

Table of Contents

Preface	xiii
Lyesse LALOUI and Alice Di DONNA	
PART 1. PHYSICAL MODELING OF ENERGY PILES AT DIFFERENT SCALES	1
Chapter 1. Soil Response under Thermomechanical Conditions Imposed by Energy Geostructures	3
Alice Di DONNA and Lyesse LALOUI	
1.1. Introduction	4
1.2. Thermomechanical behavior of soils	5
1.2.1. Thermomechanical behavior of clays	6
1.3. Constitutive modeling of the thermomechanical behavior of soils	12
1.3.1. The ACMEG-T model	12
1.4. Acknowledgments	18
1.5. Bibliography	18
Chapter 2. Full-scale <i>In Situ</i> Testing of Energy Piles	23
Thomas MIMOUNI and Lyesse LALOUI	
2.1. Monitoring the thermomechanical response of energy piles	23
2.1.1. Measuring strains and temperature along the piles	23
2.1.2. Measuring pile tip compression	27
2.1.3. Monitoring the behavior of the soil	27
2.2. Description of the two full-scale in situ experimental sites	28
2.2.1. Single full-scale test pile	28
2.2.2. Full-scale test on a group of energy piles	31
2.2.3. Testing procedure	32

2.3. Thermomechanical behavior of energy piles	36
2.3.1. General methodology	36
2.3.2. Thermomechanical response of the single test pile	38
2.3.3. Thermomechanical response of a group of energy piles	40
2.4. Conclusions	42
2.5. Bibliography	42
Chapter 3. Observed Response of Energy Geostructures	45
Peter BOURNE-WEBB	
3.1. Overview of published observational data sources.	45
3.2. Thermal storage and harvesting	46
3.2.1. Overview	46
3.2.2. Energy injection/extraction rates	47
3.2.3. Thermal fields	52
3.3. Thermomechanical effects	58
3.3.1. Overview	58
3.3.2. Structural effects	58
3.3.3. Soil-structure interactions	62
3.4. Summary	65
3.5. Acknowledgments	66
3.6. Bibliography	67
Chapter 4. Behavior of Heat-Exchanger Piles from Physical Modeling	79
Anh Minh TANG, Jean-Michel PEREIRA, Ghazi HASSEN and Neda YAVARI	
4.1. Introduction	79
4.2. Physical modeling of pile foundations	80
4.2.1. Boundary conditions	80
4.2.2. Mechanical loading system	81
4.2.3. Monitoring	81
4.2.4. Pile's behavior	82
4.3. Physical modeling of a heat-exchanger pile	83
4.3.1. Experimental setup	83
4.3.2. Mechanical behavior of a pile under thermomechanical loading	85
4.3.3. Heat transfer	89
4.3.4. Soil-pile interface	90
4.3.5. Lessons learned from physical modeling of a heat-exchanger pile	91
4.4. Conclusions	94
4.5. Acknowledgments	94
4.6. Bibliography	94

Chapter 5. Centrifuge Modeling of Energy Foundations	99
John S. MCCARTNEY	
5.1. Introduction	99
5.2. Background on thermomechanical soil–structure interaction	100
5.3. Centrifuge modeling concepts	101
5.4. Centrifuge modeling components	101
5.4.1. Centrifuge model fabrication and characterization	101
5.4.2. Experimental setup	103
5.5. Centrifuge modeling tests for semi-floating foundations	105
5.5.1. Soil details	105
5.5.2. Foundation A: isothermal load tests to failure	106
5.5.3. Foundation B: thermomechanical stress–strain modeling	110
5.6. Conclusions	113
5.7. Acknowledgments	113
5.8. Bibliography	114
PART 2. NUMERICAL MODELING OF ENERGY GEOSTRUCTURES	117
Chapter 6. Alternative Uses of Heat-Exchanger Geostructures	119
Fabrice DUPRAY, Thomas MIMOUNI and Lyesse LALOUI	
6.1. Small, dispersed foundations for deck de-icing	120
6.1.1. Heat demand and specificities of small foundations	121
6.1.2. Modeling of the pile	122
6.1.3. Results and analysis	126
6.2. Heat-exchanger anchors	131
6.2.1. Technical aspects and possible users	131
6.2.2. Method of investigation	132
6.2.3. Optimizing the heat production	134
6.2.4. Mechanical implications of heat production	135
6.3. Conclusions	136
6.4. Acknowledgments	137
6.5. Bibliography	137
Chapter 7. Numerical Analysis of the Bearing Capacity of Thermoactive Piles Under Cyclic Axial Loading	139
Maria E. SURYATRIYASTUTI, Hussein MROUEH, Sébastien BURLON and Julien HABERT	
7.1. Introduction	139
7.2. Bearing capacity of a pile under an additional thermal load	140
7.3. A constitutive law of soil–pile interface under cyclic loading: the Modjoin law	143

7.4. Numerical analysis of a thermoactive pile under thermal cyclic loading	145
7.4.1. Reaction to the upper structure	147
7.4.2. Normal force in the pile	148
7.4.3. Mobilized shaft frictions at the soil–pile interface	148
7.5. Recommendation for real-scale thermoactive piles	150
7.5.1. Effect of different loading rates for the applied mechanical load.	150
7.5.2. Effect of thermoactive piles on piled raft foundation	150
7.6. Conclusions	153
7.7. Acknowledgments	153
7.8. Bibliography	154
Chapter 8. Energy Geostructures in Unsaturated Soils	157
John S. McCARTNEY, Charles J.R COCCIA, Nahed ALSHERIF and Melissa A. STEWART	
8.1. Introduction	157
8.2. Thermally induced water flow	159
8.3. Thermal volume change in unsaturated soils	160
8.4. Thermal effects on soil strength and stiffness	161
8.5. Thermal effects on hydraulic properties of unsaturated soils	163
8.6. Thermal effects on soil–geosynthetic interaction.	164
8.7. Conclusions	167
8.8. Acknowledgments	167
8.9. Bibliography	167
Chapter 9. Energy Geostructures in Cooling-Dominated Climates	175
Ghassan Anis AKROUCH, Marcelo SANCHEZ and Jean-Louis BRIAUD	
9.1. Introduction	175
9.2. Climatic factors and their effects on soil conditions and properties	175
9.3. Saturated and unsaturated soil thermal properties and heat transfer	177
9.4. Impact of soil conditions on energy geostructures performance	179
9.4.1. Laboratory experimental design	179
9.4.2. Numerical modeling	180
9.4.3. Laboratory test and numerical results	183
9.4.4. Modeling the full pile	186
9.5. Full scale tests on energy piles	187
9.6. Conclusions	189
9.7. Acknowledgments	190
9.8. Bibliography	190

Chapter 10. Impact of Transient Heat Diffusion of a Thermoactive Pile on the Surrounding Soil	193
Maria E. SURYATRIYASTUTI, Hussein MROUEH and Sébastien BURLON	
10.1. Introduction	193
10.2. Heat transfer phenomenon	194
10.2.1. Soil properties	195
10.2.2. Energy conservation in the transient regime	196
10.3. Numerical modeling of thermal diffusion in a thermoactive pile	197
10.3.1. A two-dimensional model – internal diffusion in the thermoactive pile	198
10.3.2. A three-dimensional model – external diffusion to the surrounding soil	201
10.4. Impact of the long-term thermal operation	202
10.4.1. Groundwater flow effect on the heat diffusion	202
10.4.2. Mechanical durability under thermal cyclic stress	205
10.5. Conclusions	205
10.6. Acknowledgments	207
10.7. Bibliography	208
Chapter 11. Ground-Source Bridge Deck De-icing Systems Using Energy Foundations	211
C. Guney OLGUN and G. Allen BOWERS	
11.1. Introduction	211
11.2. Ground-source heating of bridge decks	213
11.3. Thermal processes and evaluation of energy demand for ground-source de-icing systems	214
11.4. Numerical modeling and analysis results	216
11.5. Summary and conclusions	223
11.6. Acknowledgments	223
11.7. Bibliography	224
PART 3. ENGINEERING PRACTICE	227
Chapter 12. Delivery of Energy Geostructures	229
Peter BOURNE-WEBB with contributions from Tony AMIS, Jean-Baptiste BERNARD, Wolf FRIEDEMANN, Nico VON DER HUDE, Norbert PRALLE, Veli Matti UOTINEN and Bernhard WIDERIN	
12.1. Introduction	229
12.2. Planning and design	230
12.2.1. Coordination and communication	230

12.2.2. Design management	231
12.2.3. System design redundancy.	231
12.2.4. Awareness and skills training	234
12.3. Construction	236
12.3.1. Process quality control	236
12.3.2. Installation details.	237
12.4. System integration and commissioning.	260
12.5. Summary	261
12.6. Acknowledgments	262
12.7. Bibliography	262
Chapter 13. Thermo-Pile: A Numerical Tool for the Design of Energy Piles	265
Thomas MIMOUNI and Lyesse LALOUI	
13.1. Basic assumptions	265
13.2. Mathematical formulation and numerical implementation	266
13.2.1. The load-transfer method	266
13.2.2. Displacements induced by the mechanical load	268
13.2.3. Displacements induced by the thermal load	269
13.3. Validation of the method	270
13.4. Piled-beams with energy piles	271
13.4.1. General method	272
13.4.2. Determination of the integration constants	275
13.4.3. Example of simulation	276
13.5. Conclusions	277
13.6. Acknowledgments	278
13.7. Bibliography	278
Chapter 14. A Case Study: The Dock Midfield of Zurich Airport	281
Daniel PAHUD	
14.1. The Dock Midfield.	281
14.2. Design process of the energy pile system	282
14.2.1. Pile system concept.	282
14.2.2. Problems to solve	283
14.2.3. First calculations	284
14.2.4. Second calculations.	285
14.2.5. Third calculations	287
14.2.6. Final simulations using the TRNSYS program.	288
14.3. The PILESIM program	288
14.4. System design and measurement points	289
14.5. Measured thermal performances of the system	291

Table of Contents xi

14.6. System optimization and integration	293
14.7. Conclusions	294
14.8. Acknowledgments	295
14.9. Bibliography	295
List of Authors	297
Index	299