . . .	53
2.4.4. Monitoring and real-time warning . . . . .	55
2.5. Perspectives . . . . .	57
2.6. Conclusions . . . . .	58
2.7. Bibliography . . . . .	58
<b>Chapter 3. Mechanical Stability Analyses of Fractured Rock Slopes</b> . . . . .	67
Véronique MERRIEN-SOUKATCHOFF, Jérôme DURIEZ, Muriel GASC-BARBIER, Félix DARVE and Frédéric-Victor DONZÉ	
3.1. Introduction . . . . .	67
3.2. Experimental study of rock joint behavior . . . . .	68
3.2.1. Description of natural rock joints . . . . .	68
3.2.2. Compression behavior of natural rock joints . . . . .	69
3.2.3. Shear behavior of natural rock joints . . . . .	70
3.2.4. Behavior of natural rock joints under other loading paths . . . . .	71
3.3. Failure computations of rigid blocks . . . . .	72
3.3.1. Geometrical aspects of block failure . . . . .	72
3.3.2. Mechanical aspects of failure computation . . . . .	77
3.3.3. Examples of deterministic and probabilistic stability analyses . . . . .	81
3.3.4. Conclusion on failure computations . . . . .	82
3.4. Overview of different stress-strain analyses . . . . .	86
3.4.1. Different stress-strain method . . . . .	87
3.4.2. Continuous approaches with joints . . . . .	87

3.4.3. Discrete methods . . . . .	88
3.4.4. Distinct element modeling . . . . .	88
3.4.5. NSCD method . . . . .	89
3.4.6. Hybrid methods . . . . .	90
3.5. An advanced stress-strain analysis of failure . . . . .	92
3.5.1. Framework of the analysis . . . . .	93
3.5.2. A new rock joint constitutive relation: the INL2 relation . . . . .	96
3.5.3. Stability analysis of INL2 relation . . . . .	101
3.5.4. A stress-strain analysis of a rock slope . . . . .	103
3.6. Conclusions . . . . .	105
3.7. Bibliography . . . . .	106
<b>Chapter 4. Assessment of Constitutive Behaviors in Jointed Rock Masses from a DEM Perspective . . . . .</b>	<b>113</b>
Cédric LAMBERT and John READ	
4.1. Introduction . . . . .	113
4.2. Discrete Element Modeling of rock materials . . . . .	115
4.3. Representation of rock discontinuities . . . . .	116
4.3.1. Smooth joint contact . . . . .	116
4.3.2. Synthetic rock joint . . . . .	118
4.3.3. Shear behavior of rough joints . . . . .	121
4.4. Synthetic Rock Mass modeling methodology . . . . .	125
4.4.1. Rock mass structural representation . . . . .	126
4.4.2. Equivalent rock mass model . . . . .	127
4.4.3. Rock mass constitutive behavior . . . . .	129
4.4.4. Anisotropy in rock mass properties . . . . .	131
4.5. Analysis of specific mechanical behaviors: case studies . . . . .	132
4.5.1. Sensitivity of rock mass behavior to the joint fabric . . . . .	132
4.5.2. Scale effects . . . . .	135
4.6. Conclusions . . . . .	138
4.7. Bibliography . . . . .	138
<b>Chapter 5. Methods for Predicting Rockfall Trajectories and Run-out Zones . . . . .</b>	<b>143</b>
Luuk DORREN, Ulrik DOMAAS, Kalle KRONHOLM and Vincent LABIOUSE	
5.1. Introduction . . . . .	143
5.2. Preparation of a rockfall trajectory study . . . . .	148
5.3. Definition of the release scenarios . . . . .	153
5.4. Rockfall models . . . . .	154
5.4.1. Different model types . . . . .	154

5.4.2. Rock shapes in trajectory models . . . . .	156
5.4.3. Spatial dimensions of trajectory models . . . . .	157
5.4.4. Modeled rockfall kinematics . . . . .	158
5.4.5. Accuracy of rockfall models . . . . .	160
5.4.6. Accounting for protective measures . . . . .	162
5.5. Plausibility check / validation of model output . . . . .	164
5.6. Fixing model results and translation into a readable map . . . . .	166
5.7. Future improvements . . . . .	167
5.8. Bibliography . . . . .	168
<b>Chapter 6. Rockfall Dynamics: A Critical Review of Collision and Rebound Models . . . . .</b>	<b>175</b>
Franck BOURRIER and Oldrich HUNGR	
6.1. Introduction . . . . .	175
6.2. Physical processes associated with collision and rebound . . . . .	175
6.2.1. General description . . . . .	175
6.2.2. Influence of the slope properties . . . . .	178
6.2.3. Influence of the properties of the rock fragment . . . . .	180
6.3. Review of rebound models . . . . .	181
6.3.1. Real-scale rockfall experiments . . . . .	181
6.3.2. Lumped mass models . . . . .	183
6.3.3. Models explicitly accounting for the shape of the rocks . . . . .	195
6.3.4. Statistical models . . . . .	199
6.4. Perspectives and conclusions . . . . .	203
6.5. Bibliography . . . . .	203
<b>Chapter 7. Rockfall Hazard Zoning for Land Use Planning . . . . .</b>	<b>211</b>
Vincent LABIOUSE and Jacopo Maria ABBRUZZESE	
7.1. Introduction . . . . .	211
7.2. Rockfall zoning for urban development planning . . . . .	212
7.2.1. Terminology . . . . .	212
7.2.2. Types and levels of landslide zoning . . . . .	213
7.2.3. Guidelines . . . . .	214
7.3. Zoning methodologies at the regional/valley scale . . . . .	222
7.4. Zoning methodologies at the local scale . . . . .	224
7.4.1. Rating-based approaches . . . . .	225
7.4.2. Approaches coupling energy and return period . . . . .	226
7.4.3. Other approaches based on trajectory modeling results . . . . .	232
7.4.4. Summary . . . . .	235

7.5. Sources of uncertainties and differences in hazard zoning results . . . . .	237
7.5.1. Zoning methodology . . . . .	239
7.5.2. Departure zone . . . . .	241
7.5.3. Trajectory modeling . . . . .	242
7.6. Implications of zoning results in land use planning . . . . .	243
7.7. Conclusions . . . . .	247
7.8. Acknowledgments . . . . .	249
7.9. Bibliography . . . . .	249
<b>Chapter 8. Rockfall Quantitative Risk Assessment . . . . .</b>	<b>255</b>
Jordi COROMINAS and Olga MAVROULI	
8.1. Introduction . . . . .	255
8.1.1. Rockfall hazard and risk assessment: qualitative vs. quantitative approaches . . . . .	256
8.1.2. Quantitative risk descriptors . . . . .	257
8.1.3. The risk equation . . . . .	258
8.2. Objectives of the QRA . . . . .	261
8.2.1. Approaches for the analysis . . . . .	261
8.2.2. Source of data . . . . .	263
8.2.3. Risk scenarios . . . . .	265
8.3. Assessment of the rockfall risk components . . . . .	266
8.3.1. Rockfall occurrence ( $P_R$ ) . . . . .	266
8.3.2. Rockfall reach $P(D:R_i)$ . . . . .	272
8.3.3. Exposure and vulnerability . . . . .	278
8.4. Examples of rockfall risk . . . . .	290
8.5. Bibliography . . . . .	296
<b>Chapter 9. Multi-scale Analysis of an Innovative Flexible Rockfall Barrier . . . . .</b>	<b>303</b>
Ayman TRAD, Ali LIMAM, David BERTRAND and Philippe ROBIT	
9.1. Introduction . . . . .	303
9.2. Presentation of rockfall protection nets . . . . .	304
9.3. Presentation of tools used for the numerical simulation. . . . .	306
9.3.1. Finite element method . . . . .	306
9.3.2. Discrete element method . . . . .	307
9.4. Characterization of the net . . . . .	308
9.4.1. Clip scale . . . . .	308
9.4.2. Cable scale . . . . .	309
9.4.3. Mesh scale . . . . .	311
9.4.4. Net scale . . . . .	315

9.5. Characterization of the energy dissipators . . . . .	321
9.5.1. Classical dissipators working by friction . . . . .	321
9.5.2. A new innovative dissipator working by buckling . . . . .	323
9.6. Full scale test on the barrier . . . . .	328
9.6.1. Experimental data . . . . .	328
9.6.2. DEM numerical simulations at the structure scale . . . . .	334
9.7. Conclusion and perspectives . . . . .	340
9.8. Bibliography . . . . .	340
<b>Chapter 10. A New Design Method for Rockfall Shelters Covered by Granular Layers . . . . .</b>	<b>343</b>
Francesco CALVETTI and Claudio DI PRISCO	
10.1. Definition of the impact phenomenon . . . . .	343
10.2. Real scale experiments . . . . .	345
10.2.1. Description of the shelter and testing campaign . . . . .	345
10.2.2. Description of a typical impact . . . . .	349
10.2.3. From impact force to structural response . . . . .	351
10.2.4. Soil-plate interaction and dynamic response of the shelter . . . . .	354
10.3. An uncoupled approach for the definition of impact actions . . . . .	359
10.3.1. Modeling tools . . . . .	360
10.3.2. Evaluation of the impact force (input) . . . . .	360
10.3.3. Modeling of the stress propagation (output) . . . . .	364
10.3.4. Modeling of the dynamic structural response . . . . .	369
10.4. Conclusions . . . . .	371
10.5. Acknowledgments . . . . .	372
10.6. Bibliography . . . . .	372
<b>Chapter 11. Design Procedure for a Three-Layer Absorbing System in Rockfall Protection Galleries . . . . .</b>	<b>375</b>
Norimitsu KISHI and Hisashi KON-NO	
11.1. Introduction . . . . .	375
11.2. Standard impact design formula for sand cushion . . . . .	376
11.3. Absorbing performance of sand cushion and TLAS . . . . .	379
11.3.1. General view of experiment . . . . .	379
11.3.2. Time histories of transmitted impact stress . . . . .	381
11.3.3. Time histories of impact forces . . . . .	381
11.3.4. Distribution of maximum transmitted impact forces vs. input impact energy. . . . .	382
11.4. Design concept for TLAS. . . . .	383
11.5. Estimate of impact energy transmitted to EPS bottom layer . . . . .	386
11.6. Design of reinforced concrete core slab . . . . .	387
11.7. Estimate of required thickness of EPS bottom layer . . . . .	388

11.8. Estimate of impact force transmitted to gallery roof slab . . . . .	390
11.9. Verification of proposed design procedure . . . . .	390
11.10. Conclusion . . . . .	390
11.11. Bibliography . . . . .	392
<b>Chapter 12. Ground Reinforced Embankments for Rockfall Protection: From Real Scale Tests to Numerical Modeling . . . . .</b>	<b>393</b>
Daniele PEILA	
12.1. Introduction . . . . .	393
12.2. Full-scale tests on embankments . . . . .	397
12.3. Numerical modeling of ground reinforced embankments . . . . .	411
12.3.1. Back analysis of full scale tests on ground reinforced embankments . . . . .	413
12.3.2. Parametrical analysis of ground reinforced embankments . . . . .	415
12.3.3. Back analysis of a real impact against an embankment. . . . .	419
12.4. Conclusions . . . . .	422
12.5. Acknowledgments . . . . .	422
12.6. Bibliography . . . . .	422
<b>List of Authors . . . . .</b>	<b>427</b>
<b>Index . . . . .</b>	<b>433</b>